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CONCEPTUAL STUDY OF ELECTRICAL POWER TRANSMISSION SYSTEMS TO DEEP OCEAN INSTALLATIONS (U)

August 1967

DEPARTMENT OF THE NAVY
NAVAL FACILITIES ENGINEERING COMMAND

NAVAL CIVIL ENGINEERING LABORATORY

Port Hueneme, California

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''CONCEPTUAL STUDY OF
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TO
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August, 1967''

Prepared By

GENERAL DYNAMICS CORPORATION
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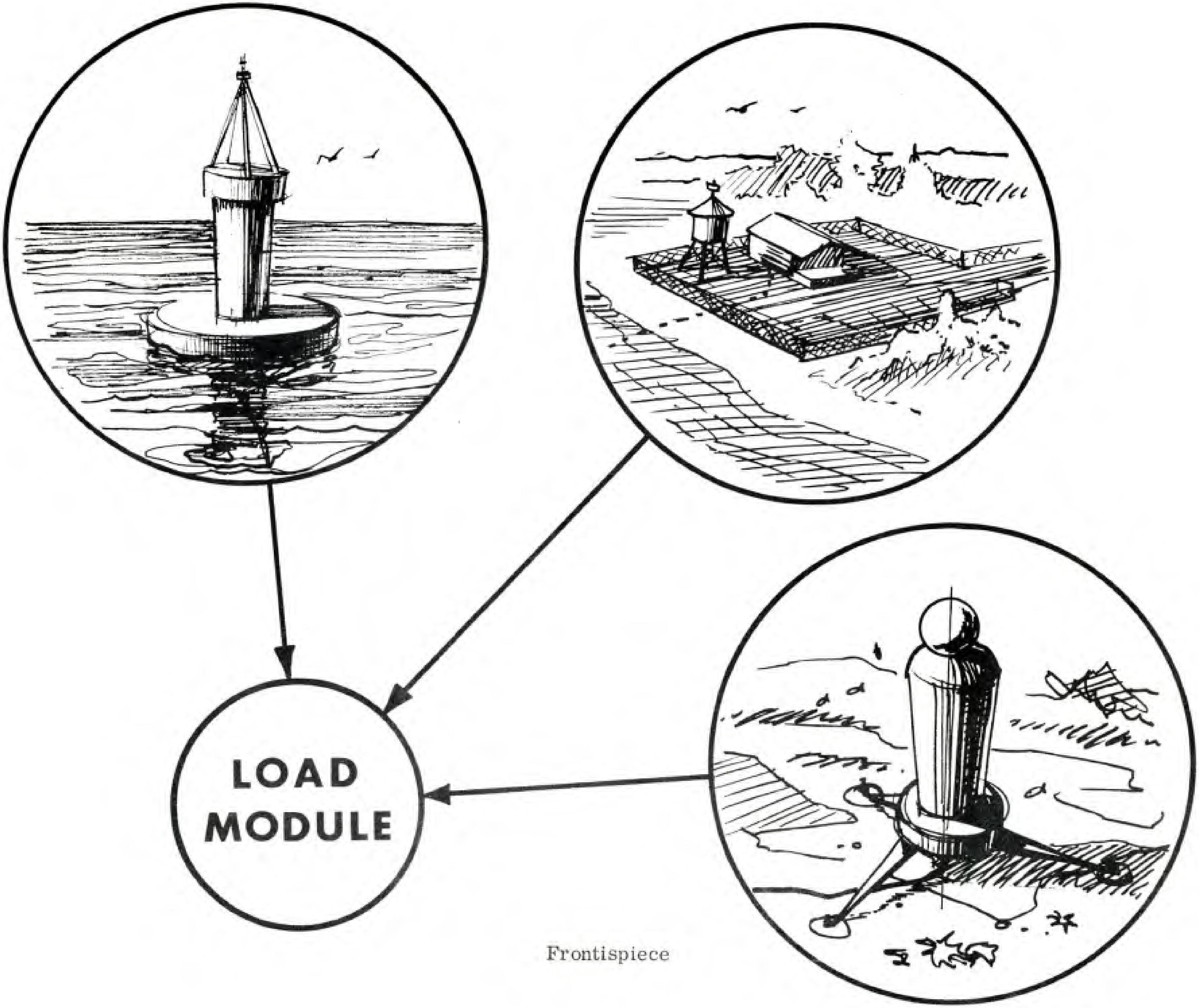
Under

CONTRACT NO. N62399-67-C-0015

For

U. S. NAVAL CIVIL ENGINEERING LABORATORY
Port Hueneme, California

REPORT NO. CR68.004



Frontispiece

PREFACE

The purpose of this study is to determine the technical feasibility and limits of transmitting electrical power to deep ocean installations, and provide comparisons of various power sources applicable to underwater power transmission systems.

This work was performed under Contract Number N62399-67-C-0015 by the General Dynamics Corporation, Electric Boat Division, for the U. S. Naval Civil Engineering Laboratory.

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Irvin M. Waitsman

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Chapter 1

CONCLUSIONS, SUMMARY, AND RECOMMENDATIONS

1.1 CONCLUSIONS

The most serious limitation associated with obtaining usable power at deep ocean depths is the present limitation of watertight cable connectors. There are mechanical and electrical problem areas associated with underwater electrical connectors and hull penetrations used to transmit power to submerged loads encapsulated in a pressure hull. Electrical problems involve meeting the current-carrying capacity at the required voltage with minimum connector contact resistance, dielectric breakdown, heat generation, and the manner of compensating for extreme voltage stress at the termination of the insulation. Mechanical problems pertain to watertightness, material compatibility, strength, the capability of mechanical connection and disconnection submerged, and the ability to terminate effectively the armor wire for the type cable considered in this study.

The limitations are controlled by connector size which affects the voltage level and pin size which affects the current carrying capacity (ampacity); the limits are 4160 volts and 1/0 pin size for a two- or three-pin connector. There are no reliable, high power connectors that can be connected and disconnected under water. The lack of "wet connectors" (Chapter 5) imposes limitations on deployment methods such that electrical connection of the power cable to the load module must be accomplished prior to load module emplacement. Emplacement flexibility is penalized because the load module must be lowered at the end of the power cable or on a common foundation with the power module (in situ). This makes it impossible to "plug into" an existing load module on or in the ocean floor. The problem in no way detracts from the capability of supplying power to the required depths; it shows the need for an underwater connector development program (Chapter 11) to create the "wet connectors" required to facilitate all feasible modes of deployment and emplacement.

Usable AC power - 30 KW to 3000 KW - can be supplied from surface tendered power plants to deep ocean installations at depths from 600 ft to 20, 000 ft within the present state-of-the-art and without technical limitation but neglecting connector limitations.

Usable power of 30 to 1000 KW from shore-based power sources can be supplied to deep ocean installations from 600 ft to 20, 000 ft and 3000 KW from 600 ft to 10, 000 ft within the present state-of-the-art without technical limitations but neglecting connector limitations.

For in situ power locations, the Reactor Power Plant Systems are the most cost effective for power ranges of 30 KW and larger. Within the present state-of-the-art in situ power plants can be deployed to supply 30 KW to 300 KW load requirements at depths from 600 ft to 20,000 ft. Load levels of 1000 KW and 3000 KW are currently depth limited to 2000 ft by hull and heat removal system technology.

Economically, shore based power sources are favored for loads situated between 10 to 50 miles offshore with the exact distance dependent on depth (i.e., true cable distance) and power level conditions. For all other locations, power levels, and depths, surface tendered power plants are most economical. In situ power sources are not economically competitive with either shore or surface sources. However, the surface or shore-based power plant concepts, although apparently more economical, do not remove undersea missions from their dependence on the sea-air interface. This dependence will hamper undersea missions of long endurance by virtue of storm conditions, at sea collisions, inability to perform covert operations, and other factors. The in situ systems have the inherent characteristics of long endurance, power growth potential, and, in certain designs, high reliability and excellent past performance. The initiation of the heat removal development program detailed in Chapter 11 will greatly improve the adaptability of reactor power plant systems to the deep ocean marine environment.

For the purposes of providing power for many varied missions within the life expectancy of the power system, a general utility underwater power transmission system was studied. This system has the capability of supplying power to various types of loads irrespective of emplacement site and length of each mission. It uses a reactor power plant system which is designed to be emplaced to depths of 6000 ft and which will provide a versatile, reliable, and relocatable system within the present state-of-the-art.

During the course of this study, in consultation with most major equipment manufacturers, it has been concluded that light weight, small volume electrical equipment and devices applicable to this study do not exist.

AC voltage transmission is more cost effective for distances up to 10 miles between the load module and power sources; distances from 10-500 miles involve an AC-DC trade-off; and beyond 500 miles, DC is most cost effective as shown by Figure 1-1. For the intermediate range it may in general be concluded that for long distances and high power, use DC; for long distance, low power and shallow depth, use DC; and for long distance, low power and deep depth, use AC.

The most cost effective in situ power system with separate power and load modules has a 480-volt, 3-phase, 60-cycle source for the 30, 100 and 300 KW loads and a 4160-volt, 3-phase, 60-cycle source for the 1000 and 3000 KW load requirements. In both cases, power is generated and transmitted at the same voltage.

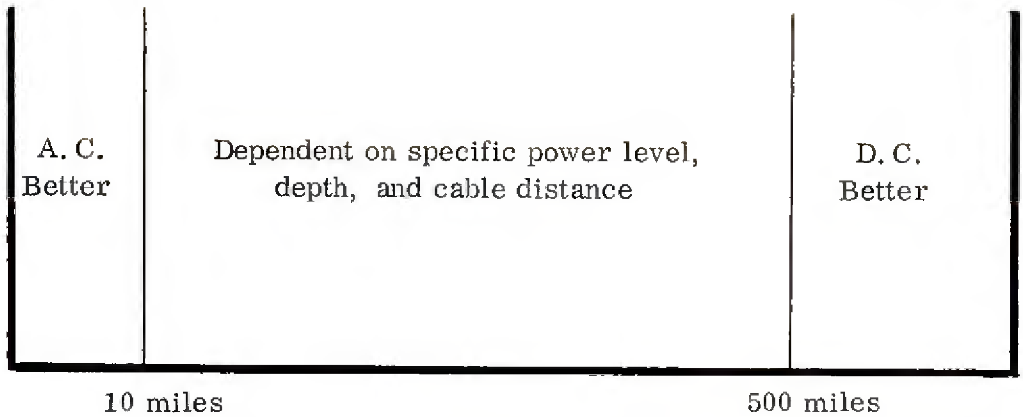


Figure 1-1. AC versus DC as a Function of Distance from Shore

Table 1-I is a summary of the most cost effective combination of transmission voltage and wire sizes. Cable distances of 100 ft apply to in situ applications: 600 to 30, 000 ft distances would be used to connect surface tendered power plants to ocean floor load modules; cable distances of 60, 000 to 3, 000, 000 ft are typical for use with load modules powered from shore bases.

1.2 SUMMARY

Diesel engine generator systems were selected for the surface and shore-based power sources because they are cost effective, reliable,and well-proven in marine usage. Nuclear reactor powered,steam generating systems were selected for each in situ application.

Surface power plant containment vessels for Underwater Power Transmission Systems are unmanned, double hull, thick disc, surface following, steel structures of modular construction and are designed to withstand 150 MPH winds, 60 foot waves, and 10 knot currents, all acting concurrently. The five power levels required will fit into three basic hull designs. Both power plant and station keeping system are fully automated.

Adequate holding power and excursion limitation for the surface tendered power plant is provided by a static,four point compound catenary mooring system with legs spaced 90° apart. Each compound catenary mooring leg, starting from the bottom, will consist of a fluke type anchor, a clump, and a polyurethane clad,wire line terminating near the surface. The weight of each mooring leg is supported by a catenary support buoy. The buoy for each leg is located 1000 ft outboard from the surface-tendered power source with the plant held in the center of the array by 4, 4-inch diameter, nylon lines.

Table 1-I. Summary of Transmission Voltages and the Sizes

CABLE DISTANCE ft / POWER KW		100	600	1000	2000	6000	10, 000	15, 000	20, 000	30, 000	60, 000	300, 000	600, 000	3, 000, 000
30	(1)	480	480	480	480	600	4160	4160	4160	4160	4160	13, 800*	13, 800*	34, 500*
	(2)	#6	#6	#6	#4	1/0	#6	#6	#6	#6	#6	#2	#2	#1
100	(1)	480	480	480	600	4160	4160	4160	4160	4160	4160	13, 800*	13, 800*	34, 500*
	(2)	#4	#4	#2	1/0	#6	#6	#6	#6	#6	#4	#2	1/0	#1
300	(1)	480	480	480	600	4160	4160	4160	13, 800	13, 800	13, 800	13, 800*	34, 500*	34, 500*
	(2)	2-1/0	4/0	4/0	350	#6	#6	#4	#2	#2	#2	1/0	#1	4/0
1000	(1)	4160	4160	4160	4160	4160	4160	13, 800	13, 800	13, 800	13, 800	34, 500*	34, 500*	34, 500*
	(2)	#4	#4	#4	#4	#2	1/0	#2	#2	#2	#2	#1	2/0	600
3000	(1)	4160	4160	4160	4160	13, 800	13, 800	13, 800	13, 800	13, 800	13, 800	34, 500	34, 500*	
	(2)	300	300	300	300	#2	#2	#2	#2	1/0	1/0	#1	350	

Notes:

(1) Indicates nominal transmission voltage
(2) Indicates A. W. G. or M. C. M. wire size
* Denotes DC -- all others AC

In situ power source hulls for submergence to 6000 ft or deeper are designed void of mechanical penetrations to provide a safe, reliable system. Mechanical penetrations for depths beyond 6000 ft are developmental and beyond the current state-of-the-art. For determining heat transfer area required for waste heat removal, the following environmental temperatures were used:

DEPTH (ft)	TEMPERATURE (°F)
Surface	85
600	75
2,000	65
6,000	55
10,000 or deeper	45

In situ power sources or load modules powered from shore or surface tendered sources are deployed by the winch down method with the winch and cable drum located in the foundation of the load module or in the case of in situ in a common base. Winch down will be against a positive buoyancy to provide well controlled ascent and descent with maximum safety and reliability.

Table 1-II lists the technical limits for transmission voltage as a function of delivered power and distance. Limits imposed are due to cable material, geometric configuration, and voltage drop. Material and geometric configuration influence cable reactance which is primarily responsible for these limits.

Table 1-II. Limits of Transmission Voltage as a Function of Power and Distance

VOLTAGE	TRANSMISSION DISTANCE	LOAD LEVEL
1. AC 4160 V	10 miles	30 to 1000 KW
	50 miles	30 to 300 KW
13800 V	10 miles	30 to 3000 KW
	50 miles	30 to 3000 KW
34500 V	10 miles	30 to 3000 KW
	50 miles	30 to 3000 KW
	100 miles	30 to 3000 KW
2. DC 4160 V	10 miles	30 to 1000 KW
	50 miles	30 to 300 KW
	100 miles	30 to 100 KW

Table 1-II. (Continued)

VOLTAGE	TRANSMISSION DISTANCE	LOAD LEVEL
13800 V	10 miles	30 to 3000 KW
	50 miles	30 to 3000 KW
	100 miles	30 to 1000 KW
	500 miles	30 to 100 KW
34500 V	10 miles	30 to 3000 KW
	50 miles	30 to 3000 KW
	100 miles	30 to 3000 KW
	500 miles	30 to 1000 KW

The electrical protection system has been designed to protect the transmission system from mechanical and electrical failure. Serious or lasting faults occurring in the power plant cause the plant to shut down. All other faults, on the transmission line or at the load module, are referred to the one main breaker in the power plant for fault isolation. Secondary distribution system status is referred to a fault location panel located in the power plant to allow appraisal of the load module condition.

A cable, having three concentric stranded copper conductors for AC systems (two conductors for DC), each insulated with polyethylene, is used for all underwater power transmission systems. The cable is provided with necessary shielding, grounded neutral, binding tapes, filler, jacketed armor wires and an extruded polyurethane jacket around the outside to provide an environmental barrier. Single lay armored cable is utilized in cables supplying power from all shore-based facilities and double lay armored cable is used to supply power from all surface tendered plants. Surface tendered cables require a 30,000 psi armor material working strength for depths to 10,000 ft while depths of 15,000 ft and over require armor material having a working strength of 125,000 psi. Cable configuration and wire sizes selected are standard or off-the-shelf items.

1.3 RECOMMENDATIONS

The further development of underwater power transmission systems is firmly recommended. Their usefulness is obvious in promoting many major undersea programs presently limited by low-power, short-duration electrical generating systems.

A connector development program, as outlined in Chapter 11, should be instituted to develop connectors suitable for connection and disconnection in a submerged environment of the size required to mate with the conductor sizes and be compatible with the transmission voltages recommended as a result of this study.

The concept of the general purpose utility underwater power transmission system capable of adaption to various missions and durations has considerable merit, is within the present state-of-the-art, and is therefore firmly recommended. An in situ general utility system should be pursued aggressively for an application within the limits of distance, depth, and power level defined in Section 9.4 with the objectives of increased versatility and reduced total costs.

A development program of the type defined in Chapter 11 should be instituted to define optimum heat rejection system concepts and parameters for deep submergence applications at the power levels and depths applicable to this study.

An aggressive review by present manufacturers of electrical equipment required in ocean environment with the objectives of reducing bulk size and weight of general purpose equipment as well as developing pressure compensated devices to reduce pressure hull requirements and costs would be well rewarded in the development of future undersea missions at lower overall costs.

Chapter 2

INTRODUCTION

The purpose of the study is to determine the technical feasibility and technical limits of transmitting electrical power to deep ocean installations and structures. In the study, a cost-effective approach has been used to develop a high-quality, highly reliable power transmission system utilizing presently available components or identifying development programs needed to supply components which are within present technology.

The systems investigated involved the transmission of 30, 100, 300, 1000, and 3000 KW power to ocean depths of 600, 2000, 6000, 10, 000, 15, 000 and 20, 000 ft from:

- surface-tendered (floating) power sources,
- in situ (emplaced on the ocean floor) power sources, and
- shore-based power sources.

Definitive criteria for the design of 30 surface-tendered, 22 in situ, and 19 shore-based systems were evolved as was an optimization for a single power system which will provide a large degree of flexibility for a variety of applications totally within the present state-of-the-art. A critical discussion of feasible power sources is included.

2.1 DESIGN CONSTRAINTS

A number of constraints were applied at the outset of the study. These constraints were as follows:

- power levels stated were to be at load module terminal point.
- usable power was defined as 480 volts, 3-phase, 60 cycles.
- a single (non-distributed) load was to be considered.
- electrical loads at deep ocean installations were to comprise lighting systems, motor-driven operation equipment, environmental control systems, and communication or electronic systems.
- protective needs were to be restricted to the transmission system and were not to include the mission requirements of the load module.
- for purposes of selecting and defining development programs, a time base of 1970-1975 was considered as the requirement for availability.
- emergency power levels and type were to be defined by the power transmission system requirements and not by the mission requirements of the load module.

2.2 PROGRAM EVOLUTION

2.2.1 Basic Approach

In order to properly develop a procedure for determining the most cost-effective concepts for each of the power source locations and for the many variables involved in the transmission of power for underwater use, several basic premises had to be established. A preliminary review of the system's gross factors (i.e., the energy sources, cables, connectors, transmission system, pressure hulls, and load modules), weighing them against such parameters as energy source and load module location, power level, and depth, established the following premises:

- Where moderate length transmission cable systems are required, the cable represented the most significant cost.
- Where cable support systems are required such as could be found in vertical water column arrangements the cost and complexity of the cable support system in conjunction with the cable represented the most significant cost.
- For in situ systems, the size, and therefore the cost, of the pressure hull became the most significant factors.

The above premises constituted the basic approach used to evaluate the cost effectiveness of the various subsystems, and to develop the most cost effective system for each power source location.

However, in some instances, the premises seemed self-contradictory. For instance, the smallest size of cable requires the highest transmission voltage, but the premise of minimum hull size dictates that the transmission voltage be kept as low as possible to eliminate large power conditioning transformers from the load module. On the basis of these contradictions it seemed that one set of premises could not be applied to all three locations of the power source. This suggested a basic approach, namely, to review the power transmission systems on the basis of significant cable lengths, viz:

a. 0 - 100 ft, representative of in situ power source locations,

b. 600 - 30, 000 ft, representative of surface-tendered power source locations,

c. 60, 000 - 3, 000, 000 ft, representative of shore-based power sources.

Items (b) and (c) could be applied to in situ plants for specific missions, and item (c) could also be applied to surface-tendered power sources to suit specific missions.

The initial analysis evolved around systems employing the moderate length cables (600-30, 000 ft). The main emphasis was to keep cable sizes to a minimum, and to thus create the most cost-effective system due to lower cable acquisition costs and simpler, less costly, cable support systems. When the moderate cable length systems (i.e., systems with the power source located on the surface) had been developed, the other extremes of cable length were investigated and subsequently required modification to the parameters and the selections of subsystems to evolve the most cost effective system for these specific areas of interest.

During the entire study program, the initial constraints specified in paragraph 2.1 were re-evaluated to insure compatibility with the results obtained in the study. Modifications were made in certain areas to insure that the constraints were realistic for all applications. In addition, development or "high risk" areas were identified, and on the basis of these findings, specific programs have been recommended. The results established in this report are valid for the previously mentioned constraints. Parameters which are mission or load module oriented such as degree of load power factor variation, total system life required, power profile and other criteria that normally define total system constraints and design criteria such as length of mission, must be taken into consideration prior to completion of detail design. The definition of these parameters (load module and mission) may have an influence on the final selection of the principal parameters for underwater power transmission systems such as voltage and cable size and transmission efficiency.

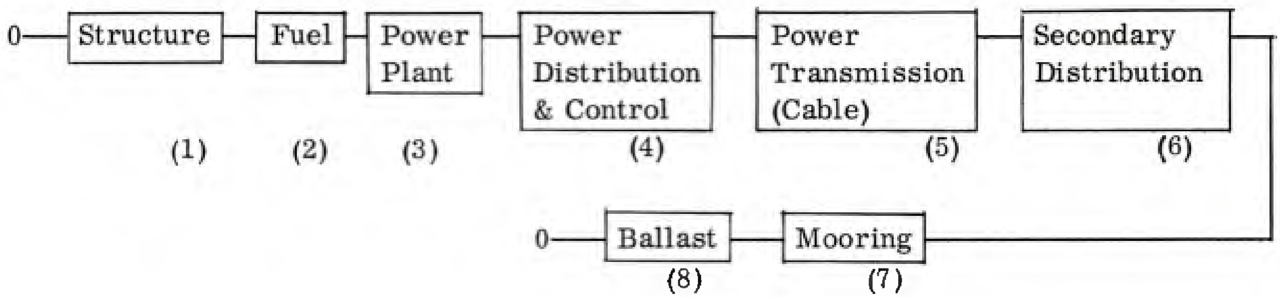
2.2.2 Reliability Considerations

The concept of long-term, uninterrupted, and unmanned system operation requires inherent reliability in the design of systems, components, and equipment. Determination of relative quantitative reliability factors for the alternate configurations within each of the three systems (e.g. intersystems trade offs) was not considered feasible during the study period. However, all trade-off decisions involved qualitative evaluation against basic reliability criteria. The latter included simplicity of design, adequacy of mechanical as well as electrical circuit protection, and minimization of potential single-point failure modes.

For intrasystem trade offs (e.g. surface vs. shore vs. in situ power sources) mission reliability requirements must be known and considered prior to choosing one method over the other. The study approach was to define the minimum system required for maximum reliability. Reliability was defined as that required of the system elements for mission success exclusive of mission-oriented factors, such as the deployment site, the type of load module, and the mission requirements regarding the true cost of mission abort (e.g., if a time -sequence mission is interrupted, then the entire mission must be repeated). There are two basic ways of maximizing reliability; namely, by utilizing components and elements in each system that are of maximum reliability, or by backing up elements and/or components with redundancy which can be either active or stand by. For each system (e.g., shore-surface or in situ) the basic reliability is different due to the number of elements in the operational systems as discussed below.

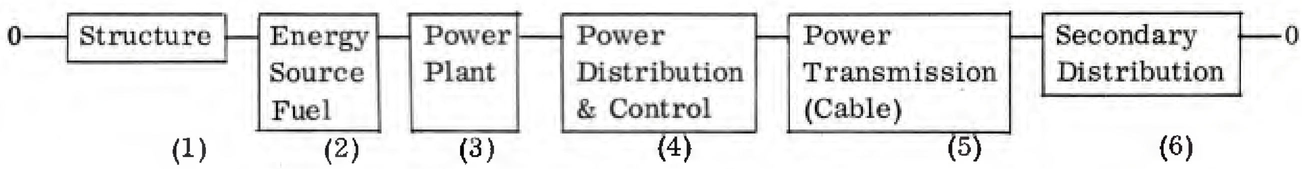
2.2.2.1 REDUNDANCY CONSIDERATIONS – The simplified functional reliability models (measured by mission success) and the reliability equations for the three configurations are:

SURFACE-TENDERED SYSTEM



$$R_{sur} = R_1 \times R_2 \times R_3 \times R_4 \times R_5 \times R_6 \times R_7 \times R_8$$

IN SITU & SHORE-BASED SYSTEMS



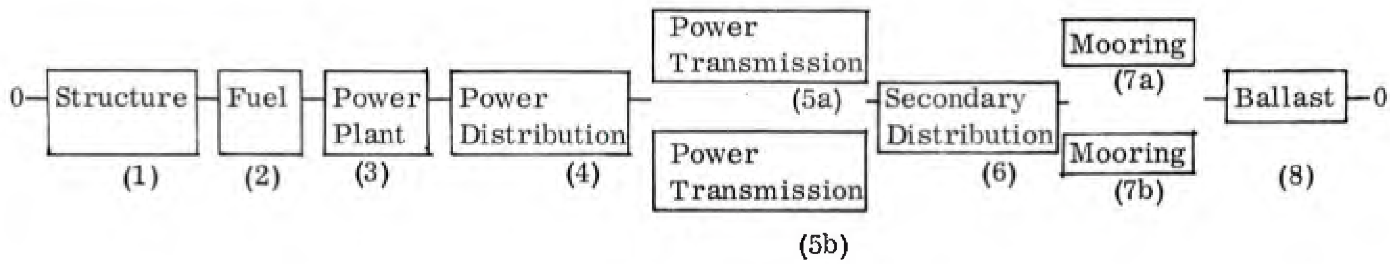
$$R_{shore} = R_1 \times R_2 \times R_3 \times R_4 \times R_5 \times R_6$$

These equations are based on the assumption that all functional blocks are critical to the success of the mission and all are in series. The models show the surface arrangement to be the least reliable (assuming equal reliability of each functional block) merely because it has more blocks in series.

Unless special area deployment is implemented by the procuring activity, the surface-tendered system is also the most vulnerable to failure from external causes, such as structural damage from storms or from collisions with ships, and damage to the mooring or power transmission subsystems caused by surface ships or submarines. For this reason, both active (parallel) redundancy for the mooring subsystem and standby redundancy for the power transmission subsystem were considered for the surface system.

The simplified functional model of the surface-tendered system with completely redundant mooring and power transmission subsystems is shown below.

SURFACE-TENDERED SYSTEM(WITH REDUNDANT POWER & MOORING SUBSYSTEMS)



$$R_{surface} = R_1 \times R_2 \times R_3 \times R_4 \times \left[2R_{5a} - R_{5a}^2\right] \times R_6 \times \left[2R_{7a} - R_{7a}^2\right] \times R_8$$

Although a valid analysis of reliability improvement through use of the redundant systems cannot be obtained without actual hardware failure rates or valid reliability indices for the functional blocks, for comparison purposes, a set of reliability indices was assigned as follows: (The higher factors are indicative of less vulnerability to damage from external causes, and greater opportunity for preventive maintenance.)

FUNCTION	SHORE	SURFACE	IN SITU
Structure	.9999	.99	.999
Fuel/Energy Source*	.9999	.99	.999*
Power Plant	.9999	.99	.999
Power Trans (Redundant)	.99	$(2)(.99)-(.99)^2 = .9999$	.999
Power Dist (Redundant)	.9999	.99	.999
Secondary Dist.	.999	.999	.999
Mooring (Redundant)		$(2)(.99)-(.99)^2 = .9999$	
Ballast		.9999	
Comparative Functional Reliability	R = .9886	R = .9571	R = .9940

Assuming ideal deployment of the surface-tendered system, with regard to area and depth the vulnerability differentials can be decreased. If all blocks in each arrangement are assigned a .99 reliability, the surface arrangement is still the lowest. A completely redundant surface arrangement, with two buoys, etc. would probably yield the highest reliability of the three with, of course, doubled cost. Making the mooring subsystem and power transmission subsystem redundant in the surface system might not decrease the vulnerability to damage from external causes, since the physical orientation can not be far enough apart to assume that the backup system would be unharmed if a ship cut one of the redundant systems.

Redundancy of critical items within the functional subsystems can be considered for improving system reliability. Critical items, as determined by a failure modes effects analysis of the hardware system, particularily those items which present single-point failure modes with high failure potential, should be made redundant. However, in cases where the probability of failure is not high, redundancy can introduce additional unreliabilities and each case must be critically examined on its own merits. In many cases it is better to have one high-reliability part than to have two that are less reliable. In these cases, the tradeoff between the additional cost of the high-reliability part and the reliability differential at the system level must be made to assist in equipment and component selection. The tradeoff would also have to be weighted by the applicable corrective and preventive maintenance factors for the particular arrangement.

For manned bottom-placed load modules, the in situ power source system represents the highest system reliability in performing the function of supplying power over the mission life. Within the in situ power source module, any redundancy of major equipment may jeopardize the overall reliability by the addition of cross-connect mechanisms. The most reliable means for protecting the load module would be a completely independent source of energy, such as a battery, located in the load module and sized to provide the required power for life support housekeeping and the necessary abort mechanisms. This location precludes any dependency on external equipment for the safe shutdown and return to the surface.

Chapter 3

ENVIRONMENT

The placement and maintenance of an underwater power transmission system is subject to all the environmental conditions of the sea-air, sea surface-subsurface, and subsurface-bottom interfaces. The effects of sea states, currents, bottom sediment, temperature variation, salinity, and marine life must be accounted for in the design of such a system.

Information on the environment in which submarine cable systems are placed is of vital interest in designing, selecting routes for, placing, and repairing this type of transmission facility. Existing data are summarized and evaluated in this chapter, and their application to underwater power transmission systems is considered.

The eventual design and deployment of an underwater power transmission system capable of supplying power to 20,000 ft will enable the user to reach more than 95% of the ocean bottoms throughout the world.

3.1 SEA-AIR INTERFACE

The purpose of defining the sea-air interface is to provide a series of design parameters for the selection of surface hull shapes. These shapes are directly influenced by the surface forces and indirectly by the forces generated on the mooring and cable systems. Surface conditions for the particular area of deployment are an important design parameter. Both the average sea state and the worst sea state expected should be considered. Figure 3-1 illustrates the weather averages and sea states in various coastal waters. Typical surface disturbances are shown in Figures 3-2 and 3-3, which illustrate the frequency of gale force winds in the north Atlantic in winter and summer, respectively.

Winds, gales and storms (storm tracks) depend to a large degree on large, well-defined regions of high and low pressure. These winds persist from month to month throughout the year or during a considerable part of it. In general, the geographic distribution of these areas of high and low pressure is fairly systematic and does not vary much between consecutive months. However, there are some large seasonal differences in the pressure patterns and prevailing winds shown on these charts for the summer and winter months.

Charts giving the prevailing or vector mean winds over the earth's surface during any month generally show a close relation to the pressure distribution. Over the oceans, bad weather consisting of widespread cloudiness, precipitation, high surface winds and turbulence is essentially a phenomenon associated with rising air currents (lows). Bad weather zones are generally absent in high-pressure areas, which are regions of descending air (regions of surface divergence). When two air streams converge, conditions conducive to the lifting of air masses exist, and bad weather zones result.

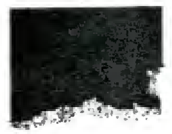
Regions favorable for bad weather are the low pressure zones near the equator and the western and northern portions of the northern hemisphere oceans. These are the regions of westerlies and migratory lows.

WEATHER AVERAGES and SEA STATES FOR SELECTED OFFSHORE AREAS

world report — Major Hazards of the Season

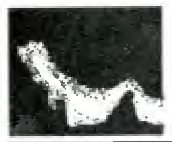
TEXAS

LOUISIANA



Spring squall lines carry heavy rain, some hail and brief winds of 40 to 60 mph for 5 to 15 minutes and gusts to 90 mph. Waves up to 25 ft. can be generated by these squall lines.

PERSIAN GULF & ARABIAN SEA



There are no well-known hazards in the Persian Gulf. The shift to the southwest monsoon in the Arabian Sea occurs as a storm.

COOK INLET

Southeast gales last through May. Ice flow occurs in the spring.

CALIFORNIA

None

NIGERIA

"Tornados" or squall lines with winds up to 35 knots last through May.

NORTH SEA

Spring storms from wave cyclones over the North Atlantic continue to stir up the North Sea through May.

Area	Months	Wind: Usual Wind Direction	Wind: Usual Wind Speed	Wind: Percent of Winds over 35 Kts	Waves (In Open Water, Percentage): Over 5 Ft.	Waves: Over 8 Ft.	Waves: Over 12 Ft.	Storms	Storms: Usual Maximum Winds	Storms: Usual Rate of Rain	Storms: Usual Maximum Deep Water Wave	Rain & Snow (Precipitation): Mean Amount	Lowest Mean	Highest Mean	Percent of Hours With Precipitation	Percent of Hours with Snow	Temperature: Mean	Coldest Month	Warmest Month	Mean Sea Temp. °F	Date of Ice Breakup	Tide & Current: Maximum Tide Range in Month	Maximum Expected Current	Fog & Cloud: Less Than 5 Miles Visibility Percent of Time	Clouds Over 80% of Sky Percent of Time
TEXAS	JUNE	S. East	4-10 Kts	1	17	2	0	Tropical Storms and less frequently Hurricanes	50 Kts	Heavy	30 ft.	4.02	0.31	11.86	5	0	81.4	79.9	82.3	84.0°		1 ft.	0.9 Kts	<5	20
	JULY	S. East	4-10 Kts	<1	14	2	0		50 Kts	Heavy	30 ft.	6.62	0.59	17.96	8	0	83.0	81.9	84.5	86.4°		1.7 ft.	0.9 Kts	<5	20
	AUGUST	South	4-10 Kts	<1	12	2	0		60 Kts	Heavy	35 ft.	4.51	2.01	13.18	6	0	83.2	82.2	84.0	86.7°		2.0 ft.	0.8 Kts	<5	20
LOUISIANA	JUNE	S. East	4-10 Kts	1	17	2	0		50 Kts	Heavy	30 ft.	6.79	2.09	11.75	8	0	82.4	79.6	83.6	82.7°		1 ft.	0.8 Kts	<5	20
	JULY	S. East	4-10 Kts	<1	14	2	0		50 Kts	Heavy	30 ft.	7.20	3.23	11.08	10	0	83.1	80.0	85.2	84.7°		2.5 ft.	1.0 Kts	<5	20
	AUGUST	S. East	4-10 Kts	<1	12	2	0		60 Kts	Heavy	35 ft.	5.86	2.81	10.87	8	0	83.5	82.8	84.9	84.9°		2.0 ft.	1.0 Kts	<5	20
PERSIAN GULF & ARABIAN SEA	JUNE	S. West	22-33 Kts	11	40	20	15	1 Tropical Cyclone in 12 Years	60 Kts	Heavy	30 ft.	0.00	.00	.00	0	0	89.9	88.5	90.9	84.0°		4 ft.	0.9 Kts	0	<1
	JULY	S. West	22-33 Kts	18	45	20	15		60 Kts	Heavy	30 ft.	0.02	.00	0.11	3	0	90.4	89.0	91.5	86.0°		4 ft.	0.8 Kts	0	<1
	AUGUST	S. West	11-21 Kts	7	40	18	12		60 Kts	Heavy	30 ft.	0.00	.00	.00	<1	0	89.1	86.7	90.5	88.0°		4 ft.	0.7 Kts	0	<1
COOK INLET	JUNE	S. West	4-10 Kts	1	3	2	2	Pacific Cyclones	40 Kts	Heavy	30 ft.	1.33	0.30	2.94	22	0	53.6	50.6	55.0	45°		10-20 ft.	1.0 Kts	15	70
	JULY	East	4-10 Kts	<1	4	2	2		40 Kts	Heavy	30 ft.	1.80	.97	3.28	21	0	57.1	55.9	59.6	48°		10-20 ft.	1.2 Kts	20	70
	AUGUST	S. West	11-21 Kts	<1	5	2	2		35-40 Kts	Heavy	25 ft.	2.38	.23	4.01	25	0	55.1	53.2	58.6	55°		10-20 ft.	1.2 Kts	25	70
CALIFORNIA	JUNE	North	11-21 Kts	<1	26	5	2	Pacific Cyclones	None	None		0.03	.00	.15	4	0	66.3	64.8	68.7	56.5°		6 ft.	0.4 Kts	12	35
	JULY	North	11-21 Kts	0	23	5	2		None	None		0.01	.00	.08	4	0	69.8	67.6	70.5	57°		6 ft.	1.2 Kts	10	60
	AUGUST	North	11-21 Kts	0	20	5	2		None			0.09	.00	.87	3	0	71.1	69.0	73.2	57.5°		1-7 ft.	1.2 Kts	10	60
NIGERIA	JUNE	S. West	11-21 Kts	0	15	1	<1	Squall Lines	40 Kts	Very Heavy	30 ft.	15.28	8.11	22.0	29	0	79.3	78.5	80.8	80.0°		8-10 ft.	1.0 Kts	5	40
	JULY	S. West	4-10 Kts	0	19	1	<1		40 Kts	Very Heavy	30 ft.	9.77	9.15	31.93	35	0	77.4	76.7	78.7	78.0°		5-8 ft.	0.5 Kts	<5	40
	AUGUST	S. West	11-21 Kts	<1	20	2	<1		40 Kts	Very Heavy	30 ft.	10.30	1.29	31.03	35	20	77.3	75.9	78.5	75.0°		5-8 ft.	0.5 Kts	5	35
NORTH SEA	JUNE	S. West	4-10 Kts	1	17	3	.2	Atlantic Wave Cyclones	40 Kts	Heavy	30 ft.	59.2 M.M.	15.7 M.M.	126.1 M.M.	15	0	17.2°C	15.4°C	19.4°C	54°		8-15 ft.	0.4 Kts	20	45
	JULY	N. West	4-10 Kts	1	21	3	0		40 Kts	Heavy	30 ft.	71.1 M.M.	25.4 M.M.	167.3 M.M.	17	0	19.2°C	17.3°C	21.3°C	58°		8-15 ft.	0.5 Kts	20	40
	AUGUST	West	4-10 Kts	1	26	3	0		50 Kts	Heavy	35 ft.	95.0 M.M.	8.8 M.M.	171.5 M.M.	12	0	18.6°C	16.1°C	21.9°C	60.0°		8-15 ft.	0.4 Kts	20	45

Figure 3-1.

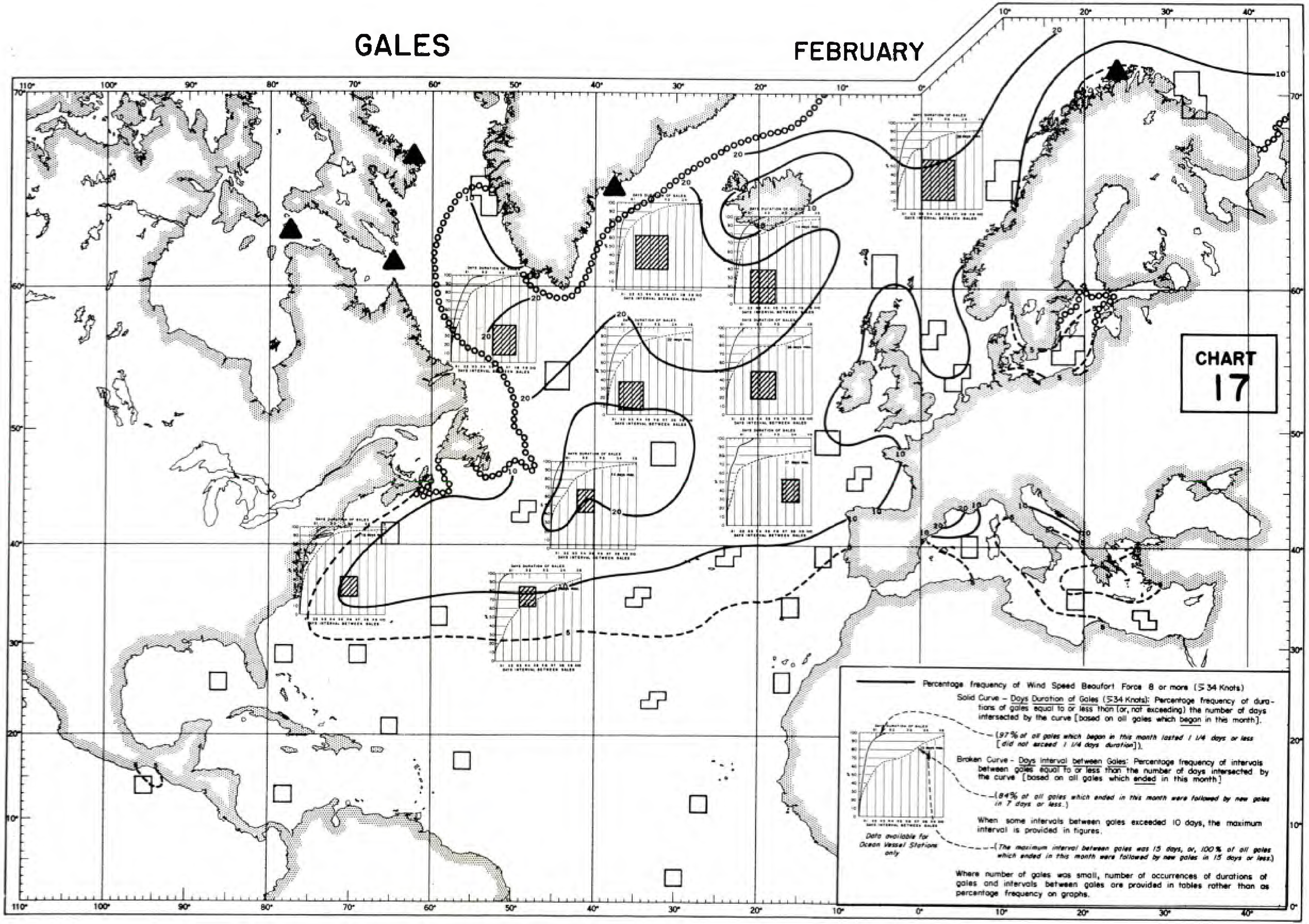


Figure 3-2. Weather in Northern Atlantic (February)

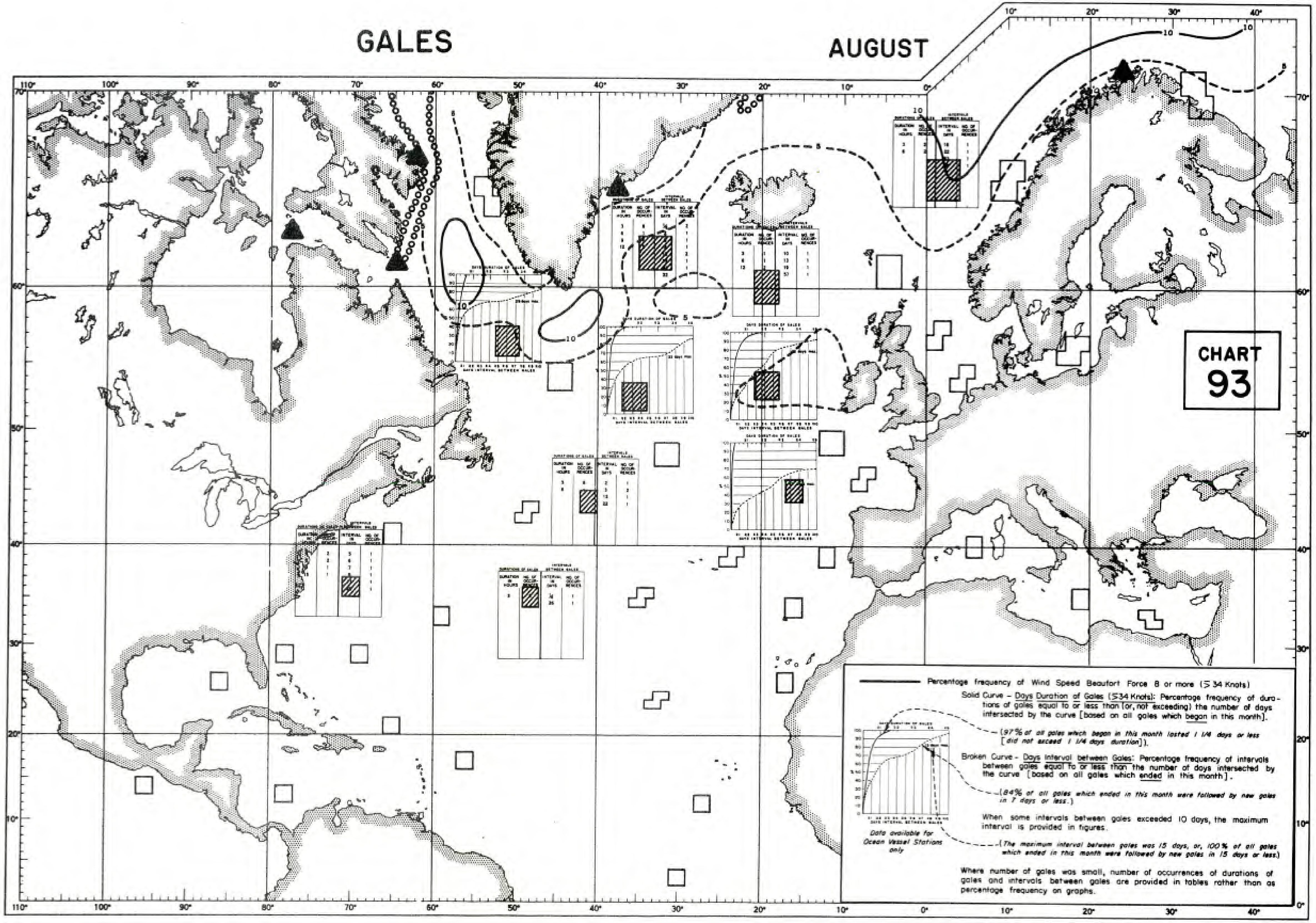


Figure 3-3. Weather in Northern Atlantic (August)

Concurrent with wind are waves generated on the water surface as a function of wind velocity and duration. The parameters used to describe wave characteristics such as height, period, length and velocity are shown in Tables 3-I and 3-II.

Table 3-III gives an indication of the worst conditions of sea state and wave forces. At hurricane condition (sea state 9), David Taylor Model Basin (DTMB) lists a wind range of 64 to 71 knots and an average wave height of 80 ft. These figures are not in close agreement with the design conditions of the Office of Naval Research (ONR) Guidance Committee recommendations or the actual data recorded by General Dynamics' Convair division's prototype Buoy Bravo during hurricane Betsy.

The Convair study states that Buoy Bravo was subject to approximately 70-80% of hurricane Betsy's impact, which resulted in wind recordings of 110 mph and waves of 50-ft height. These conditions are closer to those described in the ONR Guidance Committee design recommendations (150-mph winds with 60-ft waves) if the recorded data is extrapolated to an impact force of 100%. It is recommended that design criteria of 150-mph wind velocity and 60-ft waves be applied as design parameters for surface structures and modules associated with underwater power transmission systems.

3.2 CURRENTS

Surface and subsurface currents vary, according to location, from an extreme of approximately 5 knots to no current. In general, the average bottom currents should not exceed one knot. Generally, the equatorial and warm currents on the western sides of the oceans have surface speeds of 2 or 3 knots; specific examples are the Gulf Stream, Kuroshio current, East African current and the East Australian coastal current. Figure 3-4 shows examples of current velocity profiles in various ocean sectors. From the observations presented in Figure 3-4, two design conditions for underwater power transmission systems have evolved. Design condition "A" presents a maximum surface current of 6 knots which could be the result of average storm conditions. Design condition "B" presents a current profile for surface currents of 3 knots with stronger subsurface currents to a depth of 1000 meters (3280 ft). Available evidence suggests that velocities below 1000 meters are generally less than 0.35 knots.

The current profiles "A" and "B" may be used with other surface currents of greater or lesser magnitudes by utilizing the same ratio of decay (see Figure 3-5). An application of this principle may be extended to the ONR Guidance Committee's design recommendation for a surface current of 10 knots. A design parameter of 10 knots surface current is recommended for surface structures or modules with an anticipated deployment in oceans subject to hurricane conditions. At depths below 3660 meters (12,000 ft), design currents may be assumed to be effectively zero.

Typical current speeds versus depth are shown in Figure 3-6, A through G, for areas of potential interest.

3.3 OCEAN BOTTOM GEOLOGICAL CONDITIONS

Ocean bottom topography to 6000 ft includes the continental shelves, most of the continental slopes, shallow areas of midocean ridges, the borders of atolls and islands, and the tops of some seamounts. Depths to 20,000 ft encompass the remaining portions of the ocean floors, with the exception of deep ocean trenches and

Table 3-I. Wind Waves at Sea

1	WIND VELOCITY KNOTS	4, 5, 6, 7, 8, 9, 10, 20, 30, 40, 50, 60, 70
2	BEAUFORT WIND AND DESCRIPTION	1 LIGHT AIR; 2 LIGHT BREEZE; 3 GENTLE BREEZE; 4 MODERATE BREEZE; 5 FRESH BREEZE; 6 STRONG BREEZE; 7 MODERATE GALE; 8 FRESH GALE; 9 STRONG GALE; 10 WHOLE GALE; 11 STORM
3	REQUIRED FETCH IN MILES — FETCH IS THE NUMBER OF MILES A GIVEN WIND HAS BEEN BLOWING OVER OPEN WATER	50, 100, 200, 300, 400, 500, 600, 700
4	REQUIRED WIND DURATION IN HOURS — DURATION IS THE TIME A GIVEN WIND HAS BEEN BLOWING OVER OPEN WATER	5, 20, 25, 30, 35

IF THE FETCH AND DURATION ARE AS GREAT AS INDICATED ABOVE, THE FOLLOWING WAVE CONDITIONS WILL EXIST. WAVE HEIGHTS MAY BE UP TO 10% GREATER IF FETCH AND DURATION ARE GREATER.

5	WAVE HEIGHT CREST TO TROUGH IN FEET	1, 2, 4 WHITE CAPS FORM, 6, 8, 10, 15, 20, 25, 30, 40, 50, 60
6	SEA STATE AND DESCRIPTION	1 SMOOTH; 2 SLIGHT; 3 MODERATE; 4 ROUGH; 5 VERY ROUGH; 6 HIGH; 7 VERY HIGH; 8 PRECIPITOUS
7	WAVE PERIOD SEC.	1, 2, 3, 4, 6, 8, 10, 12, 14, 16, 18, 20
8	WAVE LENGTH FEET	20, 40, 60, 80, 100, 150, 200, 300, 400, 500, 600, 800, 1000, 1400, 1800
9	WAVE VELOCITY KNOTS	5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60
10	PARTICLE VELOCITY FEET/SEC.	1, 2, 3, 4, 5, 6, 8, 10, 12, 14
11	WIND VELOCITY KNOTS	4, 5, 6, 7, 8, 9, 10, 20, 30, 40, 50, 60, 70

This table applies only to waves generated by the local wind and does not apply to swell originating elsewhere.

WARNING: Presence of swell makes accurate wave observations exceedingly difficult.

NOTE: *(a) The height of waves is arbitrarily chosen as the height of the highest 1/3 of the waves. Occasional waves caused by interference between waves or between waves and swell may be considerably larger.*

(b) Only lines 7, 8, and 9 are applicable to swell as well as waves.

(c) The above values are only approximate due both to lack of precise data and to the difficulty in expressing it in a single easy way.

(d) Below the surface the wave motion decreases by 1/2 for every 1/9 of a wave length of depth increase.

(e) Observations and comments leading to increased accuracy and usefulness are desired.

Publication suggested by J. Pritzlaff, General Electric Advanced Technology Lab., Schenectady, N.Y.

Recopied from Vine and Volkmann, Woods Hole Oceanographic Institution, June 1950.

Table 3-II. Conditions Required to Produce Waves

	WIND VELOCITY (Knots) 20	25	30	35	40	45	50	55	60
4 ft high:									
Time (hrs)*	3.2	2.0	1.3	1.0	0.9	0.8	0.7	0.6	0.5
Fetch (nautical miles)*	11	7	5	5	5	5	5	5	5
Length (ft)*	40	43	46	49	50	51	51	52	52
8 ft high:									
Time	19.0	6.2	4.0	3.0	2.2	1.9	1.5	1.2	1.0
Fetch	120	26	13	14	11	9	7	6	5
Length	155	86	82	86	86	90	95	95	95
12 ft high:									
Time		20.0	8.0	5.4	4.0	3.1	2.8	2.2	2.0
Fetch		745	48	31	22	17	17	13	12
Length		216	133	123	125	133	138	138	141
16 ft high:									
Time			16.2	8.9	6.3	4.9	3.9	3.1	2.9
Fetch			125	59	42	32	26	20	19
Length			237	172	166	166	172	178	178
20 ft high:									
Time				14.0	9.1	7.0	5.7	4.8	4.0
Fetch				120	67	51	42	36	29
Length				258	216	206	207	210	213
24 ft high:									
Time				31.0	13.4	9.5	7.3	6.0	5.1
Fetch				320	115	76	59	48	41
Length				462	288	258	244	237	251
28 ft high:									
Time					20.9	13.0	9.7	7.8	6.4
Fetch					210	120	84	68	56
Length					406	328	296	288	280
32 ft high:									
Time					36.5	16.7	12.0	9.4	7.8
Fetch					440	170	115	87	71
Length					620	401	344	324	320
36 ft high:									
Time						24.4	15.4	11.6	9.3
Fetch						280	160	120	91
Length						533	424	379	361

* Minimum time and fetch required for winds of various velocities to produce waves of a given height, and the length of the waves produced under these conditions. (Calculated from Wave Report No. 73 (unpublished) of Scripps Institution of Oceanography, University of California)

Table 3-II. Conditions Required to Produce Waves (Cont)

	WIND VELOCITY (Knots)								
	20	25	30	35	40	45	50	55	60
40 ft high:									
Time (hrs)						42.0	19.5	14.2	11.4
Fetch (naut mi)						575	220	150	120
Length (ft)						787	512	443	415
44 ft high:									
Time							25.6	16.0	13.4
Fetch							315	180	150
Length							642	512	462
48 ft high:									
Time							43.0	21.2	16.3
Fetch							635	265	190
Length							919	608	543
52 ft high:									
Time								25.8	18.1
Fetch								340	220
Length								713	608
56 ft high:									
Time								36.1	21.5
Fetch								535	280
Length								919	677
60 ft high									
Time								52.5	26.0
Fetch								890	355
Length								1214	800

Table 3-III. Sea State Chart (DTMB)

WIND AND SEA SCALE FOR FULLY ARISEN SEA

SEA-GENERAL		WIND 1)				SEA 3)								
Sea State 1)	Description 2)	Beaufort Wind Force	Description	Range (Knots)	Wind Velocity (Knots)	Wave Height Feet: Average	Wave Height Feet: Significant	Wave Height Feet: Average 1/10 Highest	Significant Range of Periods (Seconds)	T_{max} Period of Maximum Energy of Spectra	$\bar{T}$ (Average Period)	$\bar{L}$ (Average Wave Length)	Minimum Fetch (Nautical Miles)	Minimum Duration (Hours)
0	Sea like a mirror.	0	Calm	Less than 1	a) 0	0	0	0	–	–	–	–	–	–
	Ripples with the appearance of scales are formed, but without foam crests.	1	Light Airs	1 - 3	2	0.05	0.08	0.10	up to 1.2 sec	0.7	0.5	10 in.	5	18 min
1	Small wavelets, still short but more pronounced; crests have a glassy appearance, but do not break.	2	Light Breeze	4 - 6	5	0.18	0.29	0.37	0.4-2.8	2.0	1.4	6.7 ft	8	39 min
	Large wavelets, crests begin to break. Foam of glassy appearance. Perhaps scattered white horses.	3	Gentle Breeze	7 - 10	8.5	0.6	1.0	1.2	0.8-5.0	3.4	2.4	20	9.8	1.7 hrs
					10	0.88	1.4	1.8	1.0-6.0	4	2.9	27	10	2.4
2	Small waves, becoming larger; fairly frequent white horses.	4	Moderate Breeze	11-16	12	1.4	2.2	2.8	1.0-7.0	4.8	3.4	40	18	3.8
					13.5	1.8	2.9	3.7	1.4-7.6	5.4	3.9	52	24	4.8
3					14	2.0	3.3	4.2	1.5-7.8	5.6	4.0	59	28	5.2
					16	2.9	4.6	5.8	2.0-8.8	6.5	4.6	71	40	6.6
4	Moderate waves, taking a more pronounced long form; many white horses are formed. (Chance of some spray).	5	Fresh Breeze	17-21	18	3.8	6.1	7.8	2.5-10.0	7.2	5.1	90	55	8.3
					19	4.3	6.9	8.7	2.8-10.6	7.7	5.4	99	65	9.2
					20	5.0	8.0	10	3.0-11.1	8.1	5.7	111	75	10
5	Large waves begin to form; the white foam crests are more extensive everywhere. (Probably some spray).	6	Strong Breeze	22-27	22	6.4	10	13	3.4-12.2	8.9	6.3	134	100	12
					24	7.9	12	16	3.7-13.5	9.7	6.8	160	130	14
					24.5	8.2	13	17	3.8-13.6	9.9	7.0	164	140	15
6					26	9.6	15	20	4.0-14.5	10.5	74	188	180	17
	Sea heaps up and white foam from breaking waves begins to be blown in streaks along the direction of the wind. (Spindrift begins to be seen).	7	Moderate Gale	28-33	28	11	18	23	4.5-15.5	11.3	7.9	212	230	20
					30	14	22	28	4.7-16.7	12.1	8.6	250	280	23
					30.5	14	23	29	4.8-17.0	12.4	8.7	258	290	24
					32	16	26	33	5.0-17.5	12.9	9.1	285	340	27
7	Moderately high waves of greater length; edges of crests break into spindrift. The foam is blown in well marked streaks along the direction of the wind. Spray affects visibility.	8	Fresh Gale	34-40	34	19	30	38	5.5-18.5	13.6	9.7	322	420	30
					36	21	35	44	5.8-19.7	14.5	10.3	363	500	34
					37	23	37	46.7	6-20.5	14.9	10.5	376	530	37
					38	25	40	50	6.2-20.8	15.4	10.7	392	600*	38
					40	28	45	58	6.5-21.7	16.1	11.4	444	710	42
8	High waves. Dense streaks of foam along the direction of the wind. Sea begins to roll. Visibility affected.	9	Strong Gale	41-47	42	31	50	64	7-23	17.0	12.0	492	830	47
					44	36	58	73	7-24.2	17.7	12.5	534	960	52
					46	40	64	81	7-25	18.6	13.1	590	1110	57
	Very high waves with long overhanging crests. The resulting foam is in great patches and is blown in dense white streaks along the direction of the wind. On the whole the surface of the sea takes a white appearance. The rolling of the sea becomes heavy and shocklike. Visibility is affected.	10	Whole Gale*	48-55	48	44	71	90	7.5-26	19.4	13.8	650	1250	63
					50	49	78	99	7.5-27	20.2	14.3	700	1420	69
					51.5	52	83	106	8-28.2	20.8	14.7	736	1560	73
9					52	54	87	110	8-28.5	21.0	14.8	750	1610	75
					54	59	95	121	8-29.5	21.8	15.4	810	1800	81
	Exceptionally high waves (Small and medium-sized ships might for a long time be lost to view behind the waves.) The sea is completely covered with long white patches of foam lying along the direction of the wind. Everywhere the edges of the wave crests are blown into froth. Visibility affected.	11	Storm*	56-63	56	64	103	130	8.5-31	22.6	16.3	910	2100	88
					59.5	73	116	148	10-32	24	17.0	985	2500	101
	Air filled with foam and spray. Sea completely white with driving spray; visibility very seriously affected.	12	Hurricane*	64-71	> 64	> 80 b)	> 128 b)	> 164 b)	10-(35)	(26)	(18)	~	~	~

*For hurricane winds (and often whole gale and storm winds) required durations and fetches are rarely attained. Seas are therefore not fully arisen.

a) A heavy box around this value means that the values tabulated are at the center of the Beaufort range.

b) For such high winds, the seas are confused. The wave crests blow off, and the water and the air mix.

1) Encyclopedia of Nautical Knowledge, W.A. McEwen and A.H. Lewis, Cornell Maritime Press, Cambridge, Maryland, 1953, p. 483

2) Manual of Seamanship, Volume II, Admiralty, London, H.M. Stationery Office, 1952, pp. 717-718

3) Practical Methods for observing and forecasting Ocean Waves, Pierson, Neumann, James, N.Y. Univ. College of Engin. 1953.

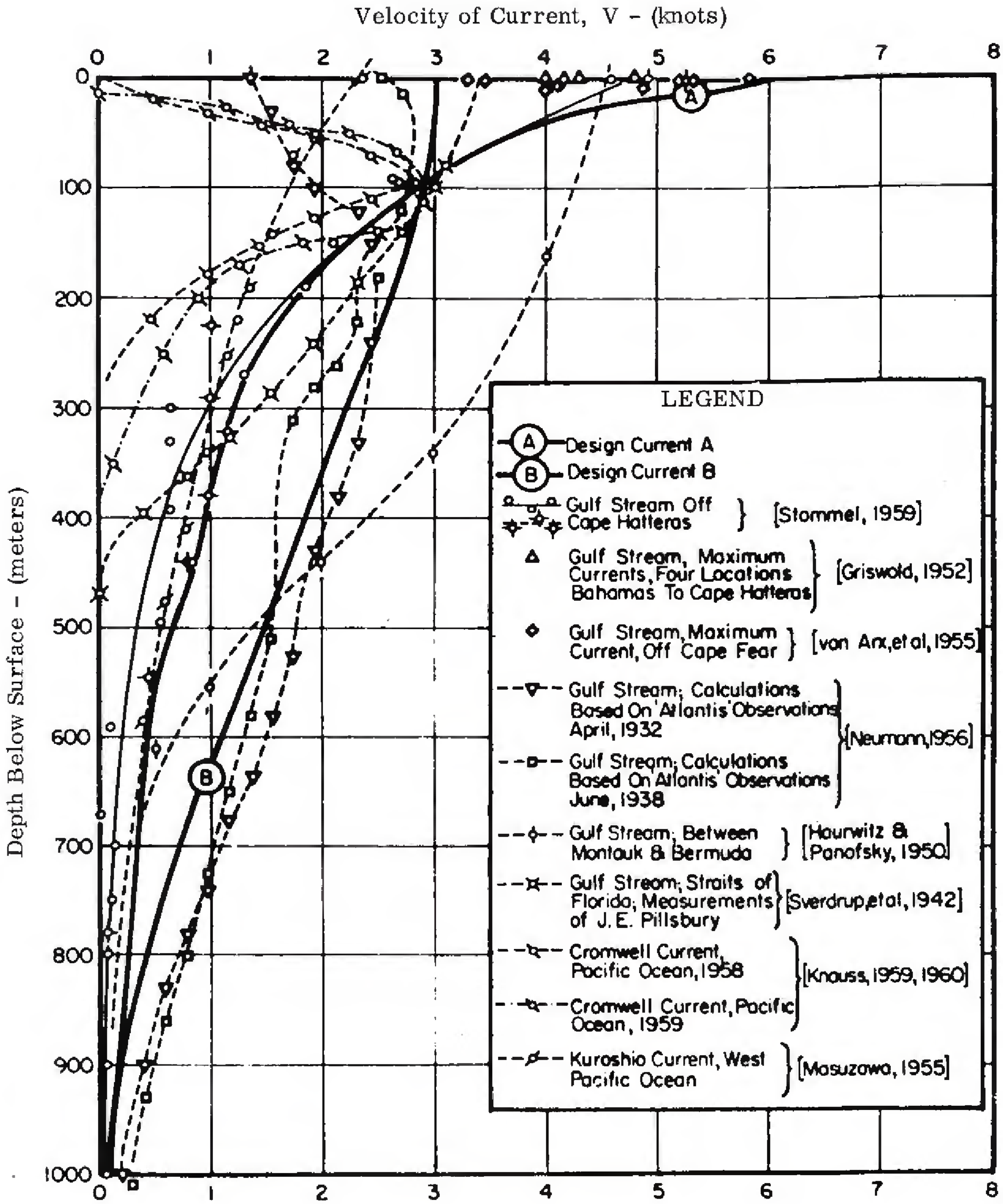


Figure 3-4. Vertical Velocity Profiles of Ocean Currents

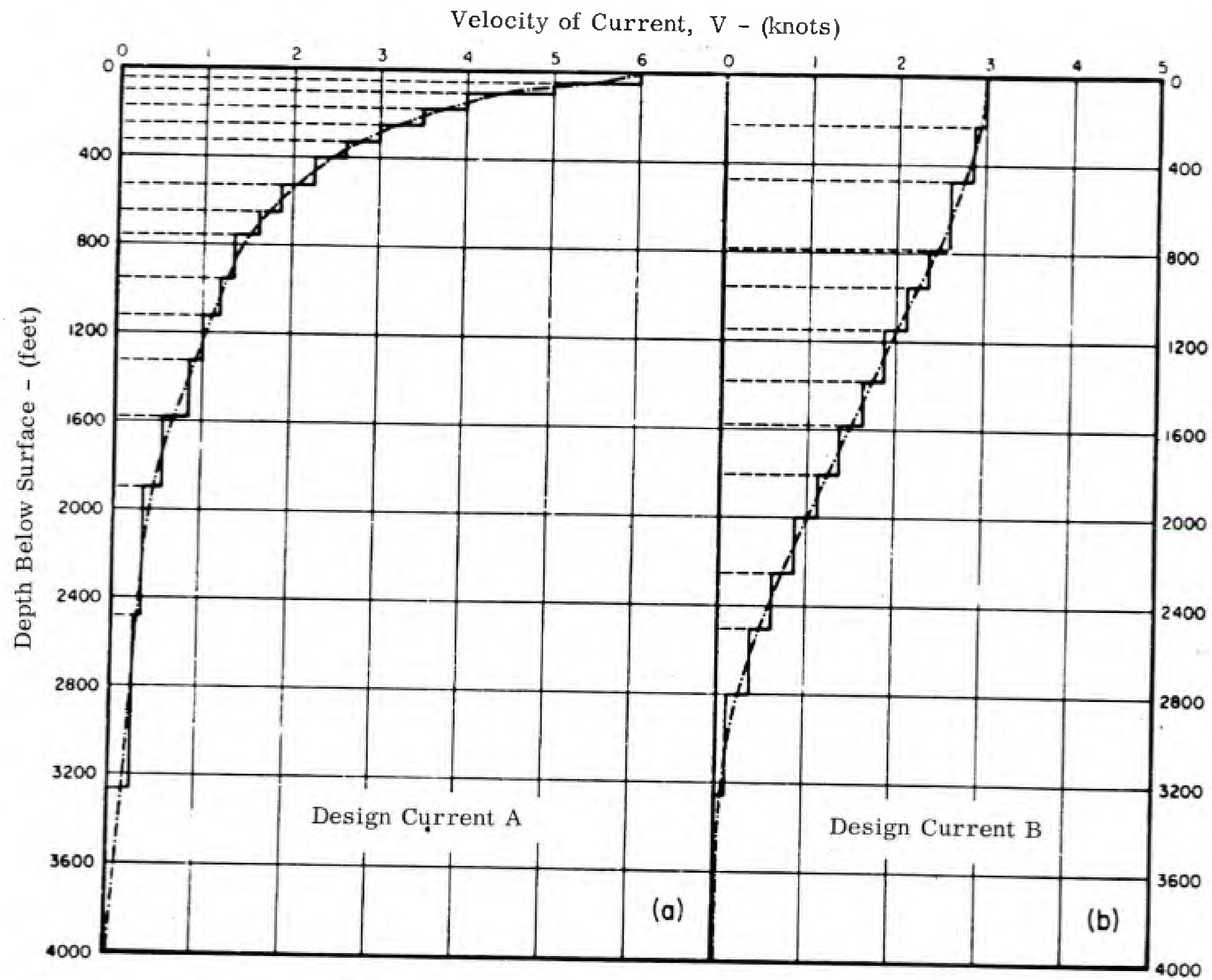


Figure 3-5. Adaptation of Design Current Velocity Profiles

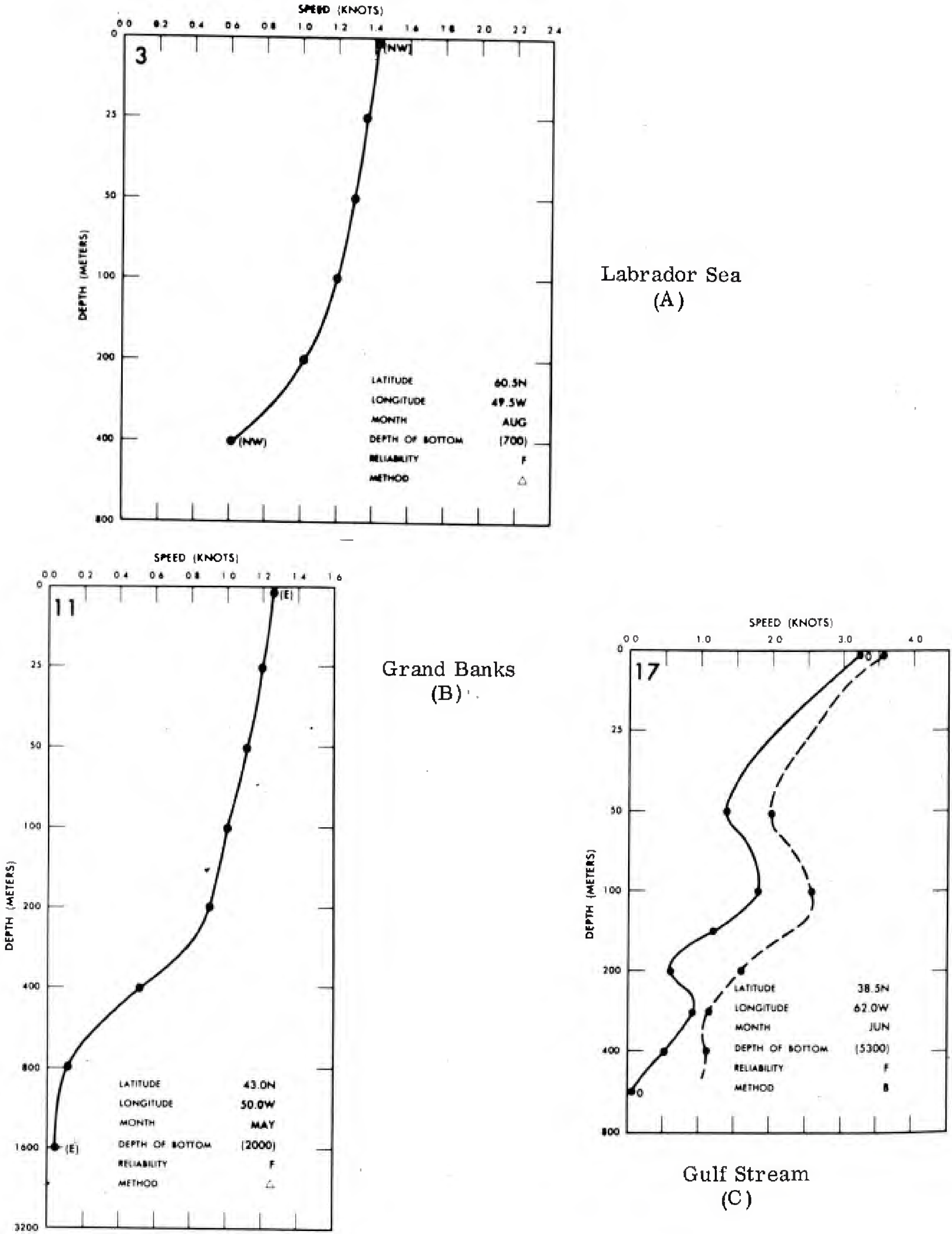


Figure 3-6. Typical Current Speed vs. Depth

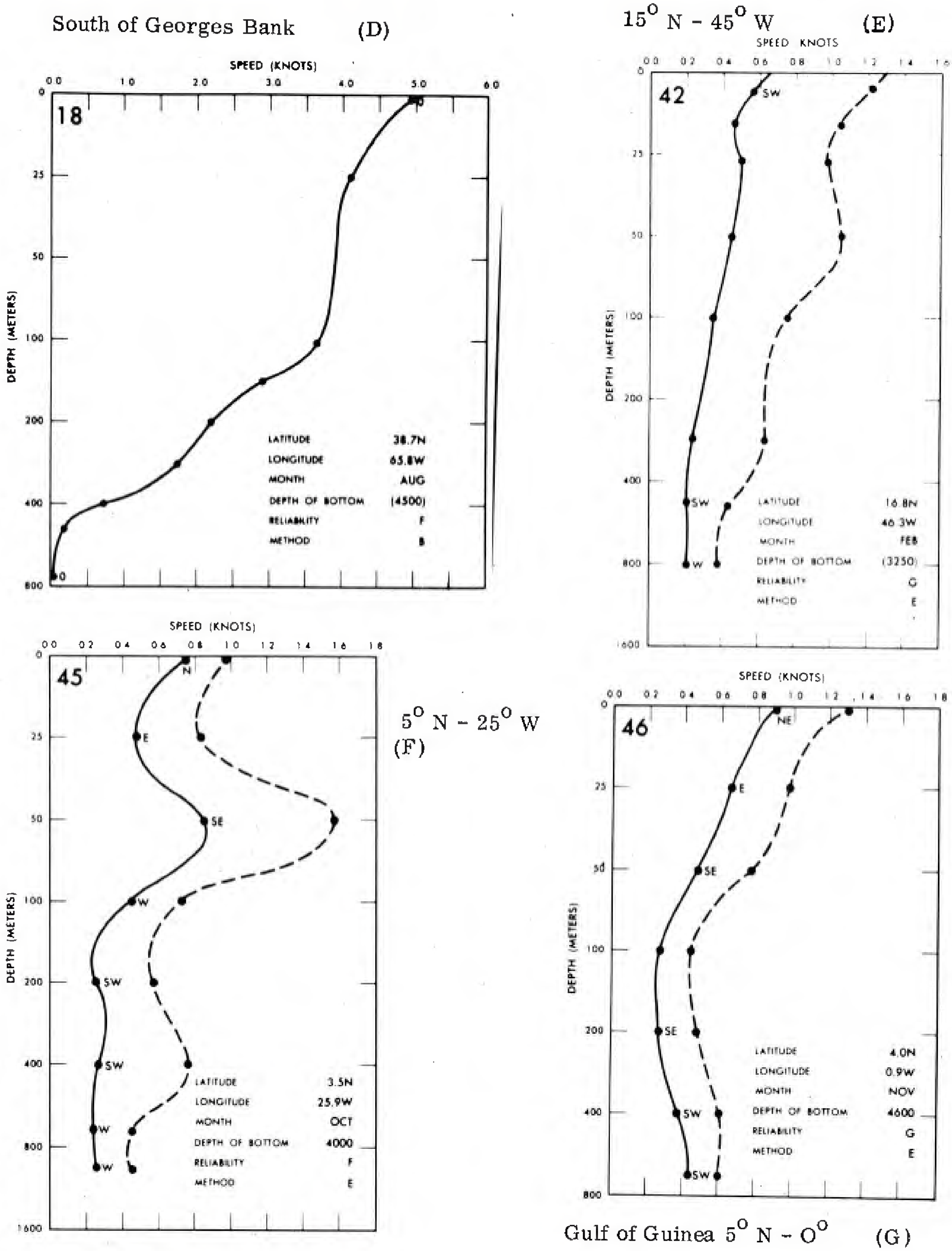


Figure 3-6. Typical Current Speed vs. Depth (Continued)

canyons which may extend to more than 35,000 ft. The continental shelves, traditionally limited by the 100-fathom curve, actually vary from 10 to 300 fathoms deep and from almost non-existent to greater than 270 miles wide. The average slope of the shelf surface is $0^{o}07'$. It is somewhat steeper over the inner than over the outer half. The continental shelf is cut by valleys and canyons with slopes as steep as any on land. Shelf sediments are primarily sands, with mud and gravel also common. An area off Southern California known as the continental border land has basins as deep as 1000 fathoms, which, in some instances, are floored with silty clay with sand layers.

A synopsis of the major continental areas follows.

The east coast of North America: Slopes are 5^{o} off Newfoundland and Nova Scotia and include jagged peaks and depressions. From Georges Bank to Cape Hatteras there are fewer hills but many submarine canyons. South of Cape Hatteras, the Blake Plateau (400-600 fathoms) slopes 1.5^{o}. Outside the Blake Plateau the slopes range to 50% in places and perhaps steeper. Off western Florida the slopes are gentle to 600 fathoms, then increase to 27^{o}. In one area the slope drops 1000 fathoms in 2 nautical miles. Sediments in this area are described as primarily mud and sand. On the Blake Plateau, sediments are gravels and sands with areas of hard phosphorites. Finer sediments have been prevented from depositing there or have been winnowed away by the bottom currents which reach speeds as high as 0.8 to 1.0 knots.

South America: Off Colombia's Magdalena River there are irregular submarine valleys and apparently unstable sediments. This is evidenced by the frequent submarine cable breaks in this region. Off the Guianas the slope is gentle. South of Cape Sao Roque (near Natal, Brazil) the slopes range from 4^{o} to 20^{o} for 1500 miles. Canyons have been found cutting these slopes. Western South American slopes average 5^{o}.

Western North America: In the Gulf of California muddy sediments are found in 20^{o} slopes. Intricate, granite-walled canyons are present. In the northern part of the Gulf of California, coarse sand and fine gravels are found to 225 fathoms. The slope off the California coast is cut with submarine canyons and ridges. North, at Yakutat Bay, there are 30^{o} slopes with 8^{o} slopes north of the Aleutian Islands.

Western Pacific: Near Japan the slopes run about 2^{o} to the 1000-fathom contour. However, there are several very large rock-walled canyons, and rock bottoms are found to 1000 fathoms.

Around the Philippines the slopes average 11^{o} to 1000 fathoms and are cut with numerous canyons.

Indian Ocean: Slopes off southwest Australia average 27^{o} to 1000 fathoms. Off northwest Australia, however, they are less than 1^{o}. On the south side of Java and Sumatra the slopes are 5^{o} or less.

Around Ceylon, slopes are 10^{o} and are cut by canyons.

Eastern Atlantic: Slopes off southwest Africa are gentle, about 2^{o}, and off the Congo River are about 1^{o}. There is a large canyon off the Congo. The Gulf of Cadiz slope is about 1^{o}. Off western France the sediments are coarse with sand, gravel, and pebbles in the 250 to 400-fathom zone.

Arctic: A 23° slope is reported off Point Barrow.

The world-wide slope average is $4^{\circ}17'$ for the first 1000 fathoms. However from the foregoing description it is obvious that greater slopes are not unusual. Most continental slopes are rugged, cut with large canyons and valleys.

Areas of the midocean ridges project above the 1000-fathom contour. Much of this area is mountainous topography of rock outcrop with sediments in intermountain basins.

Oceanic islands and atolls, especially coral islands, are surrounded by extremely steep slopes. Coral reefs in Indonesia are partly surrounded by slopes of 45° down to 200 meters, and in many cases these slopes extend to 500 to 600 meters. Marshall Islands charts show slopes of 25° down to 1000 fathoms.

The sediments of the continental slopes are less well known than those of the shelves. In general, Shepard (1963) mentions that, according to chart notations, slope sediments are about 60% mud, 25% sand, 10% rock and gravel, and 5% shells and ooze.

Table 3-IV. Sediment Types and Composition

TYPE	GRAIN SIZE (PROPORTION APPROX.)	REMARKS
Mud	80 percent of grains less than 0.062 mm.	Silt and clay particles; low calcium carbonate content in water depths greater than approximately 2,500 fathoms (red clay).
Mud-sand	More than 20 percent of grains between 0.062 and 2.000 mm and more than 20 percent of grains less than 0.062 mm.	Includes foraminiferal (globigerina and pteropod) oozes.
Sand	80 percent of grains between 0.062 and 2.000 mm.	In shallow waters dominant minerals are quartz and feldspar, concentrations of heavy minerals in places (e.g., Ilmenite), or shell sands. In deeper water they are foraminiferal remains.
Gravel	80 percent of grains between 2 and 256 mm.	Rock and coral fragments, shells, manganese nodules, etc.
Rock	Boulders larger than 256 mm.	Includes bedrock outcrops, shell reefs, coral reefs, and coral heads.

Sediments of the continental slopes have low shear strength, in the order of magnitude of 0.1 psi. In general, shear strengths of sediments range from 0.1 to 15 psi. High shear strengths are found primarily with coarse sands, although some compacted clays may have high values. An ocean-wide average of 1 psi is probably representative. Testing is required of samples from a particular site for accurate values.

Areas of fine, unstable sediments do not occur in regions of high current velocities. Catastrophic situations, such as turbidity flows in submarine canyons or down slopes, may occur, but such occasions are presently unpredictable and are considered rare.

The relations of shear strength, sensitivity, compressibility, cohesion, etc., to sediment grain size, void ratio, etc., are complex, and have been discussed in various reports.[1,2,3]

Figure 3-7 shows the bottom sediment conditions of the world's oceans.

3.4 BOTTOM PROFILES

Specific knowledge of the underwater terrain is vital when a final submarine cable route or site is being considered. Bottom profiling is necessary to estimate cable lengths due to variations in elevation and to avoid areas of potential cable hazards such as steep ledges and narrow valleys. To facilitate the estimation of cable length as a function of depth, average off-the-shore distances of major continental margins have been tabulated in Table 303. Additional profiles of the northeastern United States, northwest Africa, and various points along the Californian and Mexican coasts appear in Figures 3-8, 3-9, and 3-10.

Table 3-V illustrates the great variations in average distances involved in reaching the various design depths off the respective coast lines. There are exceptions to the data shown in Table 3-V, such as the depth of 3000 feet 5 miles off the Baja Peninsula, and the 3000-foot depths in the Japan Trench 2 miles off shore.

Since there are great distance-to-depth variations, and since the actual site or cable routes for an underwater power transmission system are not defined, we have defined the actual cable route length to reach the various design depths. Table 3-V shows a minimum average offshore distance of 21 miles and a maximum of 460 miles. Table 3-V also shows that the majority of offshore distances are less than 200 miles, and only two distances are greater than 200 miles. Therefore, it appears feasible to consider cable lengths at multiples of 10 with specific design points at 50 and 100 miles. Design distances of bottom-contoured cable lengths are established at 10 miles, 50, 100, and 500 miles. Table 3-V shows the four distances are representative of the offshore distances encountered to reach the various design depths of the oceans.

Table 3-V. Bottom Profiles of Continental Margins (Distances from Coasts in Miles)

REGION	DEPTH (FT) 600	2000	6000	10,000	15,000	20,000	BOTTOM DEPTH
EAST COAST U.S.	70	150	175	182	190	X	18,000 ft
WEST COAST U.S.	21	28	32	55	162	X	18,000 ft
SOUTHEAST ASIA	110	155	190	208	319	460	Abt 24,000 ft
SOUTH AUSTRALIA	51	48	72	110	120	X	18,000 ft

Note: "X" denotes ocean does not reach this depth except in isolated instances.

[1] The superscripted numerals in the text reference reports listed at the end of this chapter.

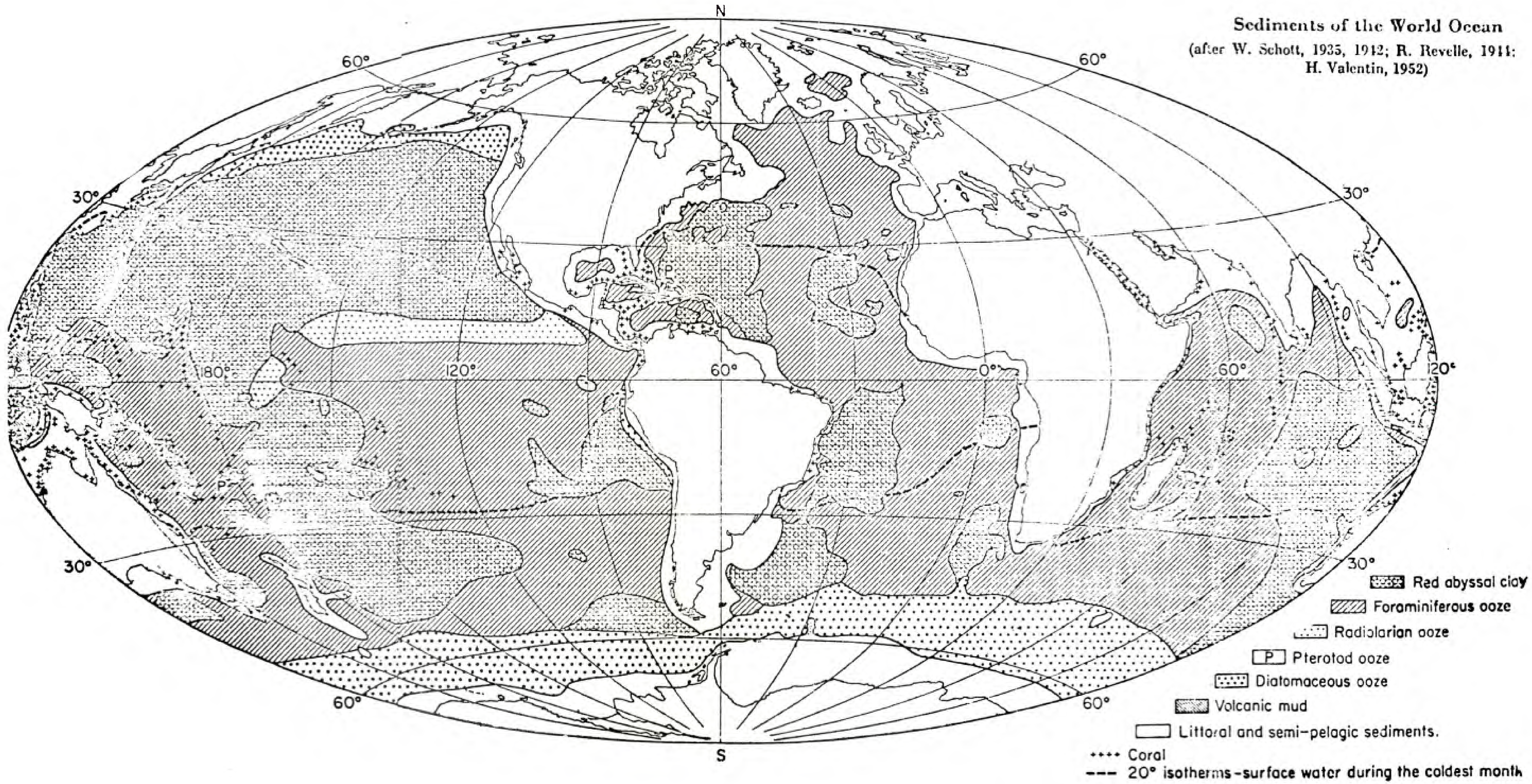


Figure 3-7. Sediments of the World Ocean

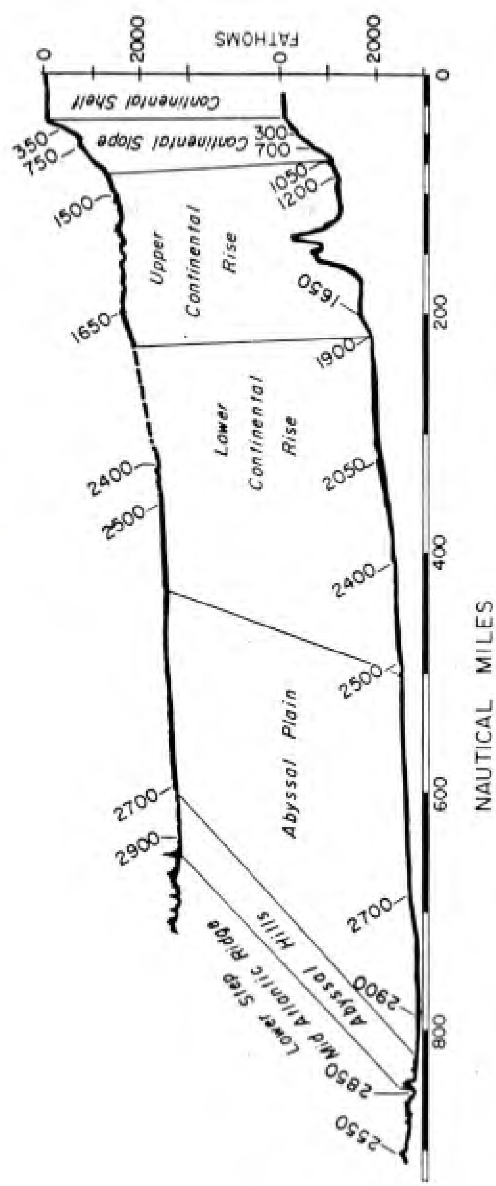


Figure 3-8. Continental Margin Provinces: Type Profiles off Northwest Africa

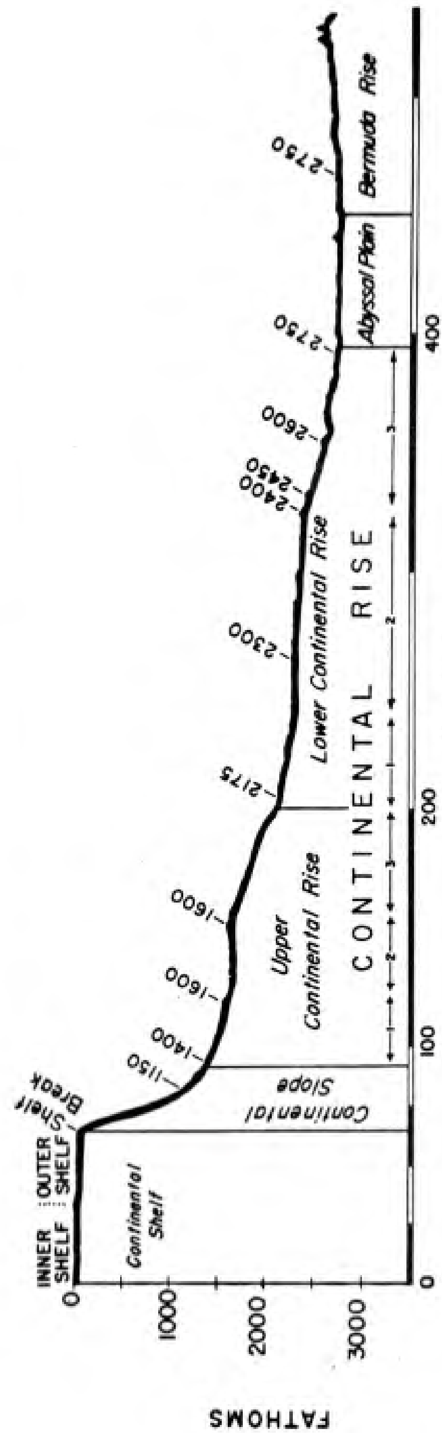


Figure 3-9. Continental Margin Provinces: Type Profile off Northeastern United States

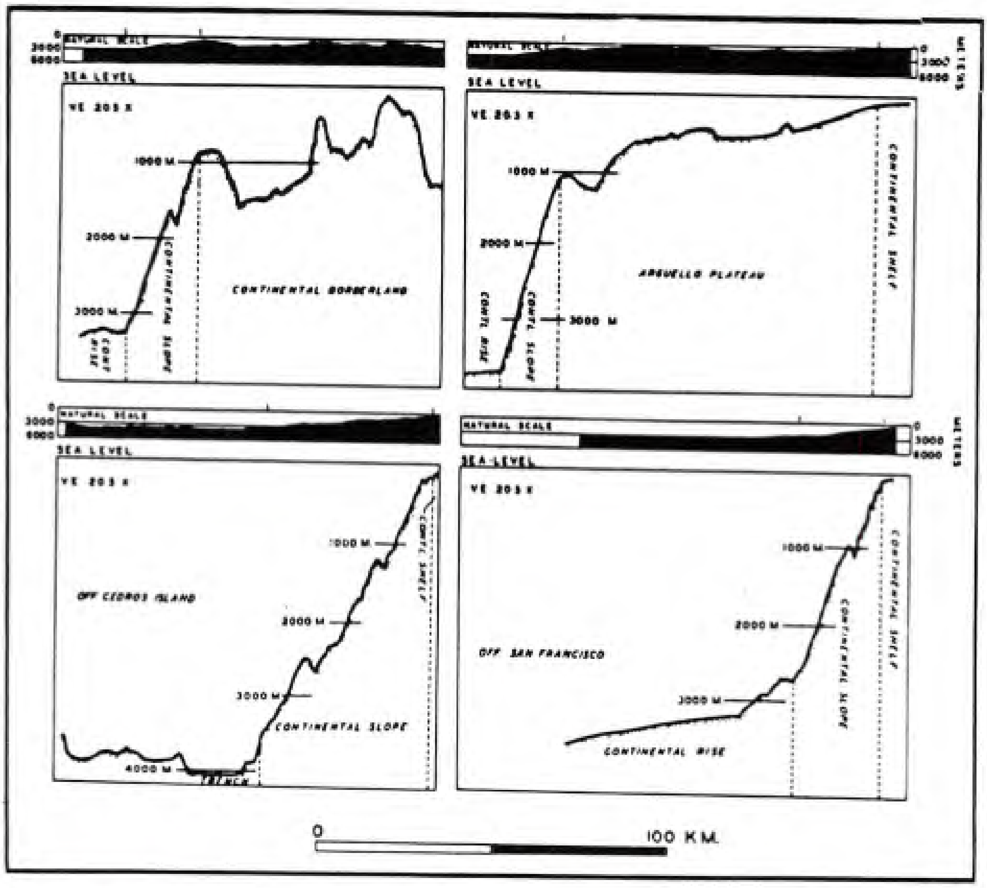


Figure 3-10. Typical Profiles of the Continental Margin off California and Mexico

3.5 SLUMPING

Slumping of bottom sediments is a potential hazard to submarine cables and structures which may be in the way or stationed on the cascading deposits. Slumping may put the structure or cables in jeopardy from either the cascading sediments or from the turbidity currents which would result from the sliding. Generally, slumping is found on the continental slopes. The normal open shelf and deep-sea areas are believed to be free of slumping. Studies of slumping phenomena have concluded that the kind and rate of sedimentation required to produce an unstable slope occurs only in specialized areas of relatively rapid accumulation. These include deltaic and canyon head environments on the inner shelf and probably canyon or gulley walls on the open shelf slopes.

Studies have indicated that the stability of a sedimentary deposit on a given slope depends basically on the shear strength of the deposit and the rate of increase of this strength with depth of burial. Factors controlling these properties are sediment grain size distribution, homogeneity, rate of accumulation, degree of lithification, and prepressure conditions. It becomes apparent, then, that a thorough bottom survey, including corings, of the site and above-site slopes should be made to ensure against slumping.

A classic example of turbidity currents associated with slumping was the submarine landslide which occurred in the Grand Banks region in 1929 following an earthquake. An estimation of the speed of the flow has been placed in the order of 50 knots.

3.6 TEMPERATURE AND SALINITY

The range of temperatures and salinities in the oceans will be anywhere from about $-2^{\circ}C$ and 20 percent to about $30^{\circ}C$ and 37 percent, with some pockets of water having higher or lower readings. Many of the extreme conditions are found in the Red Sea and the Persian Gulf.

The oceanic troposphere is the region where most of the temperature and salinity variations in the oceans exist, along with the strongest currents. It is made up of surface mixed water, the thermocline, and the sub-troposphere. In the stratosphere the temperatures, salinities and currents are more uniform.

Troposphere (mixed water)	to 100 meters
Thermocline	to 200-300 meters
Subtroposphere	to 1200 meters
Stratosphere	below 1200 meters

The mixed waters can be regarded as homogeneous, since vertical differences in temperature and salinity are very small. Its thickness is seldom greater than 100 meters. The mixed water layer is deepest in the area between $35^{\circ}S$ and $25^{\circ}N$. Poleward from these latitudes, the mixed layer stratification is slowly destroyed, and the climatic conditions begin to affect this layer.

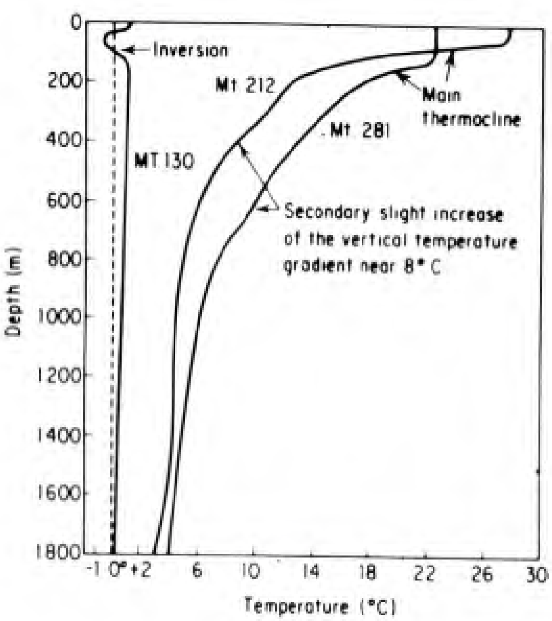
In the subtropics (30° to $20^{\circ}S$ and 20° to $25^{\circ}N$), climatically the desert regions of the world, the mixed layer extends down to about 100 meters, but it is shallower in the tropics and in regions close to the equator. In regions with cold water upwelling, such as the Humboldt and Beneguela currents, it is entirely absent.

Under the mixed water layer lies the thermocline, where the maximum vertical temperature and salinity gradients are found at depths between 100 and 200 meters. From the subtropics, where the thermocline is found at a depth of 150 meters at 20^{o} south and 200 meters at 20^{o} north, the thermocline rises steadily to a depth of about 50 meters at the equator and 10^{o} north.

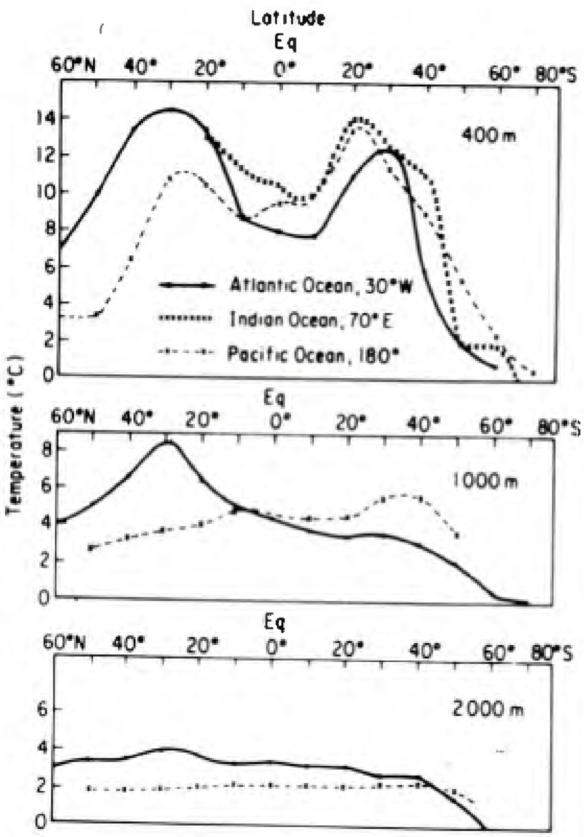
Intensity of the thermocline is greatest in the equatorial areas. There are transitional layers around 15^{o}N and 15^{o}S where intensity decreases, and on either side of this belt the intensity gradient falls rapidly.

Beneath the thermocline, from about 200 to 300 meters, the vertical temperature and salinity gradients decrease with depth and gradually change their magnitude into that of the stratosphere. This physical description, using the Atlantic Ocean as an example, may be assumed for the entire width of the oceans due to dynamic as well as climatic conditions. The chief factor modifying this description is geography.

Specific examples of temperature and salinity are given in Figures 3-11 through 3-16.



Major types of vertical temperature distribution in different latitudes of the Atlantic Ocean. Mt. 212 in 0 36'N, 29 12'W represents the equatorial type with a strong thermocline at about 75 meters below the sea surface. Mt. 281 in 18 59'N, 33 25'W represents the subtropical type in the central parts of the ocean. A weaker main thermocline is found at greater depths and the water in deeper layers is warmer. Mt. 130 in 63 43'S, 5 16'E represents conditions that are often found in polar regions.



Average meridional temperature distribution at subsurface levels in the central parts of the oceans.

Figure 3-11. Vertical Ocean Temperature Distribution

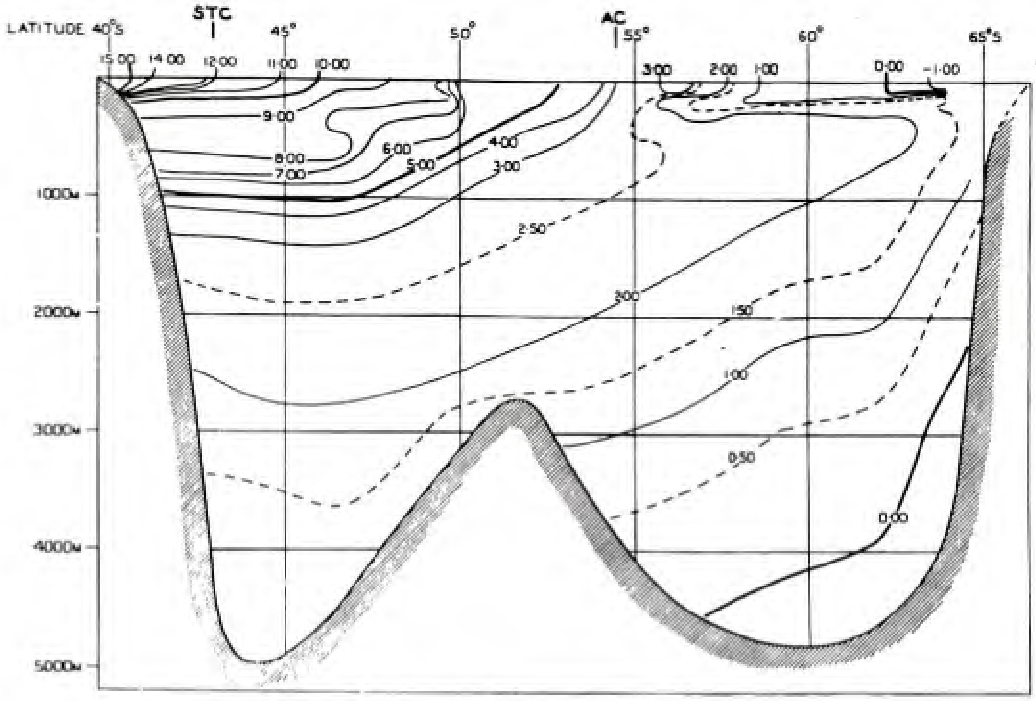


Figure 3-12. Temperature Distribution South of Australia

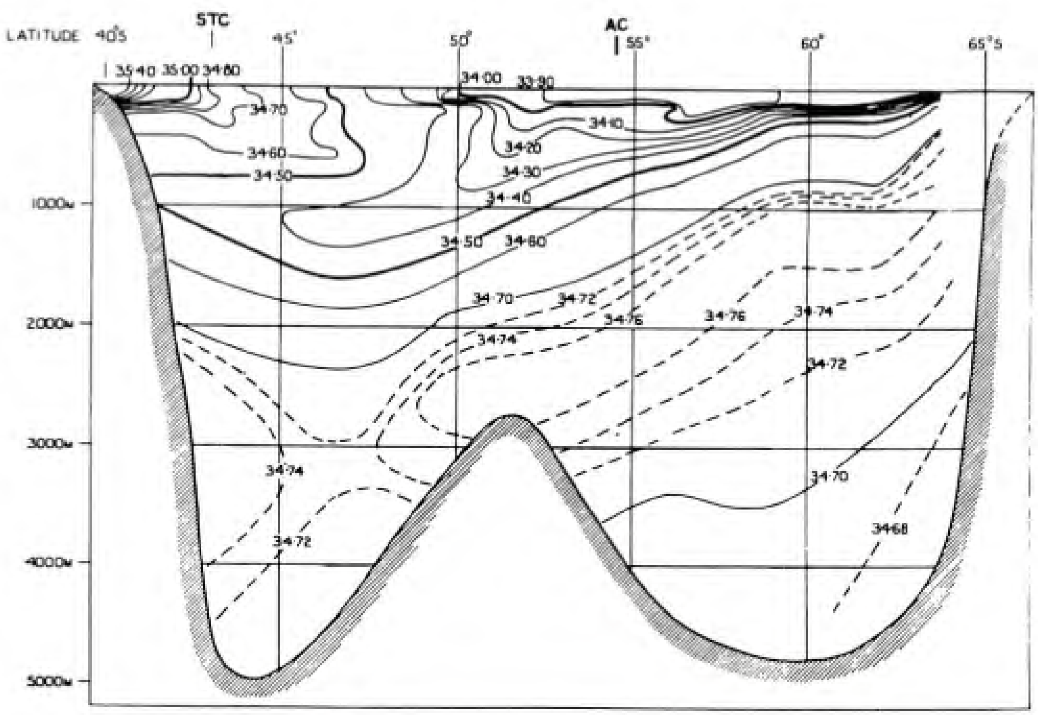


Figure 3-13. Salinity Distribution South of Australia

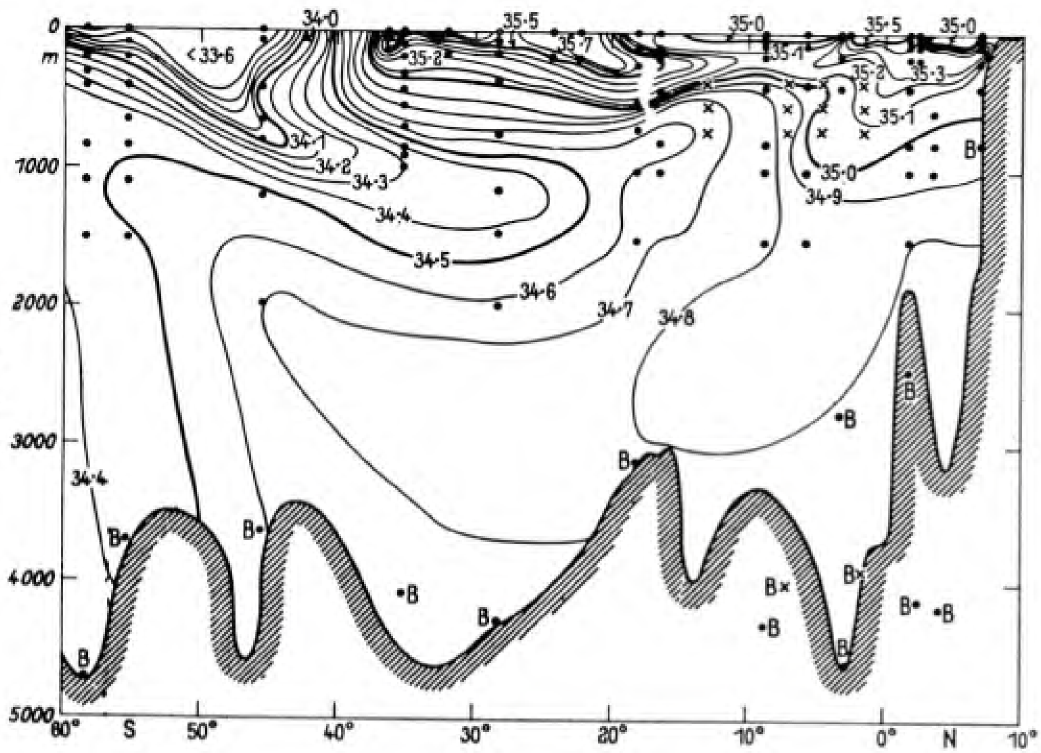


Figure 3-14. Longitudinal Salinity Section through the Central Part of the Indian Ocean

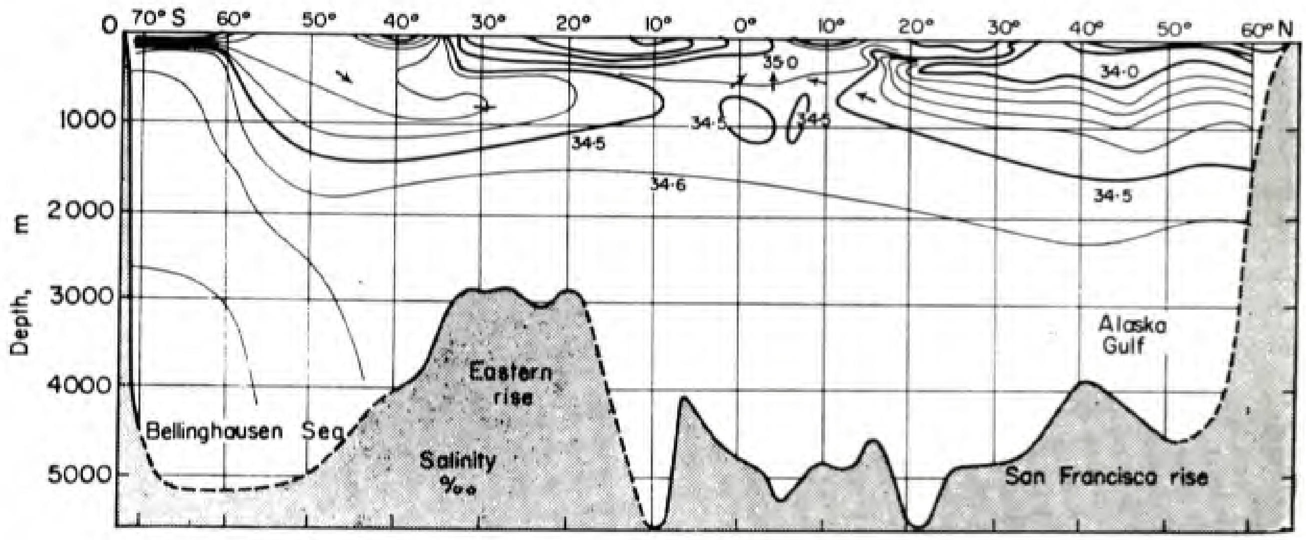


Figure 3-15. Longitudinal Salinity Section through the Central Part of the Pacific Ocean

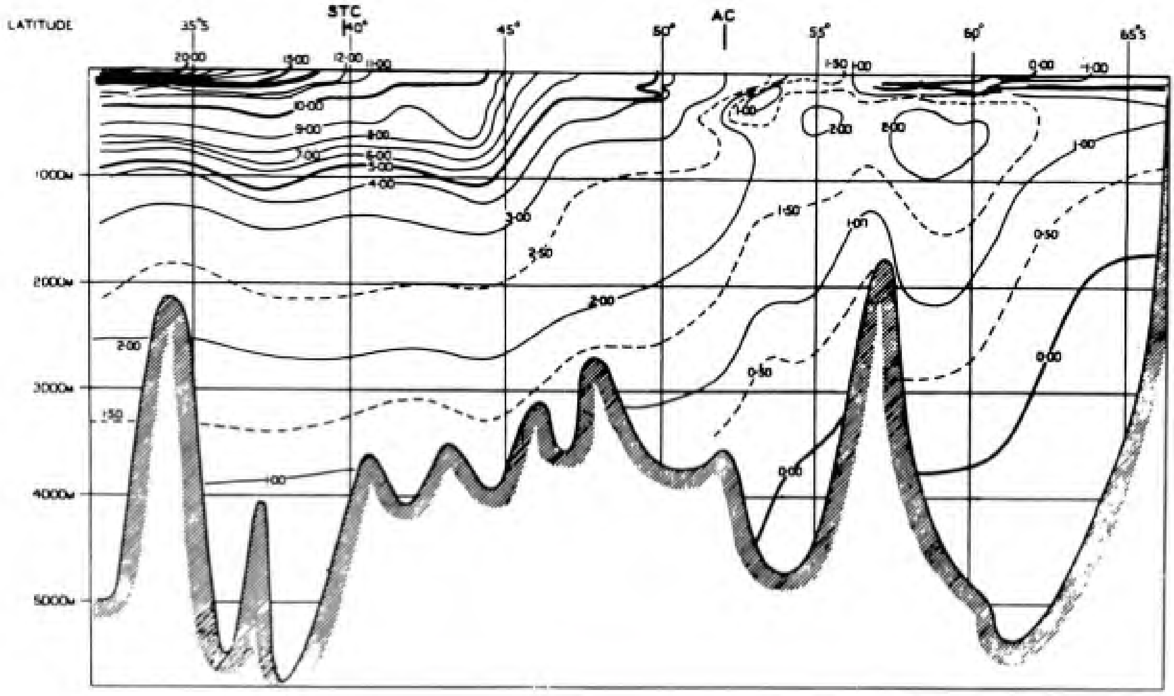


Figure 3-16. Temperature Distribution in South Indian Ocean

3.7 MARINE LIFE

In defining the environment in which a power cable, hull structure, and mooring line have to operate, it is essential to note the available information on the type of marine organisms which attack the various materials used in marine constructions. Particularly important is the need for data on the resistance of materials to attack by marine organisms. Although considerable published information exists on the behavior of natural organic materials such as wood, jute, hemp, and the like, there is little data on plastics, elastomers, casting resins, or similar materials.

Generally, the highest concentration of marine life is found in intertidal regions and to depths of 600 ft, depending on the penetration of sunlight. Beyond the 600-ft limit, to approximately 4000 ft plant life is rare, due to the lack of sunlight. However, an abundance of animal life may be found. Below 4000 ft, the water temperature approaches freezing, food is scarce, and therefore the animal population is low. Animals in this zone are mainly burrowers, such as worms and mollusks. Other inhabitants may be gastropods, hydroids, and sea urchins.

Coincident with the various forms of plant and animal life are the organisms which attach themselves to exposed surfaces resulting in what is commonly termed "fouling." Associated with the fouling organisms is a microscopic anaerobic bacteria which is predominant in accelerating corrosion and destruction of nonmetallics due to its sulfate reducing nature. Hence, a marine borer may penetrate the protective coating on a surface or submarine cable, and the bacteria present provide the means to accelerate the metallic corrosion or the leaching of a plastisizer.

The bacteria generally are single-celled organisms, a large number of which are heterotropic, that attack organic matter and use it as a source of carbon for energy. The bacteria play an important part in the biology of the sea, their most important function being to decompose organic material into carbon dioxide, water, ammonia and minerals. Bacteria are found in sea water and sediment from shallow depths to the deepest portions of the sea. Marine bacteria have been found capable of oxidizing rubber products, as well as a wide variety of gaseous, liquid and solid hydrocarbons. Although evidence to date indicates that, among the microorganisms, the bacteria are particularly likely agents of deterioration in the ocean, it is possible that fungi may also be contributors. Although bacteria are plentiful in coastal waters, where plant and animal life is abundant, they are most plentiful in the first few inches of bottom ooze and decrease in numbers with the depth of bottom deposits. This is, of course, the area where a submarine power cable, mooring lines, and power structure will be located and subjected to the combined effects of the environment.

Marine borers may also be expected to be major agents of deterioration. Marine borers are mollusks or crustaceans which bore into a material for food or shelter, depending on the particular organism involved. Of the crustaceans, the gribble, Limhoria, is the most destructive. Cellulose material, such as wood and cordage, form its food supply and natural habitat.

Although shallow water is most conducive to large numbers of marine borers, they have been found to depths of 11,500 ft. In some cases, boring mollusks have been known to have penetrated the lead sheath of submarine cables at depths of 5600 ft and greater.

3.8 SEA WATER DENSITY AND COMPRESSIBILITY

Most information on sea water density is given in the cgs system. For convenience, since densities (cgs) in the open ocean always are 1.0+, a quantity σ is used: $\sigma = (\rho - 1) \times 10^3$. For example, $\sigma = 27.50$ for $\rho = 1.02750$. Sea water density depends on a complex relation of salinity, temperature, and pressure. Frequently densities are given as σ_t (Sigma-t), which indicates the density of a parcel of water of a particular salinity and temperature, but at atmospheric pressure. Thus σ_t does not include the pressure effect. In situ densities must be calculated. The quantity α, the specific volume, is equal to $1/\rho$. Most calculations of sea water density are performed using α; corrections for salinity, temperature, pressure, etc., are written for use with α.

In the following profiles of density, the density is given at $\rho_{sto}k$, or the density without considering pressure. An empirical expression for the pressure effect is:

$$\alpha_{stp} = \alpha_{sto}(1-kp)$$

where: α_{stp} = in situ specific volume

α_{sto} = specific volume at atmospheric pressure

k = mean compression coefficient (between pressures of o and p bars)

p = pressure in bars; approximately equal to the depth in tens of meters.

For a more exhaustive treatment of the derivation of in situ densities, see references 4, 5, and 6.

Table 3-VI. Compressibility of Sea Water at 34.8 ppt Salinity $(k\ (10^8))$
(Neumann and Pierson 1966)

TEMPERATURE (°C)	DEPTH = 1000 m	DEPTH = 2000 m
-2	4637	4560
0	4580	4505
2	4528	4455
6	4374	4364
12	4221	4255

A similar but smaller effect occurs with increasing salinity at different depths.

For example, if ρ is 1.02750, at a depth of 2000 meters:

$$\frac{1}{\rho_{stp}} = \frac{1}{1.02750}(1 - 4.51 \times 10^{-5} \times 200)$$

$$\frac{1}{\rho_{stp}} = \frac{1}{1.20750} - \frac{.00902}{1.-2750} = \frac{.99098}{1.02750}$$

$$\rho_{stp} = 1.03685$$

Converted to English units a density, ρ sto of 64.1447 lb/ft^3 (i.e., 1.02750 gm/cm^2) would compress to 64.7284 lb/ft^3 (1.03685 gm/cm^2) at 2000 meters.

The above calculations use a mean compressibility k. The relationship between mean compressibility k and true compressibility K is given as:

$$K = \frac{K + p \frac{dp}{dk}}{1 - kp}$$

since $$K = \frac{1}{\alpha} \frac{d\alpha}{dp}.$$

3.9 SUMMARY

A synopsis of the preceding chapter follows, utilizing a range of limits to define the various factors of environment. The effects of depth (pressure) on underwater power transmissions system are discussed in paragraph 7.2.

An encompassing definition of the surface conditions of all the major world oceans is difficult because of the large variations in weather conditions, thermodynamics, and prevailing winds which determine the characteristics of the first 4000 ft of water. Below 4000 ft, most of the major oceans conform to a narrower range of limits which can be used to establish design parameters.

Table 3-VII summarizes the critical environmental conditions that may be experienced by a surface or subsurface module and/or components.

Table 3-VII. Underwater Power Transmission Systems Design Conditions

SURFACE CONDITIONS					
Wind Velocity (max)	150 mph				
Current Velocity (max)	10 knots				
Wave Height (max)	60 ft				
Water Temperature	85°F				
Salinity	35.0 1.5 percent				
SUBSURFACE	600 ft	2000 ft	6000 ft	10,000 ft	20,000 ft
Water Temperature (max)	75°F	65°F	55°F	45°F	45°F
Density (lb/ft^3)	64.05	64.25	64.68	65.03	65.85
Current Velocity (knots)	6	3	0.35	0.35	0.35
BOTTOM					
Sediment Shear Strength	1.0 psi				

The design parameters selected for underwater power transmission systems are predicted on load module deployment area. For the surface-tendered plant surface effects influence the hull dimensions and mooring system loads, as discussed in Chapter 7, and bottom shear strength affects the design of anchor as discussed in paragraph 8.1.2. For the in situ plant, bottom shear strength affects the design of the support pads, as discussed in paragraph 7.2.5.2 and 8, and subsurface effects influence the design of the pressure hull with respect to stability as related to velocity, heat transfer area, and descent/ascent as related to temperature (see paragraph 7.2.4.1).

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Chapter 4

POWER SOURCES

4.1 SUBMERGED POWER SOURCES

There are numerous energy sources and energy conversion systems available for power sources located below the surface of the ocean and restricted to infrequent, periodic access to the atmosphere. Many of the problems in developing a power source for use in the ocean are related to combining an energy source and a conversion system. The energy sources considered for this study include nuclear, both reactors and radioisotopes, thermal storage, and chemical, including batteries. Storage of energy by the other methods such as mechanical, electrical and magnetic, is not of interest at this time as they have high weight and volume characteristics and/or lack adequate conceptual and development status.

When adapting the various power sources to an ocean environment, the characteristics of the ocean and the source must be considered. The location of the power source on the ocean surface or at submerged depth, is also an influencing factor. Surface sources in the power range of interest are most economically provided by diesel power plants. The diesel power plant and its enclosure has been exposed to extremes of wind, wave, and temperature in the ocean surface environment for many years. Submerged power sources are adapted to their environmental conditions by the use of a pressure hull or by a pressure-compensated system. Although composite techniques may be employed, they are not considered acceptable for the deeper depths if mechanical penetrations of the pressure hull are to be used. Thus, the adaptability of a submerged power system to an ocean environment is largely one of adaptation to a pressure proof enclosure or to full submergence pressure. The only source considered for adaptation to a pressure-compensated system is the storage battery; however, batteries are adaptable, in various degrees, to a pressure hull enclosure.

Storage battery systems require pressure hulls to enclose frequency inversion equipment for an AC supply. The major environmental factor affecting the battery is temperature. Battery performance decreases with temperature; the case of the lead-acid battery, discharge capacity decreases to approximately 1/2 the room temperature capacity for a 32°F operating temperature. Pressure-compensated systems for the battery are preferred when considering overall system weight, volume, and potential gas generation in an unattended plant.

Various problems are encountered with the power systems enclosed within a pressure hull. These are primarily related to the handling of gaseous fuels or waste products and the elimination of waste heat.

All sources require some means of waste heat rejection with the quantity dependent on the efficiency of the particular source. Heat may be transferred across the pressure hull proper or by the use of hull penetrations that effectively extend the pressure hull area into "heat exchangers."

Power source efficiencies vary with capacity, operating parameters or specific system concept, but in general:

	Percent Efficiency
Storage batteries (DC)	90
(with AC inversion)	70
Fuel cells (DC)	50
(with AC inversion)	40
Chemical and thermal dynamic	30
Nuclear reactor dynamic	20
Isotope dynamic	15
Thermionic	15
Thermoelectric	10

Fueled systems including fuel cells and chemical dynamic or thermal systems, have the following limitations; 1. Handling fuel constitutes a hazard that becomes greater in the closed environment of a pressure hull. 2. Certain fuels have gaseous wastes that may be difficult to accommodate at the deeper depths where overboard discharge is not permitted. 3. Fuel capacity limits the refueling cycle to relatively short periods, thus requiring retrieval and re-deployment of the system as well as fuel handling and logistics.

The nuclear systems, reactor or radioisotopes, are perhaps the most adaptive to the submerged (in situ) power source. Except for lower efficiency and larger heat transfer requirements, nuclear systems have no technical difficulties because of the environment. Sea water acts as a radiation shield. Since the fuel supply is essentially unlimited, a system may be deployed as required by other than power plant considerations.

Paragraph 4.1.1 describes some of the energy conversion systems which appear practical for this application, and paragraphs 4.1.2 through 4.1.5 describe the most promising energy sources.

4.1.1 Energy Conversion

Conversion of energy to electric power is a basic function in the design of any power source. With the exception of the batteries and fuel cells, which convert chemical energy directly to electrical energy, all the power systems discussed in this chapter involve intermediate conversion to thermal energy, which is then converted to electrical energy.

The quality of power obtainable from each source is dependent on numerous system variables and may be significantly influenced by the weight , space, and cost of equipment that is utilized. In general, almost any power quality may be provided for a price. Power quality characterisitics such as voltage and frequency regulation, transient response, noise, etc, may be defined at many points in a system from the initial generation to the actual consumption and may vary from point to point. The various loads also become part of the system and influence its characteristics in relation to other loads.

Two types of electrical generation are characteristic of the power sources considered, direct current and alternating current. Direct current is obtained from the so-called direct conversion devices, which include storage batteries, fuel cells, thermoelectric and thermoinic devices. The quality of this power not only varies with the type of source and its characteristics, but also with the ratio of installed-to-used capacity. Alternating current is selected for the dynamic conversion systems as the type most suitable for the general application. Therefore, all direct current sources must be provided with a means for frequency inversion to be as suitable. The result is that all sources thus provide the same final output and should have the same minimum quality to be acceptable.

The following are considered as minimum system requirements to meet the general types of loads anticipated.

A. Power Quality

1. Voltage Regulation

The generator, exciter and regulator package shall provide a steady-state voltage regulation of ± 5 percent of rated voltage for applications with no transmission losses. To provide comparable quality with the longer transmission system, a more stringent requirement is placed on the source output.

The voltage regulation shall apply to any change in load from no load to full load at rated power factors and is defined as the change in the output voltage after all transients due to the load change have decayed to zero.

2. Transient Regulation and Recovery Time

When the generator is initially at rated speed, rated voltage, and no load, the sudden application of rated load at rated power factor does not cause a transient voltage deviation of more than 20 percent of rated voltage. In addition, the output voltage will recover in one second or less and remain within a band of ± 5 percent of rated voltage.

3. Motor Starting

The generation system shall be suitable for full voltage starting of induction motors with a maximum of 35 percent voltage dip under the following conditions:

a. motor full voltage inrush 5.5KVA/HP
b. motor horsepower not in excess of 0.40 HP per KW of generator capacity.
c. no initial load on generators.

B. Voltage Wave Form

For most load, the generation of a perfect sine wave gives the most satisfactory operation. An imperfect wave form has associated with it harmonics of the fundamental frequency, which have undesirable effects. Large harmonics can cause excessive heating of induction motors and transformers because of hysteresis losses and circulating current.

It is not practical from an economic viewpoint to generate a pure sine wave. It can be done, but the increase in cost and size of the generator would increase considerably. Therefore, a method devised for expressing wave form is the deviation factor. The standards of National Electrical Manufacturers Association (NEMA) limit the maximum deviation factor of the open circuit terminal voltage to 10 percent, unless otherwise specified. The deviation factor of a wave is a ratio: the maximum difference between corresponding ordinates of the wave and of the equivalent sine wave and the maximum ordinate of the equivalent sine wave (when the waves are superimposed in such a way as to make this maximum difference as small as possible).

C. Frequency

The output frequency has been specified for all AC generators in this study at 60 cycles per second. The normal deviation allowable, which depends on the system and the system protection scheme, is $\pm$ 5 percent.

The frequency control, governed by the over and under speed devices, is normally set on the prime mover through its governor speed control system, An over or under frequency relay may be used to supplement the governor control, thereby insuring that the frequency bandwidth does not exceed the desired limits. Typical recovery times is 1.5 seconds for frequency excursions outside of the steady state bandwidth.

D. Telephone Influence Factor (TIF)

One of the effects of the harmonics produced in the generated wave form is its influence on telephone circuits. Certain harmonics have a greater effect than others; a TIF curve has been developed which gives each harmonic a weighted effect. Generally, the 1941 curve is used, and a meter has been developed which measures the harmonics according to the weighted curve.

Generators in the range of 62.5 KVA through 300 KVA are required to have an open circuit, balanced TIF not in excess of 300 in accordance with NEMA standards. However, in areas where power curcuits and telephone circuits are close, a TIF of 50 may be required.

E. Voltage Unbalance

Since a synchronous generator has an internal voltage drop, any difference in current through different sets of windings will cause a voltage unbalance at the terminals of a three-phase generator. This unbalance would be kept to a minimum because of the adverse effects on the utilization equipment, as well as on the generator.

An unbalance voltage at the terminals of utilization equipment, such as motors or transformers, can cause circulating currents which result in overheating. The torque of an induction motor is affected by unbalanced voltages.

