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Technical Report

DEEP OCEAN POWER SYSTEMS

September 1968

NAVAL FACILITIES ENGINEERING COMMAND

NAVAL CIVIL ENGINEERING LABORATORY

Port Hueneme, California

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DEEP OCEAN POWER SYSTEMS

Technical Report R-597

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by

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ABSTRACT

The objective of a study program on deep ocean power transmission systems was to determine the technical and economic feasibility of transmitting electrical power of 30, 100, 300, 1,000, and 3,000 kw to ocean depths of 600, 2,000, 6,000, 10,000, 15,000, and 20,000 feet.

Environmental conditions of the sea and their effects on the elements of an undersea power system are discussed. Various power system concepts are developed and evaluated in the report. Design approaches and related studies used in the selection of the most cost effective system concepts are presented, as are preliminary designs of a few selected concepts. Recommended programs for the development of system elements considered beyond the state of the art are also included.

It was concluded that within the present state of the art (1) 30 to 300 kw of usable AC power can be supplied from in-situ power plants at depths of 600 to 20,000 feet and 1,000 kw at depths of 600 to 2,000 feet; (2) 30 to 3,000 kw of usable AC power can be supplied from surface-tendered power plants to depths of 600 to 20,000 feet; and (3) 30 to 1,000 kw of usable AC or DC power can be supplied from shore-based power plants to depths of 600 to 20,000 feet and up to 3,000 kw to depths of 600 to 10,000 feet.

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INTRODUCTION

The U. S. Navy has long recognized the importance of the world's oceans in military tactical operations. Surprise attack from beneath the sea is a serious threat to our country, and the Navy is particularly aware of this problem. This awareness has generated an ever-expanding program of ocean research.

One of the major obstacles in the development of deep ocean facilities is the unavailability of reliable electrical power for life support, lighting, communications during the construction phase, and later, for system operation as determined by the mission of the facility. A study to determine the feasibility of providing electrical power to deep ocean installations or load modules was undertaken at the Naval Civil Engineering Laboratory (NCEL) a little over a year ago.

The basic study parameters established for the transmission systems serving deep ocean bottom installations were power levels of 30, 100, 300, 1,000, and 3,000 kw at ocean depths of 600, 2,000, 6,000, 10,000, 15,000, and 20,000 feet. The transmission systems would be supplied from either shore-based, surface-tendered (floating), or in-situ power sources. The objective of the study was to determine the economic and technical feasibility limits of deep ocean electrical power systems and to establish preliminary design criteria for a few selected systems. An evaluation of feasible power sources was included within the scope of the study program. The study was accomplished in-house and by contract with Electric Boat Division of General Dynamics.*

This report presents a discussion of the environmental conditions of the sea and their effect on the elements of an underwater power system. Various power system concepts and configurations are developed and evaluated within established design and environmental constraints. Design approaches and related parametric studies are discussed for the selection of the most cost effective system concepts. Preliminary designs of six concepts

* Contract Report CR-68.004, "Conceptual Study of Electrical Power Transmission Systems to Deep Ocean Installations," Contract N62399-67-C-0015, Naval Civil Engineering Laboratory, Port Hueneme, California, Aug. 1967.

of underwater power systems selected for immediate development are presented together with budget cost estimates. A recommended research and development program, based on the findings of this study program, is included for those system elements considered beyond the current state of the art.

The constraints and assumptions applied to the study program on underwater power systems include

1. Power levels stated shall be at the load module terminal point.
2. Usable power at the load module shall be defined as 480 volts, 3 phase, 60 Hertz, for a single, nondistributed load.
3. The load module shall be assumed to contain such electrical loads, as lighting systems, motor-driven operational equipment, environmental control systems, and communications or electronic systems.
4. Protective needs shall be restricted to the power transmission system and shall not include mission requirements of the load module.
5. Emergency power levels and type of energy source shall be defined by the power transmission system requirements and not by the mission requirement of the load module.

The results established in this paper are based on the assumptions and constraints described above, and are only intended to provide guidance in making sound management decisions on the future development of underwater power systems.

ENVIRONMENT

An underwater power transmission system is subject to all ocean environmental conditions. The effect of sea states, ocean currents, bottom sediments, temperature variation, salinity, and marine life must be considered in defining design parameters for power system elements. The selection of cable routes and sites for underwater structures depends on a knowledge of bottom profiles and sediment types. Available data and information on the ocean environment are summarized in this section and evaluated as to their effect on the underwater power transmission systems and associated elements.

Sea-Air Interface

Surface conditions for a particular area of ocean deployment are important design parameters in the development of an underwater power transmission system. Hull shapes for surface-tendered systems, as well as for

mooring and cable support systems, are directly influenced by surface forces. Therefore, the sea-air interface must be defined to provide a series of design parameters for the selection of surface hull shapes. Both the average sea state and the worst sea state expected must be considered.

Winds, gales, and storms depend to a large degree on large, well-defined regions of high and low pressures. In general, the geographic distribution of areas of high and low pressure is fairly systematic and does not vary much between consecutive months. However, there are large seasonal differences in pressure patterns and prevailing winds between summer and winter months. Over the oceans, bad weather consisting of widespread cloudiness, precipitation, high surface winds, and turbulence is essentially a phenomenon associated with rising air currents or low-pressure conditions. High-pressure areas, which are regions of descending air or surface divergence, are generally free from bad weather. Regions which are susceptible to bad weather are the low-pressure zones near the equator and the western and northern portions of the oceans in the northern hemisphere, often referred to as the westerlies or migratory lows.

Winds, of course, generate waves on the sea surface, with wave heights a function of wind velocity and duration. The worst conditions of sea state and wave forces are described by the Guidance Committee of the Office of Naval Research in its design recommendations as 150-mph winds and 60-foot waves. These conditions were applied as design parameters for surface structures, including mooring and cable support systems, associated with underwater power transmission systems.

Ocean Currents

Surface and subsurface ocean currents vary in velocity, according to location, reaching an extreme of approximately 5 knots. The average bottom current velocity, on the other hand, does not exceed 1 knot. Equatorial and warm currents on the western sides of the oceans, such as the Gulf Stream, Kuroshio current, East African current, and East Australian coastal current, have speeds of 2 or 3 knots in general.

From recorded observations of surface currents, two design conditions were defined for the underwater power transmission systems. The first is a maximum surface current profile of 6 knots which, in a sense, is the result of average storm conditions. The second is a surface current profile of 3 knots, with stronger subsurface currents to a depth of 3,280 feet. Subsurface current velocities below 3,280 feet are generally agreed to be less than 0.35 knot. At depths below 12,000 feet, design currents may be assumed to be effectively zero.

The design current profiles are shown in Figure 1. These curves may be used with other surface currents of greater or lesser magnitudes by using the same ratio of decay.

Figure 1. Design current velocity profiles.

Ocean Bottom Conditions

The topography of the ocean bottom to a depth of 6,000 feet includes continental shelves, most of the continental slopes, shallow areas of mid-ocean ridges, the borders of atolls and islands, and the tops of some seamounts. Depths to 20,000 feet encompass the remaining portion of the ocean floors, with the exception of deep ocean trenches and canyons, which may extend in depth to more than 35,000 feet. The continental shelves vary from 60 to 1,800 feet in depth and from a scarcely measurable width to greater than 270 miles wide. The average slope of the shelf surface is $0^{\circ}07'$, being somewhat steeper over the inner than over the outer half. Valleys and canyons that cut the continental shelf have slopes as steep as any on land. Shelf sediments are primarily sands, with mud and gravel also common. Sediments of silty clay with sand layers are found at the bottom of the shelf valleys or basins. Sediments of the continental slopes are less well known than those on the shelves. These sediments have a low shear strength that ranges from 0.1 to 15 psi; an average of 1 psi was considered representative.