Any three-phase distribution system should have the load balanced as closely as possible. Voltage unbalance can be introduced in the distribution system as well as in the generator and the combination of these two unbalances can add up to a greater unbalance at the utilization equipment than at the generator terminals.

$$\text{Percent voltage unbalance} = 100 \times \frac{\text{Maximum voltage deviation from average voltage}}{\text{Average voltage}}$$

The percentage increase in temperature rise of an induction motor with unbalanced line voltage will be approximately two times the square of the percentage voltage unbalance. To illustrate the severity of this condition, temperature will rise about 25 percent. Recommended practice on utilization equipment is that the line voltages should be evenly balanced as closely as can be read on the usually available commercial voltmeter.

F. Special Requirements

Individual loads requiring power qualities in excess of those normally provided should be analyzed on a case basis. Local power conditioning equipment will be able to provide far better performance and at lower weight and cost for an individual load than to design the whole system to meet these special requirements. The major portion of the loads is assumed to be motors, lights, heating, etc., that will not require special consideration.

4.1.1.1 THERMAL DIRECT CONVERSION — The direct conversion of thermal energy to electric energy can be done by thermoelectric of thermionic devices. Thermoelectric converters operate in the lower range of temperatures (<1000°F) where suitable materials are available. Their reliability and low maintenance and servicing requirements have made this a desirable system for low-level power sources. However, their efficiency is extremely low -- only a few percent. This requires large energy sources and waste heat rejection systems to develop the high power levels of interest in this report. In addition, the thermoelectric system is essentially limited to low voltage and high amperage output. This presents some difficult problems, at the higher power levels, such as pressure hull penetrations for the large cable required. Loads must also use the power as generated (low voltage and direct current), or additional power conditioning equipment and a pressure hull is required. In general, thermoelectric conversion is not a suitable system for this application. A load whose characterisitics match the DC output of the thermoelectric system might find this conversion system suitable under certain conditions.

Thermionic conversion can result in efficiencies of up to 15% at temperatures around 2000°C. These systems are still highly developmental and are of little value to the immediate future. Their efficiencies are less than other systems offer at present, particularly considering their operating temperature.

4.1.1.2 THERMAL DYNAMIC CONVERSION — Thermal dynamic conversion systems are numerous, well known, and highly developed. These cycles include the Brayton, Rankine, Stirling, and internal combustion types, and are used with a wide variety of fluids. With the exception of the internal combustion cycles, the thermal energy may be obtained from any source.

The Brayton gas-turbine cycle has the lowest overall efficiency. In addition, it is only moderately efficient at high temperatures and power levels. The Brayton cycle is selected for very few applications. Brayton systems using oxygen supplied under pressure are more efficient than systems using air or closed-cycle gas because of their lower compressor power.

Stirling cycle engines are currently being developed by General Motors Corporation and are theoretically capable of very high conversion efficiencies, even at low power levels (30 KW). The Stirling cycle is not new nor is the basic engine design. Actual engine efficiencies in earlier engine tests were about 80 percent of diesel engines up to several hundred horsepower. Better performance is considered obtainable. The low noise level of the Stirling cycle engine is inherent in the design and may be of value in certain applications that require this attribute. The developmental status and relatively high cost prevent the Stirling cycle engine from competing with the diesel in surface applications. Present engines are nearly the same size and weight as the diesel.

The Rankine vapor-turbine cycle is most commonly used with water (steam) as the working fluid. This cycle has moderate efficiencies over the power range of interest and is adaptable to a wide range of thermal energy input temperatures. For temperatures below about 800°F, the Rankine steam cycle is more efficient than the Stirling cycle for larger plants. Small steam plants (~30 KW) have the same performance as the Stirling cycle for temperatures around 700°F. Increasing temperature favors the Stirling cycle, whereas increasing the power level favors the steam cycle. Steam cycle equipment is generally available, although considerable engineering and design work is required to provide equipment packaged for maximum economy of weight and space as well as cycle efficiency, particularly for low power levels. Turbine efficiency generally increases with both increased power level and speed. The change in efficiency with power level is a maximum at the lowest power levels with the major change occuring at less than 500 KW. High speed turbines require reduction gears which may result in weight space or noise problems or the use of high speed generators with the resultant high frequency electrical power.

4.1.2 Stored Thermal Energy

Stored thermal energy may be used as an energy source for an underwater power source. The storage material is charged with thermal energy at the surface and must be periodically recharged.

The lightest source of stored thermal energy is lithium hydride. Estimates of the weight for the energy storage system, including hardware, are 13 lbs/KWH(e), based on a power plant overall efficiency of 27 percent. In addition to the relatively high weight of energy storage material, this particular system also has a low density (large volume). The material also burns and may react violently with moisture in the presence of air. Another major problem is hydrogen containment at high temperature. Other proposed materials which are more easily handled require somewhat heavier systems, e.g., an amount of aluminum oxide weighing twice as much as the lithium hydride is required for the same energy storage.

Maximum efficiency of the thermal energy storage systems requires the use of the Stirling cycle engine at low power levels. The system must be enclosed within a pressure hull, including both the energy storage and conversion equipment. Estimated overall weights for the aluminum oxide/stirling cycle system are approximately 30 lbs/KWH minimum - exclusive of the pressure hull for systems with at least 7 hours of full power.

The developmental status, volume and weight limits on energy storage and the requirement to return to the surface for frequent replenishment of stored thermal energy do not make this system attractive as a main source of energy. Use of the thermal energy storage system in conjunction with the radioisotope power plant could result in a more economical system for meeting peak power levels. This combined system is also limited by the ability to efficiently incorporate power conversion equipment suitable to both average and peak loads. A pressure hull is required to enclose the entire system.

4.1.3 Chemical Energy

There are two major ways to utilize chemical energy to produce electrical power: by direct conversion and by generation of thermal energy, which is then converted by one of several methods, as discussed in paragraph 4.1.1. The direct conversion methods available are the storage battery and the fuel cell. There are a large number of chemical systems in existence. However, only a few are practical at this time. Virtually all systems (including the storage batteries) have oxygen as an initial component or derive oxygen from chemical compounds.

4.1.3.1 FUEL OIL AND OXYGEN SYSTEMS — A considerable number of thermal systems have been proposed and developed around the use of fuel oil and oxygen. These include a closed cycle diesel, gas turbine and a steam-gas turbine known as the Walter cycle. The Walter cycle employs H_2O2 (~90%) and fuel oil and derives a portion of its energy from the decomposition of H_2O_2 into steam and oxygen.

These cycles have been developed primarily to provide power sources for limited shallow-depth submerged application for vehicle propulsion. The use of fuel oil results in a gaseous waste product CO_2 which must be pumped overboard or compressed and stored as a liquid. Overboard discharge at great depths requires a major portion of the power for pumping and is not practical. The danger of an active hull penetration also makes it an unacceptable solution for all but the most shallow operating depths.

Compression of the CO_2 and storage as a liquid is generally the better method when overboard discharge is not employed. This is the lightest and most compact system for onboard storage and is readily regenerated for reuse. Sea water temperatures are low enough in most areas to maintain the CO_2 at temperatures lower than the critical temperature of 88.4°F; therefore CO_2 storage is not dependent on a powered cooling system. Additional equipment is required for the cooling and storage of the CO_2. Refrigeration may be required to provide cooling during power plant operation dependent on the particular requirements for heat transfer through the pressure hull and the ambient sea water temperature. When liquid oxygen is employed as a reactant, it can be used to provide the low temperature sink for liquifying the CO_2.

Since other regenerative systems for the absorption or adsorption of CO_2 require many times the weight and volume of the liquid storage system, they are not considered as practical solutions. Non-regenerative systems such as the hydroxides (similar to life support systems) require heavier and larger storage requirements, except where the hydroxides are produced as a by-product of oxygen generation from the superoxides. Hydroxides supplied specifically for CO_2 absorption also will significantly add to logistics requirements.

Highly concentrated H_2O_2 is considered to require extreme precautions in handling. Systems have been built and tested using this material. However, these systems must be kept extremely clean because of the ever present danger of explosion as the result of self-decomposition due to impurities acting as catalytic agents. Both fuel oil and hydrogen peroxide may be stored outside the pressure hull if active hull penetrations are permissible. External storage significantly increases the energy per unit volume and thus increases the refueling cycle.

The more efficient conversion cycles require approximately 5 lb/KWH of reactants (10% fuel oil, 90% H_2O_2), resulting in fuel costs on the order of \$2/KWH, based on shore delivery of hydrogen peroxide. Approximately 20,000 KWH of energy may be enclosed in a plant having the same volume and weight as the nuclear reactor power source for the low power levels of 30 KW and 300 KW. Computation of the net energy available must allow for the energy need for disposal of the waste product CO_2.

Other sources of oxygen that may be considered are the oxygen gas or cryogenic liquid and the super-oxides. Liquid or gaseous oxygen costs \$.20/KWH. Among the superoxides, NaO_2 costs \$3.50/KWH and KO_2 costs \$5.00/KWH.

The CO_2 waste product can be eliminated by using other fuels. Hydrogen is one of the most desirable fuels because of its high energy content with oxygen and the easily handled waste product (water). Other fuels are available either as sources of hydrogen, for direct combustion with oxygen, or as monopropellants, etc. In general, these other chemical systems, when compared to hydrogen and oxygen, are less favorable in terms of one or more of the following characteristics: weight, volume cost, safety, handling, and waste product disposal.

4.1.3.2 HYDROGEN AND OXYGEN SYSTEMS — The use of oxygen and hydrogen as reactants allows consideration of a mechanical conversion system, such as a turbine-generator, or direct conversion in a fuel cell. Of these methods, the fuel cell is more efficient, especially at low power levels.

Storage of hydrogen and oxygen aboard a submersible vehicle presents some unique problems. There are two direct methods, cryogenic liquids (subcritical) and high pressure gas. High pressure gas storage is only practical when separate pressure hulls are used to store the reactant and penetrations are made to the pressure hull containing the power source. Cryogenic liquids may be stored in a common or separate pressure hull. Fuel costs range from a low of approximately \$.25/KWH for the fuel cell to \$.50/KWH for the turbine system.

Cryogenic and high-pressure storage of hydrogen and oxygen reactants, storage configuration, and methods of transfer to the point of usage were analyzed and evaluated for various power plant configurations. Several schemes for the vaporization and control of the delivery of gaseous reactants from the various cryogenic storage arrangements were analyzed and evaluated. The evaluations considered both power plant operation and attitude. The schemes analyzed are listed below.

- Methods of storage

  Cryogenic (subcritical liquefied gas)

  High-pressure gas

- Configurations of storage

  Within a common power plant pressure hull

  Within individual pressure hulls

- Methods of transfer to obtain gas at usage point

  Natural pressure decay (applicable to high-pressure gas only)

  Natural boil-off (applicable to liquid storage only)

  Pressurized transfer using separate gas supply)

  Electric heater within the storage container

  Electric heater external to the storage container

  Heat exchanger external to the storage container using gravity feed for startup and a warm gas by-pass or pumping for continued operation

- Other sources of reactants

Cryogenic storage within a common power plant pressure hull is tentatively recommended. A more thorough safety analysis is required to establish the least hazardous arrangement. The gaseous transfer is to be accomplished by vaporizing the liquid and heating the vapor, using an external heat exchanger; the power plant's waste heat would provide the heat source. A back-up electrical heater will be installed in the cryogenic storage container to assure gas delivery in the event liquid flow cannot be obtained to the heat exchanger due to a failure in the liquid line or cooling system or excessive list angles.

Cryogenic storage (subcritical) of oxygen or hydrogen is the lightest method and requires the least volume.

Cryogenic storage is accomplished by providing an inner cryogen container and an outer protective container with an evacuated annulus. The evacuated annulus is filled with super-insulation and supports for the inner tank. The supports are constructed from materials of low thermal conductivity.

For example, for a fuel cell application, use of the aforementioned containers requires installation in a common pressure hull with the fuel cell modules. Separation of the cryogens and the fuel cell system and its associated machinery is possible by using three separate pressure hulls, one each containing the fuel cell system, hydrogen, and oxygen. For this arrangement, it is feasible to use the pressure hull as the outer protective container for the cryogen. This concept has the inherent disadvantage of requiring mechanical penetrations and piping which would be subjected to the full submergence pressure. In addition to their added weight factor, the penetrations and piping present a hazard factor. Assuming check valves are installed in each of the discharge lines, a single failure of the penetrations or external piping would allow the fuel cell hull to fill with sea water. Design of a system of hull valves and appropriate instrumentation to provide automatic closure would require an extensive development program.

Difficulties and problems associated with the storage and transfer of liquefied gases include difficulty in handling, transport, and hazard factors. Some of the engineering problems associated with cryogenic storage and subsequent transfer as a gas are:

1. Packaging: A spherical container is the most efficient from a weight and low heat-leak standpoint; however, packing spheres within pressure hulls causes considerable loss in usable volume at the interstices. Using form-fit storage containers for the cryogen increases the weight of the containers. Practically, however, for a particular application the total weight using form-fit containers and pressure hull may be less. This weight saving is due to the packing efficiency gained in the pressure hull by the use of form-fitting tanks, thus affording a smaller pressure hull for the same energy. This weight saving is therefore dependent on hull materials and depth.

2. Hold Time: During the period between fueling and power plant operation, the fuel storage tanks will increase in pressure due to heat leak. Hold time can be controlled by providing better insulation or more ullage space, but these solutions add weight and volume. Other methods include a) the supply of subcooled liquid to the storage container; this places an undue burden on the support ship, b) the use of fuel while waiting to embark; this shortens the mission time, c) the provision of a vent capability; if venting is within the vehicle, fire and explosive hazards are amplified, and if venting is external to the vehicle, mechanical pressure hull penetrations are required, adding weight and hazards.

3. Delivering Gas: Although the fuels are stored cryogenically, gas must be delivered at the required flow rate and pressure. In summary, the systems and their advantages and disadvantages are:

    a. Use of an electric heater inside the tank has the disadvantages of reducing the net available power and of presenting a potential safety hazard due to over-pressurization in the event the heater cannot be shut off or controlled.

b. Use of a heater outside the tank may restrict maximum allowable angles of list in assuring that liquid is delivered to the exterior heater.

c. Use of one heater inside and one outside the tank requires additional controls and arrangements to handle liquid flow under normal conditions and gas flow during severe operating angles.

d. Supercritical cryogenic storage of the liquids requires additional weight and volume. The added weight is a result of the increase in wall thickness required as a result of the higher pressures. (H_2 - 200 psia, O_2 - 730 psia). The added volume results from the lower densities and allcwances made in order to maintain the hold time and performance of the storage containers.

e. Other methods for cryogenic transfer were investigated and ruled out. Transfer by gas stored in a high-pressure container is not recommended due to the added weight and volume of the gas storage container. In addition, to provide for failure of the discharge regulator, the cryogenic container would probably have to be designed to withstand the storage pressure, thus increasing the total weight. Transfer of the cryogen by pump is not recommended for the following reasons: (1) reliable, variable speed, low NPSH pumps are not readily available (2) it reduces net power available for loads (3) two pumps would probably have to be installed, one for back-up (4) pumps are significantly heavier than heaters.

Transfer of gas by natural heat leak into the storage container from the sea or other sources is not recommended because of the difficulty in obtaining reliable control of the heat leak from no-load to full-load. In addition, failure in the control of heat leak could cause rapid overpressurizing.

Liquid cryogenic transferred out of the storage container may be evaporated by thermal energy from the sea, compartment ambient air, or power plant waste heat. Obtaining energy from the sea will be difficult as the sea water temperatures approach freezing. Heat transfer through the pressure container (hull) must also consider the effects of transient as well as steady state thermal gradients on the total stresses. Methods of heat transfer that result in lowering the pressure hull temperatures below 28^{o}F (minimum sea water temperature) must also consider the effect of the minimum anticipated temperature on the selection of suitable pressure container materials (e.g., nil ductility temperatures).

Hydrogen and oxygen reactants are available as chemical compounds, but this does not alter the conclusions of this study. All of these chemical compounds require an increased weight, but may show some volume reduction due to higher density. All of the sources also result in higher reactant costs. The waste products must be liquid or solid to result in the most acceptable systems for deep submergence.

4.1.3.3 FUEL CELL SYSTEMS — There are many fuel cell systems based on various types of cells and fuels. Present fuel cells are in the development or prototype stages (limited application) with the major effort being spent on the hydrogen/oxgen cell; as a result, it is the most advanced. Hydrazine/air (oxygen) cells have also had considerable development effort for terrestial applications due to the relative low cost and ease of fuel supply.

The hydrogen/oxygen cell is of primary interest due to its high efficiency, the high energy content of the fuels, the easily handled waste product (water), and the fact that reactants for the H_2/O_2 cell may be obtained from many chemical compounds.

Both cell types, however, are considered to have some potential due to their advanced state of development and characteristics. The principal fuel cell characteristics and parameters that affect submerged application are weight, volume, efficiency, load voltage regulation, ability to handle load transients (motor starting and reversal), and safety and reliability. Desirable features include low cost, systems simplicity, and minimum maintenance and servicing. Evaluations of the various H_2/O_2 and N_2H_4/O_2 fuel cells produced by several vendors (at least four major vendors of H_2/O_2 cells and 3 vendors of N_2H_4/O_2 cells) will determine the system most suitable (tradeoffs between weights, volumes, efficiency, voltage characteristics, etc.).

The H_2/O_2 fuel cell power source is lighter than the N_2H_4/O_2 system, but the H_2/O_2 requires a pressure hull enclosure. The N_2H_4/O_2 system has potential for development of an off-hull, pressure-compensated system and thus promises to provide the lightest power source. The development of lightweight hull materials will reduce or eliminate the weight advantage of a pressure-compensated system.

4.1.3.3.1 H_2/O_2 Fuel Cell Power System — The adaptation of the H_2/O_2 fuel cell to a submerged power plant requires that it be enclosed in a pressure hull. Although component weight is significant, the volumes required are more significant due to pressure hull weights. A preliminary assessment of the various vendors' systems indicates that, although significant differences exist among components and the requirements for auxiliary systems, they may be reasonably characterized at the 30 KW power level by a specific weight of 55 pounds/KW and 0.9 ft^3/KW, including all equipment (foundations, heat exchangers, access space, etc.). These values are reduced to approximately 75% for larger systems. In addition to equipment weight and volume, fuel and fuel storage weight and volumes and fuel waste product volumes are required; for the larger energy requirements, these will constitute a major portion of the equipment weights and volumes.

The major consideration in minimizing the overall power plant weight is packaging the systems to obtain minimum pressure hull volume and weight. Estimates of hull volume required for reactants and waste product storage based on a total consumption of 1.0 lbs/KWH are .063 ft^3/KWH for cryogenic storage and .085 ft^3/KWH for gas storage at 7000 psia. Corresponding weights for the cryogenic storage system are 1.7 lbs/KWH, including reactants. Pressure hull weights vary with design operating depth.

The hazards of storage of both reactants within the same pressure hull must be carefully considered. (From a weight standpoint, only cryogenic storage is considered practical for this arrangement.) It may be feasible to design against fires of short duration; however, the weight penalty involved in designing against explosion may be impractical. In addition, the impact sensitivity of oxygen may present a problem.

The use of three separate pressure hulls with appropriate valving may prevent the feeding of reactants to a fire; however, consideration must be given to the effects of explosions on valving and to the prevention of rupturing lightweight cryogenic containers. Where three hulls are employed, the shift in the center of gravity as fuels are transferred must be considered, in addition to the use of hull penetrations.

The dead-ended gas systems employed in the majority of the H_2/O_2 fuel cells require periodic purging with the reactants to rid the fuel cell gas chamber of gaseous impurities that impede the flow of reactants to the active surface. The amount of purging is dependent on the purity of the reactants. The purge gases must be stored (probably not practical for large energy requirements and field-produced reactants) and reacted to form water if not disposed of in some other way. The purge system may also present a safety hazard by allowing an explosive mixture to be formed should the burner malfunction. A system that burns the hydrogen with the oxgen could also serve as a safety valve for heat leak vaporization in the event of a complete loss of the fuel cells. Careful consideration must be given to the design of this system.

Fuel cell systems employing trapped aqueous alkaline electrolyte will require CO_2 free reactants to maintain performance. This may be accomplished by using in-line CO_2 scrubbers (specifying low maximum CO_2 content reactants because cryogenic fuels may pick up small amounts in fuel transfer), or more frequent flushing of the electrolyte. The in-line CO_2 scrubbers may be the most practical.

Product water removal varies with the particular fuel cell system. No difficulties are anticipated; however, the large energy systems may require that storage be subdivided to provide for a compact arrangement of equipment and to prevent large free water surfaces from producing rapid shifts in the plant's center of gravity during recovery operations.

The application of H_2/O_2 fuel cell systems as submerged power plants will apparently require a major design and engineering effort. Estimates range from several million to several tens of millions of dollars for the lowest power level, 30 KW. The technical feasibility of fuel cells and handling cryogenic reactants has been established for surface and space applications; however, the closed environment imposed by deep submergence presents many problems in the selection and design of safe, reliable, and minimum-maintenance systems that will also afford low weight and volume, high overall efficiency, and simplicity.

4.1.3.3.2 N_2H_4/O_2 Fuel Cell Systems — Because of the inherent safety problems associated with hydrogen and oxygen storage and transfer, either in liquid or gaseous forms, and especially in a closed environment, the potentialities of the hydrazine-oxygen fuel cell (installed inside a pressure hull and pressure-compensated off-hull) were briefly investigated.

The concept for the in-hull system will allow the nitrogen given off during reaction within the cell to build up pressure within the pressure hull. Preliminary investigations have indicated that the cell would show no deleterious effects from operating in a moderate nitrogen-pressured atmosphere. Oxygen could be stored either in a gaseous state within the pressure hull or cryogenically in a container and piped directly to the cell.

Gaseous storage within the pressure hull presents several equipment problems in that the design would have to include spark-proof as well as explosion-proof features, plus additional cleanliness requirements for all equipment in the hull. As the cell operates, it uses ambient oxygen and replaces it with nitrogen on a per-mole basis, thus maintaining a constant pressure within the hull as well as a constant differential pressure across the cell.

Cryogenic storage would operate in much the same way, with the exception that the pressure within the hull would vary from one atmosphere at the start of the mission to the maximum nitrogen pressure at the end of the mission. Cryogenic storage, although heavier, provides isolation between the equipment and oxygen during normal operation and an inert atmosphere (N_2). The added weight is a result of the cryogenic storage containers and associated piping and controls. Since the cryogenic storage container is designed with inner and outer tanks separated by an evacuated annulus, both the inner and outer tanks must be designed for the maximum internal pressure. In addition, the control regulator and system must be designed to provide varying fuel pressures in order to maintain a constant differential pressure between the cell and the ambient atmosphere within the internal hull.

An additional problem associated with the hydrazine-oxygen fuel cell system is toxicity. Hydrazine is extremely toxic and inhalation of even dilute concentrations may cause olfactory fatigue, lung damage, and inflammation of the liver. The use of hydrazine in fuel cells has been known to give off traces of ammonia, (how much is not known); this would have to be thoroughly investigated prior to incorporation in a closed atmosphere.

The alternate concept for the hydrazine-oxygen fuel cell places the entire system outside the pressure hull, exposed to ambient sea pressure. Hydrazine is supplied and effectively used by the fuel cell in liquid form. Although present cells are not capable of efficiently using oxygen directly from hydrogen peroxide (decomposition is not controllable), an alternate technique would supply gaseous oxygen at ambient pressure by decomposition of H_2O_2 on demand.

The off-hull concept would at first appear to offer the lightest system when compared to those enclosed within a pressure hull; however, the development of lightweight hull materials would result in an internally located power plant (H_2/O_2 type) with essentially the same overall weight (including pressure hull). In addition, the pressure hull-enclosed plant would result in a significant positive buoyancy, whereas the external, compensated N_2H_4/O_2 system is negatively buoyant.

The compensated system is apparently safer than the pressure-hull-enclosed system, because the plant is entirely surrounded by sea water; however, a more detailed analysis and experimentation would be necessary to verify this.

Technical feasibility of the compensated fuel cell system is yet to be demonstrated. In addition to ascertaining satisfactory operation of the fuel cell and systems, potential problems relating to gases in solution must be resolved. Nitrogen (released from the hydrazine) and oxygen will tend to permeate the system by going into solution at the high ambient pressures. (There is some potential for small amounts of ammonia.) The effects of these gases and the resultant gas bubbles as the ambient pressure is decreased must be determined. Gas bubble formation would be most predominant when returning to shallow depths. In addition to the effect of bubble formation on the power plant performance and equipment, the effect of the gas volumes on vehicle buoyancy and depth control must be evaluated.

Development time and costs for the compensated system would appear to be considerably larger than for the encapsulated H_2/O_2 system. In addition, the lack of current technical feasibility presents a certain risk in estimating time and costs and, indeed, in ever obtaining a suitable plant.

4.1.3.4 BATTERY SYSTEMS — Battery systems suitable for submerged use are the production types, lead-acid (Pb-Acid) and silver-zinc (Ag-Zn). These types have been successfully tested over the depths required (20,000 ft). The nickel-cadmium (Ni-Cd) and silver-cadmium (Ag-Cd) are more expensive and offer no advantages. The batteries may be enclosed in pressure hulls or in oil-filled, pressure compensated systems. The selection of enclosure depends on the depth and cost of obtaining buoyancy as well as safety and other considerations. For the unattended plant where explosions due to hydrogen gassing are possible, the pressure compensated system is preferred for safety and is also generally lighter and less expensive at the deeper depths.

The potential applications of batteries include emergency and auxiliary power sources for load modules or submerged power plants and main power source, either alone or in conjunction with other sources. Batteries alone as a main power source have limited energy capacity. However, they can function effectively with other power sources for loads that are cyclic or have high peak-to-average values. In the latter case, the batteries can meet the excess load during peaks and can be recharged during low demand. The basic source of energy can be a submerged (in-situ) power source, a surface power source or a shore based source. This combined system has the advantage of allowing the basic power sources and transmission facilities to be designed for near-average power levels, rather than peaks.

Disadvantages include: the requirement for frequency inverters to change the DC output to AC, a varying output voltage, efficiency losses due to charging, discharging and inversion, and the expense of two power sources.

The size, weight and cost of a battery power system is dependent on many variables, in addition to battery type, including power level, charge and discharge rate (stored energy), charge and discharge temperature, weight to displacement ratio, life required (cycles, time), operating depth, cell capacity, and enclosure (pressure compensated or pressure hull). Allowance must also be made for a reserve capacity for normal variations in battery production and charging variations and for losses due to power conditioning of voltage and frequency. Table 4-I presents typical order-of-magnitude acquisition cost and weight and displacement data comparison of the Pb-Acid and Ag-Zn pressure compensated battery systems. The effects of discharge temperature and the addition of buoyancy material are shown. The Pb-Acid system is more sensitive to temperature than the Ag-Zn over the range of 75°F to 32°F. Buoyancy material in the form of syntactic foam was assumed at a density of 38 lbs/ft^3 (projected availability 1970-71) and at two installed costs, $6 and $12 per pound.

Table 4-I does not reflect a number of the cost variables, such as quantity or battery operating depth. It shows that a major acquisition cost is that of the buoyancy material. As a result, the Pb-Acid system can have an initial cost greater than the Ag-Zn. Operational costs, considering only the battery system, tend to be lowest for the Pb-Acid type due to both a lower replacement frequency and battery cost. The Pb-Acid will have approximately 5 times the deep discharge cycle life of the Ag-Zn. However, the Pb-Acid is approximately 3 times as heavy and will require about three times the volume as the Ag-Zn, making it somewhat more difficult to deploy. The effects of the many variables will result in considerable variation in the cost of a battery system, from $50/KWH-YR to $250/KWH-YR for the Pb-Acid and from $150/KWH-YR to $300/KWH-YR for the Ag-Zn. These costs do not reflect other equipment, such as switchgear, charging equipment, frequency inverters, or protective equipment and their required pressure hull enclosures.

Table 4-I. Battery Power System Characteristics-Pressure Compensated (All values per net usable energy)

BATTERY TYPE	TEMPERATURE °F	BATTERY SYSTEM Cost $/KWH	Weight lb/KWH	Displ. lb/KWH	BATTERY PLUS SYNTACTIC FLOTATION Cost $/KWH (1)	(2)	Weight(3) lb/KWH
Pb-Acid	75	225	125	64	775	1325	215
	30	350	175	90	1100	1850	300
Ag-Zn(4)	75	650	46	23	850	1050	80
	30	800	55	27.5	1050	1300	95

(1) Syntactic Flotation at $6/lb
(2) Syntactic Flotation at $12/lb
(3) Displacement is also equal to the weight
(4) Costs estimated with Ag at $1.29 per ounce

Although a battery system may be designed to serve many applications, the individual applications can impose a wide range of requirements on the auxiliary equipment,thus requiring a separate analysis to arrive at cost data. Variation in the price of silver (recently freed from government regulation) will affect costs of the Ag-Zn battery system.

An almost unlimited buildup of capacity appears technically feasible considering only the battery systems, although a modular approach may be required for the larger sizes. However, deployment and recovery operations may become impossible with the larger total capacities due to size and weight (mass) (Reference 2).

Consideration of cost and size (weight) and alternate sources of power (cable from surface or nuclear) will probably limit the battery to energy levels no greater than 2000 to 3000 KWH. Particular applications must be individually evaluated. Conditions existing at the time may substantially alter the selection criteria.

4.1.4 Nuclear Reactor Power Sources

The nuclear reactor plant has been proven to be a very important and successful source of power for undersea applications. However, its large size and weight detract from its application to the smaller power levels unless total energy requirements are large. Energy storage with the nuclear reactor requires very small weight and space. The nuclear reactor is the only practical self-contained undersea power source for most of the power and energy levels of interest in this study.

The large weight and space of the nuclear power plants that have been built and successfully operated have led to many proposals for new systems based on various fluid and conversion schemes. Many of these proposals imply or claim advantages of weight, size, and/or cost of as much as several factors over present systems designs. Considerable care must be exercised in evaluating these proposals to ascertain that the claims are realistic when making a specific application. Some of the means for achieving their claimed advantages are by one or more of the following:

- Basic shielding requirements are relaxed or omitted or assumed to be a part of other systems.
- Essential equipment and systems are omitted.
- Compact equipment arrangements are made which are not suitable for long term use of equipment, considering maintenance and servicing.
- Successful development of complex deep-submergence pressure hull configurations are assumed, high performance equipment is assumed, or systems are used that have a limited operation range.

Reactor systems are generally classified by their coolant: gas, liquid metal, organic, pressurized water,and boiling water. Comparisons of various concepts which have the same overall performance characteristics have resulted in relatively little variation in total weight, space, and costs. A qualitative comparison of the various reactor systems,as classified by coolant to the pressurized water-cooled system,is given below:

- Gas-cooled reactors tend to be larger, heavier, and require more complex emergency cooling systems than other reactors. They must be designed against water flooding causing nuclear excursion. Primary application, to date, has been in very large, stationary, land power plants.

- Liquid metal - All designs are based on liquid metals that are highly reactive and corrosive in contact with water. Leakage of sea water will probably result in total plant loss. Although the plant is designed for unmanned operation, shielding must be provided for test operation and maintenance, and therefore there is no weight savings. Primary application has been for small, lightweight, power plants for space use. (A large military plant no longer in existence was operated for several years.)

- Organic - Poor heat transfer characteristics and thermal and radiolytic decomposition require more complex systems. Increased plant weights are estimated.

- Boiling water - Steam generators are eliminated and the direct cycle system is used with slightly higher efficiency. Steam plant equipment must have the same rigid design manufacturing and maintenance requirements as the reactor system. Weight savings are questionable. Primary applications are experimental, and are for large, land-based stationary power plants.

The pressurized water-cooled reactor with a steam Rankine cycle turbine conversion is the most suitable reactor system for a submerged power source in the immediate future. This is due to many factors, among which the major ones are: the already technological background and experience in power plants of this type for both terrestrial and marine applications, the availability of systems requiring little to no development, and the lack of alternative concepts which offer a better overall system. Some of the advantages (not necessarily unique) of the pressurized water-cooled reactor system are:

- This nearly off-the-shelf system requires virtually no development to result in a highly reliable, safe, long-life power source.

- The use of a liquid reactor coolant is most adaptable to decay heat removal systems that require no power.

- The liquid coolant retains virtually no radioactivity within a short interval after shutdown (and is effectively radiation stable), thereby minimizing extra shielding.

- The readily sealed primary coolant system minimizes loss of coolant and the elimination of radioactive carry-over to conversion equipment, etc.

- The self-regulating (load following) reactor has a high safety factor against nuclear excursions.

- A fluid common to both reactor and conversion system is readily available.

Reactor power sources are not specifically considered for applications other than the in situ power plant, since they are not economically competitive with fossil-fueled systems in the power range of interest.

Although the pressurized, water-cooled reactor with steam conversion system has seen extensive application in submersibles, there are major problems encountered in the use of these power supplies below the ocean surface. In addition to the problems related to operations, transport, and deployment[2], there are problems of design and fabrication related to equipment size and orientation, pressure hull limitations of size and materials, and waste heat removal. The difficulties increase with both power level and operating depth.

The wide range of power levels and equipment sizes results in two power plant arrangement concepts based on power level. Reactors are generally designed to occupy a vertical cylindrical space because of considerations such as safety of gravity rod insertion, natural convection heat removal, and refueling requirements. Turbine-generator equipment is normally designed for horizontal orientation. Vertical conversion equipment has been built for special application, and vertical steam turbines are commonly made for auxiliary drives such as blowers and feed pumps, however, the preferred orientation appears to be horizontal for reliable, long life performance. The low power levels (from 30 KW to 300 KW) can incorporate horizontal turbine generator sets within diameters suitable for the reactor, and therefore a vertical cylindrical pressure hull is used. The 1000 KW and 3000 KW plants are arranged in a horizontal cylinder.

The vertical cylinder arrangement is more versatile than the horizontal cylinder for deployment. The opposite is true for transport by towing. The low-power-level systems, however, are readily designed for nearly horizontal towing and vertical operation.

Increasing depth requires increased pressure hull thickness and decreases the diameters that may be fabricated. Minimum diameters have been estimated for the reactor, based on obtaining access to the pressure hull for hull inspection and maintenance (painting). For carbon steel hulls, these diameters range from 7 feet for the 30 KW plant to 10 feet for the 3000 KW plant. Two factors that will significantly modify these dimensions are type of material in the pressure hull, and the extensive use of iron shielding to suppress neutron flux levels and reduce activation of the pressure hull. The high strength steels are not the most attractive; HY-80 and HY-130 contain nickel with cobalt impurities. HP9-4-C type HY-180 steel contains almost 5% cobalt and requires diameters approximately two feet larger than the lower strength steels. Design and arrangements must consider pressure hull material activation.

Waste heat removal from the pressure hull and the present limitations on mechanical penetrations are two factors limiting the power level at deeper depths. The direct use of the pressure hull for heat transfer as a steam condenser appears technically feasible for all depths, but is considered to be developmental (see Section 11.2). The direct use of the pressure hull is also a factor limiting the power level for two reasons: the area available for heat transfer and the limitations on thermal flux because of both the thermal driving head and thermal stresses in the hull. The conventional method for removing waste heat from the hull is to use a heat exchanger piped to the sea through hull penetrations. However, the hull penetration is a higher risk hull design and results in a system that has a higher risk of sediment clogging. The largest hull penetration for this type system is 3 inches in diameter for an operating depth of 3000 ft. (Considerably larger penetrations have been used at shallower depths.) Penetrations large in diameter and/or greater depths are also considered to be developmental. (See Section 11.2). The direct transfer of heat through the pressure hull was the method selected for the 30 KW to 300 KW power plants, the criteria being safety, weight, and cost.

At the higher power levels (1000 KW and 3000 KW), the pressure hull required to house the equipment is inadequate to provide a sufficient heat transfer area. However, hull penetrations adequate for the heat removal required do not exist and have not been proven for depths of 6000 feet and deeper.

Thus, in addition to the feasibility of fabricating pressure hulls of adequate size to enclose the power plant equipment, a suitable technique for heat removal, other than using the pressure hull, must be developed for the larger submersible power plants.

The requirement for one or more highly developmental techniques in the areas of hull size and penetrations for the larger power plants (1000 KW and 3000 KW) for the 6000 feet depth and over has eliminated them from further detailed consideration in this study. Although the pressure hull appears to be a suitable means for rejection of heat to the sea, both this system and the use of hull penetrations require extensive further consideration and development as indicated in paragraph 11.2.

A potential means of meeting large power loads is to use several small power sources. There are some technical problems involved in paralleling multiple units. These problems involve both electrical characteristics and deployment and retrieval operations[2]. The cost would be very great, although it might be somewhat less than a linear projection. Some increase in power levels could also be obtained with more compact equipment and higher efficiency.

Estimates of the overall characteristics for the various reactor power plants and operating depths are shown in Table 4-II. These estimates are for the complete power source and a hull envelope necessary to house the equipment and for heat transfer where required. The power plant was assumed unmanned and there is no provision for permanent life support included in the hull.

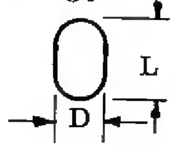
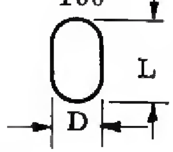
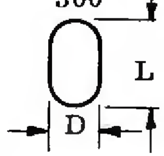
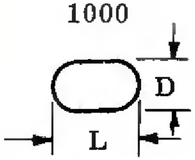
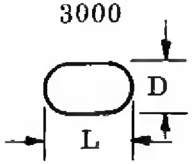
Adequate radiation shielding and space is provided for temporary occupancy to monitor operations and make plant adjustments.

Power plant arrangements and hull materials are not necessarily optimum and may be adjusted to better suit the application when it is more specifically defined. The low power plants (300 KW and less) transfer the waste heat through the pressure hull and, therefore, require adequate hull area for this purpose based on heat transfer coefficients. The use of steels with yield strengths other than those indicated for a particular hull will, to a first approximation, produce little change in the heat transfer coefficient, providing thicknesses are based on their respective strengths. The 300 KW plant is the only one with a pressure hull size determined completely by heat transfer requirements at all depths. The 100 KW plant hull sizes are heat transfer dependent at the 15,000 and 20,000-foot depths due to hull material thickness. Changes in hull thickness, materials or shape may result in changes in the hull surface area required for heat transfer. The use of titanium in place of HY-180 may be economically prohibitive or technically impractical due to its lower thermal conductivity (hull sizes must be increased to obtain adequate heat transfer area).

The power plants for 30, 100, and 300 KW are arranged in a vertical cylinder (Figure 4-1), a compact and highly functional arrangement. The reactor location at the bottom end utilizes the natural roundness of the hemispherical head to minimize shield weight and places the reactor core at a maximum distance from accessible volumes. The shield water tank, with large areas exposed to the sea, provides a means for decay heat removal using natural convection, and is a convenient heat sink for other power plant cooling requirements. The relatively small diameter of the cylinder also reduces the area of shielding necessary for personnel occupancy. The conversion machinery located immediately above the reactor is in close proximity to the heat source, and also provides added radiation attenuation for the control area. The control area is at the maximum distance from the radioactive sources for the enclosed volume (hull weight). The vertical cylinder arrangement is in general preferable for deployment on the ocean bottom due to its hydrodynamic characteristics and smaller area of contact with the bottom as discussed in Chapter 7.

The reactor, with its large shield weight located at one end, improves the vertical stability of the cylinder.

Table 4-II Power Plant Containment Vessel Parameters

POWER LEVEL (KW)		DEPTH (FT) AND TYPE OF HULL					
		600 / HTS	2000 / HY 80	6000 / HY 130	10000 / HY 130	15000 / HY 180	20000 / HY 180
30 	Inside Diameter (ft)	9	9	9	9	9	9
	Length (ft)	35	35	35	35	35	35
	Total Wt (lb)	123, 500	135, 000	167, 000	212, 000	221, 000	260, 000
	Displacement (lb)	130, 500	130, 500	130, 500	130, 500	130, 500	130, 500
	Buoyancy (lb)	+ 7, 000	- 4, 500	- 36, 500	- 81, 500	- 90, 500	-129, 500
100 	Inside Diameter (ft)	10	10	10	10	10	10
	Length (ft)	36½	36½	36½	36½	36½	36½
	Total Wt (lb)	156, 000	175, 000	215, 000	268, 000	283, 000	333, 000
	Displacement (lb)	166, 500	166, 500	166, 500	166, 500	166, 500	166, 500
	Buoyancy (lb)	+ 10, 500	- 8, 500	- 48, 500	-101, 500	-116, 500	-166, 500
300 	Inside Diameter (ft)	10	10	10	10	10	10
	Length (ft)	55	54	54	61	66	73
	Total Wt (lb)	217, 000	245, 000	322, 000	474, 000	550, 500	739, 000
	Displacement (lb)	258, 500	253, 500	253, 500	288, 500	315, 500	348, 500
	Buoyancy (lb)	+ 43, 500	+ 10, 500	+ 51, 500	-131, 500	-138, 500	-271, 500
1000 	Inside Diameter (ft)	21	21	(1)	(1)	(1)	(1)
	Length (ft)	46	46				
	Total Wt (lb)	640, 000	775, 000				
	Displacement (lb)	860, 000	860, 000				
	Buoyancy (lb)	+220, 000	+ 85, 000				
3000 	Inside Diameter (ft)	21	21	(1)	(1)	(1)	(1)
	Length (ft)	51	51				
	Total Wt (lb)	780, 000	960, 000				
	Displacement (lb)	980, 000	980, 000				
	Buoyancy (lb)	+200, 000	+ 20, 000				

(1) Diameters and hull size required for equipment and heat transfer considerations require major development.

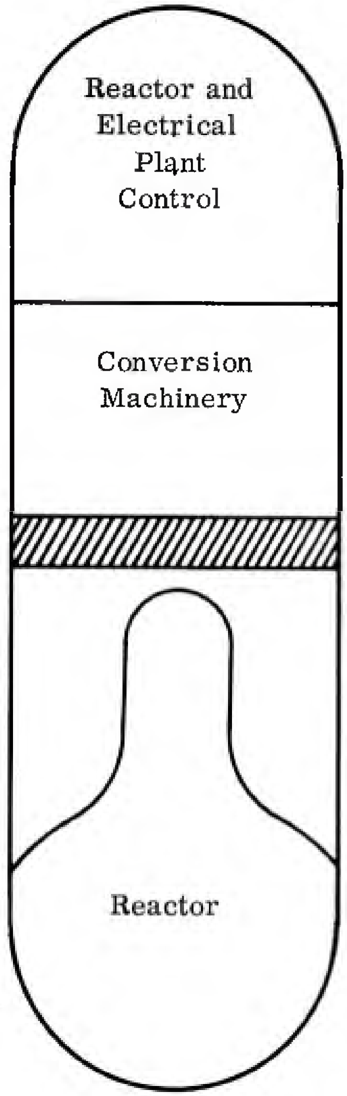


Figure 4-1. Typical Reactor Power Plant Arrangement for 30, 100, and 300 KW(e)

These conceptual arrangements are sized on the basis that a single turbine-generator set is used, except for the 300 KW plant which will probably require two half-power horizontal units to fit within the hull diameter or a single vertical shaft unit or a high-speed, high-frequency system. The 300 KW plant has adequate space for any of these arrangements because of its enlarged hull for heat transfer. A steam turbine generator in the low power level range with compact size, low weight, and good performance is not an off-the-shelf item.

There has been no economic incentive to develop the steam turbine because of its inherent, low efficiency at low power levels; the cost would be disproportionate to the results obtainable. Most turbine equipment available in the 30 KW to 300 KW range has been developed stressing low procurement cost (single stage machines) with a limited number of models to cover all power levels.

Hardware specifically tailored to the application by efficiency, size, and weight can be obtained through funding of the engineering, design, and tooling required. The improvements obtainable require examination on a case basis to ascertain if the increased costs are warranted.

Waste heat transfer from the power plant is primarily by the turbine exhaust steam condensing directly on the inside surface of the pressure hull. The condenser is formed by creating an annular space adjacent to the cylindrical pressure hull and using a portion at the lower end of the annular space as a hot well. This configuration requires the use of external hull frames to avoid entrapment of steam condensate. This also locates the frames in a readily accessible area for inspection. Natural convection heat transfer on the sea water side is assumed; however, forced convection would reduce the hull length for the 300 KW plant substantially. The selection of forced convection requires consideration of the potential loss in reliability due to the added motor and pump, the increase in auxiliary power required, and the design of the external flow path for ease of hull inspection.

There are many problem areas to be resolved and experimental data obtained to ensure the feasibility of the hull as a heat transfer surface. A heat rejection systems development program is described in paragraph 11.2. Some of the problems related to the hull heat transfer are listed below:

- obtaining and testing reliable protective coatings for the sea water side of the hull that have a high thermal conductivity and high resistance to fouling.

- obtaining and testing protective coatings for the steam side of the hull that have a high thermal conductivity and are compatible with the materials requirements of the steam system water chemistry

- heat transfer coefficients for steam condensing on the inside of large vertical cylinders

- natural convection sea water heat transfer coefficients for externally framed cylinders

- development of a means for desuperheating steam external of the hull condenser if relatively high rate of steam dumping is required

- development of a means for attaching the annular condenser to a deep submergence hull.

A potential solution to the hull coating problems are the sprayed metallic coatings. These offer good heat transfer characteristics and high resistance to corrosion.

There are two other heat removal systems within the power plant. The fresh water machinery-cooling system rejects its heat to the shield water; an air conditioning system for temperature and humidity control for the power plant control systems rejects its heat through the hull via direct contact: coolant is circulated in plastic channels bonded to the hull.

The large power plants of 1000 and 3000 KW(e) are tentatively arranged horizontally, as shown in Figure 4-2. A vertical cylinder arrangement is possible at shallow depths (larger diameter pressure hulls are technically and economically feasible), but there is little difference in overall plant size and costs. The high-power reactor plant may be constrained in orientation in or near its normal operating position, once it has been operated. This constraint is required to provide for removal of reactor core decay heat without the use of any power (natural convection) -- an essential safety feature. The horizontal arrangement should result in easier surface handling, docking, servicing, and transport operations with a resultant lower system cost.

A battery is required for starting the power plant after it is deployed. This battery also serves to power the onboard remote control equipment, provide emergency power for the power plant, and meet all other requirements of deployment and retrieval. A pressure-compensated battery external to the pressure hull avoids the potential hazard of hydrogen gas forming an explosive mixture.

A major consideration in the design of the reactor power plant is the refueling cycle: this may have a significant effect on cost. In addition to the direct cost of the refueling operation are the costs of the transport of the power plant to a refueling site, the support facilities that are required, and the loss of use of the plant during refueling. In general, a maximum length refueling cycle is preferred and is the most economical. The actual cycle however is a function of use. A specific reactor will have a specific total available energy for each core. Full power refueling cycles based on full time operation range from in excess of 10 years for 30 KW to approximately one year for 3000 KW, depending on the particular plant selected.

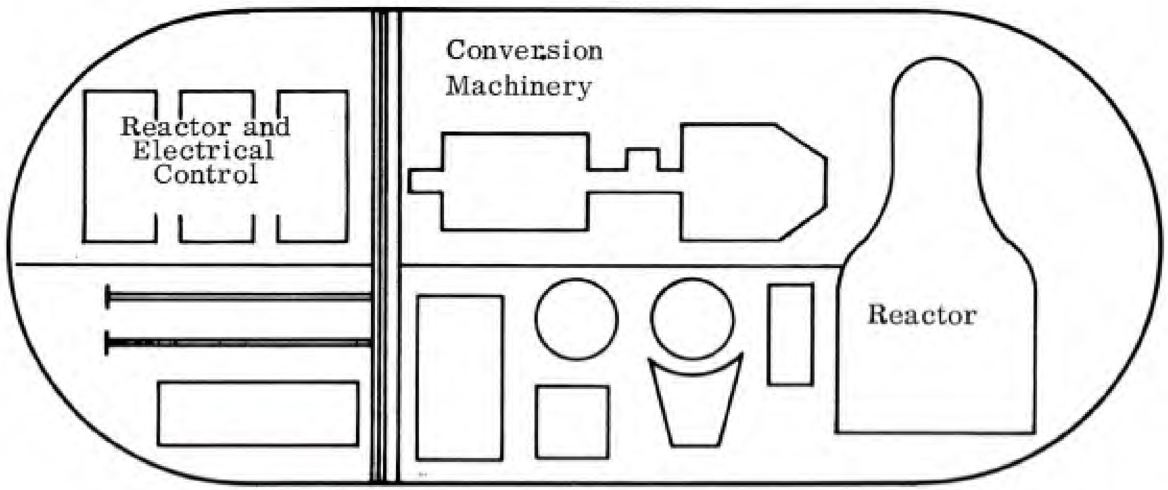


Figure 4-2. Typical Reactor Power Plant Arrangement for 1000 and 3000 KW(e)

Selecting larger reactors for small power plants can greatly increase the refueling cycle. However, this must be traded off against increased acquisition costs, weight and size. Increasing the efficiency with which thermal energy is converted to electric energy also results in longer refueling cycles.

Table 4-III shows order-of-magnitude costs for the acquisition of typical reactor power plants. These estimates do not include development costs. These costs are based on the data of Table 4-II, with the addition of syntactic foam as required for flotation.

Operational costs are difficult to define without a more complete operating schedule and a power profile; these have a large influence on the refueling costs. Preliminary estimates of investment and maintenance costs range from $150, 000 to $500, 000 per year for the 30 KW to 300 KW power plants. Maintenance and investment costs are primarily related to power level and design submergence depth. Total fuel costs for the 30 KW (e) plant may be in the range of $25, 000 to $150, 000 per full power year of operation, and for the 3, 000 KW (e) plant about $1(10)^6 per full power year. The fuel cost depends primarily on the core size (energy available) as this will determine the frequency of refueling and affect the per unit usable energy cost of the core. The fuel cost includes an estimate for the complete refueling operation as well as core cost. A more exact determination of the refueling cost will require a more detailed overall plant design. It should be noted that refueling operations costs may be a major portion of the fuel costs, in particular for the smaller power plants. A wide-spread in total fuel costs is estimated for the 30 KW (e) plant due to the wide-spread in core (reactor) sizes that may be used: Smaller core requires a higher refueling frequency thus higher cost. The lower power level plants might conceiveably eliminate refueling by using a large reactor (core energy) and thus eliminate the refueling operation cost.

Table 4-III. Preliminary Reactor Power Plant Cost Estimates ($ millions)

POWER (KW)	DEPTH (FT) 600	2, 000	6, 000	10, 000	15, 000	20, 000
30	5.7	5.8	6.3	6.7	7.5	8.1
100	6.0	6.2	6.7	7.2	8.8	10.1
300	6.5	6.6	7.3	9.0	11.8	15.8
1, 000	9.0	9.5	(1)	(1)	(1)	(1)
3, 000	13.3	14.2	(1)	(1)	(1)	(1)

(1) Power plant concept not defined due to major developmental effort required.

4.1.5 Ocean Energy

Energy may be obtained from the ocean through physical motion of the water or as thermal energy. The ocean currents, waves and tides may be harnassed to produce usable electrical energy. However, this energy source is either most irregular as in the case of waves or, in the case of tides and currents, of significant magnitudes only over a very small portion of the ocean. The relatively low velocities of the ocean currents or low tidal displacements require very large equipment in relation to the power generated. Tides and tidal-generated ocean currents are also cyclical and either result in corresponding power capabilities or require increased equipment to maintain a continuous source of power.

Thermal energy may be extracted from the sea by utilizing the difference in temperature between water masses to operate a thermodynamic conversion system. Heat is supplied to the process fluid by the warm water and is rejected to the cold water. The size and cost of the equipment will depend on the temperature difference and physical separation of the water masses. Propane has been proposed as a process fluid.[3] Usually only the warm surface water is considered where cold water is available immediately below to minimize the length of pipe. The cold water is piped to near the surface to reduce pressure differences across heat exchangers. The small temperature differences available require that large volumes of water be pumped and that heat exchanger surfaces be large. This type of power source is restricted to tropical or subtropical regions for year-round operation and for maximum temperature differentials and gradients.

The thermal energy conversion system is inherently a surface or floating type of power plant and requires anchoring and a power transmission cable.

Advantages of the system are the elimination of a direct fuel cost and supply logistics and the lack of power plant air breathing with a non-nuclear energy source. However, the restricted areas of possible operation due to water temperatures make it an impractical power source for general application. This type of source could be considered for the larger power requirements and for long term application at locations with suitable temperatures and gradients.

4.1.6 Radioisotope Power Supply

The radioisotope power supply considered for this study employs a steam Rankine cycle conversion system for obtaining electrical power from the heat produced by the decay of radioisotope fuel. The plant is essentially a larger version of the Radioisotope Power Equipment (RIPE) System described in reference 1. Only the 30 KW power level was investigated due to the high fuel inventory cost ($70, 000/KW(e)) and fuel use cost ($12, 000/KW(e)-yr). These costs result in investment and operating expenses for the radioisotope power plant in excess of those for the nuclear reactor plant at the 100 KW(e) power level. The break-even power level is dependent on many factors, but in general is substantially less than 100 KW(e). For the larger radioisotope plants, extrapolation from the figures for the 30 KW(e) plant should provide a reasonable estimate, since the major investment and operating expenses are either due to the fuel or proportional to it.

The RIPE power plant is completely self-contained within its own pressure hull, which is equipped with cable connections to supply power and for start, stop or monitoring functions as required. The plant is self-regulating and has a nearly constant output voltage and frequency from no load to full load. Table 4-IV shows tentative data for a power plant with a net electrical output of 32 KW.
At this power level the minimum size of the pressure hull is determined by the requirement to have adequate hull area for the transfer of waste heat. The use of the pressure hull as a heat exchanger, although technically required only for large ambient pressures (see paragraph 4.1.4), is part of the system concept used for all ambient pressures. Other concepts have been developed for lower ambient pressures but they do not provide distinct technical or economic advantages. Thus the power plant efficiency directly affects the size and cost of the pressure hull.

Table 4-IV. Tentative RIPE System Data

General	
Isotope	Co60
Refueling cycle (yrs)	3
Initial fuel loading (KW)	300,000
Fuel loading, end of refueling cycle (KW)	200,000
Electrical power (KW, net)	32
Overall thermal efficiency (percent)	16
Steam Cycle	
Turbine inlet pressure (PSIA)	150
Turbine inlet temperature (^{o}F)	700
Condenser saturation temperature (^{o}F)	130 (max)
Thermal efficiency at turbine shaft (percent)	20

To compensate for larger thermal resistances due to the hull thickness, hull size also increases as the operating depth increases. Each hull is sized to provide adequate heat transfer for operation at all depths from 600 feet to its design depth and at the maximum ambient temperature for each depth (see paragraph 3.6).

Condenser temperatures will reach $140^{o}F$ in $85^{o}F$ sea water (at the ocean surface) resulting in a small loss in performance. Use of this type of plant on the ocean surface is generally not economical and therefore was not considered.

Heat transfer from the power plant hull to the sea is by natural convection for both reliability and safety. Power is not required to remove heat at any time whether the power plant is operating or shut down.

Power plant equipment weight has been estimated at 14,000 lbs for 32 (KW(e). This estimate includes all machinery and shielding. Radiation levels at the outer surface of the pressure hull are designed for 200 mr/hr maximum with considerably lower levels for access and maintenance (based on new fuel in the steam generator). Machinery weights are reduced for the deep submergence plants to reflect shielding due to thicker pressure hulls.

Spherical pressure hulls will result in a minimum hull-weight-to-displacement ratio. However, the shape is not critical, and design considerations and fabrication feasibility may be more readily met with hulls made of ring-reinforced cylindrical sections and hemispherical ends. Hulls with the same surface area should weigh approximately the same but show decreasing displacements as minimum dimensions decrease. There are many combinations of materials, hull sizes, and shapes that will satisfy the requirements of the power plant. Comparative data for spherical and some cylindrical hulls are shown in Table 4-V. These are not necessarily optimal designs with regards to size, shape or material, but provide a reasonable basis for estimating power plant costs.

All plants, except those designed for the 20, 000-ft depth, can be neutral or positively buoyant without auxiliary buoyancy devices. The 20, 000-ft plant can only be made neutrally buoyant practically by auxiliary means, such as the addition of syntactic foam. Both the 15, 000 and 20, 000-ft hulls could be made of HY-130, assuming that any requirements for flotation are met by auxiliary means. Although costs vary somewhat with the materials selected, these variations are not significant to the results of this study.

Table 4-VI presents order of magnitude cost estimates for neutrally buoyant power plants for initial acquisition and total costs for 5, 10, and 20 years. These estimates are based on direct costs of the plant and do not reflect costs due to transport, deployment, and recovery or other costs that result from the use of this type of power plant. Development costs associated with this type of power source are also not included.

Cost estimates for the fuel were based on Co-60 as the most likely choice with a government interagency transfer price of $.11/curie and an assumed buyback of the remaining activity.

Refueling cycles of three years were selected on the basis of minimum fuel cost. However, both the minimum fuel cost and refueling cycle are dependent on the refueling costs and can only be accurately determined when a specific mission is defined.

Other conversion systems that could be used to generate electric power using radioisotope thermal energy are thermoelectric, Brayton cycle (gas turbine), and Stirling cycle. The thermoelectric system which is now being used for submersible radioisotope power plants at the watt power level has too low an efficiency to be considered economical for the required power levels. The Brayton cycle efficiency is also considerably lower than the Rankine cycle. The Stirling cycle is generally more efficient than the Rankine cycle. However, preliminary investigations indicate that at this power level and maximum cycle temperature the efficiencies are approximately the same. Increasing power levels would favor the Rankine cycle, whereas increasing temperatures favor the Stirling cycle. The use of Stirling cycle engines should be investigated as higher operating temperatures are obtained. The present Stirling cycle engines are similar to the diesel engine in size, weight, and speed and are not as easily enclosed in a pressure hull as the Rankine cycle equipment.

Table 4-V. Radioisotope Power Plant Hull Data
P = 32 KW(e) Net

MAXIMUM OPERATING DEPTH (Ft)	EQUIPMENT ESTIMATED WEIGHT (Lbs)	SPHERICAL HULLS				CYLINDRICAL HULLS			
		Diam. (Ft)	Material	Weight (Lbs)	Displacement (Lbs)	Diam. (Ft)	Material	Weight (Lbs)	Displacement (Lbs)
600	14, 000	10. 5	HTS	7, 800	38, 700	10	HTS	7, 100	38, 600
2, 000	14, 000	10. 6	HY 80	11, 700	40, 000	10	HY 80	11, 100	38, 600
6, 000	13, 500	11. 1	HY 130	19, 400	45, 900	10	HY 130	19, 900	43, 700
10, 000	13, 000	11. 8	HY 130	37, 000	55, 300	10	HY 130	43, 000	53, 700
15, 000	12, 500	12. 8	HY 180	51, 500	70, 200	10	HY 180	55, 100	68, 700
20, 000	12, 000	13. 8	HY 180	82, 500	87, 800	9	HY 180	91, 700	74, 000

Table 4-VI. Radioisotope Power Plant Cost Estimate ($ million)
P = 32 KW(e) Net

OPERATING DEPTH (Ft)	ACQUISITION COSTS			TOTAL COSTS		
	Equipment and Hull	Fuel Inventory	Total	5 Year	10 Year	20 Year
600	.85	2. 25	3. 10	3. 2	5. 4	9. 9
2, 000	.90	2. 25	3. 15	3. 3	5. 5	10. 0
6, 000	1. 15	2. 25	3. 40	3. 5	5. 8	10. 3
10, 000	1. 50	2. 25	3. 75	3. 9	6. 2	10. 8
15, 000	2. 10	2. 25	4. 35	4. 6	6. 9	11. 7
20, 000	3. 00	2. 25	5. 25	5. 6	8. 1	13. 0

Larger power sources are technically feasible. However, since the cost is almost proportional to power level, these rapidly become uneconomical. In addition, as the power level increases, the assumption of a buyback credit based on the remaining activity of the fuel may be less realistic. Co-60 production capability appears adequate for a limited radioisotope power program possibly up to several hundred KW(e). Annual production capability of Co-60 is estimated to exceed 1500 KW(th).

4.2 SURFACE POWER SOURCES

Power sources that have full time access to the earth's atmosphere can employ virtually any source of energy and power conversion system to produce electric power. Economics practically limits the selection to the use of the hydrocarbon fuels (solid, liquid, gaseous, liqufied gas) with the internal combustion engines or the steam or gas turbine. The specific selection of fuels and conversion system will depend on several factors including power level, efficiency, fuel logistics and cost, system availability and cost, and operating cost.

The liquid or gaseous fuels are best suited to the power levels of interest, 30 to 3000 KW, because they require a minimum of handling or processing equipment. In general the fuel oils will be the most available at the lowest cost; however, local conditions may result in a different conclusion. The fluid fuels may be used with all the conversion systems and, to a first approximation, will not influence the selection of one.

The diesel engine surpasses the steam or gas turbine as a prime mover for practically all criteria (spark ignition engines are also not considered competitive due to their low efficiency and the requirement for highly volatile liquid fuels). Of major significance is the overall efficiency. The diesel driven generator system is approximately twice as efficient as the steam or gas turbine over the power range of 30 to 3000 KW with overall efficiencies of 17% at 30KW, 27% at 100 KW, and 30% from 300 KW to 3000 KW. This results in a substantially lower fuel cost and has a large effect on logistics support. The diesel system is also lower in acquisition cost and is readily available in a wide number of capacities to match system requirements. Availability of gas and steam turbines is generally restricted to the higher power levels due to the poor performance of small machines and the consequent lack of a market. Steam equipment designed for low power levels (<750 KW) is generally made for auxiliary drive units where excess steam is readily available and efficiency is not a factor. Comparison of the diesel system with the gas turbine reveals essentially only a weight advantage for the gas turbine. This is quickly offset by the larger size and weight of fuel that must be accommodated, particularly for a plant which is not land-based. The steam plant is generally larger and heavier than the diesel system. Based on all other criteria, such as maintenance, servicing, reliability, system complexity, and safety, the diesel system is equal to or better than the steam turbine.

The diesel system has little competition as a power source for air-breathing plants and power levels in the range of 30 to approximately 5000 KW. For higher power levels, this conclusion should be reviewed in view of the better performance of the gas and steam turbines as power level is increased compared to relatively constant diesel efficiency, limitations of size of single diesel engines, and other considerations that may be due to the particular application.

The diesel power plant may be employed as the shore-based or surface power source for the 30 to 3000 KW loads. The power source must generate the net load delivered plus the plant auxiliary power and transmission losses.

Table 4-VII presents typical data for diesel engine generators over the range of interest for the surface power sources with transmission losses limited to approximately 5 percent. Shore-based plants that have to provide for larger transmission losses will require correspondingly larger power sources.

The use of a single engine-generator to meet the total load results in a minimum of complexity in instrumentation and control and the most economical installation. Reliability requirements of the load module may establish the necessity for using dual equipment. The life expectancy for the diesel generator is estimated at 20 years with programmed preventative maintenance. For the surface power source, major maintenance cycles can be scheduled to coincide with hull maintenance. Table 4-VIII is a suggested general preventative maintenance schedule.

Major systems required for the diesel power plant are fuel, air intake, exhaust, waste heat removal, engine control and instrumentation, electric power control and instrumentation, and engine starting. The wide range in power levels will result in differences in the auxiliary systems for the different power plant capacities. The low power levels from 30 KW to approximately 300 KW may use packaged or integrated engine generator units requiring a minimum of connections to separately mounted equipment. Power levels above 500 KW require more complex systems and larger equipment which requires separate mounting and interconnecting (principally in the heat rejection and starting systems).

Power plants using sea water cooling are equipped with an intermediate fresh water cooling loop to protect certain equipment against sea water contamination in the event of leakage (e.g. lube oil, generator). Air intakes will be suitably baffled and filtered to prevent the ingestion of foreign material such as salt water for the surface plant or dust for the shore-based environment.

A wide variety of commercial equipment is available from various vendors. However, the selection of a specific vendor's equipment will not substantially change the power plant data. Voltage regulation is critical with this type of power plant due to its remote location from the load and the design line load loss. Present equipment is capable of maintaining the generator output voltage within 1 percent at the low power levels and within considerably narrower limits at the higher power levels. Frequency

Table 4-VII. Typical Diesel Engine Generator Data

	LOAD (KW)					
	30	100	300	1, 000	3, 000	Remarks
Rated KW	50	125	350	1, 250	3, 500	Generator Continuous Rating
Net KW	37	116	322	1, 169	3, 288	
Gen. Voltage	230/460 Std 480 Opt.	230/460 Std 480 Opt.	2, 400 Std 4, 160 Opt.	4, 160 Std	4, 160 Std	Std - Standard Opt - Optional
Eng. Speed (RPM)	1, 800	2, 200	1, 200	600	514	
Eng/Gen Wt. (Lbs)	2, 680	3, 860	13, 750	60, 000	160, 000	Gen/Eng/Bed Plate
Eng/Gen Vol (Ft^3)	60	70	260	2, 040	5, 400	
Fuel Rate (Gal/Hr)	4. 5	11	28	85	246	Full Load
Eng. Intake Air (CFM)	180	460	1, 300	4, 600	13, 400	
Jacket Heat Reject (Btu/Hr)	132, 000	410, 000	1.26×10^6	2.5×10^6	12×10^6	Full Load
Radiant Heat Reject to Atmosphere (Btu/Min)	210	700	1, 900	7, 000	20, 500	May be internally scavenged by engine intake air

ALL DATA FOR COMMERCIAL EQUIPMENT

Table 4-VIII. Suggested Diesel Engine Preventative Maintenance Schedule (Continuous Operation)

TIME INTERVAL	REPAIR AND REPLACEMENT
1 year	Piston Rings - Compression Injection Nozzle Tip Assembly
2 years	Piston Rings - Oil Control Regroove Pistons Cylinder Liners Connecting Rod Bearings
4 years	Governor Pistons
6 years	Water Pump Impeller Lube Oil Pump Fuel Supply Pump Injection Pump Barrel and Plunger Assembly Injection Pump Tappet Assembly Main Bearings - Lower Half Scavenging Air Blower

may be held to within 3 percent with standard equipment and to within 1/2 percent for a small extra cost. The above values are for steady state. The load and transient characteristics must be defined to formulate specifications for the equipment.

The availability, cost, and equipment characteristics depend on the specifications for this equipment, including material, functional, and reliability requirements and the requirements of regulatory agencies.

Ocean vessels or other surface ships may be used as standby power sources for the surface-tendered power plants. Power may be supplied under tow conditions: 1) when the buoy generator is inoperative or 2) when the transmission cable is usable. The first condition would permit the buoy's electrical distribution and protective equipment to be used. The second condition would require that suitable electrical equipment be installed on the surface ship or that the operation be strictly an emergency. This standby power source is only available assuming the transmission cable and buoy are not lost. The suitability of a ship's power source will depend on the ship's facilities and the power required. Low level emergency power is probably obtainable from almost all ships.

4.3 REFERENCE

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2. Research and Development Study for Deep Ocean Reactor Placement, May 1965, Bechtel Corporation, NBy-32273.

3. Thermal Power from Seawater, J. H. Anderson and J. H. Anderson, Jr., Mechanical Engineering, April, 1966.

Chapter 5

CABLE SYSTEM

There are certain limiting factors in the selection of the type, size, and configuration of a cable system for use in an underwater power transmission system. The primary consideration in the selection of the cable, connectors, and support system is reliability for use in the underwater environment, including resistance to corrosion, erosion, marine fouling, and water absorption. In addition, the cable and its support system must be strong enough to support itself and any other loads induced when connected to an electrical load while submerged.

This chapter discusses the various tradeoffs which, when combined, define the cable configuration which satisfies the environmental, mechanical, and electrical criteria cost effectively.

5.1 MATERIALS

Materials must be selected for each constituent part of the cable to ensure compatibility with the environment. Material considerations are involved in the selection of:

- conductors: aluminum or copper
- insulation material: rubber, rubber-like, thermoplastic, varnished cloth, or impregnated paper
- coverings: insulation and cabled conductors sometimes require an additional covering for mechanical protection and/or conductor identification; in the case of a submarine cable this additional covering, usually thermoplastic, is also used to provide increased protection against water penetration.
- sheath: where various coverings do not provide adequate mechanical strength and where high tensile strength is required, such as in a submarine cable, an outer sheath of high strength galvanized steel armor wire is provided; to protect the galvanized surface, the armor wire is covered with a thermoplastic.

5.1.1 Cable Conductor Material

For underwater power transmission systems, strength, size, and conductivity are the primary factors for selection. The two basic conductor materials are aluminum and copper. The conductivity of aluminum is 60 percent of that of copper. Therefore, an aluminum conductor would require a cross-sectional area approximately 1.6 times larger than a copper conductor for the same current-carrying capacity. This is roughly two AWG wire sizes larger. The tensile strength of aluminum is 24,000 - 29,000 psi, while copper is 50,000 - 70,000 psi. The modulus of elasticity of aluminum is 10×10^6 while copper is 17×10^6. Because of these qualities and aluminum's high coefficient of thermal expansion which gives it a tendency to "creep" and its high contact resistance due to oxidation on the surface, which requires special preparations for joints, aluminum was eliminated and copper conductors were selected.

5.1.2 Cable Insulation Material

Insulation materials in general are of the following classes: rubber, rubber-like, thermoplastic, varnished cambric and impregnated paper. Insulation selection involves, in order of importance for a submarine cable installation:

1. voltage stability and life
2. resistance to moisture
3. resistance to temperature
4. dielectric properties
5. flexibility
6. resistance to ionization and corona
7. mechanical strength.

The primary factors determining the selection of insulation material are the first five; the last two are secondary. Of the available materials, polyethylene combines excellent electrical characteristics with outstanding stability of both electrical and physical properties during long periods of exposure to sea water. Rubber and rubber-like insulation materials require tinned conductors to prevent detrimental chemical reaction between the insulation materials and the conductor. In addition, these materials have a higher water absorption rate than polyethylene. This reduces their ability to provide long life and increases susceptibility to cable failure. The varnished cambric and impregnated papers have a long life but are not sufficiently moisture resistant to be used in sea water without a continuous lead covering. The lead would make the total weight of the cable impractical for this installation. In addition, flexing of the cable would cause the layers of insulation to separate. Based on the service and reliability required, the other materials were eliminated and polyethylene was selected for the cable insulation material.

5.1.3 Cable Sheaths and Coverings

As added protection, the submarine cable may have a water-resistant covering over its insulation. Neoprene or polyethylene may be used for this purpose. Where a cable requires additional mechanical strength and abrasion resistance, the covering is wrapped with armor wire. The armor can be bronze, copper, or stainless or galvanized steel. High strength galvanized steel was selected as the armor material since it does not create a dissimilar metal problem.

Because the armor is subject to abrasion and erosion due to the environment, an additional covering should be used to protect the armor. Polyethylene was selected as this outer covering over each armor wire to provide maximum protection.

5.2 ELECTRICAL PROPERTIES

The electrical qualities and transmission efficiency of a given steady-state power load are determined by the following factors:

number of conductors: single or multi-conductor cable

current-carrying capacity (ampacity)

voltage regulation required

shielded or non-shielded conductors

grounded or ungrounded neutral

conductor size, shape, and stranding

rated voltage and basic impulse level (BIL) required of the insulation

splicing and/or termination of the cable.

5.2.1 Number of Conductors

The choice between single and multiple conductors usually depends upon such mechanical considerations as space limitations, field conditions, strength and weight, and the electrical requirements discussed in paragraphs 5.2.2 through 5.2.7.

5.2.2 Current-Carrying Capacity

Current-carrying capacity (ampacity) of single conductors versus multiple conductors is significant when installing each in a nonmetallic duct. In considering this installation, either 3 single armored conductors or one 3-conductor armored cable is feasible. The difference between them with respect to current-carrying capacity is not significant in the sizes required.

The tradeoff should consider the effects of maintaining space between the single conductors, which determines the inductive reactance of the circuit. Increased inductive reactance increases circuit impedance and increases the I^2R loss in the conductor. This might create the necessity for a larger conductor size for a given service. In addition, the costs involved in deploying these single conductor cables, separated by a minimum distance, outweigh the cost of deploying one 3-conductor cable. Therefore, considering the cost, deployment problems, and requirements to maintain a minimum spacing, the use of a 3-conductor cable is preferred.

5.2.3 Voltage Regulation

When voltage regulation, or drop, is important, multiple conductors are preferred over single conductors. This is because three single conductors have a higher reactance than one 3-conductor cable, i.e., the greater the spacing, the higher the reactance. In an AC circuit, the higher the reactance, the higher the impedance, and the higher the impedance, the larger the voltage drop. Therefore, based on voltage drop considerations, a 3-conductor cable was selected.

5.2.4 Shielding

Shielding a cable is accomplished by wrapping material spirally around the insulation to form a continuous shield along the length of the cable. This conducting shield is grounded in 2 or more locations (usually at terminals and any splice) to ensure that the shield is held at ground potential and thus confines the entire dielectric field to the inside of the insulation material. This results in symmetrical radial stress distribution within the insulation. This also eliminates tangential and longitudinal stress on the insulation surface, thus preventing surface cracking and discharge to ground. It also isolates the braids, tapes, and fillers from the dielectric field and provides safety for personnel by maintaining a zero potential on the surface of the cable.

Shielding also provides protection against lightning and switching surges by providing a uniform capacitance along the cable length to prevent voltage buildup. Shielding raises the cable capacitance slightly but lowers the surge voltage. In most shielded cables, the shield need only provide capacity to carry charging current of the cable. However, it is desirable to have conduction tape or wire shielding material, thus providing increased capacity for fault current. Therefore, copper was selected for the shielding material. All cables will be shielded.

5.2.5 Grounds

Because each conductor of the cable is shielded, and shields are grounded at both terminals, the first order of faults, if they occur, will be phase to ground. A characteristic of an ungrounded system is that it produces low ground fault currents. The principal virtue of the ungrounded neutral system is its ability to clear ground faults without interruption. However, this feature disappears when the length of the line and/or voltage are appreciably increased. Insulation thickness on an ungrounded system is normally greater due to voltage variation as a result of faults, load changes or other voltage surges. However, manufacturers usually employ the same thickness of insulation, whether grounded or ungrounded neutral, in all cables up to 5 KV. The distinguishing factor, therefore, is the protective system to detect ground faults and effectively clear the faulted section from the source of power. In the absence of an effective way to detect these low ground currents, which because of their low magnitude will persist for some time, the system should be "effectively" grounded to provide ground faults of a greater magnitude which will provide fast relay operations, thus permitting reasonable reaction time for the plant.

5.2.6 Cable Conductor Standard Sizes

The wire sizes selected for this study were considered as standard sizes or off-the-shelf items based on consultation with the major cable manufacturers. The electrical characteristics of the various wire sizes contained in a 3-conductor underwater cable are contained in Table 5-I. There are other sizes available, but using these would require modification to existing manufacturing facilities with an increase in cost and lead time. In addition, the electrical stress concentration is much greater in smaller size wires. For this reason, industry has standardized on the smallest cable sizes to use. For example, at 15 KV the smallest size is AWG #2, at 5 KV the smallest is AWG #8. However, in comparing a #8 and a #6, the I^2R loss of a #8 is approximately 16 times greater than a #6. The larger sizes, above 1000 MCM, would seriously affect the handling and storage problems because of increased outside diameter and weight.

Table 5-I. Cable Conductor Standard Sizes

NOMENCLATURE	AREA (circular mils)
*A.W.G. Number 6	26,240
A.W.G. Number 4	41,240
A.W.G. Number 2	66,360
A.W.G. Number 1/0	105,600
A.W.G. Number 2/0	135,100
A.W.G. Number 3/0	167,800

Table 5-I. Cable Conductor Standard Sizes (cont'd)

NOMENCLATURE	AREA (circular mils)
A.W.G. Number 4/0	211,600
*MCM 250	250,000
MCM 300	300,000
MCM 350	350,000
MCM 400	400,000
MCM 450	450,000
MCM 500	500,000
MCM 600	600,000
MCM 750	750,000
MCM 1000	1,000,000

*American Wire Gauge

** Thousands of Circular Mils

5.2.7 Splicing and Termination

For the underwater power transmission system, the cable will connect directly to the generator station and the load module with no intermediate connections or splices. Cable splicing between any two terminals of high power and intermediate or high voltage systems is avoided because of the voltage stress considerations at the insulation joint (for further discussion see paragraph 6.10.1.3). Normally, this type of cable is terminated in commercially available potheads.

However, in the manufacture of continuous long-length cables, splicing is performed at the factory under controlled conditions. In these cases, the two ends of the cable are properly prepared by cutting back the jacket and shielding and tapering the insulation. The conductors themselves are fused electrically by an electrical welding process which produces a joint with higher strength than the original material. Then, a mold is made around the joint to completely fuse the splice insulation with the conductor insulations. Finally, the shielding and jackets are replaced. Such joints have been made in cable up to 138 KV with the joint in direct contact with the water. (See Figures 5-1, 5-2, and 5-3.)

In terminating this type of cable, it has already been indicated that the cable will be one piece from the generating station to the load module. In the case of the shore-based generating plant, the submarine portion of the cable will terminate in a commerically available cable terminal box. The box is provided with suitable

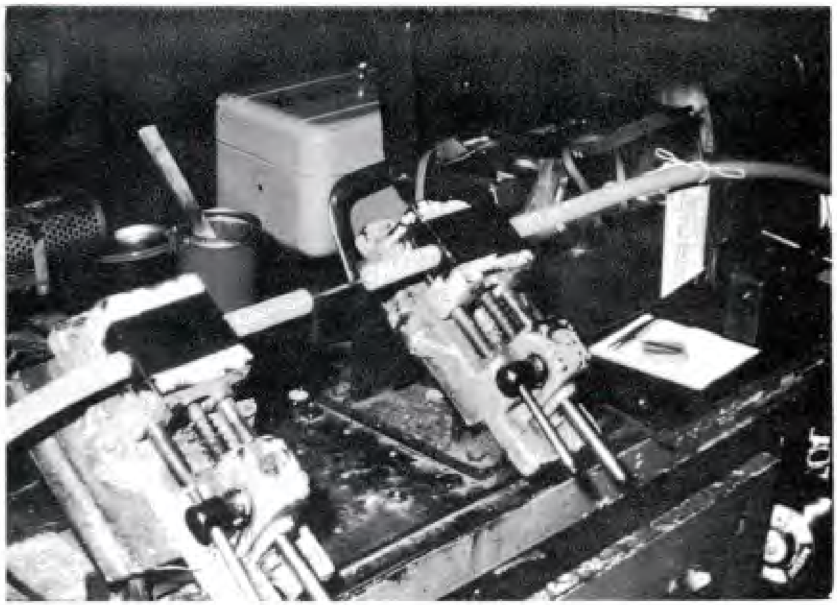


Figure 5-1. Fusion Splicing of Submarine Cable Conductor

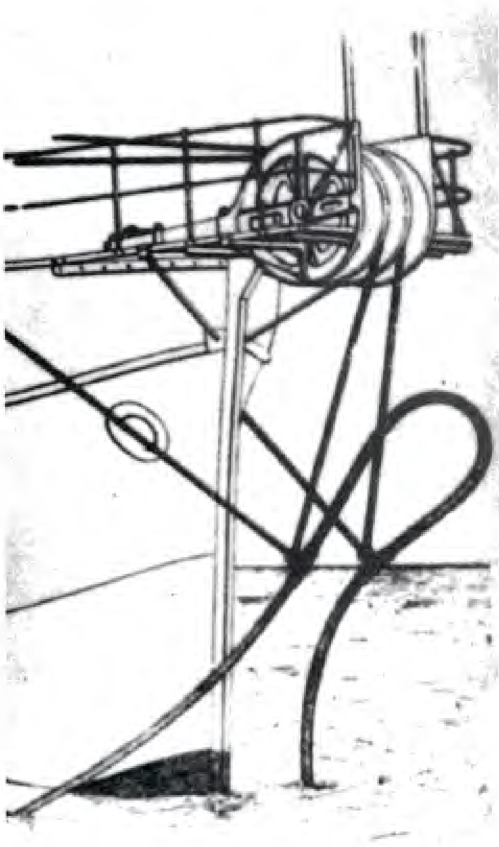


Figure 5-2. Deploying a Splice

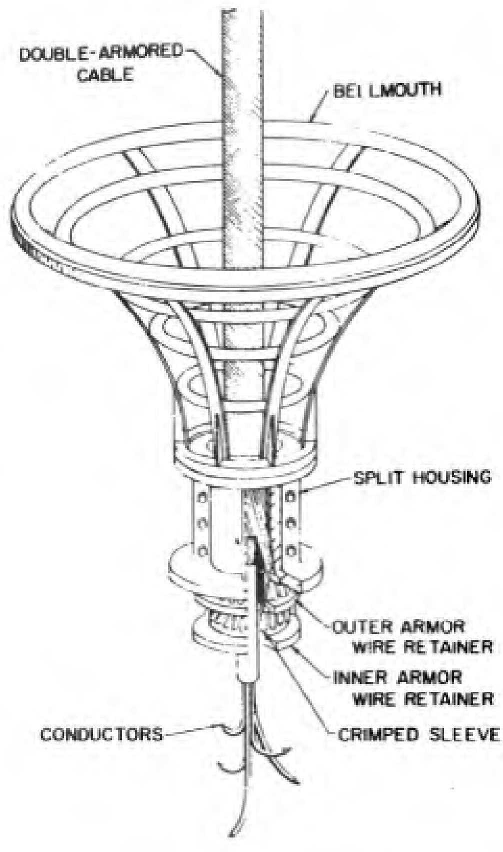


Figure 5-3. Typical-Balanced Torque Cable Termination

potheads to terminate the cable at the transmission voltage and provide the transition to standard cable to the switch gear and generator. In the case of the load module and the surface-tendered power plant, the cable will terminate in an electrical connector. A discussion of connectors may be found in paragraph 5.5 (Also see figure 5.3.)

5.3 MECHANICAL PROPERTIES

Mechanical considerations include protection of the cable in contact with rocky ocean bottoms, the mechanical strength to resist compressive, tensile, and impact forces induced by the environment, the cable weight, and the weight of the support system. Final cable design should take into consideration all the available data on cable construction, protection, and deployment.

An evaluation has been made of current manufacturing methods and techniques used in the production of continuous single length armored submarine cables.

Single and multiple conductor armored submarine cables are presently manufactured from less than 0.25 inches O.D. to over 8.0 inches O.D. in continuous lengths of up to 3000 nautical miles. Storage facilities are provided in the manufacturing plants to store cable in continuous lengths of up to 3000 nautical miles. The storage capacity is in the form of large cylindrical tanks.

However, the limit on the length of continuous cable is not in the manufacturing or storage, but the cable ship capacity. For example: using a cable of 1.25 inches O.D. and considering 12 cable laying ships, the following table indicates the maximum continuous length of cable each ship can carry within their respective storage capacity.

Table 5-II. Cable Ship Capacities

SHIP	NUMBER OF TANKS	VOLUME OF TANKS-FT^3	NAUTICAL MILES CAPACITY FOR 1.25" O.D. CABLE*
**LCM	1	6,937	80
**LCM	2	10,395	125
**LST	2	15,777	200
USS NEPTUNE	3	30,116	415
USS AEOLIS	3	43,385	610
USS THOR	3	43,385	610
USACS A.J. MEYER	4	48,000	615
MERCURY	3	106,740	1200
NEPTUNE	5	222,500	3000

Table 5-II. Cable Ship Capacities (cont'd)

SHIP	NUMBER OF TANKS	VOLUME OF TANKS-FT^3	NAUTICAL MILES CAPACITY FOR 1.25" O.D. CABLE*
MARCEL BAYARD	4	77,333	1000
LONG LINES	7	139,000	2000
SALERNUM	3	22,354	315

*Capacities are based on 80 percent of the theoretical ship cable volume.

**These ships require cable laying equipment and are not used in water over 200 fathoms.

Present manufacturing techniques, methods and equipment have produced medium and high voltage single and double armored cables of the sizes used in this study.

Cables have been produced in continuous lengths for AC voltages up to 138 KV and DC voltages up to 230 KV. Again, the limit in continuous length is a result of ship capacities. However, it is possible to provide temporary clean room facilities and splice in lengths at sea if necessary. Provisions, machinery and techniques are developed and working to produce single or double reverse wrap (balanced-torque) armored cables using armor of .030 inches O.D. up through 0.30 inches O.D. Temperature is less of a limitation using the new polymers; cables are now available which can tolerate 80 or 90°C.

Provision has been made at some submarine cable manufacturing facilities to load cable ships directly from the storage tanks to the ships. This is done by deep water wharfing facilities and overhead conveyor systems.

5.3.1 Causes of Cable Damage

The most important consideration in planning cable deployment for minimum risk of damage is the selection of the cable route. Studies of cable fault records indicate that many of the deep sea cable breaks occur where cables pass over seamounts, canyons, and areas susceptible to turbidity currents, and an effort must be made to avoid such hazards. Topographic studies form the basis for both initial route selection planning and for a preliminary description of the selected route.

Almost 50% of cable damage is attributed to breaks inflicted by fishing trawlers. Table 5-III illustrates the frequency of cable casualities as compiled by Bell Telephone Laboratories. The majority of the trawler casualities occurred at depths less than 300 fathoms (1800 feet).

Table 5-IIIa. Causes of Cable Breaks*

CAUSE	NO. OF BREAKS	% OF TOTAL BREAKS
Trawler	127	47
Chafe-Corrosion	95	34
Kink	18	7
Biological	9	3
No Report	24	9
	273	100

Table 5-IIIb. **

CAUSE	NO. OF BREAKS	% OF TOTAL BREAKS
Trawler	96	47
Chafe-Corrosion	61	30
Biological	2	1
Electrical Maint.	20	10
Other (Ship Anchor, Kink, etc.)	16	8
Unknown	8	4
	203	100

*Data for Table 5-IIIa are from Western Union Cable History Study, British Continental Shelf (Allen, 1962) and include break data for years 1930 - 1960.

**Data for Table 5-IIIb are from a compilation of break history of telegraph cables at all depths in the North and South Atlantic Ocean. Even on this ocean-wide basis, it can be seen that trawler damage forms a significant part of cable break history, and the British shelf percentages are thus representative of cable damage history in general. Period covered is 1959-1962.

5.3.2. Marine Biological Attack on Cable

Of particular importance in submarine cable design is the resistance of the various parts to marine biological attack. The results of a study program conducted within the last ten years summarizes the more important information obtained on the subject:

1. In the biochemical oxygen demand (BOD) type test it has been found that polyethylene is not utilized by the aerobic bacteria or the anaerobic, sulfate-reducing bacteria. Polyvinyl chloride plastics are attacked according to the way in which they are plasticized. All of the samples tested which had an added external plasticizer, including the rigid plastic, were attacked to some degree. In the case of the rigid plastic, the attack was apparently due to lubricants. Neither the semi-flexible, polyvinyl chloride copolymers

nor the polyvinyl chloride resin alone were utilized by the bacteria. The five elastomers assayed were all attacked by aerobic bacteria; neoprene was the most resistant. The epoxide casting resin did not serve as a source of carbon for the organisms, but more testing is required with a polyester casting resin.

2. Coiled conductors insulated in one case with a rigid polyvinyl chloride, and in the other with GR-S, were exposed half in sea water and half in marine sediment in the laboratory for thirteen months. Capacitance measurements showed that a considerable change had occurred in the GR-S insulation apparently as a result of bacterial attack. Although there was a slight rise in the capacitance values for the polyvinyl chloride-insulated conductors during the last five months of the test, further observations are necessary before attack can be considered definite.

3. In three years of actual marine exposure of plastics, elastomers and casting resins, there have been definite penetrations by marine borers of only three materials -- a test rod of silicone rubber, a 0.0035-inch film of polymonochlor-trifluoroethylene wrapped on a Lucite rod, and the Lucite rods, themselves. The first two cases represent single instances of penetration by pholads as a result of the organisms getting started in an asphalt-impregnated jute wrapping and then progressing into the Lucite.

   Secondary cellulose acetate yarn and tow have deteriorated badly, apparently from bacteria, in as short a time as six months.

   Under fouling and in the sediment area, rods of polyvinyl chloride plastics containing basic lead stabilizers have been blackened as the result of hydrogen sulfide produced by sulfate-reducing bacteria reacting with the lead salts to give black lead sulfide. This sulfiding has caused no apparent degradation of the physical properties of the plastics.

4. The examination of cable samples from service has indicated that the impregnated outer jute serves an important function in limiting corrosion of armored wire. Generally, when corrosion is present, the outer jute has been lost.

   Two unusual cases of extensive corrosion have been reported -- one in a cable 12 years old, the other in a cable which was in service 36 years. In both cases, corrosion occurred in pockets between adjacent armored wires rather than on the outside surfaces (water side) of the wires.

   The performance of the inner jute in samples from service has been generally good for as long as 30 or 40 years in deep water. In samples from relatively shallow water in the Caribbean, inner jute bedding deteriorated badly in as short a time as five years.

In the case of the cable construction and materials used for this study, it is felt that the best system available, within the state-of-the-art, as protection against corrosion is a polyethylene jacket over each galvanized steel armored wire.

Chafe in submarine cables can be caused by a number of things not the least of which are the bottom topography, turpidity and other ocean currents, and the method of laying the cable (i.e., amount of slack, etc.). The best method of protection against this condition is a detailed topographic study of the proposed route and avoidance wherever possible of sea mounts canyons and currents.

In areas where suspect of chafing conditions are suspected, an extruded, high density polyethylene jacket should be used over the jacketed armored wires.

Another area where chafing occurs is the land terminal point due to tidal conditions. Here the cable would have the additional protection of one or more of the following coverings over the jacketed armored wires:

1. Double armoring with #1 BWG armor wire
2. Single armoring with #1 BWG armor wire
3. Single armoring with #6 BWG armor wire
4. Single armoring with hi-tensile (300,000 psi) armor wire
5. Cable embedded 3 to 6 feet below the surface out to a depth of 100 feet
6. Anchor at intervals to prevent movement of cable
7. Cable wrapped with chain

The method selected will depend on the area and conditions of the bottom.

5.3.3 Cable-laying Techniques

In bottom deployed systems, one of the fundamental requirements in cable laying is the deposit of a sufficient amount of cable to cover irregularities of the bottom without introducing dangerous suspensions and without laying a wasteful amount of excess slack. Satisfaction of this requirement will require the most detailed possible knowledge of bottom topography, coupled with knowledge of the kinematics of the cable-laying process.

A determination of required cable strength does not directly call for an extremely accurate knowledge of bottom depth and contour. The required cable strength is determined by cable tension during recovery, which may be two or more times that experienced during laying. Although the required strength is directly proportional to the distance, it is also affected to a major degree by the ship speed, cable angle during recovery, and the ship motion caused by waves. The ship motion can be controlled to some extent by seamanship and choice of the time at which the recovery is to be made.

Further, the design strength of the cable is in large measure determined by the strength of available steel and the amount of steel that can be accommodated in an economical overall design. Thus, uncertainties of 5 to 10 per cent in the maximum depth of the water on a route would not affect the cable design. Yet, during a critical recovery situation, a more accurate knowledge of depth would be useful in planning and executing the operation.

In buoy-suspended cable systems the cable strength parameters are dictated by the dynamic forces transmitted by the buoy. Natural cable resonance, which could develop under certain surface conditions, is also an important design parameter. Although this design factor is more pertinent to the mooring design, an order-of-magnitude calculation should be determined for a particular cable.

5.3.4 Retrieval and Repair

The cable extends from a shore station to an underwater load module located either on the ocean bottom or at an intermediate depth of up to 20,000 feet. Cable retrieval procedure is based on the assumption that the cable ship will have more than sufficient capacity to retrieve the entire length of the cable, but that it will not be required to retrieve the underwater habitat. For example, if it is required to retrieve 500 nautical miles of submarine cable, the cable capstan will have a lifting capacity in excess of the 70 tons required. Capacity could be somewhat less for shorter lengths, but it is assumed that a fully equipped, ocean-going, cable layer is employed for cable ship data (see Appendix B and Table 5-II).

The recommended procedure is to retrieve the shore end of the cable first, floating the terminal to the ship. When the cable is on board and strung to the storage tanks, (figure 5-4 and 5-5) the ship commences hauling in from the bow, proceeding along the cable track. The ship must be maneuvered to keep a minimum strain off, and a correct lead on, the cable while hauling in. Retrieval speed in deep water is slow -- about 0.5 knots.

The cable ship should haul in to a point no closer than 6 cable miles at the habitat, at which point the cable is cut and let go. If the habitat has already been retrieved, the cable connector (if used) can be disconnected, and the entire cable can be hauled in.

If the cable ship is not large enough to carry the entire cable, the cable is retrieved in sections. Starting with the shore-end, the cable is retrieved until the ship is loaded; at which point the cable is cut and the seaward end buoyed. After unloading, the ship returns to the buoy and, retrieving it and bitter end of the cable, proceeds as before.

In the case of a broken cable, the ends are picked up by grappling hooks and a splice is made aboard ship similar to the splice technique used in paragraph 5.2.7.

Figure 5-4. Deck Storage of Cable on Small Cable Layer

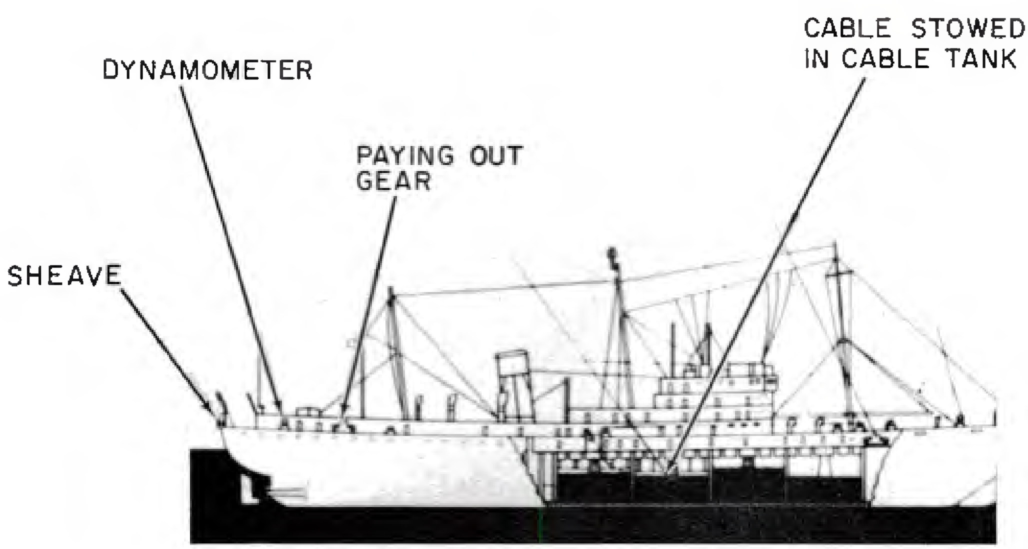


Figure 5-5. Tank Storage on Deep Ocean Layer

In the case of retrieval of cable from a surface buoy power source to an underwater habitat, it is assumed that the habitat will be retrieved prior to cable retrieval or that divers can disconnect the cable from the power module and transfer it to the cable ship. Once the cable is strung aboard ship, it can be retrieved by the same cable procedure as above, except that special precaution is necessary when the cable support buoys surface and are taken aboard. The habitat should be retrieved simultaneously with the cable. When the habitat reaches the surface, the remaining power cable can be disconnected and retrieved.

5.3.5 Effects of Pressure and Temperature on Submarine Cables

This discussion can be divided into material aspects and electrical constants. In the first instance cables deployed in depths of water with the equivalent of 10,000 psi will experience some measure of mechanical distortion. The amount of distortion will depend to a large extent on the voids or the inter-forces of the various cable constituents and plastic flow qualities of the various material used. The amount of distortion in cable has been classified as negligible due to experience gained through retrieval and close examination of cables that have been installed for years. The modern technology in cable manufacturing calls for elimination of all void areas by filling tightly with jute fillers and the selection of insulations and sheath materials with high: stiffness, graves (initiating), tear strength, yield strength, resistance to creep, resistance to permeation of liquids and gases, and brittleness. The polyethylene (voltage stabilized-high density) considered for cable insulation in this study has all these qualities, which make it ideal for the service intended.

As for the electrical constants, measurements have been "made to determine the effect of pressure on the primary constants of cable. These measurements indicated that capacitance was the only parameter affected by pressure. The capacitance increased linearly 0.1 percent for each 500 pounds per square inch of applied pressure."[1]

5.3.6 Cable Protection

For the particular environmental considerations associated with underwater power transmission systems, the multiconductor cable has decided advantages over single conductor. In the 3-conductor cable, three individual insulated and shielded conductors are cabled together. All interstitial areas are jute filled and the overall assembly jacketed with a polyethylene covering. The jute-filled interstices provide a cushioning effect for the individual conductor when subjected to impact loads. For overall mechanical protection and to provide the tensile strength required, either single or multiple conductor cables are armored with a high strength galvanized steel armor wire. It is less costly to install armor wire on one 3-conductor cable than on three single conductor cables. Therefore, from the standpoint of cost and mechanical protection, the 3-conductor cable is preferred.

[1] Submarine Cable: Oceanography, marine biology and cable mechanics. The Bell System Technical Journal, Vol. 36, pp 1047-1207, Sept. 1957

5.3.7 Pre-operational Test

Pre-operational tests conducted at the manufacturing plant consist of the following:

1. Temperature rating

   a) Covering maximum conductor operating temperature of 80^{o}C.

   b) Maximum conductor emergency overload temperature of 95^{o}C.

   c) Maximum conductor short circuit temperature of 150^{o}C.

2. Insulation resistance

   100,000 megohm constant (min) at 15.6^{o}C. (60^{o}F).

3. Test Potential

   a) AC - 150 volts/mil (average) up to 28,000 volts - 5 minute duration. Over 28,000 volts - 15 minute duration

   b) DC - 500 volts/mil (average) 15 minute duration

4. Corona level

   minimum extinction voltage equal to 1.5 times the maximum rated cable voltage to ground

5. Material qualification before application to the conductor

   a) ASTM D-1248-607 for Type 1, Grade 4, Class A with melt index of 0.2 to 0.4.

   b) single needle test - one hour characteristic voltage 50 KV minimum at room temperature in accordance with AIEE paper 62-54.

   c) after application to the conductor per IDCEA S-61-402, NEMA WC 5, Part 6.

6. Physical Tests

a)	original	after aging*
	tensile, psi 1800 (min)	75% of original (min)
	elongation % 400 (min)	75% of original (min)

*48 hours in air oven at 100^{o} (212^{o}F)

   b) environmental cracking

   in accordance with ASTM D-1693-60T (48 hours at 50^{o}C.)

   c) heat distortion

   in accordance with ASTM D-2219 latest, except sample heat conditioned at 90^{o}C. Decrease of original thickness - 25% (max) after one hour in air oven at 90^{o}C (194^{o}F)

Heat Distortion Load

Conductor size in AWG	Load on gage in grams
#7 to #1	750
#1/0 to #4/0	1.000
Larger than #4/0	2,000

7. Life and Voltage Tests

   As part of a regular testing and quality control procedure, samples of production cable are run through accelerated life and voltage tests under laboratory conditions.

After manufacture of the length of cable to be installed, the cable is placed in storage tanks. These tanks may be filled with water for environmental testing or the cable removed from the tanks and placed on board ship. Once on board, the ship, a high voltage AC or DC test may be performed in addition to megger tests of the insulation or in accordance with the customer's specifications.

In the case of a land-based power source, once the cable is installed and connected to the power plant end, and the MUS end, additional continuity, megger and voltage tests may be applied prior to operation.

Acceptance and proof testing:

Acceptance and/or proof testing is performed at the purchaser's option.

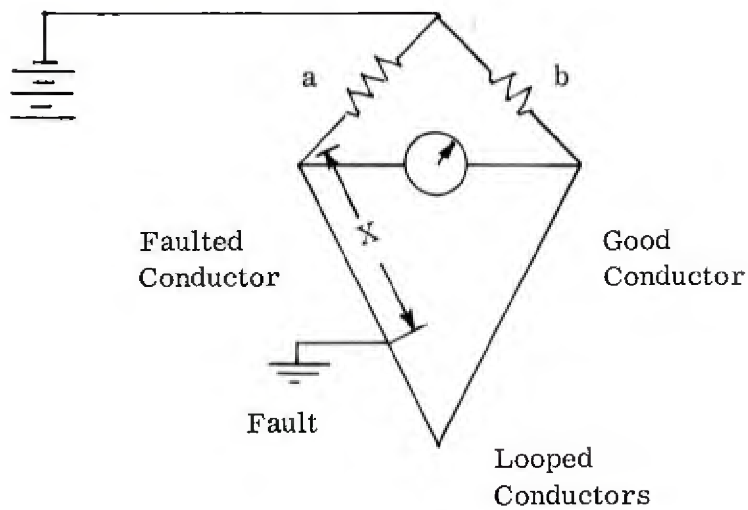
Acceptance tests are performed after installation of the cable and prior to energizing. The purpose is to check for any cable damage that may have occurred during installation and the terminal connections. The value of test voltage is normally 80 percent of that used in final factory tests.

Proof tests are performed at any time after energizing the cable to check the electrical condition of the cable.

The value of test voltage used is 60 percent of that used for final factory tests.

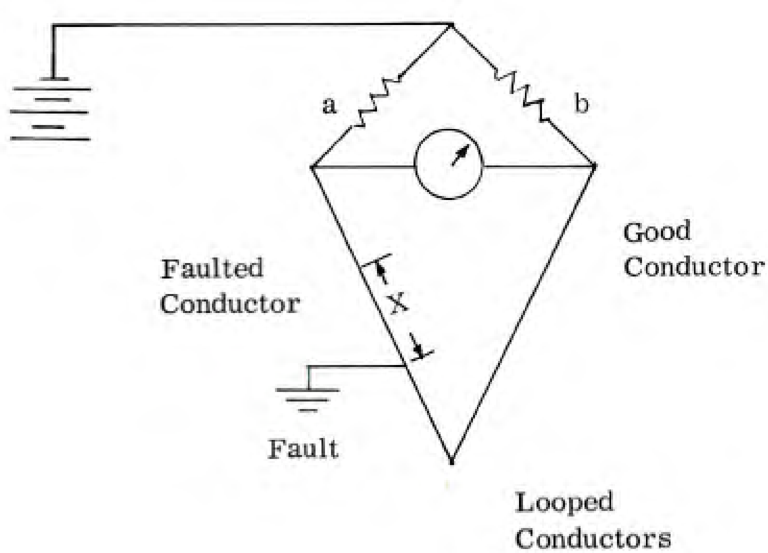
Cable Fault Location:

There are several acceptable methods used to determine fault locations. These are: the Murray and Varley loop techniques. The Murray loop is the simplest of the bridge methods for locating cable faults between a conductor and ground where there is a second conductor to use as a reference. This method is normally used for locating faults in low-resistance circuits. The circuitry for the test is shown on the following page.



$X = 2\left(\frac{a}{a+b}\right)L$ where a and b = Resistance of Bridge Arms.
L = Length of the Cable in Feet.
X = Distance to Fault in Feet.

The Varley loop test is similar to the Murray loop, but is particularly applicable in locating faults in relatively high resistance circuits. The circuitry appears below:



$X = \frac{L}{a+b}\left(2a - \frac{br}{R_c}\right)$ where a, b and r = Resistance of the Bridge Arms.
L = Length of Cable in Feet
X = Distance to Fault in Feet
R_c = Resistance of Good Conductor.

5.4 OPTIMUM CABLE CONFIGURATION

The cable configuration defined by the various tradeoffs is a concentric-stranded copper conductor, insulated with polyethylene, shielded, multiple (3-conductor) cable with a grounded neutral and provided with necessary binding tapes, filler, armor and jacket to meet the conditions of the environment. The cable will be operated at the required transmission voltage and frequency discussed in Chapter 6. The individual copper conductor sizes can range from an AWG #6 up to and including 1000, depending on the load and transmission voltage. A typical cross section of the marine cable of the type selected is shown in Figure 5-6. Tables 5-IV and 5-V show, respectively, mechanical and electrical data for the marine cable configuration selected in the basic available sizes and for the voltage ranges being considered.

5.5 CABLE CONNECTORS

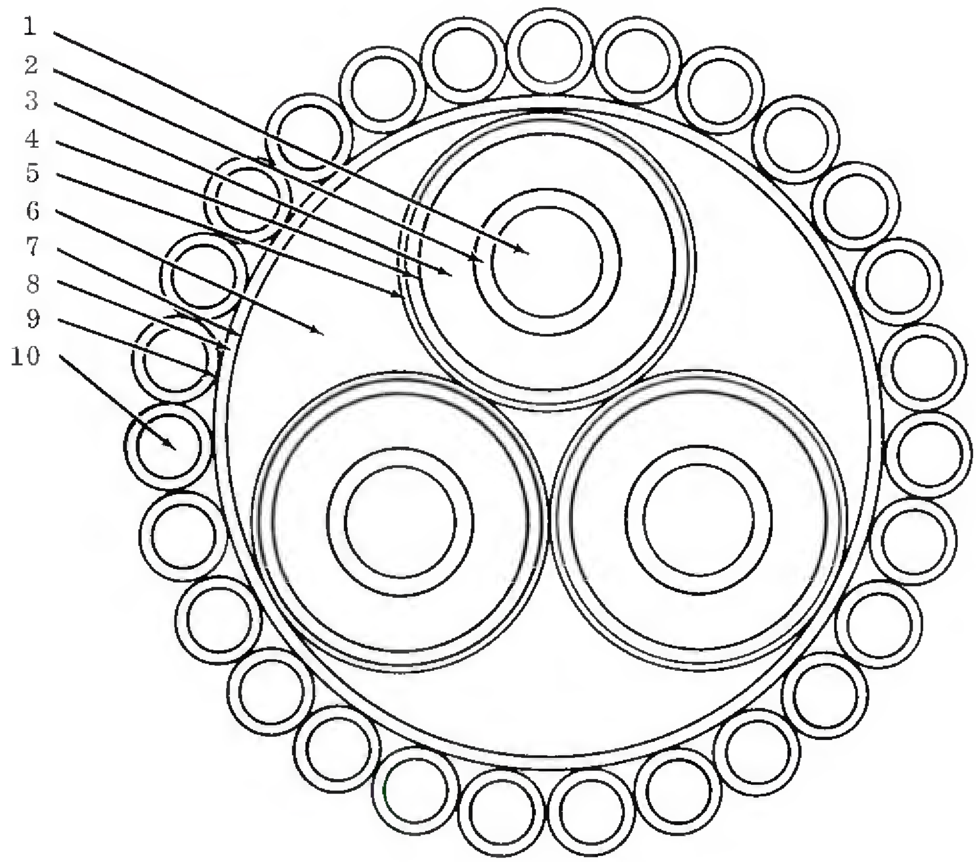
A cable connector will be required at each terminal point where the cable penetrates a pressure hull. The cable connector includes the jack, which is normally fitted to the transmission cable, and the plug, which is normally connected to the hull.

There are several problem areas associated with underwater connectors and their penetrations for the transmission of power to components (loads) encapsulated in a pressure hull. The principal problems are mechanical and electrical. The mechanical problems involve watertightness, mating (connect and disconnect under water), material compatibility, and strength. The electrical problems involve meeting the current-carrying capacity at the required voltage with minimum contact resistance through the connector.

5.5.1 Connector Design

The basic design problem of electrical underwater connectors is that of sealing polyethylene-jacketed cables that penetrate the pressure hull and providing a breakout for the armor. The cables must be sealed to the metal hull to withstand the hydrostatic pressures, and the cable internals must be blocked to prevent the flow of water into the hull should the cable jacket be severed or damaged, and provisions must be made to transfer the load from the armor to the hull. One of the first devices noted for sealing a cable on a deep-submergence pressure hull was that employed by Beebe and Barton on their 1930 and 1934 bathysphere journeys. As shown in Figure 5-7, a 1.1-in. diameter, four-conductor cable was sealed with a stuffing-box/cable-seal design. The packing was composed of four or five layers of 3/8-in. square flax pressurized from the inboard and outboard ends of the stuffing box with gland nuts. The outer gland nut was tapered to allow proper fairing out of the cable from the vessel. The cable was taped on the outboard end of the stuffing box to prevent its slipping into the bathysphere through the packing. No motion (of the cable) was observed beyond 1/3-in. slip on the deepest dive (3028 ft).

One of the primary functions of the cable-penetration fitting is that of housing the primary cable seals. This seal, located outboard of the pressure hull, is subjected to the saltwater and hydrostatic pressures, and prevents water from leaking into the pressure hull. The fitting also houses a secondary cable seal inboard of the submersible pressure hull. This comes into play if the primary seal fails. The secondary cable seal is felt to be a mandatory requirement for all submersible designs from a safety standpoint.



1. Conductor
2. Extruded strand shielding
3. Polyethylene insulation
4. Tape
5. Copper shielding
6. Fill w.p. jute
7. Binder mylar tape
8. Polyethylene jacket
9. High strength galv steel armor
10. High density polyethylene jacket over each armor wire

Figure 5-6. Typical Cross Section of Selected Marine Cable

Table 5-IV. Mechanical Characteristics of Marine Cable

WIRE SIZE OR MCM	3/C CABLE 5000 V DIA.*	WT.	15000 V DIA."	WT.	34500 V DIA."	WT.	3-1/C ONLY 69000 V DIA."	WT.	115000 V DIA."	WT.
6	1.97	4.16	2.17		2.87		2.34		2.97	
4	2.05	4.7	2.27		3.01		2.45		3.12	
2	2.19	5.47	2.39		3.19		2.58		3.30	
1/0	2.35	6.36	2.61	7.5	3.53	8.1	2.84	2.94	3.67	3.20
2/0	2.45	7.1	2.71	8.4	3.67	9.0	2.94	3.27	3.81	3.54
3/0	2.61	8.0	2.83	9.3	3.85	9.9	3.08	3.57	4.00	3.84
4/0	2.73	8.9	2.95	10.2	4.03	11.0	3.21	3.92	4.19	4.20
250	2.89	9.9	3.05	11.1	4.19	11.9	3.33	4.22	4.35	4.50
300	2.99	10.0	3.15	12.3	4.33	12.9	3.44	4.58	4.51	4.86
350	3.09	11.9	3.33	13.5	4.61	14.1	3.65	4.96	4.81	5.25
400	3.19	12.9	3.43	14.4	4.75	15.0	3.75	5.34	4.95	5.65
500	3.43	14.7	3.59	16.2	4.99	16.8	3.93	5.92	5.19	6.23
750	3.85	19.2	3.97	21.0	5.57	21.9	4.37	7.65	5.81	8.02
1000	4.17	23.6	4.35	25.2	6.13	26.1	4.79	9.02	6.40	9.36

Cable Constituents:

- Copper
- Polyethylene Insulation
- Plastex Jacketed
- Shielded
- Mylar Tape
- Jute Bedding & Filler
- #4 AWG Galv. Steel Armor Rod
- Armor Covering

Armor Wire Used (Galv. Steel) .204" Dia.

Covering Over Armor (Jacketed) .35" Thick

ARMOR MATERIAL	TENSILE PSI	ELONGATION % 2" LONG SAMPLE	DENSITY LB/CU.FT@20°C
Aluminum	13000-40000	15-20	169
Bronze	35000-40000	40	549
Monel	75000	45	520
Stainless Steel	82000-250,000	50	480
Galv. Steel	50000-750,000	1-10	490
Hard-drawn Copper	50,000-70000	2-3	550

Calculated Approx. Weight (WT in lbs. per foot
* Calculated Approx. Dia. in Inches

Table 5- V. Electrical Characteristics of Marine Cable

			3 - CONDUCTOR CABLE (C-L-P)									SINGLE COND. CABLE (POLY)				
Voltage Class			5000 Volts			15000 Volts			34500 Volts			69000 Volts			115000 Volts	
Wire Size or MCM	D.C Resist-ance	K	X_l OHMS	X_c M-OHMS	Ampa-city	X_l OHMS	X_c M-OHM	Ampa-city	X_l OHMS	X_c M-OHM	Ampa-city	X_l OHMS	X_c M-O	Ampa-city	X_l OHMS	Ampa-city
6	.410	1.0	.0396	.05	125											
4	.259	1.0	.0372	.043	170											
2	.162	1.0	.0305	.0365	220	.0429	.0576	223								
1/0	.102	1.0015	.0322	.0285	285	.039	.0475	290								
2/0	.0811	1.002	.0318	.0279	330	.0378	.0434	335	.0458	.0646	322					
3/0	.0642	1.0025	.031	.0252	375	.036	.0396	375	.0446	.0605	375					
4/0	.0509	1.004	.0297	.0214	425	.0354	.0363	431	.0429	.0576	426					
250	.0431	1.0055	.0293	.0212	475	.0339	.034	472	.042	.0537	472	130.	.083	355		
300	.0360	1.009	.0286	.0195	530	.033	.0319	520	.0407	.0509	525	128.	.076	372		
350	.0308	1.011	.028	.0182	575	.032	.03	620	.0395	.0482	570	126.	.073	392		
400	.027	1.014	.0275	.0017	615	.0315	.0282	610	.0386	.0463	619	124.	.07	410		
450	.024	1.018	.0271	.0161	665	.031	.027	650	.0378	.0446	660	123.	.067	425		
500	.0216	1.022	.0268	.0156	695	.0308	.0267	695	.0369	.0434	690	122.	.066	444	122.	433
600	.018	1.034	.0263	.0141	765	.030	.024	750	.0355	.0404	746	120.	.063	462	120.	450
750	.0144	1.052	.0257	.0128	865	.029	.022	840	.0336	.0375	830	117.	.059	485	117.	480
1000	.0108	1.079	.0253	.0112	960	.0284	.0199	960	.031	.0335	940	114.	.054	538	114.	527

X_l & X_c 60 cps All Measurements Per 1000 Ft.

K = A.C/D.C resistance Copper Temp. 90°C For Cross-Linked-Polyethylene (C-L-P); Water Temp. 20°C;
Power Factor (PF) .85; Load Factor 100%; Ratio Lay = 27.7 P.D

With respect to the primary cable seal, the use of watertight connectors is recommended. The connectors provide a positive water dam in case the cable is damaged or severed. An equally important consideration is that the disconnect feature of connectors provides a natural interface between the outboard systems and the internal systems. The use of connectors at the hull fitting also facilitates component, cable, and hull-fitting replacement if any are damaged in service as well as interchange of load modules. Connectors are also recommended, where possible, for providing the secondary cable seal. Here again a positive water dam is effected. In this

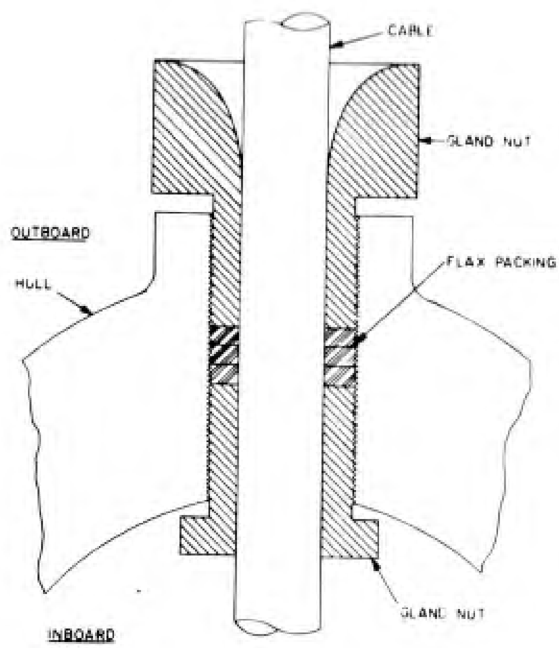


Figure 5-7. Bathysphere Cable Penetration Fitting

manner the entire hull fitting can be pressure tested prior to installation. The inboard hull-fitting connector also provides a junction point for the conductors and eliminates the need for a junction box while providing a natural circuitry test point from within the hull to the component.

For most non-military applications (i.e. no high shock) the hull-penetration fitting should be fastened to the pressure hull with a retainer nut located on the inboard end of the hull fitting. This securing device will effectively retain the fitting in the hull under normal service conditions. Welding is the most positive method of fastening a fitting to the hull, but ease of replacement and servicing is sacrificed, and it is costly. For this reason a full-penetration weld is not recommended for fastening the fitting to the hull.

The most positive method for sealing the fitting to the pressure hull is by seal welding. Here again, ease of replacement, servicing, and installation is sacrificed. For research-type pressure hulls, hull fittings can best be sealed by using O-ring gaskets. These seals provide long-term service and are inexpensive. The primary hull-fitting seal should be located outboard of the pressure hull with a secondary O-ring seal provided inboard. It normally can be housed in a spacer ring which would be located between the hull and the retainer nut. Primary and secondary hull-fitting seals are mandatory to guarantee safe operation.

For most applications, a cylindrical hull-fitting body is recommended to house the primary cable seals. The outboard length and diameter must suit the number of connectors to be housed in the fitting. The wall and cover thickness are sized to suit the design depths. Class 316 stainless steel or monel is usually used for the hull-fitting material to provide adequate corrosion resistance in the salt water environment. The fitting is usually housed in a liner (or hull-fitting insert) which provides compensation for the hull opening. The liner is a thick, doughnut-shaped cylinder which is welded to the pressure hull. For strength considerations in deep-submergence pressure hulls, hull liners are not normally used. The fittings are usually fitted into tapered holes located at the hemispherical ends of the pressure hull in thick sections of the hull. In these designs a metal-to-metal tapered primary seal is formed by closely machining the tapered hole in the hull and the tapered fitting body to provide at least 80 percent metal contact.

The outboard watertight connectors should be located radially around the fitting body. With this design, a maximum number of cables can be placed in the fitting within a limited height, and the cable is allowed maximum protection with an umbrella-type fitting cover. The secondary-connector water dam faces directly inboard and should utilize a right-angle plug to facilitate inboard packaging.

The solder-pot-termination ends of the primary and secondary cable seals (receptacles) should be filled with an elastomeric potting compound to preclude the entry of moisture in service.

The hull-fitting assembly must have complete electrical and hydrostatic pressure testing prior to installation. Protective receptacle caps must accompany the hull fitting at all times to prevent fitting damage in handling during fabrication and installation. The pressure hull must be designed to allow access to the fittings for connector assembly and disassembly. The cables running to the hull fitting and the hull fitting itself must be fully protected during construction and during in-service operations to prevent cable-fitting damage in the ocean.

The following design criteria are considered mandatory in developing reliable cable hull-penetration fittings for submerged pressure hulls:

- Primary (outboard) and secondary (inboard) cable seals should be provided in the hull fitting
- The external and internal cabling should be detachable from the hull fitting to provide the necessary hull/component interface
- The primary seal between the hull fitting and the hull may be a weld; the secondary cable seal should be an O-ring gasket

- The primary and secondary cable seals should be receptacles with hermetically sealed pin contacts
- The hull fitting should be shop fabricated from corrosion-resistant materials and fully tested prior to installation in the pressure hull.

Figure 5-8 shows a multiple-cable, hull-fitting design based on the above criteria which has been fabricated for Navy submarine use. The fitting is designed to withstand the required shock loadings. Figure 5-9 is a single-cable hull fitting which incorporates necessary design features. With respect to deep-submergence, hull-fitting designs, the multiple-connector unit shown in Figure 5-10 will provide satisfactory system service and hull compensation, and meet hydrostatic pressure requirements. Figure 5-11 shows a fitting design to be used on a research vehicle at 2000-ft depths. The two designs are similar; the deep-submergences fitting, however, uses a tapered fitting body for hull strength.

5.5.2 Connector Sizes

In order to allow transmission of the various current levels at the transmitting voltage, the pin size of the three conductors must be varied to suit. The pin sizes must be compatible and made with the cable conductor size being considered (Table 5-I). Thus the final selection of pin size, and therefore, connector size, is dependent on the length of transmission cable.

5.5.3 Connector Availability

Figure 5-12 gives the approximate availability of electrical connectors as a function of voltage and amperage rating. An extremely small area of power level is available with present connectors. Figure 5-12 depicts only "dry" connectors, because there are no "wet" connectors available for the power levels of interest. Therefore a significant development program will be required; recommendations are detailed in Chapter 11.

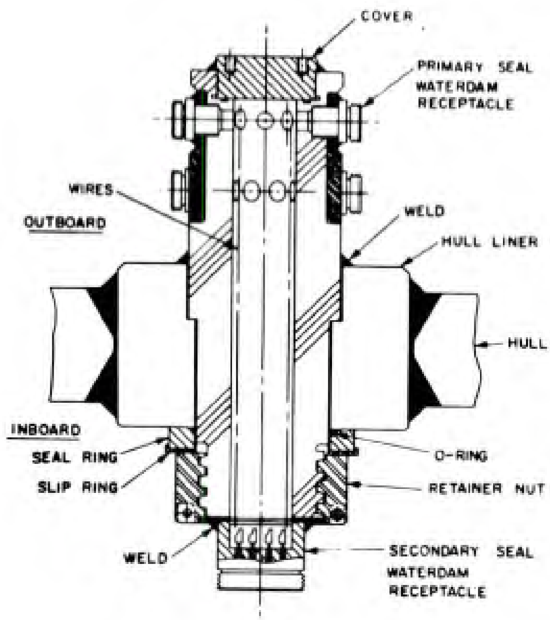


Figure 5-8. Multiple Connector Hull Fitting for Submarines

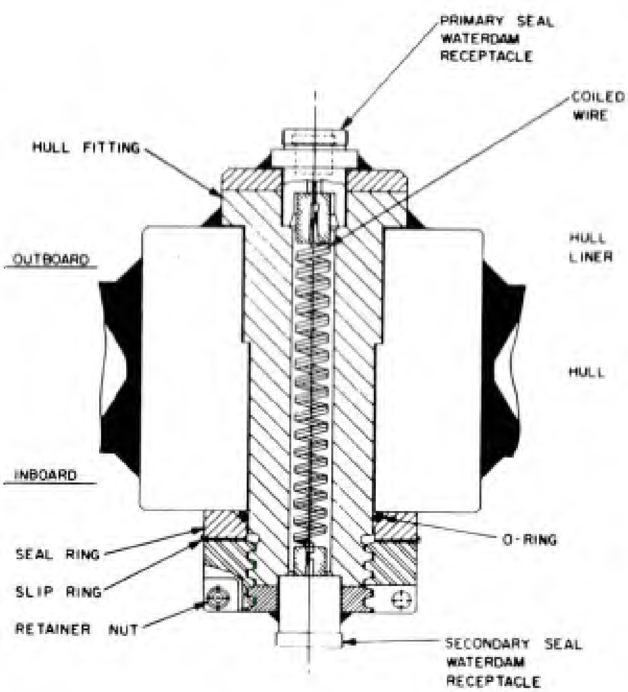


Figure 5-9. Single Connector Hull Fitting for Submarines

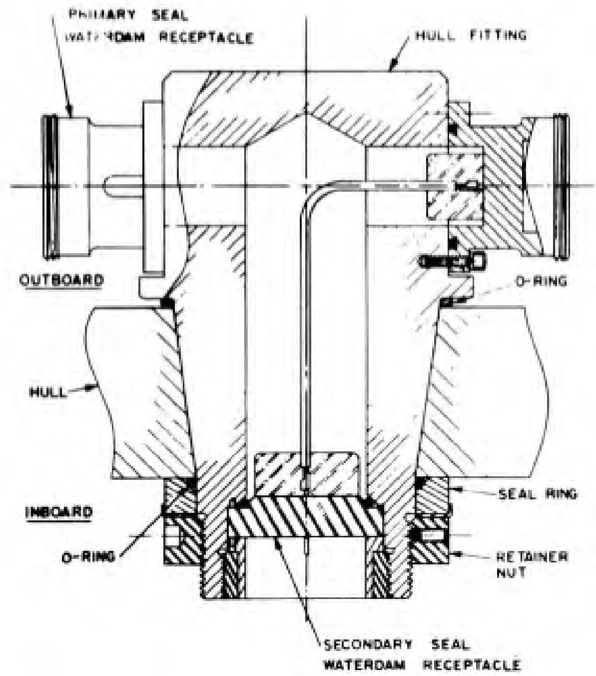


Figure 5-10. Deep-Submergence Vehicle Hull Fitting

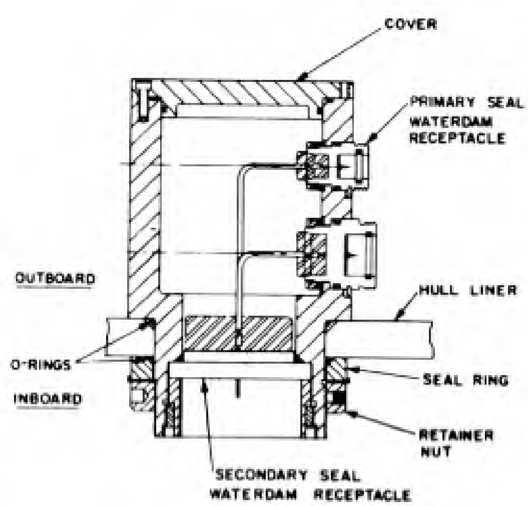


Figure 5-11. Research Vehicle Hull Fitting

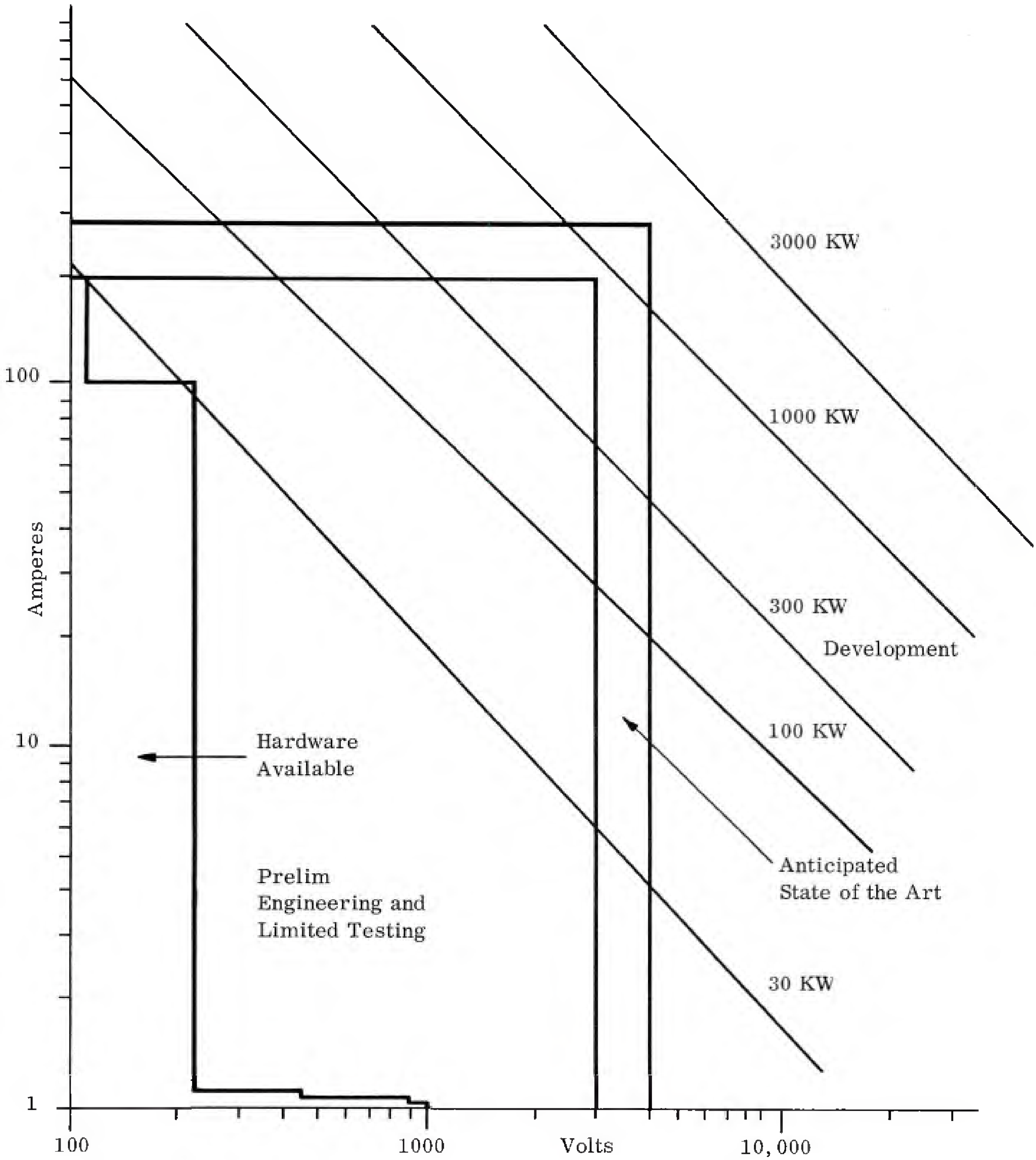


Figure 5-12. Availability of Electrical Connectors

5.6 CABLE SUSPENSION SYSTEMS

5.6.1 Support System Design Criteria

The ability of the cable to support itself is determined by its net submerged weight and its inherent strength. The analysis was based on the assumption that at no time does the cable see any loads other than those due to its own weight and the trace configuration that it assumes. The cable is not required to support the weight of the module when it is being lowered to the bottom. The dynamic loading on the cable imparted by the motions of the surface unit is within the accuracy of the study. There is a restriction on the weight that the surface unit can support, which is established at 50,000 lbs. Therefore, even if the supporting strength of the cable can exceed this loading, some mechanism has to be employed to reduce it below this level.

The weight of the cable depends on its length, which is a function of the depth of the load module and the excursion of the surface unit. The excursion depends in turn on the environment in which the surface unit is placed. Since the environment cannot be predicted, cable length cannot be derived from load module depth, and estimates of cable support requirements are based on a representative list of cable lengths rather than load module depths. The cable lengths studied (600, 1000, 2000, 6000, 10,000, 15,000, 20,000, and 30,000 ft) were chosen to include any cable length which might be required, under varying environmental conditions, to reach the required depths.

To limit the length of the cable, the center of excursion can be placed directly above the load module. However, since it cannot be predicted that the prevailing seas, currents, and winds will be in one direction, it has to be assumed that the surface unit travels through its excursion limits for an unknown number of cycles during its deployment. This cycling leads to a wrap-up of the cable during its cycling, because both ends of the cable are fixed. To preclude this, the excursion of the surface buoy should be clear of the centerline of the load module, so that the surface unit never passes above the vertical centerline of the load module.

Basically, there are two methods of supporting the cable. The first is to increase the strength of the cable by using armor or wire wrapping or by attaching the cable to a separate support cable. The second is to reduce the effective weight of the cable by attaching buoyancy materials to it. These two basic methods are discussed separately in paragraphs 5.6.2 and 5.6.3 below.

5.6.2 Cable Strengthening

If the conductor and the associated shielding, insulation, etc. cannot support any load, then strength has to be added in some form to the cable to support its displaced weight in water. The amount of a strengthening material added to the cable is a function of its own breaking strength and its ability to support both the conductor weight and its own weight. This diminishes as the toal weight of the supporting material increases, as shown in Table 5-VI. The table is based on a cable having three #6 conductors and insulation of the 5000-voltage class.

Table 5-VI. Relative Effectiveness of Increased Cable Strength

ARMOR AREA MULTIPLES (N)	RELATIVE DEPTH L_n/L
1	1
2	1.11
3	1.17

Two methods can be used to provide the strength to the cable. The first is to provide armor or wire wrapping. The second is to provide a separate cable to which the power cable is attached during deployment. If the material used for the strength member is the same in either case, and an equivalent area can be applied in each case, then it is advantageous to use the armor, because it is placed on the cable during manufacture and does not require at-sea fastening.

5.6.2.1 SINGLE ARMORED CABLE - Normally, submarine cables are supplied with a single sheathing of armor laid helically. These helically-wound armor wires tend to unlay during tensions imposed during laying operations. The tension is highest at that portion of the cable leaving the ship's cable drum and lowest on the ocean bottom.

Unlaying of the armor results in rotation of the cable as it leaves the ship. This unlaying at the ship is compensated for by laying up armor in some other portion of the cable since both ends of the cable are not free to rotate.

Thus, in the portion of the cable arriving at the bottom, which was unlaid leaving the ship, this cable is returned to normal lay. This characteristic is not considered a problem in laying cable from shore to shore or from shore to a point in the ocean. However, this may present a problem when a heavy object is lowered at the end of the cable. Under these conditions, the cable cannot recover its rotation, due to tension until the wieght reaches the bottom.

At this time, with the cable end fastened to the weight, the cable end cannot rotate and the torque left in the armor sheath can relieve itself only by twisting back towards the laying end. This condition results in undesirable kinks which can fault the cable and prevent a safe recovery of the installation.

Therefore, a single armored cable used under the conditions above must be accompanied by a holding line attached to one side of the unit being installed. This line must be held under tension during emplanting. Such a procedure is complicated and unreliable, particularly in deep water.

5.6.2.2 DOUBLE-ARMORED CABLES - For submarine cables requiring heavy double-armored sections, such as shore line transitional areas and areas subjected to fishing trawler and other boat damage, the double armor sheaths are applied in the same direction. This facilitates the coiling of the finished cable in the storage tanks and a coiling direction can be selected that will loosen all armor wires as the cable is tanked. Thus, a clockwise coiling would be used for a cable whose armor is applied with a left-handed lay. When untanked, the lays return to normal position.

Another design for double-armoring would be to provide a torque-free cable under tension. To accomplish this, each sheath of armor is layed in opposite directions. The angle of the armor application is approximately 10 degrees for each layer. This type construction is commonly used in rotation-resistant construction. However, the double armor, reverse lay, presents a storage problem and these cable are normally handled on cable drums or reels. In the case of large and/or long cables, the use of reels or drums is a problem and it is more practical to handle the cable from storage tanks. During coiling in the tank, the cable is forced to make one twist or 360 degrees for each turn laid into the tanks. When removed, the twist is removed and the cable assumes it original shape.

Coiling in this case is designed so that on tanking, the inner armor loosens and the outer armor tightens.

In estimating the strength of the armor, the equivalent of a single wrapping of .204-in. diameter wire throughout was used. For the surface unit plant with the cable suspended, unequal stress distributions occur in the armor if a single wrapping is used. Therefore, double-wrapped, reverse-lay cable with an equivalent area of the single wrapping was utilized for strength calculations.

The original estimates were made using standard, available submarine cable which has galvanized steel armor with ultimate strength in the range of 60,000 to 70,000 psi. This cable was chosen initially because its unit cost is the lowest of the materials available, and it is the standard for the industry. If a higher strength armor is used (ultimate strength 250,000 psi), the cost of the armor rises sharply. However, the total cost of the support system for the deeper depths is reduced, because the higher strength armor reduces the amount of support which must be supplied by buoyancy devices. As a result, these buoyancy devices can be placed at lesser depths, which greatly reduces their cost (see paragraph 6.6.4).

In determining the unsupported length, a safety factor of 2 was considered based on the ultimate armor strength for the standard cable and for the high-strength cable. This is within the range of the factor of safety normally used by the cable manufacturers in determining cable strengths. This provides an allowable working stress of 30,000 psi for the standard armor and 125,000 psi for the high-strength armor. Table 5-VII shows the approximate unsupported length for some of the conductor sizes selected in paragraph 5.4.

The surface power plant can support, in addition to its own internal weight, 50,000 lbs of power cable suspended underneath. Therefore, additional buoyant methods are required to prevent that cable weight which is suspended from the surface power plant from exceeding 50,000 lbs. Therefore, in addition to the study of the parameter of cable self-supporting capability, a constraint must also be established to maintain the suspended weight within the limits defined for the surface power plant buoy. For example, in standard cable configuration, a 3/0 cable can be unsupported to a maximum distance of 5390 ft ; or in the high strength cable, 22,800 ft. However, the 50,000 lb limitation would require the use of supplementary buoyancy system at a vertical suspended distance of 6,250 ft.

Table 5-VII. Approximate Unsupported Cable Length Maximums (In Air)

WIRE SIZE	VOLTAGE CLASS	DISTANCE (FT) STANDARD CABLE	HIGH - STRENGTH CABLE
#6	5000 V	7530	31, 200
#4	5000 V	7100	29, 600
#2	5000 V	6450	26, 900
1/0	5000 V	5900	24, 600
3/0	5000 V	5390	22, 800
350 MCM	5000 V	4270	17, 850
500 MCM	5000 V	3700	15, 400
750 MCM	5000 V	3300	13, 750
#6	15, 000 V	7500	31, 000
1/0	15, 000 V	5750	24, 000

5.6.3 Buoyancy Support

To extend the ability of the cable to support itself, buoyancy devices can be added either completely throughout or at discreet points in the cable system to reduce the cable's net weight. For a first approximation, if the cable could be made neutrally buoyant, then any water depth could be reached within current-loading restrictions. Neutral buoyancy can be accomplished in two ways. The first is to incorporate buoyancy material during the manufacture of the cable. The second is to add the buoyancy during deployment. For the latter method, the costing must include attaching any of a variable number of buoyancy devices and the cost of handling these units at sea.

The neutrally buoyant cable concept is not considered a practical solution to the suspension of power cables in the undersea environment. The basic limitation for the manufacture of neutrally buoyant power cables is the cable manufacturing process, which has severe limitations on the maximum diameter of the power cable, including the insulation and all buoyant materials. Therefore this concept could not be considered effective for the power ranges under study. Because a development program is required for the material itself and the manufacturing process, reliable cost data for comparison of these two systems could not be obtained. The use of the discrete buoyancy system can be more readily achieved within the time frame established for the potential use of these systems.

Optimizing the latter system, considering that the cable cost itself is effectively constant, requires definite knowledge of the actual techniques to be used for the installation of any given number and type of buoyancy devices. In this analysis it is assumed that it is necessary to minimize the actual deployment time. This requires that the number of buoyancy units be kept to a minimum. A minimum number of units is arrived at by placing them at points along the total cable length at which the weight of cable hanging below results in a maximum allowable working stress in the cable.

Figure 5-13 shows the buoyant force level requirement for a representative number of cables at their respective depths. To serve as a departure point, the first buoy in each case has been placed at 2000 feet. All cables selected can reach this depth unsupported and it is the last selected load module depth before which the cables have to be supported. For example, for a #2,500V cable at depths of 15,000 ft a total positive buoyancy system equal to 92,799 pounds must be subdivided at 3 discrete points to provide the necessary supporting system to support the weight of the power cable.

For load module depths greater than 6000 feet, the total distance to the bottom is divided into equal number of cable lengths. These lengths are determined by deriving the maximum unsupported length of cable that can exist before the cable reaches its maximum allowable safe working stress. To provide the buoyant forces necessary to maintain the cable in a generally vertical attitude, resist current drag forces and account for the load component of the surface cable (last buoy to surface unit), a multiplier of 1.3 for the effective net buoyant force has been used at this point in the study. Small variations in this multiplier are within the overall accuracy of the estimates and therefore will not materially affect the comparative results.

To provide the required buoyancy forces for each of the cable systems, two basic types of buoy were investigated:

1. hollow buoyancy spheres
2. homogeneous buoyancy materials.

For the former, a variety of materials were reviewed. Those which have acceptable weight-to-buoyancy ratios such as glass-reinforced plastics, glass, titanium, etc. are considered developmental for the purposes of this study and therefore were not considered for evaluation. Of the nondevelopmental materials reviewed, aluminum alloy 7079-T6 was selected because of its high-yield strength properties, lightness, and suitability for the marine environment. The spheres must be fabricated with a mechanical joint at the equator between two formed hemispheres, because the material has poor weldability characteristics. Since this material is susceptible to exfoliation corrosion at the exposed end grain, special provisions are required to prevent contact with sea water. Hemispheres are presently available to a maximum diameter of 84 in. To avoid unnecessary development costs, this size was used as the maximum. At all depths, multiple spheres must be used, because a single sphere of this size will not suffice for even the lightest cable.

For the buoyancy floats constructed of materials that are less dense than sea water, a syntatic foam with a weight in the air of 44 lb/ft^3 was used for evaluation purposes. Foam of this weight is available and has fairly well established properties. For the shallower depths, it is possible that more efficient foams can be utilized.

To minimize drag forces on the buoyancy units, each of the concept configurations is shaped in a clam shell type form. Typical configurations used in the study are shown in Figure 5-14.

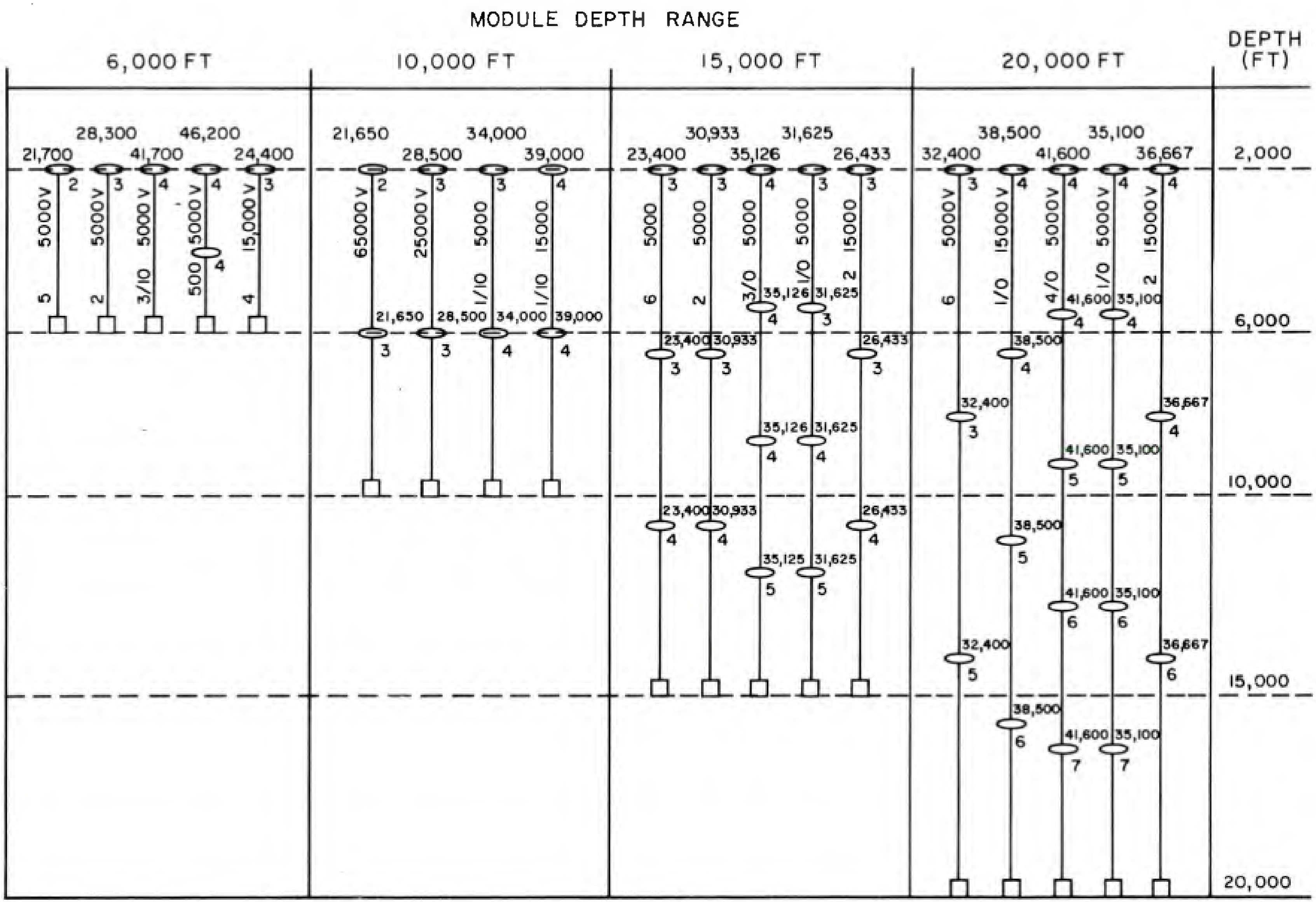


Figure 5-13. Buoyant Force Level Requirements

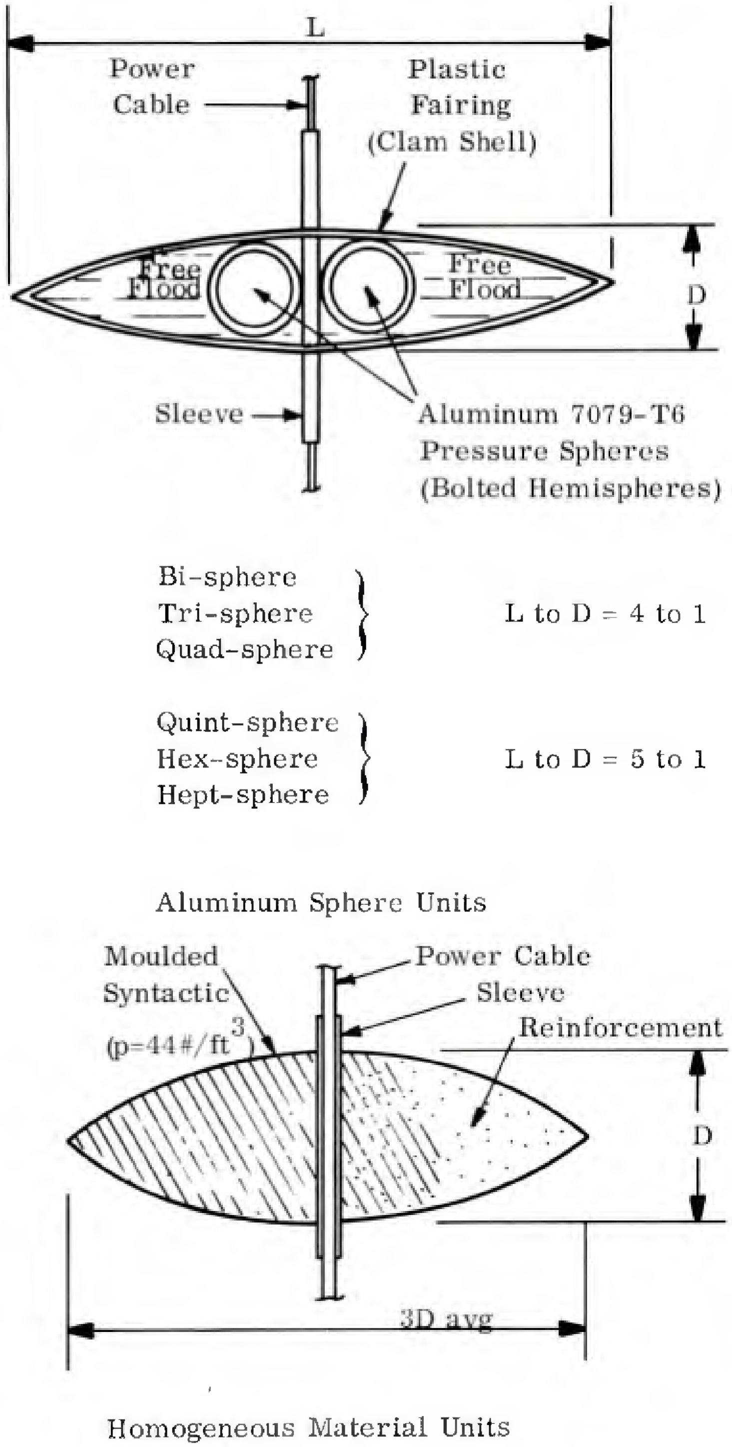


Figure 5-14. Buoyancy Support Configurations

For each of the buoyancy force levels shown in Figure 5-13, the floats for each construction method were sized and estimated for cost construction. Figure 5-14, also shows, for the aluminum sphere construction, the number of spheres within each float device required to provide the buoyancy force required. This number is arrived at by using the maximum diameter of 84 inches mentioned previously, together with the fact that, as the depth increases, the net effective buoyancy of a sphere of a given size decreases because of the greater wall thickness required.

Since the configuration concepts are considered to be within the present state-of-the-art and can be procured in a reasonable time, the selection factor then reduces to one of system cost.

Table 5-VIII depicts the relative costs between the two configuration concepts for a number of cable sizes. As is clearly evident, the aluminum sphere configuration is superior to the syntatic devices in this respect. This cost differential clearly suggests the use of buoyant aluminum spheres as the prime cable support technique.

Table 5-VIII. Relative Construction Cost of Buoyancy Floats (Syntactic Floats ÷ Aluminum Sphere Floats)

DEPTH OF LOAD MODULE							
6000 FT.		10, 000 FT.		15, 000 FT.		20, 000 FT.	
#6 - 5000 V	5. 8	#6 - 5000 V	4. 4	#6 - 5000 V	3. 3	#6 - 5000 V	3. 9
#2 - 5000 V	7. 4	#2 - 5000 V	5. 8	#2 - 5000 V	4. 3	1/0 - 5000 V	3. 8
3/0 - 5000 V	9. 9	1/0 - 5000 V	6. 4	3/0 - 5000 V	4. 3	4/0 - 5000 V	3. 7
#500 - 5000 V	7. 7	1/0 - 15000 V	7. 1	1/0 - 15000 V	4. 3	1/0 - 15000 V	3. 1
#2 - 15000 V	6. 5			#2 - 15000 V	4. 0	#2 - 15000 V	4. 1

5. 6. 4 Cable Support System Concepts

There are two basic configurations that can be considered for the cable suspension systems:

1. a taut line configuration
2. a normal catenary configuration.

Concept 1: TAUT LINE - The general taut line arrangement for any given water depth is shown in Figure 5-15. For this case, one or more buoys are suspended along the cable length. The total buoyancy of these attachments is greater than the displacement weight of the cable so that a positive vertical force is generated along the cable. Attached to the uppermost buoy is a pendant cable which can be strung to the surface unit. For a given buoyancy differential, the cable will remain vertical until it is displaced by either the resulting force from the pendant cable or forces generated through drag of the cable by current velocities. To place the concept evaluations on an equal basis, the last buoy in the vertical direction, that is, the one closest to the surface is placed at a depth equal to the 2000-ft load module depth.

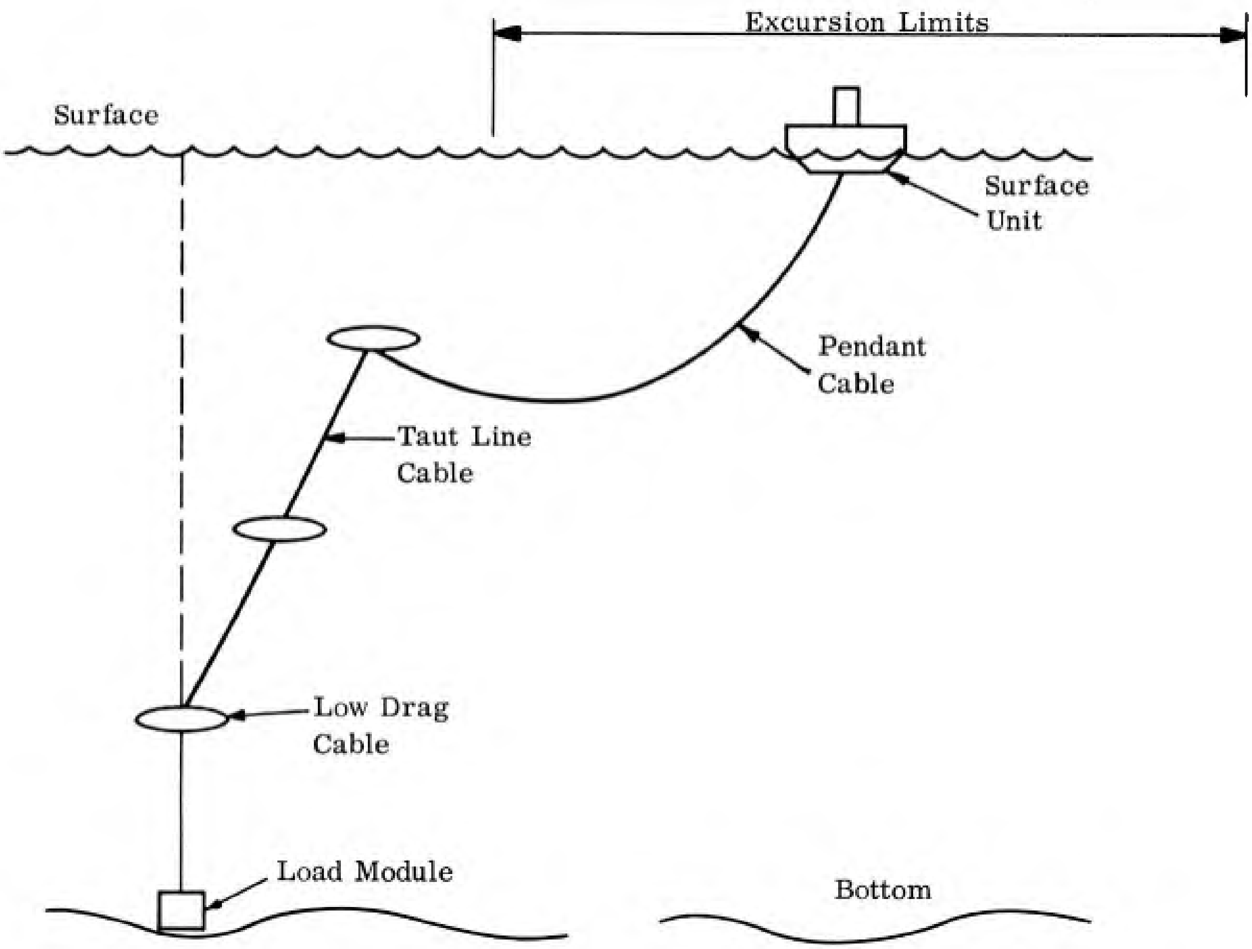


Figure 5-15. Taut Cable Support System

With a taut line suspension system, pendant cable support will be needed if the span required to handle the excursion of the surface unit exceeds its cable strength. The actual length of the pendant cable will depend on limiting the force levels on the buoy and the selection of the resulting force vector on the last buoy in the taut line portion of the suspension system. As the surface unit moves through its excursion limits, the taut line portion will move through a distance until the disturbing forces are balanced by the vertical forces component in the taut line section. It has been assumed that the taut line section remains vertical and the pendant cable is sized to accommodate the total surface unit excursions. This leads to a longer cable than is necessary. The actual design of any system will evolve the optimum combination of lengths.

A mid-span sag of .2 has been assumed to size the pendant cable. This ratio maintains the force levels in the cable below their breaking strength while giving the shortest length possible. In all cases, the cable and its support system are negatively buoyant so that the cable remains in the water column to preclude any surface disturbance.

When the surface unit excursion is at its minimum point it is assumed that the pendant cable is hanging essentially vertical with one end supported by the surface unit and the other supported by the last buoy in the taut line portion at 2000 ft. For the load module at 20,000 ft, the length of the pendant cable was postulated to approach 20,000 ft. When the surface unit is above the load module, the cable hangs to about the 11,000-ft level. The minimum excursion point in any actual design must be displaced a horizontal distance from the load module vertical centerline to reduce the possibility of entanglement of the surface unit.

Concept 2: CATENARY CONFIGURATION - In this concept (Figure 5-16), the power cable is permitted to form a nominal catenary trace from the bottom to the surface unit. The concept drawing shows discrete buoyancy units spaced along the cable at distances that will maintain safe tensile levels in the armor.

This catenary concept could also be extended from that shown to one providing uniform bouyancy material along the cable. As discussed in paragraph 5.6.3, there are severe limitations to the use of this concept, and therefore the only catenary-configuration buoyancy support system considered was that employing discrete buoyancy units spaced along the cable.

5.6.5 Concept Comparison

To compare the two concepts on an equivalent basis, they are compared up to the 2000 ft level, or to the last buoy level in the taut line concept. For the catenary trace concept,this does not present any difficulty since the remaining cable length can be considered to be supported by the surface unit. For the taut line concept, this means that the impact of the pendant cable length will be disregarded. At this point it was assumed that the cable will support itself so that the suspension component of the overall tradeoff is not affected.

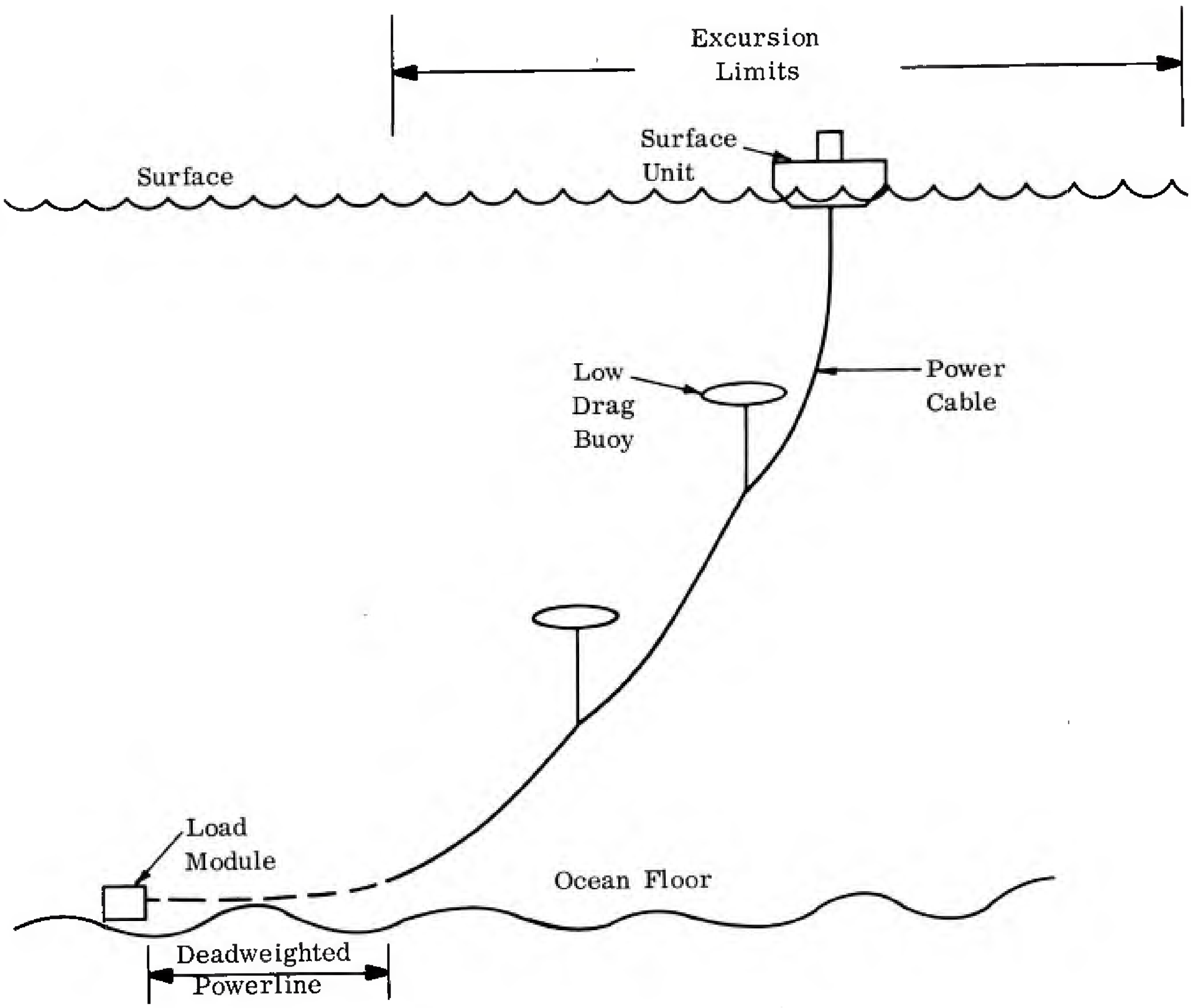


Figure 5-16. Catenary Cable Support System

BUOYANT SUPPORTS - For a given depth, since the length of the cable in Concept 2 will be greater than in Concept 1, the number of buoyancy devices will be greater for the former concept under any given set of equal conditions.

SURFACE HANDLING - If the cable to be supported is identical for both concepts, there seems to be little to choose from in the degree of difficulty involved in surface handling of each of the concepts. Each will require attachment devices to the cable itself. Concept 1 seems to be slightly more difficult since it is advantageous for the cable to pass through the center of the supporting device. This is not necessary with the arrangement in Concept 2 except that a structural unit will have to be adapted to the cable to provide proper bend radius in order to minimize the radius of curvature necessary to limit the bending stress in the cable due to the catenary profile change. Comparatively then, there seems little to choose from in the manner or the cost allocated between the two concepts.

SYSTEM RELIABILITY - The catenary concept poses a serious problem to the reliability of the surface plant system. If the catenary is sized so that the load forces on the bottom unit are horizontal at the maximum excursion point of the surface unit (i.e., the cable trace is tangential to the bottom), the cable will abraid on the bottom as the surface unit moves about from its maximum point. To prevent this, a buoyancy unit similar to that in the taut line concept must be installed in this system so that at the innermost portion of the excursion the total depth of the cable is less than that of the load module itself. For the load module at 20,000ft, the surface excursion is approximately 18,000 ft. It can be assumed, for illustrative purposes, that the cable length is equal to the minimum distance from the load module to the surface unit at its maximum excursion. Allowing the innermost portion of the excursion range to be directly above the load module the buoyancy unit has to be placed some 7000 ft above the bottom. For reliability purposes this concept now approaches Concept 1.

The above arrangement is based on the assumption that the total cable suspension system is slightly negative. If it is made positive, there is the probability that during the surface unit's excursion, the cable system will broach the surface and will be subjected to surface conditions as well as entanglement with either the surface unit and/or its mooring system.

The same argument has to be applied for the two cases in which the load module is at 600 and 2000 ft. Buoyancy has to be provided in each case so that over the excursion trace, the cable never contacts the sea floor. The required buoyancy device will provide a taut line system to a depth at which a normal catenary trace can then be used to extend to the surface unit.

Another reliability consideration is that for a given cable size and a given depth the number of identical components for system Concept 2 is greater than Concept 1. This tends to increase the probability of failure of the total system for Concept 2.

LOAD MODULE ENTANGLEMENT - For each of the concepts, the minimum system requirements are identified. This is done because it is not known what the entanglement limitations should be for each of the load modules. This will depend on such factors as the mission (unknown) and the cost to recover (unknown) as related to the cost of the unit. Since the cable length is being supported in each concept with buoyancy devices equal to slightly more than the displaced weight of the cable, each suffers from the fact that if the cable is lost at any point except directly above the attachment to the last device, the cable complex will descend to the bottom of the sea until that length of the cable is supported by the bottom which does not have its corresponding buoyancy provided for in the buoyant devices. In thecase of the taut line system, the cable has a higher probability of falling upon the load module. In either case, however, the degree of entanglement will partially depend on the loose end of the cable becoming stuck to the bottom.

CONCEPT SELECTION - Some form of taut line buoy suspension system for the power cable is required. For evaluation purposes, the configuration of Concept 1 will be analyzed with the understanding that a system design for a given task may evolve a system configuration which may be more efficient in terms of overall suspension cost.

Chapter 6

ELECTRICAL SYSTEMS

This chapter is a technical discussion of all the major considerations, suppositions and constraints used in the analysis of design concepts and the determination of final electrical characteristics for transmitting electrical power to deep ocean installations. The design parameters used and the approach to the selection of underwater power transmission systems are discussed.

The electrical system for each load at each distance was considered to include the generated voltage, step-up primary transformer, transmission line, step-down secondary transformer, and protection equipment.

Installation Requirements

All electrical equipment and devices, sub-system wiring and accessories will be installed inside of the pressure vessel (hull) in accordance with applicable specifications and codes having jurisdiction. The only exception to this would be external connectors for lighting, power cable and telephone circuits and in the case of the static capacitors used with DC transmission system.

System definition followed the normal procedure for the selection of the transmission line, equipment, and components, including selection of standard nominal voltages within the preferred voltage class insulation, circuit frequency, conductor size, voltage regulation, line losses and circuit protection. A load power factor of 85 was selected for analysis. This is representative of the type of loads specified by the design constraints. The loads, as envisioned for the load module, will consist mainly of induction motors. This type of device operates at a power factor of 0.85 lagging at full load. Stability problems due to system synchronization were not investigated since only a single generating source was considered. Circuit stability was limited to the ability of the system to respond from full load to no load and the reverse.

Parametric studies related all of the circuit operating conditions, including voltage, current, losses and regulation, to conductor sizes and lengths, as a function of acquisition cost of the system. In addition, all interface areas were described to enable the selection of a cost effective system.

The overall system investigation included protection considerations. These included the loads as steady-state and those transient conditions under a fault (short circuit) condition that could affect the underwater power transmission system.

Computations made in the cable analysis considered the cable at atmospheric pressures in an ambient temperature of 20 degrees centigrade (approximately that experienced by the cable submerged to the depths considered). The other environmental conditions imposed on the cable may be found in Appendix A-2. In relating these conditions to the conditions in the ocean environment, only one requires recognition because of the electrical effects and that is the ambient pressure to be experienced. It appears from studies made to date that the only parameter that changes due to pressure (from atmospheric to approximately 10,000 psi) is the capacitance. This change has been found to be 0.1 percent increase in capacitance with 500 pound per square inch pressure increase (See reference, chapter 5).

6.1 ANALYSIS APPROACH

A preliminary study indicated that, for some of the parameters, no overall electrical characteristics could be clearly defined that would be suitable for all lengths of transmission cable under consideration. Therefore, the analysis was initiated for moderate cable lengths of 600 to 30,000 ft which could be considered applicable to surface power-source location. After the selection of the most effective electrical characteristics as a function of acquisition cost, an analysis was inititated for longer cable length, and its selection of electrical characteristics was compared to the previous analysis.

For cable length less than 600 ft, which is characteristic of in situ power locations, the preferred electrical characteristics were related to equipment size of minimum equipment to reduce size of pressure hulls. The required modifications are discussed in paragraph 6.9.

Modifications necessary to define the most cost effective systems for transmission lengths greater than 30,000 are described in paragraph 6.10.

6.2 ALTERNATING VS. DIRECT CURRENT

The design constraint, which called for the delivery of 480-volt, 3-phase, 60-cps AC to the load module, requires additional transformation or inversion equipment at the termination of the transmission cable to provide the specified usable power to the load module whenever the voltage or frequency of transmission differs from the above constraint. The primary advantage of DC current is the reduction of cable size for an equivalent power level. However, cable size is also directly related to transmission voltage, so both electrical characteristics are analyzed simultaneously.

The basic system analyzed included the primary transformers required to produce transmission voltage from the generating voltage, the primary switchgear for instrumentation protection and control equipment, the transmission cable, the secondary transformers to reduce the transmission voltage to usable voltage, and the secondary switchgear required for control and instrumentation. Data on acquisition cost of DC equipment in the power levels under consideration were not as readily available as cost information on similar AC equipment. As a result, certain conservative assumptions were required:

- Transformers to supply rectification equipment will cost 1.75 times as much as AC transformers. This is deemped reasonable in that DC transformers must be redesigned in turns ratio to compensate for flashback when they are connected to a converter and they are normally six or twelve phase to the secondary side.

- The cost of DC switchgear will be considered equal to that of AC switchgear similarly power rated. This is deemed conservative, in that DC switchgear costs are known to be higher, but consistent cost factors could not be obtained.

- Solid state conversion equipment for the power levels studied are not available. Certain solid state conversion equipment will be available within the time table established in paragraph 2.1. However, prices were extrapolated from published data for purposes of making the tradeoff.

- For purposes of this analysis, a 5 percent allowable voltage drop was fixed for the AC system so that a reference design for AC could be compared with the DC system.

For each load over each distance from 600 to 30,000 ft, it was found that the savings in transmission losses and cable size could not offset the additional cost of DC terminal equipment at each end of the transmission line.

Figures 6-1 through 6-4 illustrate the nominal cost differential between AC and DC for the loads and length of transmission line for 600, 2400, 4160 and 13,800 volts respectively. The cost differential is much larger than shown in these curves, since added hull costs due to the DC equipment for the load module were not considered in this portion of the tradeoff.

For each voltage rating, AC costs were less than DC at each transmission length between 600 and 30,000 ft. The cost increase for DC at 30 KW power level for 600 volts was 36 percent minimum, for 2400 volts was 14 percent minimum, for 4160 volts was 18 percent minimum, and for 13,800 volts was 7 percent minimum. For higher power levels, similar cost differentials were apparent, as noted in Figures 6-2 through 6-4.

For the proposed moderate transmission length systems, an AC system was determined to be optimum for the transmission of the power required because of its simplicity, reliability, readily available circuit hardware and control devices, and its lowest cost.

6.3 FREQUENCY

AC frequencies other than 60 cps were considered. For frequencies above 60 cps, the total impedance increases with frequency. This increase in impedance will result in a larger and heavier cable for a given power level, distance, and regulation, in addition to the requirement for frequency conversion equipment. Therefore, transmission frequencies greater than 60 cps were not considered. For frequencies below 60 cps the total impedance decreases, and the limit is the DC resistance at zero frequency, i.e., DC transmission. The use of frequencies other than 60 cps requires frequency conversion equipment at the station as well as within the load module, or components and equipment within the load module must be designed to operate at the transmission frequency. Lights will flicker at frequencies of 15 or 25 cycles; motors, air conditioners, and similar equipment are not normally available in frequencies other than 60 cycle. Therefore, a frequency converter must be added to the load module as part of the secondary distribution system. Frequency conversion equipment for the 300 to 3000 KW loads is not normally produced. For the smaller loads (30 and 100 KW), the added cost of the hull to house the converter and the additional costs in the protection system are greater than the savings associated with the cable system should a lower frequency be utilized. Consequently, for the moderate length transmission systems, a 60 cps transmission frequency was selected.

6.4 VOLTAGE REGULATION

The loads envisioned for the load module require a voltage variation limit of plus or minus 5 percent to be usable for all general purpose equipment without the need for additional equipment to produce required regulation. Voltage variations which exceed these limits can cause damage to electrical equipment such as lamps, motors, and environmental control equipment. All of these units are designed to operate at a specific voltage. The performance and efficiency of the device is adversely

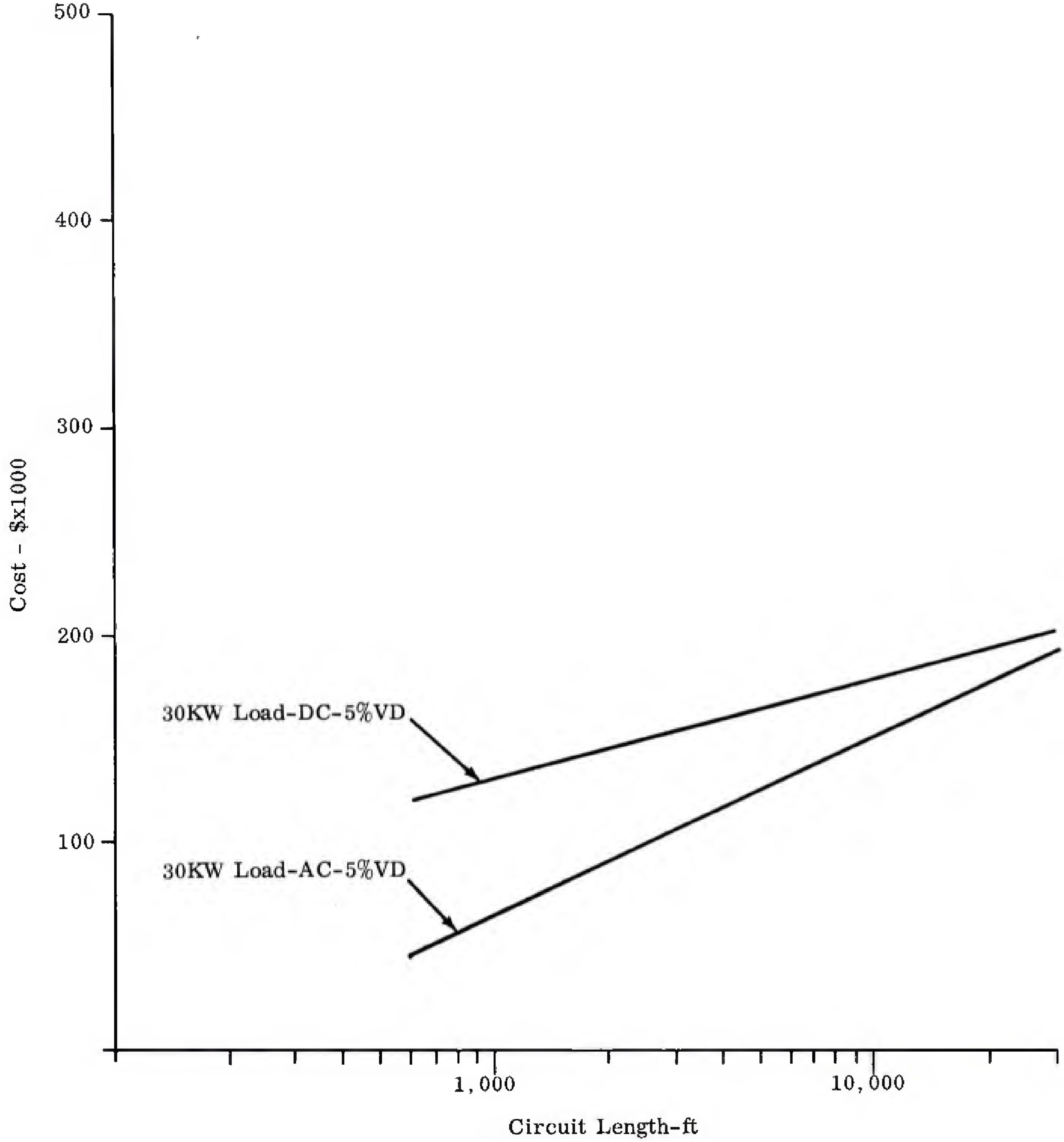


Figure 6-1. Cost Comparison, AC vs DC at 600 Volts

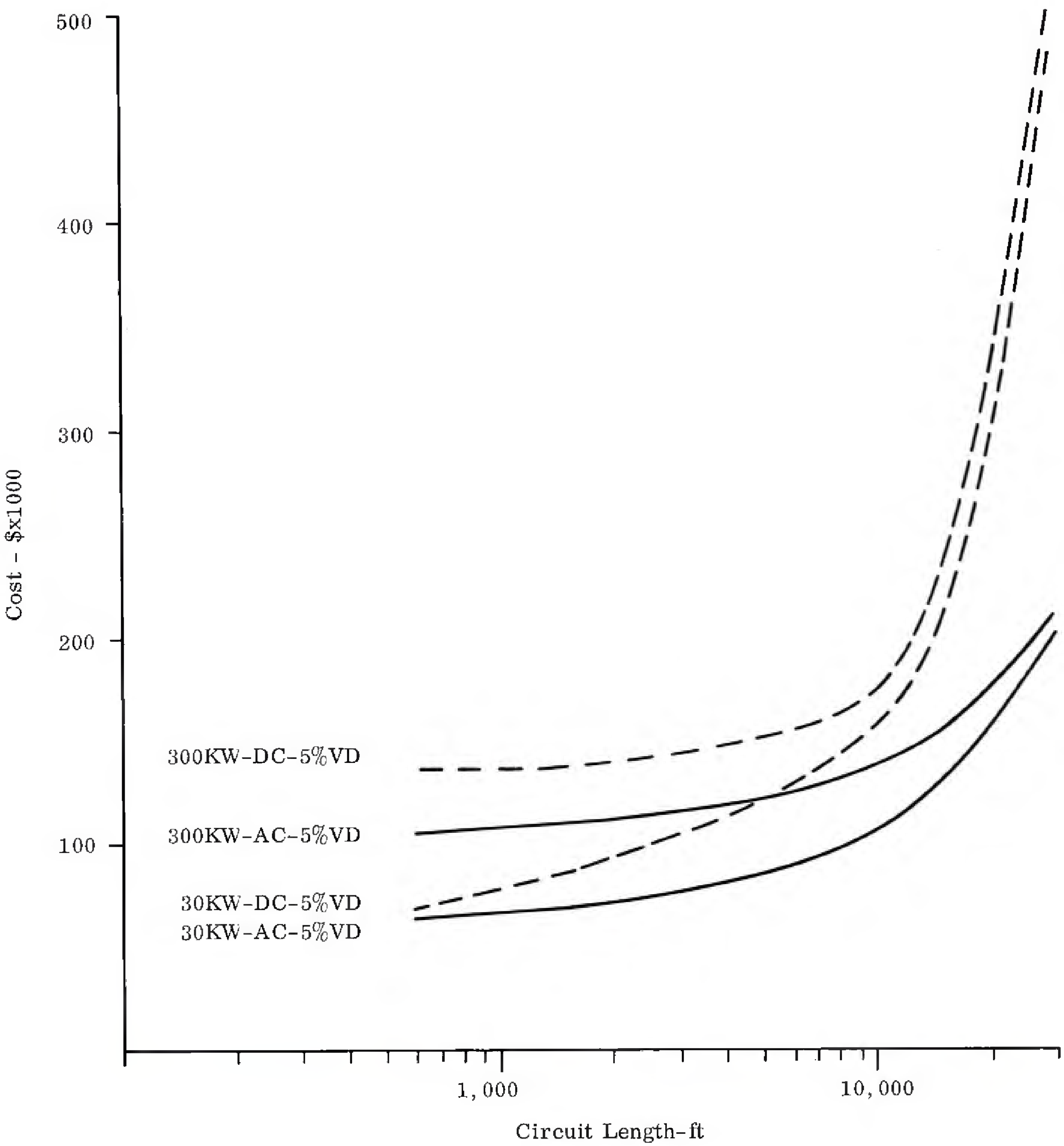


Figure 6-2. Cost Comparison, AC vs DC at 2400 Volts

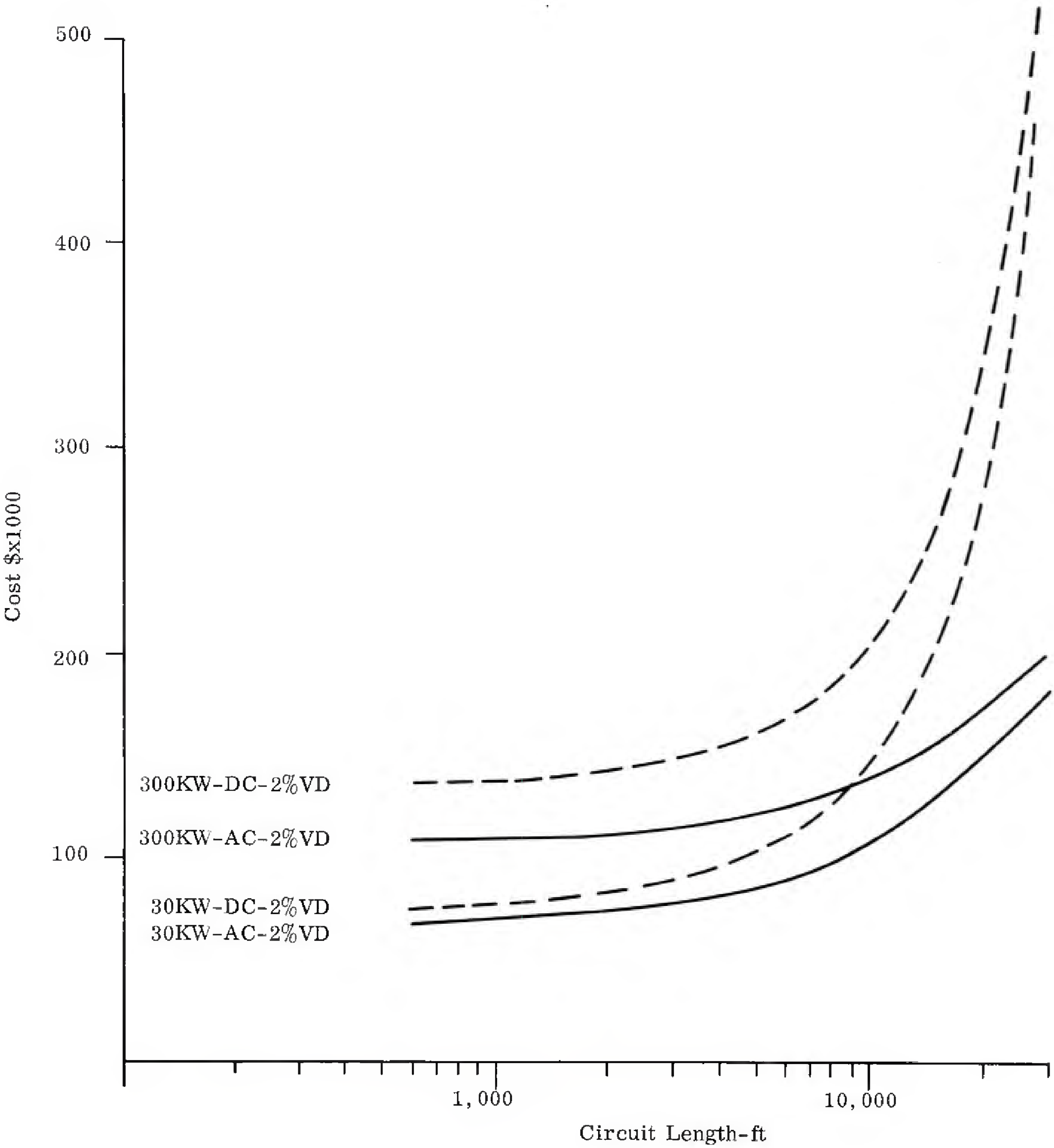


Figure 6-3. Cost Comparison, AC vs DC at 4160 Volts

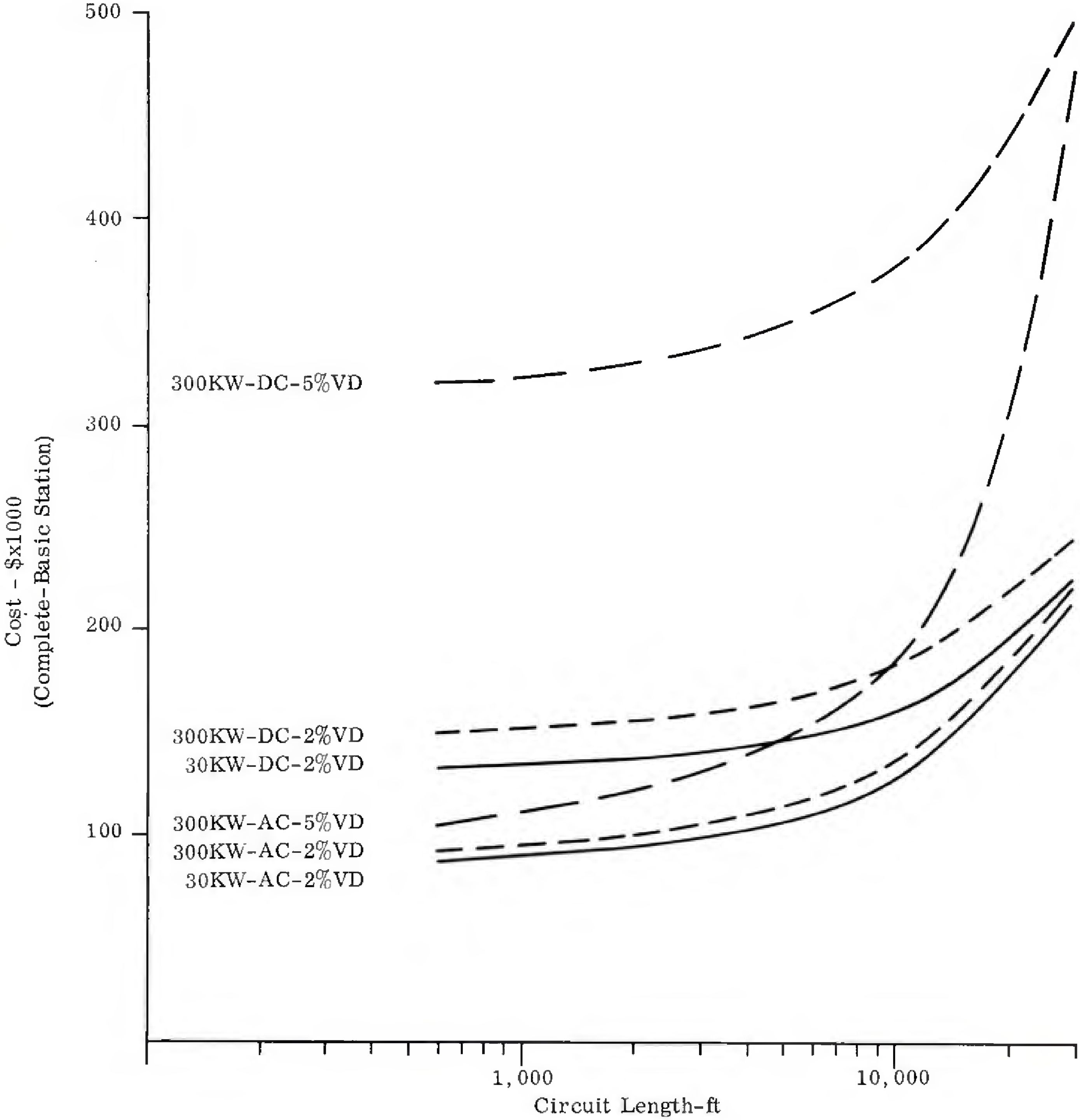


Figure 6-4. Cost Comparison, AC vs DC at 13,800 Volts

affected if connected to a circuit with lower or higher voltage fluctuation than the design value. For example, an incandescent lamp is extremely sensitive to low voltage. For a one percent voltage drop, the light output of the lamp is reduced three percent. For a five percent voltage drop, the output is reduced 16 percent. A pump motor which experiences low voltage will overheat or trip out due to high current. The starting torque of an induction motor is proportional to the square of the impressed voltage. High current also causes temperatures to increase within the equipment with subsequent reduction in operating life.

Voltage within the load module can be regulated either by adding voltage regulation equipment within the load module or by designing the electrical transmission system to a maximum of 5 percent voltage drop. In the case of constant power demand over the entire life of the system, voltage regulation equipment can be added to the power source location. It is understood that the constraint is for constant power demand. However, for selecting the proper voltage regulation, this criterion is not practical since any load module will have an average load and a peak load and these may vary as much as 50 percent. The allowable voltage drop for a circuit depends on the required regulation and/or the ampacity of the cable. Increasing the allowable voltage drop will permit the use of a smaller cable for the same power level and distance.

However, the minimum cable size depends on the power level, since the cable must be capable of carrying the full rated current. For example, for 3000 KW at 6000 ft at a transmission voltage of 4160, a 5 percent voltage drop requires a 3/0 cable; however, a 3/0 cable does not have the required ampacity and a 300 MCM cable must be used.

Table 6-I indicates the minimum standard cable size for each power level under consideration at various transmission voltages from 480 to 13, 800 volts AC; the cable size is based on ampacity only.

Table 6-I. Minimum Cable Size at Power Levels and Voltages

POWER LEVEL	VOLTS				
(kilowatts)	480	600	2,400	4,160	13, 800
30	6	6	6	6	6
100	4	6	6	6	6
300	4/0	3/0	6	6	6
1000	*	*	1/0	4	6
3000	*	*	750	300	4

*Greater than a 1000 MCM.

The selection of either of the two methods of achieving the voltage regulation involves a tradeoff of the savings in the cable system versus the costs of the voltage regulation equipment, the cost of the hull required to house the additional equipment, and the costs of larger generating equipment required to meet the added losses. One type of voltage regulation equipment which could be added to the load module is a load-tap-changing transformer. However, for the loads required and the voltages considered, these units would have to be specially engineered and are not presently available. In addition, load-tap -changing equipment requires periodic inspection and maintenance to ensure trouble-free service; this would place an undue burden on the load module. Regulation equipment of the type required must operate under load, which causes a safety hazard due to sparking or requires an oil bath, which increases weight and volume, thus increasing load module cost.

The voltage regulation system selected was to limit the voltage drop in the cable system to 5 percent. The selection was based on the apparent cost savings, the reduction in equipment necessary to provide the required regulation at the load module, and increased reliability. This system will provide more utility in general purpose application and can be adapted easily to extreme variations in load demand.

6.5 PHASES

The choice between single-phase and polyphase (three phase) power is based on the power demand, equipment availability, reliability, and losses.

In a single-phase circuit,the power delivered is pulsating, and when the current and voltage are in phase (unity power factor), zero power is delivered twice in each cycle. When the power factor is less than unity, the power is zero four times in each cycle and is negative during two periods in each cycle, causing the circuit to return energy to the generator for a portion of the time.

The same pulsations take place in a three-phase (or polyphase) system in each of the phases, but each equivalent single-phase circuit in a three-phase circuit is separated by 120 electrical degrees. Consequently, as one phase is delivering zero power or returning power, the other two are supplying the power requirements. This results in constant level of delivered power. Line losses are greater for the same power in a single-phase circuit than in a three-phase circuit, and three-phase circuits may be as much as 40 percent more efficient. Conductor weight is less in three-phase systems for the same power and distance.

Three-phase systems were selected for underwater power transmission systems because of their better performance and lower weight. Three-phase systems offer the additional advantage of increased reliability, since single-phase power may be obtained from one phase of a polyphase system.

6.6 TRANSMISSION VOLTAGE

The previous paragraphs have described some of the electrical characteristics suitable for moderate cable length transmission systems, including 60 cps, 3 phase AC with a 5 percent voltage drop, producing 480 volt, 3 phase, 60 cps usable power at the load module. Transmission voltage is the one electrical characteristic remaining to be resolved. This electrical characteristic is perhaps the most significant in that variations in transmission voltage will produce the most variation in basic electrical system costs and versatility.

Incremental transmission voltages of 480, 600, 2400, 4160 and 13, 800 volts were considered appropriate for the study in conjunction with moderate length transmission cables. Higher transmission voltages were only considered appropriate for long length transmission cables in excess of 10 miles. (see paragraph 6. 10).

At the voltages listed above, the minimum wire size was selected based on the ampacity of the conductor size selected within the limitations of maximum temperature rise and based on the plus-or-minus 5 percent voltage regulation specified in paragraph 6. 4. For each transmission voltage, the basic electrical system components and equipment were added to the cable, and the total acquisition cost was compared for each possible combination of transmission voltage, power level and distance. Electrical components considered in this analysis include primary and secondary transformers and switchgear of assumed equal reliability. Acquisition cost was used in this tradeoff on the assumption that engineering and construction costs would be approximately equal regardless of the voltage selected.

6. 6. 1 Voltage Regulation Limits

The 5 percent maximum voltage drop in the transmission cable to produce the required voltage regulation limited the cost analysis of the appropriate voltages. The lower voltages were predominantly limited by the voltage regulation requirement; only 13, 800 volts could satisfy all of the power levels and distances under study. Table 6-II indicates the various cut-off points of voltage as a function of power level and distance while not exceeding the 5 percent voltage drop. Tables 6-III through 6-VII indicate the minimum cable size for each voltage, power level, and distance, which falls within the ampacity rating of the cable and meets the voltage regulation requirement, and the voltage stress limitations.

Table 6-II Incremental Cable Distance for 5 percent Voltage Drop

POWER LEVEL	VOLTS				
(kilowatts)	480	600	2400	4160	13, 800
30	20, 000 ft	30, 000 ft	30, 000+ ft	30, 000+ ft	30, 000+ ft
100	6, 000	6, 000	30, 000+	30, 000+	30, 000+
300	2, 000	2, 000	30, 000	30, 000+	30, 000+
1000	--	--	15, 000	30, 000+	30, 000+
3000	--	--	2, 000	15, 000	30, 000+

Table 6-III Cable Size Required @ 480 Volts

POWER LEVEL (kilowatts)	DISTANCE (FT) 600	1000	2000	6000	10, 000	15, 000	20, 000	30, 000
30	6	6	4	2/0	4/0	400	750	*
100	4	2	3/0	750	*	*	*	*
300	4/0	4/0	1000	*	*	*	*	*
1000	**	**	**	**	**	**	**	**
3000	**	**	**	**	**	**	**	**

* Limited by voltage drop
** Limited by ampacity

Table 6-IV Cable Size Required @ 600 Volts

POWER LEVEL (kilowatts)	DISTANCE (FT) 600	1000	2000	6000	10, 000	15, 000	20, 000	30, 000
30	6	6	6	1/0	2/0	4/0	300	750
100	6	4	1/0	350	*	*	*	*
300	3/0	3/0	350	*	*	*	*	*
1000	**	**	**	**	**	**	**	**
3000	**	**	**	**	**	**	**	**

* Limited by voltage drop
** Limited by ampacity

Table 6-V Cable Size Required @ 2400 Volts

POWER LEVEL (kilowatts)	DISTANCE (FT) 600	1000	2000	6000	10, 000	15, 000	20, 000	30, 000
30	6	6	6	6	6	6	6	6
100	6	6	6	6	6	4	2	1/0
300	6	6	6	2	1/0	2/0	4/0	300
1000	1/0 ***	1/0 ***	1/0 ***	3/0	350	1000	*	*
3000	750 ***	750 ***	750 ***	*	*	*	*	*

* Limited by voltage drop
*** Based on ampacity

Table 6-VI Cable Size Required @ 4160 Volts

POWER LEVEL (kilowatts)	DISTANCE (FT) 600	1000	2000	6000	10,000	15,000	20,000	30,000
30	6	6	6	6	6	6	6	6
100	6	6	6	6	6	6	6	6
300	6	6	6	6	6	4	2	1/0
1000	4 ***	4 ***	4 ***	2	1/0	2/0	4/0	350
3000	300 ***	300 ***	300 ***	300	350	1000	*	*

* Limited by voltage drop
*** Based on ampacity

Table 6-VII Cable Size Required @ 13,800 Volts

POWER LEVEL (kilowatts)	DISTANCE (FT) 600	1000	2000	6000	10,000	15,000	20,000	30,000
30	2	2	2	2	2	2	2	2
100	2	2	2	2	2	2	2	2
300	2	2	2	2	2	2	2	2
1000	2	2	2	2	2	2	2	2
3000	2	2	2	2	2	2	2	1/0*

*Based on voltage drop
All others based on voltage stress

6.6.2 Connector Limitations

The severly limited availability of connectors with respect to voltage and pin sizes of the type discussed in paragraph 5.5 was considered in the selection of the most cost effective transmission voltage. Wet connectors suitable for underwater mating are nonexistent for power systems and a limited number of dry connectors are available for power transmission systems. The pin sizes for the connectors for each voltage, cable length, and power level under consideration must be capable of mating with and carrying the amperage of the conductor sizes defined in Tables 6-III to 6-VII. Therefore, the selected systems will be heavily dependent upon the recommended development program outlined in paragraph 11.1 of this report. Table 6-VIII indicates the connector availability within the state-of-the-art levels suggested in Figure 5-7 as a function of the power levels, voltages, and cable sizes under consideration.

Table 6-VIII. Connector Pin Size Availability

POWER LEVEL	VOLTS				
(kilowatts)	480	600	2400	4160	13,800
30	*	*	**	**	***
100	*	*	**	**	***
300	***	***	**	**	***
1000	-	-	***	**	***
3000	-	-	***	***	***

* Available
** Technology available, requires engineering
*** Requires development

To further limit the scope of the connector development program, a study of the effects of combining the secondary transformation equipment with the load module was performed to eliminate secondary hulls and power connectors between the hull containing the secondary transformation and distribution systems and the load module. Considering the constraint of producing 480-volt, 3-phase, 60-cps power to the load module regardless of transmitted voltage, an additional set of connectors rated at 480 volts and capable of handling power levels of 30 KW to 3000 KW is required. Table 6-IX depicts the connector pin sizes for the intermediate transmission of power at the required 480 volts to the load module. The maximum pin size available within the state-of-the-art boundary defined in Figure 5-7 is 1/0 at 4160 volts. Power levels of 1000 KW at lengths greater than 10,000 feet and 3000 KW at lengths greater than 600 feet could not be obtained. An alternate method to satisfy the requirement for usable power at 480 volts is to use multiple parallel cables for preliminary load istribution from the surface to the load module. Table 6-X indicates the number of 3-pin connectors required that use state-of-the-art connectors. The table shows the impracticability of this alternate approach.

Table 6-IX. Required Pin Size @ 480 Volts Nominal, 3-Phase, 60 Cps

POWER (KW)	PIN SIZE (A.W.G or MCM)
30	6
100	4
300	4/0
1000	1750 MCM
3000	>5000 MCM

Table 6-X. Number of Connectors with AWG 1/0 Pin Size

POWER (KW)	DEPTH (FT)							
	600	1000	2000	6000	10,000	15,000	20,000	30,000
1000	1	1	1	1	1	2	2	3
3000	3	3	3	3	3	4	5	8

NOTE: The number shown is the connectors required at each termination point.

Considering the factors discussed above, plus the added cost of a pressure hull to house the secondary transformation equipment, it is most cost effective to transmit the higher voltages directly to the load module. Therefore, certain minimum weight and volume requirements are required of the load module to house this equipment. This conclusion is further justified, for the higher power levels may operate more effectively at voltages in excess of 480 volts.

6.6.3 Electrical Acquisition Costs

The analysis of the acquisition cost of the basic electrical system versus transmission voltage can exclude the cost of low-voltage connectors, hulls to contain the secondary transformation equipment, and other related costs of transmission cable connections to the load module. Table 6-XI indicates the results of this analysis, including the acquisition costs of cable and equipment as specified by applicable manufacturers. Costs of engineering, packaging, and protective circuits are not included as they are considered to be constant for this analysis.

Table 6-XI indicates that minimum costs occur at moderate voltages. On this basis voltage selection can be based on costs for electrical characteristics. Generally the lower voltages created low costs for transformer and switchgear but higher cable costs due to larger sizes required. The higher voltages created higher equipment costs but subsequently reduced cable costs. The length of cable affected only cable costs.Theoretically, this should be a linear increase, but is modified by larger cable size due to the cost of maintaining the 5 percent drop voltage regulation, and ampacity.

Table 6-XI. Electrical Power Equipment Cost ($K) vs. Distance

VOLTAGE (volts)	POWER LEVEL (kw)	DISTANCE (FT) 600	1000	2000	6000	10,000	15,000	20,000	30,000
480	30	50.8	52.2	57.5	90.9	127.9	241.8	435	
	100	50.8	53.5	64.1	164				
	300	53.4	57	94.9					
	1000								
	3000								
600	30	52.0	53.7	57.8	87.7	121	184.3	195.5	629.5
	100	53.5	55.7	63.8	122.7				
	300	61.5	65.1	80.9					
	1000								
	3000								
2400	30	84	85.7	89.8	106.5	123.1	143.9	164.7	206.3
	100	85.5	87.2	91.3	108	124.6	153.8	192.3	274
	300	91.5	93.2	97.3	121.8	153	198.3	268.6	417
	1000	100.8	103.4	109.8	145.2	216.5	448		
	3000	121.6	129.4	148.7					
4160	30	84	85.7	89.8	106.5	123.1	143.9	164.7	206.3
	100	85.5	87.2	91.3	108	124.6	145.4	166.2	207.8
	300	91.5	93.2	97.3	114	143.7	151.4	192.3	280
	1000	99.8	101.7	106.5	129.8	160.7	206.3	276.6	336
	3000	115.6	121	131.9	175.7	229.5	461		
13800	30	106.7	109	114.3	135.8	157.3	184.3	211.2	264.5
	100	108.2	110.5	115.8	137.3	158.8	185.8	212.7	276
	300	114.2	116.5	121.8	143.3	162.8	191.8	218.7	277
	1000	122.2	124.5	129.8	151.3	172.8	199.8	226.7	280
	3000	135.6	138.1	144.1	168.3	175.5	216.8	252.3	373.8

6.6.4 Cable Support Acquisition Cost

From the cable analysis presented in Chapter 5 of this report, it is concluded that the selection of the transmission voltage must consider the cost of the electrical power equipment costs and the cable support system costs.

The cost of the cable support system is a direct function of the size of the cable and its overall length. This favors the selection of higher voltages to reduce cable size. A combination of cable support system acquisition costs defines the cost effective transmission voltage for systems having moderate cable length. To further restrain the variables, the permanent cable support system for vertical installation developed in paragraph 5.6. will be considered for acquisition costs. Tables 6-XII and 6-XIII indicate the cable support acquisition costs for the various power levels and distances as a function of voltage. Table 6-XII shows costs based on the use of 30,000-psi armor, and Table 6-XIII is based on 125,000-psi armor. Not all of the possible combinations are shown in these tables. This was done to limit the total amount of data to be carried forward to the overall system evaluation. This reduction in data was accomplished on the assumption that suspension system cost for a given depth is proportional to wire size and, therefore, cable weight. Therefore, Table 6-XII and 6-XIII do not show any power level and distance combinations for which the basic electrical-transmission-system cost (Table 6-XI) is much higher for a larger wire size, since the disparity will be even greater when the suspension system cost is added. For cable distances of 600 ft to 2000 ft inclusive, the cost of the suspension system is not fully dependent on the weight of the cable alone but on the additional requirements for a buoyant support to maintain the cable in a vertical water column in order to keep the cable from abraiding on the bottom. In this range of cable distances, the tooling and fabrication costs predominate. Therefore, a constant cost has been assigned to the cable suspension systems regardless of cable weight.

Table 6-XII shows the total cost of the cable suspension system for each acceptable combination of power level, transmission voltage, and cable distance, based on 30,000-psi armor.

Increasing the armor strength materially affects the cost picture for the suspension systems (See Table 6-XIII). The use of 125,000-psi armor (based on a safety factor of 2 for 250,000-psi armor) gives a load capability of four times that of the cable assumed in paragraph 5.6, with a negligible increase in cable weight. Its raw material cost is approximately double that of the 30,000-psi armor. In spite of this there is a net cost reduction due to the fact that, while the suspension system loads remain the same (cable weight remains the same and the surface unit can absorb no more load), the buoyancy units can be moved to shallower depths, thus making them less expensive. Therefore, since increasing the armor strength increases the cost

Table 6-XII. Cable Support System Acquisition Cost
(Based on 30, 000-psi Armor)

VOLTAGE	POWER LEVEL	600	1000	2000	6000	10, 000	15, 000	20, 000	30, 000
480	30	48	48	48					
	100	48	48						
	300	48	48						
	1000								
	3000								
600	30	48	48	48	56	119			
	100	48	48	54					
	300	48	48	58					
	1000								
	3000								
2400	30	48	48	48	50	60	218	360	527
	100	48	48	48	50	60	222	406	803
	300	48	48	48	54	63	248	734	
	1000	48							
	3000								
4160	30	48	48	48	50	60	218	360	527
	100	48	48	48	50	60	218	360	527
	300	48	48	48	50	60	222	406	803
	1000	48	48	49	51	63	248	773	1678
	3000	48	48	57	59				
13800	30	48	48	49	51	61	222	370	570
	100	48	48	49	51	61	222	370	570
	300	48	48	49	51	61	222	370	570
	1000	48	48	49	51	61	222	370	570
	3000	48	48	49	54	62	226	462	1039

Table 6-XIII. Cable Support System Acquisition Cost
(Based on 125, 000-psi Armor)

VOLTAGE	POWER LEVEL	600	1000	2000	6000	10, 000	15, 000	20, 000	30, 000
480	30	49	49						
	100	49	49						
	300	49	49						
	1000								
	3000								
600	30	49	49	49	58	74.3			
	100	49	49	55					
	300	49	49	59					
	1000								
	3000								
2400	30	49	49	49	52	67	62.5	104	241
	100	49	49	49	52	67	87	214	291
	300	49	49	49	56	71.9	168.5	280	
	1000								
	3000								
4160	30	49	49	49	52	67	62.5	104	241
	100	49	49	49	52	67	62.5	104	241
	300	49	49	49	52	67	87	214	291
	1000	49	49	50	56	71.9	168.5	280	630
	3000	49	49	57	62				
13800	30	49	49	50	54	69	78	176	252
	100	49	49	50	54	69	78	176	252
	300	49	49	50	54	69	78	176	252
	1000	49	49	50	54	69	78	176	252
	3000	49	49	52	56	71	151.5	192	341

effectiveness of the total system, the added cost of the armor should not be assigned to the cable itself, but should be considered in the study of the support system, therefore, the most cost-effective transmission voltages in terms of the cable support system were selected considering the cost of the 30, 000 psi armor for cable distances of 600 ft through 10, 000 ft (Table 6-XII) and the 125, 000 psi armor for cable distances of 15, 000 ft and longer (Table 6-XIII).

6.6.5 Selected Transmission Voltage

By comparing the support system acquisition costs from Tables 6-XII and 6-XIII with the electrical equipment acquisition costs from Table 6-XI, the transmission voltages for moderate cable lengths can be selected for each matrix point involving the parameters of power level and distance. These selected voltages are shown in Table 6-XIV.

Table 6-XIV. Selected Transmission Voltages

POWER LEVEL (KW)	600	1000	2000	6000	10, 000	15, 000	20, 000	30, 000 FT
30	480	480	480	600	4160	4160	4160	4160
100	480	480	600	4160	4160	4160	4160	4160
300	480	480	600	4160	4160	4160	13800	13800
1000	4160	4160	4160	4160	4160	13800	13800	13800
3000	4160	4160	4160	13800	13800	13800	13800	13800

6.6.6 Recommended General Utility Transmission Voltage

It is impractical for general utility purposes to select a transmission voltage different for each power level and distance. For missions requiring long term usage at a particular power level and installation, the conditions described in Table 6-XIV would be acceptable. However, for general utility, a block of power level conditions at various distances can be selected and satisfied by one or two particular transmission systems. This approach eases the logistics problems associated with spare parts and maintenance and potentially provides for cost reductions through multiple procurement techniques. The recommended variations are discussed in Chapter 9.

6.7 PROTECTION SYSTEM CONCEPTS

The protection of electrical systems can be extremely complex, depending primarily on the general approach used and the initial constraints established. For this study, the constraint was established that the protection system was to be designed to protect the electrical power transmission system but not to protect the load module devices or provide for the specific safety needs established for the mission. Furthermore, all emergency power and other control techniques were not expanded to include load module demands. This constraint was established because the load module is to be designed to meet specific mission requirements including necessary safety devices, reliability, and other special needs of the mission.

The protection system approach adopted is functionally depicted in Figure 6-5 and is shown schematically in Figure 6-6. For faults within the generation area, such as bearing failure or generator or prime mover failure, it has been determined to shut down the station. All other faults, on the transmission line or at the load module, are referred to the one main breaker at the generation station for fault isolation. This breaker is equipped with a circuit recloser for one, two or three reclosures before lockout to allow for transient conditions. With the main breaker tripped, the generator will be kept spinning until the recloser has either reclosed the breaker to pick up the load or has locked out. At the time the lock-out occurs, the generation system will also be tripped. If a fault occurs within the generation system or if the recloser locks out, the station shuts down and requires physical inspection to remove the fault and manual restart of the station.

The only other fault that shuts down the plant is complete loss of control power to the sensing devices.

The generating section uses standard differential and over-current relay protection.

However, the transmission line and load module faults will be referred by a carrier current scheme to the main breaker for fault isolation.

6.7.1 System Modes of Operation

Two modes of operation were considered for the protection system, namely, cascade and selective tripping. The selective system,as shown in Figure 6-7, was not considered beyond a preliminary stage because of the added weight and space requirements. The additional weight and volume impose an increased burden on the load module. Consideration was also given to providing an intermediate or terminal module to house the transformer and switchgear and transmit from this module to the load module at the required 480 volts, 3-phase. This too was abandoned, as discussed in paragraph 6.6.2.

This investigation resulted in the selection of the cascade system shown in Figure 6-8. In this system, a minimum weight and volume are imposed on the load module.

Faults for the proposed system are compensated for, up to and including the load transformer. It is therefore recommended that loads connected to the secondary of the load transformer be provided with adequate protection and that this protection include automatic, multiple stage reclosers. A recloser system is used to eliminate the need to shut down the plant for transient faults or voltage surges that may occur by providing the main circuit breaker and protection devices with several "looks" at the condition before shutting down the plant. Both the load protection and reclosing equipment will have to be coordinated with the transmission system for proper operation. This is to minimize the costly retrieval of the load module and eliminate the need to provide a facility for the transfer of personnel from a vehicle through a pressure lock to the load module to reset a critical breaker after a single outage. It is also recommended that the condition of all lock-out devices and load breakers be transmitted to an indicating panel at the generating station via the carrier to indicate the operating condition of the load module as shown in Figure 6-5.

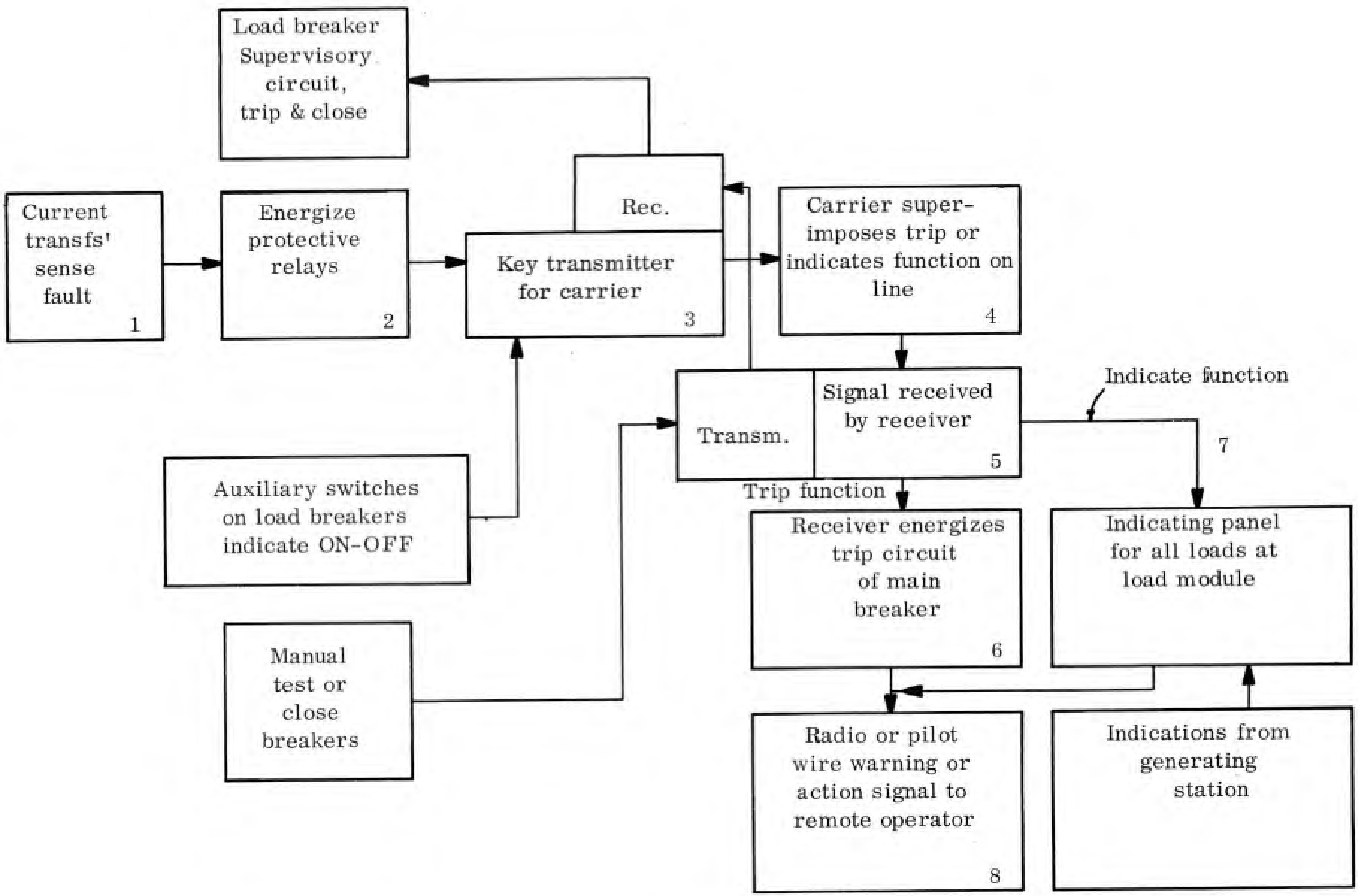


Figure 6-5. Logic Diagram for Operation of Load Module Relays and Carrier

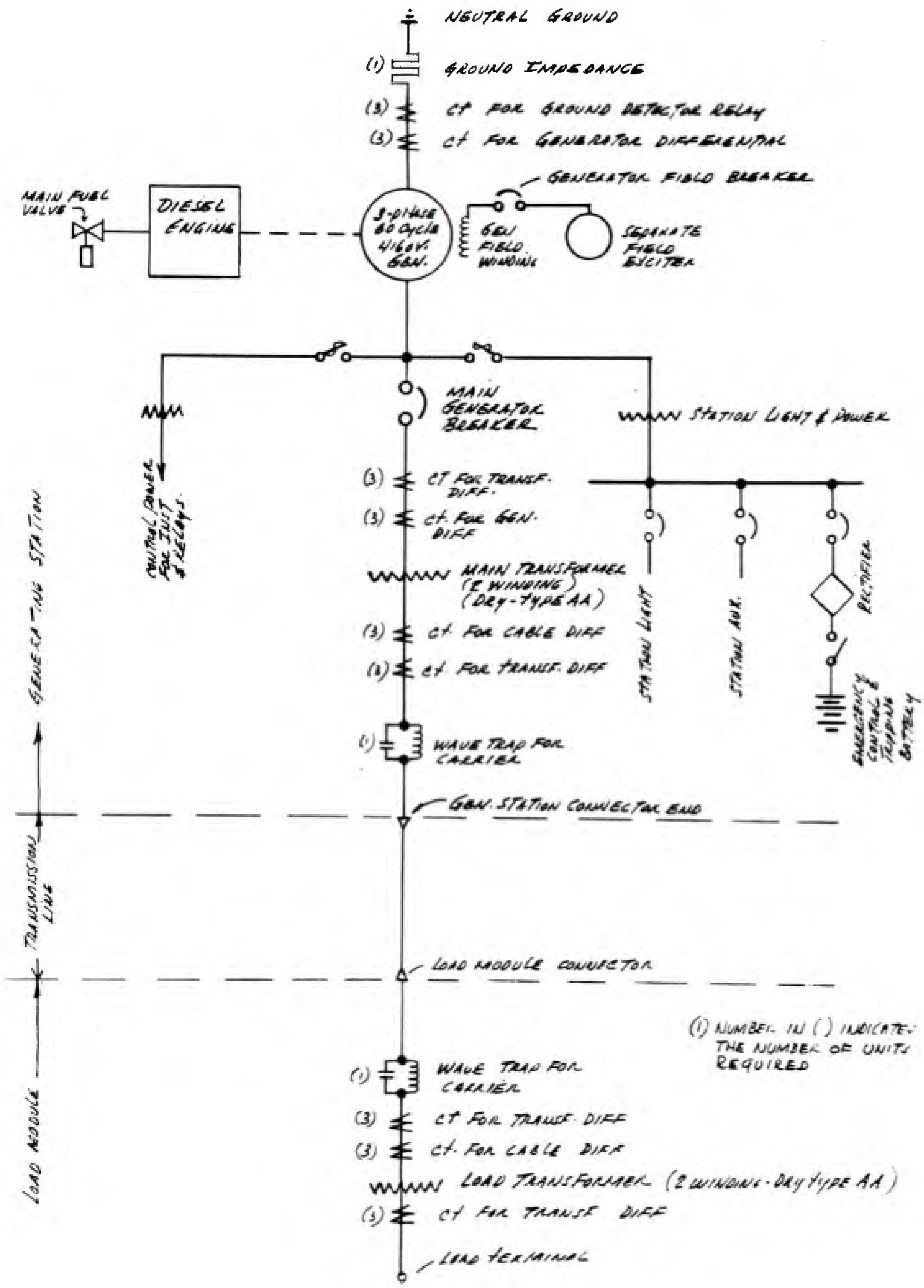


Figure 6-6. Schematic Diagram for Protection System

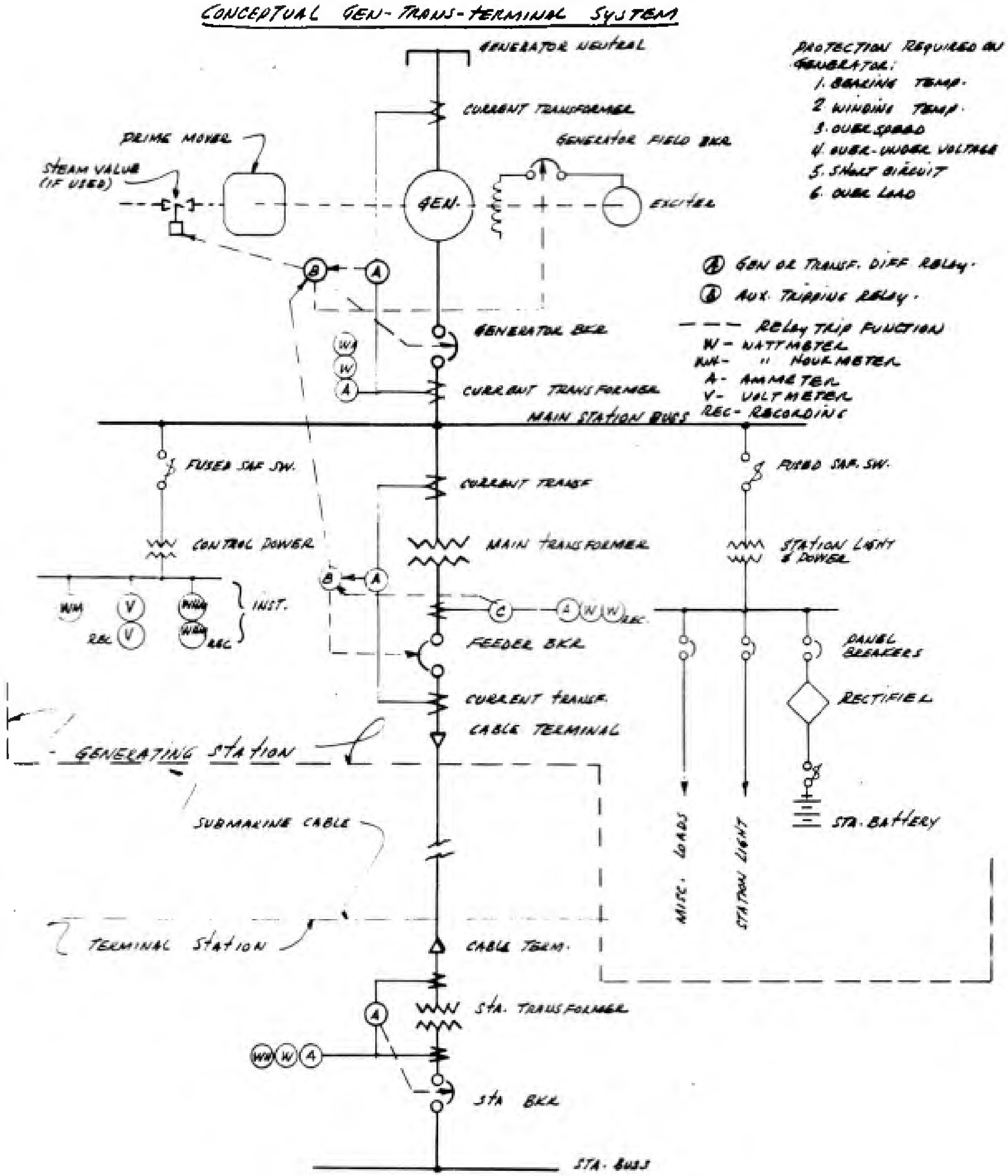


Figure 6-7. Selective Tripping System

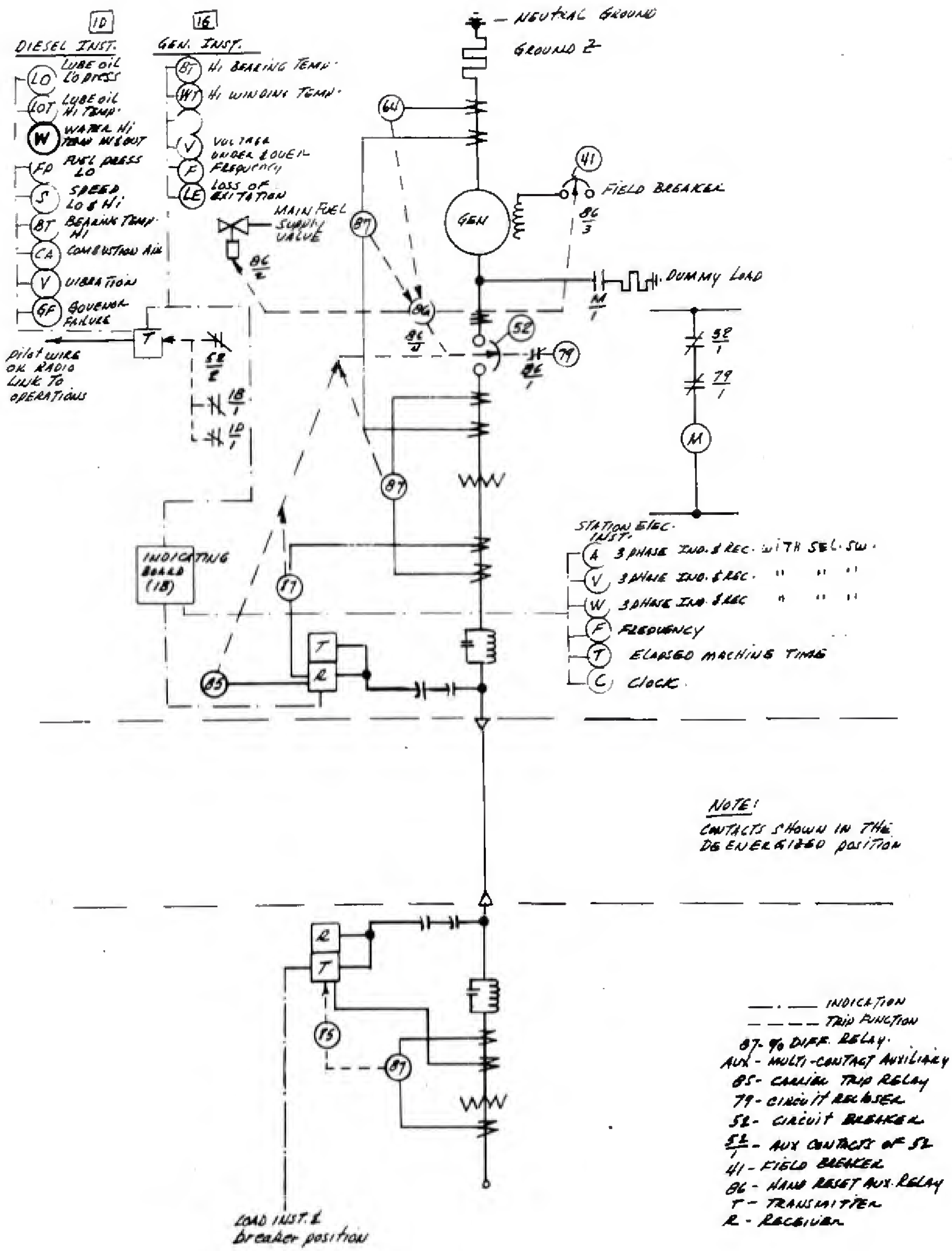


Figure 6-8. Functional Diagram of Cascade Protection System

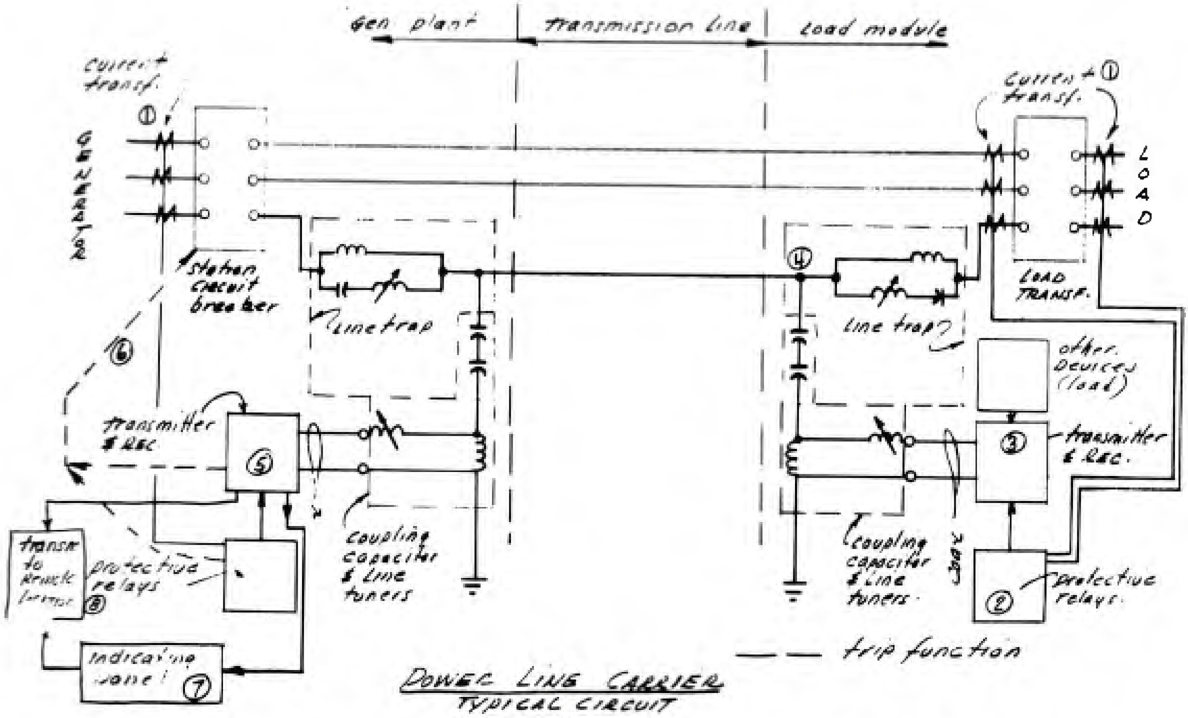
An unattended load module and generating plant as envisioned should have constant provision for displaying, for periodic inspection, the condition of the plant and its equipment. The inspector should also have available to him some method of control should he find by visual inspection of the indicating board that a breaker has tripped in the load module or generating station. At this point he may be able to determine if an actual fault has occurred, or, if he is able to close the breaker, that it was a transient condition. In addition, all trip functions and problem indicators, e.g., high water temperature, low lube oil, etc., should trip a trouble alarm which will energize a pilot wire or radio link from the generator station to some point where monitors are available. This, of course, depends on the nature of the mission and the type of load module, as well as its deployment area.

6.7.2 Operation and Configuration

A fault in the load module transformer is detected by sensors which energize a transformer differential relay. After a time delay to allow for transients, this relay closes its contact and in turn trips the carrier transmitter. This trip function is transmitted over the power line via a carrier to the generating station receiver, which in turn trips the generator breaker. In addition, signals are sent to the indicating panel to provide fault location information and status. The carrier portion of the protection system is shown in Figure 6-9. It is recommended that the differential relay be provided with an over current back-up relay as a precaution should the differential relay fail to operate for a fault.

In addition to providing a transfer trip function and indication, the carrier provides an overall differential circuit around the entire transmission line by connecting to the current transformers on the secondary side of the load transformer and the generator side of the cable terminal at the generator station. Any faults in the cable would be detected by this differential zone, trip a differential relay located at the generator plant, and, independent of the carrier, trip the main breaker.

The generating station will be provided with a generator differential and a station transformer differential relay. Faults detected by the transformer differential relay will trip the main breaker. The generator differential relay (after a time delay) trips an auxiliary relay, which in turn trips the field breaker, the main breaker, and the fuel valve to the diesel to shut down the plant. For faults outside the generator and diesel, the main breaker is tripped, but an automatic recloser is provided with multiple closures to reclose the breaker after several time delays to allow continued operation in the event that the fault has cleared.



POWER LINE CARRIER
TYPICAL CIRCUIT

System uses radio frequency energy coupled to the power line and operates in the 30 - 200 Kc range.

two types of operation are available:

1. ON - OFF
2. FREQUENCY SHIFT

line trap serves two functions:

1. reduces interference
2. prevents external faults from short circuiting the carrier on the protected line

two types of carrier available:

1. phase comparison
2. Directional comparison (for insufficient short circuit to trip phase relays)

NUMBERED BOXES OR EQUIPMENT REFERS TO THE SAME NUMBER ON LOGIC DIAGRAM 2.12

Figure 6-9. Power Line Carrier Typical Circuit

If the fault persists, the recloser goes to lockout and trips the auxiliary relay, which shuts the station down. If the fault has cleared, the main breaker closes and normal operation is resumed. The recloser is automatically reset at zero postion in preparation for the next multiple reclosures.

The generator neutral is grounded and provided with a fault detector relay as a supplement to the generator differential. In addition, the generator is provided with a bearing and winding temperature device as well as an electric tachometer. For an internal fault in the generator, diesel, or exciter, the main breaker recloser is bypassed.

It has already been indicated that the high voltage submarine cable and the generation system will have their neutrals grounded.

It remains then to define the grounding system as it applies to the circuit elements under consideration in this study.

The AIEL standard #32, Section 32-1.05 of May 1947, defines effective grounding as follows:

> "a system or portion of a system can be said to be effectively grounded when for all points on the system or specified portion thereof the ratio of zero-sequence reactance to positive-sequence reactance is not greater than 1 for any condition of operation and for any amount of generator capacity."

$$\frac{Xo}{X_1} \leq 3 \text{ and } \frac{Ro}{X_1} \leq 1.$$

There remains then, the selections of circuit elements, in consideration of the power level and length of transmission line, to provide the electrical characteristics within these parameters.

Redundancy has been kept to a minimum and appears only in the station control power system. Control power for relays, instruments and recorders is provided by a control power transformer which is connected between the generator and the first breaker. Regardless of the operation of the main breaker, the control power remains energized to ensure sensing power. However, should the main sensing power become inoperative for any reason, the system automatically switches to the emergency power source. On loss of both sources of power, the station shuts down.

The principal failure having catastrophic consequences is the loss of the power cable. This can be caused by marine attack, severe environmental conditions which cause loss of the mooring system and subsequent loss of the cable, damage by ships operating in the area, or other forms of impact. For these situations and a load module or mission requir ing a high reliability of power deliver, the in situ power source should be considered. Since any attempt of redundancy in the transmission system would not appreciably improve the reliability of the cable system. Since the failure of one of the redundant cables regardless of the cause will probably result in failure of all the cables. For example, if a load module is serviced from a shore-based power source with two independent transmission systems (cable) should a trawler cut one cable, the chances are it would cut both, since at each termination point the cables will be in close proximity to each other. The alternate of two dispersed underwater power transient systems serving the load module would preclude the selection of the two-systems on total cost comparison.

Based on the operating philosophy developed for the underwater power transmission systems, it is apparent that the loss of load must be compensated for when the main breaker trips. It has been determined to maintain the generator spinning until several reclosures have occurred and the fault has cleared. Normally, two or three reclosures are used in this application. A typical time scheme is for the first reclosure to be instantaneous, the second 15 to 45 seconds later and the third up to 120 seconds later.

For the period of loss of full load prior to the first reclosure (instantaneous), the inertia of the diesel and generator is sufficient to carry the unit through. However, if the first reclosure closes the breaker on a fault, and the breaker immediately trips again, there is a 15- to 45-second period before second reclosure, and the generator tends to overspeed and experience overvoltage. At this time the overspeed relay and/or over-voltage relay would normally operate to protect the machine. This is undesirable, since the generator should be kept spinning until the recloser has reestablished the circuit or has locked out. Therefore, an auxiliary switch on the main breaker is utilized to energize an automatic throw over switch which will provide the generator with a dummy load. At the second reclosure, an additional auxiliary switch may be energized to remove the dummy load just prior to reclosure, providing, of course, that the fault has cleared and the breaker holds in. The system, after a slight transient, returns to normal operation and the reclosure will automatically reset itself to zero.

The above sequence is predicated on either full or no load. When the final systems are selected, the operating cycle established and the load module defined, the function of relaying, recloser, and dummy load application will have to be further defined to include:

- the percentage of load that can be dropped and the minimum of dummy load required

- the exact time increment between reclosures and the number of reclosures
- method of discriminating between overspeed and over-voltage due to a fault or momentary load drop
- a diesel governor control and the speed and frequency variation allowable
- prime mover-generator inertia required to compensate for load variations with time.

The station has a power transformer which provides for station auxiliary services, including lighting, and a rectifier for maintaining the station battery at full charge. The battery provides emergency control power for relays, instruments and tripping power for the main circuit breaker.

The diesel engine has the following mechanical indicating and/or protective devices:

lube oil pressure

lube oil temperature

water temperature in and out (if water cooled)

fuel pressure

speed

bearing temperature

governor failure

vibration (as an added feature for an unattended station to detect rod knocks, etc.).

Indicating and protective devices are shown in Table 6-XV. This chart indicates the fault, probable cause, means of detection, protective device and operating procedure.

Instrumentation is provided to monitor the critical electrical and mechanical points. Recording instrumentation is provided for the major electrical quantities, such as frequency, voltage, watts and amperes, for establishing the station operating record from which a power profile may be determined.

All circuit interrupting devices (circuit breakers, fuses, switches, etc.) are capable of carrying full rated current continuously without exceeding temperature rise considerations and are capable of interrupting the maximum asymmetrical short circuit current experienced by the interrupting device. The asymmetrical current is approximately 1.14 percent higher than the symmetrical current.

6.8 TRANSFORMERS

Transformers were evaluated for all classes of voltage, size, weight, and method of cooling and were selected based on the most flexibility and reliability at the least cost

Table 6-XV. Indicating and Protective Devices

FAULT	PROBABLE CAUSE	MEANS OF DETECTION	PROTECTIVE DEVICE	OPERATION OF PROTECTIVE DEVICE TO GIVE ALARM	TO TRIP BKR.
	TRANSFORMERS				
Winding Hotspot	Hi ambient air Clogged air intake and/or outlet	Thermocouple	Thermal relay	$150^{o}C$	Long time delay
Short Circuit	Faulted windings or connections	Current and/or potential transformer	Transformer percentage differential relay with an over-current back-up and a residual ground		Short time delay
	TRANSMISSION LINES				
Short Circuit	Faulted cable and/or connecter	Current and/or potential transfer	Line differential zone with carrier coupling to the power line		Short time delay
Overload	Adding loads beyond design intent	Current transformer	Overload relay	@ 110%	@ 125%
	Intermittent short				
Overtemperature	Inconsistency in cable I^2R dielectric loss		Temperature	$60^{o}C$	
	Overload not high enough to trip overload	Thermal sensors			

Table 6-XV. Indicating and Protective Devices (Cont)

FAULT	GENERATOR PROBABLE CAUSE	MEANS OF DETECTION	PROTECTIVE DEVICE	OPERATION OF PROTECTIVE DEVICE TO GIVE ALARM	OPERATION OF PROTECTIVE DEVICE TO TRIP BKR.
Bearing Hi Temp.	Lo lube oil pressure Loss of lube oil Mechanical	Thermo sensitive bulb in contact with bearing or other	Thermal relay	$70^{o}C$	$96^{o}C+$
Winding Temp.	Hi ambient air Air inlet outlet blocked Short circuit Grounded phase Low power factor operation	Temperature detecting coils imbedded in windings and/or stator	Thermal delay	$80^{o}C$	$100^{o}C$
Loss of Excitation	Loss of field Exciter failure Field short	Potential transformer & cur-transformer	Exitation relays 1. Directional unit 2. Impedance unit 3. Instantaneous under voltage	Instantaneous	Time delay
Over Voltage	Loss of load	Potential transformer	Over voltage relay	> +5% in one second	> 10% Time delay

Table 6-XV. Indicating and Protective Devices (Cont)

FAULT	PROBABLE CAUSE	MEANS OF DETECTION	PROTECTIVE DEVICE	OPERATION OF PROTECTIVE DEVICE TO GIVE ALARM	OPERATION OF PROTECTIVE DEVICE TO TRIP BKR.
Under Voltage	Excess load Intermittent short Short circuit	Same as above	Under voltage relay	> -5% in one second	> 10% Time delay
Short Circuit	Winding ground or open Shorted windings	Current and potential transformers	Generator percentage differential relay with an overcurrent backup		Instantaneous
Field Ground	Winding insulation failure	d'Arsonval	Direct Current relay	Instantaneous	Time delay
Over Load	Load additions beyond design load Feeder faults	Current transformers	Overload relay Voltage controlled	> 110% rating	> 125% rating
Frequency	Low or high speed	On The Prime Mover			
Ground Fault	Phase to ground fault	Current transformer in neutral	Over current relay	Instantaneous	Time delay

to provide the needs of the proposed system with negligible maintenance. The dry, two-winding transformer, cooled by natural ambient air, was selected over the oil-filled type principally because of its lighter weight and smaller size. Transformers have the provision for primary and secondary voltage taps of plus 10 percent and minus 10 percent, in one-half percent increments. This flexibility allows for compensation of generator voltage variations while ensuring the delivery of the required 480-volt, 3-phase power supply to the load module distribution system.

6.8.1 Radio Frequency Interference

The term applies to electrical disturbances of a radio frequency which are commonly generated by the use of electrical equipment. The interference depends on the influence of the offending noise source, the coupling between the source and receiver, the susceptiveness of the receiver and the strength of the signal received.

When the mission is defined and final loads and equipment determined, the effect on RFI produced by the following components will be known:

1. generator-exciter
2. transformers
3. rectifiers-inverters
4. load break switches and circuit breakers

Knowing the quality and limits of the RFI produced by the above will determine the selection of communications systems and components that are compatible within these limits.

For example, the interference requirements and test limits for measurement and determination of the elctro-magnetic interference characteristics (emmision and susceptibility) of electronic, electrical and electro-magnetic devices is covered by Mil-STD-461, July 31, 1967.

The general requirements applicable to the design and construction of electronic equipment and associated and auxiliary electronic apparatus furnished as a part of a complete system intended for Naval ship or shore application is covered by MIL-E-16400 (Navy), February 24, 1966.

There are similar codes and standards for commercial and marine applications, covered by National Electric Manufacturers Association (NEMA), AIEEE, ASA and others.

6.8.2 Growth Potential in the Power System

The critical link in the whole system is the submarine cable since it carries all the power and communications from either a shore-based, surface-tendered, or in situ power facility to the load module. The cable having been sized in accordance with voltage drop considerations and ampacity (using standard sizes) of necessity dictated a larger size than actually required. This additional sizing and the fact that the termperature of the cable for ampacity selection was based on 40^{o}C. (when the environment ambient is in reality 20^{o}C.) allows additional latent capacity in the cable equal to approximately 10 percent or better.

The generation equipment has the ability by straight overload to provide additional capacity and if the machine is slightly "over-excited", will provide up to 10 percent additional continuous power.

Power switch gear, circuit breakers, and similar equipment was selected on the basis of the minimum size available in off-the-shelf items and has in most cases double the capacity required for the load module.

6.9 LIGHTING SYSTEM

The lighting system can be broken down to interior and exterior requirements. Since the station is to be unmanned, there is no requirement for interior lighting other than minimal from dockside to station prior to deployment.

In this case, final checkout is taking place on station prior to deployment. It is assumed that an operator is on board the load module while checkout is taking place and that normally the operation will take place during daylight hours. Provision will be made for minimal general illumination of the load module and adequate lighting at all control and instrumentation sections during final checkout. When final checkout has been accomplished, all interior lighting will be extinguished, except at the control console and here only if there is a requirement for telemetering T.V. pictures of the console back to the surface for immediate and contuous scanning.

Exterior lighting may be provided for periodic or continual observations of the bottom area of the load module during deployment and for observation of the landing site prior to final letdown. At other times, exterior lights may be provided for visual observation of the immediate area (up to 20 ft approximately) surrounding the load module.

In all cases of exterior lighting it is assumed that a T.V. camera or cameras will be appropriately placed for scanning the exterior areas, as required, and that the picture will be transmitted to the surface or shore-based plant for observation.

Interior lighting will be standard type meeting AN and other applicable specifications. Fixtures will be placed for maximum lighting efficiency and will derive their power from the station light and power transformer shown in Figure 6-6.

Exterior lighting, however, will require a knowledge of the mission, the type pictures required (i.e. black and white or color) and the area of final deployment. In this case, depending on the above, the following light sources are available for the depths anticipated:

	LAMP TYPE	COLOR LIGHT	LUMENS/WATTS
1.	mercury iodine	blueish	45
2.	high pressure sodium	gold-yellow	103
3.	dysprosium iodide	blue-white	80+
4.	phalium iodide	green	80+

The exterior lights, as with the interior, will derive their power from the station lighting system and is anticipated that the light units will be mounted on the exterior of the hull with exterior connectors to the inside power source. Connectors are discussed in paragraph 5.5. and Chapter 11.

In each case, interior and exterior lights may be turned on or off by an operator in either the surface buoy or shore-based plant by supervisory circuit over the carrier system.

6.9.1 Communications Systems

The main communication system for the load module consists of a carrier system, superimposed on the power cable as shown in logic diagram, Figure 6-5, functional diagram, Figure 6-8, and power line carrier circuit, Figure 6-9. It is the intent of this system to utilize the power cable for all communications and supervisory control between the load module and the surface buoy or shore-based power plant. The only other communication requirement envisioned is that required during tow from the dock-side to station and once on station for communication with the deployment vessels during final checkout--prior to deployment. In this case, certain suppositions are made:

1. tow to station and "on station" checkout accomplished during day light hours.
2. access hatch to load module is open
3. single communication circuit required

Under these conditions, a twin-conductor telephone line could be strung from the control deck of the load module - out the hatch and suspended to the two or moor line to the deployment ship. After final checkout is completed, and the load module system started and put on auto operation, the operator can disconnect the telephone line, and it can be retrieved back to the deployment ship.

An alternative method would be to provide an external telephone connector with an umbilical type connection to the deployment vessel. In this case, the operator leaves the module, closes the hatch, and disconnects the umbilical and it is retrieved by the deployment vessel. This system could be utilized later for external maintenance purposes when an "act connector" is developed.

6.10 MODIFICATIONS TO SUIT CLOSE COUPLED POWER SYSTEM AND LOAD MODULE

In the in situ facilities,the power module and load module will be separated by less than 100 ft. This conclusion is based on the fact that wet connectors do not exist. (Because of this, the load module and the power module must be electrically connected prior to emplacement.) However, the power source is suitable for remote emplacement and and can be adapted to suit longer cable lengths when connectors become available or if more complex emplacement techniques are acceptable for specific missions requiring remote in situ power sources. In this instance, the cable costs are insignificant when considering the costs to provide pressure hulls to house the generating equipment and load equipment. The tradeoff then will be in the size, weight, and volume of the pressure hulls. This, for all intents and purposes, is the variable cost element of the total cost. An increase in equipment will add size and weight to a module, requiring a larger hull, thereby increasing the cost.

6.10.1 Cable

Cable conductor sizes were selected based on the procedure and electrical characteristics developed in paragraph 5.2 and shown in Table 5-IV.

Each conductor was checked for adequate ampacity and voltage drop, although the latter in this instance is insignificant. The conductor sizes at each potential transmission voltage are shown in Table 6-XVII. In addition to these requirements, a limit is also imposed on the maximum size conductor, based on the limit of the cable connector. This was discussed fully in paragraph 5.5.

The cable selected is 3-conductor, stranded copper, shielded, grounded, polyethylene insulated, high strength galvanized steel armored, with each armor wire protected with a polyethylene jacket. The cable operates at the transmission voltage, 3-phase, 60 cycle. This is the same cable selected for the surface plant. Utilizing the same cable construction for each of the required systems--surface, land based and in situ--limits the procurement problem and, therefore, is more cost effective.

6.10.2 Electrical Characteristics

The advantage in weight and volume appears to be in the 480-volt transmission systems. This is apparent in that power can be generated and transmitted at the required voltage without the use of transformers. However, this advantage only holds true for load increments of 30, 100, and 300 KW. For loads of 1000 and 3000 KW, the 480-volt system is impractical. As can be seen in Table 6-XVI, a 1000 KW load at 480 volts would require 6 #1/0 conductors per phase, and a 3000-KW load at 480 volts would require 20 #1/0 conductors per phase to provide the necessary current carrying capacity (ampacity). Also, 480-volt generation equipment is not normally available beyond 1500 KW. Therefore, for the load requirements of 1000 and 3000 KW, the generated voltage (4160V) will be transmitted directly to the load module, terminating in the primary of a load transformer whose secondary provides the required 480-volt, 3-phase utilization voltage. Three #1/0 conductors will terminate in connectors at the load module and power module.

Therefore, for the selected systems, the power is 480 volt, 3-phase, 60 cycle for required loads of 30, 100 and 300 KW and 4160 volt, 3-phase, 60 cycle for required loads of 100 and 3000 KW. The conductor sizes required to meet the requirements of ampacity, voltage regulation, and the connector limits are shown in Table 6-XVII.

6.10.3 Protection and Control

The philosophy assumed for the design of the protection and control systems for the in situ power source is to maintain electrical power from the turbine-generator set as long as possible without causing damage to equipment. Therefore, the presence of a fault does not cause immediate shutdown. Shutdown occurs after verification of a permanent fault, as opposed to a transitory fault. Reclosures are provided for these verification. If the fault is permanent, the load module is electrically isolated from the power module. Then, the reactor goes through a controlled shutdown and power for the load module is derived from the battery for the life of the battery. For manned load modules, redundant controls are provided within the load module to enable fault detection and a remote start-up capability to enable mission continuation once the fault has been cleared.

If the assumption is made that an operator is not present in the load module to provide supervision, manual back-up, and corrective capability, there is no way to select or recommend a protection and control system. In an in situ facility, there is no external station to which notification of an operation or trip-out due to a fault can be referred. There is also no practical method by which an operator or inspector outside the system can be apprised of the proper functioning of the station.

Table 6-XVI. Circuit Requirements for Various Voltages and Loads for In-Situ Plant

LOAD (KW)	I_{FL}	VOLTAGE (Volts)	REQUIRED WIRE SIZE (B & S)	EQUIV. NO. OF #1/0 PER PHASE	NO. OF 3/C CABLES	NO. OF CONNECTORS
30	42.5	480	#6	---	1	2
100	142	480	#4	---	1	2
300	425	480	#4/0	2# 1/0	2	4
1000	1420	480	---	6# 1/0	6	12
3000	4250	480	---	20# 1/0	20	40
1000	284	4160	#4	---	1	2
3000	493	4160	300MCM	3# 1/0	3	6

Table 6-XVII. Ampacity Requirements for In Situ Plant

LOAD (KW)	VOLTAGE	AMPACITY REQ.	MINIMUM WIRE SIZE FOR 5% V.D.	MINIMUM WIRE SIZE FOR AMPACITY
30	480	42.5	#6	#6
	600	34.	#6	#6
	2400	8.5	#6	#6
	4160	4.93	#6	#6
	13800	1.48	#6	#6
100	480	142.	#6	#4
	600	113.4	#6	#6
	2400	28.4	#6	#6
	4160	16.4	#6	#6
	13800	4.93	#6	#6
300	480	425	#2	#4/0
	600	340	#6	#3/0
	2400	85	#6	#6
	4160	49.3	#6	#6
	13800	14.8	#6	#6
1000	480	1420	#1/0	N.G.
	600	1134	#2	N.G.
	2400	284	#6	#1/0
	4160	163.5	#6	#4
	13800	49.3	#6	#6
3000	480	4250	N.G.	N.G.
	600	3400	N.G.	N.G.
	2400	850	#6	750 MCM
	4160	493	#6	300 MCM
	13800	148	#6	#4

Since there is no place or method to send this information to a remote point, it is assumed that an operator is present to receive this intelligence and take corrective or substitute action to ensure, where possible, that the facility is maintained in an operable mode. It is cost effective to provide this type of operation and protection, since retrieval, replacement of components, and visits to plants of this nature are very costly.

There appear to be three methods of operation available:

- all switchgear, protective devices, and equipment to be located in the power module which would be provided with access from DSSV or DSRV type vehicle
- each module, the power and load, to have its own complement of equipment, switchgear, and controls with access from a DSSV or DSRV.
- protective devices, instrumentation, and main circuit breaker to be located in the power module with redundant protective and control devices located in the load module for manual back-up and corrective action performed by an operator.

Because of the philosophy developed and its inherent cost effectiveness, the latter mode of operation was selected and the protective system was tailored to it. There are several additional reasons for this choice:

- all three systems - land based, surface and in situ - will have similar methods of operation, thereby minimizing personnel training and development of operating techniques
- the load module probably will be similar to the power module.

The power module for all power ranges and depths contains the reactor, steam turbine and generator. As indicated previously, the only faults that would trip-out the generator are an internal electrical or mechanical failure monitored by the same mechanical instruments and generator differential protection used for the surface plant. The in situ transmission diagram is shown in Figure 6-10. The difference here is that only critical mechanical problems and electrical failure shut down the plant. In the surface plant the plant is shut down for any electrical or mechanical problem. The reason is that in a surface plant or land based plant, easy access for maintenance is provided, while access to an in situ facility is complex and expensive.

In the in situ plant, the generator differential relay disconnects the generator electrically by energizing relay 87, which,in turn,operates to energize auxiliary relay 86, and by tripping the main breaker and the exciter field breaker. It also energizes another auxiliary relay 86 located at the generator module. This second auxiliary relay 86 is energized to declutch the generator from the turbine provided that one path in the permissive circuit is energized, i.e., a mechanical failure has occurred which energizes a relay and closes its contacts, which are in the declutch trip circuit, allowing the declutching to take place. This operation is different from that of the surface

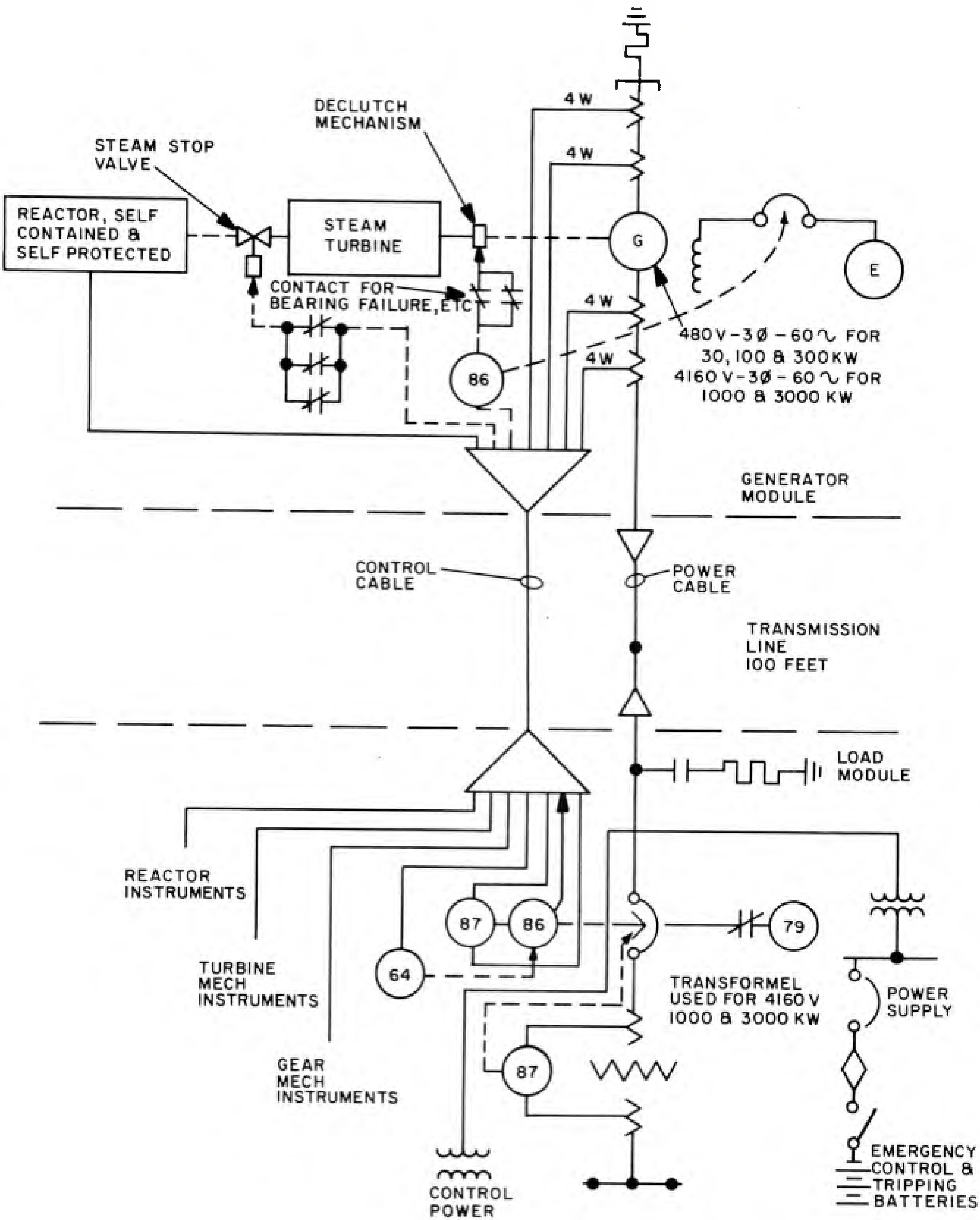


Figure 6-10. In Situ Transmission Diagram

plant explained in paragraph 6.7. In the in situ facilities, because of the complexity and cost to provide this same access, equipment should be kept in operation as long as practical and outages minimized.

Proper adaptation of the methods described in these paragraphs will achieve this compromise. In cases where turbine faults are present, such as bearing failure, loss of lube oil, etc., the turbine steam stop (or dump) valve will be actuated to remove power to the turbine. When the turbine is removed from service, the reactor component goes through an automatic, controlled shut down.

Therefore, to provide for the above operation and protection and the added back-up and manual control capability of an operator, all relays and instruments, main breaker and switchgear, and monitoring devices will be located in the power module. However, all functions and the ability to close or trip the main breaker will be carried back to the load module by a central cable. Trip functions, automatic or manual, from the load module to declutch mechanism, turbine dump valve, etc. may be transmitted to the power module by the control cable.

The load module contains all the elements indicated in paragraph 6.7 and shown in Figures 6-8 and 6-10. In addition, the following elements are also added to the load module for the in situ power systems:

- all reactor, turbine, and generator required operating instrumentation and the necessary control devices
- station light and power transformer and AC control power transformer

The load module protective system includes the load transformer differential circuit, which trips the main breaker only. The breaker is supplied with a multi-stage recloser to avoid tripping and locking out for transient conditions. The operation and typical timing cycles are the same as indicated for the surface plant in paragraph 6.7.2.

6.10.4 Other Modifications

All other paragraphs covering the general characteristics of distribution systems, interrupting devices, transformers, load module distribution, transmission systems are valid for the in situ plants.

6.11 MODIFICATIONS TO SUIT SHORE-BASED POWER PLANT SYSTEMS

For the shore-based system, the maximum length of circuit that could be tolerated while maintaining a 15-percent maximum voltage drop was considered for loads of 30, 100, 300, 1000 and 3000 KW at voltages of 4160, 13,800 and 34,500 with a brief look at 69,000 and 115,000. The maximum incremental distances of 10, 50, 100 and 500 nautical miles were chosen. These represent average distances to the depths as specified in Chapter 3. Other parameters considered were the AC versus DC tradeoff and variation in losses and cost.

Calculations were based on the lumped parameter method using an equivalent π line. All circuit conditions were considered including capacitive reactance and the charging current due to this capacitance and the transmission voltage. Charging current was lumped one-half at the load and one-half at the output of the generating plant for ease in making the many calculations that are required for a study of this magnitude. The three-phase system was traded off against the single-phase systems.

6.11.1 Cable

6.11.1.1 CONSTRUCTION - Cable construction and material considerations have been discussed fully in Chapter 5 and the conclusions reached apply to this section of the study except as follows.

In this particular installation, due to transmission line length and voltage stress, limitations exist even in the available cable sizes.

The maximum size of the 3-conductor cable is determined by the maximum diameter of the 3 cabled conductors, the insulation appropriate for the voltage level, and the limit of the cabling manufacturing process. The minimum size wire for each voltage class is dictated by voltage stress considerations and is specified by the Insulated Power Cable Engineers Association (IPCEA).

The cable limits, due to manufacturing or voltage stress limitations, are shown in Table 6-XVIII.

Table 6-XVIII. Wire Size Limits for Various Voltage Classes

3 CONDUCTOR CABLES			SINGLE CONDUCTOR CABLES	
5000	15,000	34,500	69,000	115,000
6				
4				
2	2	#1*		
1/0	1/0	1/0		
2/0	2/0	2/0		
3/0	3/0	3/0		
4/0	4/0	4/0		
250	250	250	250	
300	300	300	300	
350	350	350	350	
400	400	400	400	
500	500	500	500	
750	750	750	750	750
1000	1000	1000	1000	1000

*Not considered a standard size.