Bottom Profiles

Knowledge of the underwater terrain is vital to the successful deployment of an underwater power transmission system. Bottom profiling is a prerequisite for establishing cable routes and site requirements and for avoiding potential hazard areas such as steep ledges and narrow valleys.

Since there are great distance-to-depth variations in the ocean bottom profiles, the actual cable length to reach various design depths was used in this study. Table 1 illustrates the variations in average distances involved in reaching the various design depths off of selected coastal regions. A minimum offshore distance of 21 miles and a maximum of 460 miles is noted in the table, with a majority of offshore distances of less than 200 miles, only three distances being greater than 200 miles. Therefore, it appeared feasible to consider cable lengths at multiples of 10 miles, with specific design lengths of 50 and 100 miles. Design distances of bottom-contoured cable lengths were established at 10, 50, 100, and 500 miles.

Table 1. Bottom Profiles of Continental Margins

Region	Average Number of Miles From Coast to Reach a Depth of—					
	600 feet	2,000 feet	6,000 feet	10,000 feet	15,000 feet	20,000 feet
East Coast U. S.	70	150	175	182	190	— ¹
West Coast U. S.	21	28	32	55	162	— ¹
Southeast Asia	110	155	190	208	319	460
South Australia	51	48	72	110	120	— ¹

¹ Ocean does not reach this depth except in isolated instances. Off the East Coast, the West Coast, and South Australia the maximum depth is found approximately 3.5 miles from shore.

Slumping

The slumping or sliding of bottom sediments is a potential hazard to underwater cables and structures. The kind and rate of sedimentation required to produce an unstable slope occurs only in areas of relatively rapid sediment accumulation. These areas include deltas and canyon heads in the inner shelf slopes. 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.

The slumping of bottom sediments can jeopardize structures or cables from either the resultant cascading sediments or turbidity currents. A classic example of turbidity currents caused by slumping was the submarine landslide which occurred in the Grand Banks region in 1929 following an earthquake.* The speed of these turbidity currents has been estimated to be about 50 knots. 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.

Temperature and Salinity

The range of temperature and salinity in the oceans is anywhere from about -2°C and 20‰ to about 30°C and 37‰, with some areas having higher or lower readings. Many of the extreme conditions are found in the Red Sea and the Persian Gulf. The layers of the ocean are generally classified as:

Troposphere:	down to about 300 feet
Thermocline:	from a depth of 600 to 984 feet
Subtroposphere:	from a depth of 984 feet to about 4,000 feet
Stratosphere:	below 4,000 feet

Most of the temperature and salinity variations exist, along with the strongest currents, in the troposphere. In the stratosphere the temperatures and salinities are more uniform.

The maximum vertical temperature and salinity gradients are found between 300 and 600 feet, in the layer between the troposphere and the thermocline. An exception to the above classification occurs in the subtropics, where the thermocline is found at a depth of 500 feet at 20 degrees south and 600 feet at 20 degrees north. This layer rises steadily to a depth of 160 feet at the equator and 10 degrees north. Intensity of the thermocline is greatest in the equatorial areas.

Beneath the thermocline, the vertical temperature and salinity gradients decrease with depth down to the subtroposphere.

* B. C. Heezen and M. Ewing. "Turbidity currents and submarine slumps and the Grand Banks earthquake," American Journal of Science, 1952, pp. 849-873.

Marine Life

Several types of marine organisms attack various materials used in underwater power transmission systems. The need for information and data on the resistance of materials to attack by marine organisms is therefore important. There is considerable published information on the suitability of natural organic materials, such as wood, jute, and hemp, for marine use. Some data are now becoming available on plastics, elastomers, casting resins, and similar materials.

The highest concentration of marine life is found in intertidal regions and down to 600 feet, depending on the penetration of sunlight. Beyond 600 feet, to a depth of approximately 4,000 feet, an abundance of animal life can be found, but plant life is rare. At depths exceeding 4,000 feet, the water temperature approaches freezing, food is scarce and, therefore, marine life is rare. Marine life in this zone consists mainly of borers, such as worms, mollusks, gastropods, hydroids, and sea urchins.

Marine borers are mollusks or crustaceans which bore into a material for food or shelter. Of the crustaceans, the gribble (*Limnoria lignorum*) is the most destructive to cellulose materials. Most borers are found in shallow depths; however, some boring mollusks have been found down to 11,500 feet. Records show that the lead sheath of submarine cables were penetrated by borers at depths of 5,600 feet.

A group of marine organisms attach themselves to exposed surfaces, resulting in what is commonly termed "fouling." Associated with the fouling organisms is a microscopic anaerobic bacteria which, because of its sulfate-reducing character, is predominant in accelerating corrosion and destroying nonmetallic materials. The bacteria are generally single cell organisms, a large number of which are heterotrophic, that attack organic matter and use the carbon as a source of energy. The bacteria play an important role in the biology of the sea and are found in seawater and sediments from shallow depths to the deepest areas of the ocean. Submarine cables, mooring lines, and other power structures are particularly susceptible to deterioration by bacteria since bacteria are most plentiful in seawater as well as in the first few inches of bottom sediment.

Summary

An all-encompassing definition of surface conditions of the world's major oceans is difficult due to the large variations in weather conditions, thermodynamics, and prevailing winds which determine the characteristics of

the first 4,000 feet of water. Below this depth, the major oceans conform to a narrower range of limits. Table 2 presents a summary of critical environmental conditions established as design parameters for the development of underwater power transmission systems.

Table 2. Summary of Environmental Design Parameters

Surface Conditions					
Wind velocity, max (mph)					
150					
Current velocity, max (knots)					
10					
Wave height, max (feet)					
60					
Water temperature (°C)					
29.4					
Salinity (ppt)					
35.0 (or 3.5%)					
Subsurface Conditions	Depth (feet)				
	600	2,000	6,000	10,000	20,000
Water temperature, max (°C)	23.9	18.3	12.8	7.2	7.2
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 Conditions					
Sediment shear strength (psi)					
1.0					

SUBMERGED (IN-SITU) POWER SYSTEMS

In-Situ Power Sources

Numerous energy sources and energy conversion systems are available for power plants located below the surface of the ocean. Power plants for deep ocean use must function with infrequent, periodic exposure to the atmosphere. Many of the problems encountered in developing a power plant

for use in the ocean are related to combining an energy source with a conversion system. The energy sources considered in this study for use below the surface of the ocean are stored thermal energy, chemical energy (including batteries and fuel cells), nuclear reactor energy, and radioisotope energy. Storage of energy by mechanical, electrical, and magnetic methods are not of interest at this time because of their high weight and volume characteristics or their lack of adequate conceptual and development status.

Efficiencies for energy sources vary with capacity, temperature, and operation. In general, the efficiencies of energy sources considered in this study are

	<u>%</u>
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

Energy Conversion. The direct conversion of thermal energy to electric energy can be accomplished by thermoelectric or thermionic devices. Thermoelectric converters are generally reliable, require little maintenance or servicing, and are desirable for low-level power sources. However, their efficiency is extremely low. Large thermoelectric power sources and waste heat rejection systems would be required for power levels of interest to this study. Since this system is limited to low voltage and high amperage output, additional power conversion equipment in pressure hulls may be required. Therefore, thermoelectric conversion was not considered suitable as an underwater power source at the desired power levels.

Thermal dynamic conversion systems are numerous and highly developed. The Brayton, Stirling, and Rankine cycles are the most predominant types used for thermal dynamic conversion.

The Brayton, or gas-turbine, cycle has the lowest overall efficiency. However, it is moderately efficient at high temperatures and at the higher power levels. Brayton systems using oxygen supplied under pressure are more efficient than systems using air or closed-cycle gas because of the lower compression power required.