6.11.1.2 VOLTAGE STRESS — Voltage stress in a cable may be defined as the electrical pressure on a unit thickness of insulation material and is usually expressed in volts per mil.

In normal practice the average voltage stress is used and is determined by dividing the voltage across the insulation by the insulation thickness in mils, or

$$S_{av} = \frac{2V}{(D-d)}$$

where

S_{av} = average stress in volts per mil

V = voltage across the insulation in volts (for 3 ϕ system this voltage is the phase to neutral)

D = Outside diameter of insulation in mils

d = Inside diameter of insulation in mils

The voltage stress is not uniform in all parts of the insulation wall and finds its maximum stress at the conductor insulation interface. The voltage distribution is approximately that shown in Figure 6-11.

The stress in any point of the cable may be found by

$$S = \frac{V}{2.303\ r \log\left(\frac{D}{d}\right)}$$

where

S = Stress in volts per mil at a point in the insulation r mils from the cylindrical axis.

In accordance with this formula, the maximum stress will occur at the conductor surface (r d/2)

$$S_{max} = \frac{0.868V}{d \log\left(\frac{D}{d}\right)}$$

The average stress is the unit most used in practice, but the stress nearer the conductor will be greater than the average while the stress on the outside wall of the insulation will be less than average.

All standard cable sizes and characteristics are indicated in Table 5-III and Table 6-XVIII, with the exception of an AWG #1. Since this is not considered a standard size,it does not show in Table 5-III but does show in Table 6-XVIII, because it is a minimum size conductor specified by IPCEA at 34,500 volts.

WIRE SIZE	DC RESISTANCE	K	X_1 OHMS	X_c M-OHMS	AMPACITY
1	0.129	1.	.0493	.0758	250
					C-L-P Insulated

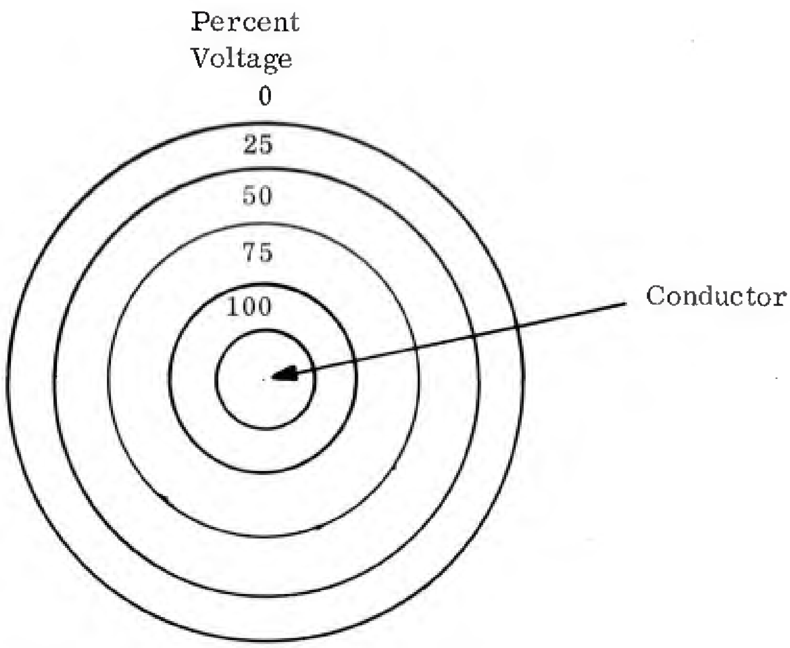


Figure 6-11. Approximate Voltage Stress Distribution Within a Shielded Cable

At 69, 000 volts and at 115, 000 volts, cable manufacturers recommended the use of single conductor cables. The 69 and 115 KV cables were considered in an attempt to transmit the higher power levels the longest possible distance. With these larger cables, insulated for 69 or 115 KV, the overall diameter of the three cabled conductors would exceed the capability of the cabling machine. Therefore, for the purpose of the shore based facilities, Table 6-XVII was used for size limitation.

6.11.1.3 VOLTAGE CONSIDERATIONS - Four voltage levels were considered for the transmission of power from a shore-based power plant. These voltage levels were: 5 KV, 15 KV, 34.5 KV, and 69 KV.

Not only are there manufacturing limitations, but, in addition, for single conductors at this voltage level, the recommendation is for a cable separation of from 90 to 600 feet, depending on retrieval, maintenance, and repair requirements. This would require multiple passes with a cable-laying vessel which would increase deployment costs appreciably. At these distances, the inductive reactance (X_1) of the circuit is excessive, as shown on Table 5-IV. With an inductive reactance of this magnitude and a capacitance which provides a charging current of many times the load current, the added distance or power level of transmission does not increase cost. Therefore, 69 and 115 KV AC cable system was abandoned.

6.11.2 Electrical Equipment

6.11.2.1 VOLTAGE RATING - The size and weight of the transformers for 69 KV and 115 KV would be prohibitive when reflected in the increased size and cost of the load module. 69 and 115 KV switchgear equipment is only manufactured in switchyard sizes (not indoor) which are very large, heavy, and bulky.

In the DC area the voltage class of 69 KV was considered only to indicate a method or system to supply all the required power levels at distances up to 500 miles.

The final tradeoffs and voltage levels considered to determine the selected systems were based on 5 KV, 15 KV and 34.5 KV only. However, if pressure-compensated equipment could be produced reliably, the higher voltage levels could be used.

6.11.2.2 EQUIPMENT AVAILABILITY - Until now, conversion equipment for high voltage DC(HVDC) has been limited to the Mercury Arc valves for large power and high voltages. These units, however, require clean room housing and degassing facilities and usually require rebuilding every five years. The future for HVDC transmission is in the development of solid state conversion equipment. One manufacturer has developed this static-type equipment; it is to be available by 1970-1975. Therefore, this equipment will be considered for the DC transmission tradeoff. The solid state conversion equipment is built in modular form of standard ratings. These modules presently are considered as 200-KV, 600-ampere modules, but they can be designed to any practical installation without sacrifice of any features. This equipment is normally designed for electric utility usage, and therefore will have, for this particular installation, some distinct disadvantages: large bushing requirements and overall size and weight.

Arc-backs that are inherent in Mercury Arc conversion equipment have been eliminated in the new solid state version.

In the new version of the HVDC terminal equipment, the transformer-converter package is designed as a complete close-coupled, oil-immersed unit made up of a transformer section and the conversion or inversion section. This offers many advantages over the Mercury Arc system, but the tradeoff considered here is between AC and DC. Therefore, this study will accept the solid state unit for its many advantages. including price, over Mercury Arc.

It may be well to note again here that in considering the cable systems for both AC and DC, AC was considered as a three conductor cable and DC as a two conductor cable. Actually, DC in submarine cable installations may be run as a single conductor using the sea as return. This determination and the analysis required is dependent on the mission, the hazards that can be accepted when using this type of system, and the adjacent equipment to be deployed. Therefore, this type of system was not considered further.

In the case of the inverter at the load module end, a supply of reactive power is required, and this reactive power may run as high as 70 percent to compensate for transient conditions. The reactive component can be a synchronous condenser or a bank of static capicitors.

If a synchronous condenser is used, for example, on a 3000 KW load, its required size would be 2100 KVAR. This is a sizable machine and would require a major increase in the size of the load module. In addition a source of AC power would have to be provided to energize this unit to synchronous speed. This would be available at the shore-based plant, but would require an AC cable to supply this power. This combination of requirements would make AC systems more cost effective under all conditions if it were not for the fact that this reactive component can be supplied by static capacitors. With static capacitors, the system and inverter would run at the natural frequency determined by the capacitors and the parameters of the connected system. The natural frequency in this case would primarily be governed by the time constant of the capacitor bank. Therefore, the static capacitor should be selected with a time constant such that the frequency variation of the system could be maintained at 10% of the 60 cycles required. Most electrical equipment today is manufactured to operate on 50-60 cycle so this condition would not create a problem. The cost differential is very small at most, and in most cases, zero.

In the tradeoff of AC vs DC, the static capacitor units were not considered to be housed in the load module, since they can be pressure compensated and mounted outside the hull.

6.11.3 Alternating vs Direct Current

In the case of the shore-based power source, three items make up the major portion of the cost and only these were considered on the assumption that the difference in deployment, engineering and equipment costs are not significant enough to the first approximation to influence the final selection of AC or DC. The items are:

1. cable costs
2. DC conversion and inversion equipment
3. the hull cost difference to house the DC inversion equipment

The hull costs were included since pressure-compensated inversion equipment is not available. To provide it would require a great deal of development work.

In the case of the cable, the voltages and the power levels considered for this tradeoff, the advantages of DC over AC are unquestionable insofar as the cable is concerned. The DC transmission cable has practically no charging current due to a unidirectional field, while the AC transmission line charging current for the higher voltages and larger cable sizes are several times the load current.

Other important factors that influence transmission cable are ionic motion in the insulation, induced current in the cable sheath, and skin effect. These factors are prevalent in AC transmission and are completely lacking in DC transmission. Thus DC is even more desirable, since these factors influence the voltage stress limitation. A DC cable has a much higher level of working stress than an AC cable, which has a direct bearing on the decreased cost of DC cables.

The effective power transmitted by DC is greater than that transmitted by AC, for the same circuit conditions. However, HVDC does have restricting factors, which are:

- Transformation: There is no easy way of transforming HVDC, which restricts this function to the AC side of both the converter and inverter sides of the transmission line.

- Reactive Power: An inverter must run at a leading power factor, thereby requiring a supply of reactive power. This power can be supplied by the AC side either by static or synchronous capacitors. The steady-state reactive requirements of the inverters may be in the order of 40-50 percent of the real power, but with respect to transients, it is advisable to have a somewhat higher percentage available: approximately 75 percent of the real power.

- Switching: The absence of switching facilities is the greatest limitation of HVDC systems. With AC the current comes to zero every half cycle, in HVDC no such current decay occurs and all the energy must be dissipated before interruption can take place. Switching can, however, be obtained by using grid control on the rectifiers.

The HVDC system has lower cable costs than an equivalent AC system but requires special transformers at each end and the necessary converter-inverter equipment. It is clear from the above discussion that HVDC has many advantages over AC in transmission, but has its main application in transmitting very large bulks of power over long distances.

All calculations were based on the load requirements of 30, 100, 300, 1000 and 3000 KW at voltage levels of 4160, 13,800 and 34,500 volts. The lengths of circuit were predicated on average distance the world over to reach the depths specified. These distances were 10, 50, 100 and 500 nautical miles. Calculations, as stated above, utilized the lumped parameter method with an equivalent π line.

The results of these calculations are shown in Tables 6-XIX and 6-XX. Table 6-XIX indicates for each DC voltage level the minimum size wire that can be used for 5, 10 and 15 percent voltage drop for each load at distances of 10, 50, 100 and 500 nautical miles. In the 4160-volt chart, only one size wire is shown in each area. This is because the voltage stress as indicated in paragraphs 5.2.6 and 6.10.2.1 does not affect this level, and the minimum size wire due to voltage drop and ampacity governs the selection. A dual number is shown in most blocks of the remaining charts - Table 6-XIX. The upper figure in each case is the minimum wire size dictated by the technical limits of ampacity and voltage drop, while the lower figure indicates the minimum wire size in each voltage given, based on voltage stress restrictions. Table 6-XX gives the same information for an AC 3-phase system, except the voltage drop is the magnitude, as discussed in paragraph 6.10.6.4.

Voltage levels were compared on the basis of standard, nominal voltages of an AC system. When static conversion-inversion equipment is produced (1970-1975), these voltages may be available from the DC system. At present, however, they are not, and the usual DC voltage ranges are in increments of 1000 KV. For a 4160-volt system, the DC would normally be 4000 volts. The use of nominal voltages was necessary for a meaningful comparison of the systems.

Table 6-XIX. Minimum Wire Size Selection (DC)

LOAD	10 MILES			50 MILES			100 MILES			500 MILES		
4160 VOLTS DC												
(KW)	5%	10%	15%	5%	10%	15%	5%	10%	15%	5%	10%	15%
30	#2	#6	#6	250	2/0	1/0	500	250	3/0			750
100	3/0	1/0	#2	750	400	250		750	500			
300	500	250	3/0			750						
1000		750	500									
3000			750									
13,800 VOLTS DC												
(KW)	5%	10%	15%	5%	10%	15%	5%	10%	15%	5%	10%	15%
30	#6 #2	#6 #2	#6 #2	#6 #2	#6 #2	#6 #2	#4 #2	#6 #2	#6 #2	4/0	1/0	#2
100	#6 #2	#6 #2	#6 #2	#2	#4 #2	#6 #2	2/0	1/0	#2	750	350	250
300	#4 #2	#6 #2	#6 #2	4/0	1/0	1/0	400	4/0	2/0			
1000	3/0	1/0	#2	750	350	250		750	500			
3000	450	450	450			750						
34,500 VOLTS DC												
(KW)	5%	10%	15%	5%	10%	15%	5%	10%	15%	5%	10%	15%
30	#6 #1	#6 #1	#6 #1	#6 #1	#6 #1	#6 #1	#6 #1	#6 #1	#6 #1	#4 #1	#6 #1	#6 #1
100	#6 #1	#6 #1	#6 #1	#6 #1	#6 #1	#6 #1	#6 #1	#6 #1	#6 #1	2/0	#2 #1	#4 #1
300	#6 #1	#6 #1	#6 #1	#4 #1	#6 #1	#6 #1	#2 #1	#4 #1	#6 #1	350	4/0	2/0
1000	#6 #1	#6 #1	#6 #1	2/0	#2 #1	#4 #1	250	2/0	1/0		600	400
3000	#2 #1	#4 #1	#6 #1	350	4/0	2/0	750	350	250			
69,000 VOLTS DC												
(KW)	5%	10%	15%	5%	10%	15%	5%	10%	15%	5%	10%	15%
30	#6 250	#6 250	#6 250	#6 250	#6 250	#6 250	#6 250	#6 250	#6 250	#6 250	#6 250	#6 250
100	#6 250	#6 250	#6 250	#6 250	#6 250	#6 250	#6 250	#6 250	#6 250	#4 250	#6 250	#6 250
300	#6 250	#6 250	#6 250	#6 250	#6 250	#6 250	#6 250	#6 250	#6 250	1/0 250	#2 250	#4 250
1000	#6 250	#6 250	#6 250	#4 250	#6 250	#6 250	#2 250	#4 250	#6 250	300	2/0 250	1/0 250
3000	#6 250	#6 250	#6 250	1/0 250	#2 250	#4 250	3/0 250	1/0 250	#2 250	1000	450	300

Table 6-XX. Minimum Wire Size Selection (AC)

LOAD	10 MILES			50 MILES			100 MILES			500 MILES			
34,500 VOLTS AC													
(KW)	5%	10%	15%	5%	10%	15%	5%	10%	15%	5%	10%	15%	
30	#6 #1	#6 #1	#6 #1	1/0	#4 #1	#6 #1		1000	3/0				Charging Current Predom-inates
100	#6 #1	#6 #1	#6 #1	1/0	#4 #1	#6 #1		1000	3/0				
300	#6 #1	#6 #1	#6 #1	1/0	#4 #1	#6 #1		1000	3/0				
1000	#6 #1	#6 #1	#6 #1	1/0	#4 #1	#6 #1		600	2/0				Load Current Increases
3000	#6 #1	#6 #1	#6 #1	2/0	#2 #1	#4 #1		350	2/0				
13,800 VOLTS AC													
(KW)	5%	10%	15%	5%	10%	15%	5%	10%	15%	5%	10%	15%	
30	#6 #2	#6 #2	#6 #2	3/0	#2	#6 #2							Charging Current Predom-inates
100	#6 #2	#6 #2	#6 #2	3/0	#4 #2	#6 #2							
300	#6 #2	#6 #2	#6 #2	2/0	#4 #2	#6 #2			400				
1000	#2 #2	#6 #2	#6 #2	350	2/0	1/0			350				Load Current Increases
3000	4/0	1/0	#2		1000	350							
4160 VOLTS AC													
(KW)	5%	10%	15%	5%	10%	15%	5%	10%	15%	5%	10%	15%	
30	#6	#6	#6		1/0	#4							
100	#2	#4	#6		2/0	1/0							
300	4/0	1/0	#2		750	350							
1000		450	250										
3000													

Table 6-XXI. AC vs DC Cost Differentials at 5% Magnitude of Voltage Drop

LOAD		600-Ft Depth Distance (NM)				2,000-Ft Depth Distance (NM)				6,000-Ft Depth Distance (NM)				10,000-Ft Depth Distance (NM)				15,000-Ft Depth Distance (NM)				20,000-Ft Depth Distance (NM)			
VOLTS	KW	10	50	100	500	10	50	100	500	10	50	100	500	10	50	100	500	10	50	100	500	10	50	100	500
4160	30	+ 29	DC	DC		+ 39	DC	DC		+ 70	DC	DC		+ 110	DC	DC		+ 130	DC	DC		+ 170	DC	DC	
	100	+105	DC			+122	DC			+ 175	DC			+ 276	DC			+ 319	DC			+ 392			
	300	AC				AC				AC				AC				AC				AC			
	1000																								
	3000																								
13800	30	- 70	-1435	DC	DC	- 60	-1425	DC	DC	- 29	-1394	DC	DC	+ 11	-1354	DC	DC	+ 31	-1334	DC	DC	+ 71	-1294	DC	DC
	100	- 6	-1371	DC	DC	+ 11	-1354	DC	DC	+ 64	-1301	DC	DC	+ 165	-1200	DC	DC	+ 208	-1157	DC	DC	+ 281	-1084	DC	DC
	300	+202	- 134	DC		+251	- 85	DC		+ 386	+ 50	DC		+ 641	+ 305	DC		+ 771	+ 435	DC		+ 971	+ 635	DC	DC
	1000	+453	AC			+542	AC			+ 733	AC			+1063	AC			+1243	AC			+1563	AC		
	3000	+598				+683				+1008				+1473				+1713				+2183			
34500	30	- 92	- 868	DC	DC	- 82	- 858	DC	DC	- 51	- 827	DC	DC	- 11	- 787	DC	DC	+ 9	- 767	DC	DC	+ 49	- 727	DC	DC
	100	- 28	- 804	DC	DC	- 11	- 787	DC	DC	+ 42	- 734	DC	DC	+ 143	- 633	DC	DC	+ 186	- 590	DC	DC	+ 257	- 517	DC	DC
	300	+180	- 596	DC	DC	+229	- 547	DC	DC	+ 364	- 412	DC	DC	+ 619	- 157	DC	DC	+ 749	- 27			+ 949	+ 173	DC	DC
	1000	+319	- 157	DC		+391	- 85	DC		+ 599	+ 123	DC		+ 929	+ 453	DC		+1109	+ 633	DC		+1429	+ 953	DC	
	3000	+514	AC	DC		+609	AC	DC		+ 924	AC	DC		+1389	AC	DC		+1629	AC	DC		+2099	AC	DC	

Table 6-XXII. AC vs DC Cost Differentials at 10% Voltage Drop

LOAD		600-Ft. Depth Miles Distance				2,000-Ft. Depth Miles Distance				6,000-Ft. Depth Miles Distance				10,000-Ft. Depth Miles Distance				15,000-Ft. Depth Miles Distance				20,000-Ft. Depth Miles Distance			
VOLTS	KW	10	50	100	500	10	50	100	500	10	50	100	500	10	50	100	500	10	50	100	500	10	50	100	500
4160	30	- 24	-431	DC		- 14	- 421	DC		+ 17	- 390	DC		+ 57	- 350	DC		+ 77	- 330	DC		+ 117	- 290	DC	
	100	+ 96	AC	DC		+113	AC	DC		+166	AC	DC		+ 267	AC	DC		+ 310	AC	DC		+ 383	AC	DC	
	300	AC	AC			AC	AC			AC	AC			AC	AC			AC	AC			AC	AC		
	1000	+412				+484				+692				+1022				+1202				+1522			
	3000																								
13800	30	- 70	-589	DC	DC	- 60	-1425	DC	DC	- 29	- 548	DC	DC	+ 11	- 508	DC	DC	+ 31	- 488	DC	DC	+ 71	- 448	DC	DC
	100	- 6	-525	DC	DC	+ 11	- 508	DC	DC	+ 64	- 455	DC	DC	+ 165	- 354	DC	DC	+ 208	- 311	DC	DC	+ 281	- 238	DC	DC
	300	+202	-107	DC		+251	- 58	DC		+386	+ 77	DC		+ 641	+ 332	DC		+ 771	+ 462	DC		+ 971	+ 662	DC	
	1000	+453	AC	DC		+455	AC	DC		+663	AC	DC		+ 993	AC	DC		+1173	AC	DC		+1493	AC	DC	
	3000	AC	AC			AC	AC			AC	AC			AC	AC			AC	AC			AC	AC		
34500	30	- 92	-696	-12000	DC	- 82	- 687	-12000	DC	- 51	- 656	-12000	DC	- 11	- 616	-12000	DC	+ 9	- 596	-12000	DC	+ 49	- 556	-12000	DC
	100	- 28	- 28	-12500	DC	- 11	- 616	-12000	DC	+ 42	- 563	-12000	DC	+ 143	- 462	-12000	DC	+ 186	- 419	-12000	DC	+ 259	- 346	-12000	DC
	300	+180	+180	-12300	DC	+229	- 376	-12000	DC	+364	- 241	-12000	DC	+ 619	+ 14	-12000	DC	+ 749	+ 144	-11700	DC	+ 949	+ 344	-12000	DC
	1000	+319	+319	- 7200	DC	+391	- 214	- 7000	DC	+599	- 6	- 6900	DC	+1129	+ 324	- 6600	DC	+1109	+ 504	- 6556	DC	+1429	+ 824	- 6136	DC
	3000	+514	+593	- 2100		+599	+ 678	- 2100		+924	+1003	- 1745		+1389	+1468	- 1280		+1629	+1708	- 1040		+2099	+2178	- 570	

Table 6-XXIII. AC vs DC Cost Differentials at 15% Voltage Drop

LOAD		600-Ft Depth Miles Distance				2,000-Ft Depth Miles Distance				6,000-Ft Depth Miles Distance				10,000-Ft Depth Miles Distance				15,000-Ft Depth Miles Distance				20,000-Ft Depth Miles Distance			
VOLTS	KW	10	50	100	500	10	50	100	500	10	50	100	500	10	50	100	500	10	50	100	500	10	50	100	500
4160	30	- 24	- 86	DC	DC	- 14	- 76	DC	DC	+ 17	- 45	DC	DC	+ 57	- 5	DC	DC	+ 77	+ 15	DC	DC	+ 117	+ 55	DC	DC
	100	+ 91	AC	DC		+108	AC	DC		+161	AC	DC		+ 262	AC	DC		+ 305	AC	DC		+ 378	AC	DC	
	300	+326	AC			+375	AC			+510	AC			+ 765	AC			+ 895	AC			+1095	AC		
	1000	+464				+536				+744				+1074				+1254				+1574			
	3000	DC				DC				DC				DC				DC				DC			
13800	30	- 70	-589	DC	DC	- 60	-579	DC	DC	- 29	-548	DC	DC	+ 11	- 508	DC	DC	+ 31	- 488	DC	DC	+ 71	- 448	DC	DC
	100	- 6	-589	DC	DC	+ 11	-508	DC	DC	+ 54	-455	DC	DC	+ 165	- 354	DC	DC	+ 208	- 311	DC	DC	+ 281	- 238	DC	DC
	300	+102	-107	-4900		+251	- 58	-4852		+386	+ 77	-4717		+ 641	+ 332	-4462		+ 771	+ 462	-4332		+ 971	+ 662	-4132	
	1000	+341	+455	-1100		+413	+527	-1036		+621	+735	- 838		+ 951	+1065	- 498		+1131	+1245	- 318		+1451	+1565	+ 2	
	3000	AC	AC			AC	AC			AC	AC			AC	AC			AC	AC			AC	AC		
34500	30	- 92	-697	-2890	DC	- 82	-637	-2900	DC	- 51	-656	-2852	DC	- 11	- 616	-2812	DC	+ 9	- 596	-2792	DC	+ 49	- 556	-2752	DC
	100	- 28	- 28	-2800	DC	- 11	-616	-2900	DC	+ 42	-563	-2759	DC	+ 143	- 462	-2658	DC	+ 186	- 419	-2615	DC	+ 259	- 346	-2542	DC
	300	+180	+180	-2600	DC	+229	-376	-2950	DC	+364	-241	-2437	DC	+ 619	+ 14	-2182	DC	+ 749	+ 144	-2052	DC	+ 949	+ 344	-1852	DC
	1000	+319	+319	-1700	DC	+391	-214	-1600	DC	+599	- 6	-1434	DC	+ 929	+ 324	-1108	DC	+1109	+ 504	- 924	DC	+1429	+ 824	- 604	DC
	3000	+514	+209	- 39		+599	+294	+ 66		+924	+619	+ 391		+1389	+1084	- 856		+1629	+1324	+1096		+2099	+1794	+1566	

From Tables 6-XIX and 6-XX, the cost differential figures of Tables 6-XXI through 6-XXIII were prepared. These tables only indicate the estimated cost difference between AC and DC for the items previously discussed. Each chart represents a particular voltage drop. The cost figures shown are in thousands of dollars and are preceded either by a+ (which means AC is more cost effective) or by a- (which means DC is more cost effective). Notations of simply AC or DC indicate that this is the only way to reach the objective within the voltage drop limitation. Blocks that are crossed out indicate that at this load, voltage, and depth the required distance cannot be reached with either AC or DC with a 15% voltage drop.

From the information shown on charts in Tables 6-XXI through 6-XXIII, a selection of systems was made, as shown in Figure 6-12. This figure is a summation of the information found in Table 6-XXII. It indicates that at distances up to 10 nautical miles, AC is the most cost effective, even though at the low power levels at higher voltages, DC seems to be the more economical system. Again, the costs used to compare the DC system with the AC system were extrapolated from published projected costs for a unit much larger than the one anticipated for this system, and the cost figures found could not be verified. In addition to this, at the 13, 800 and 34, 500 volt levels, DC switchgear costs are very high and presently are not manufactured. It was felt then that this difference was not conclusive enough to choose DC and AC was chosen for all loads at all voltages up to 34, 500 volts for the 10 miles distance. By the same token, then Figure 6-12 also shows conclusively that DC is the preferable system when considering depths from 600 to 20, 000 ft which are found at the 500-nautical-mile range. Between these two limits is the so-called gray area. Each load at each depth limit is shown and noted "AC" or "DC".

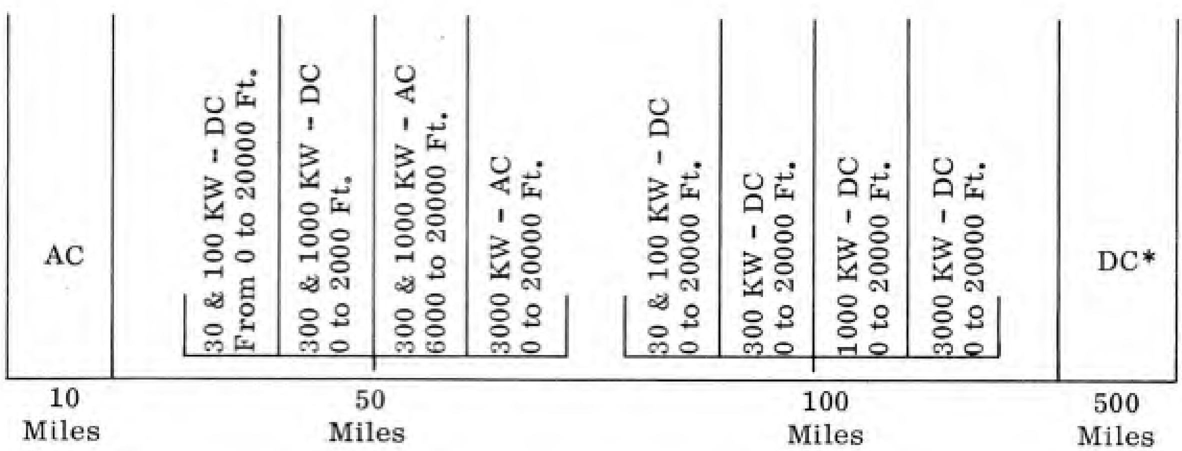
Figure 6-13 shows the preliminary system selection and indicates that, for distances of 50 to 500 miles for loads of 30, 100, 300 and 1000 KW, DC is the most cost-effective system.

For all loads at 10 miles, AC is the most cost-effective system. For 3000 KW at 10 and 50 miles, AC is the most cost effective, while DC is for 3000 KW at 100 miles.

The results of the above evaluation were used to select AC and DC transmission rating as shown in Table 6-XXIV. All estimated electrical costs have been used, including the switchgear costs at both ends, the transformers, conversion and inversion equipment. These totals were added to the cost of the cable selected for the average distances and the voltage levels considered. All equipment is public-utility-oriented for outside use and is large, heavy, and costly. This is reflected in the cost of the hull to house this equipment. No minaturization has taken place in any of this equipment and is not likely to in the immediate future. These areas will require development.

Table 6-XXIV. AC/DC Systems Selection

LOAD		TOTAL COST INCLUDING CABLE IN K$							
VOLTS	KW	SYSTEM	10	SYSTEM	50	SYSTEM	100	SYSTEM	500
4160	30	AC	332	DC	1616	DC	4158		
	100	AC	365	DC	2889	DC	7983		
	300	AC	499						
	1000	AC	927						
	3000								
13800	30	AC	493	DC	1504	DC	2800	DC	17,068
	100	AC	494	DC	1621	DC	3337	DC	29,003
	300	AC	499	DC	2217	DC	4839		
	1000	AC	508	DC	3649	DC	9367		
	3000	AC	584	AC	4137				
34500	30	AC	737	DC	1899	DC	3411	DC	15,507
	100	AC	740	DC	2018	DC	3520	DC	15,626
	300	AC	752	DC	2410	DC	3922	DC	22,858
	1000	AC	769	DC	2687	DC	4799	DC	38,975
	3000	AC	794	AC	2608	DC	7180		



*except 3000 KW

Figure 6-12. AC/DC Tradeoff

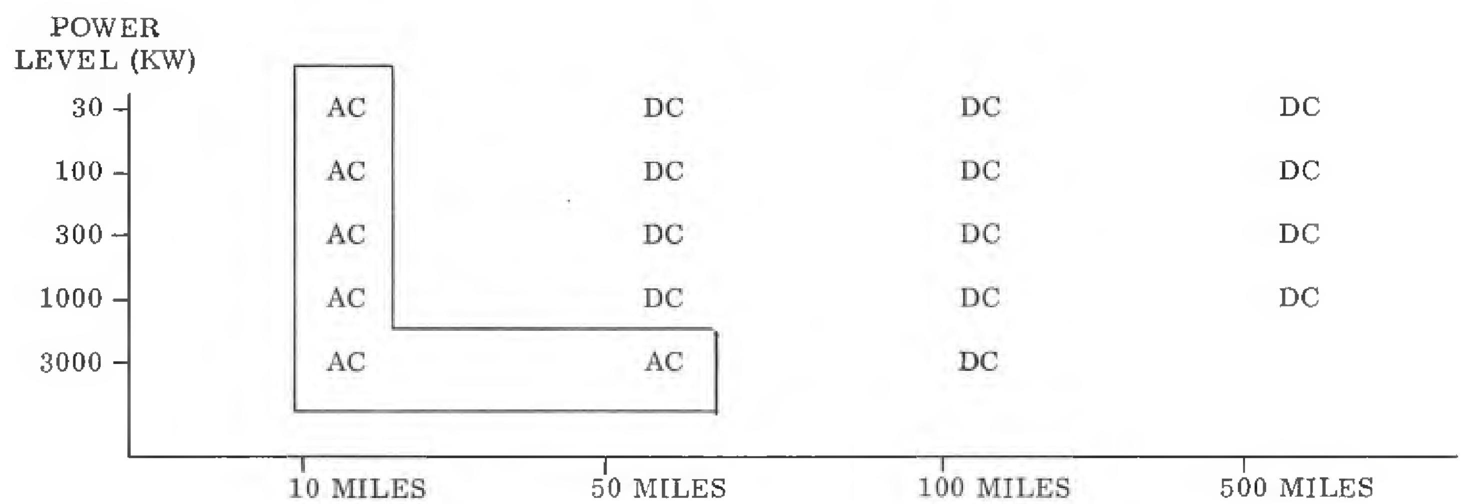


Figure 6-13. AC/DC System Selection

The selected systems are shown in Table XXV and must be tempered since the principal cost penalty for DC is the additional hull costs to house the inversion equipment. The hull costs estimated for the tradeoff were based on a minimum cylinder to house the equipment. Consequently, at deeper depths and high power levels (large inversion equipment) the penalty invoked on the DC system is severe. Therefore, for a load module that has little or no space it may be more cost effective to transmit at AC since it may not be possible for the additional hull costs for DC equipment to offset the savings between the DC cable and the AC cable. This is especially true at the 50-mile distance at deep-depth installations.

No system is shown for the 3000 KW level at 500 miles. This and greater distances can be reached by using the 69 KV level, which can be operated at 35 KV and -35KV for a DC system. It is also possible with some engineering and product development work to provide a DC system at 115 and -115 KV or 230 KV total that can more than supply the loads required up to distances of approximately 1000 nautical miles.

Table 6-XXV. AC/DC Selected Voltages

POWER (KW)	DISTANCE (FT) 60,000	300,000	600,000	3×10^6
30	4,160 AC	13,800 DC	13,800 DC	34,500 DC
100	4,160 AC	13,800 DC	13,800 DC	34,500 DC
300	13,800 AC	13,800 DC	34,500 DC	34,500 DC
1000	13,800 AC	34,500 DC	34,500 DC	34,500 DC
3000	13,800 AC	34,500 AC	34,500 DC	

6.11.4 Voltage Regulation

6.11.4.1 HVDC REGULATION - Under normal conditions the transmitted power is regulated by closed loop control of the firing angle of the rectifier, which produces the prescribed current, and by operating the inverter with the maximum firing angle necessary for safe commutation. Under normal conditions the AC voltages at each end of the link are kept within prescribed limits by means of automatic transformer tap changers. To prevent the system from "running down" during transient voltage fluctuations, it is necessary to provide a constant current regulation for the inverter. This prevents the current from falling below a given level and automatically comes into operation when it is no longer possible to regulate the current from the rectifier end. The rectifier and inverter characteristics are shown in Figure 6-14.

The current order is computed from a knowledge of theDC voltage and the power equipment.

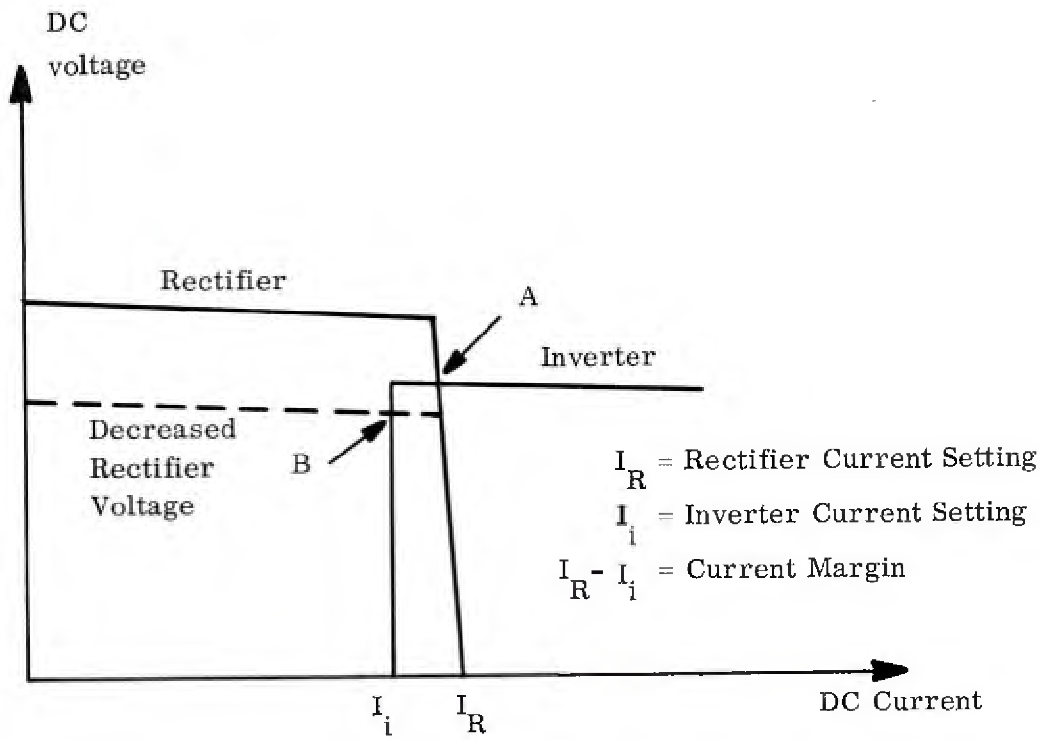


Figure 6-14. Rectifier and Inverter Characteristics

6.11.4.2 RECTIFIER REGULATION - The current order is compared with the actual current in the line, and the difference signal, in the form of a DC voltage, is fed to the control input of the phase controlled pulse generator. This produces output pulses synchronized to the rectifier supply voltages, the phase of which is controlled in accordance with the DC control signal. These pulses are shaped to provide a continuous rectifier gate firing signal which is maintained until the drive pulse appropriate to the rectifier in the next phase is initiated.

6.11.4.3 INVERTER REGULATION - Normally the inverter is fired at the maximum angle necessary for safe commutation. A safe firing angle computer calculates this angle for each firing point from a knowledge of the instantaneous inverter voltage and current and also the rate of change of current. "End stop" firing pulses are produced at the instant the available commutation angle becomes equal to the computed safe angle. Under this condition the current in the inverter is higher than the current setting in the regulation loop. This current setting is equal to the rectifier current order less a given current margin. A comparator and the phase-controlled pulse generator function in the same way as for the rectifier. Thus, the pulses produced by the phase-controlled pulse generator normally occur at a later point than the "end stop" pulses (this corresponds to working point A, Figure 6-14). The pulse selector chooses the first of the pulses which are fed to a pulse shaper. In the event the inverter current regulator loop comes into operation, the pulses produced by the phase-controlled pulse generator occur earlier than the "end stop" phases and are automatically selected for the purpose of determining the inverter firing angle (this corresponds to working point B, Figure 6-14).

6.11.4.4 AC VOLTAGE REGULATION - For long cable distances, voltage regulation between the sending end and receiving end portions of the system is affected by the charging current. The influence of the charging current is principally the product of two vectors. Figure 6-15D depicts the voltage vectors for the long cable systems. The vector E_S is a measure of the sending-end voltage. It is referenced to the receiving-end voltage by the angle gamma. Assuming that point 1 on the vector diagram is the nominal receiving-end voltage at full load, it can be seen that the magnitude of E_S, thus voltage regulation, is influenced by the magnitude of I_TZ vector and its angle relative to the E_R vector.

As noted in the diagram, as I_TZ increases in angle or magnitude, E_S varies accordingly. The arcs marked a and b on the vector diagram depict the absolute limits recommended for transmission voltage regulation. i.e., ±5 percent. As the angle alpha increases, with that constant magnitude of I_TZ, E_S will become smaller and smaller. When the angle alpha reaches a point such that I_TZ vector is at point 4, the voltage regulation affected between E_S and E_R is 5 percent. As alpha increases past this point for the same magnitude of I_TZ, E_S becomes smaller and thus the voltage regulation is below the -5 percent. On the other hand, as the angle alpha decreases, with respect to E_R, the magnitude of E_S will increase, thus surpassing the +5 voltage regulation required. Therefore, it can be concluded that the voltage regulation is principally controlled by the vector quantity I_TZ. The vector I_TZ is the product of two vectors, I_T and Z. The Z or impedance portion of the I_TZ is a function of cable geometry. As can be noted in Figure 6-15B, as X_L increases or R increases, Z increases. Conversely, as the resistance and inductive reactance decrease, the magnitude of Z will decrease. The angle phi is a measure of the vector Z relative to the E_R axis. For increasing cable sizes the magnitude of Z will decrease and the magnitude of phi will go further positive as shown on Table 6-XXV. The I_T portion of the I_TZ vector is the summation of two vectors: the charging current, which is a function of distance and cable size (see Table 6-XXVI) and the load current. As can be seen in Figure 6-15C, as the load current (I_L) increases, the I_T vector will increase; however, its angle delta relative to E_R will decrease. The load current angle theta, as shown in Figure 6-15C, has been assumed to be constant in the discussion in Chapter 6. Therefore, the changes in delta and the magnitude of I_T for a constant power level are influenced by cable size and distance. Furthermore, for constant cable size, power level and varying distance, delta will get larger, I_T will increase, and Z will increase and its angle phi will remain constant. The absolute value of I_TZ product is a measure of the voltage drop within the cable, as shown in the equivalent circuit diagram, Figure 6-15A, and plotted in Figures 6-16 through 6-20 for 34,500 V. On the vector diagram, the circle marked with points 2, 3, 4, and 5 is the locus of the I_TZ vector where its magnitude is 10 percent relative to E_R. Similarly, the points 6, 7, 8 and 9 are at 5 percent, and 11, 12, 13, and 14 are at 15 percent. The selection of voltage with the cable at ± 5 percent magnitude of the I_TZ vector will achieve the required regulation within the entire system at constant power level.

Unlike the moderate cable distances, however, the E_R voltage experienced at no load will not be the same in magnitude as E_S. It will differ by the product of the charging current lump parameter ($I_C/2$) times Z, where I_L equals zero. Where the magnitude of I_TZ is ± 5 percent, e.g., the 6, 7, 8 and 9 trace, the system is representative of ± 5 percent voltage regulation only when beta is either 0° or 180°. For all other angles, the voltage regulation is much closer to ± 5 percent. Similarly, at 10 percent magnitude of I_TZ, the system would effect 5 percent voltage regulation when alpha equals 51° and beta equals 59°. When the I_TZ magnitude is 10 percent and the angle beta is such that the vector falls between the points 4 and 5, the effective E_S relative to E_R voltage regulation would be less than 5 percent. Conversely, if the angle alpha is between points 2 and 3, then the E_S regulation would be greater than

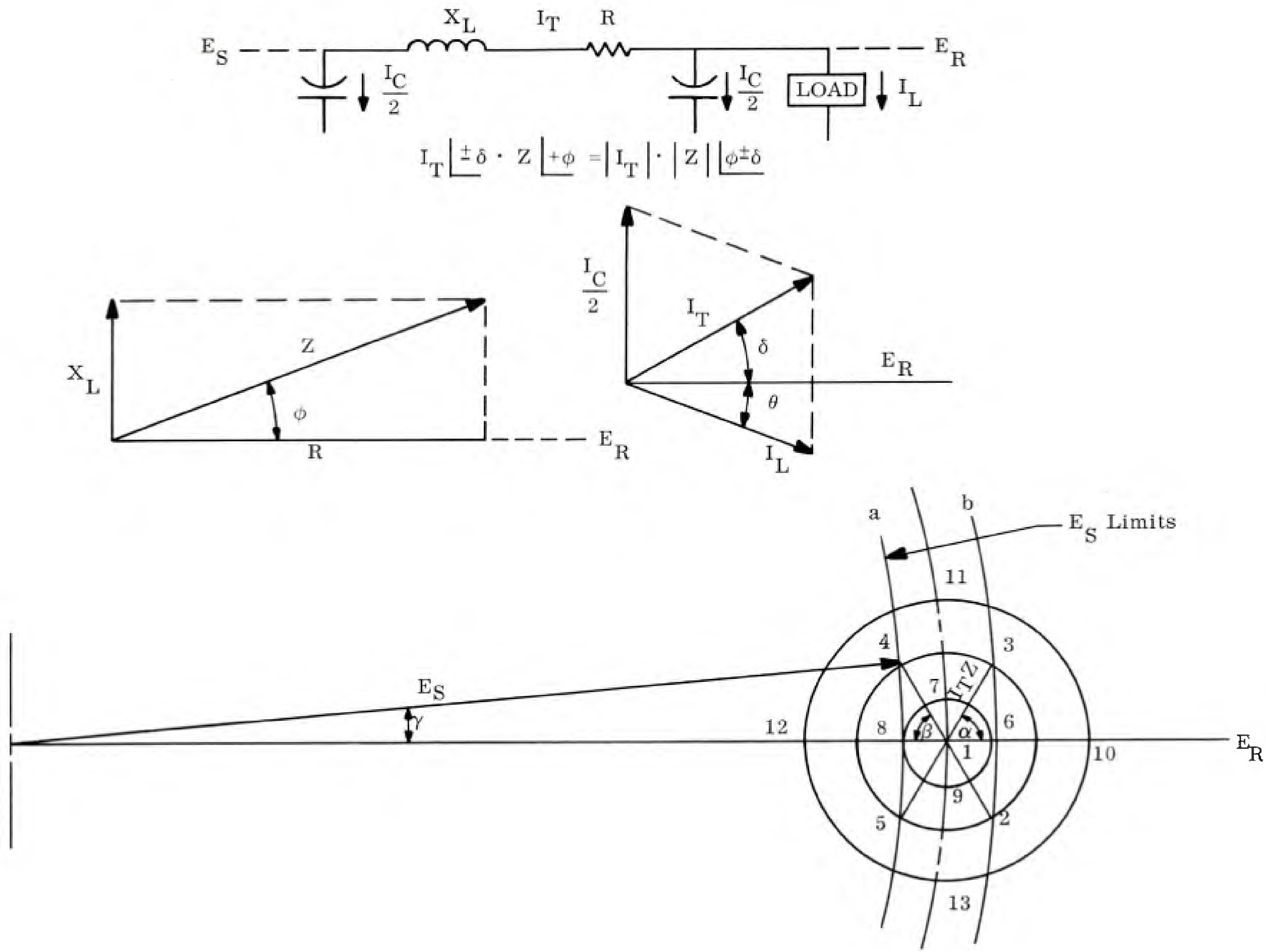


Figure 6-15. AC Voltage Regulation vs. Cable Length

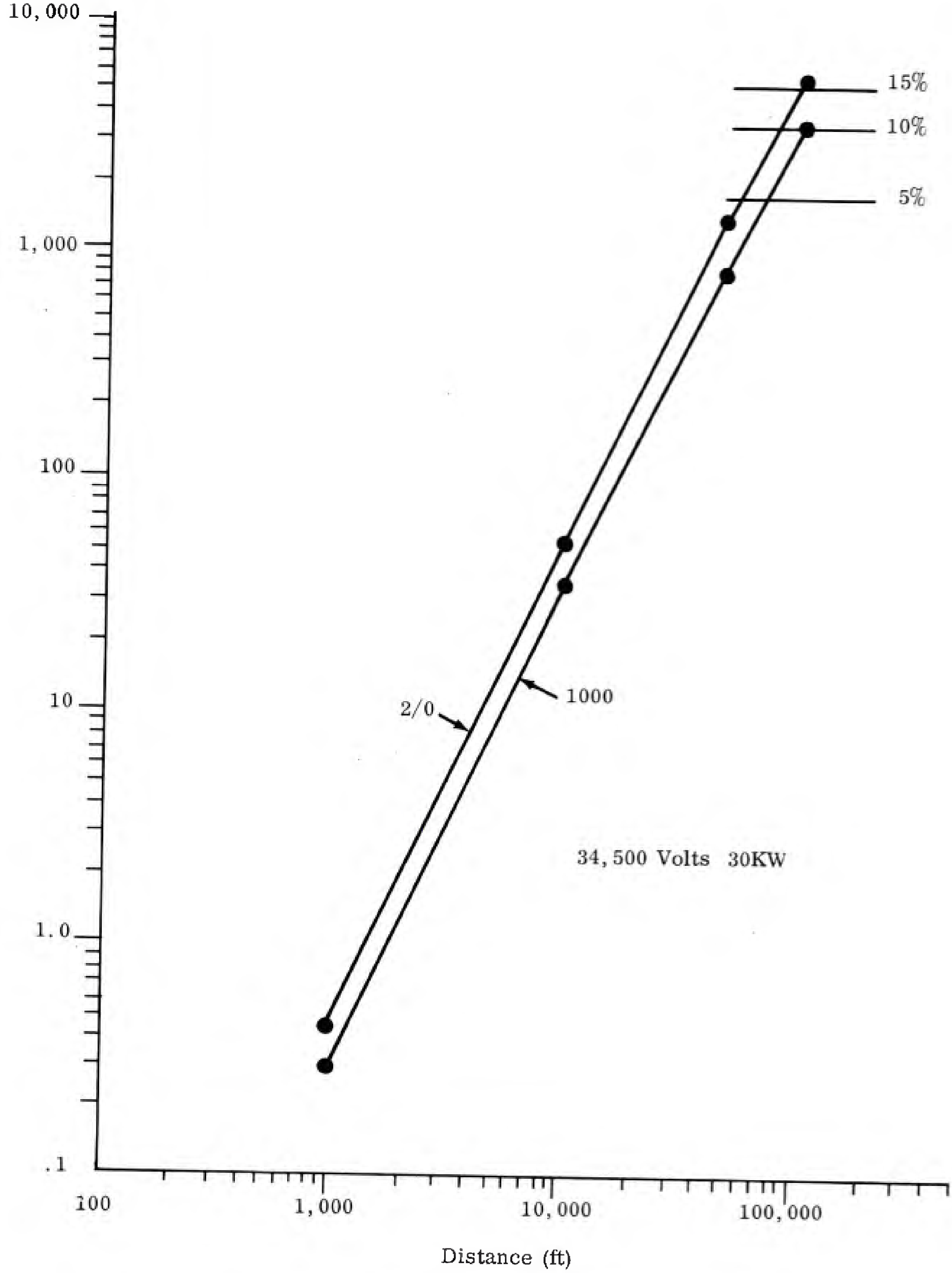


Figure 6-16. Distance Vs. Magnitude of Voltage Drop for 30 KW at 34,500 V

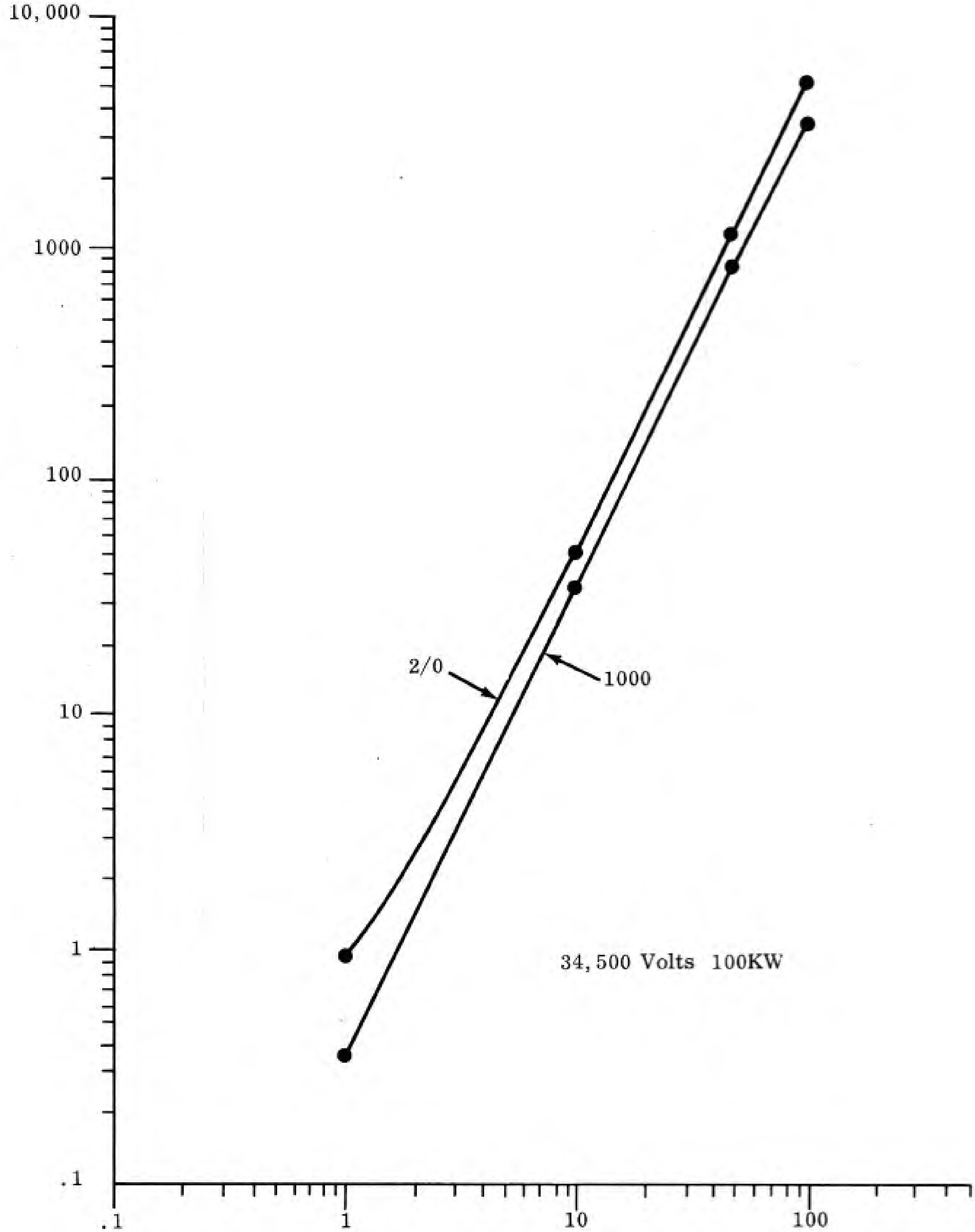


Figure 6-17. Distance Vs. Magnitude of Voltage Drop for 100 KW at 34,500 V

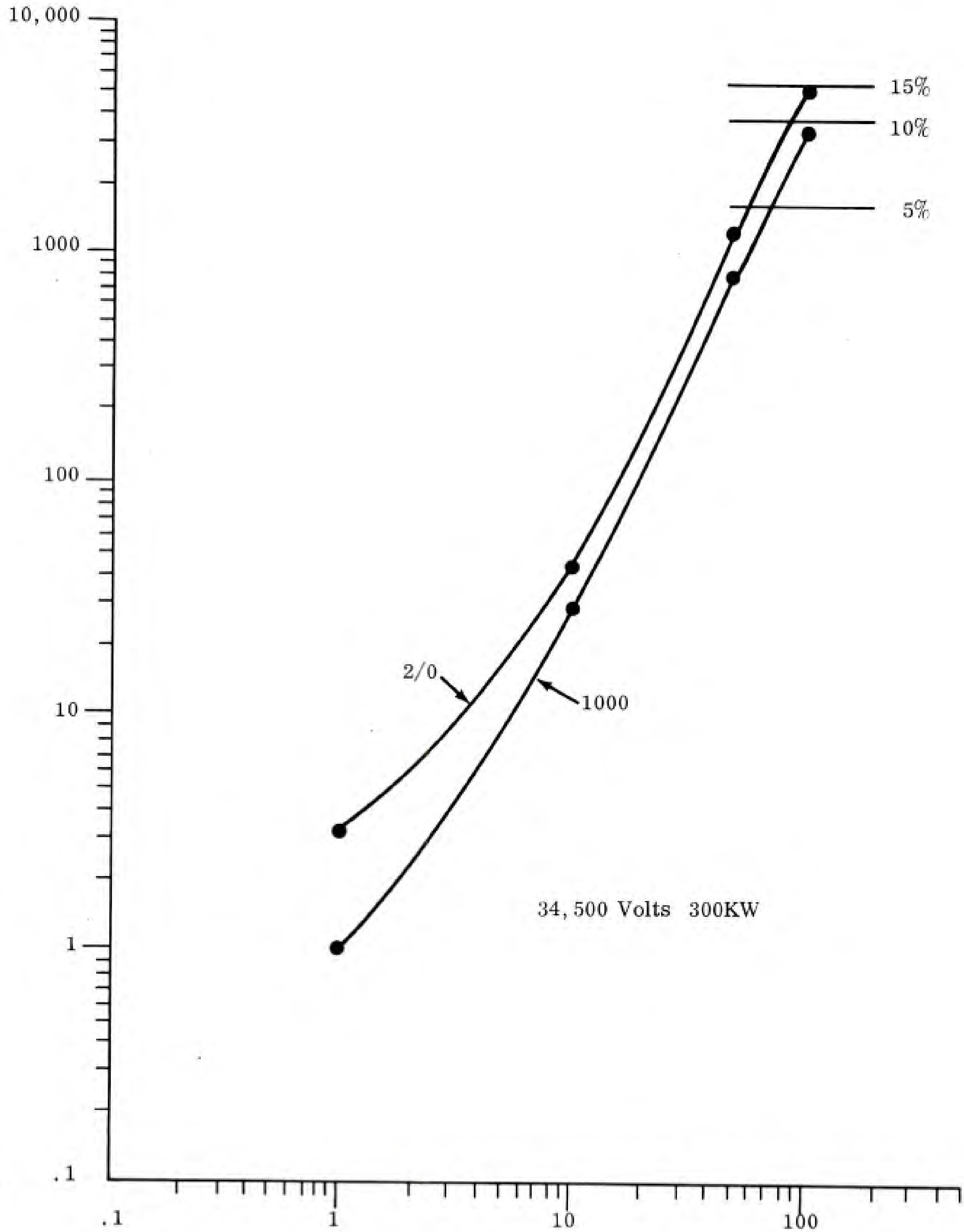


Figure 6-18. Distance Vs. Magnitude of Voltage Drop for 300 KW at 34,500 V

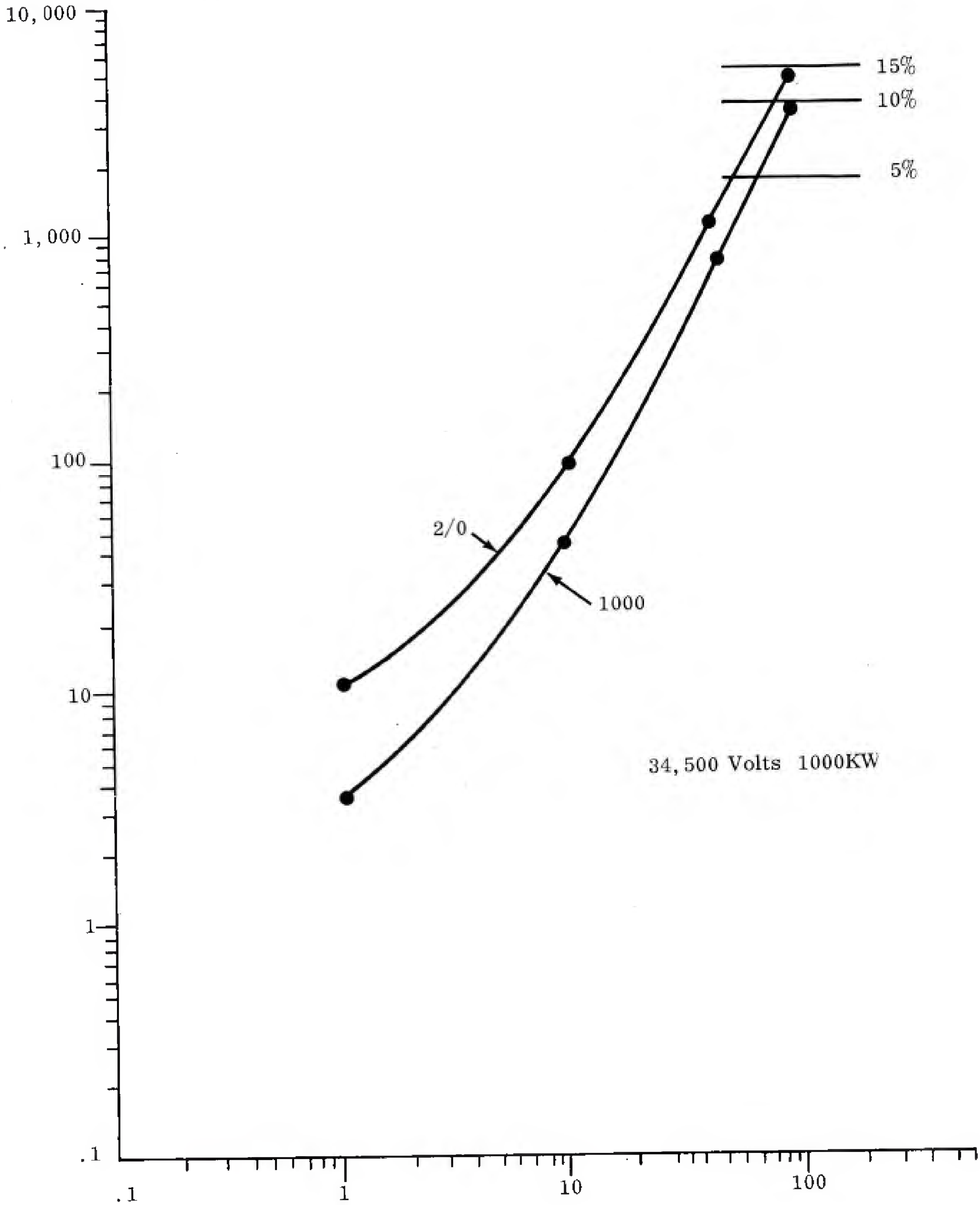


Figure 6-19. Distance Vs. Magnitude of Voltage Drop for 1000 KW at 34,500 V

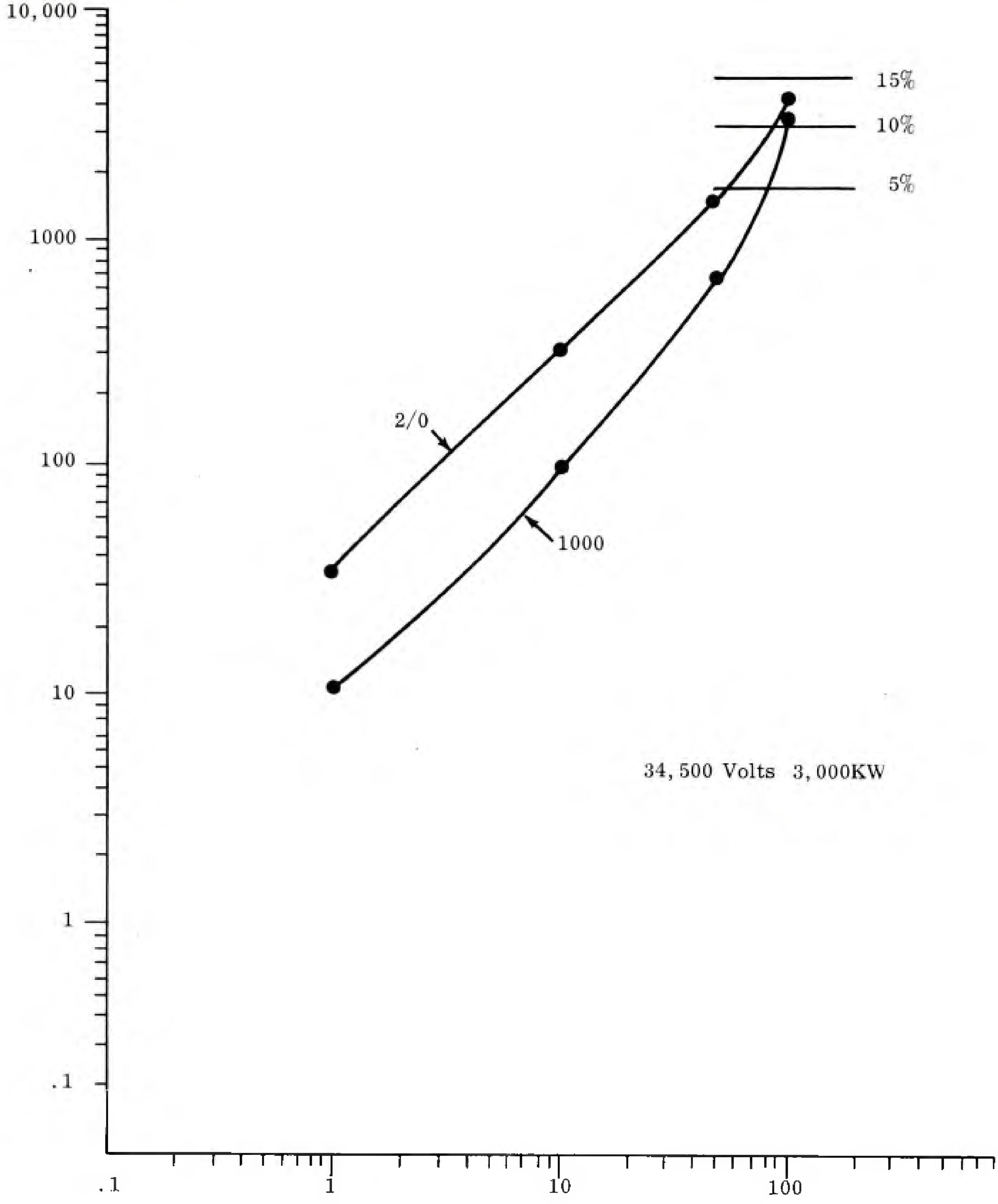


Figure 6-20. Distance Vs. Magnitude of Voltage Drop for 3000 KW at 34,500 V

Table 6- XXVI. Phi vs Cable Size

VOLTAGE CLASS A.W.G or MCM	5000 V PHI	15,000 V PHI	34,500 V PHI
6	5^{o} 31'		
4	8^{o} 10'		
2	10^{o} 40'	14^{o} 50'	
1/0	17^{o} 30'	20^{o} 54'	
2/0	21^{o} 22'	24^{o} 57'	29^{o} 25'
3/0	25^{o} 43'	29^{o} 13'	34^{o} 43'
4/0	30^{o} 10'	34^{o} 43'	40^{o} 1'
250	34^{o} 4'	38^{o} 2'	44^{o} 6'
300	38^{o} 13'	42^{o} 15'	48^{o} 16'
350	41^{o} 58'	45^{o} 46'	51^{o} 45'
400	45^{o} 8'	49^{o}	54^{o} 39'
450	47^{o} 58'	51^{o} 45'	57^{o} 7'
500	50^{o} 32'	54^{o} 22'	59^{o} 6'
600	54^{o} 43'	58^{o} 11'	62^{o} 20'
750	59^{o} 29'	62^{o} 25'	65^{o} 44'
1000	65^{o} 16'	67^{o} 41'	69^{o} 24'

Table 6- XXVII. Total Charging Current per 10 Miles of Cable

VOLTAGE CLASS A.W.G. or MCM	4160	13,800	34,500
6	2.86	5.68	12.2
4	3.34	6.63	13.8
2	3.9	7.92	15.4
1/0	4.85	9.48	17.2
2/0	5.34	10.5	18.55
3/0	5.82	11.4	19.7
4/0	6.47	12.6	20.8
250	6.75	13.25	21.7
300	7.28	14.3	23.06
350	7.83	15.2	24.4
400	8.25	16.1	25.3
450	8.75	16.5	26.2
500	9.18	17.2	27.6
600	10.0	18.8	29.4
750	11.1	20.5	31.7
1000	12.7	22.9	35.8

the ± 5 percent. This holds true for the locus of points 11, 12, 13 and 14, the ± 15 percent regulation level.

For defining the selected systems affecting tradeoffs and preliminary designs for voltage regulation, the 10 percent I_TZ magnitude is used for choosing the cable sizes at the varying voltages. This does not penalize the cable system due to the small load currents which cause alpha to approach 90^o. For example, as much as 52 percent magnitude of I_TZ could be chosen when alpha is equal to approximately 92^o, the effective regulation still could be maintained within ± 5 percent at constant full load. At this point, however, any gross change in load would have a great influence on the cable, particularly at the high power levels. At the low power levels, the charging current is the most significant portion of the I_T vector and its angle delta is fairly close to the 90^o value. The final selection for wire sizes, i.e., the effects of voltage regulation, is dependent on the true power profile that is required.

For evaluation, constant power demand is specified in those instances in which this choice is beneficial or has no effect. For purposes of voltage regulation, however, it is not reasonable to size the system for constant load. Consequently the 10 percent voltage regulation limit within the cable is selected. This does not mean, however, that the actual voltage regulation will be as depicted on the voltage diagram. This is due primarily to the basic assumptions of the equivalent system, (i.e., the π network and the effects of $\overline{I}_C/2\ \overline{Z}$). Prior to final design selection, which is predicated on load module placement, which in turn effects true cable distance, the actual cable parameters, commonly called the ADCD constants, should be determined. Cable size selection for a single shore-based power source should be based on the ABCD constants.

The cable size selection on the basis of the π network will, in general, result in a cable size increase over that computed by the use of the distributed capacitance, i.e., ABCD constants. A typical computer run based on the ABCD constants, is contained in Appendix A.

6.11.5 System Protection

The protective system for the shore-based facilities for AC operation will be similar as for the surface or in situ arrangements. The only variation in protection system involves HVDC transmission. This system protection is a proposed method of providing the scheme desired within the philosophy developed for underwater power transmission systems. This philosophy is that the system remains in service for all conditions other than those which would cause failure if immediate remedial action were not taken. From these basic conditions, a proposed method of system protection is developed.

The protective system for HVDC operation must account for failures that occur in either AC end or the HVDC link. This link includes the converter or rectifier end at the generating plant, the transmission line, and the inverter unit at the load module end.

The transformers at either end of the line, whether AC or HVDC transmission is utilized, are provided with a percentage differential relay circuit. For transformer faults, this circuit operates, after a time delay, to trip the main circuit breaker at the shore-based plant. This operates directly if the fault occurs in the generating station end or via carrier if the fault is in the load module transformer. The breaker cycles through a recloser similar to that for the surface-tendered plant. If the system operates on HVDC, additional protection is required.

In the HVDC system the conversion or rectifier unit may be provided with a failure detector, failure counter and a voltage detector. These devices are required on both ends of the HVDC link, since the control is for power reversal.

The protective system for the inverter, or load module end, covers such conditions as: commutation failure, pulse synchronization, and fire-through. The converter or generator end is protected for commutation failure and fire-through. For either of these faults an alarm is given, and an indication of the fault is recorded to allow and direct remedial action. An auxiliary pulse generator replaces the normal unit for a few cycles so that power flow can be maintained while the circuit is checked. If the fault is transient, the system automatically resets to normal operation. If the fault remains and is at the load module or inverter end, then the carrier is tripped to open the main breaker at the power plant end. If the fault is at the converter or generator end, it trips the main breaker directly.

All faults in the HVDC link have to be referred to the AC side on both ends and to the shore-based main breaker for interruption, because high-power direct-current interruptors or circuit breakers do not exist.

In the case of the fault and voltage detectors, these units should be provided with a time delay before calling for a trip action.

If a failure occurs in the HVDC line the converter at the generating plant must be stopped in order to interrupt the circuit. In this case, any fault shuts down the converter and after a suitable delay the main breaker trips. Since shut-down of the converter is accomplished by grid control, an auxiliary switch is provided at the grid so that, when the converter is blocked from operation, a contact will close, permitting the main breaker trip circuit to be energized. At the time of failure it is desirable to know whether it is a line or inverter fault. Corrective action is different in each case, since the inverter is able to recover in many cases without interruption of the transmission line. This distinction can be made by a sensing circuit which checks the DC control voltage of the phase-controlled pulse generator. The fast and reliable action of solid state devices makes it possible to detect these problems, to initiate corrective action for undesirable conditions without interruption of power flow, and to remove the equipment for a continuing fault.

The protection system proposed here may change as the state of the art advances and may be different when units of the size proposed for this application are available in the time period 1970-1975.

Chapter 7

HULLS

This chapter presents a selection of hulls for the surface-tendered and in situ underwater power transmission systems which are compatible with the power levels and depths under consideration. To properly analyze hull sizing to enable preliminary selection, an analysis was conducted on all candidate hulls with respect to the following:

- construction, material and protection from the environment (i.e., cathodic, fouling)
- arrangement, configuration, maintainability, and reliability
- hydrodynamic characteristics during deployment, station keeping, and recovery operations
- establish that the hull selected is capable of deployment/recovery.

7.1 SURFACE POWER PLANT HULLS

The operational objectives which controlled the selection of the hull shape for the surface power plant are:

- continued operation under extreme weather conditions
- unattended deployment for long periods of time
- safety of the power plant station, associated systems, and the dependent submerged load module.

Continued operation under extreme weather conditions is required to supply an uninterrupted power supply to the load. Consequently, a snorkel induction and engine exhaust system are required. Snorkel systems are state-of-the-art and can be sized for each individual power plant. The hull must be stable to ensure continued operation under the most severe weather conditions. Study shows (Chapter 3) the hulls selected should withstand 150 MPH winds, 60-ft-high waves (breaking) and 10-knot currents[1]. To prevent snorkel high vacuum or back pressure cutouts from shutting down the plant, thus interrupting the power supply, the snorkel mast must be out of the water virtually all the time, except when waves are breaking.

The recommended surface power plant and hull systems are unmanned. Unattended deployment requires all systems to be automated. Trim and compensation systems, for example, may be controlled remotely by radio or other suitable means. In the event the load module is manned, as in MUS, and the surface hull is manned, the control system is simpler. The interior volume is not space limited and, if necessary, personnel quarters can be incorporated very simply and at low cost.

Safety is of utmost importance to protect the integrity of the entire system. Double hull construction of the thick-disc buoy, together with its high stability, ensure maximum safety. Similarly, all systems are engineered with fail-safe features so that the underwater power transmission system is protected.

7.1.1 Concepts Considered

A FLIP[2]-type ship was considered, but is too costly for this application. Possibly it would be applicable for long range deployment with the larger power plants. It would be capable of storing large quantities of fuel in a compensated fuel system. Cheaper methods of fuel storage are discussed in paragraph 7.1.2.4, and for this reason FLIP was not considered further, even though it would probably provide an excellent station.

Use of a fleet submarine was also investigated, but was found to be too costly and was not pursued further. The conclusions reached in this investigation are given below.

- Fleet submarines coming out of service could be plugged into any mooring system on a short term basis of 6 months to 1-year tests. This would eliminate initial yard outfitting costs that would be incurred if the ship were taken from the mothball fleet.
- A submarine has the advantages that it does not have to be towed to site and has living quarters and auxiliary machinery aboard.
- A submarine's machinery life expectancy would be approximately 1/4 or 1/5 that of new machinery. Similarly, cost of repair would increase and operational availability decrease.
- Fleet submarines generate DC. They can meet some load requirements generating DC, but not all. Cost of converting to AC generators would be prohibitive.
- In severe sea states, a submarine would impose an excessive load on the mooring system designed for a thick-disc hull. During the worst environmental conditions, operation would probably have to be interrupted, a disconnection made and the submarine would ride out the storm under its own propulsion.
- A submarine was considered for submerged snorkel duty on station; however, it presents too many problems. It cannot be deployed deep enough to eliminate surface effects for the assumed sea conditions. It is difficult to maintain snorkel depth and would require manning. It would still present excessive drag on the mooring system envisioned. Paragraph 8.1.3 gives a formula relating drag to wetted hull surface.

NOMAD type buoys[1] exhibit resonant motion in roll and are not symmetrical, tending to make them unsatisfactory. In addition, the purpose of their basic hull design would be defeated by multiple-point mooring.

The possibility of a submerged surface plant to eliminate adverse surface effects on the hull and mooring system was investigated. A plant submerged to 100 ft or 200 ft with a snorkel mast housing intake air and exhaust gas ducting, an entrance passage, radio antenna, navigational lights, etc., was considered. Mooring would have been 2-or 3-point taut-line similar to SQUAW deployment [2]. The concept was dropped in favor of the thick-disc surface hull because the submerged hull displayed the following disadvantages.

- With the snorkel mast exposed to atmosphere, it would remain a hazard to navigation.
- A 100-or 200-ft snorkel mast is not feasible structurally and, if it were, it would still induce surface effects on the submerged plant.
- The surface plant is safer in the event of a collision due to its double hull construction, whereas even the refueling vessel could seriously damage the snorkel mast in coming alongside.
- Hull cost of the submerged vessel would be higher due to the heavier skin required.
- Submerged vessel deployment costs are higher. A built-in winch system would be required to surface or submerge the hull to its mooring foundation. When surfaced, the mast, possibly reaching 200 ft in the air, would present a stability problem. Movement of the electrical submarine cable would also have to be provided for during these position changes.

Shapes that remain vertical in the presence of some waves display resonant motion in response to others. Hull sizes practical for use as unattended oceanographic buoys or stations respond to waves of one or more critical periods. Square or rectangular barge shapes of conventional industrial proportions were considered and ruled out in favor of the round disc to ensure minimum drag loads on the mooring system. A square barge may be useful for a particular short-term application, but is not feasible for the long haul in high seas.

7.1.2 Hull Shape Selected

The surface power plant containment vessels selected are unmanned, double-hull, thick-disc, surface-following, steel structures of modular construction. The five power levels required fit into three basic hull designs. Power plant and station keeping are fully automated. Hulls are not space limited, thus eliminating arrangement problems. Snorkel systems are included with all hulls to ensure continuous operations regardless of weather. Modular construction permits complete machinery space interchange to eliminate at-sea overhaul, increase system reliability, and allow power plant interchange so that smaller power modules can be installed to achieve increased fuel capacity. Interchange of power levels among buoys provides the fuel replenishment-schedule flexibility necessary for wide deployment areas.

7.1.2.1 SURFACE POWER PLANT CONTAINMENT, THICK-DISC HULL - Table 7-I lists the dimensions of the thick-disc, double hulls selected to house the surface power plants.

Table 7-I. Thick-Disc Hull Dimensions

POWER LEVEL (KW)	OUTSIDE DIAMETER (FT)	CENTER HEIGHT (FT)
30	41	7-1/2
100	55-1/2	9-1/2
300	55-1/2	9-1/2
1000	55-1/2	11-1/2
3000	55-1/2	11-1/2

Extensive testing by the Convair division of General Dynamics, proved the thick-disc shape has superior hydrodynamic characteristics over all other shapes tested[1]. The typical configuration is shown in Figure 7-1. The hulls selected have been scaled to approximately the same proportions as the proven "Monster Buoy" dimensions to be consistent with the hydrodynamic characteristics demonstrated during the original model tests. The thick-disc hull will provide optimum performance at minimum cost because the structural engineering has been documented and the hull is of proven design. Remaining engineering consists of integrating the various systems, their interfaces, and arrangements.

7.1.2.2 HULL SIZING - Table 7-II summarizes all the pertinent information on the buoys proposed. Machinery weight and volume, hull weight, reserve buoyancy capacity, interior volume, fuel storage and trim system capacities, hull characteristics, and typical fuel replenishment schedules have all been defined. For the 30- through 300-KW plants, the hull has been selected to exhibit 3 lbs of reserve buoyancy for every 2 lbs of on-station displacement. The 1000-and 3000-KW plants exhibit more nearly a 50-50 ratio of reserve buoyancy capacity to displacement. This reduction in reserve buoyancy is recommended to provide a larger onboard fuel capacity to enable a reasonable refueling cycle for the larger power plants. Reduction of the reserve buoyancy on these buoys will not induce detrimental effects during normal or severe environmental conditions. Limited testing on large diameter "Monster"-type buoys by Convair has indicated that greater stability was exhibited with increasing hull diameter. The limit is not exactly known. It is approximately 55-58 ft.

The hull is not space limited. Therefore, arrangement will present no major problems. A double hull construction arrangement is recommended; the fuel and compensation tanks are located around the periphery and the machinery space module is in the center. The hulls recommended exhibit high freeboard. The water line should be maintained on the tapered bottom portion. To ensure this during design, it may be possible to change the angle of the tapered bottom to approximately 45° from vertical without significantly increasing drag loads. The various capacities specified in Table 7-II appeared most feasible for the recommended systems.

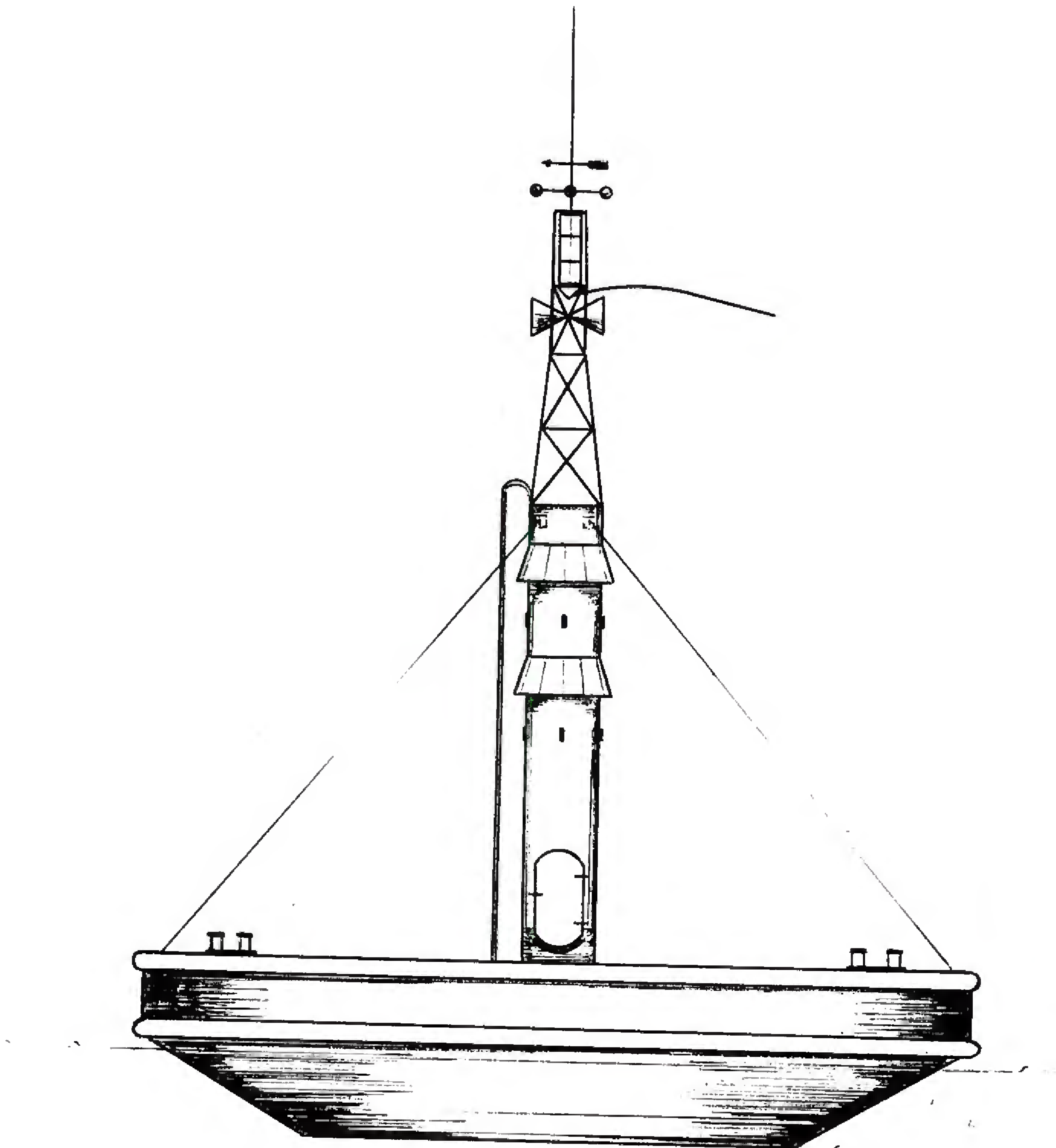


Figure 7-1. Typical Thick-Disc Hull Configuration

Table 7-II. Thick-Disc Hull Characteristics

POWER PLANT	MACHINERY REQUIREMENTS MIN WORK VOLUME	MACHINERY REQUIREMENTS WEIGHT	EST HULL WEIGHT	RESERVE BUOY CAPACITY	USABLE INTERIOR VOLUME	FUEL STORAGE CAPACITY	
(KW)	(FT^2)	(LBS)	(LBS)	(LBS)	(FT^3)	(FT^3)	(LBS)
30	541	9,080	100,000	347,000–415,500	7,100	1272	68,500
100	667	10,860	159,000	687,000	9,785	4120	228,000
300	1831	24,640	159,000	673,000	9,800	4120	228,000
1000	5040	76,225	220,000	787,000	9,800	8240	456,000
3000	9028	199,450	220,000	665,000	9,800	8240	456,000

POWER PLANT	TRIM SYSTEM CAPACITY	HULL CHARACTERISTICS OUTSIDE DIAM	HULL CHARACTERISTICS CENTER HEIGHT	HULL CHARACTERISTICS VOLUME	HULL CHARACTERISTICS WEIGHT LOADED (DISPLACEMENT)	TOTAL CONTAINMENT	FUEL REPLENISHMENT DATA SUGGESTED SCHEDULE	FUEL REPLENISHMENT DATA ONBOARD SUPPLY
(KW)	(LBS)	(FT)	(FT)	FT^3	(LBS)	(LBS)	(DAYS)	(DAYS)
30	50,000	41	7-1/2	9000	228,000	575,000	90	120
100	244,000	55-1/2	9-1/2	17775	448,000	1,135,000	90	120
300	244,000	55-1/2	9-1/2	17775	448,000	1,135,000	30	47
1000	487,500	55-1/2	11-1/2	25650	853,000	1,640,000	26	33
3000	487,500	55-1/2	11-1/2	25650	975,450	1,640,000	5-7	10

All buoys selected are sized to carry a 50,000 lb external load imposed by the submarine cable. The trim system was sized to compensate for any fraction of this load in the event lower cable loads are imposed. The largest hull (1000 and 3000 KW) which features a reduced reserve buoyancy/displacement ratio was sized to carry an additional 50,000 lb external load to allow for mooring cable and fouling loads. This was unnecessary on the 30-to 300-KW hulls because a large amount of reserve buoyancy is available. Buoyancy devices will be utilized on the transmission and mooring cables to these loads.

7.1.2.3 CONSTRUCTION - Welded, double-hull construction from low carbon steel is recommended for the hulls for the surface-tendered power plant. The outer skin and sections where higher strength is required will be fabricated from ASTM type A-212 normalized steel. Structural sections and general plates will be fabricated from ASTM type A-36 carbon steel. Typical properties of these steels are:

Material	Tensile psi	Yield psi
A-212	65-75,000	35,000
A-36	60-80,000	36,000

Where dissimilar metals must be used, such as snorkel sensors, it should be electrically insulated from the parent structure where possible. The external skin should be fabricated from at least 1/4-inch plate. All joints should be completely welded, both sides. The snorkel induction mast should be located at top center of the buoy and have an entrance hatch, navigational lights, and radio antenna at the top, as required.

The 1000-and 3000-KW plants feature engine generator sets with an overall installed height in excess of 11-1/2 ft. It is anticipated that a small superstructure, approximately 4 ft high, can be situated over these high places on deck without changing hull characteristics. This superstructure has not been included in the interior volume column of Table 7-II,and machinery compartment volume will increase in proportion to its size.

The entire machinery space can be constructed as a module. Service vehicles will be able to go to the mooring site, lift out one module (or modules), and replace them with newly overhauled units. Installation would be completed by making a minimum of piping and wiring connections. This type of construction will prove reliable and cost effective over the life of the moored station.

Preparation of the hull will consist of sandblasting it inside and out; painting all surfaces with inorganic zinc Dimetcote or the equivalent prior to vinyl painting. This treatment to date has shown outstanding resistance to corrosion in ocean environment both above and below the waterline[1]. Painting all compartments and tanks is recommended because leakage, flooding and condensation make it possible for interior surfaces to be exposed to a corrosive atmosphere. All hatch covers, manhole covers, etc., should be painted on all sides before they are sealed shut. The hull should be adequately provided with zinc anode blocks or equivalent cathodic protection system for additional protection. Anodes may be inspected and changed on a yearly schedule.

To provide further engineering and design economy, it appears feasible to fit the 300- and 100-KW plants into the same size hull (55-1/2 ft outside diameters and 9-1/2 ft thick). Similarly, the 1000-and 3000-KW plants will fit in a hull 55-1/2 ft in diameter by 11-1/2 ft thick.

7.1.2.4 FUEL STORAGE CAPACITY - Fuel storage capacity was obtained by trading off reserve buoyancy capacity, hull diameter, and height. Hull diameter and height were maintained in proportions similar to those proven in Convair tow basin tests. It is questionable how far "Monster Buoy" can be scaled up before its hydrodynamic characteristics change; therefore diameter was held at 55-1/2 ft.

Drag increases in proportion to the draft of the buoy, imposing greater loads on the mooring system. For the purpose of this conceptual study, 55-1/2 ft by 11-1/2 ft were the maximum proportions considered for hull enlargement. This is arbitrary and is based on maintaining good hydrodynamic properties. Little relative importance is placed on fuel storage, other than providing minimum requirements. It may be possible to provide increased fuel storage by increasing the hull size. However, to date, sufficient information and test data are not available to suggest a hull diameter significantly larger than 55 to 58 ft; once data is obtained from the buoys that are either deployed or about to be deployed, further investigation can be accomplished.

Limiting hulls dimensionally to the sizes recommended will result in increased fuel delivery costs. Transportation is the variable factor in fuel costs. It varies in direct proportion to the quantity and distance delivery. Optimum quantity for delivery is 150,000 gal. Quantities larger than this require tanker-size ships capable of delivering in excess of a million gallons. Quantities smaller than 150,000 gal require a vessel of essentially the same size if delivery is made over 100 miles off shore, because smaller ships would not be sea-worthy. This class of vessel costs approximately $45 per hour to operate. Typical delivery costs are 0.4 cents per gallon for delivery 90 miles off shore and 1.1 cents per gallon for delivery 240 miles off shore. Average ocean depths are 600 feet and 6000 feet at 90 and 240 miles off shore, respectively.

Several additional factors must be considered before fuel costs can be optimized to any deployed system. The number of buoys or other stations that can be serviced on any given fueling run is important. For instance, delivery to each station will utilize a portion of the ship's 150,000-gal capacity in proportion to each station's power level. For the purposes of this study, it was assumed that a single buoy will be deployed and serviced; the largest considered has a 65,000-gal capacity.

Distance off shore is also a determining factor. If the power plant is not far off shore and handy to supply, delivery cost will be a small percentage of the total operating cost. Delivery costs to a distant buoy may be a significant percentage of the total operating cost. In the latter case, fuel storage capacity is one of the prime tradeoff areas for size of containment systems.

A noncompensated fuel storage system is recommended for all buoys selected. Trim is accomplished by automatically flooding adjacent salt water tanks. This choice was made because underwater fuel storage and automatic fuel purification systems are still in the developmental stage. As these systems become operational, they offer several important advantages. Fuel storage capacity is virtually unlimited. The positively buoyant submerged fuel storage vessel can be situated between the mooring lines and acts as a large damper to add stability to the system. Storage capacity is obtained at the lowest possible structural costs, because reserve buoyancy hull space is not required. This space was shown to at least double the structure size.

Another tradeoff can also be made between power level and buoy size. The buoy size suggested for each power level (Table 7-I) are considered the most feasible. Once these three buoys are designed, it is quite feasible to interchange some power plant modules in larger hulls; i.e., the 30-KW plant in the 9-1/2 or 11-1/2 ft high hull or the 100-or 300-KW plants in the 11-1/2 ft hull. This enables greater fuel storage capacity in these configurations. This interchange involves nothing more than situating the smaller power units in a larger machinery space module. It has little influence on hull design, but significantly increases time between fuel replenishment deliveries. Using the 30-KW plant in the 55-1/2-ft by 9-1/2-ft hull enables in excess of 400 days of fuel to be carried onboard. Similarly, the 100-KW power plant module could be deployed in the 41-ft by 7-1/2-ft hull if it should ever be necessary. This feature reflects the cost effectiveness of the selected hulls.

7.1.2.5 TRIM SYSTEM - When the buoy is initially filled with fuel, the fuel tanks are full and trim tanks empty. The portion of reserve buoyancy space partitioned off into trim tanks is periodically compensated with sea water as fuel is consumed so the waterline (net reserve buoyancy) remains approximately constant. In cases where reserve buoyancy is sacrificed for additional payload, it appears feasible to consume approximately 25 percent of the fuel before beginning to compensate with sea water. An automatically controlled trim system is recommended. As an added safety feature, an emergency system capable of blowing all fuel and ballast and securing all engines in the event of serious flooding or collision is incorporated. This requires air banks. Larger power plants (1000 and 3000 KW) are equipped with compressors and air banks for engine starting. This feature imposes little added complexity. Other units can be equipped with emergency air banks that are charged when fuel is added. The trim system also compensates for any fraction of the external cable loading not utilized. If some load ballast of this type is required, fuel could be used, thus simultaneously increasing fuel storage capacity.

7.1.2.6 UPKEEP SCHEDULE — One of the major factors in deploying a system of this type is laying the multi-point mooring system. Once this system is deployed, it is not considered feasible to take it up every few years for overhaul or component replacement. For this reason, it is expected that, when a surface power plant is deployed to station, the hull will remain on station for five years. This span may not be consistent with the required engine and generator annual or biannual overhaul schedules. Since all the machinery is modular, a service vessel can go to the site, lift out one module (or more) and replace it with newly overhauled units. This plan is much preferred over attempting at-sea overhaul or lengthy maintenance of machinery. It will prove much more reliable and result in a minimum of power interruptions to the load module.

7.1.2.7 MOORING ATTACHMENT - A multi-point mooring system is within the state-of-the-art and required for all buoys under construction. "Monster Buoy" exhibited optimum hydrodynamic characteristics when a single mooring line was attached at the bottom center of the buoy. For a four-point mooring system, the four mooring lines, spaced approximately 90^{o} apart, will enter hawsepipes in the bottom of the buoy at the corners of a square approximately 10 to 15 ft on a side. This spacing is necessary to provide the buoy with a restoring couple to counteract wave-induced rotation. The buoy will exhibit essentially the same hydrodynamic properties. This arrangement of mooring points is preferred to on-deck mooring points because the latter may cause the buoy to "tow under" in heavy seas. Since all hulls will have the same attachment configuration, it would be possible to interchange hulls in a moor by transferring mooring lines one at a time.

7.1.2.8 HULL VULNERABILITY - Potential failure modes that could plague a surface-tendered power plant are as follows:

1. Ocean vessel collides with surface-tendered power plant hull.
2. Service or refueling vessel collides with hull.
3. Direct covert action.
4. Vandalism.
5. Hull or piping leakage.

Surface-tendered power plants should not be situated directly in a prescribed shipping lane. Charts must be updated to account for its presence and restricted areas will be established to in general keep shipping away from the site. The power station will be an obvious radar contact. However, shipping may be driven off course in bad weather or experience equipment failure--thus, the possibility of collision is ever present. The double hull, egg-crate construction is expected to provide good protection. The round shape of the hull and its hydrodynamic properties will minimize the impact of a collision. Except in the event where the collision path traverses the center 20 ft of the hull (head on), the collision will result in a severe fending. The head-on collision would probably sink the station if the vessel was an ocean liner traveling at standard speed. The station may have a good chance of surviving all other impacts.

The reserve buoyancy/displacement ratio of 1:2 to 3:5 for the hulls considered, coupled with the egg-crate construction, the automatic bilge (and reserve buoyancy space) pumping system, and the reserve buoyancy and fuel tank blow down system, make the surface-tendered power plants less vunerable to sinking. Interruption of the power supply would be one of the last events to take place following a sinking because of the central location of the power module. All mooring lines, the power cable, and the facilities tie to the center of the hull, minimizing their involvement if the hull is deformed at the periphery.

The likelihood of a service ship colliding with the station (e.g., during refueling) is much more likely to occur than a collision with a radar-equipped ocean liner. Because of the low relative speeds of the two hulls during approach, damage anticipated would be minor; in fact, the service ship might have welding facilities adequate to place a patch over the damaged area. Protection systems remain the same as described above. A pipe structure surrounding the hull similar to the prop guard on submarines and destroyers will minimize hull contact during servicing; it is recommended.

Damage inflicted by direct covert action (e.g., torpedo or bomb) will interrupt the supply of power; therefore, for covert operation the in situ plant should be used. Egg-crate compartmentation is the best protection against torpedoes. A man-of-war uses alternate compartments for torpedo protection. Basically, the arrangement, from outboard to inboard is, empty, full, empty, etc. Five to six, 2-ft thick compartments have been found to offer good protection. The aforementioned hull fending guard could be built up of 5 ft of foam and structure to impede torpedo progress 5 ft from the hull, thus reducing penetration. Armor plate around the periphery would also be helpful. Below the waterline the tapered-hull bottom does not afford the approaching torpedo right angle contact, thus reducing hull penetration. Consideration may be given to stretching a net between mooring lines for torpedo protection. This net would be located at a safe distance from the hull, e.g., 50 to 100 ft, and would require some small surface buoys for support. Bomb protection is somewhat more difficult to achieve but would require the same strategy, namely, deflection and early detonation. A bomb would stand a better chance than a torpedo of penetrating the vulnerable core-section of the hull where the power module is contained and interrupting the power supply. The hull stands a good chance of surviving a single bomb or torpedo hit, however, it is vulnerable to sinking if a determined enemy strikes it repeatedly.

Vandalism is ever a problem on buoys deployed at sea. The surface-tendered power plant moorings and power cable are well protected from free-breathing skin divers because they are located under the center of a massive structure. The swimmer would have to swin 20 to 50 ft underwater before he would reach the bottom cables. The deck and mast will be as void of equipment and devices as possible. Fuel supply connections will incorporate special locking devices to preclude pilfering or contamination. Coast Guard-required navigational lights and horn will be less vulnerable than on conventional navigational buoys because they will be high up on a more massive structure. The snorkel induction and exhaust holes will be inconspicuously located. Adequate spring-loaded safety valves may be included to circumvent the possibility of someone clamping a device over the snorkel ports; the determined vandal could eventually obstruct the air or exhaust system, blow off deck hatches, or drill holes in the hull.

Hull or piping damage or failure is possible; e.g., failure of engine cooling system. Bilge pumps will be sized to automatically cycle and keep the condition in check, while remote indication of the continuously operating pump will justify a service inspection. Power supply may or may not be interrupted, depending on engine temperature parameters. Hull stop valves will be provided but operated only as a last resort. If fuel oil is flooding the power module, a bilge pump is actuated; power should not be interrupted, but the problem will show up as accelerated fuel consumption as well as excessive bilge pump operation.

7.2 IN SITU POWER PLANT HULLS

Final hull design depends on the hydrodynamic characteristics of the deployment/recovery method selected, particularly for in situ underwater power transmission systems. The in situ power module could be incorporated into a hull for deployment to the operational depths completely independent of any load module; however, since the "wet electrical connectors" (see Chapter 5) required to mate the load module with the power module in the deployed state do not exist, the effort would be entirely hypothetical. The final hydrodynamic characteristics of the in situ station consider the lack of appropriate connectors and are based on deploying the load and power modules together on a common foundation. The alternate method of deploying each module separately with long electrical cables to be joined on the surface then dropped to the bottom was not considered because it jeopardizes mission reliability. If the cable is connected on the surface and dropped, it could induce large overturning moments (proportional to tension in the cable) on the station during surface splicing, or it could entangle the modules as it falls. The added costs are also an influencing factor, particularly for the deeper depths where excessive cable lengths are required. Upon availability of wet connectors (see Chapter 11), the designs could be modified to allow individual placement followed by in situ electrical uniting.

The operational objectives which controlled the selection of the hull shape and final configuration are as follows:

- Hulls must exhibit the integrity and degree of safety expected of a nuclear power plant while providing a protection from the sea for the underwater power transmission systems equipment.
- They must be able to be deployed for long periods of time unattended.
- They must possess hydrodynamic stability during all modes of operation.
- Deployment/recovery schemes must be safe, reliable, and within the state-of-the-art.

Safety was held to be of prime importance to insure the integrity of the entire system. Power module pressure vessel stress and material analysis will be required to ensure maximum construction economy for depths under consideration. A power plant-load module configuration analysis will be required to compare advantages and disadvantages of virtually all possible deployment concepts. In addition, a detailed investigation of hydrodynamic phenomena influencing the station while submerged will be required to engineer the methods of deployment and recovery.

7.2.1 Power Module

The economy of containment vessel concepts developed for underwater power transmission systems depends largely on the selection of economical structures that meet environmental conditions and service requirements. Containment vessels for the in situ stations will be constructed in a manner similar to existing submersible hulls. No major new material technology problems occur until the working depth of the station becomes very great, say more than 10,000 ft. Assuming that HY-130 steel may be used, this depth is attainable. Maintenance associated primarily with marine fouling and sea water corrosion of hull materials deployed for longer than 2 or 3 years is based on the development of suitable protection systems. The protection system for the in situ plant must also be compatible with heat transfer requirements.

7.2.1.1 PRESSURE VESSEL ANALYSIS - The two modes of failure which must be considered for thin shells subjected to external pressures are collapse by yielding and collapse by buckling. For this study, the minimum factors of safety applied to these modes will be 1.5 and 2.0 respectively, with local stresses limited to 3/4 of the yield stress at operating depth.

Nomenclature

E_S = secant modulus of elasticity

E_T = tangent modulus of elasticity

h = shell thickness

R_{LO} = local outside radius of spherical shell

a = nominal outside shell radius

σy = yield stress

σm = membrane stress

p_{cb} = critical buckling pressure

p_{cy} = critical yielding pressure

F.S. = factor of safety

Spheres and Hemi-head - The general equation for collapse by yielding of a sphere is:

$$p_{cy} \cong \frac{2h\sigma_y}{R_{LO}}$$

The basic equation of buckling in spheres is

$$p_{cb} = 0.84 \sqrt{E_S E_F} \left(\frac{h}{R_{LO}} \right)^2$$

For elastic buckling, this reduces to

$$p_{cb} = 0.84E \left(\frac{h}{R_{LO}} \right)^2$$

Cylindrical Shells - The equations governing collapse of cylindrical shells are considerably more complex than those for spheres. The method used for this study was to choose conservative shell and frame dimensions using a method developed by General Dynamics Corporation, and then refine the design in an iterative procedure.

Analysis of collapse by yielding for a cylinder plus hemi-heads was carried out using a program developed by General Dynamics entitled "Circular Cylindrical Shell with Bulkheads and Intermediate Stiffeners Subjected to Hydrostatic Pressure." This program calculates outer fiber, midfiber and innerfiber stresses at frames and mid-bay, as well as deflections and local stresses. Computer runs alternated with hand calculations to check buckling. The computer analysis was based on Reference 3. The cone ends were treated as an extension of the main cylinder for this investigation.

There are two types of buckling which are of concern in this type of cylinder. Lobar buckling occurs in the shell between frames, and can be approximated by:

$$p_b = \frac{2.42E}{(1-\mu^2)^{3/4}} \left[\frac{(h/2a)^{5/2}}{\frac{L}{2a} - 0.45 \sqrt{2ah}} \right] \quad \mu = \text{Poisson's Ratio}$$

Critical pressures for buckling in these cases are on the order of 3×10^5 psi. Buckling due to general instability occurs over the entire length of the shell and can be approximated by:

$$P_b = \frac{Eh}{a}\left[\frac{m^4}{\left(n^2 - 1 + \frac{m^2}{2}\right)\left(n^2 + m^2\right)^2}\right] + \frac{(n^2 - 1)\,EI}{R^3}$$

$m = \frac{\pi a}{L}$

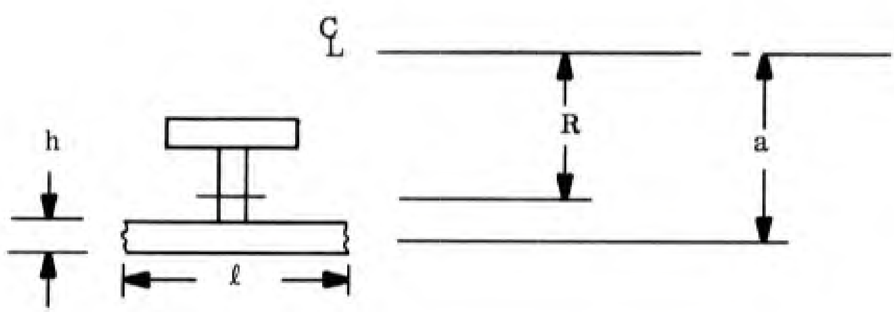
n = number of lobes

L = effective length of cylinder

= length of frame-shell section (see Figure 7-2 below)

I = moment of inertia of shell-frame section (see Figure 7-2 below)

R = radius of frame-shell section (see Figure 7-2 below)



ℓ = frame-frame length or 1.57 ah, whichever is least

Figure 7-2. Frame-Shell Section of Cylindrical Pressure Vessel

These designs are conservative and will maintain reasonable yielding and buckling collapse loads. Since a detailed analysis of the entire structure, including reinforcements, openings, etc. has not been performed, definitive collapse pressures cannot be assigned.

Reinforcements at junctions of spheres and cylinders, cone and cylinders, and sphere junction areas are conservatively designed, and weight savings may be expected in these areas.

7.2.1.2 MATERIAL ANALYSIS - The principal problems associated with submerged power plants will be encountered at very great ocean depths. The use of high strength material is required to provide sufficient buoyancy to refloat the plant. Material selection is the root of the material versus syntatic foam tradeoff. Figure 7-3 illustrates the basic material selection problem. These curves were developed primarily for spherical shells, which are generally more efficient than ring-stiffened cylinders or other shapes. The curves are invalid for shallow depths where elastic stability is the predominating design criteria. A cut-off is arbitrarily made at a yield strength of 80,000 psi. The curves show the extent to which higher strength material may improve hull weight-to-displacement ratios.

Based on the curves, the strongest state-of-the-art steel material (HY-130) allows a hull weight-to-displacement ratio ($\frac{W_s}{W_b}$) as low as 0.60 for 10,000 ft. Newer, developmental materials such as the 9 Ni-4 Co or 10 Ni maraging steels develop 180,000 psi yield strengths and would allow a $\frac{W_s}{W_b}$ of 0.9 for depths of 20,000 ft. Properties of HY-130 and representative developmental alloys are shown in Table 7-III. Steels with strengths above 180,000 psi for use in sea water are not available at this time. Other lower density developmental materials, such as the higher strength titanium alloys, develop up to 120,000 psi yield strengths and are equivalent to steels of 220,000 to 240,000 psi in terms of $\frac{W_s}{W_b}$ ratio. The low thermal conductivity of titanium and the thicker hulls required makes these alloys a poor substitute for steel where heat transfer is required. Aluminum alloys are also developmental for deep ocean application. They exhibit lower strength and elastic modulus and a desirable heat transfer coefficient. Applications in which aluminum hulls have been used have required greater than usual corrosion and anti-fouling paint schemes. To date, aluminum is better suited for applications where the hull is out of the water a large part of the time.

Table 7-III. Materials for Pressure Vessels for Depths Beyond 10,000 feet

MATERIAL	YIELD STRENGTH (ksi)	DENSITY (lbs/in^3)	RELATIVE Str/Wt	TOUGHNESS ft-lbs
HY-130	130	.285	1.00	50
HP-9-4-20	180	.285	1.38	50
10% Ni Maraging	180	.285	1.38	Not Available
Ti-6A1-4V ELI	120	.160	1.60	15
Ti-6A1-2Cb-1Ta	100	.160	1.36	20

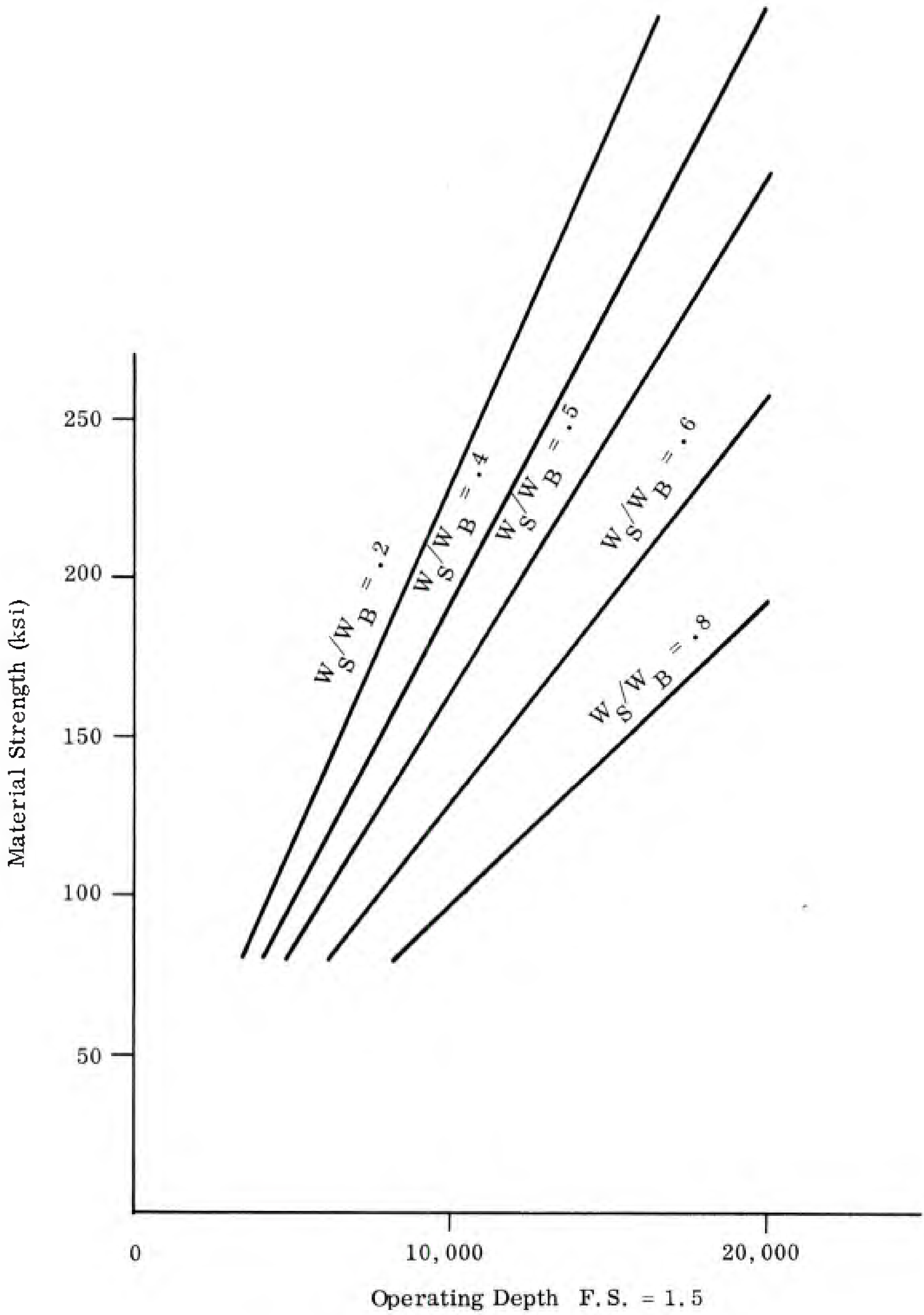


Figure 7-3. Approximate Steel Strengths for Various Buoyancy Ratios (Spherical Shells) and Operating Depths

The developmental materials mentioned above may be used for small research submersibles for operations to 20,000 ft in the next two to three years. Many developmental problems will be solved during that construction effort that will make these materials closer to state-of-the-art. However, the cost of materials and fabrication for deep ocean structures will remain very high for some time.

7.2.1.3 MATERIAL SELECTION - The choice of materials for the power plant containment vessel depends on depth, size requirements (Chapter 4), cost, and the weight-to-displacement ratio.

Hulls for the 600- to over 2000-ft depth ranges may be economically fabricated using HTS and HY-80, respectively. These are the present submarine-hull steels. The power plants considered are not weight critical at these depths and, in the case of the higher power levels, will exhibit positive buoyancy that may have to be overcome later by adding lead. In addition, elastic stability is the predominant design criterion governing wall thickness. It is considered cost effective for these hulls to use lower cost, heavy wall material in lieu of lead. This approach would be subject to change if an exceptionally heavy load module is selected which could advantageously use this positive buoyancy.

Hulls for the 6000- to over 10,000-ft depths ranges require HY-130 steel. This selection is made because it is the most applicable state-of-the-art material. As stronger materials become available, it will be desirable to re-evaluate the material selection for these depths. Power level is limited to 300 KW for these depths, because hull diameters and heat transfer requirements are considered to be outside present technology. Construction of hulls for these depths over 10-12 ft in diameter will be impossible for the foreseeable future. This dictates the use of cylinders of considerable length, (e.g., 66 ft for 300 KW at 10,000 ft).

Table 7-III lists the general properties of several materials that have been proposed for hulls for 10,000 ft or more. As stated, this class of hulls is undergoing developmental breakthroughs in DDSV-type hulls. Based on the foregoing analysis for the purpose of this study, HY-180 steel is selected for underwater power transmission system in situ power plant hulls deployed to 15,000-20,000 ft. This selection will be subject to re-evlauation at the time final design is contemplated. Power plants are similarly limited to the 300 KW power level, because larger hull diameters and heat transfer considerations require major development (see Chapter 4).

Based on power plant arrangements, it was determined in Chapter 4 that a vertical cylindrical envelope, the most efficient volumetric shape, was desirable for 30 to 300 KW power levels. Beyond this level, large-diameter horizontal cylinders are required. This cylinder aspect must be taken into consideration when determining foundation supports for both the internal components and external supports.

Methods of fabrication (welding, forging, rolling, and making closures) vary for each material. Fabrication will be in accordance with accepted standards for each class of vessel and material.

7.2.1.4 CORROSION AND FOULING PROTECTION SYSTEMS - To achieve a long-term (~5-year), no-maintenance mission with no danger of corrosion failure of a hull subject to constant marine environment, very high-quality corrosion protection systems are required. For both submerged hulls and surface buoys, several systems have been proposed. Paint-coating systems, metallized coatings, anti-fouling paints, and cathodic protection systems are currently under study at Electric Boat division for other projects. These make the five-year cycle seem reasonable.

A number of improved corrosion protection systems have been proposed as a result of these studies. They include the following:

- Paint coating systems consisting of zinc based primers followed by several coats of vinyl or straight epoxy paints, with one or two coats of copper-based anti-fouling paint on the surface.
- Metallized coating systems consisting of 3 to 5 mils of flame-sprayed aluminum sealed with a combination of vinyl sealing and top coating paints, and finished with a full wet coat of organotin anti-fouling paint.
- Cu-Ni cladding of steel hull plating by explosive or roll bonding or flame spraying to provide a corrosion resistant surface with inherent anti-fouling characteristics. Alloy selections between 70-30 and 90-10 compositions would determine the better alloy. The fouling and corrosion resistance of cupro-nickel would eliminate the need for paint and cathodic protection and could partially offset the added coat of the coating. Uniform coating thickness (i.e., 1/16 - 1/8") would prevent the possibility of galvanic attack of steel underneath by eliminating breaks in the coating.

For long service life, supplementary cathodic protection in areas of concentration of noble metals, or where stray current corrosion can occur, should be provided. Both sacrificial zinc anode and impressed current systems should be considered.

Interior surfaces in tanks and compartments where leakage or condensation can cause serious corrosion problems should be coated with a zinc primer and vinyl or epoxy topcoat as done on the hull exterior.

The question of the compatibility of coating requirements with heat transfer requirements for pressure hulls used as heat exchangers requires some study. A study to determine exactly the relative thermal resistance of several coating systems as they affect the hull heat exchanger concept should be undertaken as part of this program.

7.2.2 Arrangement Concepts

Arrangement concepts include the relative shape, position, and location of the load module and power (reactor) module.

7.2.2.1 POWER MODULE - In Chapter 4, the reactor plant was discussed and its containment vessel dimensions, cylindrical shape, weight, displacement, and aspect (vertical or horizontal), were established for the various power levels and depths under consideration. Table 7-IV summarizes power plant containment vessel parameters for the present analysis. In Chapter 4, it was determined that the reactor plant is to be unmanned and is to function automatically. No control or instrumentation cable is required between the surface and the in situ power plant. The containment vessel for the purpose of the present study is considered to be the outermost skin of the power module; it may be a pressure hull or a protective envelope around the frames for additional structural protection.

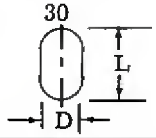
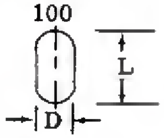
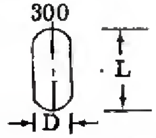
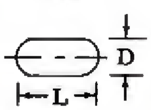
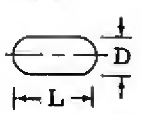
7.2.2.2 LOAD MODULE - For the purpose of this study the load module is assumed to be a vessel having the same volume as the reactor plant, but it may weigh less than the power module. Assuming modules of the same size will allow symmetrical plant arrangement, the weight assumption is justified because reactor plant shielding and large quantities of working fluids represent weights probably not required in the load module. For instance, electronic equipment may occupy the major portion of the load module and represent its entire mission. For the purpose of this study the following additional load module assumptions are made:

- The load module may be inhabited. If inhabited, personnel shielding will have to be considered in great detail, in addition to personnel transfer chambers and similar logistics problems.
- No control or instrumentation cable of any type is required between the surface and the load module. Such a cable requires surface support, is a hazard to navigation, and jeopardizes the reliability of the entire in situ plant.
- An electrical submarine power supply cable 100 ft long carries electrical power from the power plant to the load module.
- The load module, if contained in a pressure vessel, is located in a single cylinder or sphere. Cylindrical and spherical shapes are assumed based on their efficiency as pressure vessels and desirable drag characteristics.

7.2.2.3 CONFIGURATION - Possible arrangement configurations are shown in Figure 7-4 based on Table 7-IV and the foregoing assumptions. They fall into four classes:

1. power plant and load module situated side by side.
2. load module mounted atop the power plant (piggy-back).
3. load module remotely located from the power plant, such as a rock-site application, either mining or military.
4. load module and power plant united into one large containment vessel.

Table 7-IV. Power Plant Containment Vessel Parameters

POWER LEVEL (KW)		DEPTH (FT) AND TYPE OF HULL: 600 HTS	2000 HY 80	6000 HY 130	10000 HY 130	15000 HY 180	20,000 HY 180
30 	INSIDE DIAMETER	9	9	9	9	9	9
	LENGTH (FT)	35	35	35	35	35	35
	TOTAL WT. (LB)	123,500	135,000	167,000	212,000	221,000	260,000
	DISPLACEMENT (LB)	130,500	130,500	130,500	130,500	130,500	130,500
	BUOYANCY (LB)	+ 7,000	- 4,500	- 36,500	- 81,500	- 90,500	-129,500
100 	INSIDE DIAMETER (FT)	10	10	10	10	10	10
	LENGTH (FT)	36-1/2	36-1/2	36-1/2	36-1/2	36-1/2	36-1/2
	TOTAL WT. (LB)	156,000	175,000	215,000	268,000	283,000	333,000
	DISPLACEMENT (LB)	166,500	166,500	166,500	166,500	166,500	166,500
	BUOYANCY (LB)	+ 10,500	- 8,500	- 48,500	-101,500	-116,500	-166,500
300 	INSIDE DIAMETER (FT)	10	10	10	10	10	10
	LENGTH (FT)	55	54	54	61	66	73
	TOTAL WT. (LB)	217,000	245,000	322,000	474,000	550,500	739,000
	DISPLACEMENT (LB)	258,500	253,500	253,500	288,500	315,500	348,500
	BUOYANCY (LB)	+ 43,500	+ 10,500	+ 51,500	-131,500	-138,500	-271,500
1000 	INSIDE DIAMETER (FT)	21	21	(1)	(1)	(1)	(1)
	LENGTH (FT)	46	46				
	TOTAL WT. (LB)	640,000	775,000				
	DISPLACEMENT (LB)	860,000	860,000				
	BUOYANCY (LB)	+220,000	+ 85,000				
3000 	INSIDE DIAMETER (FT)	21	21	(1)	(1)	(1)	(1)
	LENGTH (FT)	51	51				
	TOTAL WT. (LB)	780,000	960,000				
	DISPLACEMENT (LB)	980,000	980,000				
	BUOYANCY (LB)	+200,000	+ 20,000				

(1) DIAMETERS AND HULL SIZE REQUIRED FOR EQUIPMENT AND HEAT TRANSFER CONSIDERATIONS REQUIRE MAJOR DEVELOPMENT

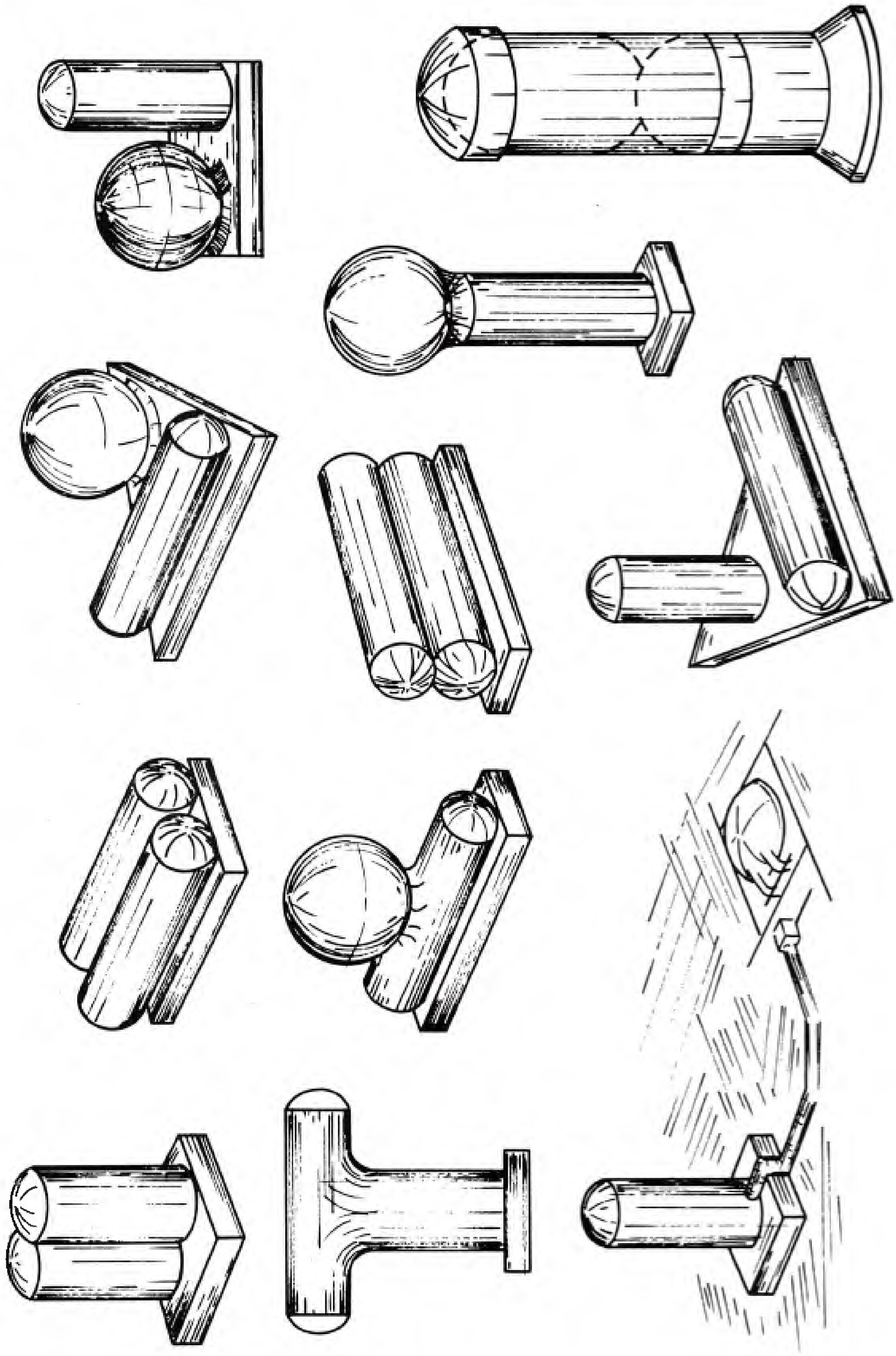


Figure 7-4. In Situ Power Plant Arrangement Concepts

Selection of the best configuration in Figure 7-4 can be made as soon as fundamental in situ plant characteristics are defined:

power level effect,

load module dimensions,

load module weight, and

load module task definitions.

7.2.2.3.1 Power Level Effect - As discussed in Chapter 4, 30-300 KW power plants are contained in vertical cylinders, while the 1000- and 3000-KW power plants are in horizontal cylinders. This imposition narrows the possible aspect selections based on power level.

7.2.2.3.2 Load Module Dimensions - There are two submersible pressure vessel shapes worthy of consideration at depths under consideration: the sphere and the cylinder. The cylinder has two feasible aspects, horizontal and vertical. The shape and configuration selected will depend on both the task definition and efficient space utilization. Relative volume effectiveness of the vessel shapes considered are:[4]

spheres	53%
horizontal cylinders	59%
vertical cylinders	93%

The total displacement required may govern the overall size of these vessels, but effective use of internal space is still a factor to be considered relative to the above analysis.

7.2.2.3.3 Load Module Weight - If the station is built as two bodies of the same or similar weight situated side by side, it will be a simple matter to achieve trim. If the bodies differ greatly in weight, it will be very difficult(and expensive) to achieve trim, in which case it may be desirable to situate the load module on top of the power module so that the load module's center of gravity coincides with the vertical axis through the power module's center of gravity. The arrangement selected must also maintain the overall center of gravity within limits governing hydrodynamic stability and must resist overturning moments. Thus, for those cases where the load module and power plant weights are similar, a side by side configuration is preferred, whereas a "piggy-back" arrangement is preferred if the load module is lighter.

7.2.2.3.4 Load Module Task Definition - Depending on the mission, the orientation of the load module relative to the ocean floor has a definite significance for in situ plant arrangement. If the load module performs work on the ocean floor, it must be situated close to the floor, rather than atop the power plant. If the module is military in nature and the mission involves scanning toward the surface, then it may be more desirable to locate it on top of the power module.

When work must be done on the ocean floor, station arrangement should be such that it may be done adjacent to or beneath the load module. The foundation is influenced by this factor because, for work on the ocean floor, the load module may be located near or cantilevered over the foundation edge. An alternate method may be to provide suitable openings in the foundation directly under the load module. In the latter case, vertical clearance between the module and floor is critical. This clearance may preclude performing certain tasks under the module, such as drilling operations.

The nature of the task may be such that the load module is not situated on the same foundation as the power plant. For instance, it may be desirable to place an in situ power plant alone and connect its electrical output cable to a rock-site or other existing hydrospace or subterranean facility. This concept is dependent on wet connector development previously discussed.

7.2.3 Hydrodynamic Factors

There are certain hydrodynamic factors that must be considered before discussing the various schemes of sinking and raising an in situ power station. These factors are discussed below.

7.2.3.1 BUOYANCY VARIATIONS — Buoyancy variations with depth must be considered in the design and operation of the in situ plant[5]. A plant which gains buoyancy during descent will be inherently safer and require less operator control than a craft, such as the Trieste or Archimedes, which loses buoyancy as the pressures are increased.

These changes in buoyancy are dependent on the physical environment in which the station operates and the characteristics of the hull and its materials. Since

$$B = dV$$

it follows that

$$\Delta B = d.\Delta V + V.\Delta d + \Delta d.\Delta V$$

where

B = buoyancy

d = density

V = volume

Δ = a change to the particular factor.

The volumetric change (ΔV) is dependent on changes in pressure and temperature that the hull experiences in going from the surface to some depth. Thus:

$$\Delta V = \Delta V_p + \Delta V_t = V_o \left(\frac{\Delta P}{K_o} + \alpha_{tv} \Delta t\right)$$

where

V_o = initial volume at zero pressure

ΔP = change in pressure = $P_1 - P_2$

K_o = effective bulk modulus of the hull(s) = $\Delta P/(\Delta V/V_o)$ (use an average over the depth range)

α_{tv} = volumetric coefficient of thermal expansion for the hull and its material

Δt = change in temperature.

The depth may be determined from the pressure (or change in pressure if the initial pressure is considered zero) by the following relationship:

$$D = 2.2438\ P\ (1 - \frac{P}{6.24 \times 10^5} + \frac{P^2}{8.44 \times 10^{10}})$$

where D is in feet and P is in psi. For depth to 6000 feet,

$$P \cong .448D.$$

An accurate determination of the bulk modulus (with initial volume at zero pressure) K_o requires volumetric calculations based on changes in hull dimensions due to pressure effects. The value is approximately 4×10^5 psi for configurations to be presented. Refinements of this value are given for each configuration based on detail calculations for specific cylinders, hemiheads, spheres and cones.

The coefficient of thermal expansion for the hull is dependent on the hull material and may be taken as $6.5 \times 10^{-6}/^{o}F$ for steel. The temperature change is a function of the depth and location selected for the dive if we consider that the hull assumes the temperature of the surrounding water. The maximum temperature change is in the order of 30°C (53°F) considering tropical waters to be as high as 85°F at the surface and everywhere approaching 32°F as the depth increases. It will be noted in the examples that thermal contractions constitute a second order effect on buoyancy changes and therefore do not warrant precise evaluations.

The change in desnity (Δd) is also dependent on pressure and temperature changes plus the effects of salinity variations. Two methods which appear to give low and high values for this change are presented here. In addition, Figure 7-5 illustrates density variations with depth for Atlantic Ocean sea water. This curve may be extrapolated to 20, 000 ft for representative values of density. Some of the figures defining typical sea water parameters were introduced in Chapter 3 and are reshown in this section for convenience of the reader.

Method I. $d = \frac{62.42}{v}$, and $\Delta d = \frac{-62.42\Delta V}{v^2}$

where d is the density in lbs/ft^3 and v is the specific volume.

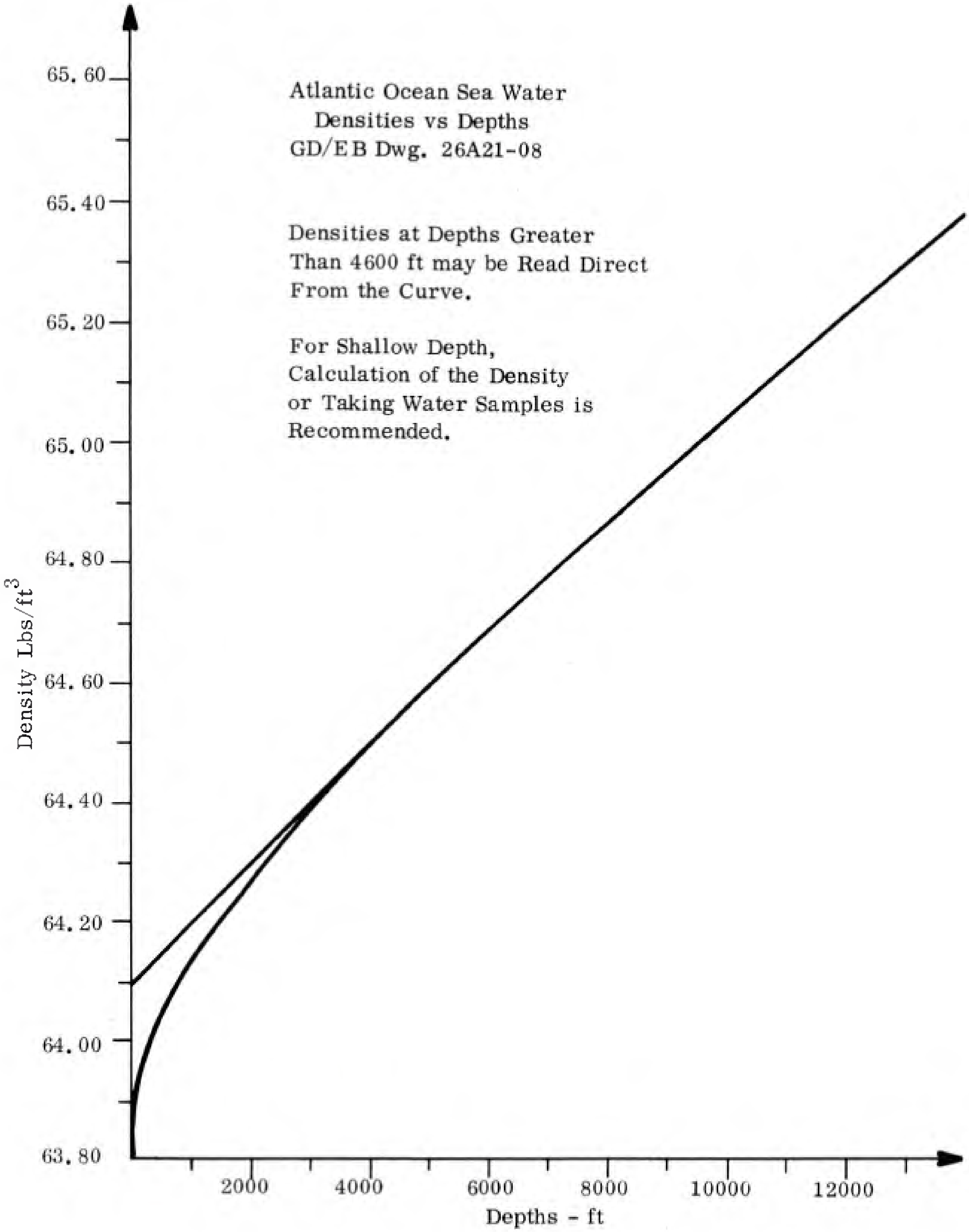


Figure 7-5. Atlantic Ocean Sea Water Density vs Depth

The change in specific volume for sea water is the result of the changes due to temperature/salinity and pressure or

$$\Delta v = \Delta v_{ts} + \Delta v_p$$

$\Delta v_{ts} = \alpha_{ts}\, \Delta t$ (see Figure 7-6 for α_{ts})

$\Delta v_p = \Delta p / K_{avg}$ (see Figure 7-7 for K)

(NOTE: Use the average value of K_0 since we are starting at essentially zero pressure at the surface.)

Method II. The change in density due to temperature and salinity is determined from the changes in specific gravity or

$$\Delta d_{ts} = 64.176\, (\rho_1 - \rho_2)$$

where $\rho = 1 + \sigma\, 10^{-3}$ (see Figure 7-8 for values)

$\Delta d_p = \dfrac{62.42\, \Delta v_p}{v^2}$ as found in Method I.

Therefore $\Delta d_p = \Delta d_{ts} + \Delta d_p$

Depth (pressure), bulk modulus of hull and sea water, and temperature change are the most significant factors in determining buoyancy changes and should therefore be determined at the site and rechecked prior to dive. The above analysis may be used to prove that a submerged object will gain buoyancy during descent. This means that the plant will have to be heavy at the surface by an amount equal to this buoyancy gain in order to attain netural buoyancy at the bottom. This behavior gives a decreasing velocity as the plant descends and allows it to return by jettisoning diving weight. Thus weight does not have to be intermittently dropped during descent in order to maintain control.

The change in buoyancy establishes the magnitude of the diving weight and presupposes that the plant without the diving weight is in neutral trim near the surface. Attainment of this neutral trim is dependent on the initial sea water density and the location of the centers of buoyancy and gravity, which in turn affects the trimming or emergency ballast. Some adjusting capability must be provided for this ballast both in weight and location to maintain the desired plant attitude.

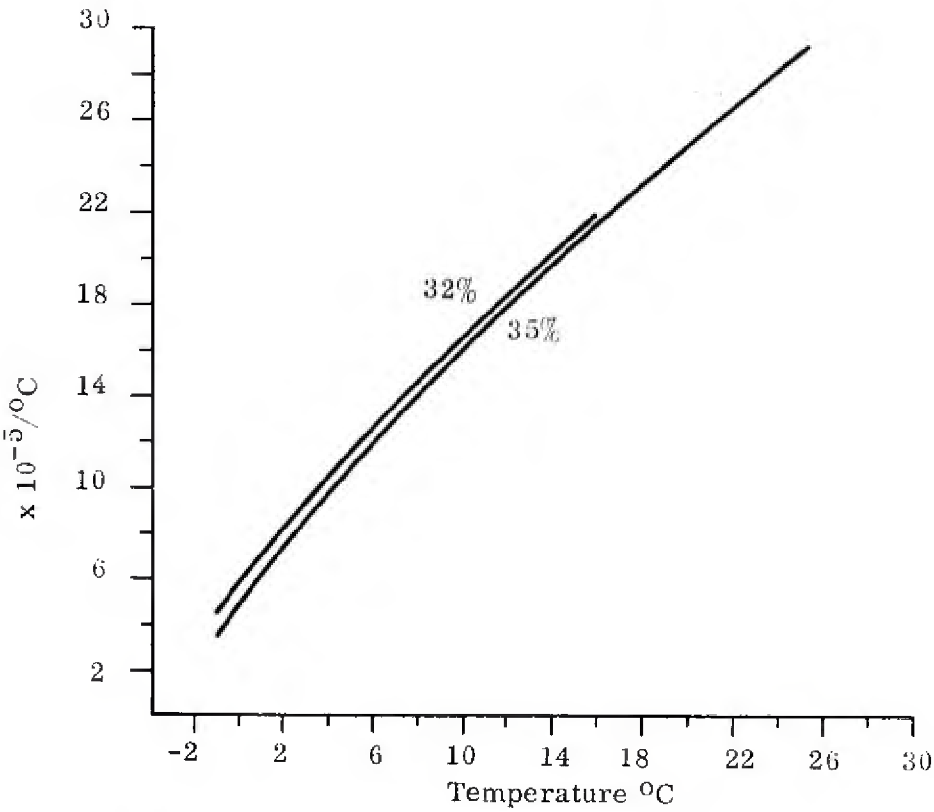


Figure 7-6. Coefficient of Thermal Expansion for Sea Water vs Temperature

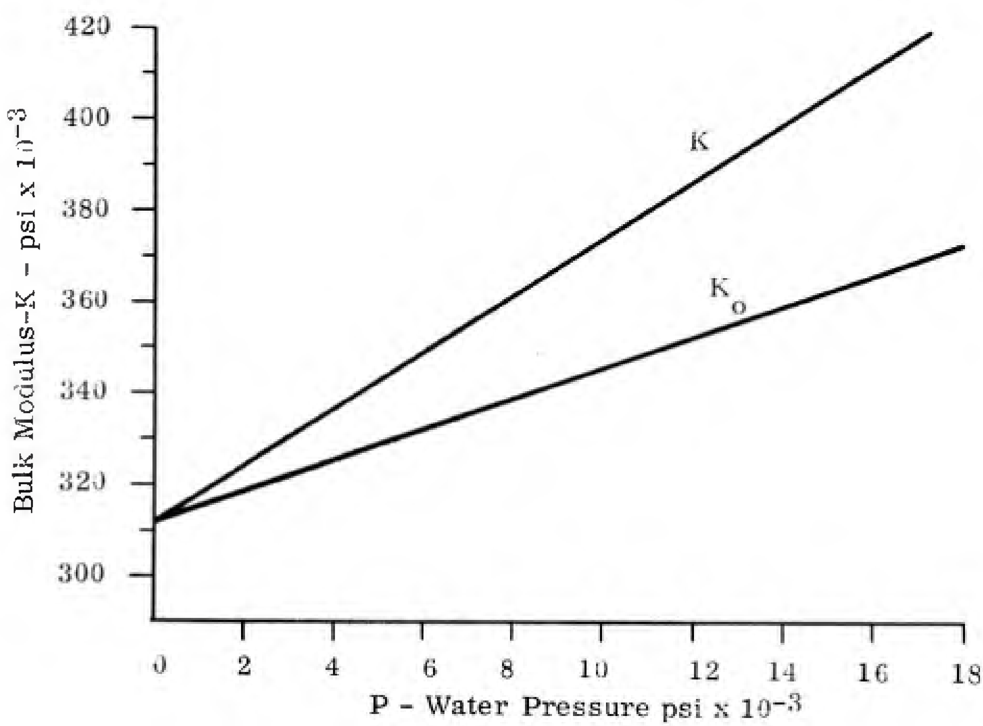


Figure 7-7. Bulk Modulus for Sea Water vs Pressure

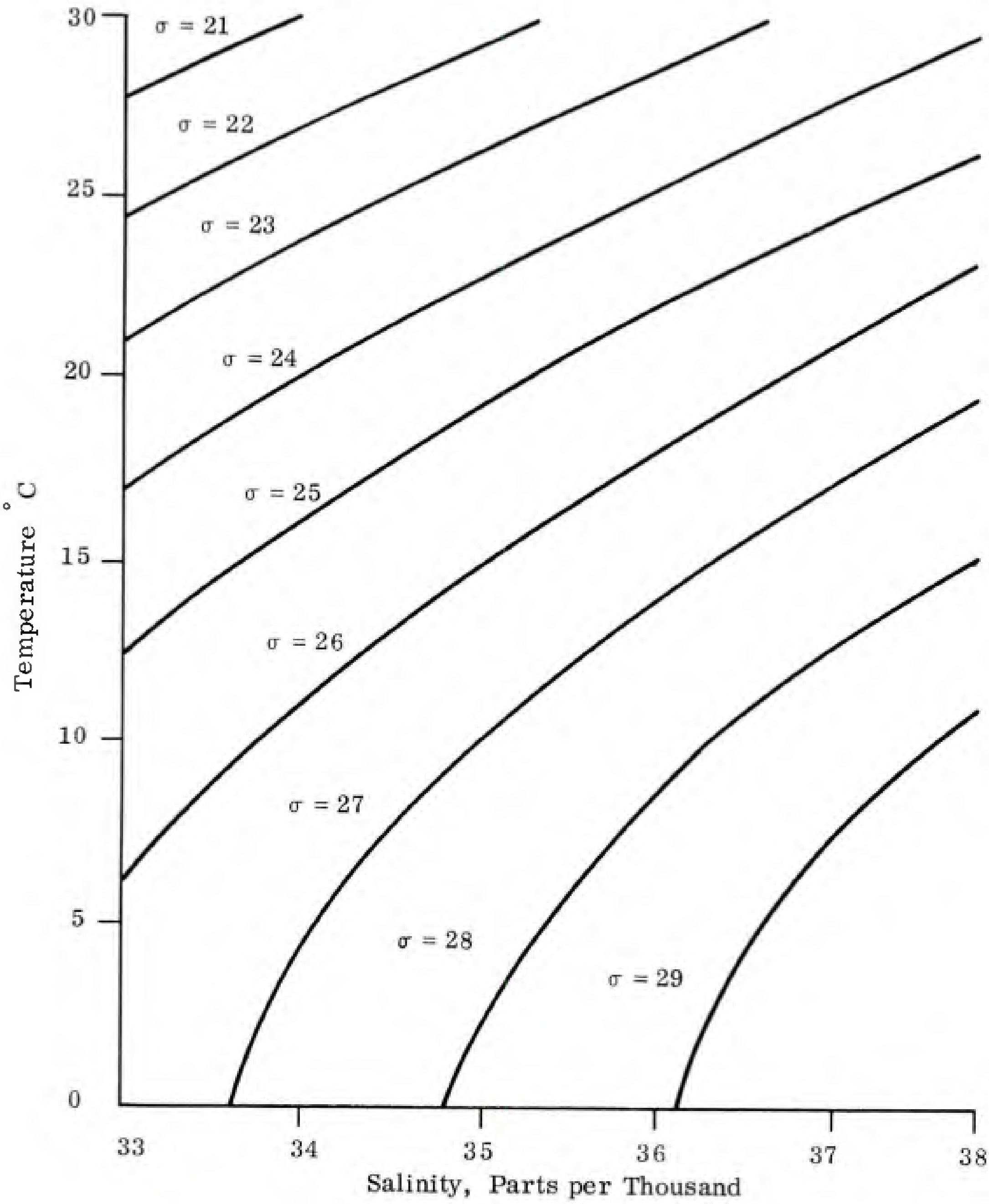


Figure 7-8. Temperature-Salinity Grid

7.2.3.2 THE VELOCITY AND DISPLACEMENT OF A BODY FREELY RISING OR SINKING IN A FLUID - Figure 7-9 presents the time history of the velocity and displacement of a body which is freely rising or sinking vertically in a liquid. The body is assumed to be unpropelled and subject only to inertia, gravity, and fluid forces. The velocity, vertical displacement, and time are all expressed in dimensionless units so that the trajectory of any body may be determined for any initial conditions after the normalizing parameters are established.

The quantities which must be calculated in order to use the curves are V_∞, the terminal velocity, and τ, the characteristic time.

$$V_\infty = \sqrt{2g \left|(c-1)\right| \nabla / C_D A}$$

$$\tau = \frac{V_\infty (c+k)}{g\left|(c-1)\right|}$$

In order to calculate these quantities, we must know the specific gravity of the body ($c = w/\rho g \nabla$), its displacement volume (∇), the drag coefficient (C_D), and the added mass factor (k). Velocities are considered positive in the direction of the terminal velocity:

when $c > 1$, V is positive downward, and when $c < 1$, V is positive upward.

Having established V_∞ and τ, the graph (Figure 7-9) is entered from the left with the initial velocity expressed as a ratio V_0/V_∞. The initial time t/τ is read from the velocity curve (broken line). The initial displacement $Z/1/2\ V_\infty \tau$ is read from the corresponding solid line at the same t/τ. At any later time t/τ, the velocity and displacement ratios may then be read from the same curves. The nomenclature is given below.

- A = appropriate reference area for drag coefficient
- B = buoyancy force
- C_D = drag coefficient
- c = ratio of mass of body to displaced mass of liquid $c = w/\rho g$
- D = hydrodynamic drag
- g = acceleration of gravity
- k = added mass factor
- M = total mass
- t = time
- V = velocity
- V_∞ = terminal velocity

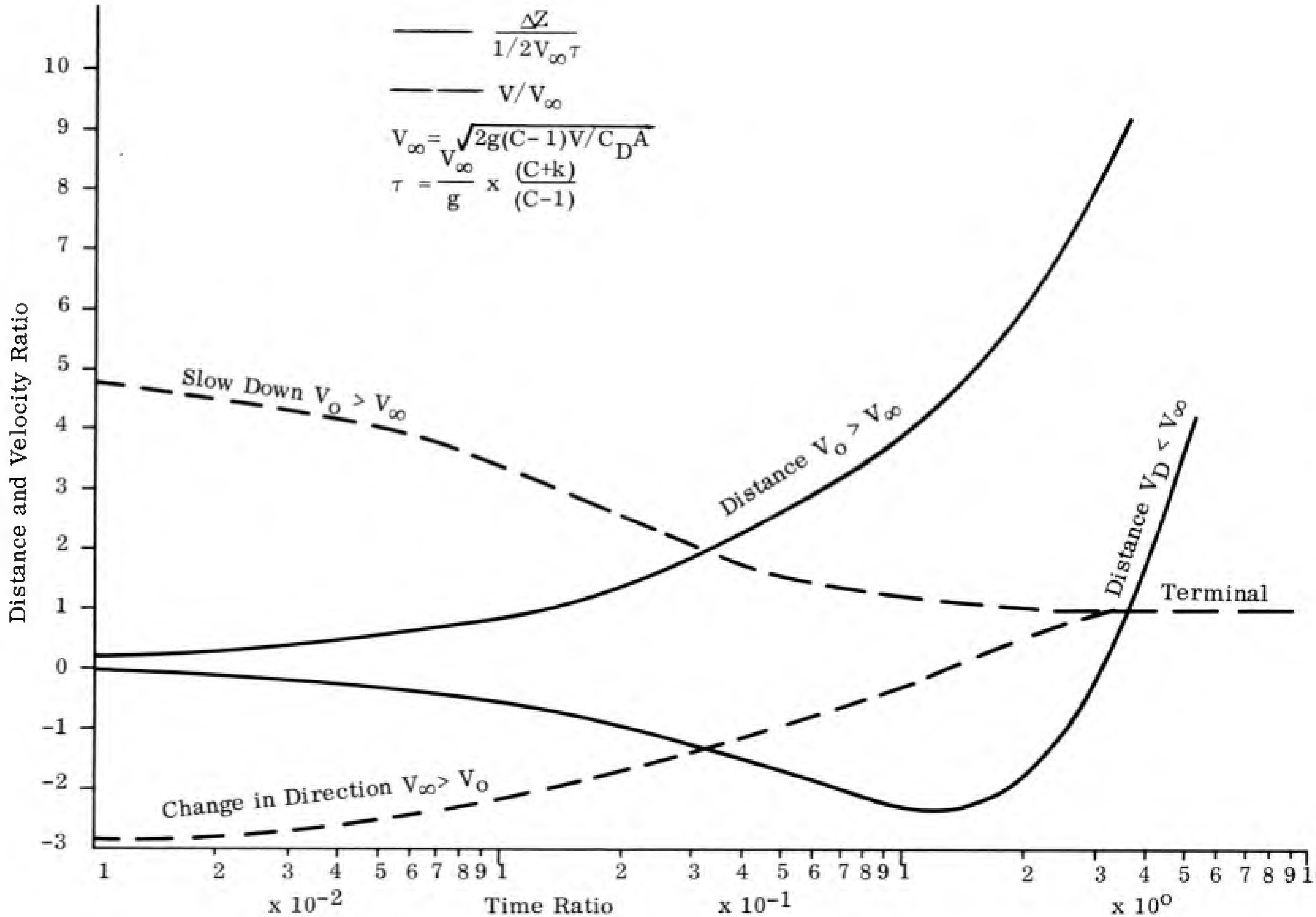


Figure 7-9. The Velocity and Displacement of a Body Freely Rising or Sinking Vertically in a Liquid

w = weight

Z = vertical coordinate

∇ = displaced volume

ρ = mass density of liquid

μ = V/V dimensionless velocity

μ_o = initial value of μ

τ = characteristic time

The velocity and displacement curves each have two branches. If the initial velocity is in the same direction and greater than the terminal velocity, the upper curve is used. If the initial velocity is less than the terminal velocity or negative (in the opposite direction), the lower branch is used.

The entire velocity and displacement history may be traced through any series of ballast, buoyancy, or configuration changes. For a single condition, the trajectory is traced by the curves as suggested above. At the time when ballast is dropped, or any other change occurs, the final velocity and depth are computed. After the change, new values of $V\infty$ and τ are computed and the new initial velocity ratio $V_o/V\infty$ is computed, using the final velocity from the previous segment of the trajectory. The history of the second segment is then read from the curves as before.

Two hydrodynamic coefficients of the body must be supplied for each configuration, the drag coefficient C_D and the added mass coefficient k. The drag coefficient can be sufficiently well estimated for most configurations with the aid of Reference 6.

Added mass coefficients may be approximated for most bodies which are surfaces of revolution by applying the known values for ellipsoids. These are presented in Table 7-V.

Table 7-V. Added Mass Coefficients of Ellipsoids of Revolution

a = major axis

b = minor axis

k_1 = coefficient for motion parallel to major axis

k_2 = coefficient for motion perpendicular to major axis

Table 7-V. Added Mass Coefficients of Ellipsoids of Revolution (cont'd)

a/b	k_1	k_2
1.0	0.5	0.5
1.5	0.305	0.621
2.0	0.209	0.702
2.5	0.157	0.762
3.0	0.121	0.804
4.0	0.081	0.861
5.0	0.058	0.896
6.0	0.045	0.917
7.0	0.035	0.934
8.0	0.029	0.945
9.0	0.024	0.054
10.0	0.021	0.960
∞	0	1.000

7.2.3.3 HYDRODYNAMIC STABILITY - An underwater transport which is capable of vertical excursions by virtue of changes in weight or buoyancy must be both hydrostatically and dynamically stable during all modes of operation. The former condition assures that it will not capsize at low speeds or when stationary at neutral buoyancy. The latter condition assures that it will not oscillate nor capsize under the influence of hydrodynamic forces when moving vertically.

When weight minus buoyancy is small, the vertical velocity is small (excluding possible transient conditions) and the hydrodynamic forces are negligible compared with gravity and buoyancy. The body will be stable when the center of gravity is below the center of buoyancy.

A conventional submarine or torpedo moving rapidly in a horizontal path will usually have its center of gravity very near or at the same longitudinal station as the center of buoyancy. For such a body, dynamic stability is attained when the body has weathercock stability with respect to its center of gravity. Weathercock stability with respect to a point means that, if the body were immersed in a stream and held stationary at the point, but allowed freely to pivot about it, the body will align itself with the fluid motion. If disturbed from this alignment, it will rotate back into the stream direction.

There is a point known as the neutral point for which weathercock stability is zero. For points forward of this, weathercock stability exists; for points aft, it does not. Consequently, dynamic stability exists if the center of gravity is ahead of the neutral point.

Acutally, due to the influence of certain damping terms in the equations of motion, this is a sufficient, but not necessary, condition for dynamic stability. Dynamic stability is attained for a limited range of conditions where weathercock stability does not exist with respect to the center of gravity; i.e., the center of gravity may be slightly behind the neutral point. (This is the case with all normal submarines and torpedoes.) However, for the present qualitative discussion, this point is not important.

For a body which descends vertically under the influence of gravity through a fluid the conditions for stability may be satisfied by placing the center of gravity low enough. The center of gravity should be ahead of the neutral point and below the center of buoyancy. Practically speaking, it may be necessary to provide stabilizing fins at the upper end of the body to assure that the netural point is behind (above) an attainable location of the center of gravity.

A detailed analysis of the equations of motion of a vertically rising buoyant body shows that in this case there is a limited range of vertical positions of the center of gravity which will result in a stable vehicle. The range will be greater if the neutral point is low, as when large stabilizing fins are provided at the lower end of the body. If the neutral point is too high, there is no location of the center of gravity which will provide a stable trajectory.

From the foregoing discussion, it is evident that a body which will both descend and ascend in a stable manner while maintaining the same orientation in both directions must have a configuration having a suitable location of the hydrodynamic neutral point for both directions of movement and must have a properly limited vertical range of locations of the center of gravity. The first condition probably requires fins or other hydrodynamic stabilizing devices at the upper extremity in descent and at the lower extremity in ascent. Consequently some retracting or pivoting mechanism for the stabilizing appendages is probably necessary to provide good stability in both directions of motion. In any case such a variable configuration will permit a much greater range of permissible locations of the center of gravity. If rates of ascent and descent are limited to very small velocities, the stability requirements degenerate essentially to the static stability problem, but such velocities are probably unacceptably low.

To assure good stability and to provide a proper program for control of the center of gravity under all conditions of ballasting and loading, an investigation of the complete equations of motion is required. It is also necessary, in order to carry out such an investigation, to have a knowledge of the coefficients representing the hydrodynamic forces and moments.

The hydrodynamic characteristics of most unconventional or irregular forms, such as these under consideration, can be reliably determined only by models tests. These tests will have to be conducted to validate the final design. Once the coefficients are determined, the conditions for stable operation may be ascertained by a numerical investigation of the equations of motion.

7.2.3.4 IN SITU STATION HYDRODYNAMIC ANALYSIS - The vertical transport role of the in situ plant requires that its overall hydrodynamic drag profile be in balance. Consider the structure to be made up of two major components of equal weight, but with one having a drag force much greater than the other, for example, a cylinder of diameter D and a sphere of diameter 2D. Drag force of a body is directly proportional to the frontal area and drag coefficient. The latter is a function of the object's shape and surface characteristics; it may be assumed that both components have the same surface finish to reduce this variable. It can be shown that drag force on the sphere side of the conveyance will be over twice that on the cylinder side, an unstable and undesirable condition. There are two ways to overcome this situation. Either the load sphere can be situated on top of the power plant cylinder, thereby exposing a single frontal area, or else a scheme to induce equivalent drag on the cylinder side can be devised. Both have advantages, and it will depend on the particular case at hand as to which approach is best. For instance, several power plants considered exhibit large amounts of negative buoyancy and will require syntactic foam. It may be possible to shape the syntactic around the top of the power plant to increase its frontal area and hence its component drag force so it will be equivalent to the sphere.

A general discussion of the hydrodynamic-parameter profiles (Figure 7-11) as they pertain to the methods of deployment and recovery may now be conducted, assuming that the plant is hydrostatically and hydrodynamically stable and in balance.

7.2.4 In Situ Station Deployment and Recovery Concepts

There are several state-of-the-art methods for the deployment and recovery of large underwater stations. This phase of operations is invariably costly and risky; costly because of the ship, crew, and hardware involved; risky in that dynamic transients and system performance are tested. For these reasons the in situ plant deployment and recovery operations are extremely important and deserve detailed analysis and careful planning.

In situ plant deployment and recovery concepts can be classified in the following categories:

- free ascent and descent
- forced ascent and descent
- guided ascent and descent
- split plant.

7.2.4.1 FREE ASCENT AND DESCENT - This concept is based upon a free, powerless descent using negative buoyancy. It is illustrated in Figure 7-10A. Downward velocity is diminished by having hanging weights hit the bottom until the station is in a state of positive buoyancy and all downward velocity has ceased. Final bottom approach is accomplished by pulling the plant down by a powered winch. Ascent is accomplished by releasing the hanging weights and allowing the plant to rise to the surface by its positive buoyancy. The prime disadvantage of this method is that bottom positioning is somewhat random.

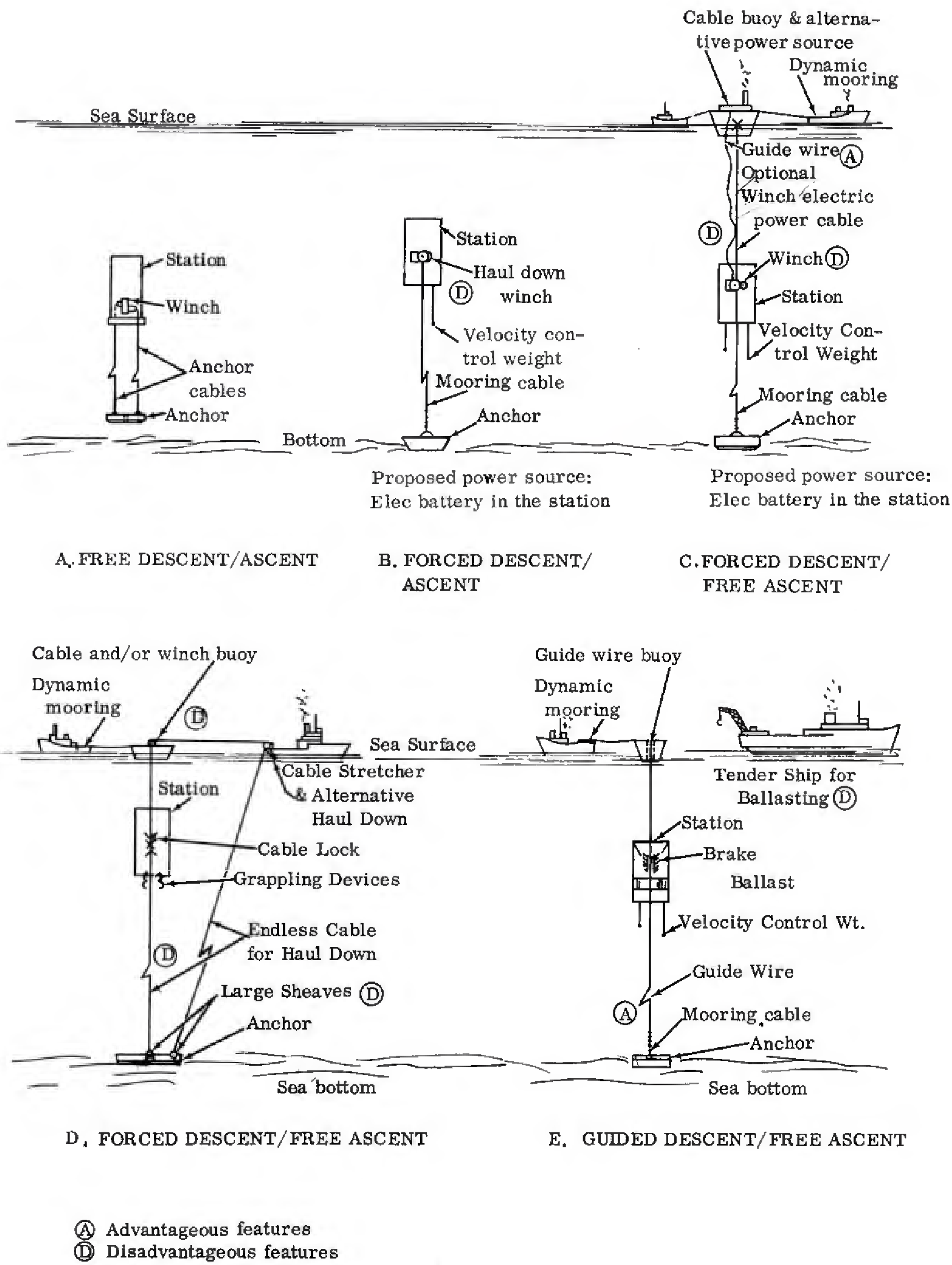
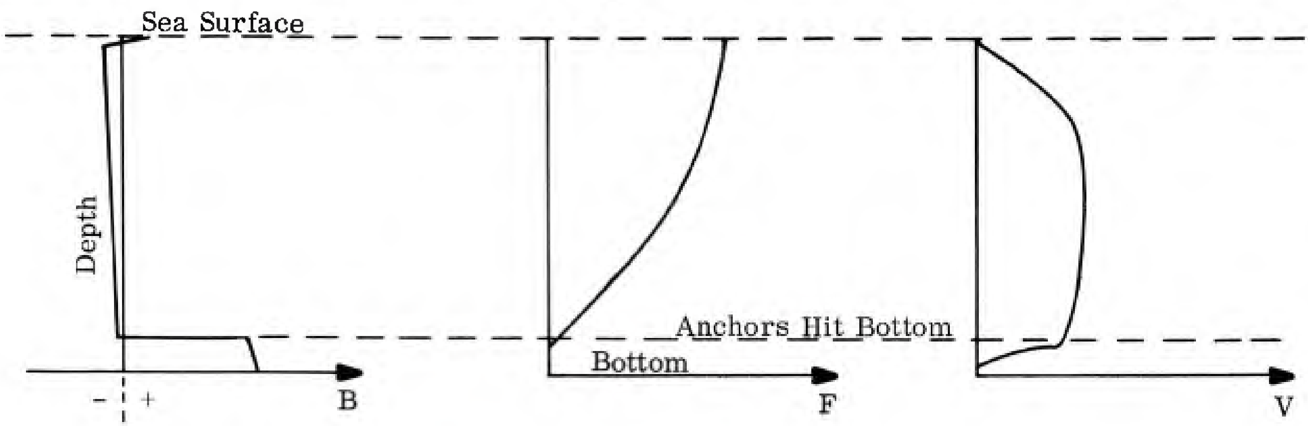
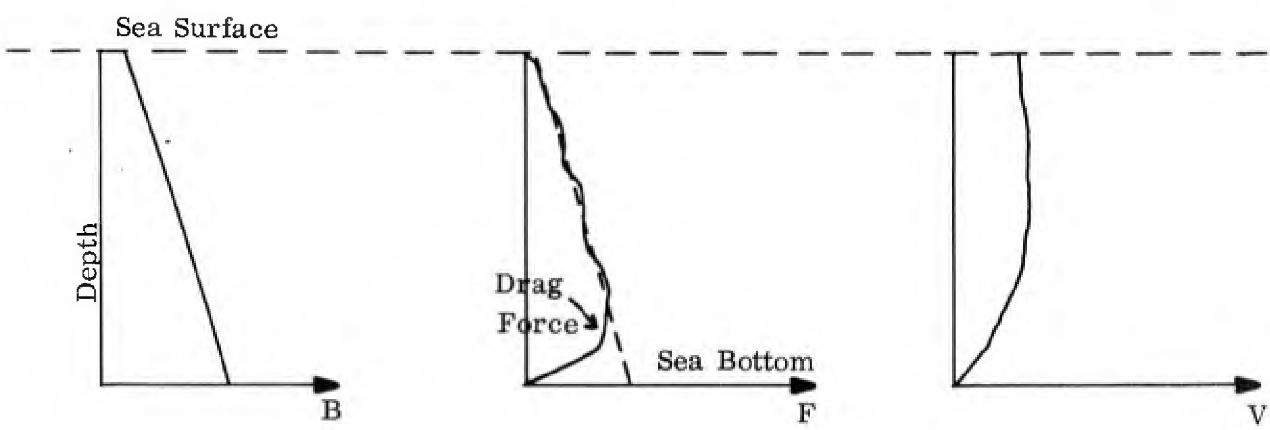


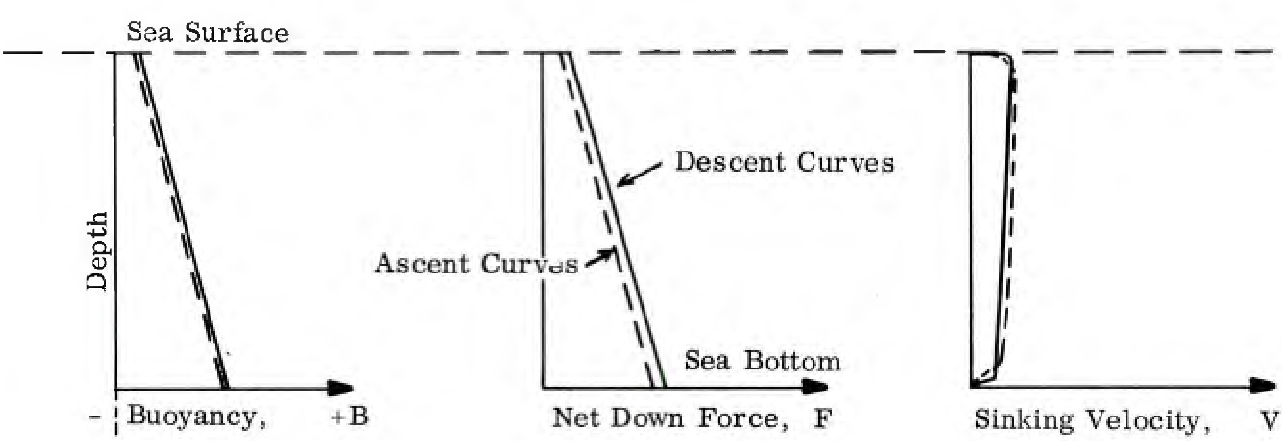
Figure 7-10. Concepts for Forced Ascent and Descent



A. - Free Descent



B. - Free Ascent



C. - Forced Descent &Restrained Ascent

Figure 7-11. Hydrodynamic Profiles of Buoyancy, Force, and Velocity

Figure 7-11A illustrates how buoyancy, net downward force, and descent velocity may be expected to vary with depth. The analysis begins with the in situ plant on the surface and rigged for free descent, i. e., stabilizers rigged, proper trim. A set of tanks may be flooded to cancel a small amount of reserve surface buoyancy. This causes the plant to take on negative buoyancy and sink. (This reserve buoyancy must be small due to reactor shielding considerations on the surface.) As the plant sinks, two parameters change; sea water density increases with pressure (depth) and external pressure causes pressure vessels to contract, thereby reducing total displacement. The net effect causes the plant to become slightly more buoyant. Thus net downward force decreases, causing the plant to gradually slow down. Analysis is required to establish the proper amount of negative buoyancy required at the surface; too much force will cause the plant to descend at excessive speed, while insufficient force will allow it to come to a stop before reaching the bottom; proper sizing will cause this plant to begin its descent at approximately 3-4 fps and initially approach the bottom at 1-2 fps. The overlap in values at 2 fps accounts for deployment at shallow depths (600 ft). A hanging weight suspended 100-200 ft below the plant will make initial contact with the bottom. When this occurs, the hanging weights rest on the bottom, the plant no longer supports their weight and it immediately becomes positively buoyant and decelerates to a stop. (Note the step change in parameter profiles at this point.) The plant rises slightly and imposes a tension on the support cable of the hanging weight. This tension is proportional to the net positive buoyant force. When stabilized at this juncture, the station may be winched toward the bottom as far as desired. The plant may be suspended at the upper end of the hanging weight cables or else winched to the bottom. In the latter case, the foundation will be sized to account for current forces and sediment strengths.

Temperature variations on the bottom must be considered. For instance, if a cold plant is placed, then heated, it will expand. This will increase the positive buoyancy, creating an upward force. Similarly, if a hot plant is placed and cooled, it will contract and lose buoyancy. Variations within possible temperature extremes must be factored into the final plant design. The plant surfaces by free ascent. The plant will rig for ascent, i.e., rig stabilizers, adjust trim, then release completely its hanging weights. The ascending force and velocity profiles are illustrated in Figure 7-11B. As the station starts its ascent in the direction of the predominating force (net positive buoyancy), it is opposed by drag and gravitational forces.

The station will reach a terminal (limited) velocity beyond which it will go no faster. As the net buoyancy force decreases, velocity will also decrease. Excessive ascending velocities are not expected; terminal velocity of 3-4 fps or less is expected.

When plants of this type are deployed for a length of time, slight water absorption will take place, and surfaces will become fouled with marine growth. Both factors contribute to retard ascending forces; i.e., marine fouling significantly increases drag.

Once on the surface, the surface tanks will be blown to restore additional reserve buoyancy to keep the plant stable.

7.2.4.2 FORCED ASCENT AND DESCENT - This concept is based upon a forced descent using the tension in a cable to pull the positively buoyant plant down. This tension may be induced by a winch submerged in the plant or on the surface. Figure 7-10B-D illustrates several variations of this concept and shows the advantages and disadvantages of each.

As discussed earlier, the buoyancy of a submerged body may be expected to increase with depth, which in this case will create a slight increase in cable tension. If the hauling cable is being would on a drum, the effective drum diameter is increasing. If a constant input torque is applied to the winch, the increased load and effective diameter will cause the in situ plant to slow down with depth.

Figure 7-10C illustrates how buoyancy, net downward force, and descent velocity may be expected to vary with depth. The analysis begins with the in situ plant on the surface and rigged for forced descent by the winch-down method. The winch and wire rope drum are contained low in the station under its overall center of gravity (Figure 7-10B). Small reserve buoyancy tanks may or may not be required; this analysis assumes they are not. Stabilizers are also not required for the forced descent. The descent commences by starting the winch. The rope will be level-wound on the drum and monitored for constant tension. This feature is included because, if tension is lost, the plant may begin to sink, in which case it would be advantageous to drop emergency ballast, i.e., the winch and drum, and make a free ascent. As the plant descends, it experiences the same buoyancy variations as the free descending plant. The increase in net buoyancy will induce additional tension on the winch-down rope. A bottom-sensing device will be required to provide a signal to decelerate the winch for bottoming. A significant tension must always be maintained in the winch cable even during and after deceleration.

Once on the bottom, the plant may be programmed to rig for bottom and carry out its mission. The effect of temperature variation discussed in paragraph 7.2.4.1 also holds for this method of descent.

The plant will surface by reversing the power winch. (A brake system was considered but is not feasible because it may become fouled and corroded after long deployment in sea water, and the system is generally unreliable.) The parameter profile during ascent is essentially the same as during descent. The buoyant force tending to assist the winch will be offset by slight material water absorption and increased drag forces due to fouling.

If an emergency arises during forced descent or ascent, a free ascent must be provided for. Two methods are possible or may be automatically sequenced in series. Should a winch failure occur, the winch, drum and rope may be jettisoned (dropped) to provide positive buoyancy and remove the anchor restraint. If the load module flooded and the power module is not flooded (or vice versa), it may be jettisoned and ascend independent of the rest of the station.

The winch rope may be either polyurethane clad steel wire rope or synthetic rope. Wire rope is preferred from a cost standpoint. In either case the problem of long term marine fouling and corrosion attack will be given careful analysis before the final selection of the deployment system.

The advantage of the forced ascent/descent method is the ability to situate the station exactly on the desired site. This is accomplished by pre-positioning the anchor.

7.2.4.3 GUIDED DESCENT, FREE ASCENT - This concept is based upon a ballasted descent in which the station slides down a vertical guide rope, as illustrated in Figure 7-10E. This cable has its lower extremity located on the desired bottom location for the in situ plant. A hanging weight slows the descending station by actuating a brake force on the rope. The plant surfaces by dropping its ballast and making a free ascent.

The magnitude and rate of application of the brake force is cirtical because it could overtension the rope; should the rope break it would collapse on the station. For this reason this concept, or any other requiring a scope of rope above the station was not given further consideration.

7.2.4.4 SPLIT PLANT - In the split plant arrangement the power plant and load module rest on separate foundations. These may or may not be deployed together. For instance, the load module may already exist on the ocean floor, i.e., a rock-site, in which case the power plant alone must be deployed. In either case, deployment may be accomplished using any of the concepts discussed above or a variation thereof. Since underwater connectors for the power levels envisioned are developmental, this method was not considered further.

7.2.5 Auxiliary Components and Systems

In addition to the major components of the in situ plant, certain optional components may be desired. The following discussion describes some feasible appendages.

The in situ station has been discussed in detail from an arrangement, hydrodynamic, deployment, and recovery concept. Throughout this discussion, balance and trim were taken for granted. Auxiliary systems used to achieve desired effects of this nature are also discussed in the following text. All auxiliary equipment discussed is powered by a compensated battery source, external to all modules, during ascent and descent.

7.2.5.1 ACCESS MODULE - The access module is a small sphere having an upper hatch intended to mate with a submersible for transfer of an inspection or work crew and necessary tools or parts. A second hatch is provided at the intersection of the load or power modules. Several factors must be investigated before it is decided if it is feasible to enter the power plant. Typical problems that must be dealt with include: radiation level, atmosphere contamination level, and lack of a power source for tools if the reactor is shut down.

7.2.5.2 BASE LEGS - The foregoing analysis was based on a box foundation. Movable base legs as illustrated by Figure 7-12 may serve several functions, including:

- acting as stabilizing surfaces during descent/ascent
- providing broad base to resist current forces and moments on the bottom
- serving as mounting for TV cameras and lights to extend the range of observation
- providing large bearing areas for soft bottoms where a box frame could get stuck
- providing a means for station leveling on sloped bottoms.

Each leg consists of a stiffened A-frame made from light-pipe sections hinged to the base. Brakes are fitted to drums mounted on this hinge pin to control the leg attitude and to absorb moments resulting from leg reactions. Leg rotation is accomplished by releasing the brakes and allowing the legs to rotate down due to their own weight. Although the operational sequence does not require elevating the legs, this could also be accomplished by installing a motor-driven worm/gear in each hinge.

Large pads may be fitted at the end of each leg. These pads consist of a snow-shoe base to provide support in soft bottoms surmounted by a cross-shaped configuration to give rotational and descending/ascending drag. This entire pad is connected to the leg end by a pin, permitting it to assume appropriate attitudes during the operational sequence. The pads have a sufficient area to reduce bearing pressures to less than 1/2 psi in currents up to 1 knot. Higher currents are expected to produce a washing effect on the lower-strength sediments. This results in a firmer bottom capable of sustaining pressures higher than 1/2 psi. The torque and thrust at the brake drum and hinge pins amounts to about 17,500 ft/lbs and 18,000 lbs, respectively, when the single leg resists a one-knot current. A weight allowance of 2,500 pounds should be provided for each leg.

7.2.5.3 MAIN BALLAST TANKS - These tanks are used to provide freeboard when the plant is on the surface. When empty, they provide sufficient freeboard even with diving and velocity-control weights and other payloads attached to the plant. Flooding of the ballast tanks on the surface provides the proper degree of buoyancy for diving. The tanks may be located in the foundation area of the station.

7.2.5.4 TRIM BALLAST WEIGHTS - These ballast weights serve a dual function. The normal function is to provide sufficient trim weight to offset the buoyancy of the pressure-proof capsules and to orient the station in a vertical attitude, correcting for unequal weight distribution. Their secondary function is to provide emergency positive buoyancy by their release from the plant. The trim ballast weights are segmented into various weight groups to provide varying amounts of positive buoyancy depending upon the emergency conditions. Shot is not recommended for ballasting in this plant. It may bridge or corrode when exposed to sea water for long periods of time, thus hindering dispensing when required. Pig iron or concrete weights are recommended.

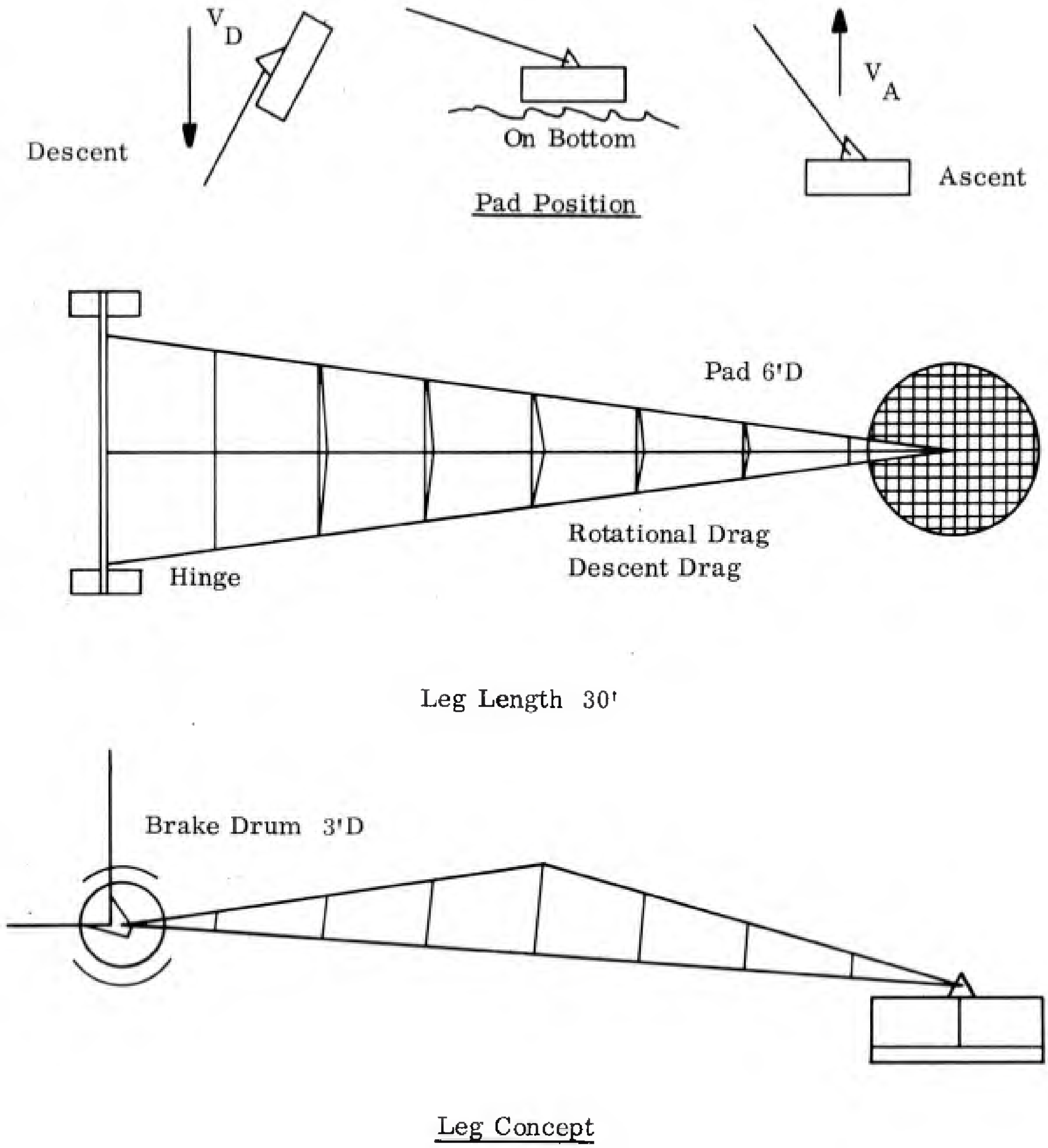


Figure 7-12. Leg Configuration

7.2.5.5 DIVING WEIGHT - This fixed weight may be used to compensate for displacement weight changes in the in situ plant during descent. The weight will be variable for each descent and is dependent upon depth (over-compressibility), salinity and temperature of the sea (sea water density). The weight (pig iron or concrete) is attached to the free descent winch rope. It is jettisoned just prior to surfacing.

7.2.5.6 VELOCITY CONTROL WEIGHT - This fixed weight may be used in free descent to provide the desired descent velocity. The fixed weight produces additional negative buoyancy for station-holding. Its magnitude is dependent on the desired velocity or descent time, taking into account ocean currents, drag coefficient of the station, and other dynamic conditions discussed in paragraph 7.2.3. This weight is attached to the diving weight by a length of rope or chain. The length of cable between the weights must be sufficient to allow the station to slow down to a lower terminal velocity once the velocity control weight hits the bottom. Using a diving and velocity control weight less than the increase in buoyancy realized between operating and collapse depth precludes the possibility of reaching collapse depth. This added safeguard must be judged against the functions of these weights, which are to counteract current forces and provide increased descent velocity.

The use of a shaped diving weight has significant advantages. The anchor for mud should have a small projected area to allow penetration into the mud. The shape should also resist pulling out. If the pulling out force is 10 or 15 times the weight of the diving weight, the plant will be able to resist the high current moments expected and still have the proper weight for minimum bottom approach velocity. In hard bottoms, the diving weight should be shaped to grab at bottom cracks or inclusions and thereby resist current moments. The use of flukes, or other claw-like protrusions, will greatly improve the grabbing capability of the anchor. Since these weights are left behind when the plant ascends, no retrieval system is necessary.

7.2.5.7 FREE DESCENT WINCH - The winch is used to control the cable length between the hanging weight (diving and/or velocity control weight) and the plant. Because the plant will be neutrally buoyant once the diving weight is resting on the ocean bottom, the winch cable must be retracted to bring the plant to the bottom when the terminal velocity approaches zero. The length of cable is a function of the distance the plant must travel after the diving weight is resting on the bottom; it will probably not exceed 200-250 ft. The cable may be wire or nylon rope.

7.2.5.8 FORCED ASCENT - DESCENT WINCH - The forced ascent-descent winch may be powered by a submersible electric motor through a gear drive. The drum will be sized to handle a scope of cable slightly greater than the depth of operations.

The winch will have constant-tension, level-wind capability in each direction. The entire winch and drum assembly may be considered droppable ballast. Any necessary devices should be designed fail safe.

7.2.5.9 FLOTATION MATERIAL - The in situ plants will utilize syntactic flotation material to achieve overall trim and stability; in addition, flotation material may be used to make certain components positively buoyant so they will ascend to the surface if jettisoned, e.g., the power plant. There are two types of flotation material, both covered by MIL-S-24154 (ships). Type I is capable of withstanding hydrostatic pressures to 4500 psig and type II can withstand pressures up to 10,000 psig. By definition, the bulk modulus (E_b) of the material is given by the equation.

$$E_b = \frac{\Delta P}{\frac{\Delta V}{V_o}}$$

where ΔP change in pressure (psi) corresponding to depth (ft)

ΔV change in volume (in.^{3}) of a body subjected to ΔP (psi),

V_o initial volume (in.^{3}).

The minimum bulk modulus of both materials is the same (350,000 psig).

Figure 7-13 is a curve showing the change in volume corresponding to pressure (depth) for type I and II flotation materials.

There are several materials manufactured which conform to these specifications. In some cases, hollow glass or plastic spheres are also cast into the foam blocks. It is important that these spheres are hydrostatically tested before they are embedded in the flotation material to ensure that they can withstand the compressive loads.

To minimize water absorption, careful analysis should be given the sealant selected and quality of application to the exterior surfaces of all formblocks required. Epoxy preparations are generally used for this service.

Flotation and ballast material may be cast in modular blocks to facilitate buoyancy distribution in the plant. The in situ plant must be in trim and balance with respect to major ballast and flotation material before leaving the shore base for a site. This will minimize weight handling at sea. Final trim may be adjusted at the site. To avoid foam additions to counteract unnecessary ballast additions (or vice versa), a tradeoff study may be conducted to determine optimum weight and flotation material distribution.

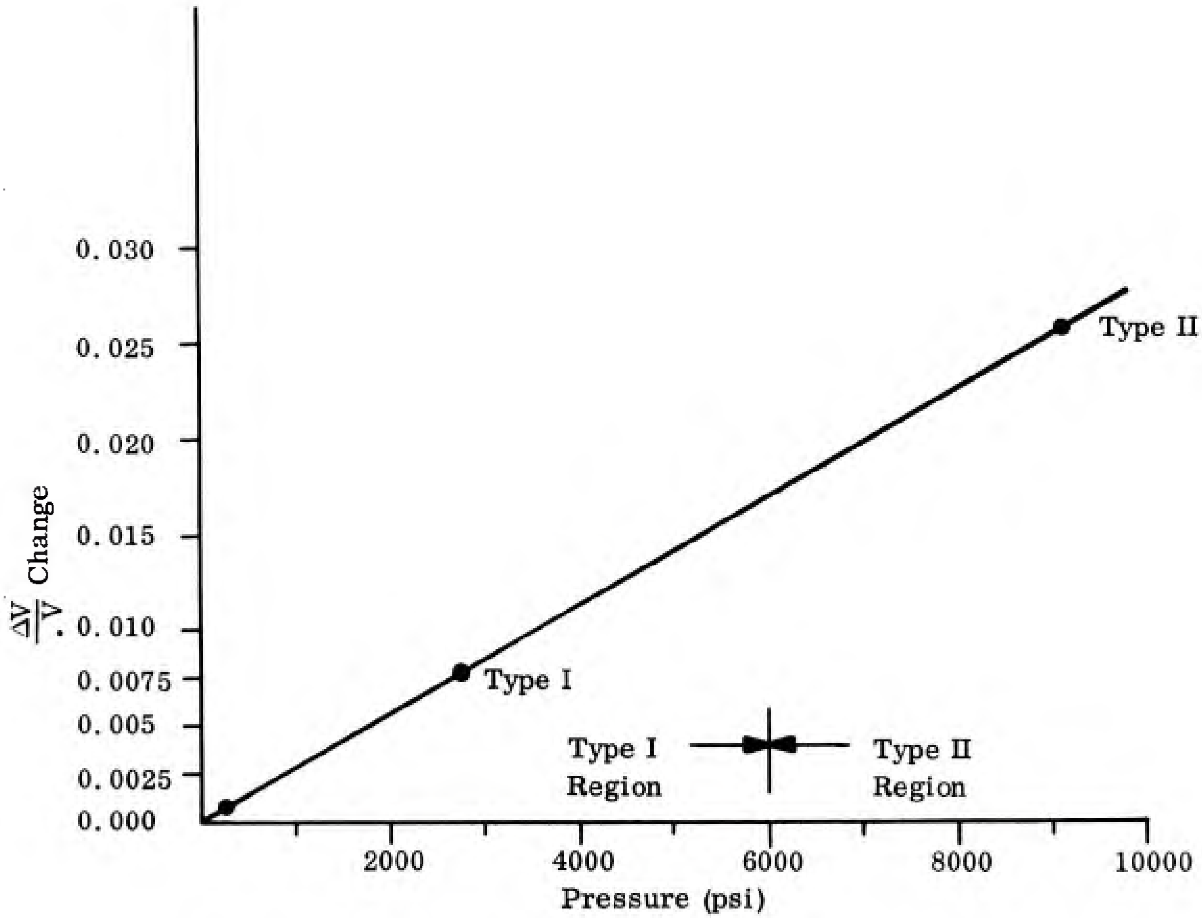


Figure 7-13. Volume Change vs Pressure for Types I and II Flotation Material

7.3 REFERENCES

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Chapter 8

MOORING AND DEPLOYMENT SYSTEMS

8.1 MOORING SYSTEMS

The purpose of this chapter is to define the forces and phenomena involved in mooring thick-disc surface power plant hulls[1] in 600 to 20,000 ft of water and to define the hardware. It is also a rudimentary tool to enable evaluation of the effect of changing any element of a predesigned mooring system.

In dealing with the problems of mooring, the following subjects are discussed:

- types of mooring systems,
- external forces acting on a mooring system,
- multi-point mooring systems,
- mooring leg equipment and component analysis,
- mooring system configuration for the surface tendered power source developed in Chapter 7.

8.1.1 Dynamic Moors

The dynamic moor consists of propulsion devices which will permit forces to be applied to the hull in any direction to hold it stationary against the forces of wind and sea. In addition, a dynamic moor requires an automatic sensing device which will accurately locate and hold the hull with respect to the desired position on the bottom.

Dynamic moors are being utilized for deep water problems in increasing numbers. Two examples are CUSS I, used in a prototype drilling operation which was to be the prelude to MOHOLE, and a support ship for the CURV vehicle which is under the operational control of NOTS, Pasadena.

For several of the depths considered, the dynamic moor is a relatively expensive solution to the problem. In addition to the high cost, there are manning and logistic problems, and the reliability of the system is questionable. For these reasons this scheme was not investigated further. When the state-of-the-art has advanced, this method may become more feasible and worthy of a re-evaluation.

8.1.2 Static Moor

A static moor consists of a wire rope or chain connecting the surface hull to a device on the ocean floor capable of developing an anchoring or holding force. Several types of anchoring devices are available, most common of which is the fluke anchor. Three basic types of static mooring systems are the simple catenary, the taut line, and the compound catenary.

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[1]The number as a superscript in the text refers to another report, the title of which is listed at the end of this chapter.

The simple catenary employs a wire rope or chain having a uniform weight per foot. By definition, a catenary is formed by a tension member having a finite weight per foot. The simple catenary uses a fluke anchor, and the wire rope or chain connecting the anchor with the surface hull is extremely long, as much as 2 to 6 times the depth.

The taut line mooring system usually employs a synthetic rope of neutral buoyancy, thus preventing a catenary curve from forming. The taut line mooring system uses the shortest possible length of line, but requires an anchoring device capable of developing a large vertical component of force. The anchor has to be fixed to the bottom by a pile grouted in place, since fluke anchors can only develop a significant holding force along a line tangent to the bottom.

The compound catenary employs wire rope or chain in various sizes and/or clumps. A fluke anchor may be used. This type of system is used to obtain the shortest possible length of wire rope connecting the anchor with the surface hull, only 1-1/2 to 3 times the depth.

Static mooring systems were evaluated for the underwater power transmission systems because dynamic mooring systems are still developmental. This selection must be reevaluated once the load module is defined and its deployment site selected. For example, if the load module is a propulsive device, then a dynamic mooring system must be selected for the power plant. Similarly, if the topography of the site selected prevented the placement of a static moor, then a dynamic or taut line moor will be considered.

8.1.2.1 SIMPLE CATENARIES - The curve described by any line having finite weight and subjected to tension is known as a catenary. The mathematical equation of a catenary is well defined and is encountered in engineering problems in many fields. A simple catenary mooring leg using an anchor, single mooring line, and either a ship or buoy at the surface is described by the following equations: [1, 2]

$$Y = \frac{H}{W}(\sec\theta_b - \sec\theta_o) \qquad (1)$$

$$S = \frac{H}{W}(\tan\theta_b - \sec\theta_o) \qquad (2)$$

$$X = \frac{H}{W}\,\ell n\,\frac{\tan(\frac{\pi}{4} + \frac{\theta_b}{2})}{\tan(\frac{\pi}{4} + \frac{\theta_o}{2})} \qquad (3)$$

$$\frac{Y}{S} = \frac{(\sec\theta_b - \sec\theta_o)}{(\tan\theta_b - \tan\theta_o)} \qquad (4)$$

Figure 8-1 illustrates a simple catenary and the nomenclature in the equations.

S = scope of mooring leg (ft)

Y = vertical projection of mooring leg (ft)

X = horizontal projection of mooring leg (ft)

H = holding power (lbs)

V = mooring leg weight (lbs)

T = mooring leg tension (lbs)

W = WT/FT in sea water of mooring leg (lbs/ft)

θ_b = angle of the mooring leg tangent with respect to horizontal (at the buoy)

θ_o = angle of the mooring leg tangent at the anchor with respect to horizontal. This value should be 0.[3]

ℓn = the natural logarithm, i.e. to the base e.

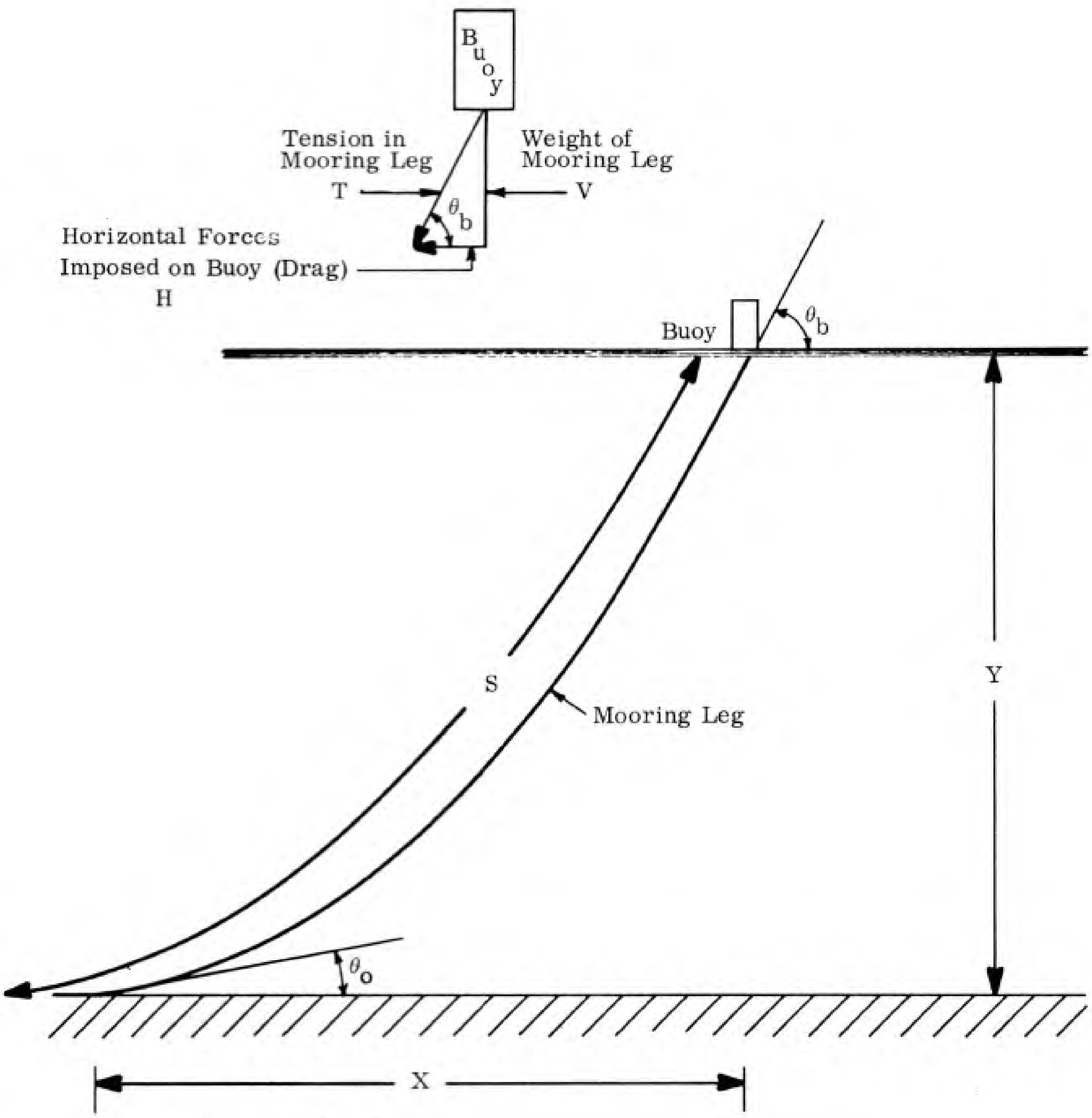


Figure 8-1. Forces on Simple Catenary Mooring Line

8.1.2.2 Forces on a Taut Mooring Line - The wire rope or chain comprising the mooring leg must have a finite weight per ft. (W). If, for instance, a synthetic mooring line were used which exhibits neutral buoyancy, a catenary curve could not be formed. The mooring leg would assume the straight line or taut configuration illustrated by Figure 8-2.[4] This figure is useful in visualizing the load forces in a simplified triangular mooring force diagram. The horizontal force (H) on the hull is counteracted by the horizontal component of cable tension. This force, $T \cos \theta$, must be exerted on the cable by the anchor held in the bottom. Since the cable is assumed to be quite flexible, the only force it can exert is in its own direction, thus reactions at the hull and anchor must be colinear with the cable. Due to this effect, a vertical component, $V = H$ than θ, pulls the cable up at the ship and down at the anchor. Total tension in the wire rope is

$$T = H^2 + V^2 = H \sec \theta \qquad (5)$$

where θ, the angle of elevation of the cable, is constant over the entire length.

Figure 8-2 illustrates why it is impossible to maintain a zero anchor shank angle with respect to the bottom for the taut mooring configuration shown. Figure 8-5 shows the marked effect that anchor pull angle has on holding power. (Reference paragraph 8.1.5.1 Anchors) The best way to achieve a taut line moor is to grout a pile equipped with a swivel connection into the bottom. Since this technique is not yet developed for all depths under consideration for the underwater power transmission systems, it will be costly. Submersible vehicles to transport, let alone emplace, the required piles to depths much beyond 6000 ft. are still in the design stage. For these reasons this method of mooring was not investigated further.

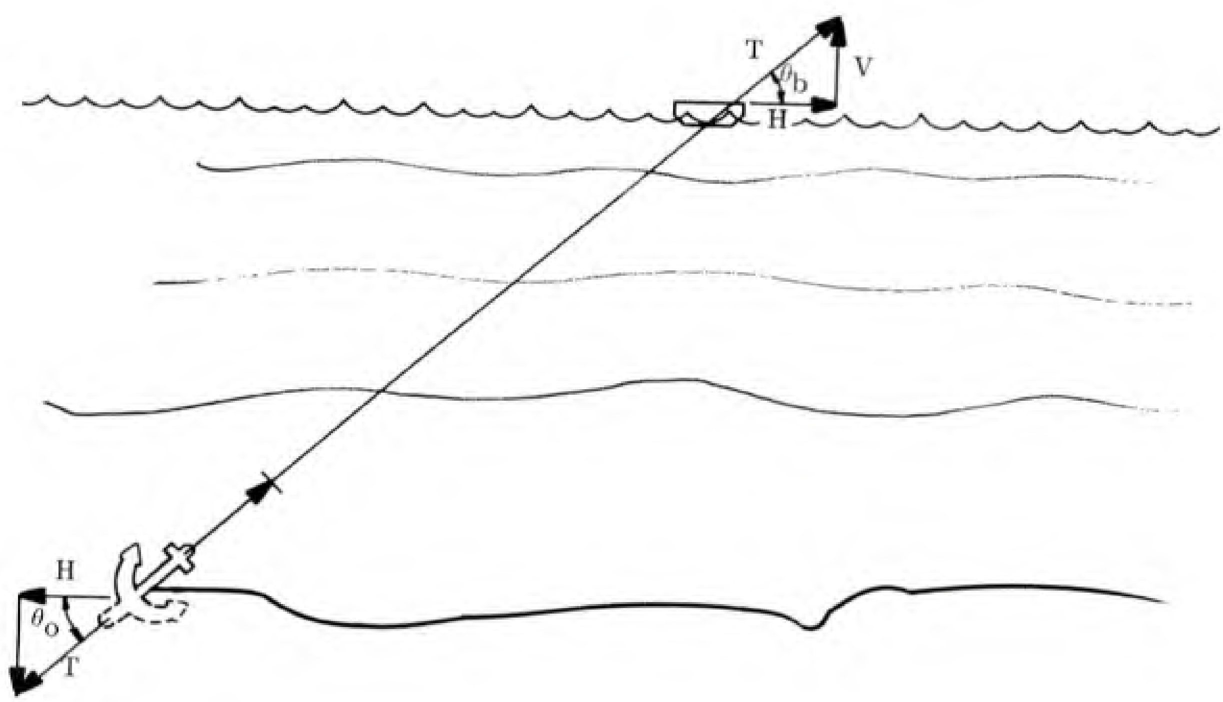


Figure 8-2. Forces on Taut Mooring Line

8.1.2.3 COMPOUND CATENARIES - As water depth increases, wire rope scope requirements of the simple catenary become prohibitive. This condition makes the mooring designer think in terms of adding weight at the lower end of the mooring line in order to modify the catenary to utilize shorter mooring legs. Figure 8-3[2] illustrates the use of chains of different weights for various segments of the mooring leg to transform the simple catenary problem into one involving a compound catenary. The basic equations which describe a compound catenary are the same as equations (1) through (5). These equations, however, must be applied to each segment of the mooring leg. For example, if a mooring leg is assembled as shown in Figure 8-3, using 27 shots (2430 feet) of 3/4-inch chain (segment b) and one shot (90 ft) of 2-1/4-inch chain (segment a), then each of these two segment must be treated as separate simple catenaries. The two catenaries may be related to each other by imposing two conditions:

Condition I

If equation (1) is solved for both segments, then the sum of the results is equal to the depth of the water in which the moor is placed (see Figure 8-3).[2]

$$Y_a = \frac{H}{W_a} (\sec \theta_1 - \theta_o), \tag{6}$$

$$Y_b = \frac{H}{W_b} (\sec \theta_2 - \sec \theta_1), \tag{7}$$

$$\text{Depth} = Y_a + Y_b. \tag{8}$$

Condition II

The angles at the ends of the catenary segments may be related by the following equation:

Tan θ_o must be assumed. It is assumed to be zero[3] for level ocean bottoms.

Therefore, $\theta_o = 0$, and the catenary is tangent to a horizontal ocean bottom.

$$\text{Tan } \theta_1 = \frac{S_a W_a}{H} + \tan \theta_o \tag{9}$$

$$\text{Tan } \theta_2 = \frac{S_b W_b}{H} + \tan \theta_1. \tag{10}$$

Therefore,

$$\text{Tan } \theta_2 = \frac{S_b W_b}{H} + \frac{S_a W_a}{H} + \tan \theta_o . \qquad (11)$$

Clumps or concentrated weights of concrete or pig iron are used to induce sharp slope increases in mooring legs. The incremental change in slope $\Delta\theta$, resulting from a clump of weight (C), is given by the equation,

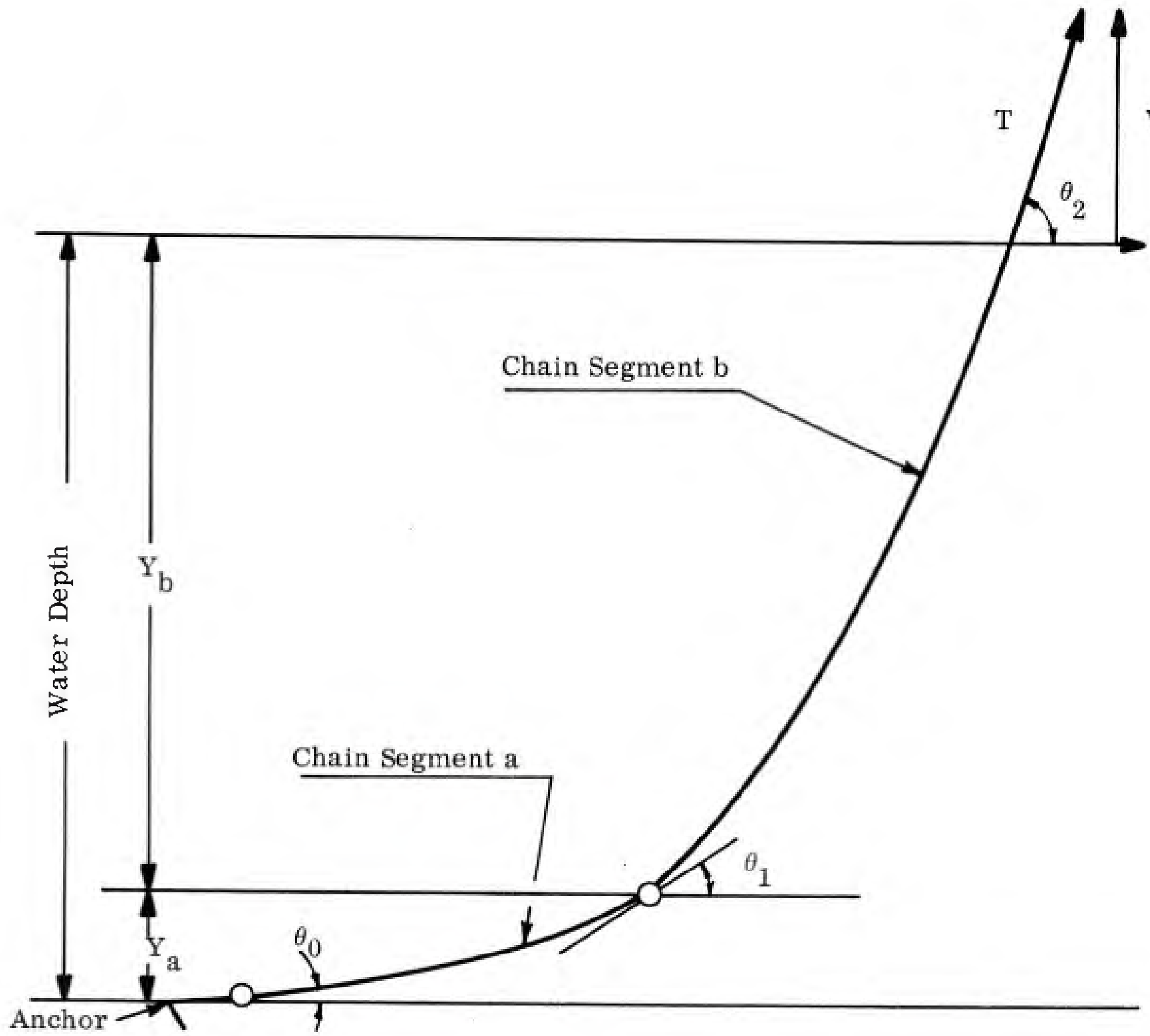
$$\Delta\theta = \tan \frac{C}{H} . \qquad (12)$$

This is derived from the free body force diagram of the mooring leg at the clump. It may be included as a term in equation (11) if a clump is used.

Utilizing clumps of relatively low-price material allows a significant reduction in the scope of wire rope necessary. These savings are reflected mainly in wire rope cost.

Mooring system weight increases in proportion to anchoring or holding power (H) and depth. The weight (V) of the entire mooring leg with the exception of the anchor must be supported from the surface as shown by Figure 8-3. The moored surface hull may be large enough to accommodate this load. If not, either an intermediate catenary support buoy must be added to support the weight of each mooring leg or the size of the hull must be increased as required. If catenary support buoys are used, the main hull to be moored is then tied off in the center of the catenary support buoy array. This buoy should exhibit 8 to 16 percent reserve buoyancy to dampen surface effects as much as possible. At times in heavy seas this buoy may be submerged as waves break over it. It has to be structurally strong enough to withstand sea pressures at a depth corresponding to the 60 ft maximum wave height expected (paragraph 3.1). It is also conceivable that if this buoy were momentarily submerged at the instant the mooring leg was subjected to its maximum horizontal loading, tension in the wire rope could exceed the allowable stress by the reserve buoyancy inherent in the support buoy. For those mooring systems in which catenary support buoys are utilized, the buoys must be designed to withstand this force.

Mooring system for the underwater power transmission system will utilize compound catenary mooring legs made up of an anchor, one shot of chain, a clump, two shots of chain, wire rope, and a catenary support buoy if required.



V = Mooring leg weight (lbs)
T = Mooring leg tension (lbs)
S_a = Scope of segment a (ft)
S_b = Scope of segment b (ft)
w_a = Weight per foot in water of chain a (lb/ft)
w_b = Weight per foot in water of chain b (lb/ft)
H = Holding power (lbs)
Y_a = Vertical projection of chain a (ft)
Y_b = Vertical projection of chain b (ft)
$\text{Sec}\ \theta_0$ = Secant of angle θ_0
$\text{Tan}\ \theta_0$ = Tangent of angle θ_0
θ_0 = Angle of anchor chain at the anchor
θ_1 = Angle of chain a and chain b at their juncture
θ_2 = Angle of chain b at the water surface

Figure 8-3. Forces on Compound Catenary Mooring Line

8.1.2.4 ANCHOR HOLDING POWER - The ability of a moor to develop its required holding power depends to a large part on the anchors holding power. The ability of a conventional anchor to hold to the ocean bottom depends upon several factors:

- Fluke shape,
- Fluke angle with respect to the shank,
- Type of ocean bottom,
- Angle of pull exerted on the shank measured in the vertical plane,
- Distance anchor is dragged over the bottom to permit it to dig in.

The important parameter in the shape of the fluke is the moment of the fluke area about the trunion. The greater the first moment of the fluke area, the greater is the anchor's holding power. Since a family of anchors, such as the LWT or the EELS, all have basically the same shape and proportion, the holding power of a given anchor in each of these types is approximately proportional to the anchor weight for any given bottom or direction of pull.

The holding power of a conventional anchor may also be estimated using the following formula:

$$H = k(\text{anchor wt}) \qquad (13)$$

where:

H = anchor holding power (lbs)

k = a constant peculiar to an anchor family and the ocean bottom involved.

The maximum angle which the fluke makes with the shank affects the holding power of an anchor in any given bottom. The optimum fluke angle is not the same for all bottoms, and experiments indicate that for a mud bottom the maximum holding power is attained when the fluke angle is approximately 50°, whereas on a sand bottom the optimum angle appears to be about 26°. Figure 8-4 illustrates the effect of fluke angle in two types of bottom. It is this variance in the fluke angle that has led to the development of the LWT "Wedge Block" anchor which may be adjusted to a maximum angle of either 30° or 50° by changing the wedge block, depending upon whether the holding ground is to be sand or mud. [3]

The maximum holding power of an anchor is developed when the pull exerted is parallel to the ocean bottom. If the anchor end of the mooring leg rises so that the angle of pull begins to assume finite values, the flukes of the anchor tend to break out of the bottom. Another way of visualizing the same problem is to realize that pull at positive angles raises the shank and is effectively reducing the angle which the flukes make with respect to the ocean floor, thus the holding power decreases. Figure 8-5 illustrates the effect of the angle of pull upon the holding power of an anchor. A few hundred feet of chain and a clump are generally attached to the anchor shank to help hold it on the bottom and maintain the desired shank angle. [3]

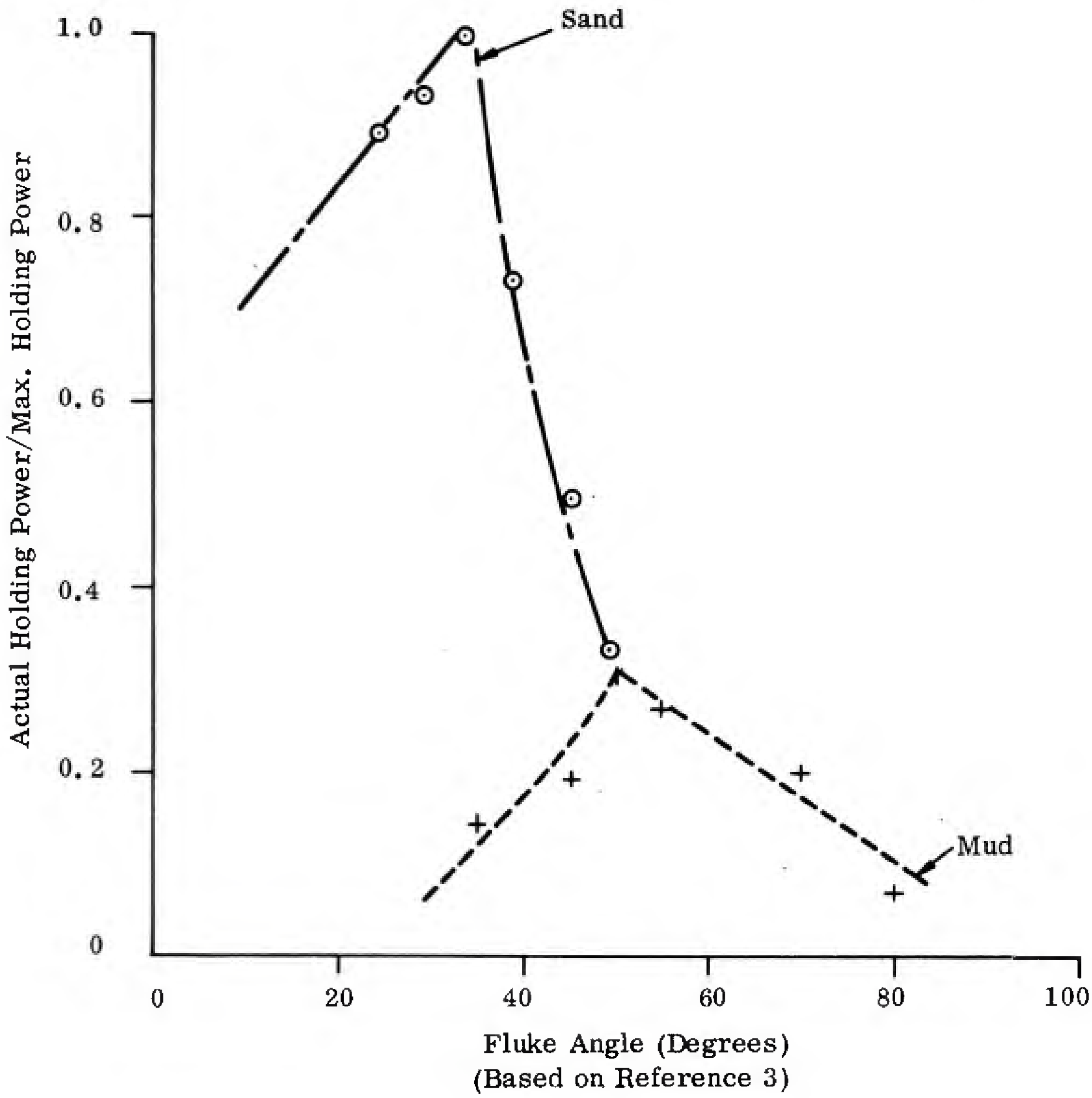


Figure 8-4. Effects of Fluke Angle and Bottom Condition

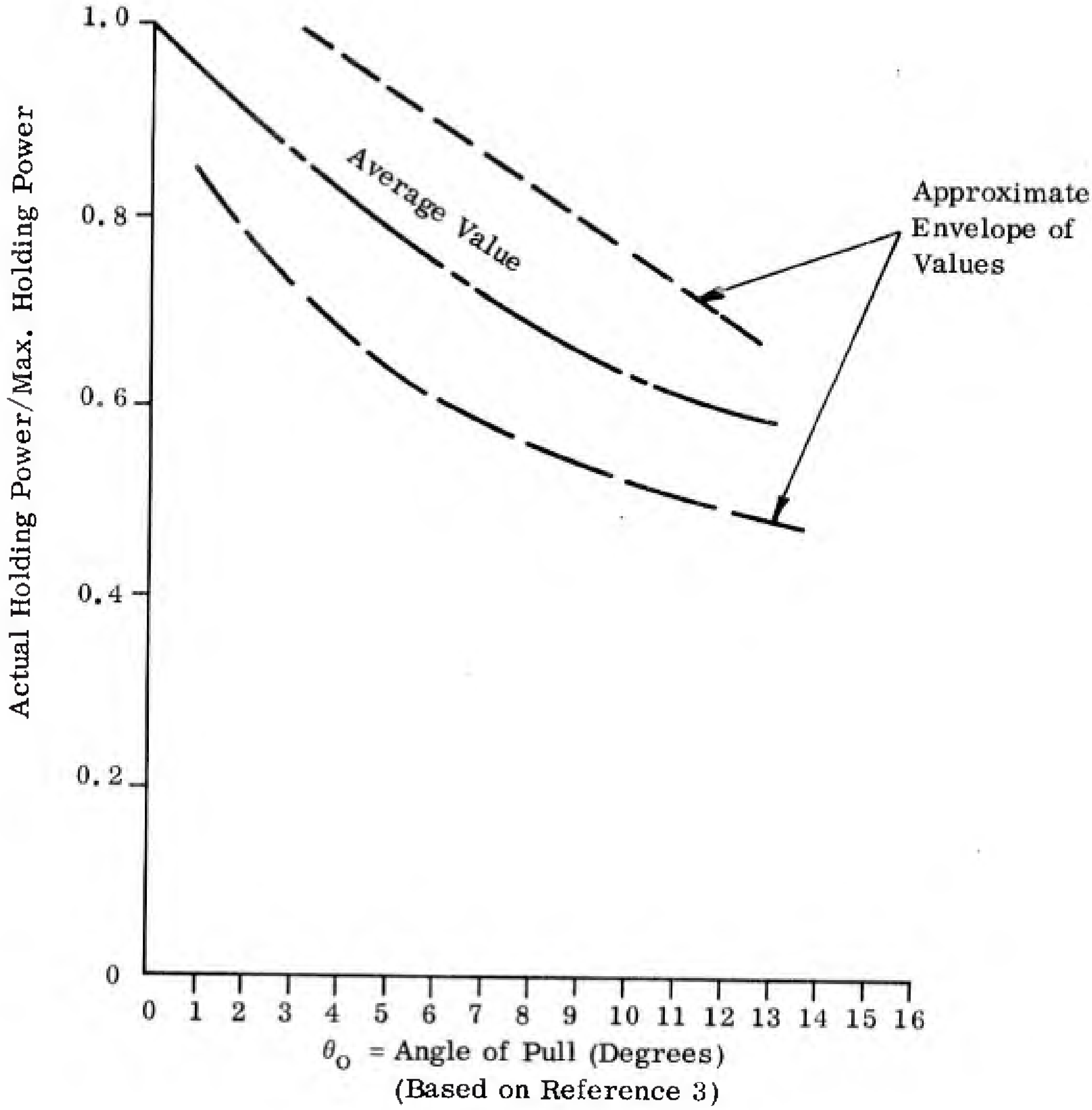


Figure 8-5. Effect of Angle of Anchor Pull on Holding Power

An anchor does not immediately develop its hull holding capability. Rather it must be pulled over to the bottom until its flukes dig in. The distances involved vary from approximately 40 to 100 ft, depending upon the ocean bottom and anchor size. Figure 8-6 illustrates the effect of anchor drag upon holding power. The essential point is that in laying a moor, the mooring leg should be subjected to a strain so that the canchor can begin to dig itself in and develop its holding power.[3]

8.1.2.5 SUBSURFACE CONDITIONS - The holding power calculated using the catenary equations (1) through (5) represents a catenary under static conditions described by those formulas.

Any number of conditions may prevent the catenary moor from behaving as predicted by catenary calculations. These conditions include:

- bottom conditions which will not permit the anchor to develop its designed maximum holding power
- dynamic forces imposed by wind, wave, or current which impose transient forces on the anchor or tend to cause it to break out
- subsurface current conditions which cause the catenary to be a three-dimensional curve rather than the two-dimensional curve assumed by equations (1) through (5)
- wind drag on the hull which does not coincide with the current causing the drag due to ocean current on the mooring leg to move the hull out of a single plane, requiring a three-dimensional analysis of the catenary.

For the underwater power transmission systems study, ideal conditions are assumed to prevail throughout the mooring system environment.

8.1.3 Forces Acting upon a Static Mooring System

The forces acting upon a moored hull are created by three phenomena: wind, waves, and current. In Chapter 3, the environmental design conditions established for the underwater power transmission system surface tendered power source were: 150-mph winds, 10-knot current, and 60-ft-high waves, breaking.

8.1.3.1 WIND FORCES - Wind forces actually have a three-fold effect in that they not only apply a force to that portion of the structure which rises above the waterline, but they create waves and surface currents as well. Model tests were run at the David Taylor Model Basin for each ship type to estimate the force which the wind imparts on a moored hull due to wind velocity. In extrapolating these wind forces from the scale model to full size, the following formulation was used:

$$D_W = (k_A)(A_A)(W_A^2)$$

where:

D_W = drag force due to wind velocity (lbs). (14)

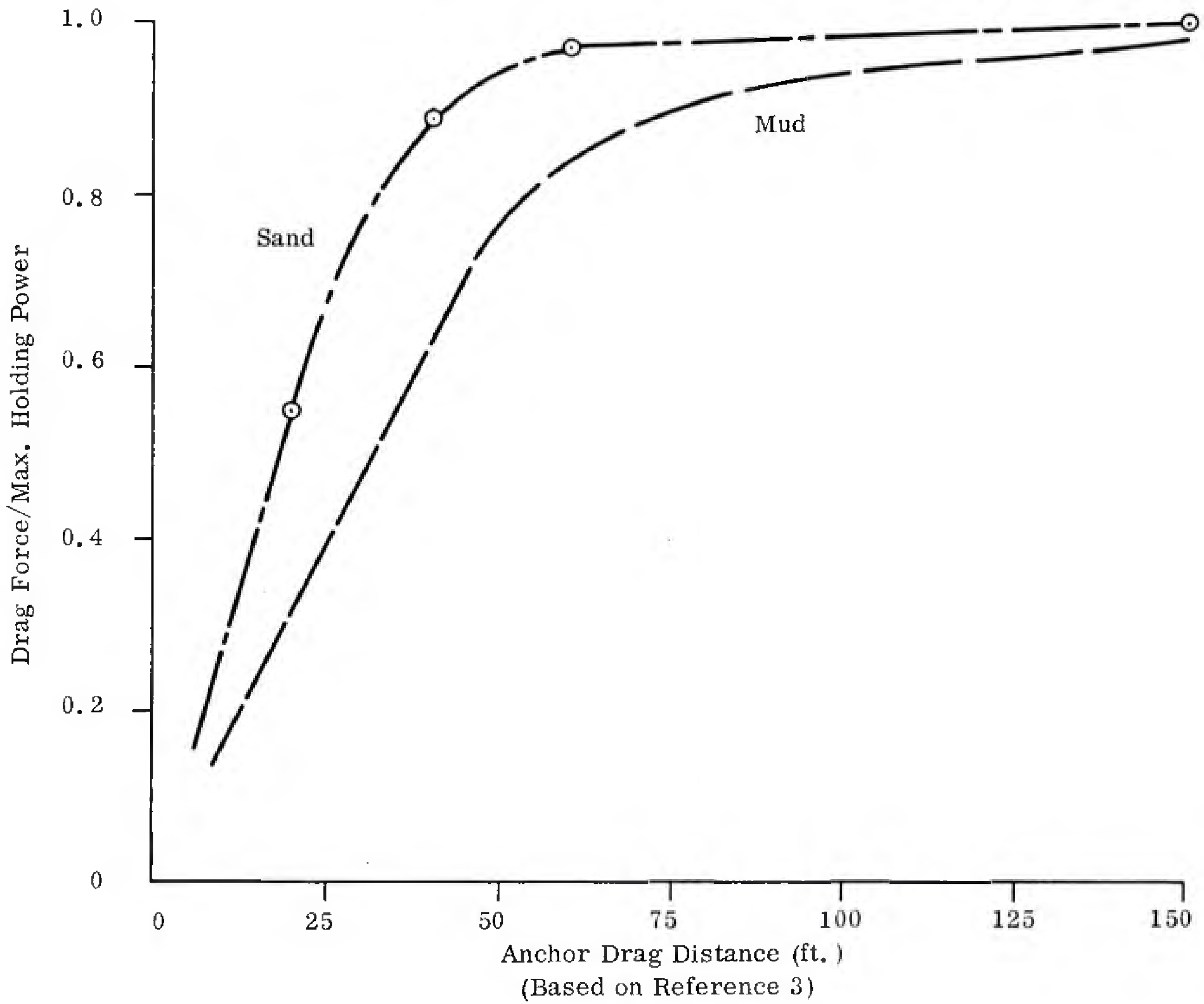


Figure 8-6. Effect of Drag Distance on Holding Power

k_A = dimensional coefficient for drag

A_A = the projected profile area of the vessel above the waterline (ft^2)

W_A = the maximum wind velocity encountered in the moor (kts).

The values of k_A generally vary between 0.003 and 0.0042. A value of k_A of 0.004 is recommended for estimating the force on any given ship type if a more refined coefficient is not available[5]. This 0.004 value will be used for underwater power transmission system computations and pre-design.

8.1.3.2 CURRENT - The current acting upon a hull produces forces due to skin friction. The basic formulas for wind and current are similar, but since the specific gravity of water is many times that of air, the forces induced by even slow ocean currents are significant. Ships exhibit an optimum aspect when their bow is headed into the current, whereas the thick-disc hull under consideration is symmetrical, thus cancelling the aspect variable.

A basic formula[2] for estimating the drag imposed by a current upon a given ship is:

$$D_c = K_c A V_c^2 \qquad (15)$$

where:

D_c = drag force due to current (lbs),

K_c = drag coefficient due to current velocity; it varies from 0.016 for a ship with its bow headed into the current to 0.30 for a ship presenting its beam aspect to the current; a value of 0.10 was selected for the thick-disc surface-following hull,

A = wetted surface of ship bottom (ft^2),

V_c = velocity of current (kts) (See Ref. 5).

8.1.3.3 WAVE FORCES - Wave forces acting upon a moored hull are fluctuating and stem from three characteristics of the wave. These characteristics are:

- heave of the hull as it is buoyed up by an oncoming wave.
- the sloped surface of the wave which, as the wave approaches, causes the hull to attempt to slide down the sloped face of the wave (Figure 8-7).
- increased velocity of the water due to orbital motion as the wave crest passes.

The wave forces are periodic in nature and the hull-mooring leg-anchor system reacts very much as a weight on a spring. In this analogy the hull corresponds to the weight and the spring is represented by the catenary in the mooring leg. The problem of analyzing the transitory force on the mooring leg when it is disturbed by the wave force is complex, and any solution is peculiar to a given situation. The possible situations which may exist are infinite. For this reason, moors are usually designed neglecting wave forces, allowing a sufficient safety factor to assure the moor will be adequate under the environmental design conditions[2].

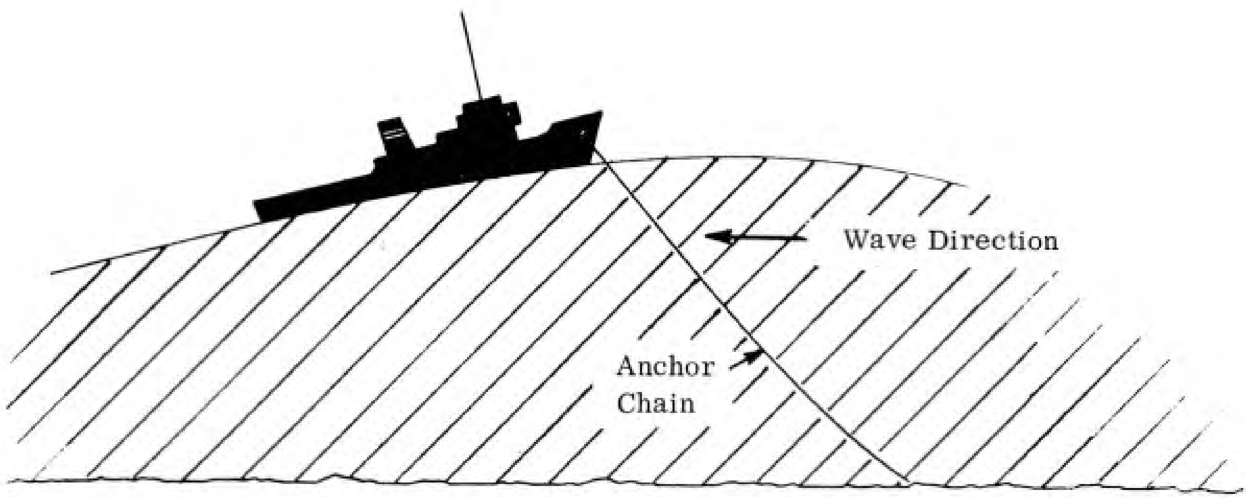


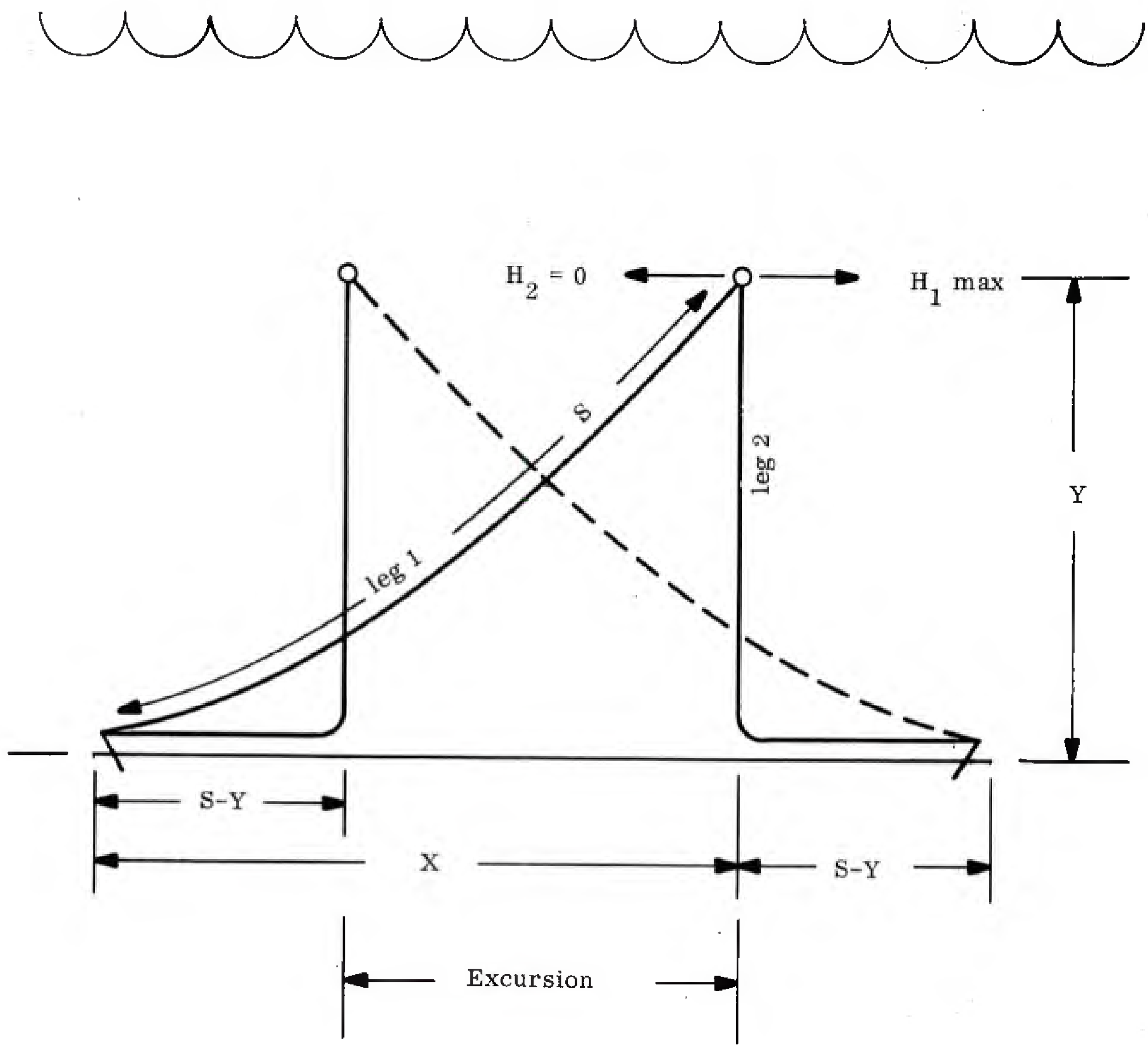
Figure 8-7. Wave forces on a Moored Hull

8.1.4 Static Multi-Point Mooring

Figure 8-8 is an elevation view of a 2-point moor. When leg 1 is delivering its maximum holding power it will experience a maximum horizontal projection X. At this time, leg 2 must drop perpendicular to the bottom to let the moor exert a net force on the moored object equal to the leg 1's maximum holding power (H). Between this perpendicular increment and the leg 2 anchor, a segment (S-Y) will lie on the bottom. This configuration is necessary because if a horizontal projection existed under leg 2, an opposing force $H_2 \neq 0$ would be set up, detracting from the design holding power H_1.

Figure 8-8 also shows that excursion (E) in a 2-point moor will be given by the equation,

$$E_2 = X - (S+Y). \qquad (16)$$



Excursion = X-S+Y

Figure 8-8. Elevation View of a Two-point Moor

A four-point moor may be considered as a system of two 2-point moors lying in normal planes. Other four-point configurations are possible but they apply only to special situations, i.e., environmental forces applied from one or two particular directions. The elevation view of one plane of a typical four-point mooring system is illustrated in Figure 8-9. This figure shows that

$$\text{anchor spacing} = X + S - Y + 2\ell, \text{ and} \tag{17}$$

$$\text{thick-disc hull neutral position} = \tfrac{1}{2}\left[X + (S-Y)\right] + \ell \tag{18}$$

where ℓ is the horizontal distance between the hull to be moored and any intermediate catenary support buoys. A configuration analysis will determine if ℓ is required.

Figure 8-10 is a plan view of the excursion boundary realized in a four-point moor. This envelope is circumscribed using the maximum horizontal projection (X) of each mooring leg as a radius emanating from its anchor. The path of the relaxed leg (S-Y) is also shown. A small vector diagram at the point of extreme excursion describes the direction of the holding forces experienced by the four mooring legs. As shown in Figure 8-10, if leg 1 is considered colinear with the imposed leg-loading force (H) at the excursion extreme, legs 2 and 4 will exhibit component forces assisting leg 1 while leg 3 opposes. At no location will X overlap S-Y, which means mooring cables will not be dragged back over themselves. This is an essential design requirement of the mooring system. It can be shown that when H is applied colinear to any single mooring leg, the moor is holding in its weakest condition; the strongest condition occurs when H is applied at 45^o to any leg and a major component of two adjacent legs do the holding. Maximum excursion in a four-point moor is given by the equation,

$$E_{max} = 2(X-S+Y). \tag{19}$$

Mooring leg pretensioning would reduce this excursion; however a larger wire rope, anchor and additional mooring legs would be required, adding to the cost and weight of the overall system. When the nature of the load module is such that excursion has to be limited to make the system functional, the added cost and expense are justified.

Figure 8-11 is similar to Figure 8-10 and illustrates excursion and holding power characteristics in a classic three-point moor. The shaded portions indicate the slack wire rope in excess of (S-Y) that can be laid on the bottom. This slack is apt to foul, kink, and entangle and would definitely be undesirable in a moor. It would have to be eliminated by pretensioning each leg to reduce (S-Y) by the shaded amount. What is worse, the vector diagram in the extreme excursion condition has two leg components (2 and 3) opposing the main holding leg (1). This indicates that each leg would have to be oversized by the amount of the opposing leg for a component and a pretension allowance.

A four-point moor was selected for the underwater power transmission system to satisfy holding power requirements that may be experienced when the environmental conditions selected in Chapter 3 are imposed on the mooring system from any direction. Had other specific information, i.e., environmental conditions, excursion limits or bottom topography been specified, another mooring system might have been selected, e.g., 3, 6, or 8 points.

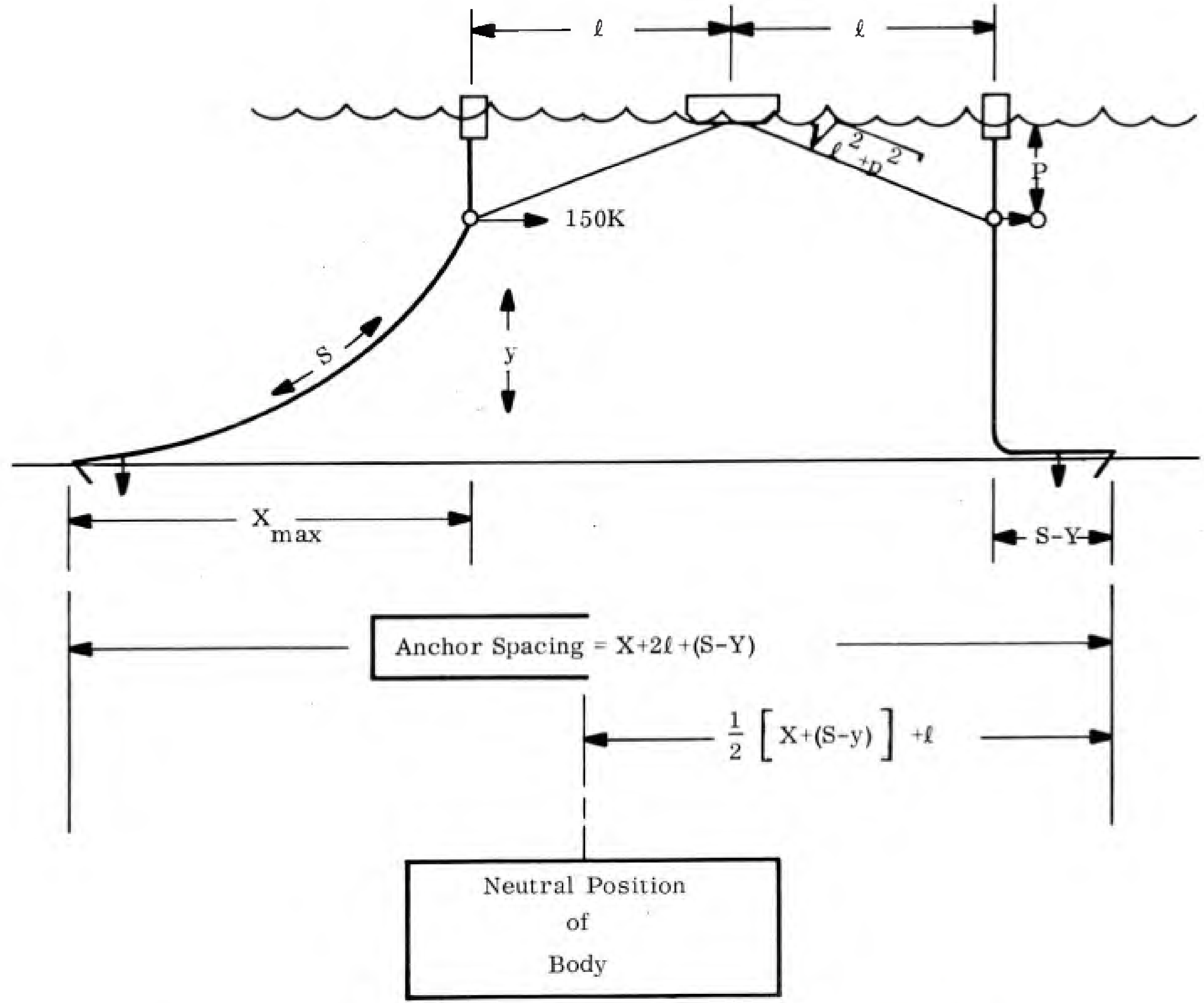


Figure 8-9. Elevation View of One Plane of a Typical Four-point Moor

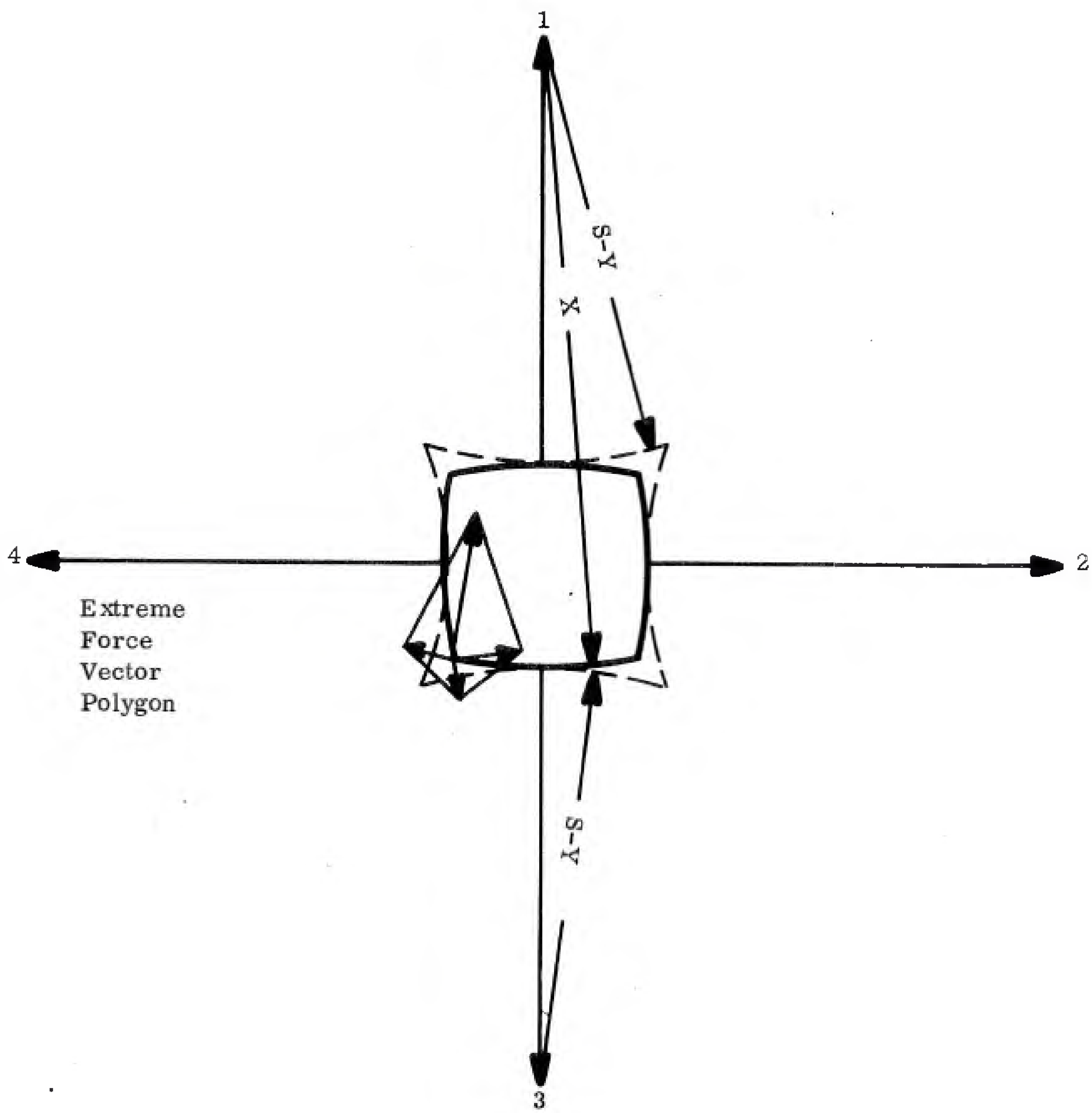


Figure 8-10. Four-point Mooring System Excursion

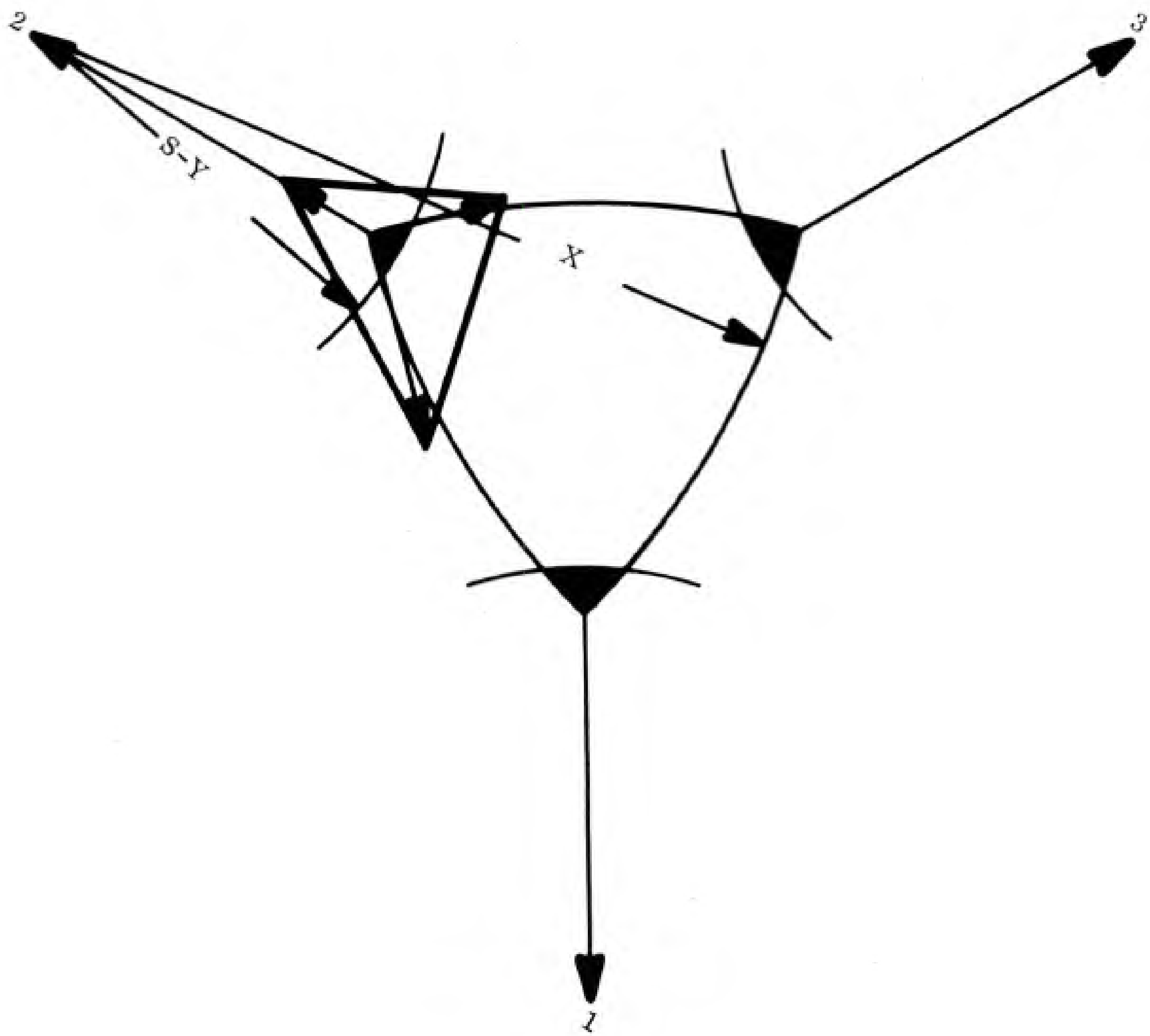


Figure 8-11. Three-point Mooring System Excursion

8.1.5 Mooring System Hardware Analysis

8.1.5.1 ANCHORS - The ability of a conventional anchor to hold to the ocean bottom was shown to depend upon several factors. The anchor should develop a minimum holding power equivalent to the maximum drag force plus the wave force allowance. If these forces are greater than the holding power of the anchor, two or more mooring legs may be required in the general direction from which the most adverse wind or current conditions are anticipated. Table 8-I gives anchor holding power for various conventional anchor types and weights.

Table 8-I. Anchor Types and Holding Power (Ref. 2)

TYPE	WEIGHT	MAXIMUM HOLDING POWER (SAND)
LWT	4,000 lb	75,000 lb
LWT wedge block	6,000 lb	106,000 lb
LWT wedge block	10,000 lb	175,000 lb
LWT wedge block	25,000 lb	430,000 lb
EELS	8,000 lb	80,000 lb

A device is available to determine tension in the mooring leg without using fittings or links to indicate when the anchor is adequately dug in. It allows, in effect, a "design test" of the leg to determine when the anchor has developed its design holding power. Figure 8-12 illustrates a tension measuring instrument designed by the David Taylor Model Basin for continuous recording.[4] Standard SR-4 strain gage dynamometer links have also been used.[6]

Conventional anchors described thus far are established pieces of hardware with reliability proven over the years. Currently developmental work is progressing to create new and better anchors. Traditionally anchors have been pulled over the bottom to make them dig in; this method will not suffice much longer. The new method will be to grout the anchor into the bottom or use explosives to drive it in. Advantages of the new systems are high reliability and a holding power that is not directionally dependent. This includes pull in the vertical direction which in itself is a distinct advantage over conventional anchors limited to horizontal holding force. It is unfortunate that equipment to deploy grouted pile anchors at all depths under consideration will probably not be available by the time the initial underwater power transmission systems are deployed.

Limiting capacity of hoisting equipment and inherent personnel safety hazards involved in handling deep ocean mooring rigs have long concerned mooring engineers; to circumvent this, free fall anchors are undergoing tests; the wire rope is deployed by a free payout method. This system allegedly allows a mooring system to be deployed from a moving ship in any sea state permitting deck handling.[7]

To summarize, the following new types of anchors[6,7] are being developed and may replace conventional anchors and/or clumps in hydrospace mooring rigs in the future:

- free fall anchor with free wire rope payout,
- drilled-in and cemented piling,
- driven piling,

- explosive anchors
- jetted in or driven "dead men."

Conventional anchors, preferably of the LWT wedge block design, are recommended for the underwater power transmission system because they have been well proven in similar applications at sea. When reliability and economics of developmental anchors improve, it may prove advantageous to re-evaluate their use.

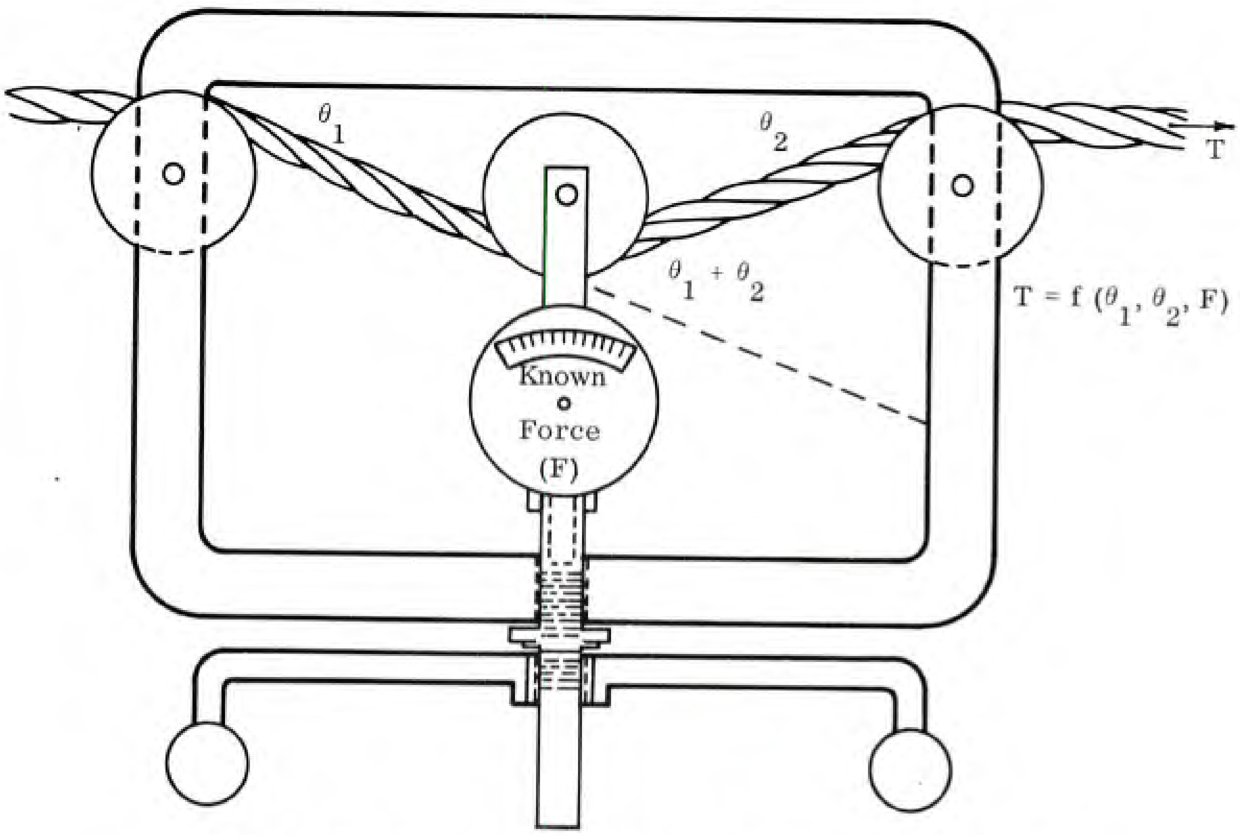


Figure 8-12. Diagram of a Tension-measuring Instrument

8.1.5.2 WIRE ROPE - Programs are now being conducted by wire rope manufacturers and the petroleum industry to significantly advance undersea wire rope state-of-the-art. Current work will develop much information beneficial to the deployment of the type of system recommended in this study.

Using stainless steel wire rope in underwater applications is a problem because it is susceptible to chloride stress corrosion. This type of corrosion is most apt to occur in crevices where a "cell" is created. Crevices are prevalent in all types of wire rope. Stainless steel wire rope failures at sea have occurred as early as 4-5 months after deployment with a surprisingly low inherent stress level. Cathodic protection systems are developmental with no sure solution in sight.

Programs to date utilizing plain steel and zinc-coated steel wire rope indicate it is not practical to deploy these ropes in sea water for more than 3 years.

Case histories indicate fishbite does not penetrate a 3/16" coating of polyurethane whether it is placed on steel or synthetic underwater tension members.

For the purpose of the underwater power transmission system, a polyurethane clad, three-strand, torque-balanced steel rope is recommended, because it is currently feasible and should provide at least the 5-year desired life expectancy. Stainless steel wire rope was ruled out because it costs more, has less strength, and has an unpredictable life span. Five standard wire rope sizes, 1-3/4, 1-5/8, 1-1/2, 1-3/8, and 1-1/4 were investigated. Typical physical characteristics of this clad wire rope are shown in Table 8-II. These ropes will not unwind or rotate appreciably at loads approaching 75 percent of the breaking strength. Yield strength is based on the .2 percent offset method. Conventional wire rope construction should not be utilized because the rope will unwind under load unless the ends are fixed. The necessity of swivels in the system precludes end fixing.

Figure 8-13 is a conceptual sketch showing a method for attaching the wire rope to a terminal swivel socket. It utilizes epoxy and neoprene to make a watertight connection expected to have a long life in sea water. Many wire rope moorings are suspected of fatigue failure at the socketed connections due to bending and/or vibration. A vibration damper should be attached to the nose of the socket to minimize the vibration effects. The polyurethane jacket acts as a vibration dampener in addition to offering salt water protection.

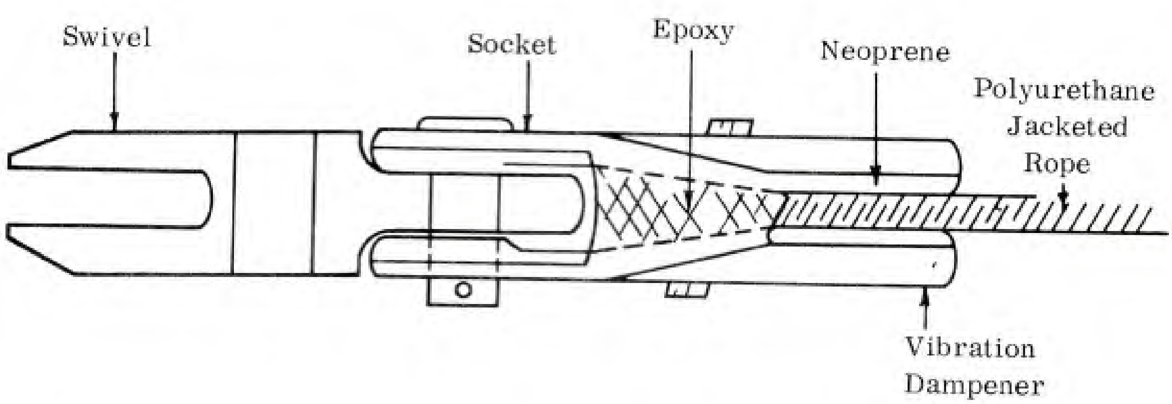


Figure 8-13. Method of Attaching Wire rope to a Terminal Swivel Socket

8.1.5.3 SYNTHETIC ROPE - Synthetic deep-sea mooring tope, such as dacron, nylon and polypropolene, are currently available in various types. Their characteristics are described below.

Table 8-II - Polyurethane-clad, Three-strand, Torque-balanced Rope

DIAMETER (Inches)	CONSTRUCTION*	POLYURETHANE JACKET THICKNESS (Inch)	O.D. (Inch)	WEIGHT (lb/ft)	WT IN AIR (lb/ft)	WT IN WATER (lb/ft)	BREAKING LOAD (lb)	.2% YIELD STRENGTH (lb)	MAXIMUM PRESENT (ft)	LENGTH PROPOSED (ft)
1-1/4	3x46 Seale FW	.100	1.514	.354	2.95	2.15	158,000	139,000	5,000	15,500
1-3/8		.100	1.637	.384	3.48	2.54	188,000	165,000	4,200	12,900
1-1/2		.110	1.784	.460	4.15	3.04	222,000	195,000	3.500	10,800
1-5/8		.110	1.938	.503	4.93	3.62	265,000	233,000	2,900	9,200
1-3/4		.110	2.063	.537	5.66	4.17	304,000	267,000	2,500	8,000

*Properties quoted by U.S.S. Corp., New Haven, Conn., for 3x46 Seale FW wind rope construction.