Stirling cycle engines are currently being developed and are theoretically capable of very high conversion efficiencies. Actual engine efficiencies in earlier engine tests were about 80% of diesel engines up to several hundred horsepower. However, improved performance is considered feasible. An advantage of the Stirling cycle is its inherent low noise level. In size and weight, it compares with the diesel engine. The use of the Stirling cycle as a power source for deep ocean applications was not considered advantageous because of its developmental status and its relatively high cost.

The Rankine, or vapor-turbine, cycle is most commonly used with 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 427°C, the Rankine cycle is more efficient than the Stirling cycle, and an increasing power level favors the Rankine cycle. Rankine cycle equipment is generally available, although considerable engineering and design work is required for maximum economy of weight and space as well as improved efficiencies at low power levels.

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 weight of energy storage materials is relatively high, the lightest being lithium hydride. An estimate of the weight for a lithium hydride storage system, including hardware, is 13 lb/kw-hr. The overall plant efficiency would be about 27%. Since lithium hydride has a low density, this storage material requires a large volume. The material burns and may react violently with moisture in the presence of air. Hydrogen contamination at high temperature is also a problem. The developmental status, the volume and weight units, and the requirement to frequently replenish the thermal energy at the surface do not make the thermal energy storage system attractive for underwater use.

Chemical Energy. Electrical power may be produced by utilizing chemical energy. The two most predominant methods of converting chemical to electrical energy are by direct conversion and by the generation of thermal energy, which is then converted to electrical energy. Methods currently available for direct conversion employ storage batteries and fuel cells. There are a large number of battery and fuel cell systems in existence; however, only a few are practical at this time. Virtually all chemical systems, including batteries, either have oxygen as an initial component or derive oxygen from chemical compounds.

A considerable number of chemical systems using fuel oil and oxygen have been proposed and developed. These include closed-cycle diesel, gas turbine, and steam-gas turbine, known as the Walter cycle. These cycles have

been developed primarily to provide power sources for limited shallow-depth ocean applications for vehicle propulsion. The use of fuel oil results in a waste product, carbon dioxide, which must either be pumped overboard or compressed and stored as a liquid. This problem can be avoided by using hydrogen as fuel.

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 or as monopropellants; however, these systems do not compare with a hydrogen-oxygen system in terms of weight, volume, cost, safety, handling, and waste product disposal.

The use of hydrogen and oxygen as reactants allows the use of a mechanical conversion system, such as a turbine-generator, or direct conversion in a fuel cell. Of these conversion systems, the fuel cell is more efficient, especially at low power levels. Fuel costs range from a low of about \$0.25/kw-hr for the fuel cell and \$0.50/kw-hr for the turbine system.

Some unique problems are encountered in the storage of hydrogen and oxygen within a submersible hull. Cryogenic and high-pressure methods are available for storing these reactants. High-pressure gas storage is only practical when two separate pressure hulls are used, with hull penetrations made to the power source hull. Cryogenic liquids may be stored in a common or separate pressure hull.

Cryogenic and high-pressure storage of hydrogen and oxygen reactants, storage configuration, and methods of transfer to point of usage were analyzed and evaluated for various power plant concepts included in the study program. Cryogenic storage within a common power plant pressure hull was considered the most suitable method since it is the lightest and requires the least volume. The gaseous transfer method could be accomplished by using an external heat exchanger to vaporize the liquid. The power plant's waste heat or seawater would provide the heat source with a backup electrical heater to assure gas delivery in the event liquid flow could not be obtained by the main heat exchanger.

Difficulties and problems associated with the storage and transfer of liquified gases are numerous. Spherical containers are most efficient for the cryogenic storage of gases, but in pressure hulls such containers cause considerable loss in usable volume. On the other hand, form-fit containers weigh more than spherical containers. However, the reduction in size of the pressure hull by the use of form-fit containers results in an acceptable trade-off. Another problem encountered with liquified gas is the increase of pressure due to heat leakage during the holdtime between fueling and power plant operation. Methods which require further study in solving this problem include providing a supply of subcooled liquid to the storage container, using

the fuel during holdtime, and providing a vent capability. The next major problem or difficulty would involve the transfer of gas from cryogenically stored containers. The gas must be delivered at controlled flow rates and pressures. A suitable control system must, therefore, be developed.

Many fuel cell concepts exist for a wide variety of cell types and fuels. At present, fuel cell systems are either in development or prototype stages, with the major effort being applied to the hydrogen-oxygen cell, which is the most advanced type. Hydrazine-air or oxygen cells have also had considerable development effort for land applications because of their relatively low cost and the availability of their fuel supply.

Hydrogen-oxygen cells are of primary interest for underwater power systems because of their high efficiency, high energy content, and easily handled waste product (water), as well as the availability of their reactants (hydrogen and oxygen) from numerous chemical compounds. The hydrogen-oxygen fuel cell power source is lighter than the hydrazine-air type, but requires a pressure hull enclosure. The hydrazine-air cell has potential as an off-hull, pressure-compensated system which would then provide the lightest power source.

The application of hydrogen-oxygen fuel cells as submerged power plants will require a major design and engineering effort. The technical feasibility of fuel cells and the handling of cryogenic reactants has been established for surface and space applications, but the ocean environment presents many problems to be resolved for safe, reliable, and maintenance-free deep ocean fuel cell power sources. Therefore, the feasibility of utilizing suitable fuel cells for deep ocean applications is not apparent at this time, and fuel cells were excluded from the study program.

Lead-acid and silver-zinc battery systems are suitable for submerged use. Both types are in production and have been successfully tested down to the required depth of 20,000 feet. Nickel-cadmium and silver-cadmium batteries are more expensive and offer no advantages. Batteries may be enclosed in pressure hulls or in oil-filled pressure-compensated systems. The selection of enclosure depends on the depth of power plant submergence, on the cost of obtaining buoyancy and on safety. For the unattended system where explosions due to hydrogen gassing are possible, the pressure-compensated system was selected since it is safer, lighter, and less costly.

Batteries alone have a limited energy capacity as the main power source. However, they can function effectively as emergency or auxiliary power sources. The disadvantages of battery systems are the need for inverters for converting DC to AC, the varying output voltage, and the losses involved in multiple energy conversions.

Table 3 presents comparative data for lead-acid and silver-zinc pressure-compensated battery systems. The lead-acid system is more sensitive to temperature, has a higher initial cost because of the buoyancy material required, has a lower replacement frequency, lower battery cost, has approximately five times the deep discharge cycle life, and is three times as heavy as the silver-zinc system. The effects of many variables will result in considerable variation in the cost of the battery system.

Nuclear Reactor Energy. There have been many proposals for underwater power systems which produce electrical power from nuclear energy by means of various fluid and conversion systems. Reactor systems are generally classified by their coolant, namely, gas, liquid metal, organic, pressurized water, or boiling water. A comparison of the various systems with the same overall performance characteristics has shown relatively little variation in total weight, space, and cost. Gas-cooled reactors tend to be larger and heavier and require more complex emergency cooling systems than other reactors. They must be designed against water flooding, which causes a nuclear excursion. Their primary application has been for very large, stationary, land power plants. Liquid metal plants are primarily small and lightweight, have a very short life, and are used for space applications. The liquid metals are highly reactive and corrosive in contact with water. Water leakage will probably result in a total plant loss. Although the plant is designed for unmanned operation, shielding must be provided for test operation and maintenance. Boiling water systems eliminate the need for steam operators by using a direct cycle with higher efficiency; however, weight savings are questionable. Primary applications are experimental and are for large land-based stationary power plants. Organic coolants have poor heat transfer characteristics and require more complex systems with increased overall plant weights.

A pressurized water-cooled reactor was considered the most suitable reactor system for a submerged power plant in the immediate future. The reactor has several advantages. The concept of a pressurized water reactor is well tested and will require a minimum amount of development effort for this application. Besides being a long-life power source, such a reactor is highly reliable and safe. The use of a liquid coolant is most adaptable for providing decay heat removal systems that require no power. In addition, since the coolant retains virtually no radioactivity within a short interval after shutdown, shielding is minimized. The coolant system is readily sealed to minimize loss of coolant and eliminate radioactive carry-over to conversion equipment. The pressurized water coolant provides a fluid which is common to both reactor and conversion systems, thus making for simplicity of design.