All synthetic fibers creep under load (cold flow characteristic). For a 5-year life at sea, creep will not present a problem if the working strength is kept below 25 percent and 30 percent of breaking strength for nylon and dacron, respectively. This is the steady continuous load; loads to 50 percent or 60 percent of breaking strength imposed on an intermittent cyclic basis for up to a week each year should not cause the mooring to fail before 5 years. The ability to withstand very short-term loadings equivalent to 90 percent of breaking strength is not unrealistic.

Synthetic rope is susceptible to failure if a significant portion of its fibers are abraded. This requires that the line must not be allowed to lie on the bottom or pass over jagged crevices, and that all rigging be designed with this requirement in mind. Chain is generally used where these adverse conditions prevail.

Synthetic rope generally fails near splices or connections. It is important that all such junctures be designed according to the manufacturer's recommendations. These are as varied as types of line available and each manufacturer has his own definite specifications.

The braiding and plaiting of a rope are responsible for the major portion of its elongation. As the rope is subjected to tension, the braiding is pulled tighter. The rope could be compared to a helical torsion spring. Development is taking place to produce a no-lay-rope, produced under the trade name Nolaro.* In this rope, all fiber strands are parallel to the longitudinal axis. They are held in a bundle by a polyurethane jacket. The advantage is maximum strength utilization of any given fiber with minimum elongation and twist neutrality.

Synthetic rope manufacturers have probably solved their fishbite problem. They established that fishbite cannot generally penetrate a 3/16 inch polyurethane sheathing or a fraction of an inch of rope material, i.e., polypropolene. They could coat low-elongation Nolaro rope with an extruded polyurethane jacket; similarly they could wind the outside of the large braided rope with 1/4 inch or 3/8 inch polypropolene rope. Polypropolene tends to make the rope neutrally buoyant. Both sheathings would also eliminate minor or short-term abrasion problems that may arise.

A compound nylon-polypropolene rope (Powerbraid) has been developed, the advantage being that it exhibits neutral buoyancy in water.**

Certain color application processes can throw synthetic rope off balance. Colored rope, to date, has experienced fishbite the same as white rope; since white is the natural color and simplest to manufacture, there is no reason why it should not be used.

Synthetic lines were not recommended for the catenary mooring legs of the mooring system in lieu of wire rope for the following reasons:

- They cost approximately 3 to 4 times as much per foot as steel on an equivalent working strength basis;
- The 30 percent elongation at the normal maximum working load with excursions to 50 percent elongation makes fixed positioning and integrity of the total system questionable;
- Steel wire rope mooring systems deployed to date have exhibited a higher degree of reliability.

*Columbian Rope Co., Auburn, N.Y.
**Sampson Cordage Co., Boston, Mass.

Table 8-III. Synthetic Mooring Line Characteristics

LINE DESCRIPTION diam.	LINE DESCRIPTION circum.	MATERIAL	BREAK STRENGTH (lb)	WORK STRENGTH (lb)	WT/FT IN AIR (lb/ft)	S. G.	APPROX WT/FT IN WATER (lb/ft)	COST ($/ft)	ELASTIC STRETCH
5"	15"	Nylon (2-1 Brand)	670000	40% B.S. max 30% B.S. prefer 268000	6.6	1.14	0.925	14.75	18% @ 40% BS 16% @ 30% BS 14% @ 20% BS 10% @ 10% BS
5"	15"	Nylon-Poly-prop. Core (Powerbraid)	580000	232000 174000	5.75	1.03	0.017	12.90	15% @ 40% BS 14% @ 30% BS 12% @ 20% BS 9% @ 10% BS
4"	12"	Nylon (2-1 Braid)	430000	172000	4.2 3.6	1.14	0.59	9.50 ft	
		Nylon -Poly-propolene (Powerbraid)	380000	152000	3.6		0.011	8.00 ft	
3"	9"	Nylon (2-1 Braid)	240000	96000	2.3	1.14	0.32		
		Nylon-Poly-propolene (Powerbraid)	220000	88000	2.0	1.03	0.006		
4"	12"	Nylon Plated (85T)	360000	40% B.S.	3.8	1.14	.532		
		Dacron Plated (85T)	300000	40% B.S.	4.6	1.38	1.75		
3"	9"	Nylon Plated	200000		2.10	1.14	0.294		
		Dacron Plated	174000		2.6	1.38	0.99		
2-1/2"	7-1/2"	Nylon Plated	140000		1.5	1.14	0.21		
		Dacron Plated	122000		1.8	1.38	0.685		

In certain links of the mooring system where a spring characteristic is desirable, synthetic rope will be very useful. It is recommended that nylon rope be used as a taut line connecting the thick-disc hull with the top of the mooring leg when catenary support buoys are used. This is illustrated in Figure 8-9. In this application, elongation of the nylon line will dampen a major portion of the wave forces before they reach the catenary mooring leg. Table 8-III shows typical synthetic rope characteristics for several representative materials and methods of construction.

8.1.5.4 CHAIN - Two types of welded chain are feasible for underwater power systems. The first is 1020 carbon steel chain covered by the general Mil-Spec RRC-271A. Second is 8620 high strength steel alloy chain covered by Mil-Specs RRC-271A and 205000 to the 1-1/4 inch size. Choice of the latter material is recommended for chain requirements in the underwater power transmission system moorings because 8620 chain is used throughout industry where a high degree of reliability is required, e.g., hoists or draglines. In addition, 1020 chain is not manufactured in the full range of sizes worthy of consideration, 1-1/4 inch being the longest. Physical properties of this chain are shown in Table 8-IV.

Table 8-IV. Typical Physical Properties of Chain

SIZE (in.)	WT/FT IN AIR (lb)		BREAKING STRENGTH (lb)	
	1020 steel	8620 steel	1020 steel	8620 steel
1 1/4	12.5	17.5	145,000	228,000
1 1/2		21.5	Not Available	320,000
1 3/4		30.0	Not Available	400,000
2		38.0	Not Available	520,000

Chain manufacturers do not welcome X-ray inspection of welds but rather advocate a proof test of half the breaking strength, then industrially rate the chain at half the proof test value. Excessive deformation begins when the chain is loaded above 50 percent of breaking strength. It is recommended that chain be sized so the maximum mooring tension it would ever experience does not exceed 40 percent breaking strength.

It can be argued weight is always needed at the anchor takeoff point and it may as well be chain as a clump. Since chain costs 9 times as much per lb as clump material, the argument cannot be justified; however chain is easy to handle on deck, is not subject to abrasion damage and has performed well in mooring system application.

8.1.5.5 CATENARY SUPPORT BUOY CONSTRUCTION - Catenary support buoys may be fabricated from 1/8-inch A-212 normalized steel plate with internal structural members and ribs fabricated from A-36 silicone steel using basically the same construction as the surface power plant hull (Chapter 7). The buoy should also have the same surface preparation and finish as the main buoy: sandblast and coat with zinc Dimecote and a vinyl paint finish. It would be wise to periodically inspect these buoys at sea and apply touch-up paint as necessary. The maximum corrosion pitting depth that can be expected per year is 1/16-inch. Thus, if paint were damaged on initial installation, the buoy could leak in four years.

It is recommended that each catenary support boy required be equipped with a leak detector capable of transmitting an alarm signal to the thick-disc hull protective alarm system. This is important because, if a catenary support buoy sinks, the leg weight is transferred to the surface power plant hull. In this event it may be advisable to sever the damaged mooring leg from the main hull. An emergency, battery-powered bilge pump in the catenary support buoy is recommended to help eliminate the jettison need.

On the Toto II moor, these buoys were filled with a light foam to increase rigidity. Catenary support buoys have not been sized for foam filling because it is conceivable that even a foam-filled buoy could begin to leak if it were rammed by a ship as suspected in Toto I. The use of foam may be further investigated during the final design study.

A better method of protection is recommended for the underwater power transmission system catenary support buoys. It consists of a circumferential pipe structure having a radius 4 to 5 feet larger than the support buoy. This structure is envisioned similar to the prop guards on submarines and destroyers. This structure would fend the buoy away from the oncoming ship and provide some degree of spring action.

This buoy would be equipped with navigational lights and an adequate structural connection to support the mooring leg. The lights would be mounted on a mast at the proper elevation to comply with U.S. Coast Guard or similar nautical standards.

8.1.5.6 ENVIRONMENTAL PROTECTION - State-of-the-art techniques will be used to protect the mooring systems from corrosion and fouling (TOTO II, SQUAW). The major portion of the mooring system will be polyurethane-clad wire rope. Intermediate swivels, ground rings, shackles, and hardware should all be of the same material to avoid setting up electrolytic cells. Based on a maximum pitting rate of 1/16'' per year, suitable corrosion allowance may be provided. Hardware should be painted to retard corrosion as long as possible. In addition, sacrificial zinc anode blocks may be provided. Similarly, in the anchor-chain-clump section, sacrificial zinc anodes should be provided; they will weigh several hundred pounds. Since anchor and chain will become covered with sediment, their surfaces will be in an anaerobic state, reducing corrosion rate to that induced electrolytically.

8.1.6 Surface Tendered Power Plant Mooring System Analysis

8.1.6.1 MOORING LEG HOLDING POWER - The first step in sizing the mooring systems for the underwater power transmission system surface power plants is the determination of the mooring leg holding force required. Equations (14) and (15) were used to compute wind and current drag forces for all components subjected to their influence. Component drag forces calculated for each power level at all selected depths are shown in Table 8-V. Wind and current drag forces were combined into a total drag force (column 8) for each condition. A maximum holding power of 150,000 lbs (column 9) was assumed. The difference between maximum holding power and total drag force represents the wave force allowance (column 10). The ratio of wave force allowance to maximum holding power (column 11) represents 0.6 of the maximum holding force for the smallest hull-power-depth combination and 0.15 for the largest. It was necessary to arrive at a constant holding power value in order to make a meaningful comparison of the mooring legs under consideration. Table 8-I indicates that a

Table 8-V. Mooring System Drag Force Profile

System Description and Depth	Thick Disc-Hull Wind Drag (lb) 1	Thick Disc-Hull Current Drag (lb) 2	Electrical Trans-mission Cable Drag (lb) 3	Mooring Cable Drag ea (lb) 4	Mooring Cable Drag x4 (lb) 5	Catenary Support Buoy Drag ea (lb) 6	Catenary Support Buoy Drag x4 (lb) 7	Total Drag Force 1 2 3 4 5 6 7 8 (lb) 8	Maxi-mum Hori-zontal Force (lb) 9	Wave Force Allow-ance 9-8 10 (lb) 10	Wave Force Max. Force 10/9 11
41x7 1/2' Buoy 30 KW-Plant											
600 ft	19700	13100	3500	3500	14000	2250	9100	59400	150000	90600	60.4
2000 ft			4200	4200	16800			62900		87100	58.1
6000 ft			4300	4300	17200			63400		86600	57.7
10000 ft			4400	4400	17600			63900		86100	57.4
15000 ft			4500	4500	18000			64400		85600	57.0
20000 ft			4600	4600	18400			64900		85100	56.6
55 1/2x9 1/2' Buoy 100 & 300 KW Plants											
600	35000	24600	3500	3500	14000	9500	38000	115100	150000	34900	23.3
2000			4200	4200	16800			118600		31400	20.9
6000			4300	4300	17200			119000		31000	20.7
10000			4400	4400	17600			119400		30600	20.4
15000			4500	4500	18000			119800		30200	20.1
20000			4600	4600	18400			120200		29800	19.8
55 1/2x11 1/2' Buoy 1000 & 3000 KW Plants											
600	33300	26500	3500	3500	14000	10000	40000	117300	150000	32700	21.8
2000			4200	4200	16800			120800		29200	19.5
6000			4300	4300	17200			121300		28700	19.1
10000			8700*	4400	17600			126100		23900	15.9
15000			8900*	4500	18000			126700		23300	15.5
20000			9100*	4600	18400			127300		22700	15.1

*Values shown for 3000KW Cable, half for 1000 KW installation.

25,000 LWT wedge block anchor is capable of developing this holding power and Figures 8-4, 5, and 6 indicate that it will be satisfactory for virtually all bottom soil conditions.

It is assumed that underwater power transmission systems will at first be deployed at the lower power levels and shallower depths, i.e., continental shelf operations, typical of the pre-design examples of Chapter 10. Greater wave force allowances are utilized for these initial ventures. Exact values may be accurately established from tests on preliminary systems and factored into the larger and deeper system designs to follow.

8.1.6.2 WIRE SIZING ANALYSIS - Having determined the required mooring leg holding power (H) as 150,000 lbs and knowing the allowable tension of representative wire sizes (Table 8-II), it is possible to trigonomentrically compute the limiting angle (θ) and magnitude of the corresponding vertical component of force (V) for the standard wire rope size under consideration (Figure 8-3). These wire rope parameters are shown in Table 8-VI and are based on the following equations.

$$\text{limiting angle, } \theta = \cos \frac{H}{T} \tag{20}$$

$$\text{vertical force component, } V = T \sin \theta \tag{21}$$

Table 8-VI. Wire Rope Design Parameters

WIRE DIAMETER (in.)	WEIGHT PER FT IN WATER (lb/ft)	BREAKING STRENGTH (lbs)	YIELD STRENGTH .2% OFF-SET (T) (lbs)	HOLDING FORCE (H) (lbs)	LIMITING ANGLE (degrees)	VERTICAL FORCE COMPONENT (V) (lbs)
1-3/4	4.17	304,000	267,000	150,000	55	218,000
1-5/8	3.62	265,000	233,000	150,000	49	176,000
1-1/2	3.04	222,000	195,000	150,000	39	122,000
1-3/8	2.54	188,000	165,000	150,000	24	67,000

Since each wire size has a limiting tension and angle, it is reasoned that the lightest possible mooring leg would be obtained by using successively smaller wire sizes as the mooring leg traverses downward. The next smaller wire would be used as soon as its allowable tension and limiting angle matched the actual mooring leg conditions. For instance, the vertical component of force at any point in a catenary is equal to the total weight of the leg suspended beneath it. Thus from Table 8-VI it can be seen that 1-3/4 inch wire rope will support a leg weighing 218,000 lbs, 1-5/8 inch supports 176,000 lbs etc. The difference between these two vertical force components represents the weight of the 1-3/4 inch wire rope scope (s) that should be used.

$$\Delta W = 218{,}000 \text{ lbs} - 176{,}000 \text{ lbs} = 42{,}000 \text{ lbs} \tag{22}$$

$$s_{1\text{-}3/4} = \frac{42{,}000 \text{ lbs}}{4.17 \text{ lbs/ft}} = 10{,}025 \text{ ft.} \tag{23}$$

If a longer scope is required, 1-5/8 inch wire would be used below 10,025 ft. The 1-5/8 inch scope is calculated in the same way.

Table VII is based on this analysis and shows the scope (column 6) of each wire rope size for various mooring rigs, both with and without clumps.

8.1.6.3 MOORING LEG COMPOUND CATENARY ANALYSIS - The method for determining the size of the mooring legs for the underwater power transmission system was to establish curves and alignment charts. Using catenary theory (paragraph 8.1.2) Y, S, X and θ were computed for each wire size assuming no clump and then assuming 25, 50, 75 and 100 Kip (K) clump sizes. The solutions were plotted in Figures 8-14 through 8-18.

Equations (1) through (13) were solved for mooring leg parameters. The following terms have been established:

H	=	150,000 lbs (paragraph 8.1.6.1)
θ_t	=	limiting upper catenary angle of each wire size based upon H, 1-3/4 - 55°, 1-5/8 - 49°, 1-1/2 - 39°, 1-3/8 - 24°. (see Table 8-VI)
θ_o	=	angle the catenary anchor shank makes with the ocean floor; assumed to be 0°.
W	=	wire rope weight (lbs/ft)(see Table 8-VI)

Knowing these parameters, the catenary equations can be solved for

S	=	total mooring leg scope (ft)(see Figure 8-3)
s	=	incremental scope of each wire size making up S (ft)
Y	=	total mooring leg vertical projection (ft)
y	=	incremental vertical projection of each wire size (ft)
X	=	total mooring leg horizontal projection (ft)
x	=	incremental horizontal projection of each wire size (ft)
θ_b	=	mooring leg angle at the bottom of each catenary wire increment.

This analysis was used to determine that, for H = 150,000 lbs, a total scope (S) of 69,425 ft could be supported using four wire sizes. The corresponding depth and horizontal projection is 32,500 ft and 57,500 ft. These values are significant because they represent the deepest possible moor, utilizing 1-3/4 inch diameter, balanced-wire, mooring rope of standard manufacture.

It is characteristic of catenary theory that for mooring legs of equal weight and bottom angle (θ_o), the angle at the top of the catenary (θ_t) will remain constant regardless of weight distributions along its length, while the scope will vary. Accumulating leg weight into a clump tends to sharply change the slope of the catenary at the clump. Consider the effect of adding a clump to the deepest (limiting) mooring system described above. The lower end of the catenary can be shortened by a scope length s until the product sW equals 25, 50, 75 and 100 K. This equivalent weight is put into the clump. Parameters X, Y, and S will decrease as clump weight is increased. The change in slope at the clump is predicted by equation (12). As a general rule the

Table 8-VII Mooring Leg Catenary Parameters

WIRE SIZE (in.) AND CLUMP SIZE (K)	WIRE WT (lb/ft)	WORKING STRENGTH (K)	V (K)	V (K)	S	Y	S/Y	X
No Clump								
1-3/4	4.17	267	218	42	10000	7950	1.26	6120
1-5/8	3.62	233	176	54	14900	10400	1.49	10900
1-1/2	3.04	195	122	55	18100	8900	1.90	15400
1-3/8	2.54	165	67	67	26400	5500	4.62	25000
Total				218				
25K Clump, 5.1K Chain				30.1				
1-3/4				42	10000	7950	1.26	6120
1-5/8				54	14900	10400	1.49	10900
1-1/2				55	18100	8900	1.90	15400
1-3/8				36.9	14500	4140	3.5	13400
Total				218.0				
50K Clump 5,1K Chain				55.1				
1-3/4				42	10000	7950	1.26	6120
1-5/8				54	14900	9600	1.49	10200
1-1/2				55	18100	8900	1.90	15900
1-3/8				11.9	4690	1770	2.65	4300
Total				218.0				
75K Clump 5.1K Chain				80.1				
1-3/4				42	10000	7950	1.26	6120
1-5/8				54	14900	9600	1.49	10200
1-1/2				41.9	13750	7650	1.80	11320
Total				218.0				
100K Clump 5.1K Chain				105.1				
1-3/4				42.0	10000	7950	1.26	6120
1-5/8				54.0	14900	9600	1.49	10200
1-1/2				16.9	5560	3450	1.61	4700
Total				218.0				

heavier the clump, the shorter the scope required. From a cost effective standpoint, a portion of wire rope at about \$5 per foot can be replaced with equivalent clump weight worth \$.35 which develops the same holding power. There is a limiting value of clump weight which is governed in part by the deployment ship winching system capacity and also by the limiting vertical force component of wire rope tension.

Based on holding power requirements and the above analysis, a typical anchor-chain-clump configuration was used at the bottom of each mooring leg. It is comprised of a 25000 LWT wedge block anchor, one shot of 1-1/2 inch chain, a clump ranging from 25-100 K, two additional shots of 1-1/2 inch chain, and the scope of wire rope. Nomographs or alignment charts were designed to provide the same information that is otherwise obtained from trial and error solutions. A key is provided on each chart to illustrate its use. Charts (Figures 8-14 through 8-16) provide incremental values of x, y, and s for the various wire sizes considered. Figure 8-17 is similar and is used to determine the catenary angle (θ) change corresponding to various clump sizes for the wire sizes and hold power under consideration. Incremental data shown in Table 8-VII was obtained from these alignment charts.

Figure 8-18 is a curve showing depth versus the $S/_Y$ ratio for the various wire and clump sizes considered. This curve is based on Table 8-VII. It is possible to enter this curve at the selected depths and pick the wire-clump configuration resulting in the smallest scope. Squares indicate points representing optimum leg sizing for the six selected depths, 600, 2000, 6000, 10,000, 15,000 and 20,000 ft. The wire size curves break off abruptly at the lower left hand side. Wire size curves should not be extrapolated without exercising caution. They are limited by the weight the wire rope can support (V), i.e., chain, clump, and wire rope weight, when delivering maximum holding power. As an example, the 1-3/8 inch wire rope is limited to a minimum $S/_Y$ ratio of 2.65 at about 1800 ft. Extrapolating this to 600 ft and $S/_Y = 2.3$ would be a mistake because the cable would snap before it developed 150,000 lbs, the required holding power. It is permissible to extrapolate the 50 K clump curve to locate the 600 ft select point at $S/_Y = 2.8$. A weight balance shows total leg weight = 50 K(clump) + 5 K (chain) + 4.3 K (wire) = 59.3 K compared to 67 K the wire is capable of supporting in a catenary. This indicates clump weight can be further increased to 57 K, and $S/_Y$ becomes 2.65. Maximum hoisting load is 25 K (anchor) + 55 K (clump) + 5 K (chain) + 1.5 K (rope) = 86.5 K. This compares favorably to the 165 K yield strength of the 1-3/8 inch wire rope.

Based on Table 8-VII, Figure 8-19 was plotted to show total horizontal projection X as a function of vertical projection Y for the mooring system configurations considered. This is useful because the alignment charts provide incremental values (s, x, y), whereas this curve shows the total projection (S, X, Y).

Figure 8-20 was plotted to illustrate mooring leg wire rope weight as a function of depth. Wire rope weight is critical because any given catenary is capable of supporting just so much weight. Pay out more cable during deployment and the leg could be overloaded; probably just when the maximum holding force H is required.

The foregoing analysis shows that the weight of each of the four mooring legs will be in excess of 60 K. Since this amounts to much more than the power plant's thick-disc hull is capable of supporting, it justifies the use of a catenary support buoy to carry the weight of each mooring leg. It is recommended that the thick-disc hull be secured to each catenary support buoy by 4-inch diameter (2-1 braid) nylon rope (see Table 8-III).

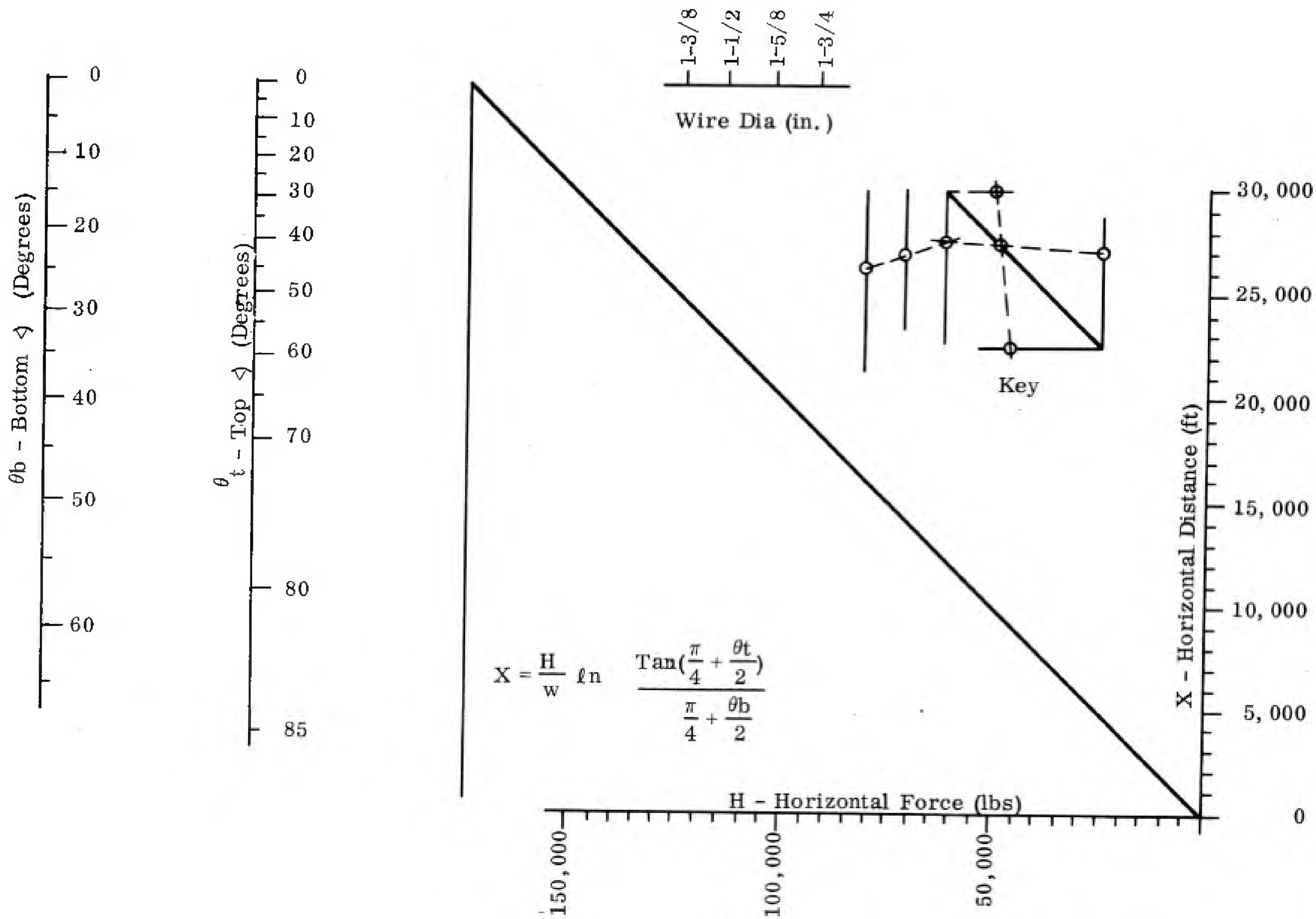


Figure 8-14. Mooring Leg Catenary Alignment Chart (Horizontal Projection)

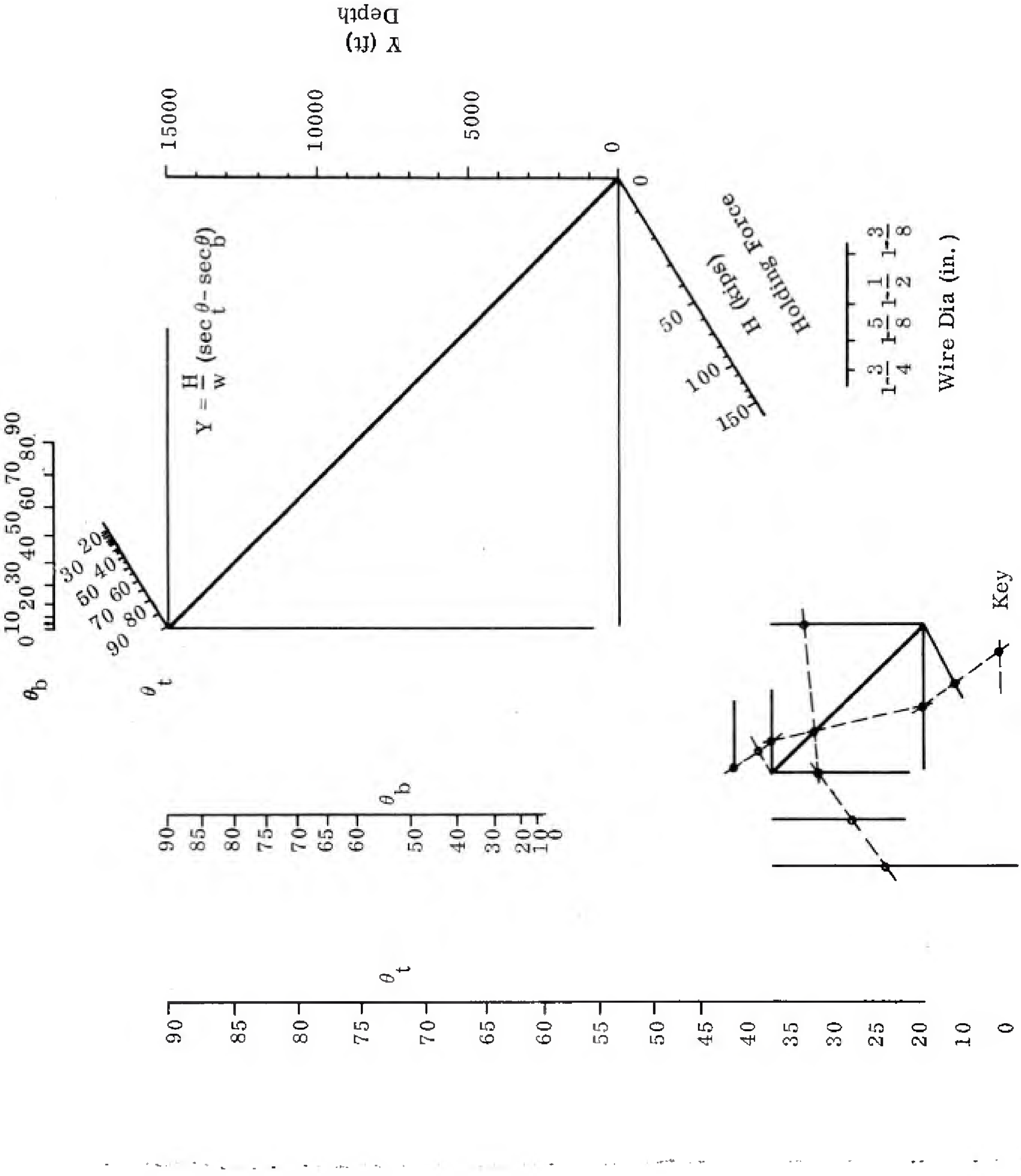


Figure 8-15. Mooring Leg Catenary Alignment Chart (Vertical Projection)

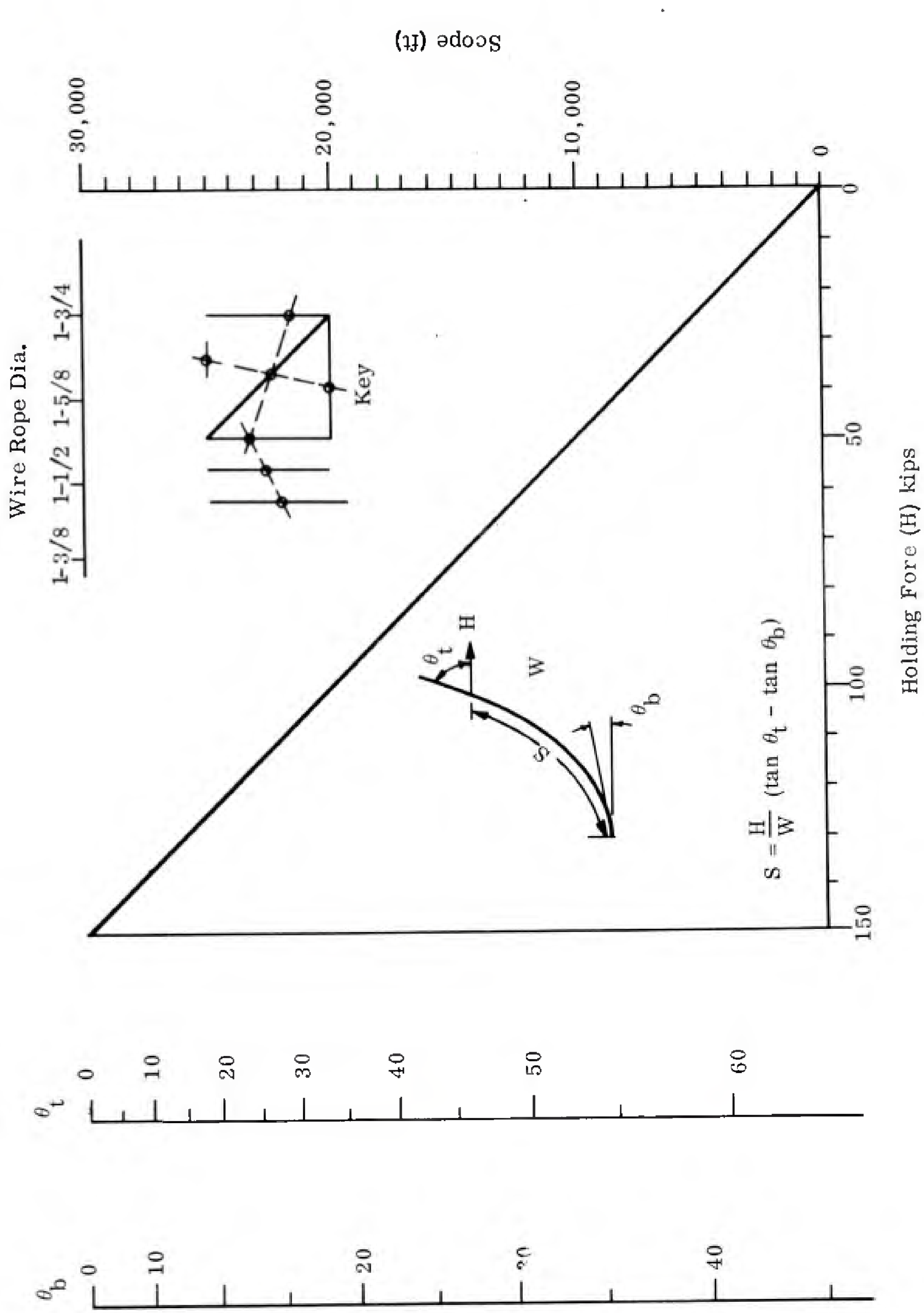


Figure 8-16. Mooring System Alignment Chart (Scope)

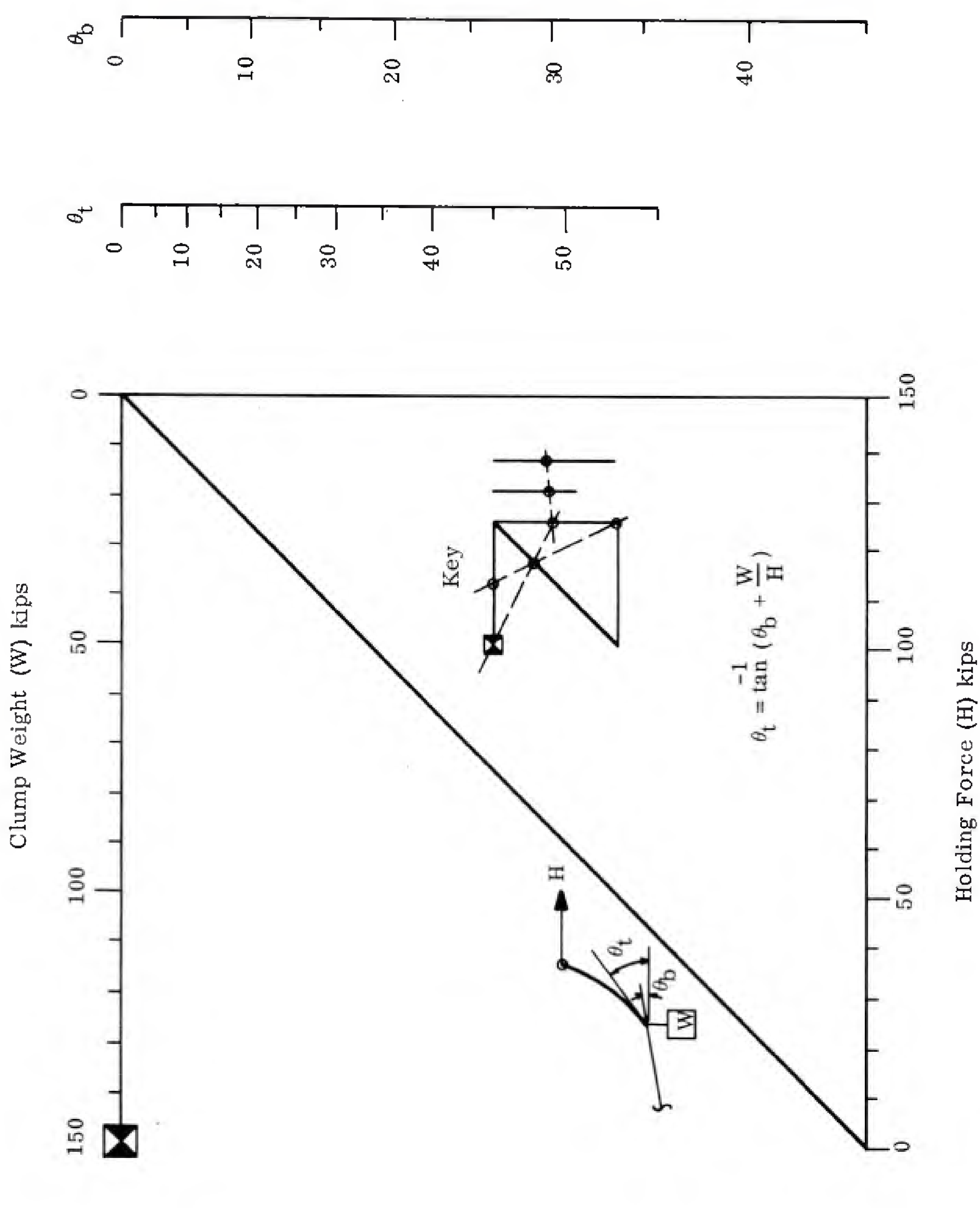


Figure 8-17. Mooring System Alignment Chart (Clump θ_t)

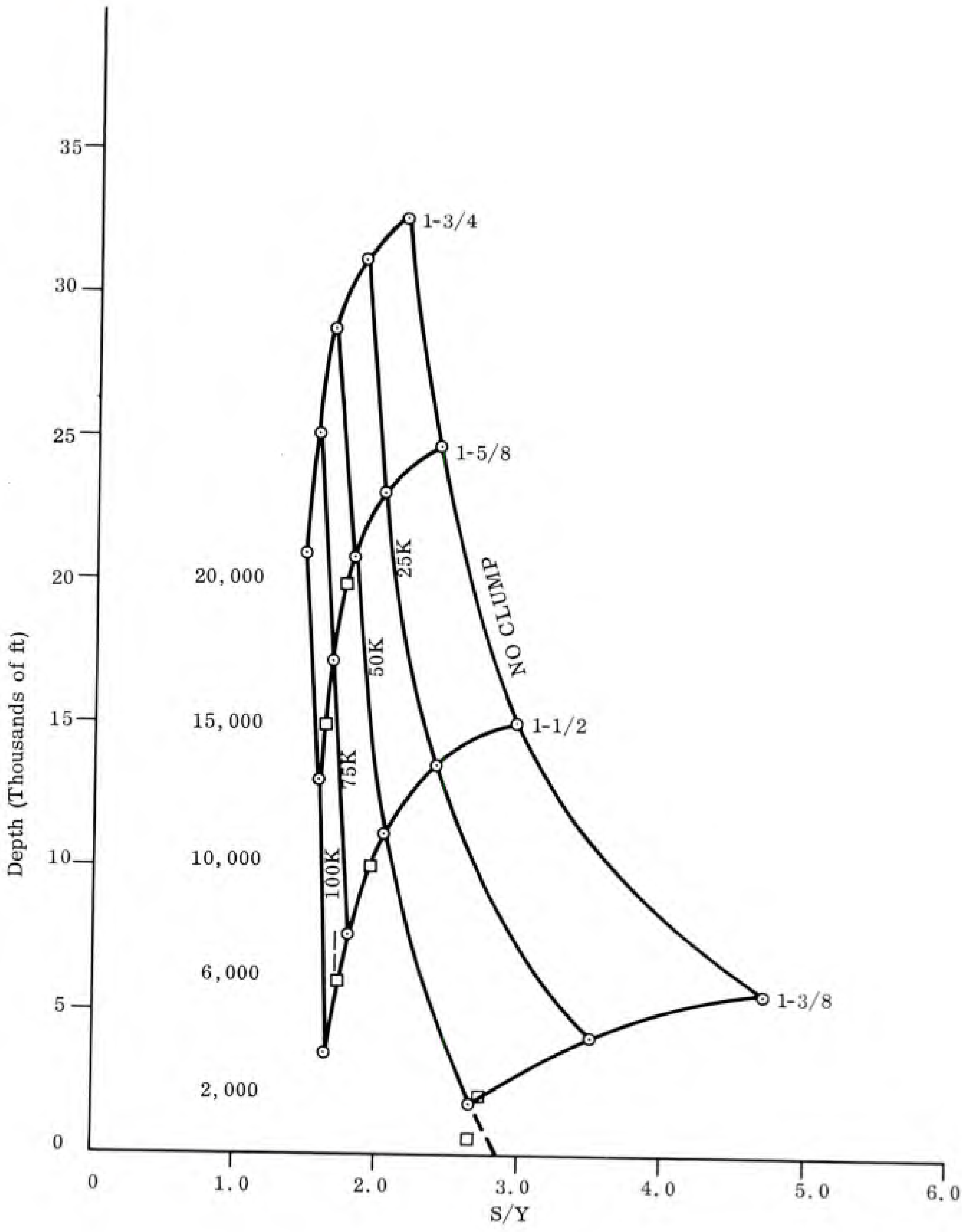


Figure 8-18. Mooring Leg Selection Chart

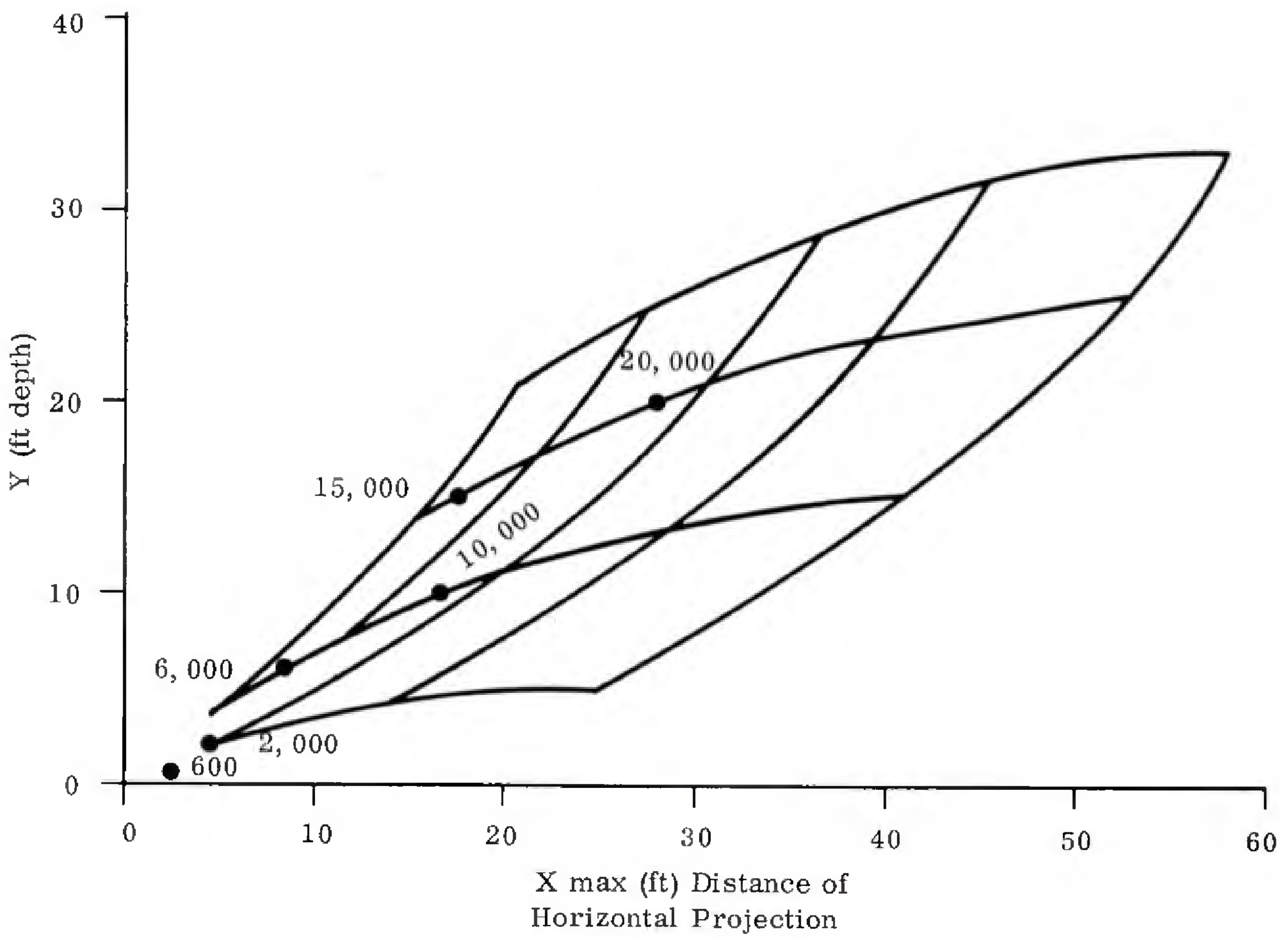


Figure 8-19. Mooring Leg Maximum Horizontal Projection

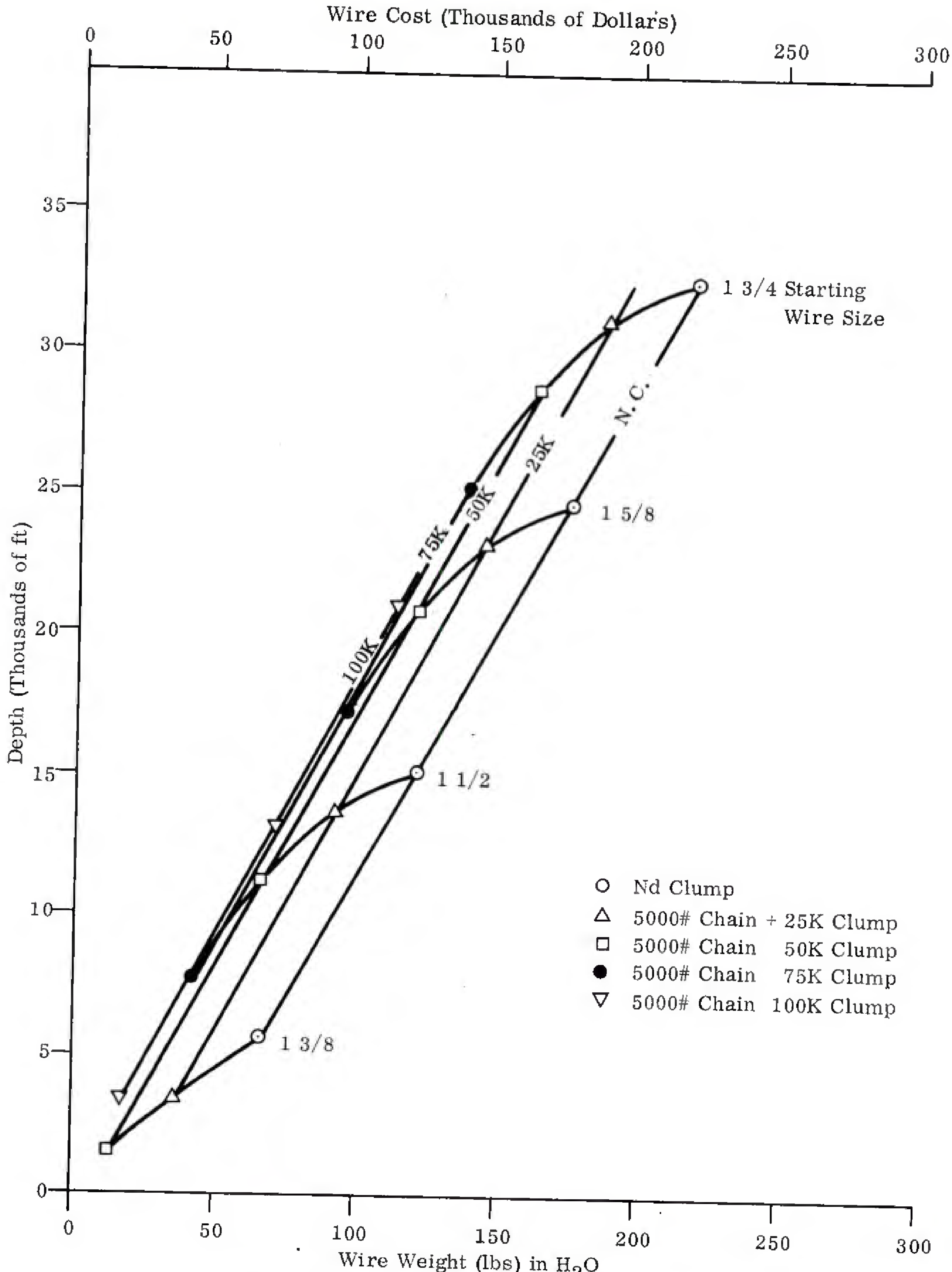


Figure 8-20. Mooring Leg Wire Rope Weight

8.1.6.4 CATENARY SUPPORT BUOY ANALYSIS - The catenary support buoy must be sized to support the entire mooring leg weight supported in a catenary when H_{max} is applied. Table 8-VIII shows the various size buoys required to support the determined mooring leg weights.

Table 8-VIII. Catenary Support Buoy Characteristics

CATENARY SURFACE WIRE DIAM (in.)	WEIGHT OF MOORING LEG (less anchor) (lbs)	EST WT OF BUOY (lbs)	RESERVE BUOYANCY (lbs)	TOTAL BUOY DISPL (lbs)	BUOY DIMENSION L (ft)	BUOY DIMENSION DIAM (ft)
1 5/8	176,000	7,700	16,300	200,000	17.5	15
1 1/2	122,000	6,800	22,200	150,000	22	12
1 3/8	67,000	4,400	13,600 (8-16%)	85,000	12	12

Catenary support buoys should be located approximately 1000 ft away from the power plant hull to provide a sufficient scope of nylon rope to act as a damper. The nylon rope will dampen the wave forces so each mooring leg will be subjected to a more constant holding force.

8.1.6.5 SURFACE POWER PLANT MOORING SYSTEM SELECTION - Table 8-IX shows mooring leg summary data for the underwater power transmission system surface power plant moorings at 600, 2000, 6000, 10,000, 15,000 and 20,000 ft depths. This table is a weight balance that checks all prior curves and calculations. Anchor and chain weight were taken as 25,000 and 5100 lbs respectively. Clump weight and wire rope scope are variable and are determined from Figure 8-18. Also, 67,000, 122,000, and 176,000 lbs are the maximum loads (V) that 1-3/8 inch, 1-1/2 inch, and 1-5/8 inch wire rope can support in a catenary (see Table 8-IV). Incremental wire scope can be determined from the following equations.

$$s_{1\text{-}3/8} = \frac{67{,}000 - (\text{clump wt} + \text{chain wt})}{W_{1\text{-}3/8}} \tag{26}$$

$$s_{1\text{-}1/2} = \frac{122{,}000 - (\text{clump wt} + \text{chain wt} + sw_{1\text{-}3/8})}{W_{1\text{-}1/2}} \tag{27}$$

$$s_{1\text{-}5/8} = \frac{176{,}000 - (\text{clump wt} + \text{chain wt} + sw_{1\text{-}3/8} + sw_{1\text{-}1/2})}{W_{1\text{-}5/8}} \tag{28}$$

$$S = s_{1\text{-}3/8} + s_{1\text{-}1/2} + s_{1\text{-}5/8} \tag{29}$$

$$W = sw_{1\text{-}3/8} + sw_{1\text{-}1/2} + sw_{1\text{-}5/8} \tag{30}$$

where $s = \Sigma$ incremental scope of 1-3/8, 1-1/2 or 1-5/8 wire rope.

$w = \Sigma$ 2.54 #/ft for 1-3/8 rope, 3.04 #/ft for 1-1/2 rope, and 3.62 #/ft for 1-5/8 rope.

The anchor weight is not included because it is resting in the bottom and is not supported by the catenary. Anchor weight is added to the catenary support weight to arrive at the total weight of one mooring leg, Table 8-IX. Anchor weight must also be used to determine the hoisting weight.

$$\text{Hoisting weight} = \text{anchor wt} + \text{chain wt} + \text{clump wt} + \text{wire wt} \qquad (31)$$

where

$$\text{wire wt} \sum_{0}^{y} s_{1\text{-}3/8} + s_{1\text{-}1/2} + s_{1\text{-}5/8} \text{ as required and in that order.}$$

(y = depth.)

Hoisting weight must always be less than allowable wire tension. An allowance must be applied to the hoisting weight to allow for ship and hoisting surges while lowering the leg to the bottom.

8.1.6.6 SURFACE POWER PLANT MOORING SYSTEM CONFIGURATION - Equations (17) through (20) were solved to convert the coplanar dimensions resulting from the analysis of a single compound catenary mooring leg to dimensions indicative of the simple three-dimensional, four-point moor selected for the underwater power transmission system. The geometry of the four-point mooring system was defined in Figures 8-5 through 8-7. The results of these computations are given in Table 8-X.

The four-point mooring system recommended is considered to be the minimum number of mooring legs required to restrain the surface-tendered power plant in the sea state condition established in Chapter 3. Ideal bottom conditions were assumed. Redundancy was not considered in order to make an economic comparison on a basic strength requirement basis. Redundancy will vary geographically. For instance, in shallow waters where fishing banks and vessel traffic is highest, the cost of redundant mooring legs will be lowest and will not severely penalize the project. Deeper ocean moors, requiring the most costly mooring legs, will be located in regions not usually frequented by trawlers because of the absence of fish. It is also reasonable to assume that deep water moors will be situated well away from prescribed shipping lanes to reduce the chance of collision.

A couple of years ago, an eight-leg, oil, rig platform failed in a severe storm when its anchors allegedly dragged. The key to avoiding a similar situation is to take a systems approach to the design of the mooring system. From anchor to hull hydrodynamics, all factors must be carefully analyzed. The system will have to be tested and evaluated for all exposure conditions.

As a general rule, excursion in a four-point moor of the geometry assumed is approximately equal to the depth of moor.

Consider the condition where each leg of the moor would be situated on a flat bottom of a different elevation. The figures would still be useful for calculating the individual parameters of each leg. Configurations of this type are likely to exhibit tension in opposing legs that would act much like pretensioning the simplified system. If there are significant variations in depth between these legs, additional legs would be required.

Table 8-IX. Mooring System Summary Data for Selected Systems

DEPTH Y (ft)	CLUMP WEIGHT (lbs)	INCREMENTAL WIRE ROPE SCOPE (1-3/8) ft	(2.54 lbs/ft) lbs	(1-1/2) ft	(3.04 lbs/ft) lbs	(1-5/8) ft	(3.62 lbs/ft) lbs	TOTAL WIRE ROPE SCOPE ft	lbs	HOISTING WEIGHT lbs	CATENARY SUPPORT WEIGHT lbs	TOTAL MOORING LEG WEIGHT lbs
600	57000	1590	4040					1590	4040	86700	67	92
2000	48000	5400	13700					5400	13700	83200	67	92
6000	85000			10400	31600			10400	31600	133400	122	147
10000	58000	1575	4000	17925	54500			19500	58500	117700	122	147
15000	89000			8900	27000	15100	54700	24000	81700	167600	176	201
20000	56000	2000	5100	18000	55000	15000	54300	35000	114400	146200	176	201

Table 8-X. Mooring System Dimensions

SCOPE S	DEPTH Y	S-Y	X MAX.	2 OR 4-POINT ANCHOR SPACING X+ S-Y +2ℓ	PLANAR EXCURSION X-S+ Y	MAX. 4 PT MOOR EXCURSION 2(X-S+ Y)	NEUTRAL POSITION OF BUOY W/N TO ANCHOR 1/2 X+ (S-Y) +ℓ
35000	20000	15000	28000	45000	13000	18420	22500
24000	15000	9000	17000	28000	8000	11330	14000
19500	10000	9500	16500	28000	7000	9920	14000
10300	6000	4300	8600	14900	4300	6093	7450
5400	2000	3400	4800	10200	1400	1983	5100
1590	600	990	1350	4340	370	523	1670

If an anchor shank is located on a downhill slope, an additional scope of mooring wire will be required to maintain the catenary tangent of 0^o at the bottom, and conversely shorter scope will be required if the shank can be dug in on an upward slope. Basic analysis of these classic variations are described in Reference 4.

8.2 DEPLOYMENT

The criterion for placement and recovery of the mooring system, power cable, and related modules is maximum safety for the personnel and equipment with no tradeoffs being made where personnel safety is concerned.

The problems of cable loading and heavy load-handling equipment multiply in complexity as the depth of operation increases.

The deployment of the three underwater power transmission systems - surface-tendered, in situ, and shore-based - involves some unique problems in cable handling in the deep ocean, both in power and in mooring lines. These problems include induced cable oscillations due to ship motion, high single-cable loading on storage drums, twist induced in long cable lengths, and the placement and recovery of the large modules and associated components.

Deployment of large subsurface loads, structures, and cables at sea is difficult due to the constant instability of the sea surface, which in turn imparts its motion to the decks and structures of a ship on the surface. Information gained from recent studies concerned with the prediction and experimental determination of the forces involved in heavy load handling in deep ocean environment has illustrated the dynamic forces which may arise in cable due to oscillations induced by the various components of wave motion. In planning an installation at sea where heavy lifting is involved or a maximum control of components is desired, it is to the advantage of the installer to work in calm seas, with sea state 3 being considered an absolute maximum.

Paramount to the design and deployment of an underwater power transmission system is the data obtained from a route and site survey. A bottom survey is conducted to determine topography, sediment characteristics, temperature, and current profiles. Topography information is needed to determine hazardous cable and structure locations as well as an accurate estimate of power cable length required for power transmission to a submerged load module from a shore-based or surface-tendered power source. Sediment data is necessary to determine the correct anchor type and anchoring configuration to obtain the maximum holding power necessary for the mooring of a surfaced-tendered power source. The adjustment of the anchor wedge angle to ensure an optimum holding capability is also determined by sediment conditions. Temperature and current profiles are needed to define the termperature effects on structures and flotation materials as well as the current forces which cables and structures may be subjected to during all phases of the installation.

8.2.1 Surface Tendered Power Source

The sequence of deploying a surface tendered power source and the related power cable is considered in three phases: establishment of the moor, emplacement of the surface power plant, and connection and emplacement of the load module.

8.2.1.1 COMPONENTS AND EQUIPMENT - A winch capacity of 150, 000 lbs at 100 ft/min is necessary for depths up to 10,000 ft beyond which a 200, 000 lb capacity winch is required. Table 8-XI shows that a winch with 150,000 lb capacity will be able to handle all installations except the 15,000 and 20,000 ft moor. The winch should have variable speed and automatic-tensioning provisions, with a drive system independent of the cable drum to remove high-wire-rope tensions and to prevent the rope from knifing through the underlying windings. Tension sensing and control of the wire rope is paramount due to the possibility of fouling or rope kinking, if the rope should be allowed to go slack. A winch with a capacity for 150,000 lbs is larger than winches presently being used on oceanographic and cable-laying ships for mooring and oceanographic work. A specialized heavy lift or modifications to the ship would required to accommodate this winch, which could be used to install the mooring anchor, clumps, and wire rope. If the winch has a 200, 000 lb capacity plus sensing and control devices, it could be used to install deep ocean moorings.

Table 8-XI. Mooring System Weight Summary

DEPTH (ft)	ANCHOR WT (lb)	CHAIN (lb)	CLUMP (lb)	WIRE ROPE (lb)	TOTAL (lb)
600	25×10^3	5.1×10^3	55×10^3	1.6×10^3	86.7×10^3
2000	25×10^3	5.1×10^3	48×10^3	5.1×10^3	83.2×10^3
6000	25×10^3	5.1×10^3	85×10^3	18.3×10^3	133.4×10^3
10000	25×10^3	5.1×10^3	58×10^3	25.6×10^3	117.7×10^3
15000	25×10^3	5.1×10^3	89×10^3	21.5×10^3	167.6×10^3
20000	25×10^3	5.1×10^3	56×10^3	55×10^3	146.2×10^3

An alternate method of lowering a heavy load with a lower capacity winch would be the use of a flotation device whereby a low-density buoyancy material or a low-density fluid would be housed in a container attached to the load being deployed. Upon reaching the bottom, the buoyancy device could be released and returned to the surface for reuse or remain attached to the load for retrieval. The use of flotation devices is most attractive at the deeper depths due to the greater weight-to-buoyancy ratio attainable as compared to a standardized hard float or stiff shell concept. The mooring deployment vessels and equipment should have the capability to install one leg of the moor without the need of cable resupply during the installation as this means stopping the deployment vessel, transferring the cable while maintaining cable tension, and making a time-consuming,in-line splice. A minimum of three deployment ships are envisioned with one ship having heavy lift capability, one ship to act as the termination and collection point of the mooring legs, and one to act as a wire rope and cable supply and assist ship. A fourth ship such as a seagoing tug may be necessary for mooring tensioning and inter-ship transfer.

8.2.1.2 ESTABLISHMENT OF MOOR - Upon arrival at the mooring site, the three ships take position over the site of the first mooring leg anchor. The anchor is lowered in a controlled manner, keeping a constant rate of tension on the wire rope in order to place the anchor on the bottom as opposed to dropping it. The use of a battery-powered, bottom-sensing pinging device attached to the anchor serves to inform the winch operator of the depth and anchor position relative to the bottom. No bottom lighting or TV system is envisioned during anchor placement of the deep sea mooring system; camera and light damage would result. Anchor location will be dependent upon a pre-deployment site survey that determined bottom topography, sediment bearing strengths, and current profile. Another use of the pinging, bottom-sensing device is as a navigational marker for surface or subsurface vessels in the area. A scheme utilizing a different frequency pinger for each anchor would provide an accurate positioning system as well as the capability of monitoring anchor dragging after deployment. Mooring systems deployed to date (TOTO II) did not use any anchor-position communication to the surface during or after deployment.

A specific example of an anchoring system is shown in Figure 8-21. The anchor, a single shot of chain, a clump, and at least two additional shots of chain are attached to the steel wire rope and deployed to distance S. At distance S, a wire rope is connected to the terminal ring and to the catenary support buoy. A nylon mooring line is attached to the terminal ring. This mooring line is carried to a second ship located at the central position of the moor which becomes the station-keeping ship. A tension is set in the line by the station-keeping ship while the legs 180° apart are deployed by the heavy lift ship. An estimation of mooring time per leg is one day in depths to 6000 ft[1] and two or three days per leg in depths greater than 6000 ft.

8.2.1.3 SURFACE POWER PLANT EMPLACEMENT - Upon completion of all legs at the mooring system, the surface-tendered buoy is towed to the ship on station. The nylon mooring lines are transferred from the station-keeping ship to the power plant buoy by divers. This involves passing the loose ends of the lines through hawser pipes in the buoy to their respective structural termination points (bits on deck). Any final pretensioning required is put into the lines by the winch and boom system of the station-keeping ship before final securing.

8.2.1.4 LOAD MODULE CONNECTION AND EMPLACEMENT - The load module is positioned on the surface relative to the bottom position and slightly off-center along a bisector of the mooring legs, such as the northeast bisector of the east-west, north-south mooring legs. The power cable deployment ship is brought alongside and the power cable is attached to the load module. If it is required to supply power to the load module during descent, then the free end of the power cable must be terminated and connected to a rotary connector at the cable drum axis. Upon completion of the lowering of the power cable, the connector is transferred to the buoy power plant connector. The submergence of the load module and the paying out of the power cable from the cable ship storage drum are synchronized. Power cable tension and length is monitored continuously during descent of the load module until a predetermined length of cable is reached (see Figure 5-10).

There are two basic modes of module deployment available, each with various advantages and disadvantages. Basically the deployment techniques stem from or are a combination of the free fall concept and the tethered concept. The free fall technique is based on a self-contained vehicle making a descent and ascent by virtue of the

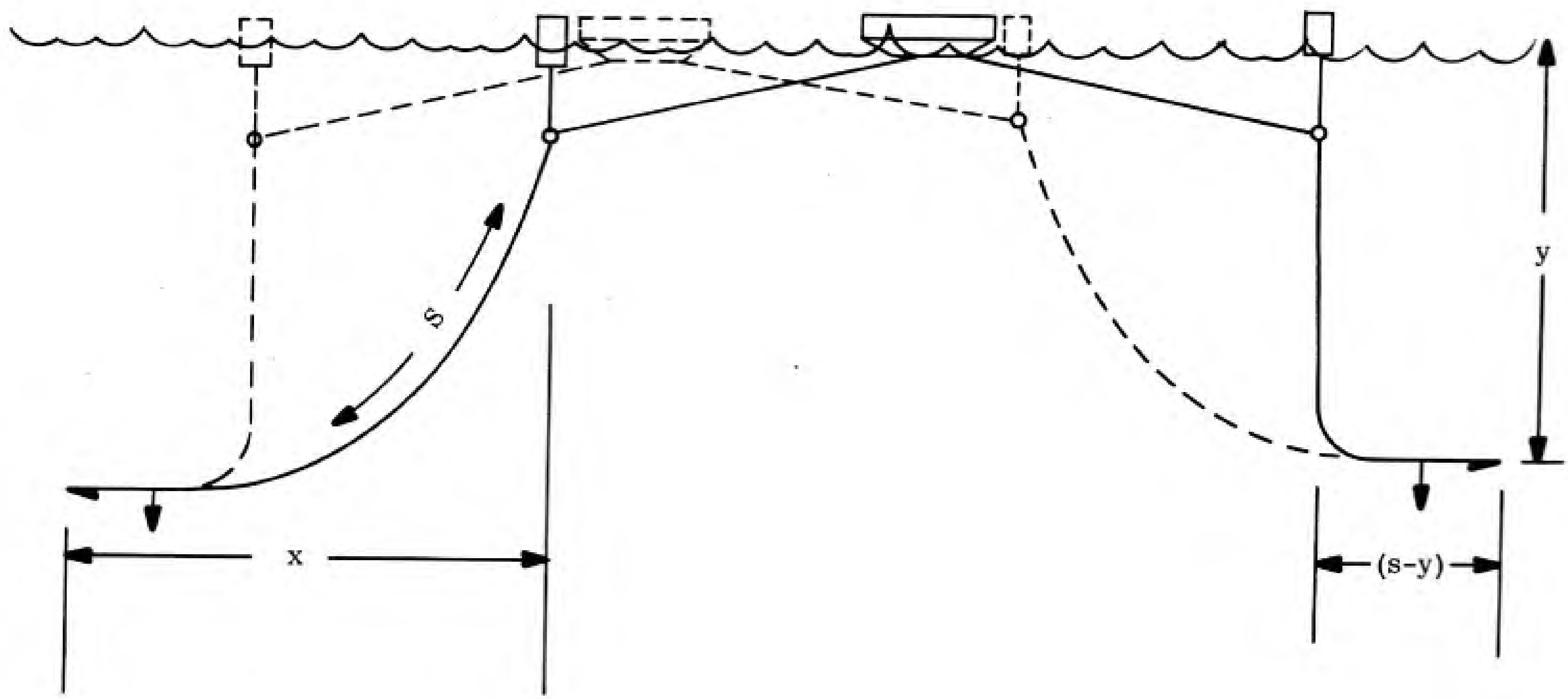


Figure 8-21. Surface Buoy Anchoring System

vehicle's buoyancy characteristics, which may be controlled manually or automatically. A freely falling body in the deep ocean is subject to various environmental factors which must be compensated for and which, due to the magnitudes of weights involved, require a delicate balance. Factors which must be considered in this case, as in all the following cases, are:

- temperature variations and the resulting effect on the structure and buoyancy
- density variations and the effect on buoyancy
- pressure effects on structures and flotation materials
- current profiles and hydrodynamic effects
- mass acceleration-deceleration forces involved in controlling the vehicle's motion; small bodies or masses are more easily controlled by virtue of the mass involved.

A deployment scheme of this nature does not provide for any midrange versatility whereby a module could be stopped and held at a constant depth, e.g.,1/4, 1/2, 3/4, of the way down. Deployment using the free fall method alone requires that compensation be made for current forces, which would tend to displace the module from the selected site, and that compensation be made for the deceleration of the module as it approaches the bottom so that a "soft" landing results.

The second system involves tethering with the point of reference at the ocean surface or ocean bottom. A module tethered to the surface is winched down from a barge or ship with the module being negatively buoyant during the descent and while on the bottom. The tethering cable may or may not be left connected to the submerged module. This method provides for a more controlled, more precise method of placement; however, there is a hazard in handling a heavy load at the end of a tethering cable. If the tethering cable should fail, the module could become fouled with the tethering cable and break the power cable, complicating necessary emergency measures. A module tethered to the bottom and winching down against a positive buoyancy provides the best controlled ascent/descent mode with maximum safety. If a cable should part or foul during a descent or ascent, the cable would drop away from the module, leaving it free to surface. Or, if the winching system should become inoperative, the module or modules may be separated from the winch and returned to the surface by means of its positive buoyancy. Nylon or polypropolene cable should be considered for use on submerged winch because it is non-corrosive and has a density less than steel cable and thus would have less influence on net buoyancy during the winched ascent and descent.

The bottom-tethered, down-winch system is the most desirable for maximum safety and control.

8.2.2 In Situ Power Source

The in situ emplacement includes two modules (the power plant and the load) which are rigidly coupled and attached to a common base which may have negative or positive buoyancy, depending on the nature of the mission or the desire to retrieve the base. However, each module is independently positively buoyant and is provided with a fail-safe method of separating from the base and/or other module in an emergency.

The in situ power plant system has a common base with provisions for a ballast system composed of soft tanks for sea water blowing or flooding and/or buoyancy material. The ballast tanks are used for trimming the unit for towing, diving, and

and retrieving attitudes while on the surface. The same pressure-compensated tanks may be used to provide positive, negative or neutral buoyancy compensations due to environmental conditions on the bottom (salinity, temperature, etc.). In this case, the same tanks used for ballasting on the surface are used as pressure compensated cavities for housing flotation material. Included in the common base are the cable and winch-down system which provide a controlled descent and ascent.

The installation of an in situ power system involves heavy hulls and structures that may become unwieldy at sea. A maximum amount of preassembly should be done at shore facilities, and emphasis should be on simplicity of deployment of all components. The present limitation on power cable connections requires that they be made above water due to the unavailability of a submersible wet-mating connector. An additional requirement for nuclear power plants is to provide adequate thermal cooling and radiation shielding once the power plant is operational. This generally requires certain limitations on power plant attitude and constant immersion of a portion of the hull.

Bottom emplacement of the in situ power plant is accomplished by towing the pre-assembled system to the work site; the anchor is lowered to the bottom and the module complex is trimmed out to the required positive buoyancy. Negative buoyancy may be adjusted by the use of the free flowing tanks, bar weights or shot; while positive buoyancy is adjusted by the use of syntactic foams capable of depths of 20,000 ft or low density fluids, or a combination of fluids and small pressure spheres. Descent of the unit is accomplished by winching down against the positive buoyancy. A system of leveling legs or minor anchor blocks may be used for leveling when the system nears the bottom.

If an emergency arises during the mission, the power unit may be shut down, the power cable disconnected (by explosive or mechanical unlatching or unbolting), thus freeing the power module to ascend upon release from the common base.

Retrieval of the in situ complex at the end of a mission involves a reversal of the deployment steps: the unit ascends to the surface by winching from the anchor; upon breaking surface, the unit is trimmed for towing or surface replenishment, and the anchor is retrieved by the heavy lift ship or abandoned if the cost of retrieval is excessive relative to the cost of the anchor.

In instances where a distinction is made in load module size and where it is impractical to deploy the two modules on a common base or where it is desirable to make the power module stationary and change the load module location, precaution must be taken in the handling of the power cable. Recognizing that the power cable and winch cables must be kept free from fouling, an automatic tensioning winch is used to maintain a controlled tension on the cable.

Deployment of the two modules without a common base, connected with a short link coupling, has inherent cable fouling problems due to the excursion of the independent modules and synchronization of the dual winch-down system. Deployment of two modules without a common base is possible if the mission or task requires a central power source with a power load module having a working radius greater than the depth of the water it is submerged in. In this instance the power module would be submerged in a central location by use of a winch-down or surface-lowered system, and the load module would be emplaced by a similar technique. Details of this system are modifications of the shore-based power system which is described below or a combination of the winch-down or surface-lowered system.

8.2.3 Shore-based Power Source

The utilization of a shore-based source of power involves three time-consuming phases: power site construction, the power cable deployment, and the termination and deployment of the load module. Where long off-shore distances are involved in reaching the load module, the power cable may be deployed while the final phase of power plant construction is in process. Terminating and deploying the load module as the last step allows for testing the operational power distribution system while connected to the load module.

One disadvantage involved in this sequence of cable laying and load module deployment is the accuracy involved in assuring that the load module is at the extremity of the arc that the end of the power cable transcribes from surface to bottom (Figure 8-24). If the load module is deployed short of the arc, excessive cable may foul the load module. If positioning of the load module is attempted beyond the limit of the cable, excessive stress may be placed on the power cable resulting in breakage or unstability of the load module.

A reverse process of load module deployment with cable laying toward the shore may be considered if emphasis is placed on positioning the load module first and then laying the cable toward shore. One advantage to this sequence would be the deployment of the power cable from the load module without fear of fouling due to excess cable or high stresses due to a foreshortened cable length. A disadvantage would be the deployment of the load module without full power throughout the cable laying process or, alternatively, the necessity of supplying power from the cable-laying ship through the cable storage drum during the cable laying toward shore.

8.2.3.1 POWER CABLE DEPLOYMENT - The cable laying procedure is basically the same as used for submarine power cable installations with the exception of deep water laying where a non-supporting cable (a cable not capable of supporting itself) must be deployed by use of buoyancy devices.

A cable route and site selection is determined following a bottom topography survey whereby a more accurate determination of required cable length may be estimated. A cable laying ship having the required cable stowage and cable handling capacities, as outlined in Table 8-XII, is used for the emplacement. To eliminate environmental effects, the cable is laid from the shore seaward, with the tidal zone section of the cable buried at least six feet below the low tide level.

Bottom cable laying may be done from ships using spiral-wound cable tanks provided that the recommended cable tension is maintained by the winches on the ship. If the cable becomes so long that it can no longer support itself, cable buoyancy must be provided.

One state-of-the-art buoyancy system which can be employed to give a maximum buoyancy control is the use of a 42 lb/ft^3 syntactic foam and 44 lb/ft^3 aviation gasoline. Syntactic foam under submergence increases in net buoyancy by 2 percent due to its relative incompressibility and temperature independence as compared to sea water. Aviation gasoline decreases in buoyancy by about 8 percent at 20,000 ft due to compressibility and temperature effects.

Table 8-XII. Cable Ship Data

SHIP	NO. OF CABLE TANKS	VOLUME OF CABLE TANKS IN FT ^{3}	CAPACITY IN NAUTICAL MILES WITH 1.25" DIA CABLE USING 80% CAPACITY
LCV	1	6,937	80
LSM	2	10,395	125
LST	2	15,777	200
USS NEPTUNE	3	30,116	415
USS AOLIS	3	43,385	610
USS THOR	3	43,385	610
USACS A. J. MEYER	4	48,000	615
SS MERCURY	3	106,740	1200
SS NEPTUNE	5	222,500	3000
SS MARCEL BAYARD	4	77,333	1000
SS LONG LINES	7	139,000	2000
SS SALEMUM	3	22,354	315

Ships are equipped with automatic tensioning devices to compensate for sea condition except for LCV, LSM, AND LST. See Remarks.

Figures 8-22 and 8-23 represent systems whereby a non-supporting cable is deployed by attaching floats containing aviation gasoline every 2000 ft. Initially, the first 2000 ft of cable is neutrally buoyant. When the aviation gasoline starts cooling and contracting the weight of the cable provides negative buoyancy and it begins to sink. As the aviation gasoline float further submerges, the system becomes increasingly negatively buoyant as shown in Figure 8-22. However, there is some increasing cable tension experienced over the entire length of the cable, as shown in Figure 8-23. Also shown in Figure 8-23 is the magnitude of cable tensions as a function of cable density using the same surface-neutral buoyant deployment scheme. The greater cable tension associated with 10 lb/ft cable is due to the higher density of the cable; that is, the cable is of small outside diameter due to the lower voltage class of 5000 V, which requires less dielectric insulation than that of the 15 lb/ft cable at 34, 500 V.

By using varying ratios of syntactic and aviation gasoline, the cable system may be made negatively, positively or neutrally buoyant with or without a release mechanism which would return the floats to the surface. A retrievable flotation system uses rubberized fiber bags containing the avgas-syntactic mixture, which would be released by an imploding glass ball or spring-loaded trip mechanism upon reaching the bottom. A permanent buoyancy system uses the same rubberized bag in a protective metallic housing to reduce puncture possibilities due to grappling or scarfing conditions. The buoyancy floats are attached at regular intervals depending on the cable being used and the condition of buoyancy required.

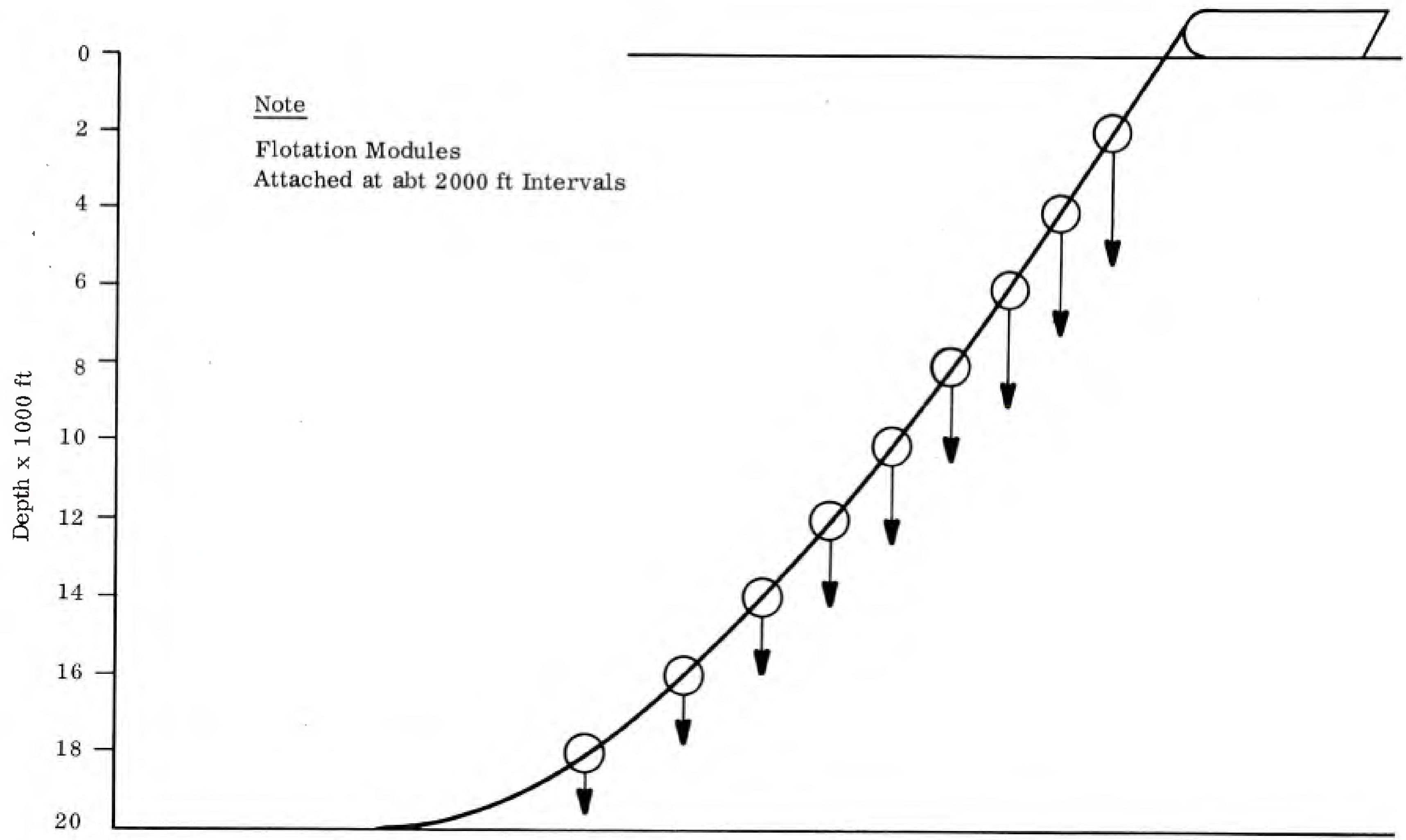


Figure 8-22. Cable Tension Schematic

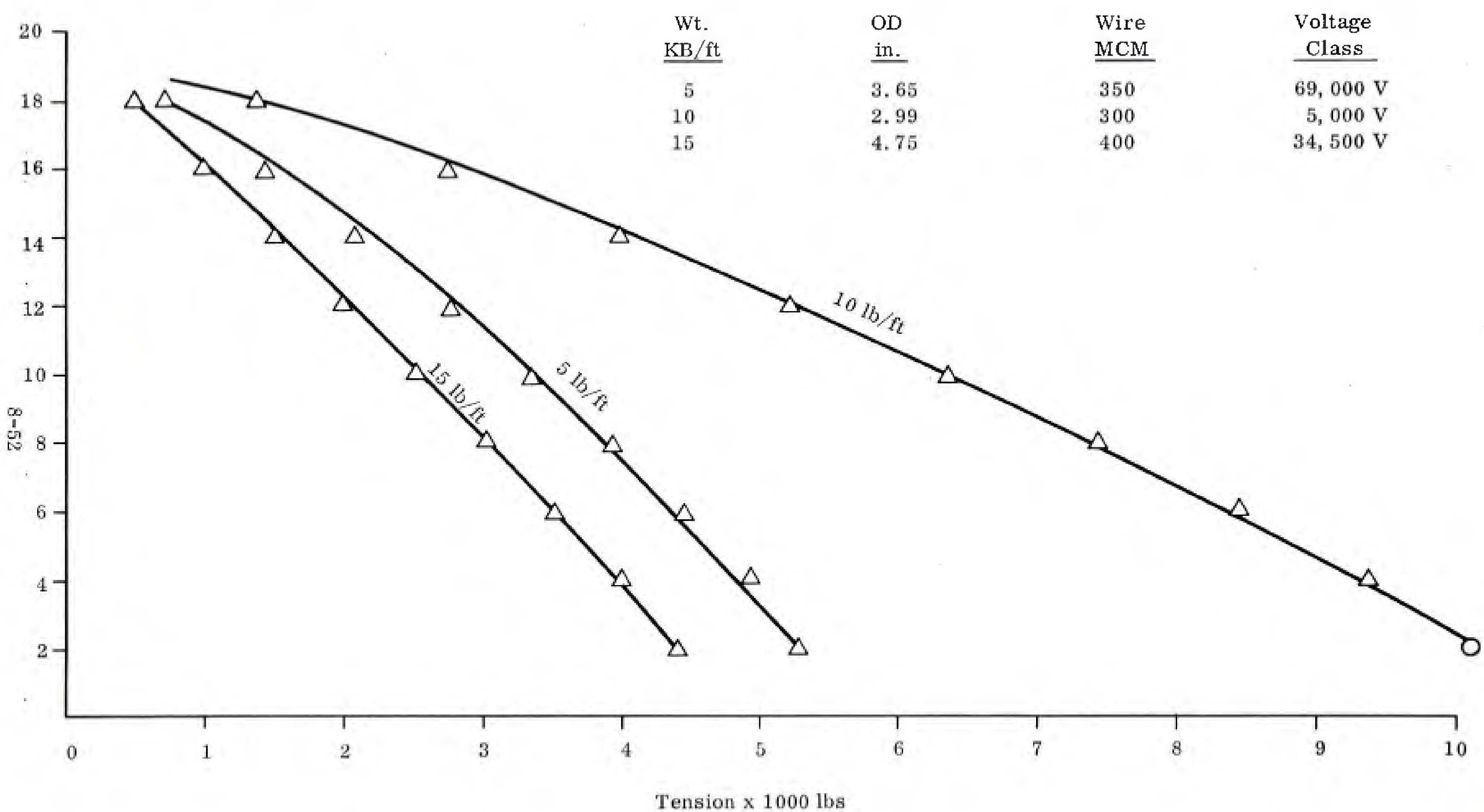
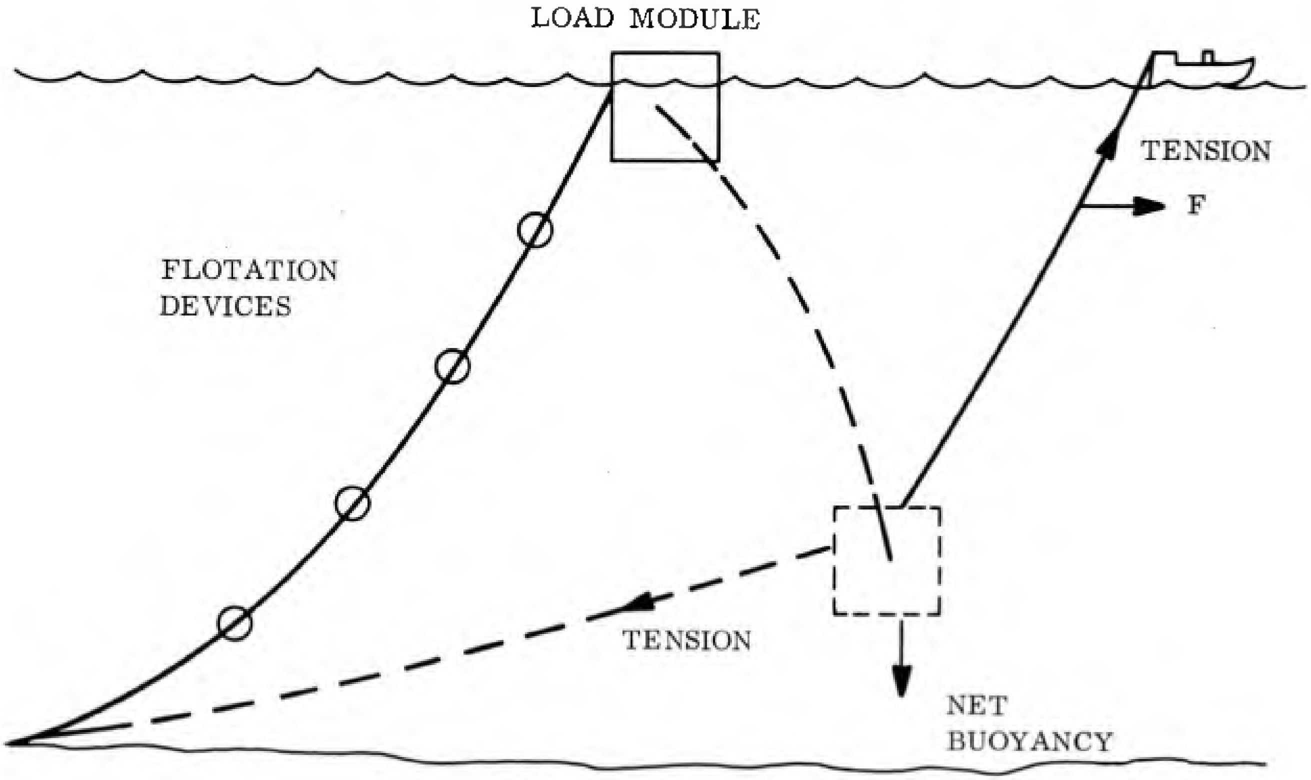


Figure 8-23. Cable Tension Using Aviation Gas as Flotation

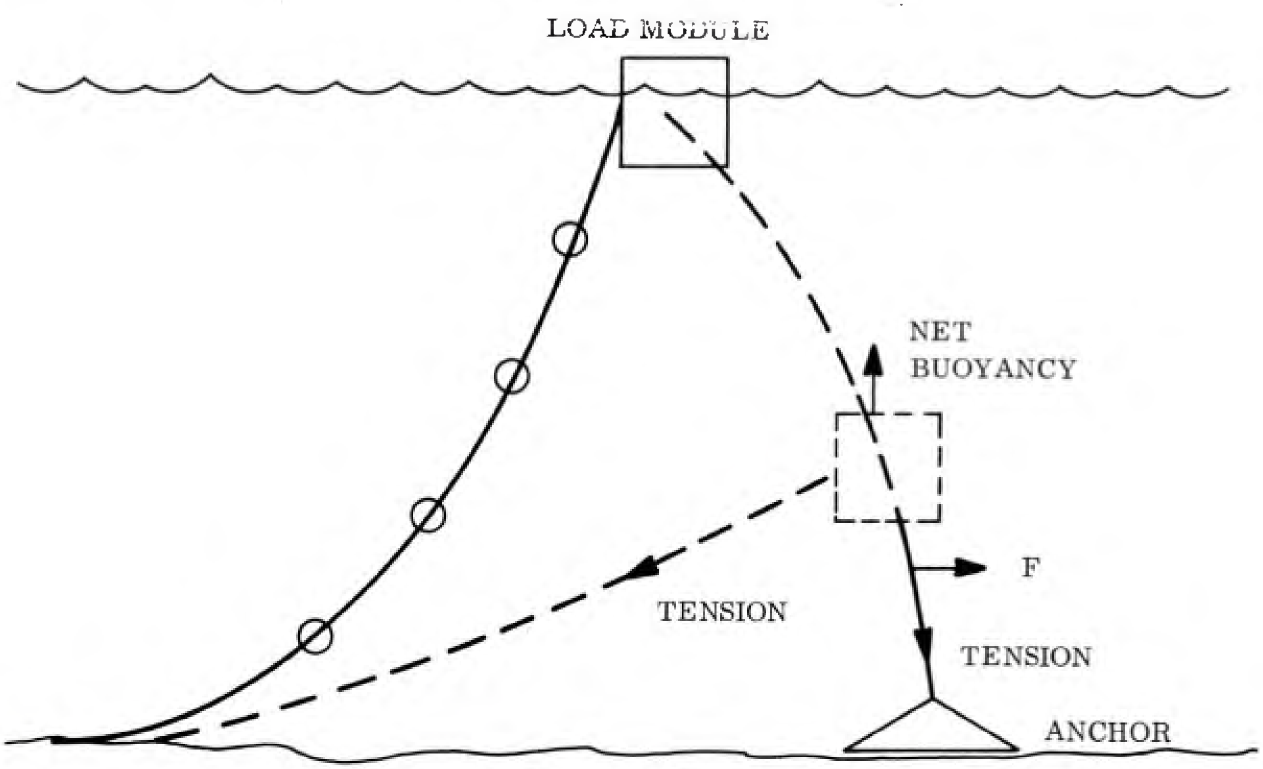
Termination of the cable laying results in a direct termination in the load module or stoppering the cable in a moored buoy until the load module is readied for emplacement. Cable laying devices using supporting cables from the cable ship or auxiliary ships were considered impractical due to the need to separate the supporting cables from the power cable and the resulting dangers of a loose cable trolling behind a ship during rewind.

8.2.4 Power Cable Handling Precautions During Emplacement

To prevent power cable fouling during the emplacement of the load module, it is important the power cable is not given the opportunity to relax. This is necessary due to the manner in which cable is stored in cable laying tanks. Cable stored in tanks is given a spiral twist similar to a clock spring, which, if held by its apex, will illustrate the twist in the cable coming out of the tanks. The twist is tolerable if the cable is laid on the ocean floor where the surrounding friction forces tend to secure the cable; however, in open water the cable would tend to coil. One way to eliminate this problem is to unwind the cable from a drum in a tangential manner. If the load module is to be lowered from the surface, then an outward force should be maintained through the arc of deployment as shown in Figure 8-24A. Figure 8-24B illustrates a precise positioned, self-submerged (by winching) load module. Retrieval of the submerged load module is in reverse order



A. Surface-tethered



B. Bottom-tethered

Figure 8-24. Load Module Deployment

8.3 REFERENCES

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Chapter 9

SELECTED POWER TRANSMISSION SYSTEMS

This chapter is a description of the recommended systems resulting from the evaluations and optimization processes described in detail in Chapters 4 through 8. This chapter describes the most cost-effective techniques of supplying:

- 30, 100, 300, 1000 and 3000 KW of usable power from a surface-tendered power source to load modules deployed at depths of 600, 2000, 6000, 10, 000, 15, 000 and 20, 000 ft,
- 30, 100 and 300 KW from an in situ power source to load modules at depths of 600 to 20, 000 ft (power source and load module at same depths),
- 1000 and 3000 KW of power from an in situ power source to load modules at depths of 600 and 2000 ft,
- 30, 100, 300 and 1000 KW of usable power from a shore-based power source to load modules deployed at distances of 60, 000, 300, 000, and 600, 000 and 3×10^6 ft from the power plant,
- 3000 KW from a shore-based power source to load modules 60, 000, 300, 000 and 600, 000 ft from the power plant.

Preliminary designs are discussed in Chapter 10 for:

- 30 KW surface-tendered plants transmitting power to load modules at depths of 600 and 6000 ft,
- 100 KW in situ plants at depths of 600 and 6000 ft
- 300 KW shore-based plants transmitting power to load modules 10 and 50 miles off shore.

For surface and shore-based power sources, power is transmitted by long cable. For in situ power sources, the power source is at or near the load module at its depth, and power is transmitted via a relatively short cable. If the in situ power source with a relatively long cable is the system selected for a particular application, its characteristics can be synthesized using the data presented in Chapters 4 and 6.

The supply of 1000 and 3000 KW of power from an in situ plant to load modules at depths greater than 2000 ft is not described, due to the technical limitations of hull materials, heat rejection systems, and geometry of conversion equipment, as detailed in Chapter 4. A system for delivering 3000 KW of power from a shore-based facility to load modules at 3×10^6 ft off shore was not evolved, due to the voltage drop occurring for these conditions. This limitation is discussed in Chapter 6.

The cost estimates shown in this chapter are for engineering, construction, and test. These figures do no include costs for development programs or advanced engineering in the case of connectors (paragraph 9.2.2) and are based on standard commercial marine practices. Deployment costs are not included, and, for the shore-based plants, property acquisition costs and site preparation costs are not included. The cost of the in situ common base (paragraph 9.2.5) is not included. In no case is transportation cost accounted for.

9.1 SURFACE-TENDERED POWER SOURCE SYSTEMS

All thirty (five loads at each of six depths) of the recommended systems for transmitting power from surface-tendered power plants to submerged load modules have similar characteristics. These are described for each subsystem in general terms in paragraphs 9.1.1 through 9.1.4. The parameters for each load at each depth are summarized in Tables 9-I through 9-V. Some of the parameters for each system, such as cable size, vary with depth, while some, such as hull size and transmission voltage, vary with both depth and power level. The thirty systems described in this section are predicated on long-term use (5 to 6 years) at the specified depth and power level. Cost data is shown in Table 9-VI.

9.1.1 Electrical System

A three-phase, 60-cycle-per-second electrical system has been selected for each of the surface-tendered power plants. The electrical system consists of the components and equipment necessary to transmit, monitor, and control the power from the surface power plant (power end) to the submerged load (load end) via the cable. The generated voltage is produced by a diesel-generator set. In some cases, the generated voltage is stepped up to the transmission voltage by a transformer. The cable carries the transmitted voltage and the instrumentation signals. The load module transforms the transmitted voltage to usable voltage and provides the necessary distribution. Instrumentation is provided to monitor and protect the system. The load end instruments are referred to the power plant end for corrective action (cascade tripping system) and recording. Instrumentaion power is derived from the main transmission system through potential transformers, with battery backup. The sensing power for protection devices is derived from current and/or potential transformer power supply.

The battery was sized based on the requirement that it must assume the complete control and instrument power load, plus tripping duty, for a 24-hr period as backup for the AC instrument power supply. This is provided as backup for loss of normal AC control and instrument power due to a blown fuse, or a shorted or open circuit. On this basis, considering the major burdens, a 24-kilowatt-hour, manchex plante battery was selected. The battery will be provided with a suitable rectifier to maintain it in the fully charged condition while AC power is available. When AC power is lost an annunciator will record the event and the trouble alarm will apprise the monitor of the condition. In addition, a second alarm will tell the monitor when the battery system has been on for 12 hours, indicating that only 12 hours of battery power remains.

The load end distribution equipment, instruments and transformers (current and voltage) are installed in the load module.

9.1.2 Cable System

The cable system consists of the complete cable from the load to the power source, the watertight connectors and hull penetrations, in addition to the cable support system. The cables for each system have three conductors in one 3-conductor cable (1-3/c), each conductor carrying one phase of the three-phase, alternating-current voltage. The cable is armored with a high strength galvanized steel wire which has a minimum working stress of 30 psi for deployment depths up to 10,000 feet and 125,000 psi for deployment depths of 15,000 feet and greater.

The three-pin connectors are sized to carry the voltage and current from the power source to the cable and from the cable to the load module. The cable support system consists of a series of buoyancy devices placed to support the dead and live loads of the cable and provide no more than 50 kip load on the buoy mooring system.

The conductors vary both with power level and deployment depth. The size of the conductors is based on the smallest size that will transmit the voltage at no greater than 5 percent voltage drop and carry the required current from the power source to the load module within the voltage stress limits established by IPCEA.

9.1.3 Power Source

Diesel generators have been selected for all power levels for the surface-tendered power sources. The power source system consists of the diesel generator, automatic controls, alarms and protective devices, heat exchanger, starting system and the intake and exhaust plenums. The diesel-generator controls are integrated with power distribution equipment, thus providing an unattended, reliable power source system.

9.1.4 Hull and Deployment System

The hull and deployment system for each surface-tendered power source is a thick-disc, wave-following buoy positioned by a four-point mooring system. The hull is sized to provide adequate reserve buoyancy while providing fuel storage capacity commensurate with reasonable refueling rates and exhibiting good hydrodynamic characteristics. The emplacement system consists of four mooring legs, each having a scope of wire rope, chain, clump, and anchor positioned to allow buoy motion resulting from surface effects while at the same time assuring excessive loads are not transferred to the power cable. Electrical power cable deployment technique and a proposed method of installation are discussed in Appendix B.

Table 9-I

Parameters For 30 KW

Surface-Tendered Underwater Power Transmission Systems

SYSTEM	DEPTH OF LOAD MODULE (FT) 600	2000	6000	10,000	15,000	20,000
ELECTRICAL						
A. Transmission voltage (KV)	0.48	0.60	4.16	4.16	4.16	4.16
B. Transformer (load)						
1. Primary/secondary voltage	Direct Transmission	480/600	480/4.16 →			
2. Rating		45 KVA →				
3. Weight		500 lb →				
4. Volume		7.7 FT^3 →				
5. LWH inches (dry type AA)		16 x 26 x 32 →				
C. Transformer (power)			Same as above			
1. Primary/secondary voltage						
2. Rating						
3. Weight						
4. Volume						
D. Switchgear (includes main circuit breaker* instrumentation, protection and carrier)						
1. Load end						
a. Weight	1800 lbs →		3200 lbs →			
b. Volume	90 FT^3 →		168 FT^3 →			
c. LWH (in.)	36 x 48 x 90 →		52 x 62 x 90 →			
2. Power end						
a. Weight	3300 lbs →		5900 lbs →			
b. Volume	180 FT^3 →		443 FT^3 →			
c. LWH (in.)	72 x 48 x 90 →		104 x 62 x 90 →			

*Applies to power end only.

Table 9-I (Continued)

SYSTEM	DEPTH OF LOAD MODULE (FT) 600	2000	6000	10, 000	15, 000	20, 000
CABLE						
1. Copper size	#3	1/0	#6	#3	#6	#6
2. Total length	1, 000	6, 000	10, 000	15, 000	20, 000	30, 000
3. Total weight	4, 170 lbs	25, 020 lbs	41, 700 lbs	62, 550 lbs	83, 400 lbs	125, 100 lbs
POWER SOURCE						
A. Type	←		DIESEL GENERATOR			→
B. Rating (KW)	50	50	50	50	50	50
C. Operating point (KW)	33.3	32	32.8	32.9	33.1	33.3
D. Full load fuel consumption (gal/hr)	3.2	3	3	3	3.2	3.2
E. Major overhaul period	←		2 yrs			→
F. Heat rejected (bti/min)	←		2100			→
G. Weight (lbs)	←		2400			→
H. Volume (ft^3)	←		63			→
I. Auxiliary battery						
1. Type	MANCHEX PLANTE					→
2. Rating	200 Ampere Hours					→
3. Weight	7830 lbs					→
4. Volume	57 FT^3					→
5. Capacity	24 Kilowatt Hours					→

Table 9-I (Continued)

SYSTEM	600	2000	6000	10,000	15,000	20,000
	DEPTH OF LOAD MODULE (FT)					
HULL						
1. Type	THICK - DISC					
2. Diameter (ft)	41	41	41	41	41	41
3. Height (ft)	7-1/2	7-1/2	7-1/2	7-1/2	7-1/2	7-1/2
4. Weight (lbs)	100, 000	100, 000	100, 000	100, 000	100, 000	100, 000
5. Displacement (lbs)	228, 000					
6. Material	Steel, ASTM A-36 & A 212					
EMPLACEMENT						
1. Type	4 point mooring system, legs 90° apart					
2. Anchoring type	25, 000 lbs LWT wedge block					
3. Clamp weight (lbs)	57, 000	48, 000	85, 000	58, 000	89, 000	56, 000
4. Chain (1-1/2" steel alloy)						
a. Min. length (ft)	270	270	270	270	270	270
b. Min. weight (lbs)	5100	5100	5100	5100	5100	5100
5. Mooring leg material	Steel wire rope					
6. Protective covering	3/16'' extruded Polyurethane Sheathing					
7. Diameter (in.)	1-3/8	1-3/8	1-1/2	1-3/8 1-1/2	1-1/2 1-5/8	1-3/8 1-1/2 1-5/8
8. Incremental scope (ft)	1590	5400	10400	1575 17925	8900 15100	2000 18000 15000
9. Total scope (ft)	1590	5400	10400	19500	24000	35000
10. Total mooring leg wt. (lbs)	92000	92000	147000	147000	201000	201000
11. Catenary support buoy						
a. Diameter (ft)	12	12	12	12	15	15
b. Height (ft)	12	12	22	22	17-1/2	17-1/2
c. Weight (lbs)	4400	4400	6800	6800	7700	7700
d. Material	Steel ASTM A-36 and A-212					
e. Distance from power plant	1000 ft.					
f. Number Required	4 (1 per leg)					

Table 9-II
Parameters For 100 KW
SURFACE-TENDERED Underwater Power Transmission Systems

SYSTEM	600	2000	6000	10,000	15,000	20,000
			DEPTH OF LOAD MODULE (FT)			
ELECTRICAL						
A. Transmission voltage (KV)	0.48	4.16	4.16	4.16	4.16	4.16
B. Transformer (load)						
1. Primary/secondary voltage	Direct	480/4,160	→	→	→	→
2. Rating	Transmission	112 KVA	→	→	→	→
3. Weight		850 lbs	→	→	→	→
4. Volume		16.4 FT^3	→	→	→	→
5. LWH inches (dry type AA)		19 x 39 x 38	→	→	→	→
C. Transformer (power)			Same as above			
1. Primary/secondary voltage						
2. Rating						
3. Weight						
4. Volume						
D. Switchgear (includes main circuit breaker* instrumentation, protection and carrier)						
1. Load end						
a. Weight	1800 lbs	←	6900 lbs	→	→	→
b. Volume	90 FT^3	←	336 FT^3	→	→	→
c. LWH (in.)	36 x 48 x 90	→	→	→	→	→
2. Power end						
a. Weight	3600 lbs	←	6250 lbs	→	→	→
b. Volume	180 FT^3	←	455 FT^3	→	→	→
c. LWH (in.)	72 x 48 x 90	←	104 x 48 x 90	→	→	→

*Applies to power end only.

Table 9-II (Continued)

SYSTEM	DEPTH OF LOAD MODULE (FT) 600	2000	6000	10,000	15,000	20,000
CABLE						
1. Copper size	#2	#6	#6	#6	#6	#6
2. Total length	1,000	6,000	10,000	15,000	20,000	30,000
3. Total weight	5,460 lbs	25,020 lbs	41,700 lbs	62,550 lbs	83,400 lbs	125,100 lbs
POWER SOURCE						
A. Type	← DIESEL GENERATOR →					
B. Rating (KW)	125	125	125	125	125	125
C. Operating point (KW)	111.8	107.5	108.8	110.4	112.1	115.4
D. Full load fuel consumption (gal/hr)	9.5	9	9	9.5	9.5	9.75
E. Major overhaul period	2 yrs →					
F. Heat rejected (btu/min)	← 6700 →					
G. Weight (lbs)	← 3900 →					
H. Volume (ft^3)	← 68 →					
I. Auxiliary battery						
1. Type	MANCHEX PLANTE					
2. Rating	200 Ampere Hours					
3. Weight	7860 lbs					
4. Volume	57 FT^3					
5. Capacity	24 Kilowatt Hours					

Table 9-II (Continued)

SYSTEM	DEPTH OF LOAD MODULE (FT) 600	2000	6000	10,000	15,000	20,000
HULL						
1. Type	← THICK DISC →					
2. Diameter (ft)	55-1/2 →					
3. Height (ft)	9-1/2 →					
4. Weight (lbs)	159,000 →					
5. Displacement (lbs)	448,000 →					
6. Material	Steel ASTM A-36 and A-212 →					
EMPLACEMENT						
1. Type	4 point mooring system, legs 90° apart →					
2. Anchoring type	25,000 lb LWT wedge block →					
3. Clump weight (lbs)	57,000	48,000	85,000	58,000	89,000	56,000
4. Chain (1-1/2" steel alloy)						
a. Min. length (ft)	270	270	270	270	270	270
b. Min. weight (lbs)	5100	5100	5100	5100	5100	5100
5. Mooring leg material	Steel wire rope →					
6. Protective covering	3/16" extruded Polyurethane Sheathing →					
7. Diameter (in.)	1-3/8	1-3/8	1-1/2	1-3/8 1-1/2	1-1/2 1-5/8	1-3/8 1-1/2 1-5/8
8. Incremental scope (ft)	1590	5400	10,400	1575 17925	8900 15100	2000 18000 15000
9. Total scope (ft)	1590	5400	10,400	19,500	24,000	35,000
10. Total mooring leg wt. (lbs)	92,000	92,000	147,000	147,000	201,000	201,000
11. Catenary support buoy						
a. Diameter (ft)	12	12	12	12	15	15
b. Height (ft)	12	12	22	22	17-1/2	17-1/2
c. Weight (lbs)	4,400	4,400	6,800	6,800	7,700	7,700
d. Material	Steel ASTM A-36 and A-212 →					
e. Distance from power plant	1,000 ft. →					
f. Number Required	4 (1 per leg) →					

Table 9-III
Parameters For 300 KW
SURFACE-TENDERED Underwater Power Transmission Systems

SYSTEM	600	2000	6000	10,000	15,000	20,000
			DEPTH OF LOAD MODULE (FT)			
ELECTRICAL						
A. Transmission voltage (KV)	0.48	4.16	4.16	4.16	13.8	13.8
B. Transformer (load)						
1. Primary/secondary voltage	Direct Transmission	480/41.6 →	→	→	4.16/13.8 →	→
2. Rating		500 KVA →	→	→	→	→
3. Weight		2750 lbs →	→	→	→	→
4. Volume		45.8 ft^3 →	→	→	→	→
5. LWH inches (dry type AA)		27 x 43 x 68 →	→	→	→	→
C. Transformer (power)			Same as Above			
1. Primary/secondary voltage						
2. Rating						
3. Weight						
4. Volume						
D. Switchgear (includes main circuit breaker* instrumentation, protection and carrier)						
1. Load end						
a. Weight	1800 lbs	3200 lbs →	→	→	4000 lbs →	→
b. Volume	90 ft^3	168 ft^3 →	→	→	290 ft^3 →	→
c. LWH (in.)	36 x 48 x 90	52 x 62 x 90 →	→	→	72 x 78 x 90 →	→
2. Power end						
a. Weight	3600 lbs	6400 lbs →	→	→	8150 lbs →	→
b. Volume	180 ft^3	336 ft^3 →	→	→	481 ft^3 →	→
c. LWH (in.)	72 x 48 x 90	104 x 62 x 90 →	→	→	144 x 78 x 90 →	→

*Applies to power end only.

Table 9-III (Continued)

SYSTEM	DEPTH OF LOAD MODULE (FT) 600	2000	6000	10,000	15,000	20,000
CABLE						
1. Copper Size	4/0	#6	#6	#4	#2	#2
2. Total length	1,000	6,000	10,000	15,000	20,000	30,000
3. Total weight	8,970 lbs	25,020 lbs	41,700 lbs	72,450 lbs	96,600 lbs	144,900 lbs
POWER SOURCE						
A. Type	← DIESEL GENERATOR →					
B. Rating (KW)	350 →					
C. Operating point (KW)	337	333	345	319	326	331
D. Full load fuel consumption (gal/hr)	21.5	21	21.8	19.8	20	21
E. Major overhaul period	2 years →					
F. Heat rejected (btu/min)	← 20,000 →					
G. Weight (lbs)	← 19,000 →					
H. Volume (ft^3)	← 364 →					
I. Auxiliary battery						
1. Type	MANCHEX PLANTE					
2. Rating	200 Ampere Hours					
3. Weight	7860 lbs					
4. Volume	57 FT^3					
5. Capacity	24 Kilowatt Hours					

Table 9-III (Continued)

SYSTEM	600	2000	6000	10,000	15,000	20,000
HULL						
1. Type	← THICK DISC →					
2. Diameter (ft)	55.5 →					
3. Height (ft)	9.5 →					
4. Weight (lbs)	159,000 →					
5. Displacement (lbs)	448,000 →					
6. Material	Steel	ASTM	A-36 and	A212 →		
EMPLACEMENT						
1. Type	4 point mooring system, legs 90° apart →					
2. Anchoring type	25,000 lbs LWT wedge block →					
3. Clump weight (lbs)	57,000	48,000	85,000	58,000	89,000	56,000
4. Chain (1-1/2" steel alloy)						
a. Min. length (ft)	270	270	270	270	270	270
b. Min. weight (lbs)	5,100	5,100	5,100	5,100	5,100	5,100
5. Mooring leg material	Steel wire rope →					
6. Protective covering	3/16 inch extruded Polyurethane Sheathing →					
7. Diameter (in.)	1-3/8	1-3/8	1-1/2	1-3/8 1-1/2	1-1/2 1-5/8	1-3/8 1-1/2 1-5/8
8. Incremental scope (ft)	1,590	5,400	10,400	1,575 17,925	8,900 15,100	2,000 18,000 15,000
9. Total scope (ft)	1,590	5,400	10,400	19,500	24,000	35,000
10. Total mooring leg wt. (lbs)	92,000	92,000	147,000	147,000	201,000	201,000
11. Catenary support buoy						
a. Diameter (ft)	12	12	12	12	15	15
b. Height (ft)	12	12	22	22	17-1/2	17-1/2
c. Weight (lbs)	4,400	4,400	6,800	6,800	7,700	7,700
d. Material	Steel ASTM A-36 and A-212 →					
e. Distance from power plant	1000 ft. →					
f. Number Required	4 (1 per leg) →					

Table 9-IV
Parameters For 1000 KW
Underwater Power Transmission Systems

SYSTEM	600	2000	6000	10,000	15,000	20,000
	DEPTH OF LOAD MODULE (FT)					
ELECTRICAL						
A. Transmission voltage (KV)	4.16	4.16	4.16	13.8	13.8	13.8
B. Transformer (load)						
1. Primary/secondary voltage	Direct Transmission	Direct	Direct	4.16/13.8	→	→
2. Rating				1500 KVA	→	→
3. Weight				4,225 lbs	→	→
4. Volume				65 ft^3	→	→
5. LWH inches (dry type AA)				30 x 48 x 78	→	→
C. Transformer (power)				Same as above		
1. Primary/secondary voltage						
2. Rating						
3. Weight						
4. Volume						
D. Switchgear (includes main circuit breaker* instrumentation, protection and carrier)						
1. Load end						
a. Weight	1800 lbs	→	→	4000 lbs	→	→
b. Volume	90 ft^3	→	→	290 ft^3	→	→
c. LWH (in.)	36 x 48 90	→	→	52 x 78 x 90	→	→
2. *Power end						
a. Weight	3600 lbs	→	→	9625 lbs	→	→
b. Volume	180 ft^3	→	→	500 ft^3	→	→
c. LWH (in.)	72 x 48 x 90	→	→	144 x 78 x 90	→	→

*Applies to power end only.

Table 9-IV (Continued)

SYSTEM	DEPTH OF LOAD MODULE (FT) 600	2000	6000	10,000	15,000	20,000
CABLE						
1. Copper size	#4	#2	1/0	#2	#2	#2
2. Total length	1,000	6,000	10,000	15,000	20,000	30,000
3. Total weight	4,710 lbs	32,760 lbs	63,600 lbs	72,450 lbs	96,600 lbs	144,900 lbs
POWER SOURCE						
A. Type	← DIESEL GENERATOR →					
B. Rating (KW)	← 1,250 →					
C. Operating point (KW)	1,056	1,113	1,117	1,080	1,095	1,125
D. Full load fuel consumption (gal/hr)	71.5	75.7	76	73.5	74.5	76.5
E. Major overhaul period	2 years →					
F. Heat rejected (btu/min)	← 65,000 →					
G. Weight (lbs)	← 60,000 →					
H. Volume (ft^3)	← 2,040 →					
I. Auxiliary battery						
1. Type	MANCHEX PLANTE					
2. Rating	200 Ampere Hours					
3. Weight	7860 lbs					
4. Volume	57 FT^3					
5. Capacity	24 Kilowatt Hours					

Table 9-IV (Continued)

SYSTEM	600	2000	6000	10,000	15,000	20,000
	DEPTH OF LOAD MODULE (FT)					
HULL						
1. Type	← THICK DISC	→	→	→	→	→
2. Diameter (ft)	55-1/2	→	→	→	→	→
3. Height (ft)	11-1/2	→	→	→	→	→
4. Weight (lbs)	220, 000	→	→	→	→	→
5. Displacement (lbs)	853, 000	→	→	→	→	→
6. Material	Steel	ASTM	A-36	A-212	→	→
EMPLACEMENT						
1. Type	4 point mooring system, legs 90° apart	→	→	→	→	→
2. Anchoring type	25, 000 lbs LWT wedge block	→	→	→	→	→
3. Clump weight (lbs)	57, 000	48, 000	85, 000	58, 000	89, 000	56, 000
4. Chain (1-1/2" steel alloy)						
a. Min. length (ft)	270	270	270	270	270	270
b. Min. weight (lbs)	5, 100	5, 100	5, 100	5, 100	5, 100	5, 100
5. Mooring leg material	Steel wire rope	→	→	→	→	→
6. Protective covering	3/16 inch extruded Polyurethane Sheathing	→	→	→	→	→
7. Diameter (in.)	1-3/8	1-3/8	1-1/2	1-3/8 1-1/2	1-1/2 1-5/8	1-3/8 1-1/2 1-5/8
8. Incremental scope (ft)	1, 590	5, 400	10, 400	1, 575 17, 925	8, 900 15, 100	2, 000 18, 000 15000
9. Total scope (ft)	1, 590	5, 400	10, 400	19, 500	24, 000	35, 000
10. Total mooring leg wt. (lbs)	92, 000	92, 000	147, 000	147, 000	201, 000	201, 000
11. Catenary support buoy						
a. Diameter (ft)	12	12	12	12	15	15
b. Height (ft)	12	12	22	22	17-1/2	17-1/2
c. Weight (lbs)	4, 400	4, 400	6, 800	6, 800	7, 700	7, 700
d. Material	Steel ASTM, A-36 and A-212	→	→	→	→	→
e. Distance from power plant	1000 ft.	→	→	→	→	→
f. Number Required	4 (1 per leg)	→	→	→	→	→

Table 9-V
Parameters For 3000 KW
Underwater Power Transmission Systems

SYSTEM	DEPTH OF LOAD MODULE (FT) 600	2000	6000	10,000	15,000	20,000
ELECTRICAL						
A. Transmission voltage (KV)	4.16	13.8	13.8	13.8	13.8	13.8
B. Transformer (load)						
1. Primary/secondary voltage	Direct Transmission	4.16/13.8 →				
2. Rating		3750 KVA →				
3. Weight		6050 lbs →				
4. Volume		93 ft^3 →				
5. LWH inches (dry type AA)		33 x 54 x 90 →				
C. Transformer (power)						
1. Primary/secondary voltage		Same as above →				
2. Rating						
3. Weight						
4. Volume						
D. Switchgear (includes main circuit breaker* instrumentation, protection and carrier)						
1. Load end						
a. Weight	1800 lbs	4000 lbs →				
b. Volume	90 ft^3	290 ft^3 →				
c. LWH (in.)	36 x 48 x 90	72 x 78 x 90 →				
2. Power end						
a. Weight	3600 lbs	11,450 lbs →				
b. Volume	180 ft^3	528 ft^3 →				
c. LWH (in.)	72 x 48 x 90	144 x 78 x 90 →				

*Applies to power end only.

Table 9-V (Continued)

SYSTEM	DEPTH OF LOAD MODULE (FT) 600	2000	6000	10,000	15,000	20,000
CABLE						
1. Copper size	300 MCM	#2	#2	#2	#2	#1/0
2. Outside diameter						
3. Total length	1,000	6,000	10,000	15,000	20,000	30,000
4. Total weight	10,950 lbs	32,940 lbs	54,900 lbs	82,350 lbs	129,600 lbs	225,900 lbs
5. Support system						
a. No. of buoys						
b. Size & location						
POWER SOURCE						
A. Type	← DIESEL GENERATOR →					
B. Rating (KW)	← 3,500 →					
C. Operating point (KW)	3,118	3,193	3,261	3,346	3,304	3,292
D. Full load fuel consumption (gal/hr)	214	220	225	231	228	227
E. Major overhaul period	2 years →					
F. Heat rejected (btu/min)	← 194,000 →					
G. Weight (lbs)	← 160,000 →					
H. Volume (ft^3)	← 54,000 →					
I. Auxiliary battery						
1. Type	MANCHEX PLANTE					
2. Rating	200 Ampere Hours					
3. Weight	7860 lbs					
4. Volume	57 FT^3					
5. Capacity	24 Kilowatt Hours					

Table 9-V (Continued)

SYSTEM	DEPTH OF LOAD MODULE (FT) 600	2000	6000	10,000	15,000	20,000
HULL						
1. Type	← THICK DISC →					
2. Diameter (ft)	55-1/2 →					
3. Height (ft)	11-1/2 →					
4. Weight (lbs)	220,000 →					
5. Displacement (lbs)	975,450 →					
6. Material	Steel ASTM, A-36, A-212 →					
EMPLACEMENT						
1. Type	4 point mooring system, legs 90^{o} apart →					
2. Anchoring type	25,000 lbs LWT wedge block →					
3. Clump weight (lbs)	57,000	48,000	85,000	58,000	89,000	56,000
4. Chain (1-1/2" steel alloy)						
a. Min. length (ft)	270	270ω	270	270	270	270
b. Min. weight (lbs)	5,100	5,100	5,100	5,100	5,100	5,100
5. Mooring leg material	Steel wire rope →					
6. Protective covering	3/16 inch extruded Polyurethane Sheathing →					
7. Diameter (in.)	1-3/8	1-3/8	1-1/2	1-3/8 1-1/2	1-1/2 1-5/8	1-3/8 1-1/2 1-5/8
8. Incremental scope (ft)	1,590	5,400	10,400	1,575 17,925	8,900 15,100	2,000 18,000 15000
9. Total scope (ft)	1,590	5,400	10,400	19,500	24,000	35,000
10. Total mooring leg wt. (lbs)	92,000	92,000	147,000	147,000	201,000	201,000
11. Catenary support buoy						
a. Diameter (ft)	12	12	12	12	15	15
b. Height (ft)	12	12	22	22	17-1/2	17-1/2
c. Weight (lbs)	4,400	4,400	6,800	6,800	7,700	7,700
d. Material	Steel ASTM A-36 and A-212 →					
e. Distance from power plant	1000 ft. →					
f. Number Required	4 (1 per leg) →					

Table 9-VI. Estimated Cost of Surface-Tendered Power Source ($K)

POWER (KW)	DEPTH (FT) 600	2,000	6,000	10,000	15,000	20,000
30	1,226.1	1,381.3	1,634.1	1,927.9	2,336.4	3,050.1
100	1,439.2	1,609.1	1,847.1	2,142.4	2,549.4	3,263.6
300	1,535	1,708.1	1,961.2	2,268.4	2,783.9	3,445.9
1000	2,155.7	2,297.4	2,553.7	2,883.8	3,362.4	4,019.8
3000	2,619.0	2,775.3	3,010.2	3,423.3	3,824.5	4,660.6

9.2 IN SITU POWER SOURCE SYSTEMS

The in situ power source systems selected for the various power loads and depths under study are all characterized by a short transmission cable system. The load module and power module are directly connected by a common base for deployment purposes. The secondary distribution system is located in the load module to eliminate the need for a third pressure hull to house this equipment. A reactor power plant has been selected for all of the 22 recommended systems and, therefore, a long operating life is characteristic of these systems. Tables 9-VIII to 9-XII provide the pertinent data for each of the selected systems. Cost data is shown in Table 9-XIII.

9.2.1 Electrical System

For loads of 30 to 300 KW, a 3-phase, 60-cycle, 480-volt direct transmission from the power module to the load module is utilized. For loads of 1000 and 3000 KW, a 3-phase, 60-cycle, 4160-volt direct transmission is also used from power module to the load module. However, in the latter system, a transformer is required in the load module to step down the 4160-volt transmission level to the specified 480-volt utilization voltage.

The power module will be equipped with three sections of switchgear which will house all instrumentation, protective, monitoring control and recording devices. In addition, the switchgear unit will house the one main circuit breaker. In this particular installation, there will be redundancy in control, protective and instrumentation systems. These will be carried back to the load module, providing duplicate monitoring and control in both the power and load module. This information and control capability will be transferred from the power module to the load module via a multiconductor control cable.

The load module will contain a two-section switchgear unit and, in the case of the 4160-volt transmission, a suitable transformer.

9.2.2 Cable and Connectors

All transmission cables terminate directly in the load module through pin connectors, described in Chapter 5. For the larger loads of 300 KW to 3000 KW, multiple cables and pin connectors are recommended in order to limit the scope of connector sizes required to be developed (see Table 9-VII). Power cable sizes were selected by the ampacity rating of the standard size marine cables available.

Table 9-VII Recommended Systems and Method of Termination for In Situ Facilities

TRANSMITTED VOLTAGE	KW LOAD	CONDUCTOR SIZE	CONNECTOR AVAILABLE	RECOMMENDED TRANSMISSION METHOD
480	30	#6	Yes	
	100	#4	Yes	
	300	#4/0	No	2 #1/0 Cables
4160	1000	#4	Yes	Requires Engineering
	3000	300 MCM	No	3 #1/0 Cables

Table 9-VII indicates that there is no restriction on connectors for loads of 30 and 100 KW within present technology. However, the 300 KW load of 480 volts requires the use of two 1/0 conductors per phase. This arrangement, which is the capacity equivalent of a 4/0, is recommended because there is no connector available with 4/0 pin size. At 4160 volts for the 1000-KW load, a connector is available but requires engineering. The connector available has been tested for 4160-volt operation, and a pin size equivalent to the capacity required has been tested, but at a lower voltage. Therefore, it is recommended that the two proven parameters be incorporated in a reliable connector design. At 4160 volts with a load of 3000 KW, connectors are not available; therefore, three 1/0 conductors per phase are recommended.

When the final deployment method is selected and the distance between the power and load module defined, the cable trace and forces imposed on terminal connectors will have to be considered.

To prevent the electrical cable trace from inducing excessive stress in the cable and/or connector at the connectors, some form of terminal support may be required. One possible method may be to utilize a relatively light support rope span between the two modules and transfer the tensile load from the electrical cable to the support rope, as shown in Figure 9-1. It may be desirable to install a separate support cable for each electrical cable, i.e., power, control. The support cable and saddles selected will offer adequate environmental protection, i.e., polyethylene-coated metal straps.

9.2.3 Control and Protection

The system is provided with the necessary instrumentation, protection, transformers (where required), control devices, and a means of surveillance of the system from a fault-location panel within the load module. The system will be kept in operation until loss of power is inevitable. Then the plant will shut down. It will also shut down for loss of control power if both AC and DC sources are lost due to open or shorted circuits or to other causes. The protection system is selected and tailored to the installation providing the operating means and selectivity required for a manned load module. This may change, however, when the mission is clearly defined and it is

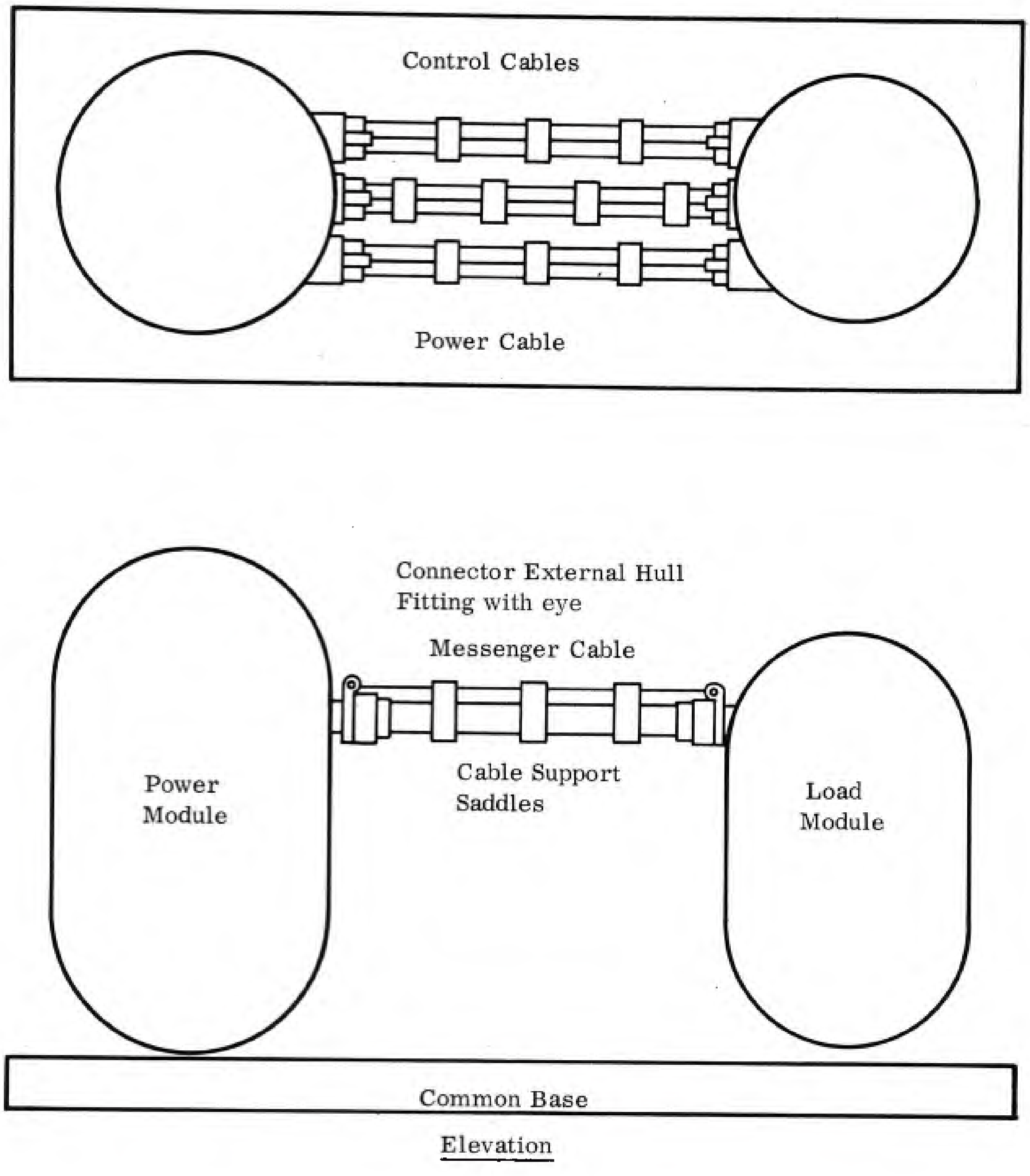


Figure 9-1. Typical Cable Support for In Situ Power Plant

established that the load module will be manned or unmanned. In the case of a manned station, as has been assumed for this application, life support and emergency systems will have to function to sustain life until rescue is available or the entire unit udergoes an automatic surfacing.

Control power will be provided from an AC transformer connected open delta and energized between the generator and the main circuit breaker to insure control power source. The transformer will be protected by fuses in both the primary and secondary side. In case of failure of this system, control power will be instantaneously switched to the battery source. If both systems are lost due to circuit conditions or to other causes, the plant will shut down.

9.2.4 Power Source

The power plant module for each of the selected systems includes a pressure hull properly configured to house the equipment and to provide access for maintenance. In addition, utilization of the hull provides an adequate heat transfer area or includes the required hull penetration. The internal equipment includes a typical pressurized, water-cooled reactor and shielding as the primary system. The secondary system includes the steam turbine generator system which provides the required power at the transmission voltages. For the power loads up to 300 KW, the turbine steam exhaust is condensed and the waste heat is removed by contact with the steel pressure hull. For 1000 KW and above, standard condensing techniques are required, utilizing hull penetrations to provide circulating sea water cooling. All monitoring circuitry is transferred to the load module for operational observation and fault isolation; thus, the power module does not require manning.

9.2.5 Deployment System

Deployment techniques for these power transmission systems are similar to those envisioned for the load modules in the surface-tendered systems. The load module and power plant are winched down to position by a previously positioned anchor. For each different load module applied to the power source, a suitable base must be designed to provide the necessary trim ballast and controlled positive buoyancy required for descent and ascent.

Table 9-VIII Parameters For 30KW Recommended In Situ Underwater Power Transmission Systems

SYSTEM	DEPTH OF IN SITU PLANT (FT) 600	2000	6000	10, 000	15, 000	20, 000
POWER SOURCE SYSTEM						
A. Type	← PRESSURIZED WATER REACTOR - STEAM →					
B. Heat Rejected						
1. Quantity	← $9(10)^5$ BTU/HR →					
2. Method	← PRESSURE HULL HEAT EXCHANGER →					
ELECTRICAL SYSTEM						
A. Transmission Voltage (KV)	0.48 →					
B. Transformer	DIRECT TRANSMISSION →					
C. Switchgear (Power Module)						
1. Weight (lbs)	2, 700 →					
2. Volume (ft^3)	135 →					
3. LWH (in.)	54 x 48 x 90 →					
D. Switchgear (Load Module)						
1. Weight (lbs)	1, 800 →					
2. Volume (ft^3)	90 →					
3. LWH (in.)	36 x 48 x 90 →					
E. Power Cable						
1. Copper Size	#6 →					
2. Outside Diameter (in.)	1.97 →					

Table 9-VIII (Cont.)

SYSTEM	DEPTH OF IN SITU PLANT (FT)					
	600	2000	6000	10,000	15,000	20,000
POWER PLANT						
A. Total Weight (LT)	55.2	60.3	74.7	94.6	98.8	116
B. Total Displacement (LT)	58.3	58.3	58.3	58.3	58.3	58.3
C. Buoyancy (LT)	+3.1	-2.0	-16.4	-36.3	-40.5	-57.7
DEPLOYMENT SYSTEM Forced Ascent-Descent (Winch Down)						
A. SW Density, In Situ (lbs/ft^3) ($64.0\ lb/ft^3$ at surface)	64.12	64.28	64.68	65.04	65.48	65.92
B. Flotation Material						
1. Density (lbs/ft^3)						
a. Type I		38	38	38		
b. Type II					44	44
2. Buoyancy (lbs/ft^3)						
a. Type I		26	26	26		
b. Type II					20	20
3. Volume (ft^3)		173	1,400	3,150	4,550	6,450
4. Weight (lbs)		6,600	53,400	119,000	200,000	284,000
C. Ballast (Pig Iron*)						
1. Density (lbs/ft^3)	490					
2. Volume (ft^3)	10.2					
3. Weight (lbs)	5,000					

*All or part of this weight may be supplied as additional reactor shielding (lead) or hull reinforcement.

Table 9-VIII (Cont.)

SYSTEM	DEPTH OF IN SITU PLANT (FT) 600	2000	6000	10,000	15,000	20,000
D. Winch-Down **System**						
1. **Total rope length** 1.2 x depth (ft)	720	2,400	7,200	12,000	18,000	24,000
2. Material	Steel or Nylon	Steel or Nylon	Steel & Nylon	Steel & Nylon	Steel & Nylon	Steel & Nylon
3. Diameter (in.)	3/4'' 1-3/8''	3/4'' 1-3/8''	3/4'' 1-3/8''	3/4'' 1-3/8''	7/8'' 1-3/8''	1'' 1-1/2''
4. Length (ft)	720 720	2,400 2,400	3,600 3,600	4,000 8,000	6,000 12,000	8,000 16,000
5. Weight (lbs)			3,600 2,000	4,000 4,400	8,750 6,600	13,600 10,000
6. Anchor Weight	11,000	11,000	11,000	11,000	11,000	11,000
7. **Winch Weight**	8,000	8,000	8,000	10,000	10,000	10,000
PRESSURE HULL						
A. Orientation	← VERTICAL CYLINDER →					
B. Diameter	← 9 Ft →					
C. Length	← 35 Ft →					
D. Material	HTS	HY 80	HY 130	HY 130	HY 180	HY 180

Table 9-IX Parameters For 100 KW Recommended In Situ Underwater Power Transmission Systems

SYSTEM	DEPTH OF IN SITU PLANT (FT) 600	2000	6000	10,000	15,000	20,000
POWER SOURCE SYSTEM						
A. Type	PRESSURIZED WATER REACTOR - STEAM →					
B. Heat Rejected						
1. Quantity	← $2.7 (10)^6$ BTU/HR →					
2. Method	← PRESSURE HULL HEAT EXCHANGER →					
ELECTRICAL SYSTEM						
A. Transmission Voltage (KV)	0.48 →					
B. Transformer	DIRECT TRANSMISSION →					
C. Switchgear (Power Module						
1. Weight (lbs)	2700 →					
2. Volume (ft^3)	135 ft^3 →					
3. LWH (in.)	54 x 48 x 90 →					
D. Switchgear (Load Module)						
1. Weight (lbs)	1,800 →					
2. Volume (ft^3)	90 →					
3. LWH (in.)	36 x 48 x 90 →					
E. Power Cable						
1. Copper Size	#4 →					
2. Outside Diameter (in.)	2.05 →					

Table 9-IX (Cont.)

SYSTEM	DEPTH OF IN SITU PLANT (FT) 600	2000	6000	10,000	15,000	20,000
POWER PLANT						
A. Total Weight (LT)	69.7	78.2	96.0	119.5	133.0	169.5
B. Total Displacement (LT)	74.5	74.5	74.5	74.5	81.0	87.8
C. Buoyancy (LT)	+4.8	-3.7	-21.5	-45.0	-52.0	-81.7
DEPLOYMENT SYSTEM Forced Ascent-Descent (Winch Down)						
A. SW Density, In Situ (lbs/ft^3) ($64.0\ lb/ft^3$ at surface)	64.12	64.28	64.68	65.04	65.48	65.92
B. Flotation Material						
1. Density (lbs/ft^3)						
a. Type I		38	38	38	38	38
b. Type II						
2. Buoyancy (lbs/ft^3)						
a. Type I		26	26	26	26	26
b. Type II						
3. Volume (ft^3)		327	1,865	5,080	5,820	9,175
4. Weight (lbs)		12,400	70,800	223,500	256,000	404,000
C. Ballast (Pig Iron*)						
1. Density (lbs/ft^3)	490					
2. Volume (ft^3)	16.9					
3. Weight (lbs)	8300					

*All or part of this weight may be supplied as additional reactor shielding (lead) or hull reinforcement.

Table 9-IX (Cont.)

SYSTEM	DEPTH OF IN SITU PLANT (FT) 600	2000	6000	10,000	15,000	20,000
D. Winch-Down System						
1. Total rope length 1.2 x depth (ft)	720	2,400	7,200	12,000	18,000	24,000
2. Material	Steel or Nylon	Steel or Nylon	Steel & Nylon	Steel & Nylon	Steel & Nylon	Steel & Nylon
3. Diameter (in.)	3/4'' 1-3/8''	3/4'' 1-3/8''	3/4'' 1-3/8''	3/4'' 1-3/8''	7/8'' 1-3/8''	1'' 1-1/2''
4. Length (ft)	720 720	2,400 2,400	3,600 3,600	4,000 8,000	6,000 12,000	8,000 16,000
5. Weight (lbs)			3,600 2,000	4,000 4,400	8,750 6,600	13,600 10,000
6. Anchor Weight	11,000	11,000	11,000	11,000	11,000	11,000
7. Winch Weight	8,000	8,000	8,000	10,000	10,000	10,000
PRESSURE HULL						
A. Orientation	← VERTICAL CYLINDER →					
B. Diameter	← 10 ft →					
C. Length			36 1/2 ft		39 1/2 ft	42 1/2 ft
D. Material	HTS	HY 80	HY 130	HY 130	HY 180	HY 180

Table 9-X Parameters For 300 KW Recommended In Situ Underwater Power Transmission Systems

SYSTEM	DEPTH OF IN SITU PLANT (FT) 600 — 2000 — 6000 — 10,000 — 15,000 — 20,000
POWER SOURCE SYSTEM	← PRESSURIZED WATER REACTOR - STEAM →
A. Type	
B. Heat Rejected	
1. Quantity	← $7.0\ (10)^6$ BTU/HR →
2. Method	← PRESSURE HULL HEAT EXCHANGER →
ELECTRICAL SYSTEM	
A. Transmission Voltage (KV)	0.48 →
B. Transformer	DIRECT TRANSMISSION →
C. Switchgear (Power Module	
1. Weight (lbs)	2700 →
2. Volume (ft^3)	135 →
3. LWH (in.)	54 x 48 x 90 →
D. Switchgear (Load Module)	
1. Weight (lbs)	1,800 →
2. Volume (ft^3)	90 →
3. LWH (in.)	36 x 48 x 90 →
E. Power Cable	
1. Copper Size	2# 1/0 PER PHASE REQUIRED 2-3/C#1/0 CABLES →
2. Outside Diameter (in.)	2.36 EACH →

Table 9-X (Cont.)

SYSTEM	DEPTH OF IN SITU PLANT (FT) 600	2000	6000	10,000	15,000	20,000
POWER PLANT						
A. Total Weight (LT)	96.8	109	143.5	211	246	330
B. Total Displacement (LT)	119.8	115	126.5	155.5	176	196
C. Buoyancy (LT)	+23	+6	-17	-55.5	-70	-134
DEPLOYMENT SYSTEM Forced Ascent-Descent (Winch Down)						
A. SW Density, In Situ (lbs/ft^3) ($64.0\ lb/ft^3$ at surface)	64.12	64.28	64.68	65.04	65.48	65.92
B. Flotation Material						
1. Density (lbs/ft^3)						
a. Type I			38	38		
b. Type II					44	44
2. Buoyancy (lbs/ft^3)						
a. Type I			26	26		
b. Type II					20	20
3. Volume (ft^3)			1,480	4,840	7,800	15,000
4. Weight (lbs)			56,300	183,500	364,000	670,000
C. Ballast (Pig Iron*)						
1. Density (lbs/ft^3)	490					
2. Volume (ft^3)	113	26.5				
3. Weight (lbs)	55,400	13,000				

*All or part of this weight may be supplied as additional reactor shielding (lead) or hull reinforcement.

Table 9-X (Cont.)

SYSTEM	DEPTH OF IN SITU PLANT (FT) 600		2000		6000		10,000		15,000		20,000	
D. Winch-Down System												
1. Total rope length, 1.2 x depth (ft)	720		2,400		7,200		12,000		18,000		24,000	
2. Material	Steel or Nylon		Steel or Nylon		Steel & Nylon		Steel & Nylon		Steel & Nylon		Steel & Nylon	
3. Diameter (in.)	3/4''	1-3/8''	3/4''	1-3/8''	3/4''	1-3/8''	3/4''	1-3/8''	7/8''	1-3/8''	1''	1-1/2''
4. Length (ft)	720	720	2,400	2,400	3,600	3,600	4,000	8,000	6,000	12,000	8,000	16,000
5. Weight (lbs)					3,600	2,000	4,000	4,400	8,750	6,600	13,600	10,000
6. Anchor Weight	11,000		11,000		11,000		11,000		11,000		11,000	
7. Winch Weight	8,000		8,000		8,000		10,000		10,000		10,000	
PRESSURE HULL												
A. Orientation	← VERTICAL CYLINDER →											
B. Diameter	← 10 ft →											
C. Length	57		55		60		73		82		91	
D. Material	HTS		HY 80		HY 130		HY 130		HY 180		HY 180	

Table 9-XI Parameters For 1000KW Recommended in Situ Underwater Power Transmission Systems

SYSTEM	DEPTH OF IN SITU PLANT (FT) 600	2000	6000	10,000	15,000	20,000
POWER SOURCE SYSTEM						
A. Type	PRESSURIZED WATER REACTOR - STEAM		CONCEPT NOT APPLICABLE TO THESE DEPTHS SEE SECTION 4.1.4			
B. Heat Rejected						
1. Quantity (Btu/Hr)	$2.0(10)^7$	$2.0(10)^7$				
2. Method	SHELL AND TUBE					
ELECTRICAL SYSTEM						
A. Transmission Voltage (KV)	4.16 →	→				
B. Transformer (Load Module)						
1. Prim/Sec Voltage	4.16/480 →	→				
2. Rating	1500 KVA →	→				
3. Weight (lbs)	4225 →	→				
4. Volume (ft^3)	65 →	→				
5. LWH in in. (dry type AA)	30 x 48 x 78 →	→				
C. Switchgear (Power Module)						
1. Weight (lbs)	4800 →	→				
2. Volume (ft^3)	252 →	→				
3. LWH (in.)	78 x 62 x 90 →	→				
D. Switchgear (Load Module)						
1. Weight (lbs)	3,200 →	→				
2. Volume (ft^3)	168 →	→				
3. LWH (in.)	52 x 62 x 90 →	→				
E. Power Cable						
1. Copper Size	#4 →	→				
2. Outside Diameter (in.)	2.19 →	→				

Table 9-XI (Cont.)

SYSTEM	DEPTH OF IN SITU PLANT (FT)					
	600	2000	6000	10,000	15,000	20,000
POWER PLANT						
A. Total Weight (LT)	285	345				
B. Total Displacement (LT)	383	383				
C. Buoyancy (LT)	+98	+38				
DEPLOYMENT SYSTEM Forced Ascent-Descent (Winch Down)						
A. SW Density, In Situ (lbs/ft^3) (64.0 lb/ft^3 at surface)	64.12	64.28				
B. Flotation Material						
1. Density (lbs/ft^3)						
a. Type I						
b. Type II						
2. Buoyancy (lbs/ft^3)						
a. Type I						
b. Type II						
3. Volume (ft^3)						
4. Weight (lbs)						
C. Ballast (Pig Iron*)						
1. Density (lbs/ft^3)	490					
2. Volume (ft^3)	510	207				
3. Weight (lbs)	250,000	101,000				

*All or part of this weight may be supplied as additional reactor shielding (lead) or hull reinforcement.

Table 9-XI (Cont.)

SYSTEM	DEPTH OF IN SITU PLANT (FT) 600	2000	6000	10,000	15,000	20,000
D. Winch-Down System						
1. Total rope length, 1.2 x depth (ft)	720	2,400				
2. Material	Steel or Nylon	Steel or Nylon				
3. Diameter (in.)	3/4" 1-3/8"	3/4" 1-3/8"				
4. Length (ft)	720 720	2,400 2,400				
5. Weight (lbs)						
6. Anchor Weight	11,000	11,000				
7. Winch Weight	8,000	8,000				
PRESSURE HULL						
A. Orientation	HORIZONTAL CYLINDER					
B. Diameter	21 Ft I. D.					
C. Length	46 Ft					
D. Material	HTS	HY 80				

Table 9-XII Parameters For 3000KW Recommended in Situ Underwater Power Transmission Systems

SYSTEM	DEPTH OF IN SITU PLANT (FT) 600	2000	6000	10,000	15,000	20,000
POWER SOURCE SYSTEM						
A. Type	PRESSURIZED WATER REACTOR - STEAM			CONCEPT NOT APPLICABLE TO THESE DEPTHS SEE SECTION 4.1.4		
B. Heat Rejected						
1. Quantity (Btu/Hr)	$5.5(10)^7$	$5.5(10)^7$				
2. Method	SHELL AND TUBE					
ELECTRICAL SYSTEM						
A. Transmission Voltage (KV)	4.16 →					
B. Transformer						
1. Prim/Sec Voltage	4.16/.480 →					
2. Rating	3750 KVA →					
3. Weight (lbs)	6050 →					
4. Volume (ft^3)	93 →					
5. LWH in in. (dry type AA)	33 x 54 x 90 →					
C. Switchgear (Power Module)						
1. Weight (lbs)	4800 →					
2. Volume (ft^3)	252 →					
3. LWH (in.)	78 x 62 x 90 →					
D. Switchgear (Load Module)						
1. Weight (lbs)	3,200 →					
2. Volume (ft^3)	168 →					
3. LWH (in.)	52 x 62 x 90 →					
E. Power Cable						
1. Copper Size	3 #1/0 PER PHASE REQUIRED 2-3/c#1/0 CABLES					
2. Outside Diameter (in.)	EACH 2.35					

Table 9-XII (Cont.)

SYSTEM	DEPTH OF IN SITU PLANT (FT)					
	600	2000	6000	10,000	15,000	20,000
POWER PLANT						
A. Total Weight (LT)	348	428				
B. Total Displacement (LT)	437	437				
C. Buoyancy (LT)	+89	+9				
DEPLOYMENT SYSTEM Forced Ascent-Descent (Winch Down)						
A. SW Density, In Situ (lbs/ft^3) ($64.0\ lb/ft^3$ at surface)	64.12	64.28				
B. Flotation Material						
1. Density (lbs/ft^3)						
a. Type I						
b. Type II						
2. Buoyancy (lbs/ft^3)						
a. Type I						
b. Type II						
3. Volume (ft^3)						
4. Weight (lbs)						
C. Ballast (Pig Iron*)						
1. Density (lbs/ft^3)	490					
2. Volume (ft^3)	464	41				
3. Weight (lbs)	227,000	20,000				

*All or part of this weight may be supplied as additional reactor shielding (lead) or hull reinforcement.

Table 9-XII (Cont.)

SYSTEM	600	2000	6000	10,000	15,000	20,000
	DEPTH OF IN SITU PLANT (FT)					
D. Winch-Down System						
1. Total rope length 1.2 x depth (ft)	720	2,400				
2. Material	Steel or Nylon	Steel or Nylon				
3. Diameter (in.)	3/4" 1-3/8"	3/4" 1-3/8"				
4. Length (ft)	720 720	2,400 2,400				
5. Weight (lbs)						
6. Anchor Weight	11,000	11,000				
7. Winch Weight	8,000	8,000				
PRESSURE HULL						
A. Orientation	HORIZONTAL CYLINDER					
B. Diameter	21 Ft I.D.					
C. Length	51 Ft					
D. Material	HTS	HY 80				

Table 9-XIII Estimated Costs of In Situ Power Source ($ millions)

POWER (KW)	DEPTH (FT) 600	2,000	6,000	10,000	15,000	20,000
30	5.7	5.8	6.3	6.7	7.5	8.1
100	6.0	6.2	6.7	7.2	8.8	10.1
300	6.5	6.6	7.3	9.0	11.8	15.8
1000	9.0	9.5				
3000	13.3	14.2				

9.3 SHORE-BASED POWER PLANT

The shore-based power systems are generally characterized by extremely long power transmission cables required to reach depths of 600, 2000, 6000, 10,000, 15,000 and 20,000 ft. The detailed analysis in Chapter 3 defined the average distances from shore to reach the various ocean depths.

The basic components of the shore-based power plants are a diesel-electric generating plant in a steel-framed, corrugated-covered building, with all of the required auxiliaries, handling equipment and plant services, monitoring and control devices, and intermediate and high voltage transmission cables over distances of 10, 50, 100 and 500 nautical miles. Table 9-XIV shows the voltage levels, loads, frequency, conductors size, and losses of the selected systems. In most cases, DC transmission is used. These DC systems require conversion or rectifiers at the shore-based plant and the equivalent inverter at the load module end. A list of standard equipment for the shore plant is shown in Table 9-XV. The load module will be equipped with subsystems similar to those required with the surface-tendered plant, with the exception of the DC inversion equipment required when transmission from the shore-based plant is at direct current. In addition to the inverter, the load module requires a bank of static capacitors to provide the reactive component for the capacitor and to provide the blocking voltage to stop the inverter if this becomes necessary. The static capacitors are pressure-compensated and are mounted outside the hull. Table 9-XVI lists the equipment weights, volumes and dimensions of the electrical equipment required in the load module when power is supplied by a shore-based plant. Weights, volumes and dimensions were not given for the shore plant, since these factors are not critical for this facility.

The diesel generators are self-contained in the 30 KW to 300 KW power levels, utilizing forced convection radiators for cooling and battery starting systems. The 1000 KW and 3000 KW diesel generators require heat exchanger/cooling tower installations for engine jacket cooling water and the 250 psi compressed air starting systems.

Tables 9-XVII through 9-XXI list the parameters of the recommended systems for shore-based power sources. The diesel generators are sized to adequately meet the transmission system full load operating point with the excess power rating providing an effective "spinning reserve" in the generator. The diesel-generator systems are instrumented and automatically controlled to provide a reliable, unattended power source. Cost estimates for the shore-based systems are given in Table 9-XXII. Electrical cable deployment techniques and a proposed method are discussed in Appendix B.

Table 9-XIV. Selected Cable Systems for Shore-Based Plant

TRANSMISSION DISTANCE (MILES)	LOAD (KW)	VOLTAGE LEVEL (KV)	FREQUENCY	WIRE SIZE	FULL LOAD LOSSES (KW)
10	30	4.16	AC	#6	1.39
	100	4.16	AC	#4	12.00
	300	13.8	AC	#2	5.1
	1000	13.8	AC	#2	66.0
	3000	13.8	AC	4/0	202.0
50	30	13.8	DC	#2	1.3
	100	13.8	DC	#2	15.3
	300	13.8	DC	1/0	85.5
	1000	34.5	DC	#1	202.0
	3000	34.5	AC	#1	204.0
100	30	13.8	DC	#2	2.7
	100	13.8	DC	1/0	19.2
	300	34.5	DC	#1	36.0
	1000	34.5	DC	2/0	246.0
	3000	34.5	DC	350	280.0
500	30	34.5	DC	#1	1.8
	100	34.5	DC	#1	20.0
	300	34.5	DC	4/0	69.0
	1000	34.5	DC	600	231.0
	3000	*	*	*	*

*A 3000 KW load at 500 miles cannot be reached at the voltages considered.

Table 9-XV. Standard Power Source Equipment for Shore-Based Transmission System

POWER SOURCE

- Type - diesel generator
- Rating - as required
- Engine control panel
- Lubrication system and necessary auxiliaries
- Governor - as required
- Alarms - as required
- System for automatic start

FUEL SYSTEM

- Storage tank
- Transfer facilities to diesel
- Necessary strainers and pressure regulators

WATER SYSTEM

- Tank or well
- Transfer and pressure system to plant
- Cooling system for diesel

AUXILIARY BATTERY

- Rated at 200 ampere hours

RECTIFIER

- To maintain battery in full charged condition

GENERATOR

- 3-phase star connected (wye)
- Rated as required for loads
- Enclosure for duty
  - Grounding device
  - Dummy load
    - Size and type to be determined
    - Throwover switch for dummy load

GENERATOR EXCITER

- Static type
- Accessory controls

Table 9-XV. (Cont.)

ELECTRICAL	
Necessary switchgear to house:	
Main circuit breaker	
Instruments	
Protective relays and control	
Transformers (power)	
Rated as required with ± 10% taps in 1/2% steps	
Annunciation with capacity to handle all functions	
CARRIER EQUIPMENT	
Size for circuit parameters with transmitter and receiver	
Coupling capacitor for carrier	
CONVERSION EQUIPMENT	
Transformer	
Transition section	
Converter rectifier	(As required by load and voltage)
Control devices	
Control panel	
ALARM SYSTEM TO MONITOR	
Trouble alarm with trip for either microwave or leased line connection	
STATION POWER AND LIGHT AND HEAT	
Sizes as required	
FIRE PROTECTION SYSTEM	
Automatic by rate-of-rise and maximum temperature sensors	
FENCE AND DOOR SECURITY ALARM SYSTEM	

Table 9-XVI Load Module Equipment For Shore-Based Plant

		AC TRANSMISSION								DC TRANSMISSION					
DISTANCE	LOAD	TRANSFORMER					SWITCHGEAR			TRANSFORMER INVERTER			STATIC CAPACITOR		
(Miles)	(KW)	Rating (KVA)	Primary/Secondary Voltage (KV)	Weight (Lbs)	Volume (Ft^3)	LWH (In.)	Weight (Lbs)	Volume (Ft^3)	LWH (In.)	Weight (Lbs)	Volume (Ft^3)	LWH (In.)	Weight Ea*(Lbs)	Volume Ea*(Ft^3)	LWH Ea*(in.)
10	30	45	.48/13.8	500	7.7	16 x 26 x 32	1800	90	36 x 48 x 90						
	100	112		850	16.4	19 x 39 x 38	1800	90	36 x 48 x 90						
	300	500	4.16/13.8	2750	45.8	27 x 43 x 68	4000	290	72 x 78 x 90						
	1000	1500		4225	65	30 x 48 x 78	4000	290	72 x 78 x 90						
	3000	3750		6050	93	33 x 54 x 90	4000	290	72 x 78 x 90						
50	30									2850	75	42 x 54 x 58	25	2.7	10 x 18 x 26
	100									6000	158	49 x 83 x 68	25	2.7	10 x 18 x 26
	300									16000	424	67 x 91 x 121	25	2.7	10 x 18 x 26
	1000									24000	620	77 x 101 x 138	25	2.7	10 x 18 x 26
	3000	3750	4.16/34.5	6050	93	33 x 54 x 90	4000	290	72 x 78 x 90						
100	30									2850	75	42 x 54 x 58	25	2.7	10 x 18 x 26
	100									6000	158	49 x 83 x 68	25	2.7	10 x 18 x 26
	300									16000	424	67 x 91 x 121	25	2.7	10 x 18 x 26
	1000									24000	620	77 x 101 x 138	25	2.7	10 x 18 x 26
	3000	3750	4.16/34.5	6050	93	33 x 54 x 90	4000	290	72 x 78 x 90						
500	30									2850	75	42 x 54 x 58	25	2.7	10 x 18 x 26
	100									6000	158	49 x 83 x 68	25	2.7	10 x 18 x 26
	300									16000	424	67 x 91 x 121	25	2.7	10 x 18 x 26
	1000									24000	620	77 x 101 x 138	25	2.7	10 x 18 x 26
	3000														

*16 units required per phase.

Table 9-XVII Power Source Parameters for 30 KW Shore-Based Transmission System

Distance (Miles)	10	50	100	500
Type	← Diesel Generator →			
Rating (KW)	50 →			
Full Load Operating Point (KW)	35	43	44	44
Full Load Fuel Consumption (Gal/Hr)	3.3	4	4	4
Cooling System	Radiator - Forced Convection →			
Heat Rejected (BTU/Min)	2200	2800 →		
Major Overhaul Period	2 years →			
Engine Generator Weight (Lbs)	2300 →			
Approximate Dimensions (Ft)	6 L x 3 W x 4 H (72 Ft^3)			
Starting System	Battery →			

Table 9-XVIII Power Source Parameters for 100 KW Shore-Based Transmission System

Distance (Miles)	10	50	100	500
Type	← Diesel Generator →			
Rating (KW)	175 →			
Full Load Operating Point (KW)	121	148	152	153
Full Load Fuel Consumption (Gal/Hr)	9.5	11.5	11.5	11.6
Cooling System	Radiator - Forced Convection →			
Heat Rejected (BTU/Min)	7600	9700 →		
Major Overhaul Period	2 years →			
Engine Generator Weight (Lbs)	4400 →			
Approximate Dimensions (Ft)	8 L x 3-1/2 W x 5 H (140 Ft^3)			
Starting System	Battery →			

Table 9-XIX Power Source Parameters for 300 KW Shore-Based Transmission System

Distance (Miles)	10	50	100	500
Type	← Diesel Generator →			
Rating (KW)	350	500 →		
Full Load Operating Point (KW)	329	461	427	463
Full Load Fuel Consumption (Gal/Hr)	29	42	35	37
Cooling System	Radiator - Forced Convection →			
Heat Rejected (BTU/Min)	18,500	32,000	27,000	30,000
Major Overhaul Period	2 years →			
Engine Generator Weight (Lbs)	14,000 →			
Approximate Dimensions (Ft)	13 L x 5 W x 7 H (460 Ft^3)			
Starting System	Battery →			

Table 9-XX Power Source Parameters for 1000 KW Shore-Based Transmission System

Distance (Miles)	10	50	100	500
Type	← Diesel Generator →			
Rating (KW)	1,250	1,750	1,500	1,750
Full Load Operating Point (KW)	1,120	1,570	1,330	1,580
Full Load Fuel Consumption (Gal/Hr)	89	119	105	121
Cooling System	Heat Exchanger/Water Tower →			
Heat Rejected (BTU/Min)	70,500	99,000	84,000	100,000
Major Overhaul Period	2 years →			
Engine Generator Weight (Lbs)	90,000 →			
Approximate Dimensions (Ft)	26 L x 9 W x 11 H (2,600 Ft^3)			
Starting System	250 psi Compressed Air →			

Table 9-XXI Power Source Parameters for 3000 KW Shore-Based Transmission System

Distance (Miles)	10	50	100	500
Type	← Diesel Generator →			
Rating (KW)	3500	3500	4000	
Full Load Operating Point (KW)	3340	3340	3785	
Full Load Fuel Consumption (Gal/Hr)	242	242	263	
Cooling System	Heat Exchanger/Water Tower →			
Heat Rejected (BTU/Min)	210, 000	210, 000	240, 000	
Major Overhaul Period	2 years →			
Engine Generator Weight (Lbs)	158, 000 →			
Approximate Dimensions (Ft)	40-1/2 L x 11 W x 14-1/2 H (6450 Ft^3)			
Starting System	250 psi Compressed Air →			

Table 9-XXII. Estimated Costs of Shore-Based Power Source ($K)

POWER (KW)	DISTANCE (FT) 60,000	300,000	6000,000	3×10^6	15,000	20,000
30	1,160	2,362	3,857	18,238		
100	1,300	2,464	4,436	18,339		
300	1,515	2,798	4,535	26,368		
1000	1,700	2,990	5,421	44,837		
3000	2,140	4,232	11,339			

9.4 GENERAL UTILITY UNDERWATER POWER TRANSMISSION SYSTEM

A logical extension of the results and conclusions of this study program is an analysis of a potential power plant and transmission system that has maximum utility in providing the required power for many varied missions, as yet undefined, at varying depths, distances and environmental conditions. An analysis of this requirement, summarized in Table 9-XXIII, indicates that significant changes in transmission voltage and cable size, in addition to general power plant configuration, occur for each of the matrix points of power and depths under study. The 480-volt level covers up to 2000 ft at 30 KW, 1000 ft at 100 KW, and 600 ft at 300 KW. The 600-volt level covers up to 6, 000 ft at 30 KW and 2000 ft at 100 and 300 KW. These distances appear too restrictive for the various exploration, research, and habitation missions possible in the ocean.

The present limitation on cable size due to connectors is AWG #1/0 at 4160 volts.

It is logical to assume that, with present materials and techniques, possible deployment areas, and anticipated missions, that power levels required of a general-utility plant would not exceed the range of 30 to 300 KW. This is based on a mission that is non-military and for scientific exploitation only (i. e. , ocean floor mineral investigation, sea life study, effects of earth disturbances on ocean movements, and the like).

It is therefore recommended that an underwater power transmission system be considered with a power source rated at 30 to 100 KW with a 300 KW (e) capability (compatible with the general utility reactor program now under study by NCEL under Contract No. N62399-67-0046) and a 4160-volt power generation and transmission system.

Figure 9-2 depicts the maximum distances of transmission using 4160 volts in a three-conductor, 1/0 cable at power levels of 30, 100 and 300 KW. It is indicated that, for a 30-KW load, a transmission distance of 50 nautical miles can be achieved; at the 100 KW level, approximately 40 nautical miles; and at the 300 KW level, approximately 10 nautical miles. A standard 3-phase, star-connected generator would be coupled to the turbine operating in the power ranges of 30 to 300 KW at 4160 volts.

The penalty for using the general utility system at the lower power levels is very small when compared to the cost to design, construct and deploy, cost effectively, a system tailored to each possible combination of power, distance and depth. The principal penalties are slightly reduced efficiency and the cost differential for 600-volt class equipment and 5000-volt class equipment. These penalties, depending on deployment depth, range from 14 to 20 percent.

In conclusion, then, it may be stated that the first-generation, general-utility underwater power transmission system is possible and requires an engineering effort to make it a working reality.

Table 9-XXIII. Summary of Transmission Voltages

POWER (KW)		DISTANCE (FT) 600	1, 000	2, 000	6, 000	10, 000	15, 000	20, 000	30, 000
30	Voltage	480	480	480	600	4, 160	4, 160	4, 160	4, 160
	Wire Size	#6	#6	#4	1/0	#6	#6	#6	#6
100	Voltage	480	480	600	4, 160	4, 160	4, 160	4, 160	4, 160
	Wire Size	#4	#2	1/0	#6	#6	#6	#6	#6
300	Voltage	480	480	600	4, 160	4, 160	4, 160	13, 800	13, 800
	Wire Size	4/0	4/0	350	#6	#6	#4	#2	#2
1000	Voltage	4, 160	4, 160	4, 160	4, 160	4, 160	13, 800	13, 800	13, 800
	Wire Size	#4	#4	#4	#2	1/0	#2	#2	#2
3000	Voltage	4, 160	4, 160	4, 160	13, 800	13, 800	13, 800	13, 800	13, 800
	Wire Size	300	300	300	#2	#2	#2	#2	1/0

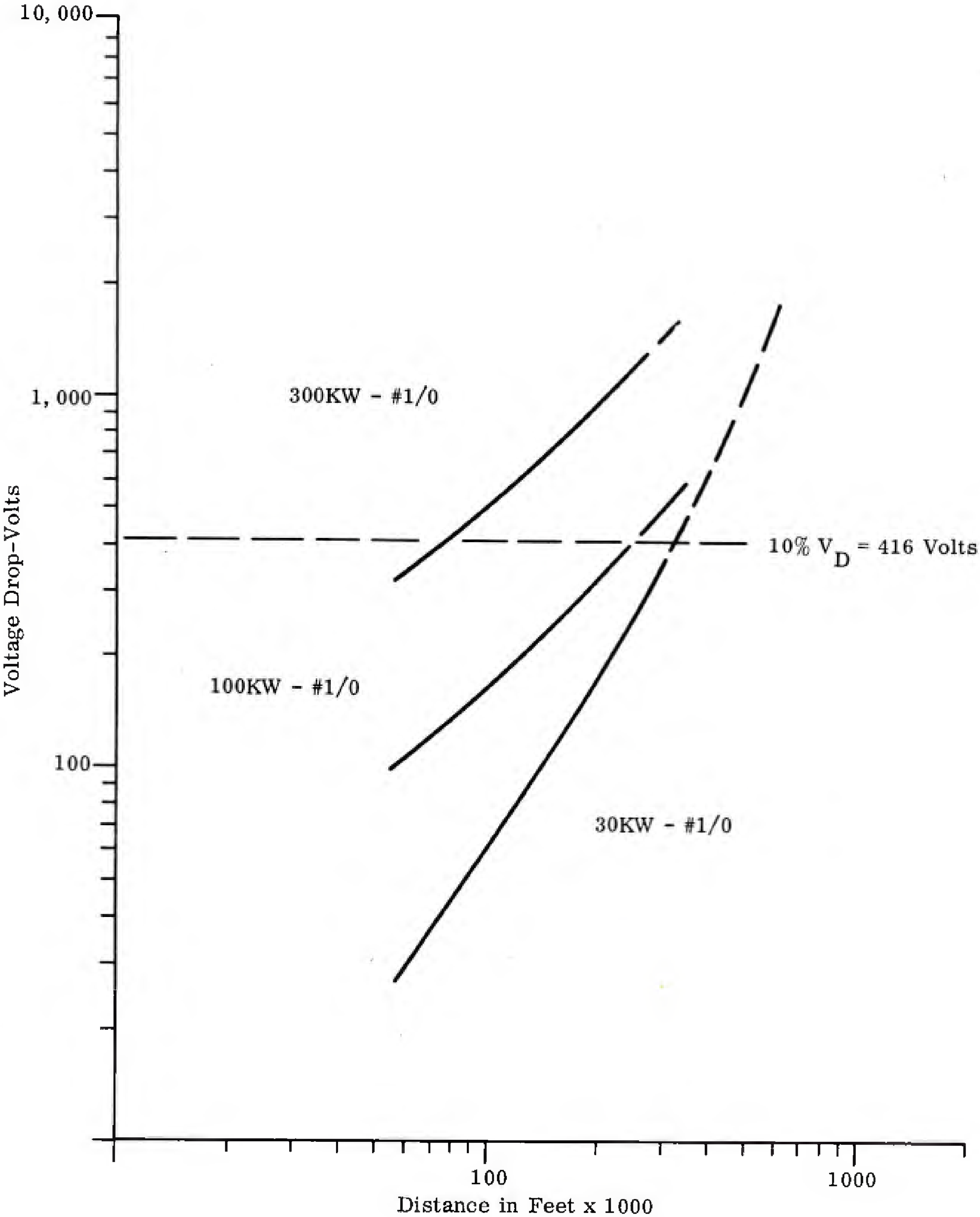


Figure 9-2. Maximum Transmission Distances for 4160 Volts with Three-Conductor, 1/0 Cable

Chapter 10

PRELIMINARY DESIGNS

The three preliminary designs discussed in this chapter are:

- 30 KW surface-tendered systems for supplying power to ocean depths of 600 ft and 6000 ft.
- 100 KW in situ systems emplaced on the ocean floor at depths of 600 ft and 6000 ft.
- 300 KW shore-based systems at cable distances of 60, 000 ft and 300, 000 ft.

These systems are not necessarily the most promising power transmission systems, but they are useful as preliminary designs for each of the three basic power source locations, thus enabling selection once a mission and load module deployment location have been established. In general, the surface-tendered systems can be selected for interim testing of submerged load modules where the deployment location is not in a heavily travelled sea thoroughfare. The shore-based facility can be utilized for close-to-shore, off-shore bottom drilling rigs. The in situ facility can be utilized for any covert, military or inhabited load module to eliminate the air/sea interface as well as the danger of collision.

The surface-tendered systems are the most promising because they cost the least. The in situ systems have the advantage of being operable below the sea-air interface, eliminating the hazards of surface storms and tidal actions. The shore-based power systems are valuable where an experimental facility is desired, such as San Clemente Island.

Selection of the surface-tendered and shore-based systems was based on the results of the study for the Manned Underwater Station (MUS) program. In MUS the power transmission requirement was interim power of 30 KW in 6000-ft depths transmitted from a surface buoy or shore-based facility. The in situ selection of 100 KW was based on a study of a general utility reactor rated at 100 KW or greater which is capable of operation at the 6000-ft depth.

10.1 PRELIMINARY DESIGN FOR A 30 KW DIESEL-ELECTRIC SURFACE-TENDERED POWER SOURCE MOORED IN 600 AND 6000 FT OF WATER

10.1.1 Overall Structure

This concept employs a standard commercial diesel-electric power plant which is installed in a modified Convair "Monster Buoy" (see Figures 10-1 through 10-4). The buoy is 41 ft in diameter, has a 7 1/2-ft overall height, and is equipped with a 20-ft high, 5-ft diameter mast and stack (Mack). The buoy has a double hull, the outer hull being circular and the inner hull being square and containing the powerplant, auxiliary systems, electrical control and instrumentation equipment, and the protection networks. An egg-crate structure between the inner and outer hulls serves to stiffen the hulls and provides a baffled fuel storage area to minimize fuel agitation (see Figure 10-2). Four hawsepipes vertically traverse the fuel storage area, allowing passage of the mooring lines.

The Mack contains snorkel air induction and exhaust valves and ducting as well as the access hatches, one at the base of the Mack and one at its top.

10.1.2 Power Source

The power source is a turbocharged diesel generator rated at 50 KW continuous and 60 KW intermittent operation. The unit is self contained with internal or block-mounted filters, strainers, sumps, and fuel oil and cooling water pumps. The engine has sensors to indicate cooling water temperature, lube oil pressure, and engine overspeed.

An integral fresh water cooling system removes 2100 BTU/min from the engine jacket, rejecting the heat to the sea via a fresh water heat exchanger. The heat exchanger is a shell-and-tube type with sea water in the tubes and fresh water in the shell.

The fresh water system consists of the engine water pump, an external thermostat and heat exchanger bypass, heat exchanger, and fresh water expansion tank (to allow for changes in temperature and to provide a means for adding chemicals, if required). The normal full-load operating temperature differential of the engine jacket inlet and outlet cooling water is 15° F at a flow rate of 17 g.p.m. The sea water circulation system is provided with the requisite controls and components to permit operation in a sea water temperature range between 45 and 85° F.

Engine intake air is drawn from the engine room compartment at ambient conditions, partially scavenging the radiated engine heat and various atmospheric vapors. Additional engine room ventilation by a 3000 cubic ft per minute fan is required to dissipate radiant engine heat. An exhaust muffler is installed between the engine and the overboard exhaust plenum. A battery is used for engine starting. The generator enclosure is of splash proof construction, air cooled, and with remote high temperature and overspeed alarm provisions which are connected to the fault display location panel. The generator output is rated at 50 KW, 62.5 KVA, 60-cycle 480 volts, 3-phase continuous, and 60 KW, 75 KVA, 60-cycle 480 volts, 3-phase intermittent. Voltage regulation is specified at 1% bandwidth of steady-state voltage and 0.5% frequency variation. No-load to full-load recovery time is 4 seconds with an isochronous governor regulating speed and frequency to 0.5%. The same 50-KW generator is used for the 600-ft and 6000-ft transmission systems.

The unit's fuel consumption curves are shown in Figures 10-5 and 10-6 for the 600-ft and 6000-ft systems, respectively. Included in the curves is the power necessary to operate the unit's auxiliary equipment.

Table 10-I contains a listing of the diesel-engine generator characteristics.

A feature of the surface buoy concept is the modular arrangement of components and the whole power plant. There are three compartments in the power module, the largest being the engine and generator compartment. Electrical and electronics components are in a separate compartment as is the oil handling and filtering equipment. Any of the major units can be hoisted out of the buoy through large access hatches in the deck (see Figure 10-1) without disturbing the moor. This allows replacing all the units at one time without the expense of abandoning the moor to take the buoy back to port and then establishing a new moor. Another advantage is that if at a later date more power is needed, this 30 KW buoy can house up to a 100 KW power module without modification. The only difference in this exchange would be a shortening of refueling cycle from 90 days to 22 days. The advantage here is that more power can be delivered to a larger load module without the expense of establishing a new moor. In addition no change would be required in the power cables of either the 600 ft moor or the 6000 ft moor as the cables used for the 30 KW plant are fully capable of carrying the 100 KW load (see Table 6-VI on power cables).

Interchangeability was an objective used in selecting a hull configuration (see Chapter 7). Lower power level modules may be placed in larger hull sizes to realize greater fuel storage capacity. This is desirable, for instance, if deployment is in a remote area where high fuel delivery costs prevail. Conversely, larger power levels in some cases may fit into smaller hull sizes. The mooring system recommended allows complete hull interchangeability in the moor with a slight decrease in wave-allowance/holding-power ratios for the larger hulls. Interchangeability involves transferring mooring lines one at a time.

This flexibility can be utilized when it becomes necessary to deploy additional load modules in close proximity to existing ones; for instance, in situations where establishing a new moor would jeopardize existing load modules. Similarly, it is possible to interchange a higher powered load module for an existing one without going to the expense of laying a new mooring system.

10.1.3 Electrical System

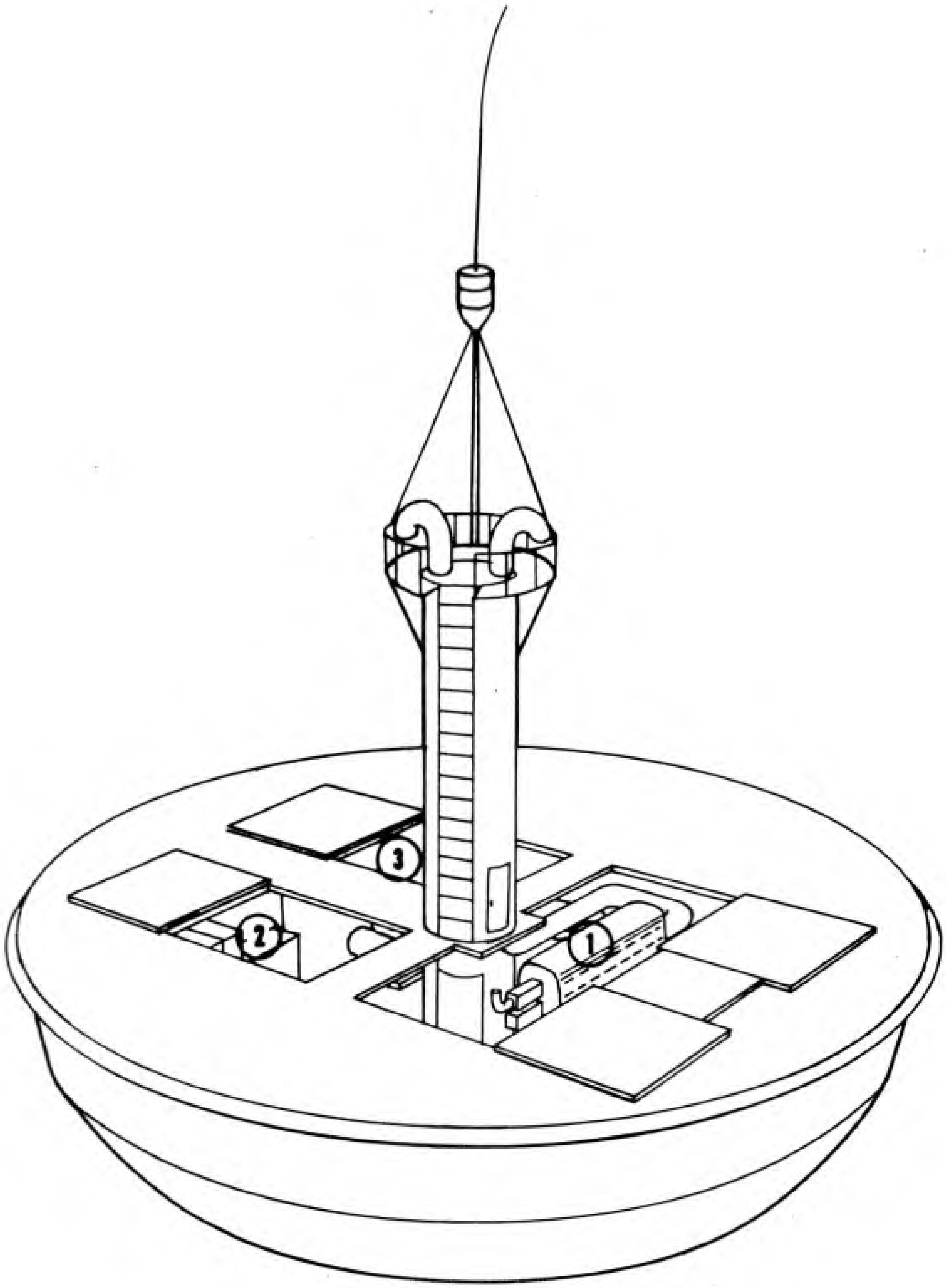
The electrical systems selected for use with the surface tendered buoy system are:

- 480-volt, 3-phase, 60-cycle for 600-ft depths, and
- 4160-volt, 3-phase, 60-cycle for 6000-ft depths.

In each case the power generation equipment and switchgear will be mounted in the surface buoy. The electrical instrumentation, alarms, protective devices, main circuit breaker, control devices and carrier equipment are mounted in the switchgear unit. This unit will be of standard design rated at 600 volts for the 480-volt system and 5000 volts for the 4160-volt system. Both units will use four vertical sections.

The 480-volt system will transmit directly to the load module without transformation, while the 4160-volt system will use a generated voltage of 480 and an ambient air (type AA) dry transformer, with a capacity of 45 KVA, 3 phases. This transformer will be mounted in a unit similar to the switchgear unit and adjacent to it.

The one main circuit breaker mounted in the switchgear unit is sized for the continuous load duty required of either system; its interrupting duty is based on the magnitude of a 3-phase fault. The cables selected for the two systems are in accordance with the conclusions reached in Chapter 5. For the 480-volt and 4160-volt systems the insulation level will be 5000 volts. Both cables will use three concentric-stranded, copper conductors, shielded with a grounded neutral and armored as appropriate for the depths considered. The conductor size selected for both systems is a #6 AWG. For the 480-volt system at 600 ft, 915 ft of this cable will be required. For the 4160-volt system at 6000 ft, 11,790 ft of cable will be required. These lengths have been predicted on the maximum surface excursion of the buoy. The #6 AWG conductor was selected both for its current-carrying capacity (ampacity) and the limits of the 5% voltage drop allowed. Either cable system will terminate at the buoy and load module in multi-connector fittings of the type discussed in Chapter 5.



(1) Engine & Generator Compt

(2) Electrical & Electronic Control Compt

(3) Oil Handling and Oil Filtering Compt

Figure 10-1. Surface-Tendered Power Source Buoy

1. Hull
2. Fuel Oil Storage
3. Mast
4. Snorkel Induction
5. Snorkel Exhaust
6. Navigational Lights
7. Whip Antenna
8. Power Module
9. Hawsepipe

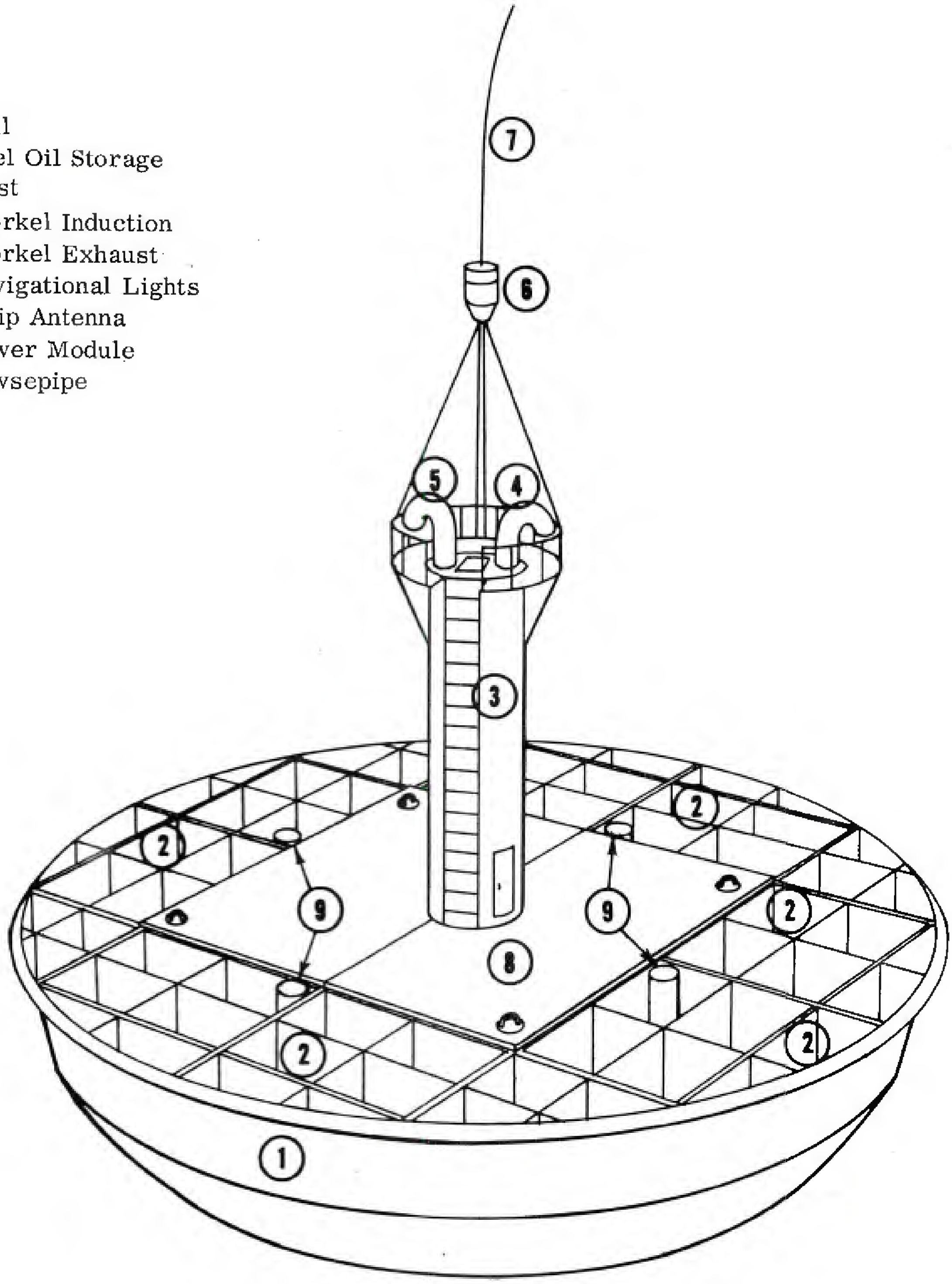
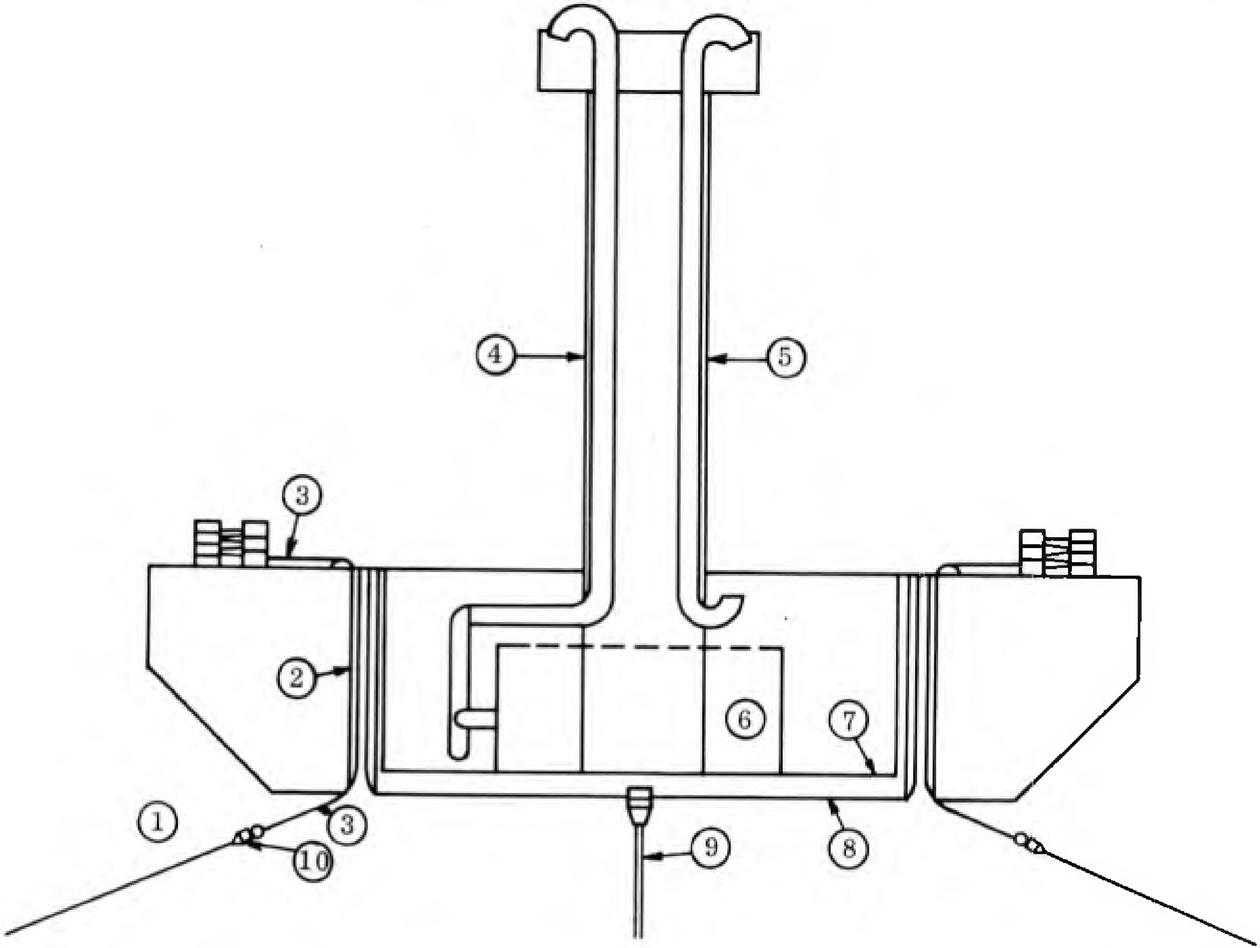
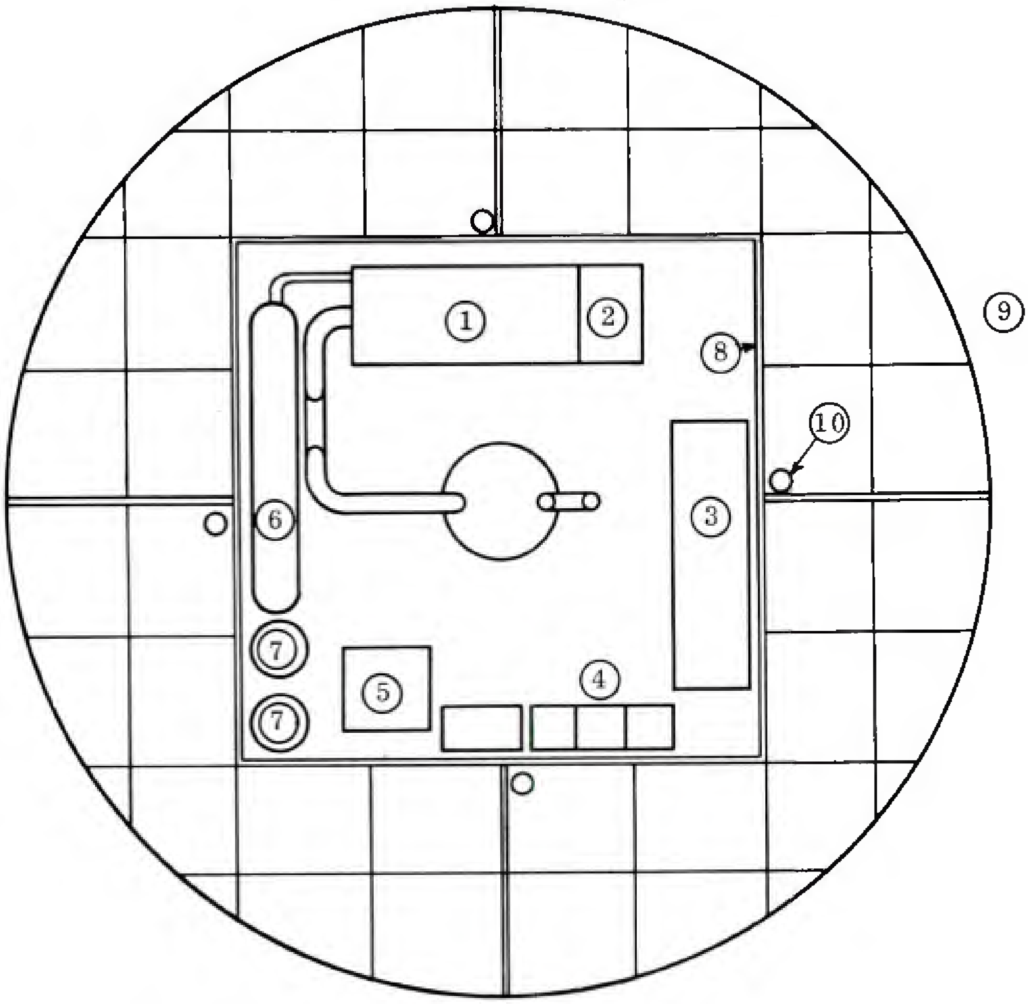


Figure 10-2. Power Source Buoy Cutaway



1 Mooring Line
2 Hawsepipe
3 Steel Rope
4 Exhaust
5 Air Intake
6 Power Plant
7 Inner Hull
8 Outer Hull
9 Power Cable
10 Swivel Connector

Figure 10-3. Power Source Buoy, Elevation Drawing



1 Engine
2 Generator
3 Transformer
4 Elec/Elx Equip. Racks
5 Oil Purifiers
6 Cooler
7 Pumps
8 Inner Hull
9 Outer Hull
10 Hawsepipe

Figure 10-4. Power Source Buoy, Plan View

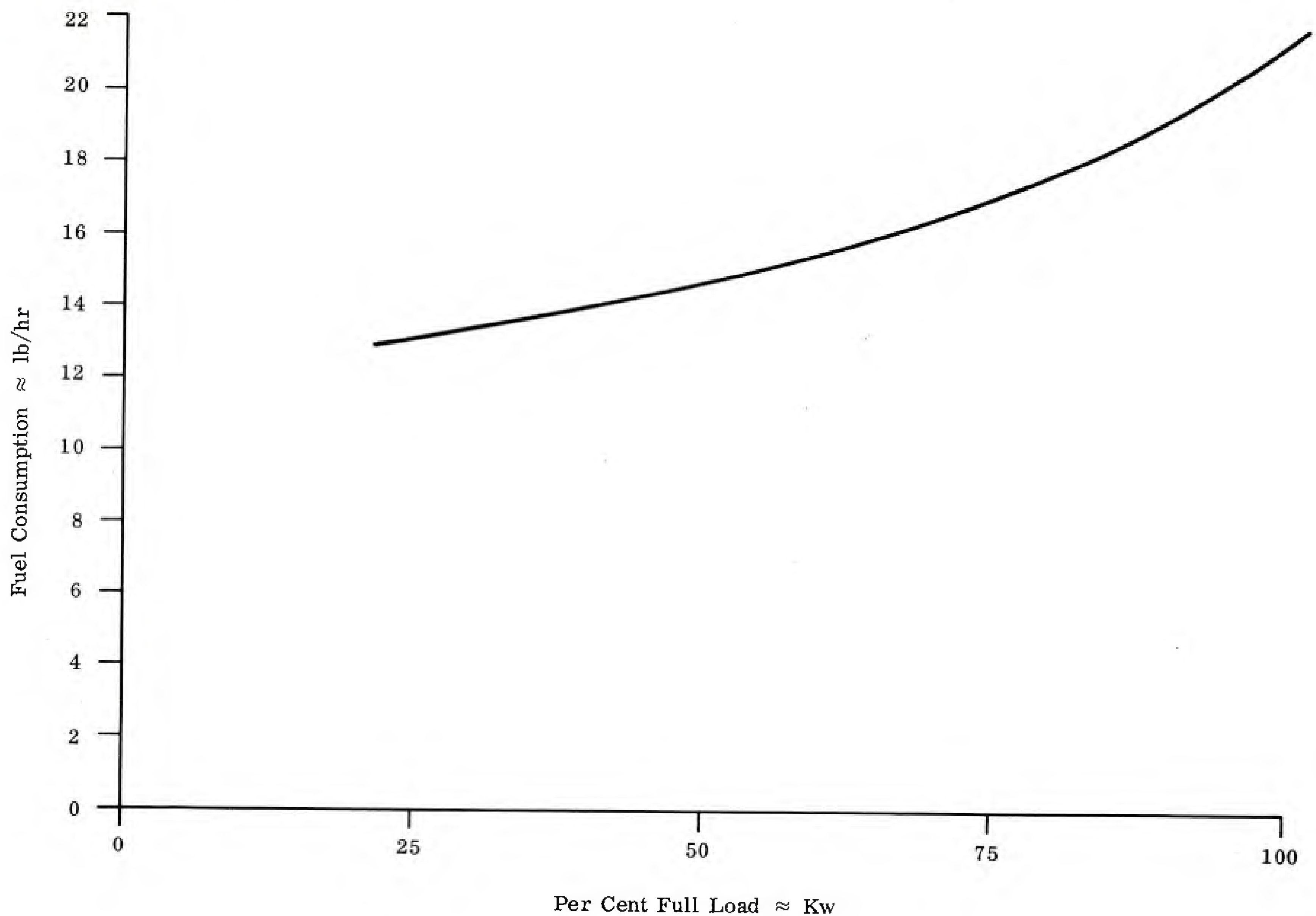


Figure 10-5. Fuel Consumption Curve for 600-Ft Surface-Tendered System

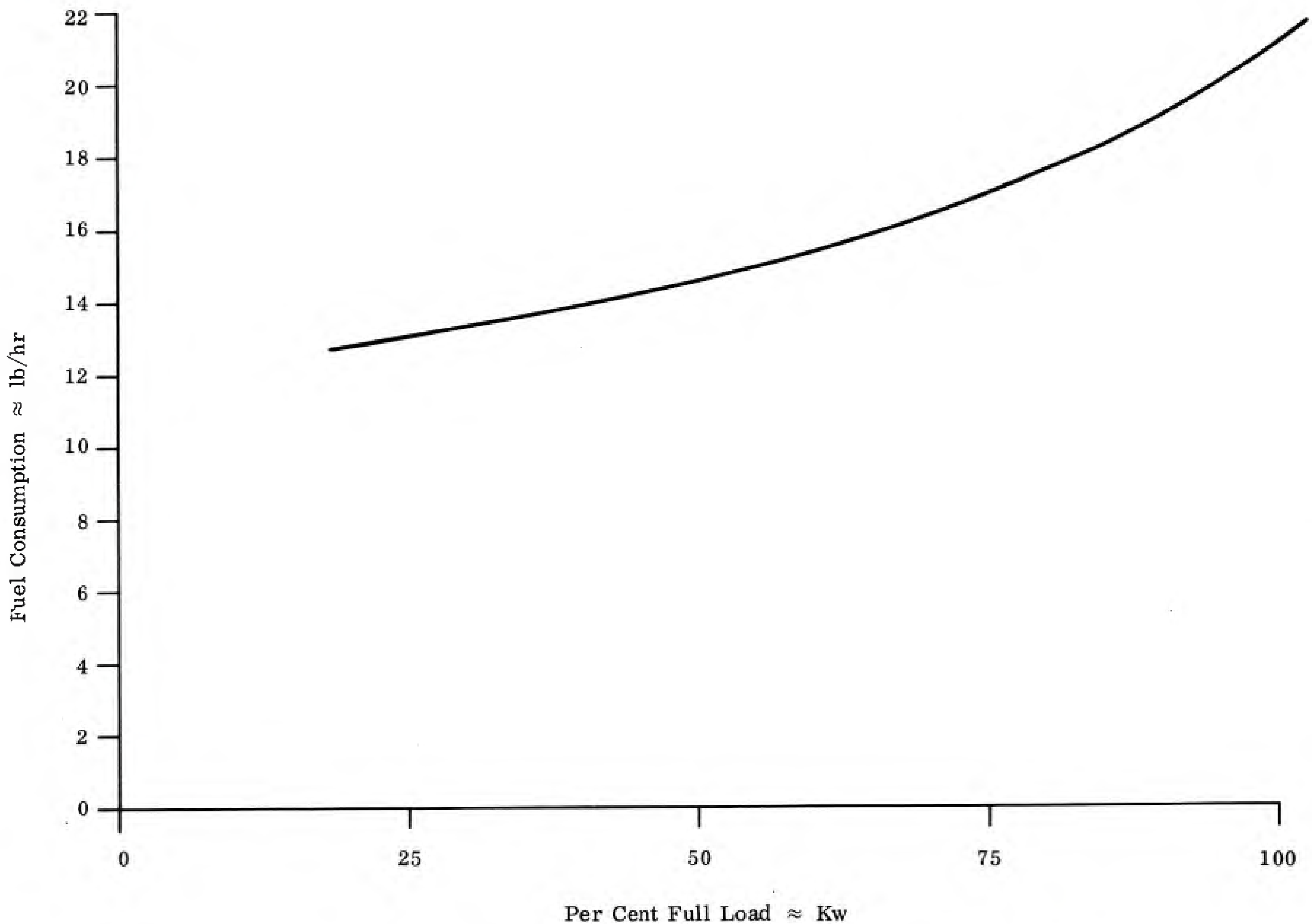


Figure 10- 6. Fuel Consumption Curve for 6000-Ft Surface-Tendered System

Table 10-I.

30 KW Diesel-Engine Generator for 600-Ft and 6000-Ft Surface-Tendered Buoy

ITEM	CHARACTERISTICS
Diesel Engine - Turbocharged-After Cooled	
Rating:	50 KW @ 1800 RPM Continuous 60 KW @ 1800 RPM Intermittent
Approx. Volume:	6' L x 3' W x 3 1/2' H (63 Ft^3)
Approx. Weight:	2400 lbs
Governor:	0.5% Speed Control
Heat Exchanger	Single pass shell and tube
Capacity:	5000 BTU/Min.
Generator - Splash Proof Enclosed	
Voltage:	480 V @ 60 cycles 3 phase
Rating:	50 KW @ 70^{o}C Continuous with 25% overload capability for 2 hours
Regulation:	1% Steady State
Attached Accessories	
Turbo Charger & After Cooler Generator & Exciter	
Air Filter	
Lube Oil Pump & Filter (Self By-Passing)	
Fuel Oil Pump & Filter (Self By-Passing	
Water Pump	
Detached Accessories	
Heat Exchanger	
Heat Excahnger Pump	
Exhaust Muffler	
Alarms & Gauges	

The load module end for either system will use a 2-vertical-section switchgear unit housing all protective sensing devices, instrumentation, and carrier systems. The units in each system will have ratings similar to the equivalent unit in the surface buoy. The 4160-volt system will have, in addition to the switchgear, a dry type AA transformer of equivalent rating as that at the buoy end. The switchgear in the load module requires only two sections because of the effect of the cascade type protection system. The choice of this particular type of protective system was based on saving as much weight and volume in the load module as was possible. The elimination of the breaker, relays, and associated equipment allowed this reduction without loss of reliability. A carrier was substituted to provide not only transfer trip functions but a means of recording, at the surface buoy, the system condition in the load module. The unit can also be provided with audio communication, if required. This reduction in equipment and number of sections helped to reduce the size, weight, and cost of the load module.

10.1.4 Buoy Mooring System

The thick-disc concept embodied by the Monster Buoy configuration has been proven in model tests and actual use as a stable platform capable of being moored in deep water. A major change to the concept lies in the use of a four-point moor (Figure 10-7) instead of a single-point moor. The four mooring ropes enter the bottom close enough to the center to retain desirable characteristics of a single-point moor but far enough outboard to provide a restoring couple to prevent rotation, thus eliminating dangerous twists in the electrical cable. The four-point moor reduces electrical cable length by reducing excursion. The mooring lines could be run over the bulwarks of the buoy to padeyes in its deck. However, this is undesirable, since it may cause the hull to tow under in high sea states.

Three ships are required to set the four-point moor:

- a heavy lift ship (HLS),
- a supply ship (SS),
- a station keeping ship (SKS).

1. Hawsepipe
2. Mooring Line
3. Power Cable

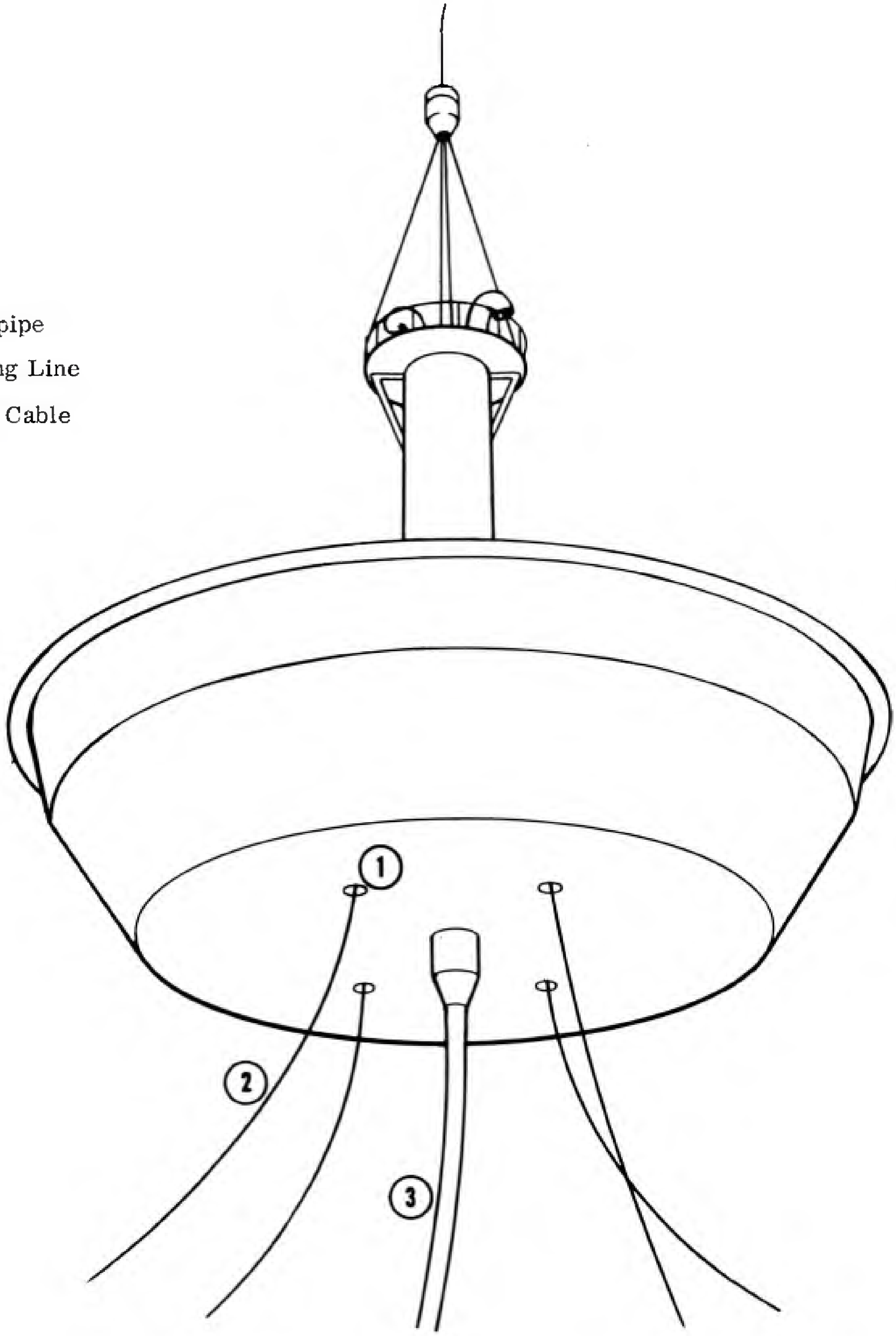


Figure 10-7. Four-Point Moor Accommodations on Surface Buoy

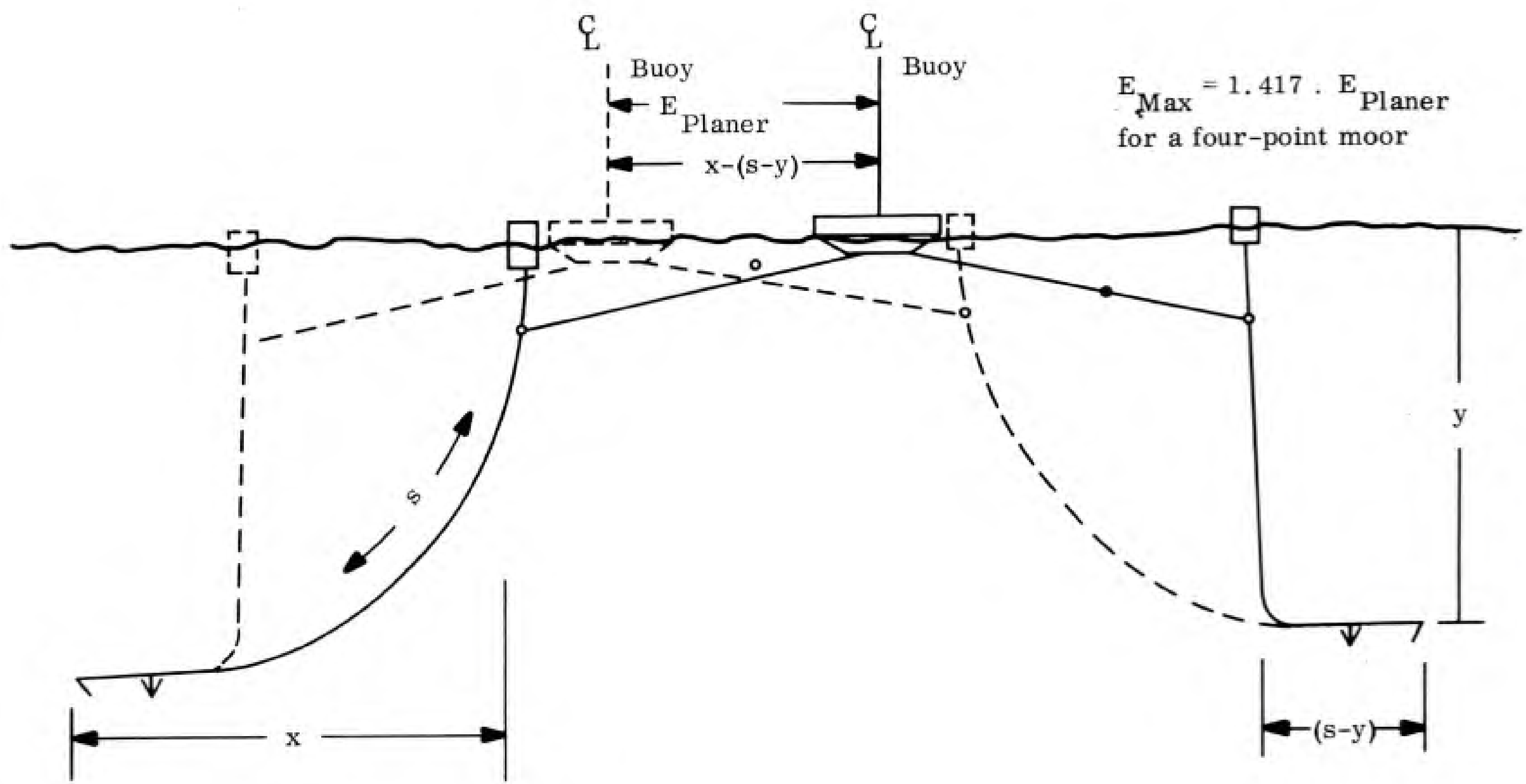
In establishing a moor either the HLS or the SS may be used to tow the buoy to the site. The HLS has aboard and rigged all the tackle necessary to set leg #1 of the moor (see Figure 10-8). The SS is used to carry the tackle for the remaining legs with the exception of the heaviest gear (e.g., clumps and anchors) which are stowed on board the HLS to avoid the hazards of at-sea transfer. The SKS should be a stable platform, preferably capable of acting as a backup HLS or SS. All three ships should be equipped with thrusters and precise station-keeping navigational equipment.

Upon arriving at the site the SKS should establish and record the site geography so that it can be compared with the results of the prior site survey. The SKS should then position itself at the center of the moor and the SS should take up a position, preferably 90° relative to the HLS. The HLS should then position itself over the leg #1 anchor location (approximately 2350 ft from the center for 6000 ft depths). The HLS commences laying leg #1 of the moor. Once the lower rig tackle is in the water, wire ropes are added to the anchor rode as necessary. The tackle is lowered slowly to prevent the effects of wave surge or emergency stops from overtaxing the wire rope. Once the anchor has bottomed, the HLS should proceed very slowly towards the center of the moor to prevent the clump from landing on the anchor. When the clump bottoms, hoisting weight will be sharply reduced and the HLS should steam toward the SKS using its thrusters to compensate for set and drift and to prevent paying out excessive wire rope.

Before it reaches the location of the catenary support buoy (CSB), the HLS stops the cable to set the anchor, exercising caution to apply enough strain to lift the clump and develop an anchor-holding force but not enough strain to part the cable. When the anchor is set, the HLS proceeds to CSB location, paying out the remaining cable required to complete the mooring leg catenary. A swivel and terminal connection are then attached to a ground ring. Based on past experience, final at-sea computations will be required to establish the exact location of the catenary terminal point. The CSB vertical support cable (100 ft of 1-3/8 inch wire at 600-ft depths and 200 ft of 1-1/2 inch wire at 6000-ft depths), a hoisting painter of the same length, and a 4-inch diameter 2-1 braid nylon line are then attached to the catenary terminal ground ring. The ring is then lowered over the side using the hoisting painter until the bitter end of the vertical support cable is reached. The CSB is then attached to the vertical support cable and lowered into the water where it will gradually assume the mooring leg load. A slight tension should be held on the nylon line while the hoisting painter is attached to the CSB.

When the CSB has been launched, the HLS proceeds to the SKS and transfers the bitter end of the nylon line to the SKS which will hold this and the subsequent lines from other legs of the moor.

It is expected that leg #1 of the moor can be set in one daylight day. After setting leg #1, the HLS will moor alongside the SS and on-load the gear required to set leg #2. This leg is set in a similar manner to leg #1 discussed above and is deployed 180° from the leg #1 anchor. The operations for setting each of the remaining legs are expected to take one daylight day each.



When $y = 600$ ft
$s = 1590$ ft
$x = 1350$ ft

$E_P = 370$ ft

$E_{Max} = 523$ ft

When $y = 6,000$ ft
$s = 10,300$ ft
$x = 8,600$ ft

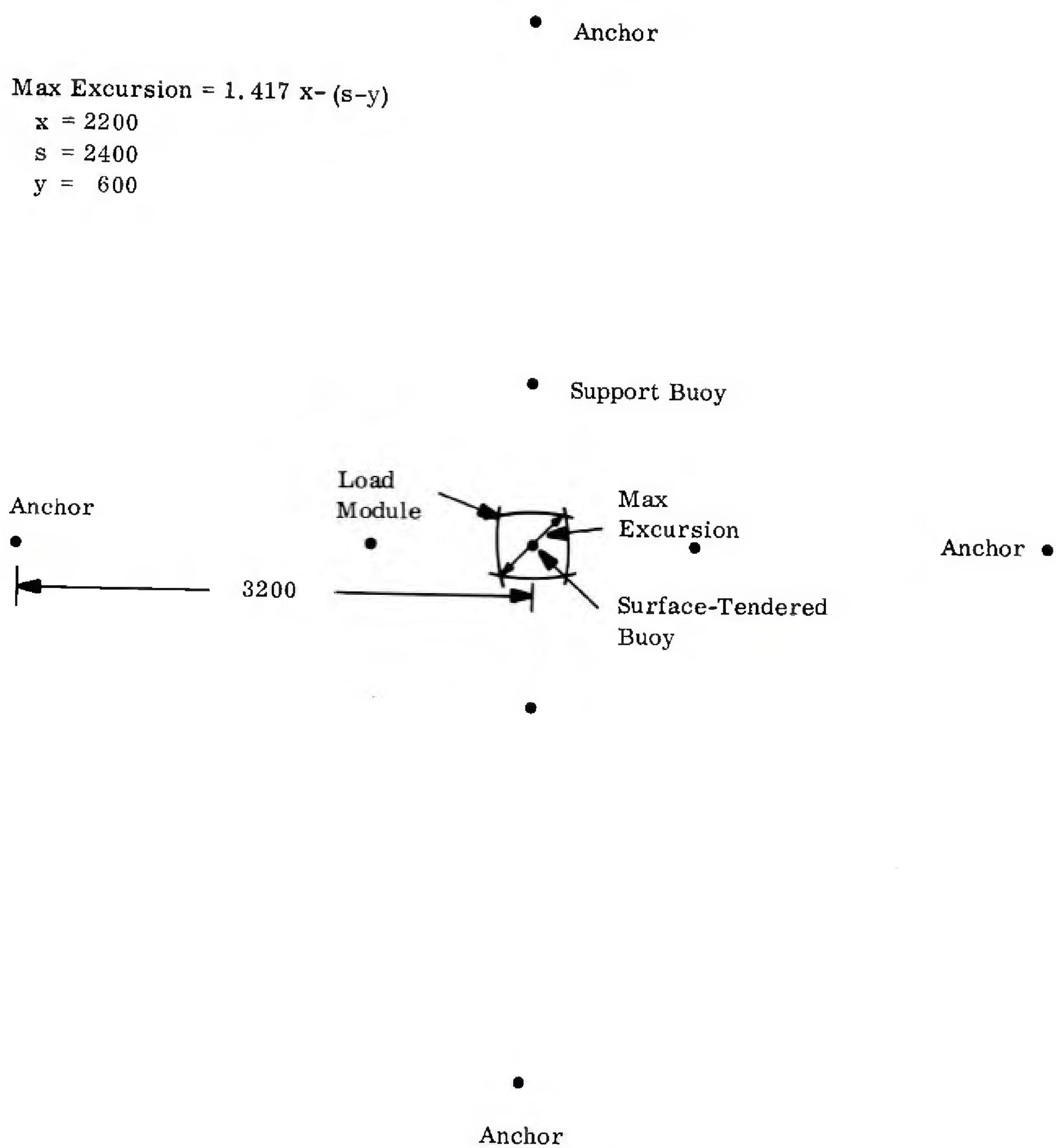
$E_P = 4,300$ ft

$E_{Max} = 6,093$ ft

Figure 10-8. Basic Configuration - Four-Point Moor

When the four legs of the moor have been set, the SS tows the power source buoy to the center of the moor. Wire rope securing cables are then attached to the nylon lines on board the SKS. Painters are then passed down through the hawsepipes in the buoy and are attached by divers to the wire rope securing cables. This done, the securing cables are drawn up through the hawsepipes and made fast to bitts on the buoy deck. The geometry for the two moors is shown in Figures 10-9, 10, and 11a and b.

Figure 10-12 is the major milestone chart for the surface-tendered concept. The schedule is the same for the 600-ft and 6000-ft deployment depths. Table 10-II shows budget cost estimates for the selected surface-tendered plants. These estimates do not include costs of development programs, and are based on standard commercial practices. Transportation and deployment costs are not included.



600 ft Depth Max Excursion 566 ft
Scale 1/2'' = 500'

Figure 10-9. Moor Geometry at 600-ft Depth

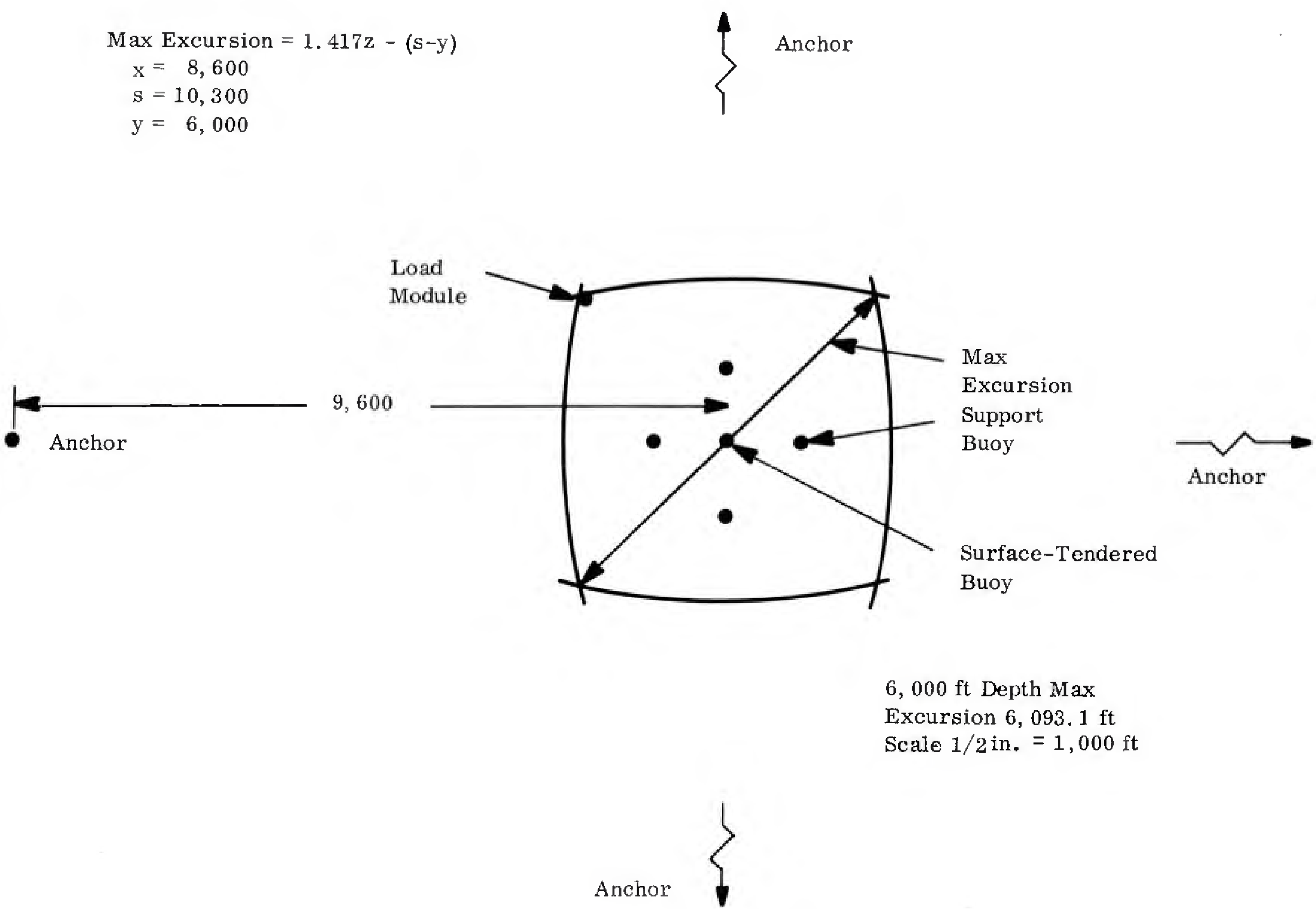


Figure 10-10. Moor Geometry at 6000-ft Depth

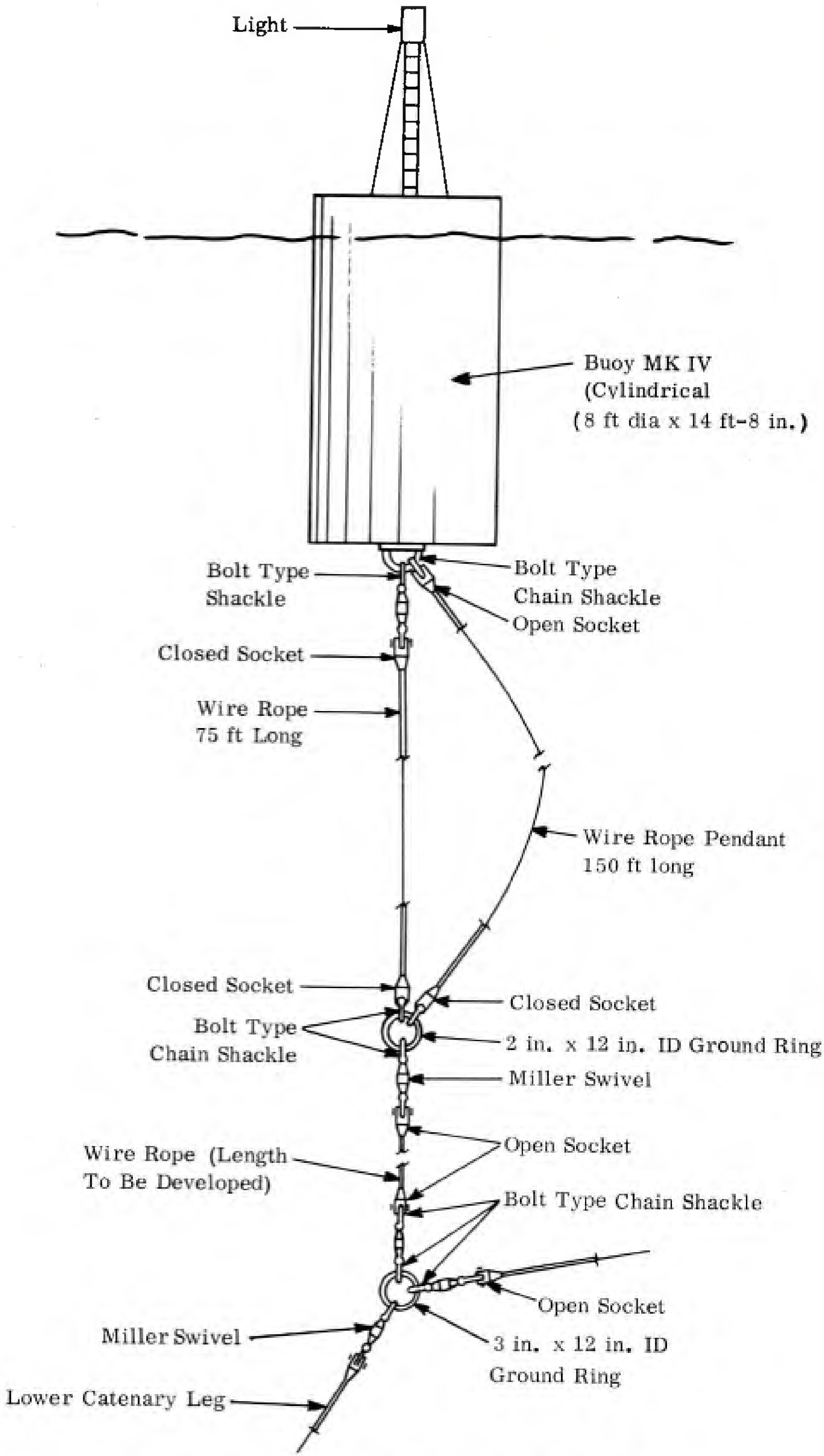


Figure 10-11a. Details of a Buoy and Riser for TOTO II Moor

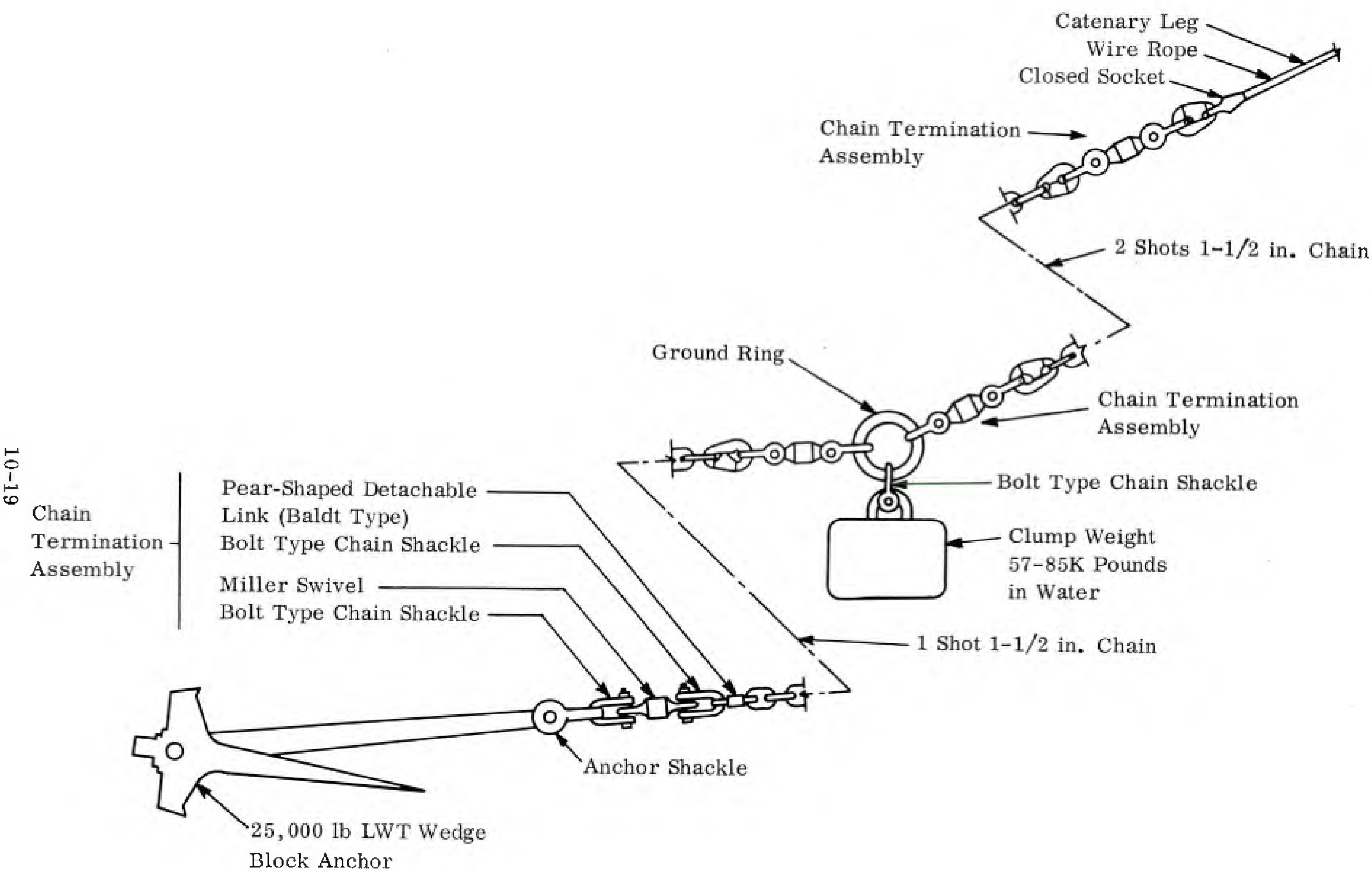


Figure 10-11b Details of the SQUAW Mooring Leg

Table 10-II. Budget Cost Estimates for 30 KW Power Source For Surface-Tendered Concept ($K)

	600 ft	6000 ft
Conceptual Development Engineering	65	75
Contract Guidance Plans and Specification Preparation	110	110
Detail Design, Manufacturing and Test	1.23*	1.64*

*Indicates millions of dollars; all others in thousands of dollars.

10.2 PRELIMINARY DESIGN FOR A 100 KW NUCLEAR REACTOR IN SITU POWER SOURCE MOORED 600 FT BELOW THE SURFACE

The in situ plant consists of a power module, a load module, a suitable foundation, and auxiliary systems and components as shown in Figure 10-13. The power module contains the reactor power plant (primary and secondary systems), the electrical and electronic systems, the cable, and its connectors. The auxiliary systems consist of winches and trim and ballast components. The load module contains the equipment that utilizes the delivered power.

10.2.1 Power Plant

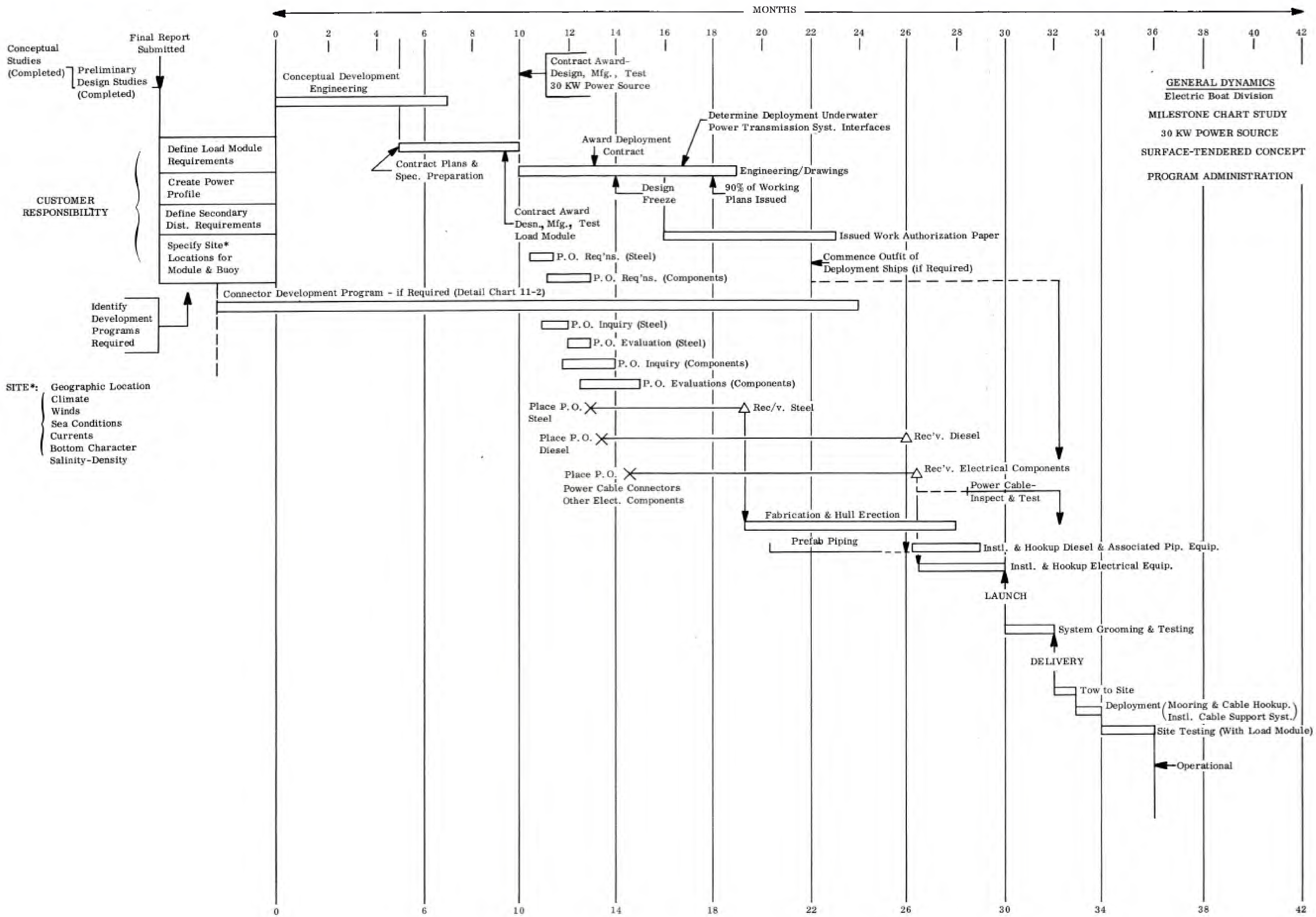
The preliminary designs of the 600-ft and 6000-ft power source systems have identical features and arrangements. The differences are in the hull weight, strength, and the heat exchanger size, and are results of the difference in operating depth - 600 ft versus 6000 ft. Figure 10-14 shows the design concept.

10.2.1.1 DESCRIPTION - The plant consists of a nuclear reactor steam generator and a Rankine cycle turbine generator power conversion system, which provides 100 KW(e) net power. The steam generator is derived from General Atomic's TRIGA Oceanographic Power Supply (TOPS-300) and features light water cooling in a pressurized primary coolant loop.

The secondary steam system provides steam on load demand to a high speed turbine which is geared to a 60-cycle electric generator. The generator supplies power for the plant auxiliary loads as well as the delivered load. Start-up and plant emergency power is supplied by a storage battery.

Power plant equipment is provided for automatic remote start-up and control with provision for manual control during maintenance and servicing.

10.2.1.2 PRESSURE HULL - The general configuration of the pressure hull is cylindrical with external frames and hemispherical heads on each end. The external frames allow a smooth inside surface for use as a heat exchanger. The top hemispherical head is used for all the electrical penetrations and an access hatch.



MONTHS
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42
GENERAL DYNAMICS
Electric Boat Division
MILESTONE CHART STUDY
30 KW POWER SOURCE
SURFACE-TENDERED CONCEPT
PROGRAM ADMINISTRATION
Conceptual Studies (Completed)
Preliminary Design Studies (Completed)
Final Report Submitted
CUSTOMER RESPONSIBILITY
Define Load Module Requirements
Create Power Profile
Define Secondary Dist. Requirements
Specify Site* Locations for Module & Buoy
Identify Development Programs Required
SITE*: Geographic Location
Climate
Winds
Sea Conditions
Currents
Bottom Character
Salinity-Density
Conceptual Development Engineering
Contract Plans & Spec. Preparation
Contract Award- Design, Mfg., Test 30 KW Power Source
Determine Deployment Underwater Power Transmission Syst. Interfaces
Award Deployment Contract
Engineering/Drawings
Design Freeze
90% of Working Plans Issued
Contract Award Desn., Mfg., Test Load Module
Issued Work Authorization Paper
P.O. Req'ns. (Steel)
P.O. Req'ns. (Components)
Commence Outfit of Deployment Ships (if Required)
Connector Development Program - if Required (Detail Chart 11-2)
P.O. Inquiry (Steel)
P.O. Evaluation (Steel)
P.O. Inquiry (Components)
P.O. Evaluations (Components)
Place P.O. Steel
Rec/v. Steel
Place P.O. Diesel
Rec'v. Diesel
Place P.O. Power Cable Connectors Other Elect. Components
Rec'v. Electrical Components
Power Cable- Inspect & Test
Fabrication & Hull Erection
Prefab Piping
Instl. & Hookup Diesel & Associated Pip. Equip.
Instl. & Hookup Electrical Equip.
LAUNCH
System Grooming & Testing
DELIVERY
Tow to Site
Deployment (Mooring & Cable Hookup. Instl. Cable Support Syst.)
Site Testing (With Load Module)
Operational

Figure 10-12

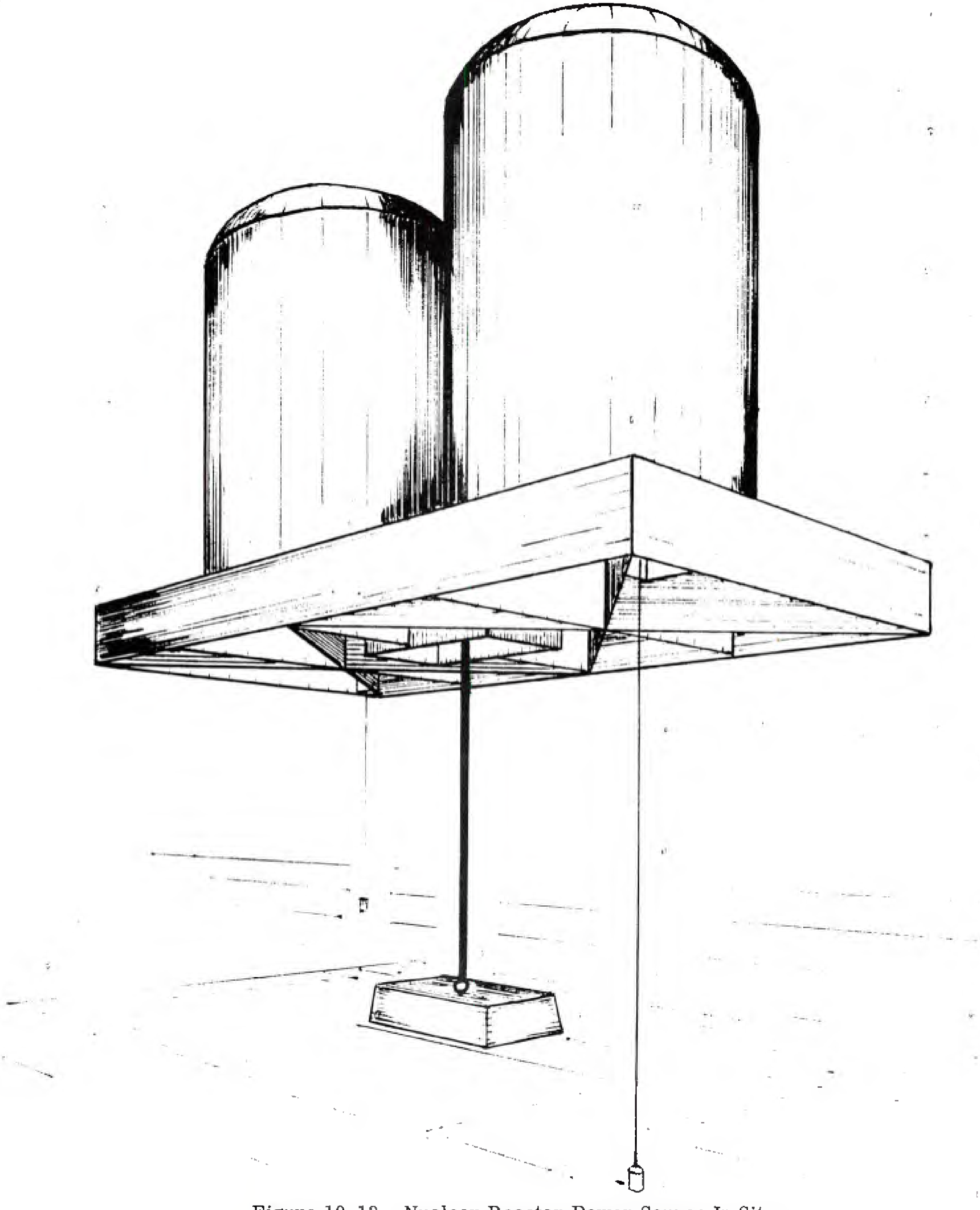


Figure 10-13. Nuclear Reactor Power Source In Situ

Main power, plant monitoring and control, and battery power cable penetrations are required. A number of spare or blank types should be provided for both power and instrumentation. The access hatch may be equipped to receive small submersibles for underwater servicing or maintenance of the power plant. A note of caution should be observed; that is, a plant sealed for a period of time may have radiation levels that are hazardous to personnel attempting access. This area requires additional study.

A bolted hemispherical top has certain advantages for the replacement of large equipment and refueling of the reactor. An alternate to the bolted head could be a large access hatch. However, an access hatch equipped to receive a small submersible is limited in size. A more complete analysis of equipment sizes is required to establish the better approach.

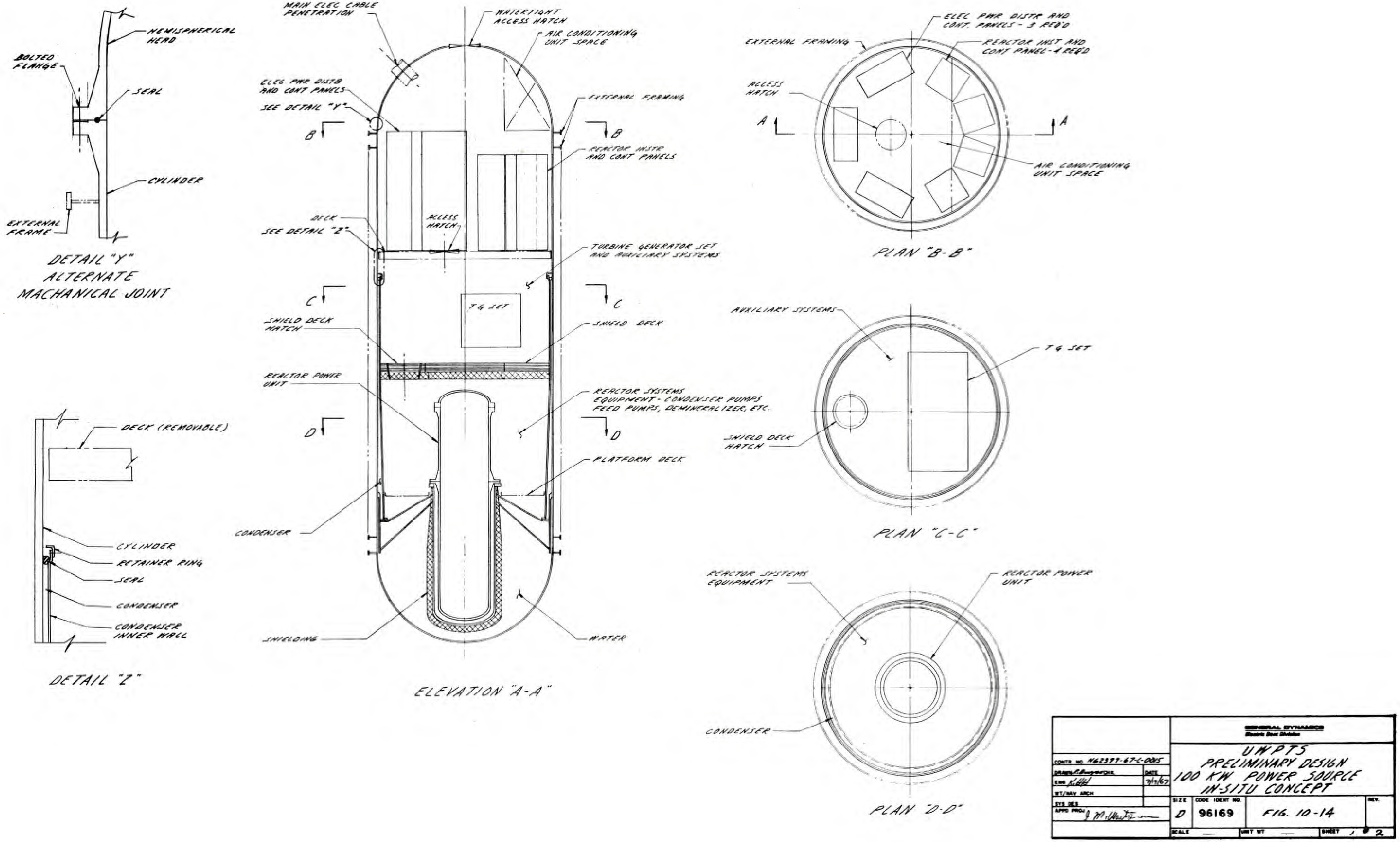
The pressure hull for the 600 ft operating depth has been estimated for HTS and a minimum of 1/2-inch plate. The 6000 ft operating depth hull has been estimated for HY-130. Typical hull design dimensions are shown in Figure 10-15. These hull estimates include factors of safety of at least 1.5 on yielding and 2.0 on buckling.

By increasing hull weight 10%, the pressure hull cylinder has been designed for use as a heat exchanger. This percentage was estimated from calculations performed on a similar hull with a higher heat flux and temperature gradients. Final design will require coordination of the stress and heat transfer characteristics as related to frame design and obtaining minimun weight.

10.2.1.3 MACHINERY WEIGHT ESTIMATES - Estimated power plant weights are shown in Table 10-III. All weights are conservatively estimated. The shield and structural steel weights combined are approximately 2/3 of the total. These weights are interrelated as the structural steel contributes to radiation attenuation. The shield is also contoured to take advantage of longer attenuation paths due to slant angles. The conservative weight estimate insures that considerations of the weight effect on deployment are adequate. Substantial changes in the total weight are not anticipated as the design is finalized.

Table 10-III Preliminary Reactor Power Plant Weights

COMPONENT		WEIGHT
Shielding		
Lead		35,000
Polyethylene		3,500
Water		20,000
Reactor and Structural Steel		35,500
Machinery and Equipment		28,000
	Total	122,000


BOLTED FLANGE
HEMISPHERICAL HEAD
SEAL
CYLINDER
EXTERNAL FRAME
DETAIL "Y" ALTERNATE MACHANICAL JOINT
DECK (REMOVABLE)
CYLINDER
RETAINER RING
SEAL
CONDENSER
CONDENSER INNER WALL
DETAIL "Z"
MAIN ELEC CABLE PENETRATION
WATERTIGHT ACCESS HATCH
AIR CONDITIONING UNIT SPACE
ELEC PWR DISTB AND CONT PANELS
SEE DETAIL "Y"
EXTERNAL FRAMING
REACTOR INSTR AND CONT PANELS
DECK
SEE DETAIL "Z"
ACCESS HATCH
TURBINE GENERATOR SET AND AUXILIARY SYSTEMS
T G SET
SHIELD DECK HATCH
SHIELD DECK
REACTOR POWER UNIT
REACTOR SYSTEMS EQUIPMENT - CONDENSER PUMPS FEED PUMPS, DEMINERALIZER, ETC.
PLATFORM DECK
CONDENSER
SHIELDING
WATER
ELEVATION "A-A"
EXTERNAL FRAMING
ELEC PWR DISTR AND CONT. PANELS - 3 REQ'D
REACTOR INST AND CONT PANEL - 4 REQ'D
ACCESS HATCH
AIR CONDITIONING UNIT SPACE
PLAN "B-B"
AUXILIARY SYSTEMS
T G SET
SHIELD DECK HATCH
PLAN "C-C"
REACTOR SYSTEMS EQUIPMENT
REACTOR POWER UNIT
CONDENSER
PLAN "D-D"
GENERAL DYNAMICS
Electric Boat Division
CONTR NO. N62399-67-C-0015
UWPTS
PRELIMINARY DESIGN
100 KW POWER SOURCE
IN-SITU CONCEPT
SIZE D
CODE IDENT NO. 96169
FIG. 10-14
SHEET 1 OF 2

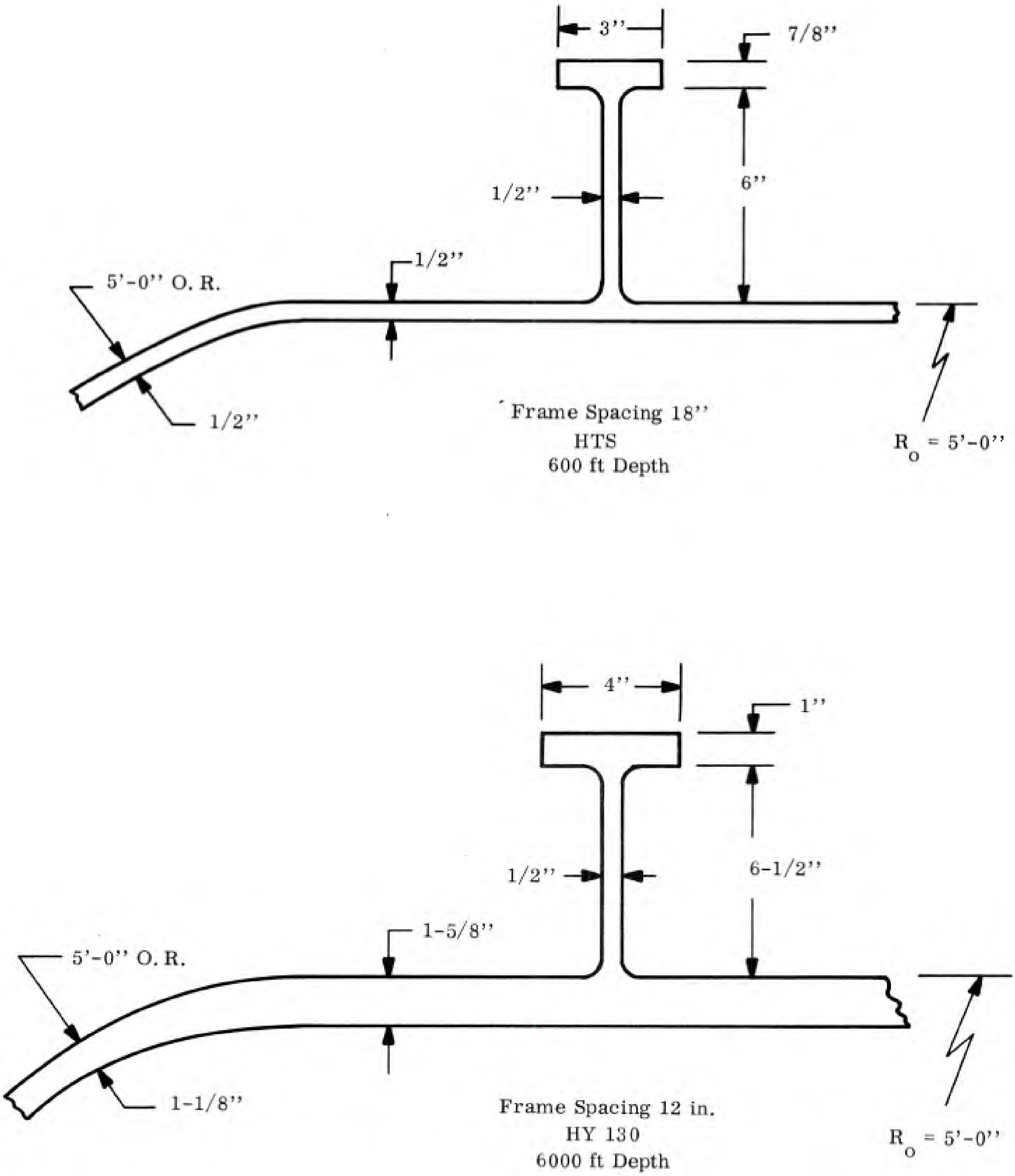


Figure 10-15. Typical Pressure Hull Designs

10.2.1.4 ARRANGEMENTS - The arrangement of the power plant is shown in Figure 10-14. It is the same for both operating depths, 600 and 6000 ft. The pressure hull is used for condensing steam. Preliminary characteristics are listed in Table 10-IV. Power equipment, except the batteries, is enclosed in a cylindrical pressure hull with hemispherical ends. Normal operation is with the axis oriented vertically, however, full power may be obtained when tipping 15° from the vertical. During transportation the power plant may be almost horizontal.

Table 10-IV Preliminary Power Plant Characteristics

100 KW(e)

OPERATING DEPTH, ft	600	6000
Outside diameter (less frames), ft	10	10
Length overall, ft	36 1/2	36 1/2
Hull Material	HTS	HY-130
Hull weight, lbs	34,000	93,000
Machinery weight, lbs	122,000	122,000
Total weight, lbs	156,000	215,000
Displacement, lbs	166,500	166,500
Buoyancy, lbs	+10,500	-48,500

The lower portion of the pressure hull contains the reactor, its auxiliary systems and shielding, the secondary system condensate and feed pumps and fresh water cooling system. The mid-section contains the turbine generator and its auxiliary systems. They are separated from the lower compartment by a shield deck, through which there is limited access while operating. The upper level contains all the electrical and electronic equipment, the power plant control equipment and cabinets, the primary distribution equipment, sonar if required, and the instruments and cabinets for the transmission control circuitry. Also located in the upper level is an air conditioning unit for temperature and humidity control. In the upper hemispherical head are the access hatch and cable penetrations. The upper head is attached by welding or bolting (to be evaluated).

Batteries for power plant start-up and standby power are located external of the hull to avoid the potential of hydrogen buildup in the hull.

A cylinder inside the pressure hull forms the steam condenser. This cylinder supports almost all of the equipment in the mid section. To prevent pressure hull deflections from disturbing the equipment, the cylinder meets the hull only through a flexible skirt at the upper end of the cylinder. The bottom end of the cylinder is fastened to the shield tank structure. To preserve the cylinder's flexiblility, the deck above the cylinder is connected to the shield deck by stanchions.

This inner cylinder provides a structure on which the complete power plant may be assembled, tested and installed within the pressure hull without disassembly. It should be noted that, prior to installation, operating time and power level may be limited to the amount of residual radiation which would not prohibit handling during installation. Subsequently, as refueling or maintenance is required, the inner cylinder with the two deck levels may be detached and removed as a unit.

The plant operating at 600 ft may use a conventional shell and tube exchanger as a condenser. The greater reliability of the pressure hull heat exchanger as a passive system appears to offset any economic gains, and potential weight savings are not required for positive buoyancy.

10.2.1.5 RADIATION DOSE RATES AND SHIELD ESTIMATES - The maximum radiation levels for the power plant are tentatively established as shown in Figure 10-16. These levels are based on limited access to the area above the shield deck for servicing and maintenance up to full power. The tolerance in hours per day is based on continuous occupancy and meeting AEC regulations of not exceeding 1-1/4 rem per calendar quarter. As the plant will not be manned regularly, occupancy times can only be predicted, therefore maximum permitted radiation level may be lower than necessary. As manning times become better defined, it may be possible to allow higher radiation levels, which would permit a reduction in shield weight. Portable shielding may be used for in-port or surfaced conditions.

Primary shielding, which is lead and shield tank water, is designed to permit limited access to the exterior of the pressure hull after the reactor is shut down (30 days). This will allow inspection and maintenance during the normal drydocking period. Therefore, dose rates during operation will be high in the water surrounding the reactor compartment. Deployment in shallow water where divers may have access will require a protective screen. Manned installations adjacent to the plant will have to make allowances for the radiation and provide for distance and material attenuation of the radiation. Neutron flux levels are negligible at 10 ft or more in water from the reactor centerline. However, gamma radiation will require added material or somewhat longer distances. Special shielding should be designed for each particular application where required.

Shield requirements have been conservatively estimated on the basis of preliminary calculations to obtain approximate shield arrangements and weights. The final design will minimize weight or dose rate consistent with cost and incorporate the effect of structural details.

10.2.1.6 CONTAINMENT PROVISION - The necessity for incorporating a special containment vessel for this power plant has not been firmly established. The functions of such a vessel would be to (1) protect the pressure hull from overstress caused by thermal gradients resulting from secondary steam or primary coolant relief valve lifting or primary coolant system leakage or rupture; and (2) to provide additional protection against the release of fission products to the outside atmosphere.

Whether or not a containment vessel is needed depends on the thermal stress gradient across the hull which would result from a primary leak. The gradient has not been calculated, but, if a containment vessel is required, an appropriate vessel can be provided by modifying the present arrangement to use the inner cylinder, closing off

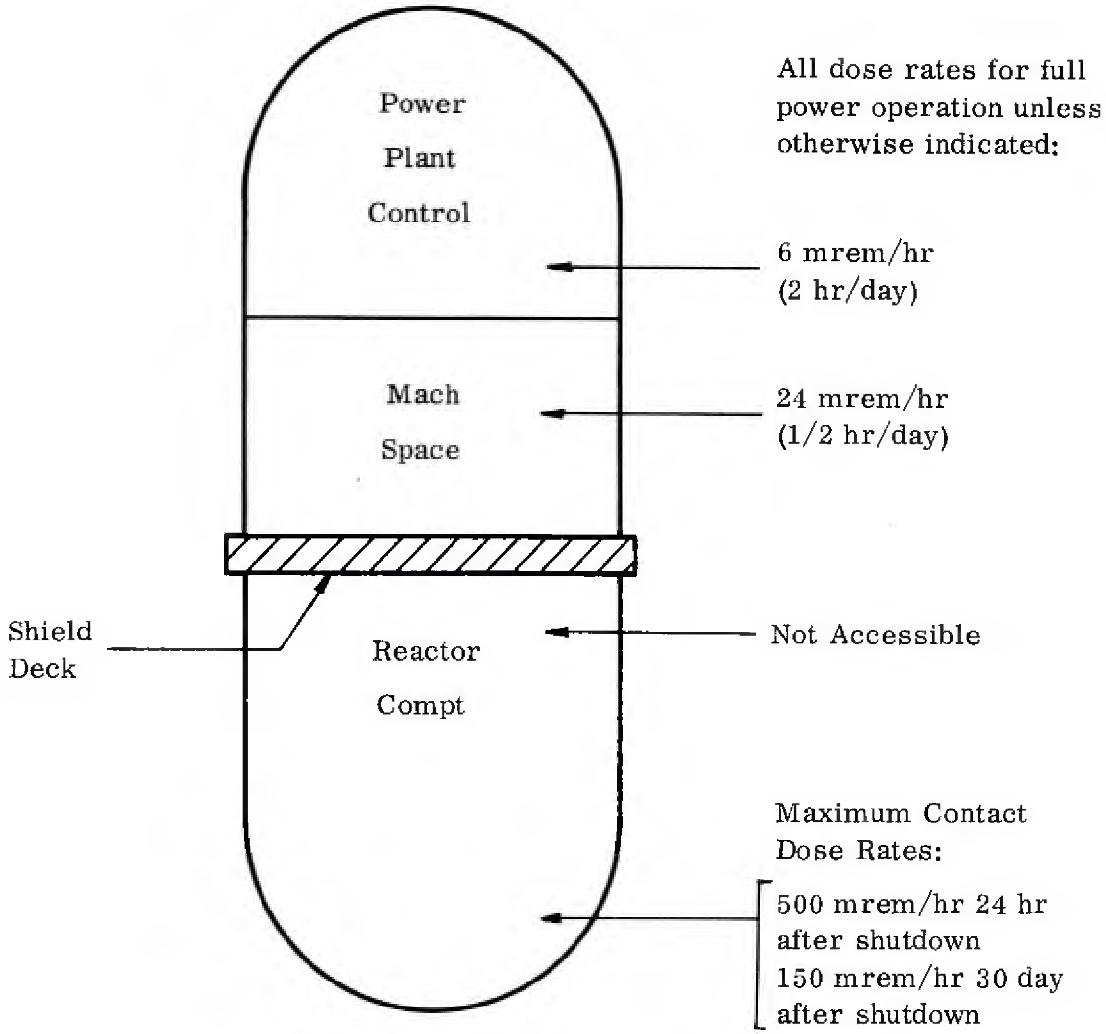


Figure 10-16. Maximum Radiation Levels

the upper end of it. Weight increases would be small; however, fabrication complexities may be significantly increased.