Table 3. Characteristics of Pressure-Compensated Batteries
(All values per net usable energy)

Battery Type	Submergence Depth (ft)	Temperature (°C)	Battery System			Battery Plus Syntactic Flotation		
			Cost ¹ (\$/kw-hr)	Weight (lb/kw-hr)	Displacement (lb/kw-hr)	Cost (\$/kw-hr)		Weight (lb/kw-hr)
						a ²	b ³	
Lead-Acid	surface 20,000	23.9	225	125	64	775	1,325	215
		1.1	350	175	90	1,100	1,850	300
Silver-Zinc ⁴	surface 20,000	23.9	650	46	23	850	1,050	80
		1.1	800	55	27.5	1,050	1,300	95

¹ Cost does not include switchgear, charging equipment, inverters, or protective equipment.

² Syntactic flotation at \$6/lb.

³ Syntactic flotation at \$12/lb.

⁴ Costs estimated with silver at \$1.29/oz.

The pressurized water-cooled reactor with a steam conversion system has seen extensive application in submersibles. However, major problems encountered in the use of this power plant below the ocean surface include design and fabrication problems relating to equipment size, orientation, pressure hull limitations, and waste heat removal. Additional problems that must be considered are those related to transportation, deployment, and operation. These difficulties will increase with both power level and operating depths.

The wide range of power levels established for this study program resulted in the establishment of two power plant arrangements, or concepts, based on power level. The 30-kw, 100-kw, and 300-kw plants are arranged in a vertical cylinder, as shown in Figure 2.* Reactors are generally designed to occupy a vertical cylindrical space for safety requirements of gravity rod insertion, natural convection heat removal, and refueling. Turbine-generator equipment, which is located in the conversion machinery area, is normally designed for horizontal orientation to achieve long-life performance. The vertical cylinder arrangement is suitable for deployment but not for transportation by towing. The plant can readily be designed for nearly horizontal towing and vertical operation. The reactor location at the bottom places the reactor core at a maximum distance from accessible areas. The shielded water tank, with large areas exposed to the sea, provides

Figure 2. In-situ power plant arrangement for 30, 100, and 300 kw.

* A concept for a 30-kw power plant was developed under contract to Gulf-General Atomic Inc. and is contained in Contract Report No. CR68.011, "TRIGA Oceanographic Power Supply for a Manned Underwater Station." (In process of publication.)

a 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 close to the heat source and attenuates radiation to the control area. The control area is at the maximum distance from radioactive sources in the cylinder. The vertical cylinder arrangement is, in general, preferable for deployment on the ocean bottom due to its hydrodynamic characteristics, its small area of contact with the bottom, and its stability.

This conceptual arrangement is designed on the basis that a single turbine generator set will be used for the 30-kw or 100-kw plant. The 300-kw plant will probably require two 150-kw horizontal units to fit within the hull diameter, or one single vertical unit, or a high-speed, high-frequency unit. Since a 300-kw plant will require a larger hull for heat transfer than the 30-kw or 100-kw plant adequate space is available for any of the three alternative 300-kw arrangements. 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.

Waste heat is transferred from the power plant primarily by the turbine exhaust steam condensing directly on the inside surface of the pressure hull. There are many problem areas to be resolved and experimental data that must be obtained to ensure the feasibility of the hull as a heat transfer surface. The provision and testing of reliable protective coatings are required on the seawater side of the hull for high thermal conductivity and high resistance to fouling.

There are two other heat removal systems within the power plant which do not appear to pose any development problems. The freshwater machinery-cooling system rejects its heat to the shield water, and an air conditioning system for the plant control systems rejects the heat through the hull via direct contact with plastic channels bonded to the hull.

The 1,000-kw and 3,000-kw plants are arranged in a horizontal cylinder, as illustrated in Figure 3. This arrangement would have features similar to the smaller plants. Some additional problems are noted for the larger plants. A vertical arrangement is possible at shallow depths, but there is little difference in plant size or cost between the vertical and horizontal arrangements for the large plants. However, to ensure adequate natural convection heat transfer from the core, a high-power reactor is generally oriented permanently in one direction once it has been operated. It must also be transported in the same orientation.

At these power levels, the pressure hull required to house the equipment is inadequate as a sufficient heat transfer area. 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 technology has not yet been developed that would allow the hull penetrations required for adequate heat removal at the high power levels for depths of 6,000 feet and more.

In addition to the feasibility of fabricating pressure hulls of adequate size to enclose the power plant equipment, a suitable technique for heat removal must be developed for large submersible power plants. Because of the major developmental effort that would thus be required, the larger power plants of 1,000 and 3,000 kw at depths of 6,000 feet and over were eliminated from further consideration in this study program.

A potential means of meeting large power loads is to use several small power sources. However, some of the technical problems involved in paralleling multiple units are related to electrical characteristics, deployment, and retrieval. In addition, the cost would be very great for multiple units.

Figure 3. In-situ power plant arrangement for 1,000 and 3,000 kw.

The physical parameters of pressure hulls for various reactor power plants at operating depths of interest are shown in Table 4. 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 vary from 9 feet for the 30-kw plant to 21 feet for the 3,000-kw plant. Two factors which will significantly modify these dimensions are the 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, HY 80 and HY 130, which contain nickel with cobalt impurities, are not the most effective for shielding. HY 180 steel contains almost 5% cobalt and requires diameters approximately 2 feet larger than the lower strength steels. Material activation is of importance in the design of the pressure hull.

A major consideration in the design of the reactor plant is the refueling cycle, which may have a significant effect on cost. In addition to the direct cost of the refueling operation, there are costs for retrieving and transporting the power plant to a refueling site, providing refueling facilities, and being without the plant during refueling operations. Full-power refueling cycles based on full-time operation range from more than 10 years for 30 kw to about 1 year for 3,000 kw, depending on the particular plant selected. Selecting larger reactors for smaller power plants can generally extend the refueling cycle, but this must be traded off against increased acquisition costs, weight, and size. A larger refueling cycle is also possible by increasing the efficiency of converting thermal energy to electric energy.

Radioisotope Energy. The radioisotope power supply considered for the study program employs a steam Rankine cycle conversion system for obtaining electrical power from the heat produced by the decay of radioisotope fuel. Only the 30-kw power level was investigated because of the high fuel inventory cost, estimated at \$70,000/kw, and fuel use cost, estimated at \$12,000/kw/yr. The break-even power level is dependent on many factors, but in general is substantially less than 100 kw. For larger radioisotope plants, extrapolation from the figures for the 30-kw plant should provide a reasonable estimate since the major investment and operating costs are either due to the fuel or proportional to it.

The 30-kw radioisotope power plant of interest here is completely self-contained within its own pressure hull. The hull is equipped with cable connections for supplying 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 5 presents tentative system data on the plant.

At the 30-kw power level, the minimum size of the pressure hull is determined by the requirement for adequate hull area for the transfer of waste heat. Each hull is sized to provide adequate heat transfer for operation at all depths from 600 feet to its design depth and at a maximum ambient temperature for each depth. Heat is transferred from the power plant hull to the sea by natural convection for both reliability and safety.

The 30-kw radioisotope power plant is estimated to weigh 14,000 pounds, including all machining and shielding. Radiation levels at the outer surface of the pressure hull are limited to 200 milliroentgens/hour maximum, with considerably lower levels for access and maintenance.

Spherical pressure hulls will result in a minimum hull weight-to-displacement ratio. However, the hull shape is not critical. For design considerations and feasibility of fabrication, it appears that hull shapes made of ring-reinforced cylindrical sections and hemispherical heads would be desirable.