If a special containment vessel is not required, there are still three barriers to fission product release. These are fuel element cladding, primary coolant pressure vessel, and pressure hull. The most disastrous event would be collision at the reactor location by a vessel with sufficient displacement and speed to penetrate to the fuel elements. This type of disaster is highly improbable.

The requirement for a special containment vessel does not appear to exist. With this compact power plant arrangement, additional protection against collision that would be obtained from a minimal design containment vessel is marginal.

10.2.1.7 POWER CONVERSION SYSTEM - The power conversion system has a single turbine generator with a main steam, a condensate, a feed, an auxiliary steam, a makeup water and a purification system. Full capacity redundant condensate and feed pumps are provided for improved reliability.

Figure 10-17 shows the power conversion system flow diagram. Superheated steam is obtained from dual full capacity once-through steam generators. Steam flow is through a stop valve and is controlled to the turbine by a throttle valve which is governor regulated to control speed. The stop valve is closed automatically to protect against overpressure, overspeed, or loss of lubrication. Exhaust steam is condensed in the annular hull condenser and recycled through a full flow demineralizer to maintain water purity for the once-through steam system. Preliminary power conversion system data are shown in Table 10-V. Figure 10-18 shows the full power heat balance.

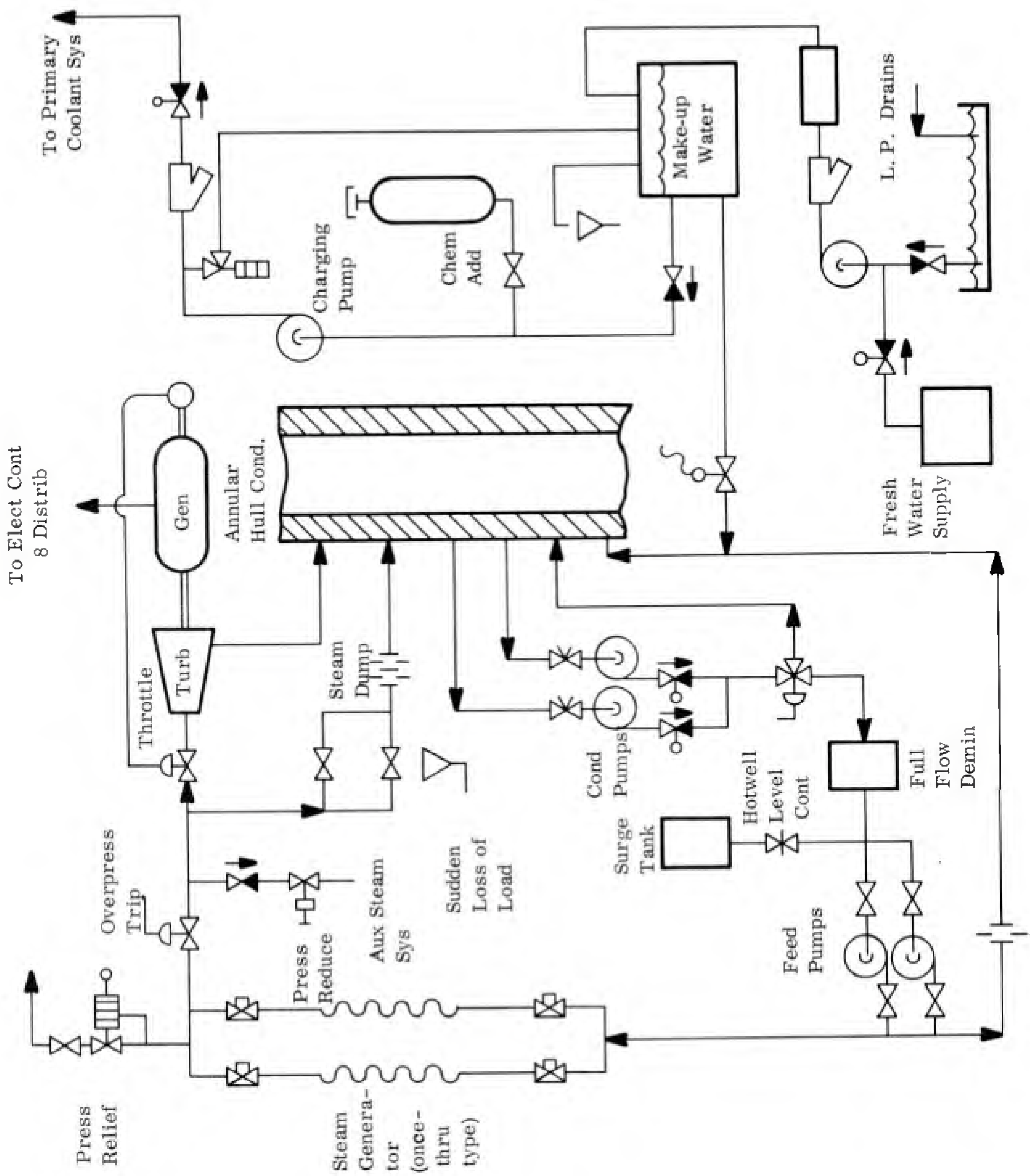


Figure 10-17. Preliminary Power Plant Conversion System Data

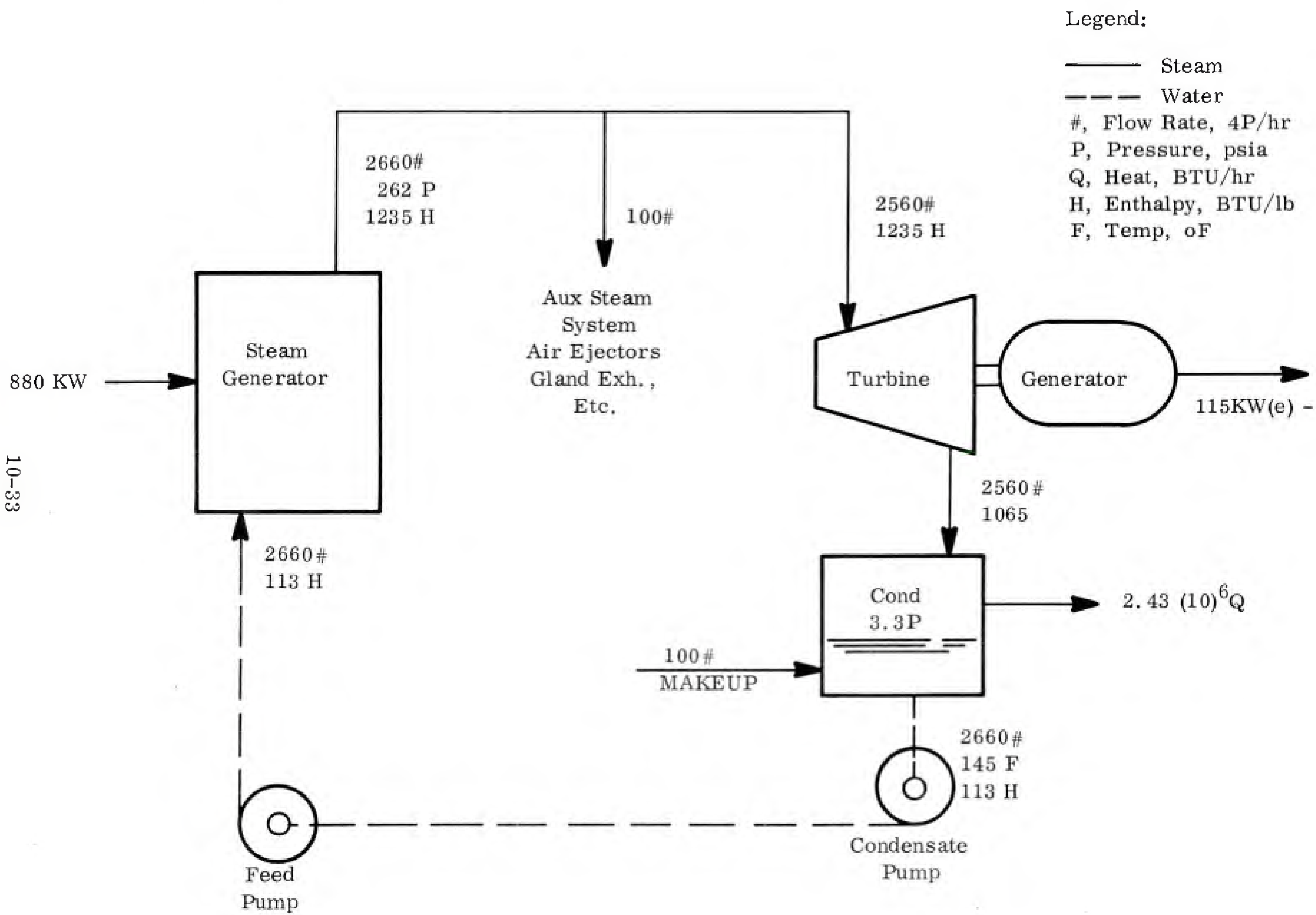


Figure 10-18. Preliminary Full Power Heat Balance

Table 10-V Preliminary Power Conversion System Data

General	
Electric power (net), KW	100
Overall efficiency, %	11.4
Thermal power, KW	880
Steam Cycle	
Turbine inlet pressure, psia	262
Turbine inlet temperature, $^{\circ}F$	455
Turbine inlet superheat, $^{\circ}F$	50
Turbine exhaust pressure, psia	3.3
Turbine steam flow, lb/hr	2560
Turbine steam consumption, lb/bhp-hr	15.0
Turbine	
Speed, rpm (estimate)	13,000
States (estimate)	4 - 5
Efficiency, %	56
Thermal efficiency, %	15.1
Generator	
Type drive	Gear
Speed, rpm	3600
Power, KW(e)	115
Voltage, volts	480
Frequency, cps	60
Phases	3

10.2.1.8 CONDENSER - The condenser is formed by making a space between the pressure hull and an inner cylinder. A tentative annulus of 3/4 in. will allow for pressure hull deflection of about 5/32 in.as well as for irregularities in fabrication, etc. As shown in Figure 10-14, the lower end may be rigidly attached (bolted or welded). The upper end is attached to the hull, but only by a flexible seal whose purpose is to avoid loading the inner cylinder with sea pressure deflections of the pressure hull. The seal has both advantages and disadvantages. The vacuum in the condenser tends to force the seal in between the inner cylinder and pressure hull. It is restrained from going in only by its size and the width of the annulus, which decreases at the seal because of the inner cylinder design. This arrangement will be self-relieving should the pressure in the annulus rise above the internal ambient. If necessary, a spring-retaining device may be incorporated. The inner cylinder should be flexible enough to permit relatively low gasket forces to deflect it into the same shape as the pressure hull. As an alternate scheme, a reinforced diaphragm seal may be mechanically fastened to both the inner cylinder and pressure hull.

Preliminary data for the pressure hull condenser is shown in Table 10-VI. Sea water circulation is by natural convection. Adequate hull surface is available with natural convection to provide both the steam condensing surface and hot well at the base for maintaining adequate head on the condensate pump. Although forced convection would result in a smaller area and might reduce fouling, the requirement for a pump at ambient sea pressure and the problems of shrouding the hull make it a less reliable system. The minimum pressure hull size for these power plants is determined by the equipment volume required and not heat transfer area. However, the 6000-ft power plant cannot have adequate head transfer for operation at full power in 85°F sea water without increasing the hull size. Preliminary estimates indicate that operation up to 2/3 of full power at 85°F and full power at 75°F sea water are possible with the present hull size. The 600-ft power plant with a thinner hull will be capable of full power at 85°F.

Table 10-VI Preliminary Condenser Data

Operating depth, ft	600	6000
Sea water temp., °F (max)	75	55
Condenser temp., °F	145	145
Condenser heat, BTU/hr	$2.43\ (10)^6$	$2.43\ (10)^6$
Heat transfer coef., BTU/hr ft^2°F	75	52
Pressure hull area, ft^2	480	520
Hull length, ft	15.3	16.5

10.2.1.9 FRESH WATER COOLING SYSTEM - The fresh water cooling system diagram is shown in Figure 10-19. This system provides cooling for the air ejector and gland exhaust condenser, turbine-generator lube oil and air cooler, reactor plant auxiliary systems, and machinery spaces. Fresh water is circulated through the fresh water cooler, heat exchanger where heat is removed. The cooled water is then distributed to the various coolers. Machinery space cooling is required as the hull condenser effectively insulates these spaces. Heat is transferred from the fresh water to the shield water by a shield water circulating system. Final rejection of the heat is through the pressure hull to naturally circulating sea water.

Shield water would be used directly to provide the fresh water cooling functions if it could be made sufficiently free of radioactivity. However, both rust inhibitors and corrosion products will become slightly radioactive and would cause difficulties in system maintenance, particularly when the plant is deployed.

The total fresh water heat load is estimated to be less than 250,000 BTU/hr. Additional heat loads are received by the shield tank from reactor conduction losses and radiation absorption resulting in a total shield tank load estimated at less than 300,000 BTU/hr. Adequate pressure hull area is available to remove the heat load within a satisfactory temperature rise.

10.2.1.10 AIR CONDITIONING - A relatively warm interior is possible using a major portion of the pressure hull for heat transfer. However, humidity will be high because of the large number of water and steam systems. To maintain a reasonable temperature and humidity for the power plant electronic and control equipment, the upper level is thermally insulated from the rest of the plant, and an air conditioning unit is installed. Heat loads are expected to be relatively small; a forced convection cooler using water circulating against the pressure hull may be able to provide adequate

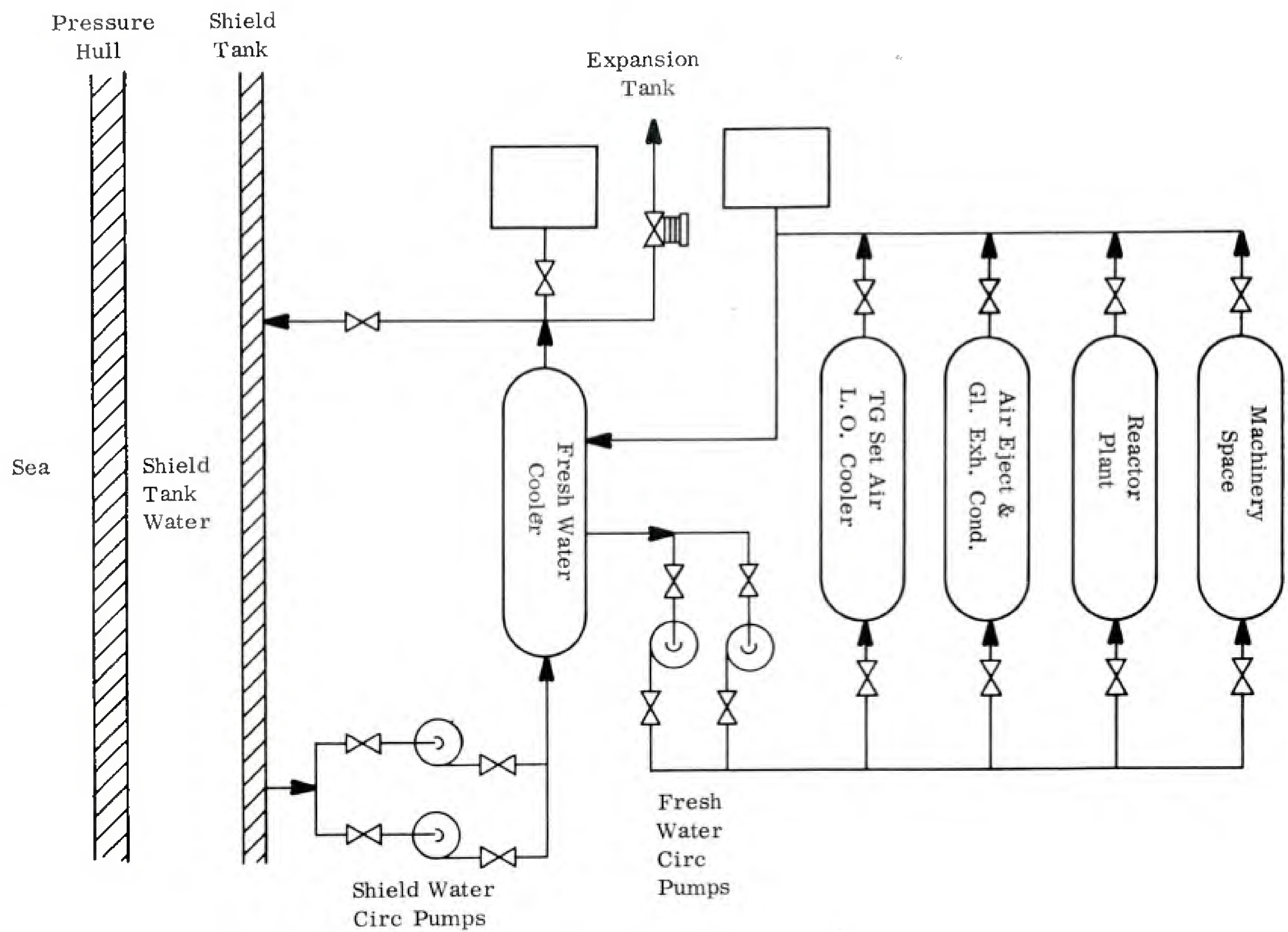


Figure 10-19. Preliminary Fresh Water Cooling System Diagram

cooling. Powered units employing thermoelectric devices or conventional refrigeration cycles may be used if required. In addition to equipment protection, the system makes the space more habitable for maintenance.

To prevent condensation dripping on the equipment, the pressure hull in the upper level will be lightly insulated. Coolant circulation against the hull may be by channeled plastic sections.

10.2.1.11 BATTERY SUPPLY - A pressure-compensated battery supply located outside the pressure hull supplies power for power plant startup, monitoring and standby, deployment and recovery operations, and emergency power. The power plant will be operated only while in position or as testing requires and thus will not be available for use during deployment or recovery. Inadvertent release of the power plant from the bottom will automatically shut the systems down requiring emergency power for navigation lights and a signaling device. The total energy for the power plant requirements is estimated not to exceed 15 KWH with approximately 5 KWH allowed for plant startup. The battery type selected will reflect the total requirements as to energy capacity, weight and volume constraints, operational frequency, and system reliability and cost. A charging system is included to automatically maintain the battery at full charge.

10.2.1.12 COMPONENT ENGINEERING AND DEVELOPMENT - The availability of equipment and the amount of engineering design and testing required will depend on the component specifications (material, functional, reliability, and regulatory) required. They also will have a major bearing on the cost and the schedules. Although a major equipment development program may not be required for the power conversion systems, major components as the turbine generator and feed pump may not be off-the-shelf items. The turbine generator estimates are extrapolated from figures for a larger machine. Lower efficiency single-stage machines are available in the low power range, but would require substantial increases in the steam condenser size as well as more frequent refueling. Water chemistry of the once-through steam system will place some constraints on component materials selection.

The heat transfer problems for the large depths should be resolved as recommended in Chapter 11. Condensing exhaust steam from the turbine is of major importance. The use of the pressure hull as a condensing surface is dependent on developing satisfactory solutions to the protection of the hull and without serious penalty to the heat transfer coefficient. Protection must be provided on both the interior and exterior surfaces. Metallic coatings appear to provide a solution, but these have not been adequately tested. In addition test data should be obtained on both the steam and sea water coefficients including the effects of hull geometry (frames) to determine the interrelations between strength-to-weight ratio, heat transfer, and thermal stress. Means for de-super heating steam external of the condenser must also be found if steam dumping is required.

10.2.2. <u>Electrical Systems</u>

The electrical system selected produces a power level of 100 KW. This is transmitted without transformers from the power module to the load module at 480 volts, 3-phase, 60 cycles via a 3-conductor, shielded, grounded neutral, armored submarine cable.

Sized according to ampacity, the cable is made of 3 American Wire Gage (AWG) #4 conductors. The transmission system in all cases terminates in multipinned connectors at the load module.

The power module will be equipped with three sections of switchgear. Located on level-1 as shown in Figure 10-14, these sections house devices for instrumentation, protection, monitoring control and recording, plus the one main circuit breaker. In this particular installation there are redundancies in the control, protective and instrumentation systems; these are carried back to the load module, providing duplicate monitoring and control in both the power and load modules. This control capability is transferred from the power module to the load module via a multi-conductor control cable.

The load module contains a two-section switchgear unit for housing the duplicate instrumentation, protective equipment and control ability as well as the control instrumentation and protective equipment for the load module. The sizes, weights, and volumes of the required equipment for a 100 KW system have been shown in Chapter 9.

10.2.3 Control and Protective System

The protection of the overall system and subsystems has been defined in Chapters 6 and 9, however, the philosophy is restated as follows:

> The system will be kept in operation until such time as loss of equipment is inevitable. Then the system will shut down. It will also shut down for loss of control power if both AC and DC sources are lost due to open or shorted circuits or other.

The protection system will be selected and tailored to the installation, providing the operating means and the selectivity developed in the philosophy. Currently, the system includes standard percentage differential relay circuitry for the generator, a differential zone which includes the cable from the power module to the load module, fuses protecting both the AC and DC control power sources, and provision for protection of the generator exciter circuitry. Later,when the mission is more clearly defined and it can be established that the load module will be manned or unmanned, the system may change. In the case of a manned station, as has been assumed for this station, life support and emergency systems will have to function to sustain life until rescue is available or the whole unit may be provided with automatic surfacing ability. In the case of an unmanned station, the system will not be required to sustain life.

Control power will be provided from an AC transformer connected to an open delta mounted in the switchgear unit of the power module and energized between the generator and the main circuit breaker to insure control power source. The transformer will be protected by fuses in both primary and secondary sides. In case of failure of this system, control power will be instantaneously switched to the battery source. If both systems are lost due to circuit conditions or other, the plant will shut down.

10.2.4 Cable Systems

The recommended systems will operate at alternating current, 3-phase, 60 cycles, using a submarine type cable as defined in Chapter 5. The cable size is AWG #4 based on ampacity requirements. The method of installation of the cable between power and load module will depend on the conditions of deployment and the distances between the power modules. When these conditions have been defined, then considerations such as cable droop and the forces exerted on the cable connectors may become problems when the distance between modules is greater than 20 feet. One solution to the problem of cable droop is to provide an eye in the cable fitting at the hull for attaching a messenger cable between the two modules. This cable would be used to support the power and control cables. There should be one installed for each penetration. The messenger will be selected from suitable material to prevent the problem of dissimilar metals as well as to provide the suspension required. The support saddles from the messenger to either the power or control cables will be selected similarly.

10.2.5 Deployment

For this preliminary study, it is assumed that a load module will have the characteristics shown in Table 10-VII. For comparison, equivalent power plant also will be given.

Table 10-VII. Typical In Situ Plant Characteristics

CHARACTERISTICS	ASSUMED LOAD MODULE 600 ft	ASSUMED LOAD MODULE 6000 ft	POWER PLANT 600 ft	POWER PLANT 6000 ft
Containment Hull Configuration	Vert Cyl	Vert Cyl	Vert Cyl	Vert Cyl
Diameter (ft)	10	10	10	10
Height (ft)	36.5	36.5	36.5	36.5
Weight in air (lb)	104000	168000	156000	215000
Displacement in water (surf) (lb)	166500	166500	166500	166500
Net Buoyancy ± (lb)	+ 62500	-1500	+10500	-48500
Center of Gravity (assumed) w/r bottom of vert cyl	1/3 H	2/5 H	1/4 H	1/4 H

Load module missions are assumed as follows.

600 ft	6000 ft
Oil well head pumping station	General Oceanographic combined with Military Undersea Station (MUS)

The 4 key in situ plant characteristics having been defined, the overall plant configuration was selected as follows:

- Power level (100 KW) – This is a vertical cylinder configuration for the power plant.
- Load module dimensions – Vertical cylinder, 10 ft diameter x 36 ft high. Assume this was partly based upon most efficient internal space utilization.
- Load module weight – Since it is similar to power plant weight, it makes the twin vertical cylinder approach possible. In the case of the well head, the major portion of the weight would be in the large electric motor and pump. In the remote undersea station, it is assumed that the weight comprises a slightly heavier hull, minor lead shielding, and a large motor generator set.
- Load module task definition – In the case of the well head, it is required that the load module be adjacent to the ocean floor. In the case of the undersea station, it is assumed that a portion of the station also must be close to the floor for oceanographic observations of marine life and seismic detection.

To satisfy both of the assumed task definitions, it will be desirable to pinpoint the location of the plant on the ocean floor. This will require a forced ascent-descent (winch-down) deployment recovery concept. The anchor may be located on the bottom simply by using soundings in conjunction with a leveling device, or by a more elaborate method employing a remote television camera mounted on the anchor cable. In the latter case, the camera, lights, and lead wires would be attached to the anchor cable close to the anchor. The anchor would be lowered close to the bottom. Lights and camera would be actuated so the actual plant site could be selected. The anchor could be moved over the bottom from the surface. Once the site is selected the anchor could be lowered the few remaining feet to the bottom. The camera-light assembly could be released by an explosive actuator and returned to the surface. The TV camera method of bottom location probably would be used in the case of the well head, while a bottom-leveling device and surface soundings probably would suffice for the 6000-ft remote station. The in situ plant would not be attached to the cable while the anchor is being located on the bottom. It would be attached to the plant winch drum. Attachment may be accomplished using a simple shackle on the end of a short wire permanently attached to the drum. A suitable recess in the drum may be provided to house this shackle. The alternate of feeding the anchor cable through the constant tensioning-level wind mechanism on the winch is considered undesirable seamanship. The anchor envisioned is a clump type designed for the hard site sediment conditions.

10.2.5.1 - FORCED DESCENT - When the anchor has been placed on site and its cable attached to the winch, the in situ plant may be rigged for descent. The rig-for-descent procedure may be as follows:

1. Power plant primary and secondary systems-secured but rigged for remotely actuated start-up.
2. Winch power (compensated battery) supply energized.
3. Winch-down cable secured to the drum with attachment shackle wound on drum. Inspected by diver. Tension and level wind mechanisms checked; operational and tension monitored.
4. Descent stabilizers rigged for descent.
5. Final ballast and trim adjustment made.

Descent may be started by flooding small main ballast tanks to eliminate surface reserve positive buoyancy. Once the ballast tank is flooded, winch-down is started. The plant will not leave the surface until winch-down is begun because of the positive buoyancy force allotted for the winch to work against. As such, the winch will always work against a constant tension and the station will be positively buoyant. Both are very desirable both from a safety and reliability standpoint.

A bottom-sensing weight will hang approximately 150 to 200 ft below the plant. This weight will decelerate the haul-down winch to a very slow rate of descent. When the plant is on the bottom, a triggering device on the cable will trip a switch causing the winch to stop.

10.2.5.2 EMERGENCY ASCENT PROVISIONS - Emergency ascent provisions are based on retrieving as much of the in situ plant as possible in an emergency. The winch is used for ascent. If the batteries fail or the winch is inoperative, the free ascent method will be used. In this case, there are three possibilities:

The entire plant (power plant, load module and foundation) may ascend as a unit.

The power plant may ascend independently (Figure 10-20).

The load module may ascend independently.

Sequence jettisoning may create a condition in which one component, such as the power plant, comes to the surface followed by the other component, and the second component collides with the first at the surface. This event may be avoided by allowing the most desirable component to automatically surface first and releasing the second component later by a signal after the surface had been cleared. For this preliminary study, it is assumed sufficient to release the power plant and allow it to free ascend to the surface, leaving the remainder of the plant in situ. The ascent rate is critical because the ascending body should not jump out of the water when it surfaces. Flotation material must be securely fastened in order for it to stay on when the upper portion of the power plant drops back in the water. On the surface the power plant will have very little reserve buoyancy because of shielding and head rejection materials.

10.2.5.3 HYDRODYNAMIC ANALYSIS OF AN EMERGENCY POWER PLANT FREE ASCENT - A preliminary analysis of force interaction was conducted to determine the hydrodynamic characteristics of a free ascending-descending body the size of the power plant. This analysis was conducted only on the power plant because it represents the worst possible condition. When the entire plant descends or ascends by winch-down, it will move slowly. Also, if the entire plant makes a free ascent, it will present a greater frontal profile area and consequently experience higher drag forces, thus it too will move slowly.

The 100 KW, 6000-ft in situ nuclear power plant was analyzed as housed in a vertical cylinder 10 ft in diameter and 36-1/2 ft high. A similar analysis could be conducted for the plant at 600-ft depth.

Sample Solution:

Pressure at 6000 ft = 6000 ft x 0.455 lb/ft = 2730 psi

Condition of the 100 KW plant on the surface:

Total Plant Displacement	+ 166500	lbs
Total Plant Weight	- 215000	lbs
Net Negative Buoyancy	- 48500	lbs

$$\text{Total Volume (V)} = \frac{\text{Displacement (D)}}{64.0\ \text{lb/ft}^3\ \text{density of S.W.}}$$

$$V = \frac{166500\ \text{lbs}}{64.0\ \text{lbs/ft}^3}\quad 2600\ \text{ft}^3$$

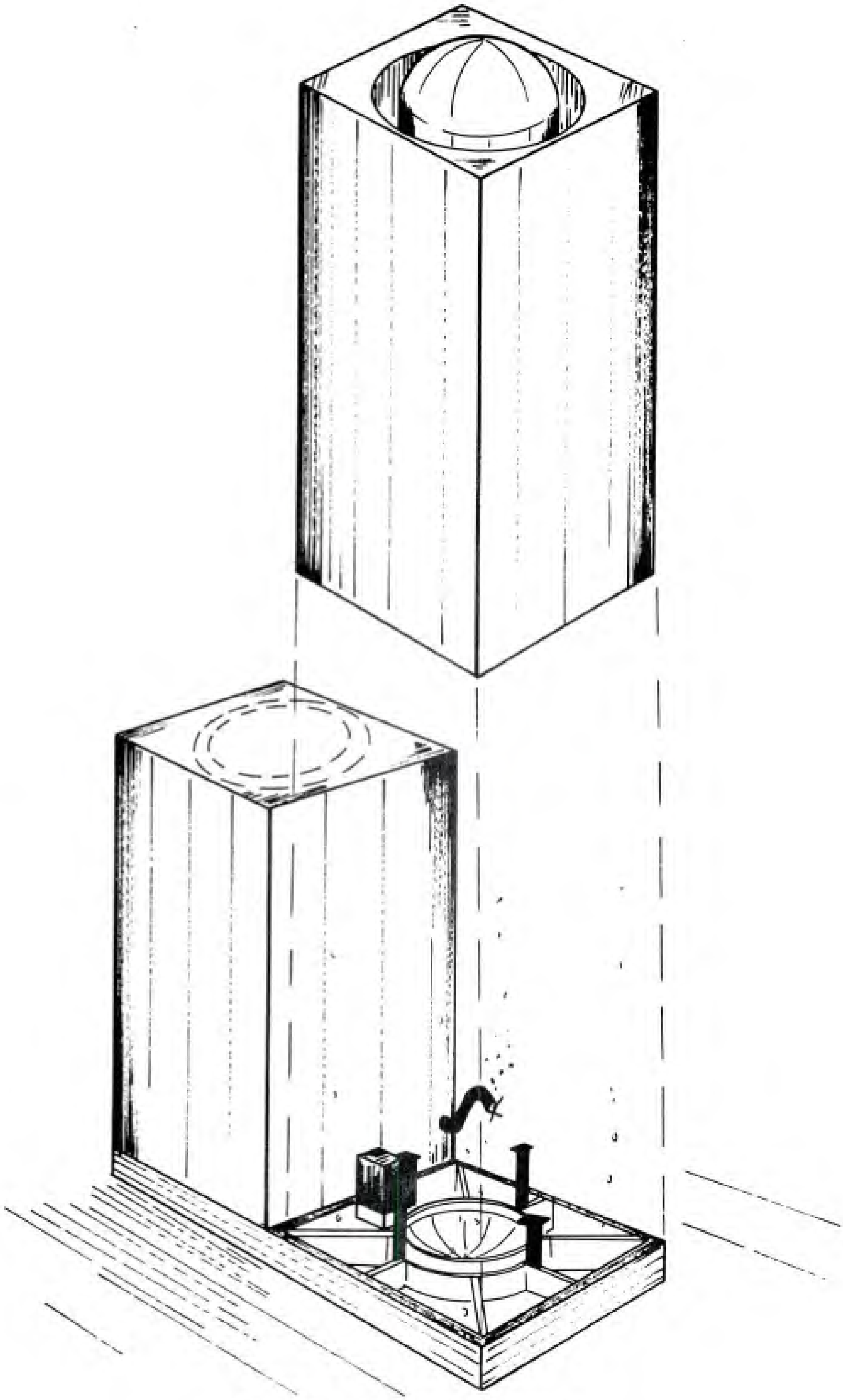


Figure 10-20. Emergency Ascent

Choose Class I flotation material:

Density 38 lbs/ft^3
New buoyancy=64 lbs/ft^3 (SW) - 38 (lbs/ft^3) syntactic = 26 lb/ft^3
Ultimate maximum compressive strength = 6000 psi
Water absorption (long term) = 5% maximum

Flotation material required:

$$\text{Volume} = \frac{\text{Net negative buoyancy of plant}}{\text{Net positive buoyancy of syntactic per ft}^3}$$

$$V = \frac{48500 \text{ lbs}}{26 \text{ lbs}} = 1865 \text{ ft}^3, \text{ or a cube 12.3 ft on a side}$$

Weight = 1865 ft^3 x 38 lb/ft^3 = 70900 lbs in air

Total Weight of Power Plant with enough syntactic flotation material to make it neutrally buoyant on the surface as follows:

Total plant weight = 215000 lbs
Syntactic weight = 70900
285900 or 127.5 long tons

The plant at 6000 ft in situ:

Assume salt water density of 64.70 lb/ft^3
Pressure contraction of steel hull will be approximately .66%
This will cause a volume decrease of .0066 x 2600 ft^3 = 18 ft^3
Hull volume in situ = 2600 ft^3 - 18 ft^3 = 2582 ft^3
Hull displacement in situ = 2582 x 64.7 = 167060 lbs
Hull displacement surface= 166500 lbs
Hull buoyancy increase = 560 lbs

Flotation Material also will contract approximately .007% due to pressure

Volume at surface = 1865 ft^3
Weight at surface = 70900 lbs

In situ decrease in volume = 0.007 (1865) = 13.1 ≅ 15 ft^3
In situ total volume = 1865 - 15 = 1850 ft^3
In situ displacement = 1850 (64.70 lab/ft^3) = 119,500 lbs
Weight -70,900 lbs
Net positive buoyancy 48,600 lbs
Surface net positive buoyancy -48,500 lbs
Net buoyancy increase 100 lbs

Total increase in power plant buoyancy = hull 560 lbs + syntactic 100 lbs = 660 lbs.

Consider now the drag force when the power plant hull and its flotation material make a free ascent (or descent).

A velocity of approximately 2 ft/sec is anticipated. The required flotation material is contained in a block shape 38 ft high and about 14 ft square.

Drag force (D) will be given by the following equation:

$$D = C \frac{f}{2} A V^2$$

where

D = Drag force (lbs)

C = Drag coefficient which may vary from 1.0 to 2.0; assume 1.5 for preliminary investigation

$P = \frac{\text{Density Seawater}}{g} = \frac{64}{32} = 2$

A = Frontal profile area = $(14)^2 = 196\ ft^3$

V = Vertical velocity = 2 fps (i.e. 4 fps considered maximum allowable)

$$D = 1.5\ (\frac{2}{2})\ (196)\ (2)^2 = 12000\ lbs$$

This is the approximate amount of net positive buoyancy the "block" must possess to ascend to 2 fps. It was earlier shown that the station will increase its net buoyancy by 660 lbs because sea water density increases at 6000 ft. Values for water absorption and marine fouling also have not been included.

Water absorption (long term) may amount to approximately 5%	0.05 (70900) = 3545 lbs
Marine fouling (approximately) 0.1 lb/ft^2	0.1 (1500)ft^2 = 150 lbs
Total	3695 lbs

The final weight balance:

Water absorption and fouling allowance	-3695 lbs	
Drag force	-1200 lbs	
	-4895 lbs	
Buoyancy due sea water density change	+ 660 lbs	
	-4235 lbs	
Final foam net positive buoyancy addition	+4235 lbs	(162.5 ft^3)

Table 10-VIII is a summary of in situ plant data. Figure 10-21 is the major milestone chart for the in situ concept. The schedule is the same for both deployment depths. Table 10-IX shows budget cost estimates for the selected in situ plants. These estimates do not include costs of development programs and are based on standard commercial practice. Transportation, deployment, and the cost of the common base for the load module and power module are not included.

Table 10-VIII Summary of Data for In Situ Plant

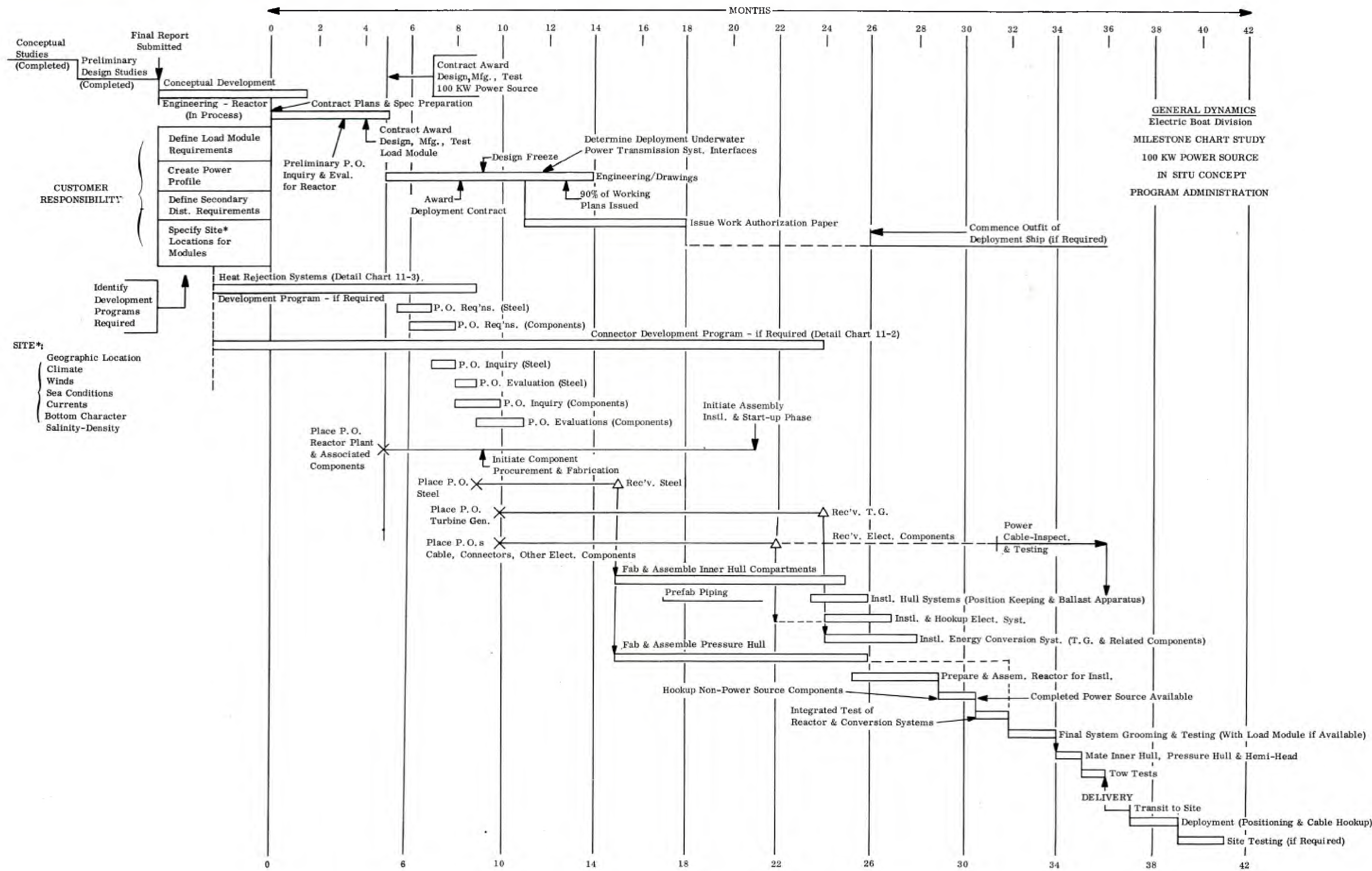
CHARACTERISTICS	ASSUMED LOAD MODULE 600 ft	ASSUMED LOAD MODULE 6000 ft	100 KW POWER PLANT 600 ft	100 KW POWER PLANT 6000 ft
Containment Hull Configuration	Vert Cyl	Vert Cyl	Vert Cyl	Vert Cyl
Diameter (ft) D	10	10	10	10
Height (ft) H	36.5	36.5	36.5	36.5
Weight in air (lb)	104,000	168,000	156,000	215,000
Displacement in water (surf) (lb)	166,500	166,500	166,500	166,500
Net buoyancy - (lb)	+ 62,500	-1 ,500	+10,500	-48,500
Center of gravity (assumed) w/r bottom of vert cyl	1/3 H	2/5 H	1/4 H	1/4 H
Flotation material				
Type	I	I	—	I
Density lbs/ft^3	38	38	—	38
Volume read (ft^3)	—	58	—	1,865
Wt (in air) reqd (lbs)	—	2,200	—	70,800
Ballast addition (pig iron 490 lbs/ft^3)				
Volume (ft^3)	146	—	25	—
Weight (lbs)	72,000	—	12,100	—
On surface: Net buoyancy after flotation or ballast material addition	Neutral	Neutral	Neutral	Neutral
In situ: Buoyancy increase (lbs) (due to buoyancy materials and density increase)	102	575	6	660

Table 10-VIII. (Continued)

CHARACTERISTICS	600 ft	6000 ft
Load Module Mission (assumed)	Oil well head pumping station	General Oceanographic combined with Military Undersea Station
Load (KW)	100	100
Depth (ft)	600	6000
Site Survey Findings (assumed)		
Sediment	Sand, occasional refrigerator	Coarse aggregate
Topography Profile	Basic 5° slope running NW to SE	Basic 25° N to S slope with flat ledges approximately 1/2 mile square; no boulders
Current Profile	Bottom - 0.50 KT N-S	Bottom - 0.1 KW NE-SW
	500' .5 N-S	5000' 0.1 NE-SW
	400' .6 N-S	4000' 0.15 NE-SW
	300' 1.0 NE-SW	3000' 0.30 NE-SW
	200' 1.75 NE-SW	2000' .5 NE-SW
	100' 2.25 NE-SW	1000' .5 NE-SW
	Surf 2.30 NE-SW	Surf. 2.78 N-S
S.W. Density Surface (lbs/ft^3) assumed	64.0	64.0
S.W. Density In Situ (lbs/ft^3) assumed	64.12	64.12
Method of deployment & recovery	Forced ascent-descent (winch-down)	
Winch (gears & equipment - lbs)	8000	10000
Location	In foundation of in situ plant	
Power characteristic	Submersible DC motor through reduction gear - reversible, battery powered	
Drum size		
Length (in.)	30	40 48
Diameter surface (in.)	30	40 48
Diameter Bottom (in.)	36	48 68
Rope		
Material	Steel	Steel & Nylon
Diameter (in.)	3/4	3/4 1 3/8
Length (ft)	600	3600 3600

Table 10-VIII. (Continued)

CHARACTERISTICS	600 ft	6000 ft
Anchor (lbs) (wet)	11000	11000
	It is desired to engage a leveling device-pinger alarm system capable of emitting a signal if the anchor horizontal aspect is inclined more than 12° when resting on the bottom. This unit will operate via a self-contained short term battery pack.	
Emergency Ascent Provisions		
Entire station (jettison winch & drum)		
Jettison	Yes	Yes
Positive Buoyancy (lbs)	7000	8500
Power Plant alone		
Jettison	Yes	Yes
Positive Buoyancy (lbs)	1200	1200
Load Module Alone		
Jettison	Yes	Yes
Positive Buoyancy (lbs)	1200	1200
Foundation & Structure & 50 ft tanks		
Weight (dry) (lbs)	75000	80000
Equalizing Flotation Material, type I, (lbs)	95500	102000
Volume (ft^3)	25000	



MONTHS
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42
Conceptual Studies (Completed)
Preliminary Design Studies (Completed)
Final Report Submitted
Conceptual Development
Engineering - Reactor (In Process)
Contract Plans & Spec Preparation
Contract Award Design, Mfg., Test 100 KW Power Source
CUSTOMER RESPONSIBILITY
Define Load Module Requirements
Create Power Profile
Define Secondary Dist. Requirements
Specify Site* Locations for Modules
Preliminary P.O. Inquiry & Eval. for Reactor
Contract Award Design, Mfg., Test Load Module
Design Freeze
Determine Deployment Underwater Power Transmission Syst. Interfaces
Engineering/Drawings
Award Deployment Contract
90% of Working Plans Issued
Issue Work Authorization Paper
Commence Outfit of Deployment Ship (if Required)
GENERAL DYNAMICS
Electric Boat Division
MILESTONE CHART STUDY
100 KW POWER SOURCE
IN SITU CONCEPT
PROGRAM ADMINISTRATION
Identify Development Programs Required
Heat Rejection Systems (Detail Chart 11-3)
Development Program - if Required
P.O. Req'ns. (Steel)
P.O. Req'ns. (Components)
Connector Development Program - if Required (Detail Chart 11-2)
SITE*:
Geographic Location
Climate
Winds
Sea Conditions
Currents
Bottom Character
Salinity-Density
P.O. Inquiry (Steel)
P.O. Evaluation (Steel)
P.O. Inquiry (Components)
P.O. Evaluations (Components)
Initiate Assembly Instl. & Start-up Phase
Place P.O. Reactor Plant & Associated Components
Initiate Component Procurement & Fabrication
Place P.O. Steel
Rec'v. Steel
Place P.O. Turbine Gen.
Rec'v. T.G.
Place P.O.s Cable, Connectors, Other Elect. Components
Rec'v. Elect. Components
Power Cable-Inspect. & Testing
Fab & Assemble Inner Hull Compartments
Prefab Piping
Instl. Hull Systems (Position Keeping & Ballast Apparatus)
Instl. & Hookup Elect. Syst.
Instl. Energy Conversion Syst. (T.G. & Related Components)
Fab & Assemble Pressure Hull
Prepare & Assem. Reactor for Instl.
Hookup Non-Power Source Components
Completed Power Source Available
Integrated Test of Reactor & Conversion Systems
Final System Grooming & Testing (With Load Module if Available)
Mate Inner Hull, Pressure Hull & Hemi-Head
Tow Tests
DELIVERY
Transit to Site
Deployment (Positioning & Cable Hookup)
Site Testing (if Required)
0 6 10 14 18 22 26 30 34 38 42

Figure 10-21

Table 10-IX. Budget Cost Estimates for 100 KW Power Source for In Situ Concept ($K)

	600 ft	6000 ft
Conceptual Development Engineering	85	95
Contract Guidance Plans and Specification Preparation	110	110
Detail Design, Manufacturing and Test	6*	6.7*

*Indicates millions of dollars; all others in thousands of dollars.

10.3 PRELIMINARY DESIGN FOR A 300 KW DIESEL-GENERATOR SHORE-BASED POWER SOURCE

10.3.1 Overall Structure

The land-based generator complex (Figure 10-22) consists of a building which encloses a diesel-generator system, a water tank or well, a microwave antenna (where required), an area provided for a quarters building, and a vehicle turnaround area. An access driveway services the complex. The entire complex is contained within a fenced-in area measuring approximately 120 ft x 120 ft.

An insulated corrugated steel building (Figure 10-23) houses the diesel-generator system. A 10-ton bridge crane is provided for installation and maintenance and is integrated with the structure forming the building frame. The crane extends 8 ft beyond a rollaway overhead front door and services the entire building interior and to 3 ft beyond the outside loading platform. The loading platform allows delivery of shipment without requiring access into the building.

All equipment associated with the diesel-generator system is housed within the building and is oriented to facilitate maintenance and service (Figure 10-24). A clear work area is provided forward of the diesel generator for removed equipment or replacement equipment. There is also open service area provided around all equipment.

To permit single location surveillance, switchgear and transformer equipment has been integrated into one console facing the diesel-generator control panel. This forms the plant operating aisle.

Troughs with removable covers are located in the floor to contain interconnecting wires or piping. The submarine cable terminal unit is also located in a covered well in the floor facilitating access.

The emergency battery enclosure is vented externally to control and exhaust contaminant gasses. The batteries are serviced through a self-sealing top hatch.

All accessory equipment, fuel pump, filter, day tank, etc., is located in one shallow drain basin. This basin assures no puddling of combustible fuels, and allows quick surveillance of the condition of the equipment. Free space is provided around this equipment for service and maintenance (see Figure 10-23).

The facility may also include a microwave or telephone link to a monitor station. This link will transmit station and load module conditions, and may also be provided with a voice channel. A closed circuit T. V. system can be incorporated into the facility for remote monitoring of equipment.

The diesel fuel tank is located underground adjacent to the building. A loading zone is provided for servicing the fuel tank through an outside filler pipe.

Power and communication are provided to the load module by a cable. This cable originates at the cable terminal unit located at the rear of the building and extends via an underground conduit to the sea. The conduit is installed below the frost line and enters the sea at a level 6 ft below the mean low water mark. Communication by the power cable is provided by a carrier system.

A water tower shown near the building supplies supplementary cooling water to the diesel if required and can provide water for sanitation and fire protection. In some geographical locations a drilled well instead of a water tower may be used. If a microwave system is used the antenna will be incorporated into the water tower structure.

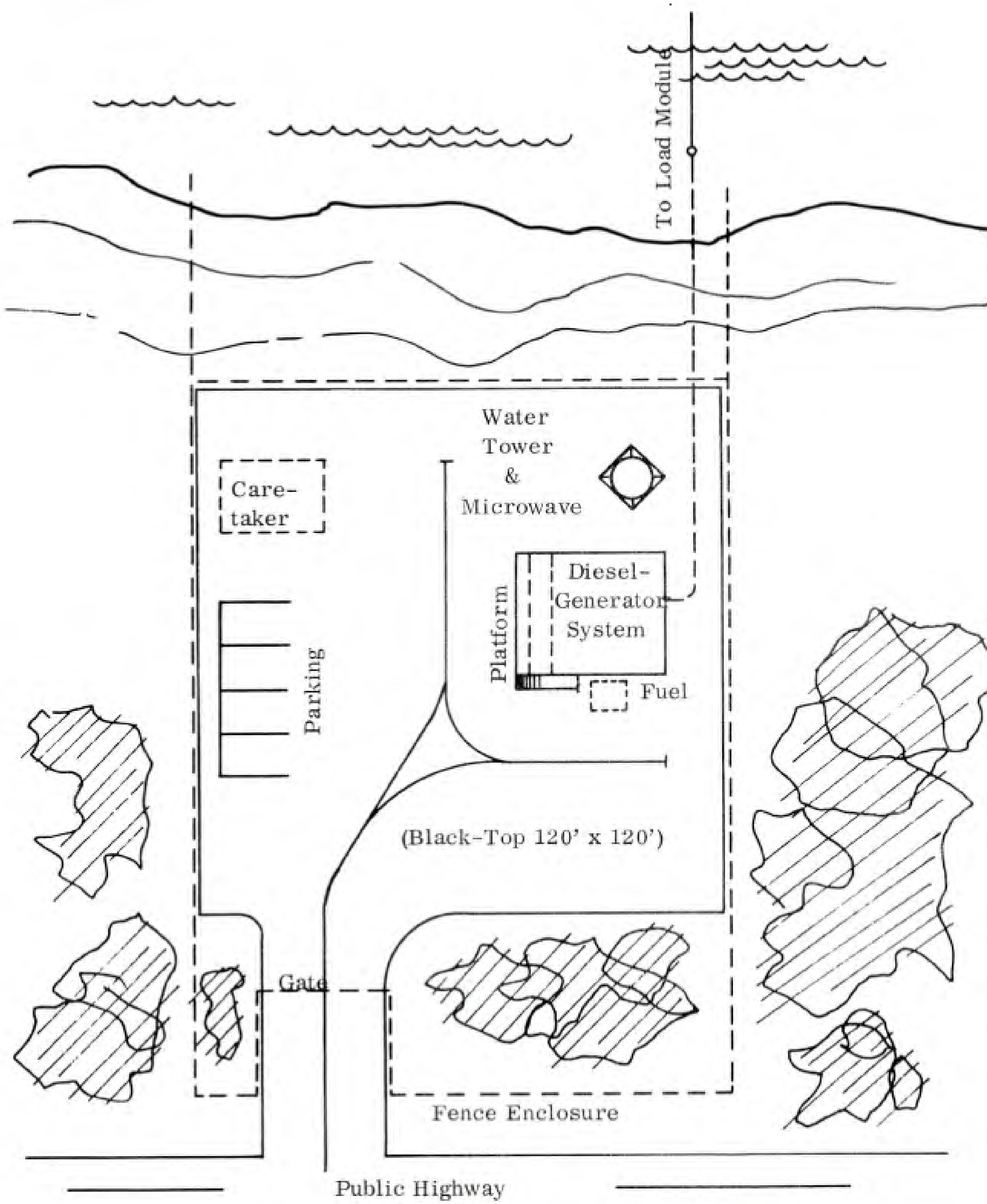


Figure 10-22. Shore-Based Generator Complex

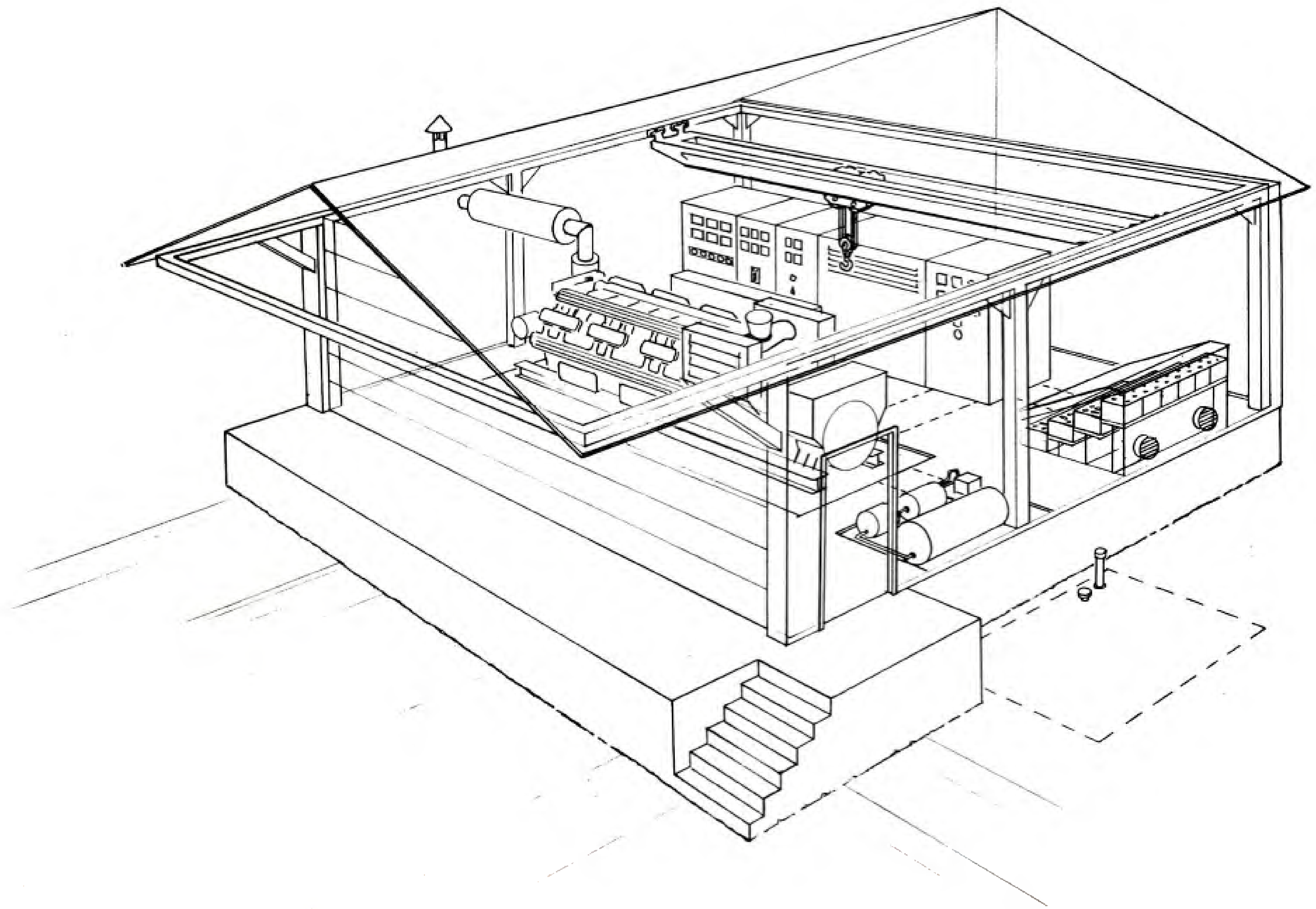


Figure 10-23. Shore-Based Power Source Building

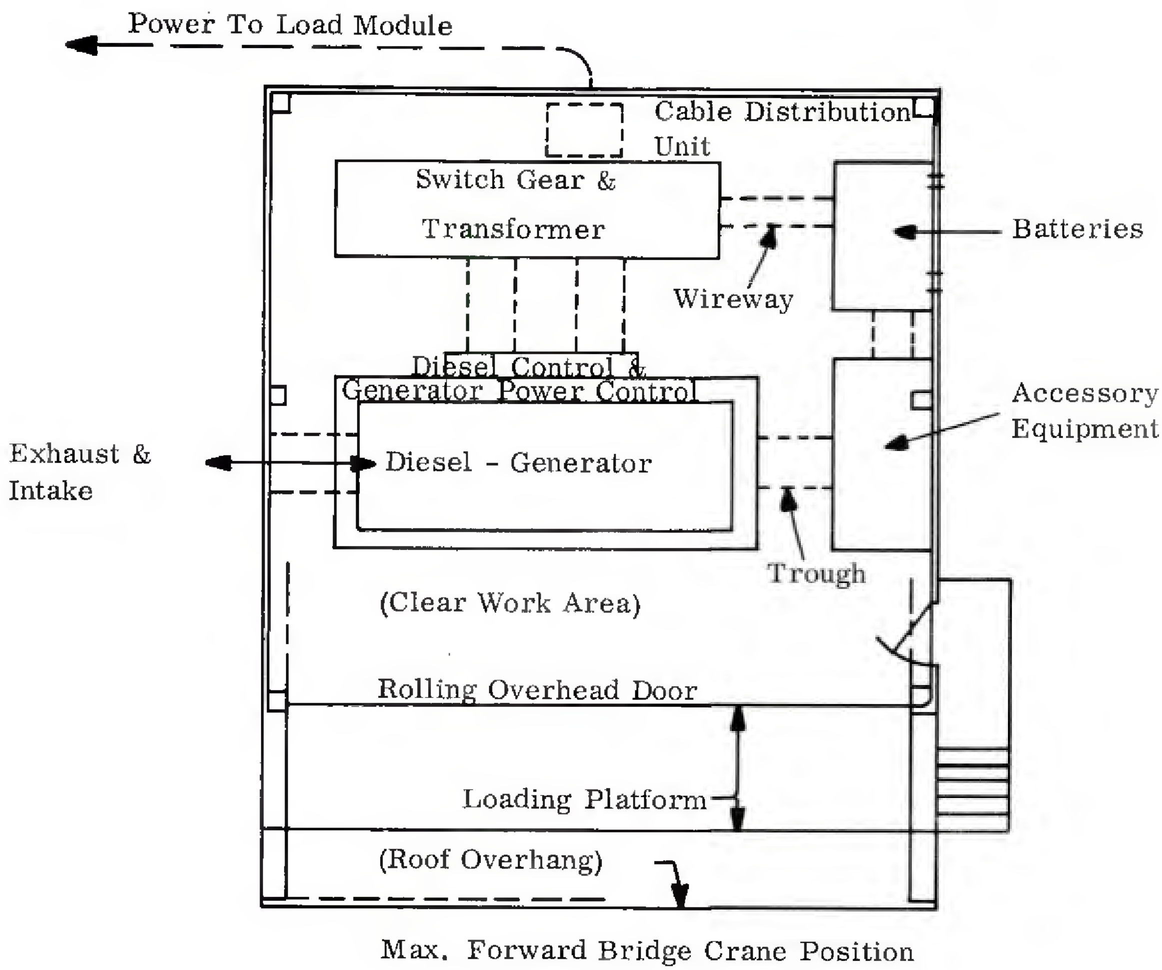


Figure 10-24. Shore-Based Power Source Building Layout

10.3.2 Power Source

The diesel-generator power source is rated at 500 KW @ .8 pf continuous and 550 KW @.8 pf intermittent operation. The unit is self-contained.

The diesel engine is equipped with supercharging or cylinder air scavenging for reduced operating temperatures and higher efficiencies. The engine is instrumented with sensors to indicate cooling water and lube oil temperatures, lube oil pressure and engine over-speed.

A fresh water cooling system rejects the engine jacket heat to a forced convection radiator requiring a minimum air flow of 29,000 cubic ft per min. Radiant heat from the engine and generator (approximately 10% of the rated brake horsepower at full load or about 7500 BTU/min) is exhausted from the engine room with a ventilation fan.

Engine intake air is drawn from outside the building through an intake silencer/filter. Exhaust gases are ventilated through a muffler and exhaust stack. A battery is used for engine starting.

The generator enclosure is of drip-proof construction, air cooled, and has remote alarm provisions for over-temperature and over-speed indication on the display board. The generator output is rated at 500 KW, 625 KVA, 60 cycle, 4160 V, 3-phase continuous and 550 KW, 685 KVA, intermittent operation. Steady-state voltage regulation of ± 1/4 of 1% and a no-load to full-load regulation of 7% at a recovery time of 5 sec is available with an isochronous governor.

The improvement of the steady-state voltage regulation of ± 1/4 of 1% at the 300 KW power level as compared to 30KW steady-state regulation of ± 1/2 of 1% is explained by the fact that larger power generation equipment is subject to a fly wheel effect of the engine and generator. This effect is found in power-generating equipment from 300 KW and greater.

The fuel consumption curves shown in Figures 10-25 and 10-26 illustrated the 7% difference in fuel consumption necessary to transmit 300 KW over the additional 40 miles of submerged cable. Reflected in the fuel consumption curves is the power necessary to operate auxiliary engine equipment and the losses incurred by transmission cable and conversion equipment.

Table 10-X is a listing of the diesel-engine generator characteristics.

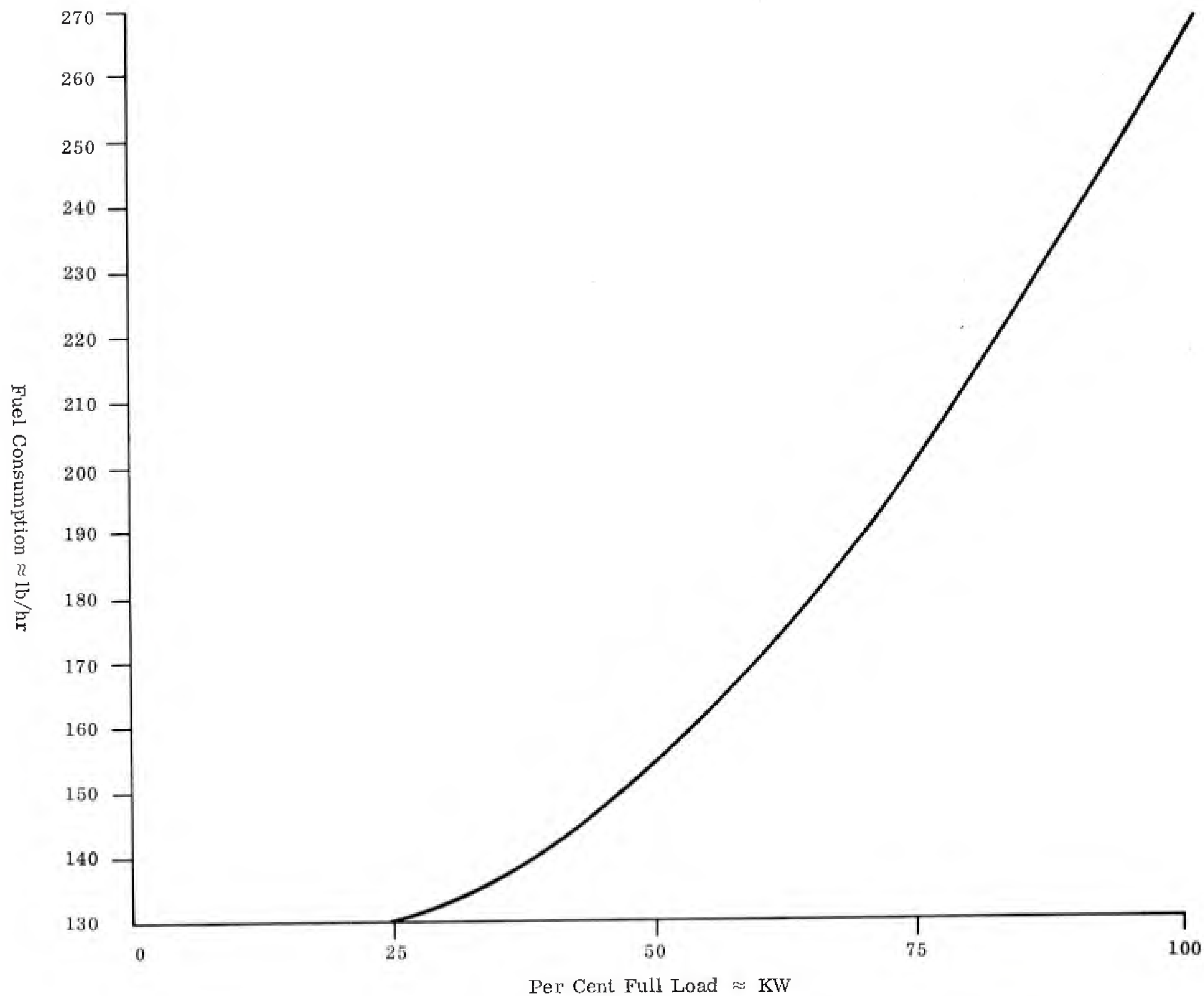


Figure 10-25. Fuel Consumption of Shore-Based 300-KW Power Source at 50 Miles

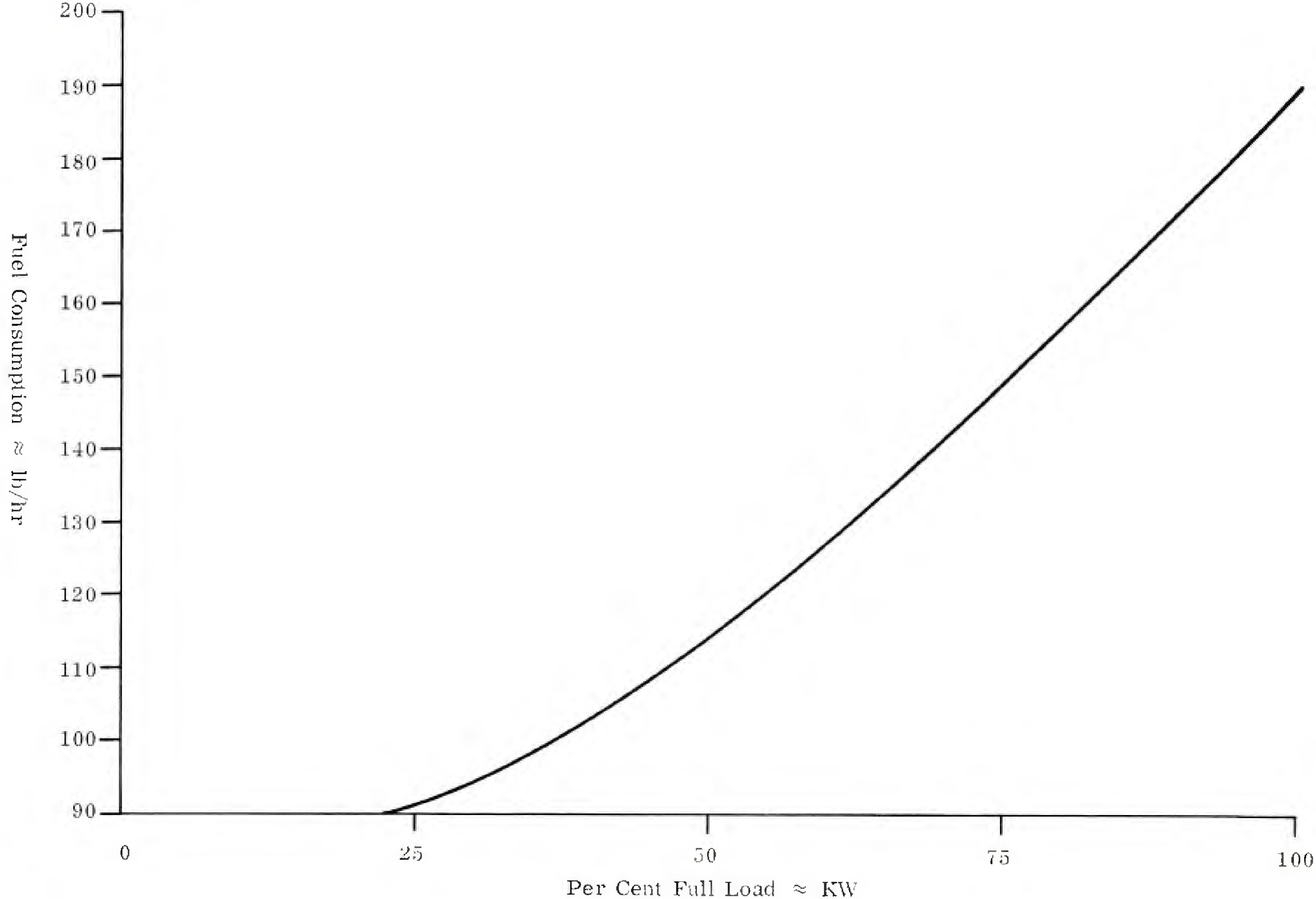


Figure 10-26. Fuel Consumption of Shore-Based 300-KW Power Source at 10 Miles

Table 10-X

Shore-Based

300 KW Diesel-Engine Generator for Power

Transmission Over 10 Miles and 50 Miles

Diesel Engine		Supercharged or cylinder scavenged
Rating	:	500 KW @ 1200 RPM Continuous
		550 KW @ 1200 RPM Intermittent
Approx Volume	:	14 ft long x 5 ft wide x 7 ft high (490 ft^3)
Approx Weight	:	21,000 lbs
Governor	:	0.25%
Cooling	:	Radiator, forced convection 29,000 CFM
Generator		Drip-proof
Rating	:	500 KW @ 70°C continuous
Voltage	:	4160 V @ 60 cycles, 3-phase
Regulation	:	0.25% steady state

Attached Accessories

Supercharger or scavenging blower
Generator & exciter
Lube oil pump & filter (self by-passing)
Fuel oil pump & filter (self by-passing)
Water pump
Cooling fan

Detached Accessories

Air filter/silencer
Radiator
Exhaust muffler
Alarms & gauges

10.3.3 Electrical System

The shore-based plant can supply a load of 300 KW over distances of 10 and 50 nautical miles,for the former distance using a 13,800-volt, 3-phase alternating current system and for the latter using a 13,800-volt direct current system. The types of equipment, both AC and DC, have already been discussed in Chapter 9. Conductors were selected on the basis of considerations discussed in Chapter 5 and are, for the 13,800-volt AC system, 60,000 ft of 3-conductor shielded, grounded neutral, armored cable, using a #2 AWG. The 13,800-volt direct-current system uses 60,000 ft of a 2-conductor shielded, grounded neutral, armored cable using a #1/0 AWG.

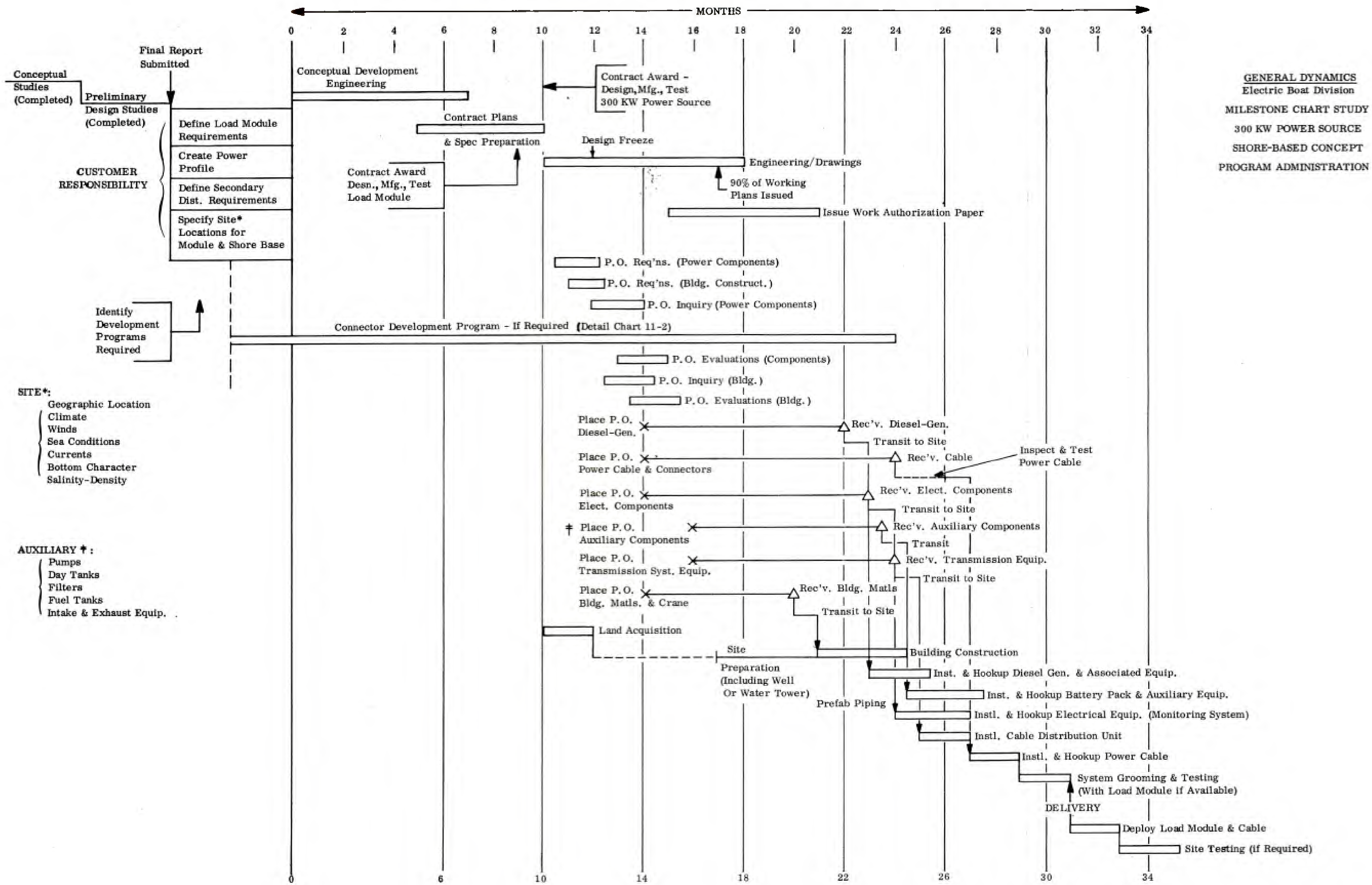
Two aspects of the shore-based cable system differ from the other cable system. These are the cable deployment and the criticality of the voltage drop condition. In the case of the voltage drop, due to the length of the circuit, all parameters were investigated,including magnitudes of all quantities as well as all phase angle relationships to determine the voltage drop, line current and load losses. Table 10-XI is a summary of these circuit conditions based on a constant power factor of 0.85. All current (amperes) data were based on nominal transmission voltages (13,800).

Table 10-XI Alternating Current System

Load Cond.	Max Current $I_T \angle\phi$	Max Impedance $Z \angle\theta$	Losses $I_T \cdot Z \angle\phi+\theta$	Voltage E_S with 2% Boost Pri/Sec	Voltage E_R Pri /sec	3-Phase KW Losses
No load	$\frac{I_c}{2}$ 3.96 $\angle 90^o$	$10.1\angle 14.8^o$	$39.8\angle 104.8^o$	$480/14076 \angle 0^o$	14092/490	0.5
1/4 load	—	$10.1\angle 14.8^o$	—	$480/14076 \angle 0^o$	—	0.4
1/2 load	—	$10.1\angle 14.8^o$	—	$480/14076 \angle 0^o$	—	1.2
3/4 load	—	$10.1\angle 14.8^o$	—	$480/14076 \angle 0^o$	—	2.7
Full load	13.14 $\angle -17.1^o$	$10.1\angle 14.8^o$	$132.1\angle -2.3^o$	$480/14076 \angle 0^o$	13847/481.6	5.1

A discussion of the deployment equipment and techniques may be found in Appendix B.

Figure 10-27 is the major milestone chart for the shore-based facility. The schedule is the same for both deployment distances. Table 10-XII shows budget cost estimates for the selected shore-based plants. These estimates do not include costs of development programs, and are based on standard commercial practice. Transportation, deployment, property acquisition, and site preparation costs are not included.



GENERAL DYNAMICS
Electric Boat Division
MILESTONE CHART STUDY
300 KW POWER SOURCE
SHORE-BASED CONCEPT
PROGRAM ADMINISTRATION
MONTHS
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34
Final Report Submitted
Conceptual Studies (Completed)
Preliminary Design Studies (Completed)
CUSTOMER RESPONSIBILITY
Define Load Module Requirements
Create Power Profile
Define Secondary Dist. Requirements
Specify Site* Locations for Module & Shore Base
Identify Development Programs Required
SITE*:
Geographic Location
Climate
Winds
Sea Conditions
Currents
Bottom Character
Salinity-Density
AUXILIARY ✝:
Pumps
Day Tanks
Filters
Fuel Tanks
Intake & Exhaust Equip.
Conceptual Development Engineering
Contract Plans & Spec Preparation
Contract Award Desn., Mfg., Test Load Module
Contract Award - Design, Mfg., Test 300 KW Power Source
Design Freeze
Engineering/Drawings
90% of Working Plans Issued
Issue Work Authorization Paper
P.O. Req'ns. (Power Components)
P.O. Req'ns. (Bldg. Construct.)
P.O. Inquiry (Power Components)
Connector Development Program - If Required (Detail Chart 11-2)
P.O. Evaluations (Components)
P.O. Inquiry (Bldg.)
P.O. Evaluations (Bldg.)
Place P.O. Diesel-Gen.
Rec'v. Diesel-Gen.
Transit to Site
Place P.O. Power Cable & Connectors
Rec'v. Cable
Inspect & Test Power Cable
Place P.O. Elect. Components
Rec'v. Elect. Components
Transit to Site
✝ Place P.O. Auxiliary Components
Rec'v. Auxiliary Components
Transit
Place P.O. Transmission Syst. Equip.
Rec'v. Transmission Equip.
Transit to Site
Place P.O. Bldg. Matls. & Crane
Rec'v. Bldg. Matls
Transit to Site
Land Acquisition
Site Preparation (Including Well Or Water Tower)
Building Construction
Prefab Piping
Inst. & Hookup Diesel Gen. & Associated Equip.
Inst. & Hookup Battery Pack & Auxiliary Equip.
Instl. & Hookup Electrical Equip. (Monitoring System)
Instl. Cable Distribution Unit
Instl. & Hookup Power Cable
System Grooming & Testing (With Load Module if Available)
DELIVERY
Deploy Load Module & Cable
Site Testing (if Required)

Figure 10-27

Table 10-XII. Budget Cost Estimates for 300 KW Power Source for Shore-Based Concept ($K)

	600 ft	6000 ft
Conceptual Development Engineering	50	50
Contract Guidance Plans and Specification Preparation	80	80
Detail Design, Manufacturing and Test	1.25*	2.8*

*Indicates millions of dollars; all others in thousands of dollars.

Chapter 11

DEVELOPMENT PROGRAMS

The development programs outlined in this section involve:

- the development of electrical connectors, both wet and dry, which are needed to provide suitable connection points between the transmission cable and the secondary distribution system within the load module
- the development of heat rejection system concepts for removing heat loads, providing condenser surfaces without sea water circulation for moderate loads and deep depths, and providing hull penetrations for the circulation of sea water for high loads and moderate-to-deep depths
- the development of two general utility transmission systems for application to potentially available power sources.

The study program and its selection of cost effective systems considered portions of these development programs necessary to complete the preliminary design of some systems. Certain portions of this program, although not required to complete the systems selection, will greatly improve the cost effectiveness of the selected system in lieu of the alternate selections made.

11.1 CONNECTOR DEVELOPMENT

11.1.1 State of the Art

For each selected system for the surface-tendered power source and shore-based power source, two different connectors are required for each system. The first is the high voltage connection between the power source and the transmission line. The second connection is from the transmission cable to the load module.

For the in situ plants, two connectors are required, one out of the power source module and one into the load module. Because the secondary distribution module is an integral part of the power source, both connectors would be identical and require voltage capability equal to the load module basic requirements.

Connectors can be characterized as two basic types, "wet" and "dry." The dry connector is essentially an electrical device providing the necessary continuity between a cable and a particular module. It is characterized by its ability to prevent water seepage into the connection point, thereby preventing short circuits and other electrical failures. The connection must be made in a relatively dry atmosphere. Therefore, connections of this type have to be made prior to emplacement of the load module in the ocean environment. The wet connector has the same capabilities as the dry connector. Its primary advantage is that the electrical connection can be made in the ocean environment. The availability of wet connectors for underwater power transmission systems would be a tremendous advantage in that it would allow load modules to be emplaced in the ocean environment without initial cable connections.

Figure 11-1 indicates the availability of dry connectors for use in the marine environments applicable to this study. The availability of hardware is extremely limited. Only one power level, 30 KW, can be made with existing hardware. Even at this

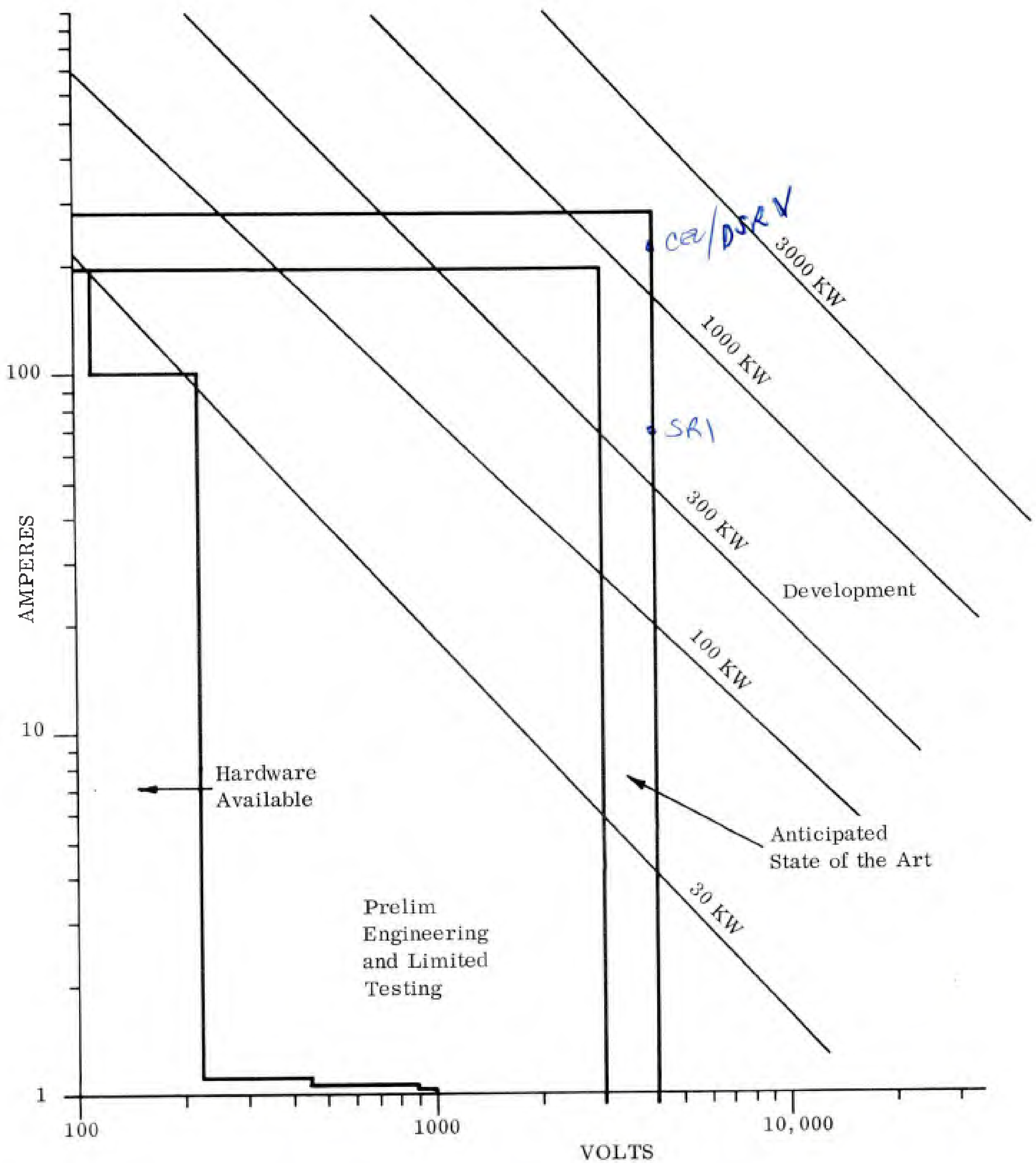


Figure 11-1. Availability of Dry Connectors

power level, more economical voltages would not be available in that 220-volt, 100-amps is the only power condition satisfying the 30-KW power level for available connector hardware.

Study of available connectors and discussions with various suppliers indicate that a broader range of connector availability can be established, as shown in Figure 11-1, so that power ranges up to 1000 KW can be satisfied, although not at the optimum voltages selected for transmission. For the connections required between the transmission cable and the load module, power levels of approximately 100 KW could be satisfied to the level of preliminary engineering and limited testing. Connectors for the 3000 KW range are not available and would not be available without substantial development work.

Wet connectors are not available for any of the power ranges under study. The wet connectors are almost exclusively limited at the present time to telemetering and other extremely low power experimental devices.

11.1.2 Recommended Development Program

The recommended development program consists of a series of phases required to develop the technology for both wet and dry connectors so that an extension of the state-of-the-art can be accomplished providing suitable connectors for underwater power transmission systems.

PHASE I - Concept Formulation and Tradeoff Analysis

1. The first period involves determination of the design objectives in terms of engineering parameters. This involves discussions and cross fertilization to arrive at engineering tradeoffs for the optimum system parameters concerning power, voltage, depths, and transmission characteristics.
2. Concurrent with step (1), investigations of existing hardware and literature reviews are accomplished to specifically determine the effects of design, hardware, and testing, relative to the parameters involved.
3. Based on the determinations of the existing states-of-the-art and existing hardware, preliminary cable, hull penetration, and connector designs are evolved. This stage comprises basically four parallel categories:

   a. Cable, hull penetration, and connector design, wet - pressure compensated

   b. Cable, hull penetration, and connector design, wet - not pressure compensated

   c. Cable, hull penetration, and connector design, dry - pressure compensated

   d. Cable, hull penetration, and connector design, dry - not pressure compensated

   The evaluation of the cable, hull penetration, and connector design is a joint project to ensure system compatibility as well as determination of the method to terminate not only the cable insulation but the armor as well.

   Voltage and amperage characteristics for each type of connector suggested above involve the following ratings:

   4000 volts @ 50 amp. maximum rating 300 KW,

   4000 volts @ 200 amp. maximum rating 1000 KW,

   4000 volts @ 500 amp. maximum rating 3000 KW,

   13000 volts @ 150 amp. maximum rating 3000 KW.

These levels were selected in reviewing the data presented in Figure 11-1 and the selected general purpose transmission voltages recommended.

4. Upon the evolution of the preliminary designs, a review and evaluation of the various concepts is conducted relating to the required system parameters. For the various depths and electrical power requirements, it is entirely possible that several "final" design approaches may be pursued as there is no assurance that one approach will provide the best answer to all the possible combinations. It is assumed that basically four representative concepts will be pursued further. The final design may incorporate more than four specific hardware sizes and groups. However, at this time it is only necessary to fabricate and test a limited number of types to establish the validity of the specific design concepts.

PHASE II, Prototype Design and Test - This phase, develops the most favorable concepts involving the dry connectors including the pressure-compensated and not-pressure-compensated versions for a 4000-volt, 50-amperes rating suitable for all depths down to 20,000 ft. This program, with prototype testing, provides a suitable base on which to evaluate remaining dry concepts for larger power rating, so that improvements to previously selected concepts can be made prior to development engineering and test. This phase also generates the basic test requirements, criteria for acceptance, and the necessary test stands to accomplish all of the prototype tests contemplated for the entire program.

PHASE III - This phase involves a parallel program, utilizing the experience gained in Phase II, to develop and test prototype connectors of the wet types for rating of 4000 volts and 50 amperes. In addition, the revised dry concepts are developed and tested for ratings of 4000 volts at 160 amperes.

PHASE IV - This phase is essentially similar to Phase III and involves higher power levels for both the wet connector and the dry connector. Suggested rating for the wet connector developed and tested in this phase is 4000 volts at 200 amperes. The dry type connector rating involves 4000 volts and 500 amperes such that the entire spectrum of power levels up to 3000 KW can be accommodated with suitable dry connectors at the 4000 volt transmission voltage.

PHASE V - This phase involves a major jump in transmission voltage to 13,000 volts and 150 amperes for the dry connector so that more economical high voltage transmission systems can be applied to underwater use. The last remaining wet connector involving a rating of 4000 volts and 500 amperes is also developed and tested in this final phase. It is anticipated that wet type connectors are applicable to high voltage transmission systems and therefore are not recommended at this time.

PHASE VI - This phase involves the final design of the entire family of connectors developed and tested in previous phases. It includes the basic standards, specifications, material selections, and test requirements for all power transmission connectors for use in the underwater environment.

11.1.3 Development Cost and Schedule

The anticipated cost of each phase of the connector development program and the anticipated schedule for each phase are shown in Table 11-I and Figure 11-2, respectively.

GENERAL DYNAMICS
Electric Boat Division

MILESTONE CHART STUDY

DEVELOPMENT PROGRAMS

CONNECTOR DEVELOPMENT

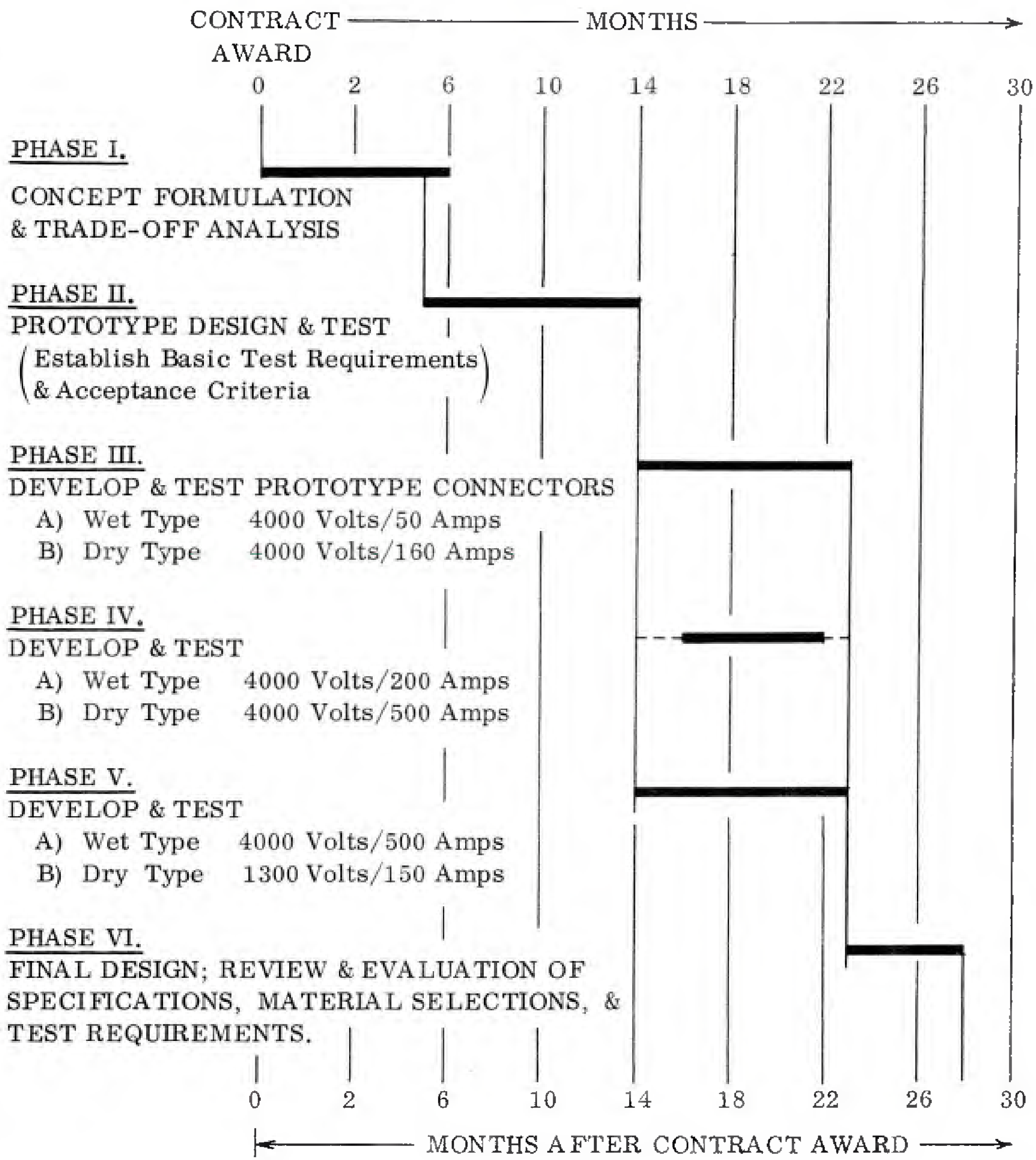


Figure 11-2. Connector Development Program Milestone Schedule

Table 11-I. Cable Connector Program Schedule and Cost

PHASE	TIME		COST ($K)
I	6 months		70
II	9 months	Can start 3-5 mos. after start of phase I	200
III	9 months	These can be concurrent	100
IV	6 months		80
V	9 months		150
VI	5 months	Conclusion type task at end	100

11.2 HEAT REJECTION SYSTEMS DEVELOPMENT

11.2.1 State of the Art

In each of the power ranges and depth parameters studied for the in situ power source, a reactor power plant has been selected as the most effective prime power source. The reactor power plant using a secondary steam turbine-generator plant as the energy conversion system requires significant heat removal capability to condense the exhaust steam of the turbine to its reusable state as feed water. This heat removal (condensing) can be accomplished in either or a combination of two basic approaches,

- use of circulating sea water through appropriate hull penetrations,
- condensing steam on the normally cooler pressure hull.

The obvious advantage of the circulating sea water system is its theoretically unlimited heat removal capability. However, there are significant disadvantages in that hull penetrations call for higher risk hull designs, excessive weight of transition forgings at the hull penetration, and high pressure piping systems and internal heat exchangers Perhaps most important is the inherent danger of sediment clogging when power systems are used in stationary structures in close proximity to the ocean bottom. Presently the largest hull penetration for sea water cooling systems is 3 inches in diameter and is capable of withstanding design pressures equivalent to 3000-ft depths.

Heat removal via hull structure substantially reduces the high risk design and the sediment clogging problems, but its inherent limitation is the heat flux density capability of the hull itself. As a result an oversize hull system may be required solely for heat transfer. Finned surfaces and external or internal circulation techniques could improve the heat flux density capability of pressure hulls.

11.2.2 Recommended Development Program

A concept-formulation phase and subsequent development phases should be instituted to advance the state-of-the-art in heat rejection systems.

PHASE I - Concept Formulation and Tradeoff Analysis - Various concepts are formulated and sufficient criteria developed to select the most promising heat rejection systems for submerged power plants. These concepts include both heat rejection through the hull and the use of circulating sea water through hull penetrations. The hull heat transfer concepts include internal arrangements, junction design of the exhaust vacuum system of the turbine and the main pressure hull and the use of auxiliary techniques to improve heat transfer coefficients. Effective ranges of both concept approaches are generated to show the feasible upper limit of hull heat transfer and the cost effective low limit of hull-penetration, sea-water-circulation systems.

PHASE II - Hull Heat Rejection Concept Development - Using the concepts formulated and selected as most promising during Phase I, concept development studies are initiated during this phase. The parameters used for this development represent the upper limit of effectiveness for the through-hull heat rejection approach. Sufficient analytical stress analysis are accomplished to prove the adequacy of hulls with thermal stresses applied, the adequacy of the vacuum segment of the exhaust area and the joint between this segment and the hull. Sufficient details of the concept are developed so that it can be applied in a final design process where the application warrants such use.

PHASE III - Hull Penetration Concept Development - A development program similar to Phase II to study in detail the selected concept for hull-penetration, sea-water circulation system is recommended. This study involves the stress analysis of the transition forging at the hull and the pipe stress analysis centered in the problem area of thermal gradients coupled with hull and pipe compression techniques. Its goal is to minimize the weight of the high pressure piping and the transition forging by the use of multiple systems or concentric inlet and exhaust systems. The parameters to be used for this study phase represent the high and low end of the range suggested in the Phase I portion of the study.

Sufficient details of the selected concepts are developed to provide an extension of the state-of-the-art and to ensure that the concepts selected can be applied to a final design where applicable. Application for hull penetrations extend beyond the reactor power plant systems and include other areas such as sea water processing for oxygen generation or potable water, mining, and sediment processing.

11.2.3 Development Cost and Schedule

The anticipated cost of each phase of the heat rejection system development program and the anticipated schedule for each phase are shown in Table 11-II and Figure 11-3.

Table 11-II. Heat Rejection Systems Development Program Schedule and Costs

PHASE	TIME		COST ($K)
I	5 months		65
II	7 months	can be concurrent	95
III	8 months		120

11.3 GENERAL UTILITY POWER TRANSMISSION DEVELOPMENT PROGRAM

The first generation utility power transmission system should be immediately developed, applying the results of this study program into a workable general utility underwater transmission system.

A surface electrical power generation system rated at approximately 30 KW is being contemplated for the Manned Underwater Station being developed for NCEL under Contract #N62399-67-C-0044. This surface power plant is considered as an interim power source until an in situ power plant becomes available. Basic parameters are generation of 30 KW electrical power to load modules in depths to 6000 ft. Its minimum

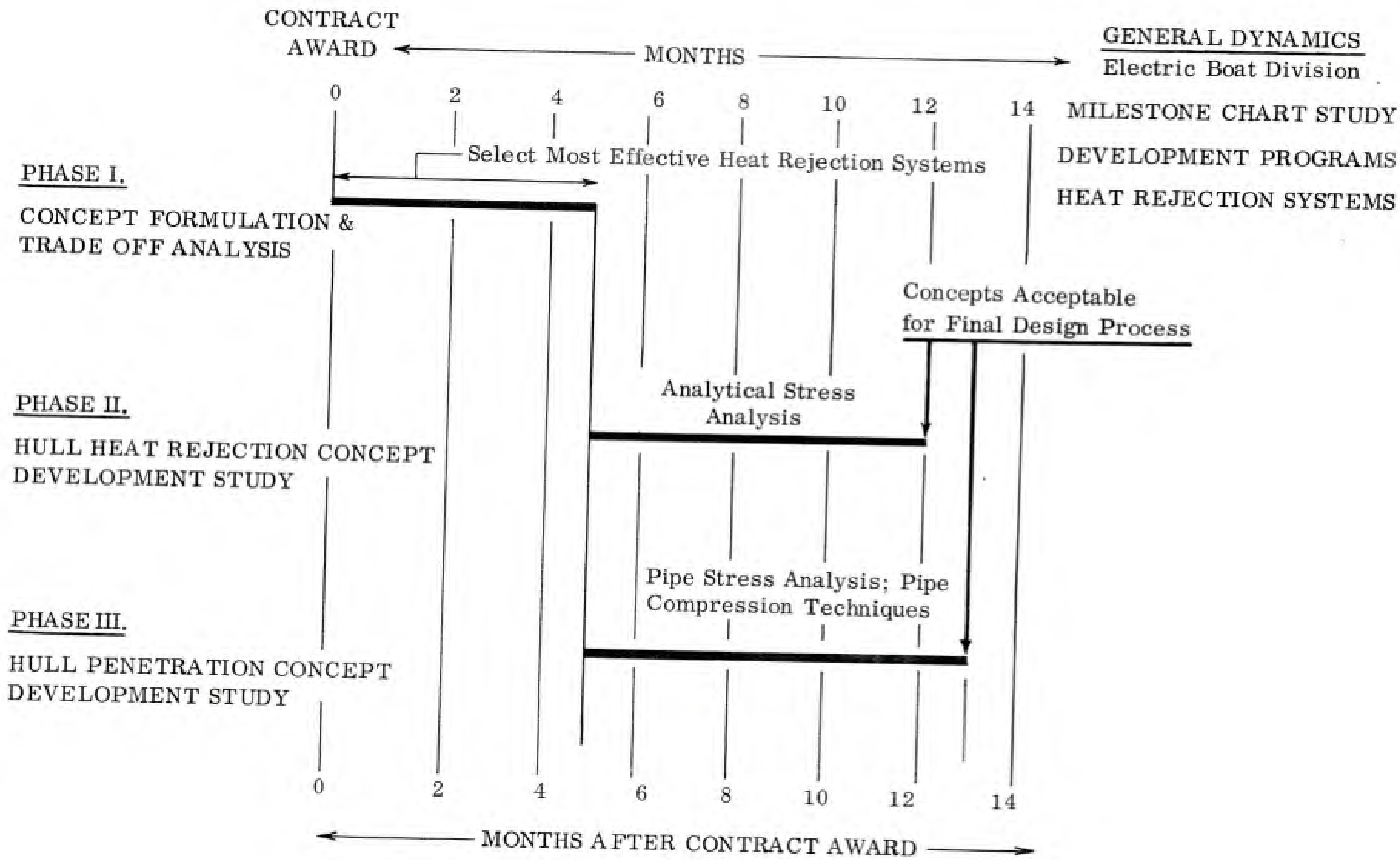


Figure 11-3. Heat Rejection System Development Program Milestone Chart

endurance is presently considered to be 30 days. It is therefore recommended that a power distribution system for general purpose applications be developed in detail using this power source.

In addition to the above 30 KW power sources, an additional contract #N62399-67-R-0046 has been issued by NCEL for the preliminary development of a general utility reactor power plant capable of producing 100 KW electrical power and capable of operation in depths to 6000 ft. The growth capability of the reactor system is such that with some modifications it can produce up to 500 KW electrical for use with the Manned Underwater Station or other in situ applications.

The development program as suggested would include the tasks described below:

- Concept formulation of two secondary power-splitting modules which would be used as the Power Distribution Center. These will be capable of accepting primary power of 30 to 100 KW and 100 KW to 300 KW, respectively, at the selected transmission voltage and of distributing this power at various increments to several external cable connectors. The module will include the necessary electrical equipment to remotely-operate circuit breakers, vary levels of power at varying AC voltages at 60 cycles, and be potentially capable of providing DC and 400 cycles. This degree of flexibility of the equipment will be possible using the concept of modules for distribution; the modular distribution system can be easily adapted to meet a variety of mission requirements calling for power conditioning multiples of power condition types as well as varying levels of output. The modular pressure hull will be capable of operating in depths down to 6, 000 ft and the total system less primary and secondary external cables will be neutrally buoyant at the 6, 000-ft depth.

- Using the results of this study, a general utility power transmission system capable of operating within the limits of 30 to 100 KW electrical power including a secondary power splitting module and the necessary primary power conditioning equipment is developed in detail for adaptation to either the potentially available surface power plant or the in situ power plant.

  The selected general utility system includes enough universal equipment so that minimum modifications are required to operate at any power level for depth ranges of 600 to 6, 000 ft.

- An additional power transmission system is developed with a rating of 100 to 300 KW electrical including the primary power conditioning equipment and secondary power splitting module for adaptation to the potentially available in situ reactor power plant. Power cable lengths up to 6000 ft are considered. The development program utilizes as much universal equipment as possible so that minimum modifications are required to suit variable power demands and variable relative location between the load module and the in situ power source.

- The recommended development program for each system includes a definition of all major equipment, its availability, a potential schedule of major milestones in its development and construction, placement and recovery techniques, and logistics support.

With this development program, it is presumed that two power transmission systems would be developed to encompass the needs of underwater load modules with power requirements of 30 KW to 300 KW down to 10,000-ft depths. These two systems would therefore encompass a substantial area of present interest as defined by the parameters stated in this study program.

The anticipated cost of each phase of the general utility power transmission development program and the anticipated schedule for each phase are shown in Table 11-III and Figure 11-4.

Table 11-III. General Utility Power Transmission Development Program Schedule and Costs

PHASE		TIME	COST ($K)
I	Concept Formulation - Power Distribution Modules	4 months	45
II	Concept Development - 30 KW to 100 KW System	4 months	60
III	Concept Development - 100 KW to 300 KW System	6 months	85
IV	Adaptation and Modification to Proposed Power Sources Available	3 months	35

11.4 IN SITU 3000 KW POWER SOURCE DEVELOPMENT PROGRAM

During the course of the study, it became apparent that reactor power systems of the 1000 and 3000 KW electrical output could not be easily adapted to depths of 6000 to 20,000 ft. There are many problems associated with the system's physical size and weight that would require a separate study to formulate concepts for the power source when an application becomes apparent and defined in greater detail. This study would involve the formulation of concepts to resolve the material and buoyancy problems, solutions to heat transfer techniques, general arrangements, placement and recovery and the logistics support necessary for an object of this size. Costs and schedules are not included because definitive criteria should be established before any concept formulation.

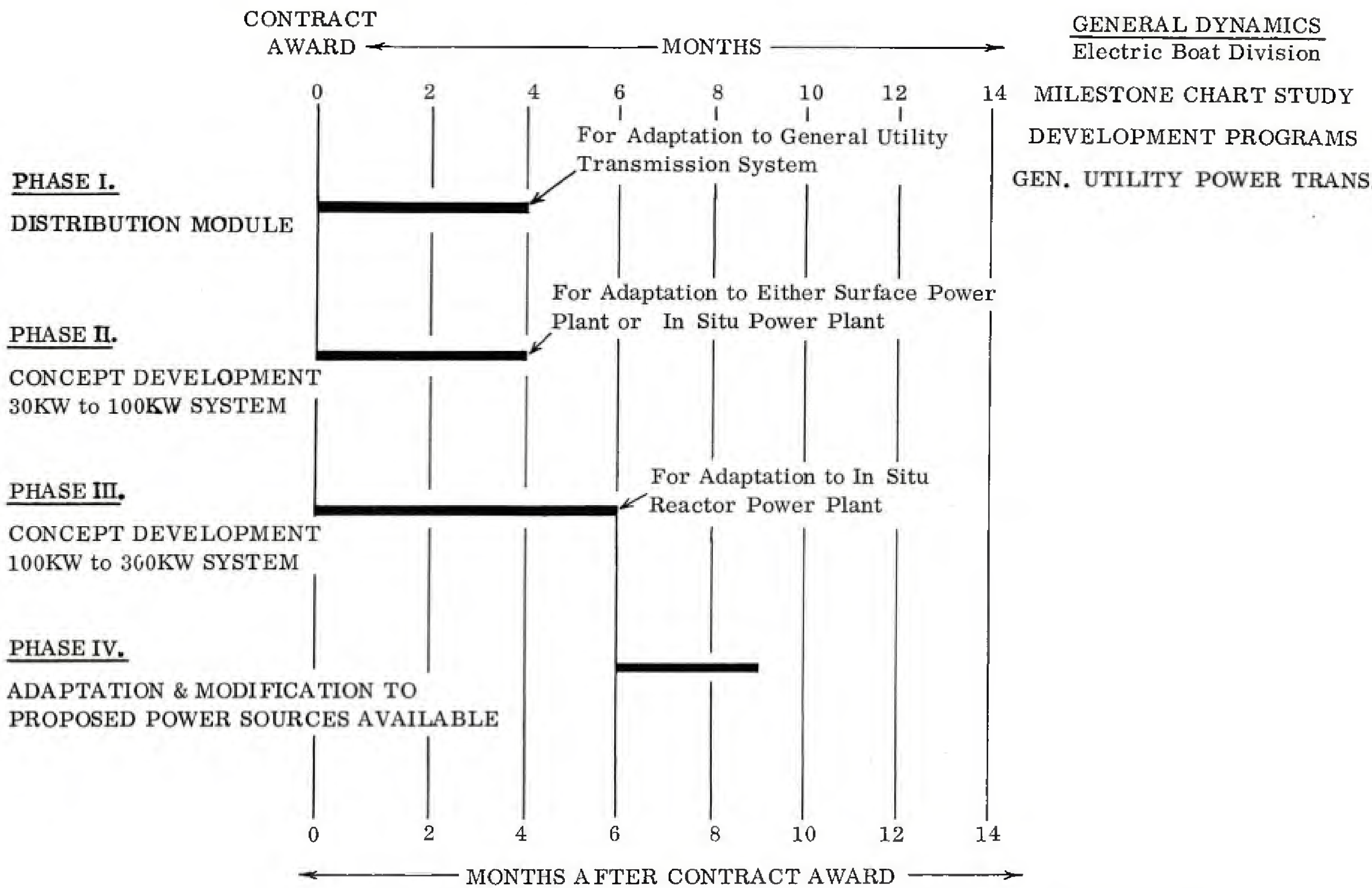


Figure 11-4. General Utility Power Transmission Development Schedule Milestone Chart

APPENDIX A-1

to

CONCEPTUAL STUDY OF

to

DEEP OCEAN INSTALLATIONS (U)

Simplex Wire and Cable Company has performed a "FORTRAN" computer run for polyethylene and cross-linked-polyethylene (C-L-P), insulated submarine cables in the 5000, 15,000, 34,500, 69,000 and 115,000 volt classes, with readouts for: receiving end voltage magnitude (E_R mag), phase angle of E_R (angle E_R), sending end current magnitude in amperes (I_S mag), phase angle of I_S (angle I_S), and percent voltage regulation (VR) for one mile increments from one mile to 50 miles.

Table A-1 indicates the representative wire sizes used for the computer run and shows: type cable (*single conductor 1/C or three conductor 3/C) wire size or MCM, type insulation used (**polyethylene or C-L-P), and the voltage class. The ampacity and line capacity in MVA is also shown for comparison of the two types of insulation.

The C-L-P was used in the study for its greater current carrying capacity (ampacity), which allows for possible load growth and a higher operating temperature. The higher operating temperature will allow higher magnitudes of fault current for slightly longer periods without damage to the insulation.

The environmental conditions imposed on the conductors are:

Copper temperature	=	80°C for poly insulation
Copper temperature	=	90°C for C-L-P insulation
Water temperature	=	20°C
Load power factor	=	0.85
Load factor	=	100%

Table A-1

Type* Cable	Wire Size or MCM	Type** Insulation	Voltage Class in Volts	Ampacity Amps.	Line Capacity MVA
3/C	6	poly	5000	120	.600
3/C	1/0	poly	5000	274	1.370
3/C	4/0	poly	5000	408	2.040
3/C	500	poly	5000	668	3.340
3/C	1000	poly	5000	922	4.610
3/C	6	C-L-P	5000	125	.625
3/C	1/0	C-L-P	5000	285	1.425
3/C	4/0	C-L-P	5000	425	2.120
3/C	500	C-L-P	5000	695	3.480
3/C	1000	C-L-P	5000	960	4.800
3/C	2	poly	15000	206	3.090
3/C	2/0	poly	15000	303	4.550
3/C	4/0	poly	15000	399	5.990
3/C	500	poly	15000	644	9.660
3/C	1000	poly	15000	889	13.300
3/C	2	C-L-P	15000	223	3.340
3/C	2/0	C-L-P	15000	327	4.900
3/C	4/0	C-L-P	15000	431	6.460
3/C	500	C-L-P	15000	695	10.400
3/C	1000	C-L-P	15000	960	14.400
					CAP. MVA
3/C	1	poly	34500	225	7.7
3/C	2/0	poly	34500	298	10.3
3/C	4/0	poly	34500	394	13.6
3/C	500	poly	34500	639	22.0
3/C	1	C-L-P	34500	244	8.4
3/C	2/0	C-L-P	34500	322	11.1
3/C	4/0	C-L-P	34500	426	14.7
3/C	500	C-L-P	34500	690	23.8
1/C	250	poly	69000	355	24.5
1/C	500	poly	69000	444	30.6
1/C	1000	poly	69000	538	37.2
1/C	500	poly	115000	433	49.8
1/C	1000	poly	115000	527	60.6

APPENDIX A-2

Since Appendix A-1 discusses the computer run and the mention of conductor operating temperature and fault current effects, it is appropriate here to briefly discuss these two factors which appreciably affect the operating life of a cable.

Temperature limits are imposed on cables to eliminate or minimize damage to the cable due to the detrimental effects of high temperature on the insulation. Another consideration would be the effect of temperature increase on the resistivity of the conductor.

Resistance of a conductor depends directly on the length of the circuit and, inversely, upon the cross-sectional area of the conductor.

$$R = \rho \frac{L}{A} \qquad (1)$$

where R = resistance in ohms,

ρ = resistance of one mil foot of conductor, (10.4) for copper,

L = length of the circuit in feet,

A = area of the conductor in circular mils.

A resistance change with temperature may be expressed as

$$R_T = R_o (1 + \alpha t) \qquad (2)$$

where R_T = resistance at temperature t°

R_o = resistance at O°C.

α = temperature coefficient of resistance of copper taken as 0.00427 at 0°C.

For example, if the resistance of a copper conductor is 10 ohms at 0°C, and it is desired to know its resistance at 20°C, then using (2) and substituting,

$$R_T = 10 \left[1 + .00427(20)\right] = 10.854 \text{ ohms;}$$

but most temperature problems are not at 0°C; therefore, a method is needed to find the resistance due to a change from normal operating temperature (e.g. 80°C, Appendix A-1) to a higher operating temperature:

R_1 and R_2 are resistances corresponding to

temperatures t_1 and t_2.

by equation (2)

$$R_1 = R_o (1 + \alpha t_1) \text{ and}$$

$$R_2 = R_o (1 + \alpha t_2).$$

These equations are divided:

$$\frac{R_1}{R_2} = \frac{1 + \alpha t_1}{1 + \alpha t_2}. \qquad (3)$$

If α for copper at 0°C is = .00427,

$$\frac{1}{\alpha} = 234.5 \text{ and} \qquad (4)$$

$$\frac{R_1}{R_2} = \frac{234.5 + t_1}{234.5 + t_2}.$$

The temperature coefficient of copper at any initial temperature other than 0°C may be found by solving equation (2) for α.

$$\alpha_1 = \frac{1}{234.5 + t_1}. \qquad (5)$$

Thus the temperature coefficient at 80°C is

$$\alpha_{80} = \frac{1}{234.5 + 80} = .00319.$$

A #6 AWG poly-insulated cable has a resistance of 0.412 ohms at 80°C. What is its resistance at 150°C, the temperature limit due to short circuit conditions?

$$R_2 = 0.412 \frac{(234.5 + 150)}{(234.5 + 80)} = .503 \text{ ohms.}$$

To calculate the temperature rise of a conductor with current flowing throught it,

$$t_2 - t_1 = \left(\frac{R_2 - R_1}{R_1}\right)\left(\frac{1}{+ t_1}\right). \qquad (6)$$

Another consideration mentioned in Appendix A-1 was the condition of short circuit magnitude and its effect on temperature rise. An explanation of this limit and Figure A-2 follows:

Recent increases in the KVA capacity of power cables (Appendix A-2, Figure A-1) may result in short circuit currents of a magnitude such that the conductor insulation may be seriously damaged by the resulting high conductor temperatures.

As a guide in preventing damage, maximum allowable short circuit temperature has been established and is for the polyethylene insulation 150°C.

Figure A-1 shows the current which, after flowing for the time indicated, will produce this temperature for the conductor sizes shown. The short circuit capacity, the conductor cross-sectional area, and the circuit breaker opening time should be such that the maximum fault current is not exceeded.

Figure A-1 is shown for the polyethylene insulation material as specified by IPCEA. It is known that the continuous operating temperature of C-L-P is higher than poly and that the short circuit current limit is somewhat higher than shown.

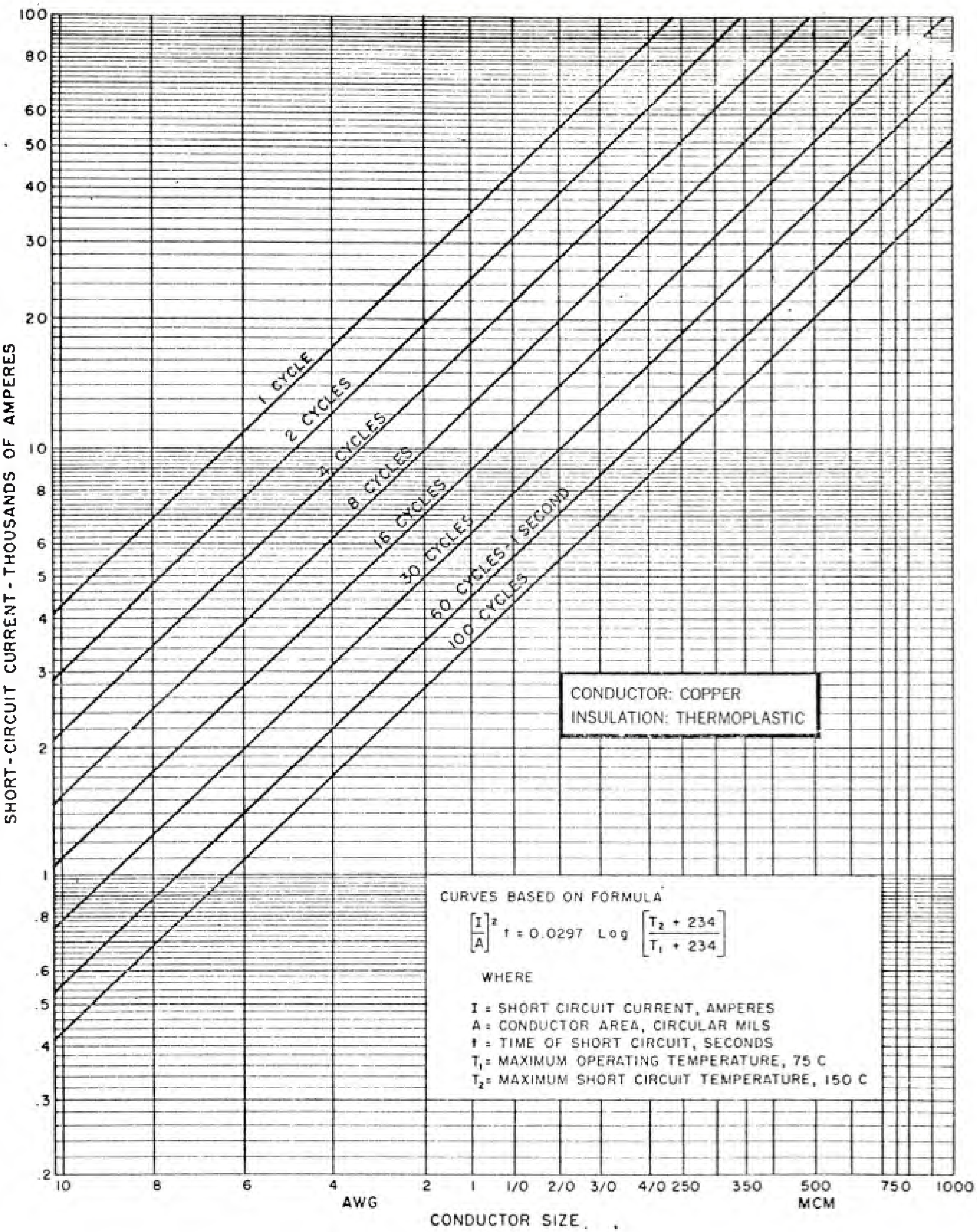


Figure A-1. Short-Circuit Currents for Insulated Cables

APPENDIX B

UNDERWATER POWER TRANSMISSION SYSTEMS

POWER CABLE INSTALLATION

Prepared for

General Dynamics Corporation

Electric Boat Division

Groton, Connecticut

By

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Hydrospace Systems Division

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Newington, New Hampshire

Section I

POWER CABLE INSTALLATION - MOORED SURFACE POWER SOURCE

The following discussion covers the installation of a submarine power cable from a power source moored on the ocean surface to a load module on the ocean floor, in water depths of 600 and 6000 feet. Applicable lengths of power cable are 1000 and 10,000 feet respectively. Of necessity, this discussion is in broad general terms.

The power cable involved is a 3-conductor cable with two layers of armor wire (reverse lay) to provide a non-rotating or balanced torque construction. The cable considered has an outside diameter of two inches and weighs 4.2 pounds per foot in air. The cable will be handled on a reel and be in one continuous length (either 1,000 or 10,000 feet). Reel dimensions are: head diameter - 120"; traverse - 90"; and drum diameter - 60". The combined weight of 10,000 feet of cable, reel and reel stand is approximately 29 tons.

Basic assumptions predicating the following implantment discussion are:

1. The power source is at the implantment location, and moored on a four point moor.
2. The load module is being carried and implanted by a separate vessel.
3. Adequate tug or assisting boat services are available.
4. The load module will be located on the ocean floor outside of the power source "watch-circle".

The cables will be furnished complete with end terminations, including connectors, and floatation device accessories. The load module and power source will be required to have a bellmouth at the cable connection point to prevent bending of the cable to a radius less than the minimum bending radius (5 feet). Such bending could occur during heavy seas, implantment or retrieval if protective devices are not provided.

Floatation devices consisting of a spherical buoy and suitable cable connectors will be utilized to keep the cable in a verticle position over the load module, and to support the catenary between the buoy and power source. In depths greater than 4,000 feet the upper buoy will be at the 2000 feet mark. The number of buoys to be included in the cable will be specified.

A large barge is recommended for cable implantment. Required major implantment equipment includes: the cable reel, reel stand, reel drive, cable capstan, cable overboarding sheaves, and a crane to facilitate handling cable buoys and other large items. Generating equipment will be needed for a power source. Supporting services such as tugs, small boats, and divers should be at the site.

The installation commences with attaching the cable to the load module. This can be done by bringing the cable barge alongside the load module craft and lifting the cable on board. A second method would be to float (with small inflatable floats) the end of the cable on the surface and tow it to the load module craft with a tug or small boat. The floats being detached when the connection is complete.

When the cable is connected, the load module is overboarded and lowering commenced. Simultaneously, the cable will be payed out by the cable barge. Lowering continues until the first cable buoy attachment is required. At that stage, the cable must be stopped off and the buoy attached. When installed, the buoy is overboarded from the barge and lowering of the load module and paying out of the cable resumed. This procedure is repeated for each cable buoy attachment.

When the load module bottoms, the lowering wire slipped and recovered, the load module craft should stand clear. At this time, the cable barge will move toward the power source - paying out cable. The end of the cable can be floated to the power source, and the connection made. Upon completion of connecting, the small surface floats are removed and the cable lowered into the water.

There is considerable risk of damage to the cable involved in using a surface power source due to chafing, twisting, parting of buoy mooring wires, and movement of the buoy due to wind and sea.

Similar installations have been accomplished by Simplex Wire and Cable Company in the AUTEC complex and the Tongue of the Ocean Area.

Section II

POWER CABLE INSTALLATION

SHORE-BASED POWER SOURCE

This section discusses the installation of a ten-mile 3-conductor 15 KV power cable from a load module on the ocean floor to a shore-based power source. Many factors, such as bottom conditions, depths, tide and current data are unknown which have an effect on the type and size of cable ship. Photos are shown on page B-5.

The cable diameter is approximately 3 inches and cable weight is estimated at seven pounds per foot. The cable would be furnished in one continuous length with a termination and connector on the load module end. The shore end would be capped and sealed.

An intermediate landing craft type ship has been proven to be an excellent vessel for an implantment of this type. Simplex Drawing ND-2068 illustrates an LSM type ship outfitted for a similar project. The cable would be loaded at the manufacturers plant and the cable ship dispatched to the implantment location.

It is assumed that the load module would be transported and lowered from a separate vessel. Therefore, at arrival on site the cable ship would float the cable end on the surface (using inflatable floats and a towing craft) to the module carrying vessel. It would be hoisted on board and the necessary electrical and strength connections made.

The load module would then be overboarded and lowered to the bottom with the cable ship paying out cable and standing well clear of the module lowering vessel. When the module is on the bottom, the lowering line slipped and retrieved and the cable ship then procedes to the shore landing, paying out cable en route. This general principle is utilized in either shallow or deep water.

The method of landing the shore end may vary somewhat depending upon the nature of the site. If possible the landing craft type vessel can work well into shallow water. When beached, or nearly so, the cable ship floats the shore end into the site. If the slope of the landing area is steep enough, the ship may be able to beach out near the waterline. In this instance, a bight, or the end can be passed ashore. Once the cable is ashore it is led to the terminal box, cut, and anchored in place. Trenching is recommended in surf and beach areas for protection. It may be found necessary, due to shore landing conditions to land the shore end prior to laying the seaward cable. If this is required, a short length is laid, buoyed off, and spliced to the deep sea cable after it has been laid.

For installing a fifty mile length of power cable, the general procedure would be as noted above. The only major change would be utilizing a larger ship, such as a Landing Ship Tank type vessel, to adequately cope with the increased weight of cable involved. Simplex Drawing NE-897 illustrates the outfitting of such a vessel used on a recent installation project in the San Juan de Fuca Straights.

It will be noted that this power source approach and the implantment of its cable is not as complex an operation as with the moored surface power source.

Figure B-1. Trenching the Shore End

Figure B-2. Floating Shore End of Cable to Ship

Figure B-3. Laying Sea End of Cable

Figure B-4. Tensioning Control Console and Capstan

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13. ABSTRACT

The study considered the technical feasibility and limits of transmitting electrical power to deep ocean installations and to provide comparisons of various power sources applicable to underwater power transmission systems. (U)

The most serious limitation associated with obtaining usable power at deep ocean depths is the present limitation of watertight cable connectors. There are mechanical and electrical problem areas associated with underwater electrical connectors and hull penetrations used to transmit power to submerged loads encapsulated in a pressure hull. (U)

Usable AC power - 30 KW to 3000 KW - can be supplied from surface-tendered power plants to deep ocean installations at depths from 600 ft to 20,000 ft within the present state-of-the-art and without technical limitation but neglecting connector limitations. (U)

Usable power of 30 to 1000 KW from shore-based power sources can be supplied to deep ocean installations from 600 ft to 20,000 ft and 3000 KW from 600 ft to 10,000 ft within the present state-of-the-art without technical limitations but neglecting connector limitations. (U)

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13. ABSTRACT (Continued)

For in situ power locations, the Reactor Power Plant Systems are the most cost effective for power ranges of 30 KW and larger. Within the present state-of-the-art in situ power plants can be deployed to supply 30 KW to 300 KW load requirements at depths from 600 ft to 20,000 ft. Load levels of 1000 KW and 3000 KW are currently depth limited to 2000 ft by hull and heat removal system technology. (U)