Table 4. Power Plant Hull Parameters

Power Level (kw)	Depth (ft)	Type of Steel	Inside Diameter (ft)	Length (ft)	Total Weight (lb)	Displacement (lb)	Buoyancy (lb)
30	600	HTS	9	35	123,500	130,500	+7,000
	2,000	HY 80	9	35	135,000	130,500	-4,500
	6,000	HY 130	9	35	167,000	130,500	-36,500
	10,000	HY 130	9	35	212,000	130,500	-81,500
	15,000	HY 180	9	35	221,000	130,500	-90,500
100	20,000	HY 180	9	35	260,000	130,500	-129,500
	600	HTS	10	36½	156,000	166,500	+10,500
	2,000	HY 80	10	36½	175,000	166,500	-8,500
	6,000	HY 130	10	36½	215,000	166,500	-48,500
	10,000	HY 130	10	36½	268,000	166,500	-101,500
300	15,000	HY 180	10	36½	283,000	166,500	-116,500
	20,000	HY 180	10	36½	333,000	166,500	-166,500
	600	HTS	10	55	217,000	258,500	+43,500
	2,000	HY 80	10	54	245,000	253,500	+10,500
	6,000	HY 130	10	54	322,000	253,500	+51,500
1,000	10,000	HY 130	10	61	474,000	288,500	-131,500
	15,000	HY 180	10	66	550,500	315,500	-138,500
	20,000	HY 180	10	73	739,000	348,500	-271,500
	600	HTS	21	46	640,000	860,000	+220,000
	2,000	HY 80	21	46	775,000	860,000	+85,000
3,000	6,000	HY 130	-	-	-	-	-
	10,000	HY 130	-	-	-	-	-
	15,000	HY 180	-	-	-	-	-
	20,000	HY 180	-	-	-	-	-
	600	HTS	21	51	780,000	980,000	+200,000
3,000	2,000	HY 80	21	51	960,000	980,000	+20,000
	6,000	HY 130	-	-	-	-	-
	10,000	HY 130	-	-	-	-	-
	15,000	HY 180	-	-	-	-	-
	20,000	HY 180	-	-	-	-	-

Note: Dashes indicate that the diameters and hull sizes required for equipment and considerations of heat transfer require major development.

Table 5. Tentative Data for the Radioisotope System

General	
Isotope	Co ⁶⁰
Refueling cycle (years)	3
Initial fuel loading (kw)	300,000
Fuel loading, end of refueling cycle (kw)	200,000
Electrical power (kw, net)	32
Overall thermal efficiency (%)	16
Steam Cycle	
Turbine inlet pressure (psia)	150
Turbine inlet temperature (°C)	371
Condenser saturation temperature (°C)	54 (max)
Thermal efficiency at turbine shaft (%)	20

Radioisotope power plants would have limited application in underwater power systems because of the large volume per unit of energy available. At the higher power levels of interest to the study program, nuclear power plants were preferred for submerged power systems.

In-Situ Plant Hulls

Hull designs for in-situ plants depend on the hydrodynamic characteristics of the deployment and recovery method selected. The in-situ power source and associated energy conversion equipment could be incorporated into a pressure hull as a power module for deployment to the operational depths. The load module, which was assumed to contain conventional operational systems, as described earlier, could be deployed completely independent of the power module. However, since wet connectors required to mate the power module with the load module in the deployed state do not exist, both modules must be deployed together, preferably on a common foundation. Mating the two modules at the surface with long cables and then deploying each module separately was considered hazardous to mission reliability.

Safety was considered of prime importance to ensure the integrity of the entire system. A stress and material analysis of the in-situ power plant pressure hull was required to determine the most cost effective hull for the

depths under consideration. A configuration analysis of the load module was also required to compare all possible deployment concepts. A detailed investigation of the hydrodynamic phenomena influencing the submerged station was necessary to establish methods of deployment and recovery.

Pressure hulls for in-situ plants would be constructed in a manner similar to existing submersible hulls. The only two pressure hull shapes worthy of consideration for the depths under study are the sphere and the cylinder. The shape selected depends on both the mission definition and efficient space utilization. Relative volume effectiveness of the two shapes is 53% for spheres, 59% for horizontal cylinders, and 93% for vertical cylinders.

Pressure Vessel Analysis. There are two modes of failure which must be considered for thin shells subjected to external pressures: collapse by yielding and collapse by buckling. Minimum factors of safety applied to these failure modes were established at 1.5 and 2.0, respectively, with local stresses limited to 3/4 of the yield stress at operating depth.

The following equation was used for computing the collapse of spheres by yielding:*

$$P_{cy} \cong \frac{2 h \sigma_y}{R_{LO}}$$

The basic equation used for computing the collapse of spheres by buckling was

$$P_{cb} = 0.86 \sqrt{E_S E_T} \left(\frac{h}{R_{LO}} \right)^2$$

or for elastic buckling

$$P_{cb} = 0.84 E \left(\frac{h}{R_{LO}} \right)^2$$

where E = modulus of elasticity
 E_S = secant modulus of elasticity
 E_T = tangent modulus of elasticity
 h = shell thickness, in.

* The reader is referred to the list of symbols on the foldout page at the end of this report.

P_{cb} = critical buckling pressure, psi

P_{cy} = critical yielding pressure, psi

R_{LO} = local outside radius of a spherical shell, in.

σ_y = yield stress, psi

The equations governing the collapse of cylinder shells are considerably more complex than for spheres. A method developed by General Dynamics* was used to analyze the collapse by yielding of a cylinder and hemispherical cylinder heads. This method calculates outer fiber, midfiber, and inner fiber stresses at frames and midbay as well as deflections and local stresses.

Computations were made for two types of collapse of a cylinder by buckling. Lobar buckling was approximated by

$$P_b = \frac{2.42 E}{(1 - \mu^2) \frac{3}{4}} \left[\frac{\left(\frac{h}{2a} \right)^{5/2}}{\frac{L}{2a} - (0.45)(2ah)} \right]$$

Buckling by instability was approximated by

$$P_b = \frac{E h}{a} \left[\frac{m^4}{\left(n^2 - 1 + \frac{m^2}{2} \right) (n^2 + m^2)^2} + \frac{(n^2 - 1) E I}{R^3} \right]$$

where P_b = lobar buckling, psi

E = modulus of elasticity

h = shell thickness, in.

a = nominal outside shell radius, in.

μ = Poisson's ratio

n = number of lobes

m = a/L

L = effective length of cylinder, in.

I = moment of inertia of shell frame

R = radius of frame-shell section, in.

* General Dynamics, Electrical Boat Division. "Circular Cylindrical Shell with Bulkheads and Intermediate Stiffeners Subjected to Hydrostatic Pressure."

The above computations are considered conservative for nominal pressure hull collapse loads. However, a detailed analysis of the final structure design for a submersible hull is required before definitive collapse pressures can be defined.

Material Selection. The selection of materials for in-situ plant pressure hulls depends on submergence depth, size, cost, and weight-to-displacement ratio. HTS and HY 80 steels were selected for hulls at depths of 600 to 2,000 feet, HY 130 steel for hulls at depths of 6,000 to 15,000 feet, and HY 180 steel for hulls at depths of 15,000 to 20,000 feet. As stronger material becomes available, a reevaluation of the material selection should be made for these depths.

Corrosion and Fouling Protection Systems. A 5-year or more no-maintenance mission was established for the in-situ plant pressure hull. To meet this requirement, very high quality corrosion protection systems are required. Paint coating systems, metallized coatings, antifouling paints, and cathodic protection systems were considered. The preferred systems selected for a 5-year no-maintenance life include the following.

1. 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-base antifouling paint on the outer surface.
2. 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 antifouling paint.
3. Cupronickle plating systems for steel hulls applied by explosive or roll bonding or flame spraying to provide a corrosion-resistant surface with inherent antifouling characteristics.

For long life, supplementary cathodic protection should be provided in areas where noble metal is concentrated or where stray electrical currents can occur. Both sacrificial zinc anode and impressed current systems can serve this purpose. The preferred protective coatings would have to be analyzed further to determine their relative heat transfer characteristics on pressure hulls used as heat exchangers.

Analysis of In-Situ Plant Configuration

Several constraints, assumptions, and requirements dictate the configuration or arrangement of the in-situ power plant and its deployment. Since it was established that the load module would be deployed with the

power module, additional assumptions must be made. For the purposes of this study, the load module is assumed to have the same volume as but less weight than the power module. It was also assumed that the load module was contained in a single cylindrical or spherical pressure hull. If the load was inhabited, personnel shielding and personnel transfer chambers, which add weight and volume to the load module, would have to be considered.

Several arrangements were considered for the power and load module configurations. The conceptual arrangements included power plant and load modules side by side, load module mounted atop the power plant (piggy back), load module remotely located from power module, and load module and power module in a common pressure hull. Figure 4 illustrates some of the conceptual arrangements considered in this study.

The in-situ plant configuration would be selected on the basis of power level, load module dimensions, load module weight, and load module mission. The power level effect is determined by the requirement for vertical cylinder or horizontal cylinder pressure hulls. A limitation on the selection of a configuration can be made by considering the weight of the load module. To avoid requirements for trimming, the load module could be situated side-by-side with the power module if the weights are identical. If the weights are not equal, then the load module (assumed the lightest) could be mounted atop the power module. The arrangement selected must maintain the overall center of gravity within limits governing hydrodynamic stability and must resist overturning moments. The mission of the load module and the orientation of the load module relative to the ocean bottom have a definite effect on the selection of the in-situ plant configuration.

Buoyancy Variations. Variations of buoyancy with depth must be evaluated before a final in-situ plant configuration is selected. These changes in buoyancy are dependent on the physical environment in which the plant operates and the characteristics of the pressure 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, lb/ft³

V = volume, in.³

Δ = a discrete 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 ΔV_p = change in volume due to pressure

ΔV_t = change in volume due to temperature

V_o = initial volume at zero pressure

ΔP = change in pressure

K_o = effective bulk modulus of the hull = $P/(V/V_o)$

α_{tv} = volumetric coefficient of thermal expansion for the hull and its material

Δt = change in temperature

An accurate determination of bulk modulus (K_o) requires volumetric calculations based on changes in hull dimensions due to pressure effects. The value of the bulk modulus used for configurations under consideration was 4×10^5 psi.

The coefficient of thermal expansion for the hull is dependent on the hull material and was taken as $0.117 \times 10^{-4}/^\circ\text{C}$ for steel. The maximum temperature change applied to the analysis was 11.7°C .

The change in density is also dependent on pressure and temperature changes plus the effects of salinity variations. Two methods were used in the buoyancy analysis to determine the change in density. In the first method density was determined from

$$d = \frac{62.42}{v}$$

$$d = \frac{62.42 \Delta V}{v^2}$$

where d = density, lb/ft³

v = specific volume

ΔV = change in volume

A = power module
B = load module

Figure 4. In-situ power plant arrangements.

The change in specific volume for seawater as a result of the changes due to temperature, salinity, and pressure was determined from

$$\Delta v = \Delta V_{ts} + \Delta V_p$$

where $\Delta V_{ts} = \alpha_{ts} \Delta t$

$$\Delta V_p = \Delta P / K_o$$

α_{ts} = coefficient of thermal expansion

Δt = temperature change

Δv = change in specific volume

K_o = effective bulk modulus

In the second method the change in density due to temperature and salinity was determined from changes in specific gravity, or

$$\Delta d_{ts} = 64.176 (\Delta P)$$

and
$$\Delta d_p = \frac{64.42 \Delta V_p}{v^2}$$

The above analysis demonstrates that a submerged object will gain buoyancy during descent. This behavior results in a decreasing velocity as the plant descends to the bottom and allows it to return to the surface by jettisoning diving weight. The change in buoyancy establishes the amount of diving weight required and presupposes that the plant without this diving weight is neutrally buoyant near the surface.

Hydrodynamic Stability. A careful study of the plant's hydrodynamic characteristics was required to achieve both hydrostatic and dynamic stability and to properly configure an in-situ plant for successful deployment. A detailed analysis of the equations of motion of vertically rising or falling bodies in a fluid established velocity and displacement history curves and determined the drag coefficient and amount of ballasting required for neutral buoyancy at the bottom.*

For the plant to be hydrostatically stable, the center of gravity must be below the center of buoyancy to assure that the plant will not capsize. The center of gravity of the plant should also be ahead of the hydrodynamic neutral point. Consequently, it may be necessary to add stabilizing devices (fins) at the upper end of the plant in descent and at the lower end in ascent.

* Contract Report CR-68.004, op. cit.

The investigation of the complete equations of motion would require a complete knowledge of the coefficients representing hydrodynamic forces and moments. Since the in-situ plants under study may have irregular or unconventional forms, model tests should be undertaken to more accurately establish hydrodynamic characteristics for validating the final design.

In-Situ Plant Emplacement and Recovery. The emplacement and recovery of an in-situ power plant is costly and risky. For this reason, these operations are extremely important and deserve detailed analysis and careful planning.

Emplacement and recovery concepts considered for analysis were free descent and ascent, forced descent and ascent, guided descent and ascent, and combinations of these concepts.

The concept of free descent and ascent is based on a free, powerless descent using negative buoyancy. The prime disadvantage of this concept is that the bottom positioning during free descent is somewhat random. Figure 5 illustrates how buoyancy, net downward force, and descent velocity may be expected to vary with velocity.

A free descent begins with the in-situ plant on the surface and rigged for free descent (stabilizers rigged, proper trim, etc.). A set of tanks may be flooded to cancel a small amount of reserve surface buoyancy. The plant then will take on negative buoyancy and sink. As the plant sinks, two parameters change: seawater density increases with pressure and external pressure causes the pressure hull to contract, thereby reducing total displacement. The net effect causes the plant to become slightly more buoyant with a proportionate decrease in net downward force, which causes the plant to gradually slow down. With proper negative buoyancy, the plant should begin its descent at about 3 to 4 fps and approach the bottom at 1 to 2 fps. A hanging weight suspended 100 to 200 feet below the plant will make the initial contact with the bottom and the plant will immediately decelerate to a stop. The plant could be positioned at the bottom by mechanical means such as a power winch. If the plant is to be positioned on the bottom, a foundation analysis will be required. Temperature variations encountered during descent and while the plant is positioned at the bottom will affect the plant's buoyancy. These variations must be factored into the final in-situ plant pressure hull design. Water absorption and fouling should also be considered for an extended deployment time. The plant may be surfaced by free ascent. Prior to ascent, the stabilizers must be rigged at the bottom, the trim adjusted, and the plant must then be released completely from hanging weights. As the plant ascends it is opposed by drag and gravitational forces and will reach its terminal velocity when the net buoyancy forces, and therefore the velocity, decrease. A terminal velocity of 3 to 4 fps is expected. Once on the surface, the surface tanks can be blown for reserve buoyancy to keep the plant stable.

(a) Free descent.

(b) Free ascent.

(c) Forced descent and restrained ascent.

Figure 5. Hydrodynamic profiles of buoyancy, force, and velocity.

Forced descent and ascent can be accomplished by using the tension in a wire rope to pull the positively buoyant plant down. Tension may be induced by a winch in the plant or on the surface of the plant. The effective drum diameter will increase as the plant descends which, with constant torque applied, will cause the plant to slow down with depth. The analysis begins with the plant on the surface and rigged for forced descent by the winch-down method. The winch and rope must be contained below the plant's center of gravity. Reserve buoyancy tanks and stabilizers were not included in this analysis. The rope would be level-wound on the drum and monitored for constant tension. Loss of tension would indicate that the plant is sinking, which requires dropping emergency ballast for more positive buoyancy. As the plant descends, it experiences the same buoyancy variations as the free descending plant. A bottom-sensing device would provide a signal to decelerate the winch for bottoming. A certain amount of tension must always be maintained in the winch rope during and after deceleration. Temperature variations would also affect this method of deployment. The plant would surface by reversing the winch operation. The advantage of the forced descent method is that it allows the plant to be positioned on the desired site. A free ascent must be provided for emergencies. Should a winch failure occur, the winch, drum, and cable would be jettisoned to remove the anchor restraint. If the load module becomes flooded and the power module is not flooded, the load module could be jettisoned.

In a guided descent the in-situ plant slides down a vertical guide rope in a ballasted descent. The rope would be anchored at the desired bottom location. A hanging weight slows the descending station by actuating a brake on the guide rope. The plant surfaces by dropping ballast in a free ascent. The magnitude and rate at the brake is applied when bottoming is critical because the rope could break. For this reason, the guided descent was not given further consideration.

In-Situ Plant Hardware. Base legs for the in-situ plant would provide stabilizing surfaces during descent and ascent, a broad base when the plant is on the bottom, large bearing areas for soft bottoms, and a means for plant leveling. The legs could also be used to house TV cameras and lighting. Each leg would consist of a stiffened A-frame made from light pipe sections hinged to the plant base. Brakes would be fitted to drums mounted on the hinge pin to control the leg attitude and to absorb moments resulting from leg reactions. Leg rotation (down) is accomplished by releasing the brakes. Although the operation does not require it, the legs could be elevated by using a motor-driven worm gear in each hinge. Large pads could be fitted at the end of each leg. The pads would consist of a snow-shoe base to provide support in soft bottoms. The entire pad is connected to the leg end by a pin, permitting it to

assume an appropriate attitude with the bottom topography and leg orientation. The pads would have sufficient area to reduce bearing pressures to less than 1/2 psi in currents up to 1 knot. The torque and thrust at the brake drum and hinge pins amount to 17,500 ft/lb and 18,000 pounds, respectively, when a single leg resists a current of 1 knot.

Main ballast tanks would be used to provide free-board when the plant is on the surface. Flooding the tanks on the surface would provide the proper buoyancy for diving. The tanks could be located in the foundation area of the in-situ plant.

The use of a shaped diving weight has significant advantages. In mud bottoms, the diving weight should have a small projected area to allow penetration into the mud, and the shape should also resist pulling out once in the mud. For hard bottoms, the diving weight should make use of flukes or claw-like protrusions. No retrieval system is necessary for the diving weights.

A free descent winch would be provided to control the rope length between the hanging weight (diving or velocity control) and the plant. Once the hanging weight is resting on the ocean bottom, the winch is used to bring the plant into its operational position.

The forced descent and ascent winch could be powered by a submersible electric motor through a gear drive. The drum could be sized to handle a length of rope slightly larger than the depth of operations. The winch could have constant-tension, level-wind capability in each direction. The entire winch and drum assembly could be considered jettisonable ballast.

Syntactic flotation material could be utilized to achieve overall trim and stability and to make components positively buoyant so that they will return to the surface if jettisoned. Two types of flotation material are available. The first type is capable of withstanding hydrostatic pressures up to 4,500 psig and the second type can withstand pressures up to 10,000 psig. Flotation 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 it can be deployed from a shore base to an operational site.

SURFACE POWER SYSTEMS

Surface Power Sources

Any power plant that has unlimited access to the earth's atmosphere can employ virtually any energy source and energy conversion system. Economically, however, the selection is limited to the use of the hydrocarbon

(fossil) fuels with internal combustion engines and steam or gas turbines. The specific selection of fuels and conversion system will depend on such factors as power level, efficiency, fuel logistics, system availability, and operating cost.

The liquid and gaseous fluid were considered the best suited for power levels of 30 to 3,000 kw because they require a minimum of handling or processing equipment. Fuel oils are generally the most readily available at the lowest cost. Further, the fluid fuels may be used with all conversion systems and will not influence the selection of any one conversion system.

The diesel engine was preferred to the steam or gas turbine as a prime mover for practically all the criteria established for the study program. Spark ignition engines were not considered because of their low efficiency and the requirement for highly volatile fuels. The diesel-driven generator system is approximately twice as efficient as the steam or gas turbine for the power range of 30 to 3,000 kw, with overall efficiencies of 17% at 30 kw, 27% at 100 kw and 30% from 300 to 3,000 kw. Increased efficiency results in substantially lower fuel cost and has a large effect on logistics support. The diesel engine also has a lower acquisition cost and is readily available in a wide range of capacities to match system requirements.

Steam and gas turbines are generally restricted to higher power levels because of poor performance and because of their limited availability at the low power levels. The gas turbine weighs less than the diesel engine, but this advantage is quickly offset by the increased weight of fuel that must be provided for the gas turbine. The steam plant is generally larger and heavier and, for the power levels of interest, less efficient than the diesel system. Reactor power sources were not specifically considered for applications other than the in-situ power plants since they are not economically competitive with fossil-fueled systems at the power levels of interest.

The diesel engine may be employed as the shore-based or ocean surface power plant for the 30 kw to 3,000 kw power levels. Table 6 presents typical data for diesel engine generator sets over the range of interest for the surface power systems, with transmission losses limited to approximately 5%. Shore-based systems with long transmission lines will require correspondingly larger power plants.

A single engine generator set results in a minimum of complexity in instrumentation and control and is the most economical installation. However, reliability of the load module may require redundant equipment. Life expectancy of a diesel generator is estimated at 20 years, with programmed preventive maintenance. For ocean surface power plants the major maintenance cycles can be scheduled to coincide with hull or buoy maintenance.

Table 6. Typical Data for Diesel Engine Generator Sets

Power Level (kw)	Rated Output (kw)	Net Output (kw)	Generator Voltage		Engine Speed (rpm)	Engine—Generator Weight (lb)	Engine—Generator Volume (ft ³)	Fuel Rate ¹ (gal/hr)	Engine Air Intake (cfm)	Jacket Heat Reject (Btu/hr)	Radiant Heat Reject to Atmosphere (Btu/min)
			Standard	Optional							
30	50	37	230/460	480	1,800	2,680	60	4.5	180	132,000	210
100	125	116	230/460	480	2,200	3,860	70	11	460	410,000	700
300	350	322	2,400	4,160	1,200	13,750	260	28	1,300	1.26 x 10 ⁶	1,900
1,000	1,250	1,169	4,160	—	600	60,000	2,040	85	4,600	2.5 x 10 ⁶	7,000
3,000	3,500	3,288	4,160	—	514	160,000	5,400	246	13,400	12 x 10 ⁶	20,500

¹ At rated output.

Major systems required for the diesel power plant are fuel, air, intake, exhaust, waste heat removal, engine control and instrumentation, electrical power control and instrumentation, and engine starting. Seawater cooling can be used with plants equipped with a freshwater loop to protect the equipment against seawater contamination.

A wide variety of commercial equipment is available for diesel power plants and will not substantially change the power plant design data. Present equipment is capable of maintaining a steady-state voltage regulation of 1% at the low power levels and a much narrower limit at the high power levels. Steady-state frequency can be held within 3% with standard speed-governing equipment and within 1/2% with electronic frequency-sensing equipment.

Surface Plant Hulls

The selection of hull shapes for surface-tendered generator plants was based on the following considerations: continuous operation under extreme weather conditions; unattended deployments for long periods of time; and safety of the generator plant, associated systems, and load module. The environmental sea-air conditions established previously required the surface plant to withstand 150-mph winds, 60-foot waves (breaking), and 10-knot ocean currents.

Since the surface plant is to be unmanned, all systems must be automated. For example, trim and compensation systems for the surface hull would be controlled by radio or other suitable means. Safety is of the utmost importance to protect the integrity of the entire system and to assure continuity in the supply of electrical power.

Surface Hull Concepts. The use of a floating instrument platform (FLIP) type ship was considered as a surface plant hull. Although it would provide an excellent surface plant, it was eliminated from further analysis because of excessive cost. Similarly, use of a Fleet submarine was eliminated due to high cost. Nomad-type buoys were investigated, but such buoys exhibit resonant motion, which would be detrimental to a surface plant. The possibility of using a submerged surface plant to eliminate the effects of the sea-air interface was also investigated. Such a plant would have to be submerged at least 100 to 200 feet, requiring a snorkel mast of equivalent height. A snorkel mast of this height was not considered structurally feasible, and if it were it would induce surface effects on the submerged plant. The snorkel mast could be seriously damaged by refueling or by other vessels. The submerged plant would also have a higher hull cost and a higher deployment cost. For these reasons, it was also eliminated from further investigation.

The surface power plant containment hulls selected for study were unmanned, double-hull, thick-disc, surface-following steel structures of modular construction. Three basic hull designs were established for the five power levels selected for the study program. The hulls are not space limited and, therefore, eliminate arrangement problems. Snorkel systems are included with all hull designs. Modular construction permits the complete interchange of machinery space to eliminate at-sea overhaul and increase reliability. A typical configuration of a thick-disc hull for a surface power plant is illustrated in Figure 6.

Figure 6. Configuration of a thick-disc hull for a surface power plant.

The hulls selected have been scaled to approximately the same proportions as the dimensions of the General Dynamic monster buoy.* Since the structural design is available, the thick-disc hull would provide optimum performance at minimum cost. Table 7 summarizes all the characteristics of the thick-disc hull. Machinery weight, hull weight, reserve buoyancy capacity, usable interior volume, fuel storage and trim system capacities, hull characteristics, and typical fuel replenishment are all defined in the table. The reserve buoyancy capacity for larger plants was reduced to allow for a larger on-board fuel supply. This added fuel supply would provide a more reasonable refueling cycle for the larger plants. All surface hulls were sized to carry an additional 50,000-pound external load imposed by the underwater transmission cable. The trim system was sized to compensate for variations of the external load.

A welded, double-hull construction from low carbon steel was recommended for the surface hulls. The external skin should be fabricated from 1/4-inch plate of higher strength steel. An entrance hatch, air intake and exhaust stacks, navigational lights, and radio antenna would be supported or contained in the snorkel mast. All surfaces of the hull would be painted with corrosion-resistant coatings for protection against the ocean environment, leakage, flooding, and condensation.

* A. R. Devereaux and F. Jennings. "The monster buoy," Geomarine Technology, April 1966.

Table 7. Characteristics of Surface Plant Hulls

Power Plant (kw)	Machinery Requirements		Reserve Buoyancy Capacity (lb)	Fuel Storage Capacity		Hull Characteristics						Fuel Replenishment Data		
	Floor Area (ft ²)	Weight (lb)		(ft ³)	(lb)	Trim System Capacity (lb)	Outside Diameter (ft)	Center Height (ft)	Volume (ft ³)	Usable Interior Volume (ft ³)	Established Weight (lb)	Weight Loaded (lb displacement)	Suggested Schedule (days)	Onboard Supply (days)
30	541	9,080	347,000-415,500	1,272	68,500	50,000	41	7-1/2	9,000	7,100	100,000	228,000	90	120
100	667	10,860	687,000	4,120	228,000	244,000	55-1/2	9-1/2	17,775	9,785	159,000	448,000	90	120
300	1,831	24,640	673,000	4,120	228,000	244,000	55-1/2	9-1/2	17,775	9,800	159,000	448,000	30	47
1,000	5,040	76,225	787,000	8,240	456,000	487,500	55-1/2	11-1/2	25,650	9,800	220,000	853,000	26	33
3,000	9,028	199,450	665,000	8,240	456,000	487,500	55-1/2	11-1/2	25,650	9,800	220,000	975,450	5-7	10

Fuel Storage. Transportation is the variable factor in fuel costs, which vary in proportion to the quantity of fuel and the distance of delivery. The number of surface hulls serviced affects the cost of fuel. For distant surface hulls, fuel costs can be a significant percentage of the total operating cost. Optimum quantities for delivery would be 150,000 gallons. Quantities larger than this require tanker-size ships. Typically, delivery costs are 0.4 cents per gallon for a 90-mile delivery and 1.1 cents per gallon for a 240-mile delivery. These delivery distances would represent the average distances necessary to reach depths of 600 to 6,000 feet, respectively. The largest surface hull considered had a fuel capacity of 65,000 gallons.

The fuel storage capacities of a surface hull, shown in Table 7, were obtained by trading off reserve buoyancy capacity, hull diameter, and height. The maximum proportion of diameter and height for surface hulls was established at 55-1/2 feet by 11-1/2 feet; these values are based on values scaled from the monster buoy to maintain good hydrodynamic characteristics.

Trim System. An automatic trim system was recommended to trim the surface hulls as fuel is consumed. An emergency system is also incorporated and is capable of pumping overboard all fuel and seawater ballast and securing all engines in the event of serious flooding or collision. This emergency system requires air banks and compressors which would normally be required for the larger generator plants. The trim system would also compensate for variations of the external transmission cable loading.

Upkeep Schedule. A major factor in deploying a surface hull is the laying and installation of the multipoint mooring system. It is not considered feasible after deployment to take the hull up periodically for overhaul or component replacement. For this reason, a mean-time-between-overhaul was established at 5 years for the surface plant hull. This may not be consistent with machinery overhaul within the plant; however, the machinery can be interchanged with overhauled equipment. This arrangement is preferred to at-sea overhaul or lengthy maintenance of the machinery.

Surface Plant Mooring Systems

The forces and phenomena involved in mooring thick-disc hulls for surface-tendered power plants were defined and analyzed. Once the mooring requirements were established, mooring system configurations were developed and evaluated for the most cost effective systems. An investigation of mooring systems, forces acting on mooring systems, and auxiliary mooring equipment and components were all included in the analysis.

Dynamic Moor. A dynamic moor consists of propulsion devices which will permit forces to be applied to the hull in any direction to keep it in a stationary position against forces of wind and sea. The dynamic moor requires an automatic sensing device which will accurately locate and hold the hull with respect to the desired position on the bottom.

A dynamic mooring system is relatively costly because of manning and logistics problems, and its reliability for use with underwater power systems is questionable. For these reasons the dynamic moor was not investigated further. As the state of the art of this mooring technique advances, a reevaluation would be recommended.

Static Moor. A static moor consists of a wire rope or chain connecting the surface hull to a device on the ocean bottom which is capable of developing an anchoring or holding force. Several anchoring devices are available, the most common of which is the fluke anchor. Three types of static mooring systems were considered: the simple catenary, the taut line, and the compound catenary. They are illustrated in Figure 7.

The chief disadvantage of a simple catenary is the extremely long scope required for great depths. On the other hand, a taut mooring line requires an anchoring device capable of developing a large vertical component of force. Such an anchoring device would have to be fixed to the bottom by grouting. Because techniques for emplacing a fixed anchor were considered developmental the taut mooring line was not considered further in the study program.

A four-point compound catenary mooring line was selected for the surface plant mooring system because it would provide reasonable scope requirements and adequate holding power by means of a fluke-type anchor.

Static Multipoint Mooring. A four-point moor may be considered as a system of two 2-point moors lying in normal planes. An elevation of one plane of a typical four-point moor is illustrated in Figure 8. The anchor spacing would be equal to $X + (S - Y) + 2\ell$ and the thick-disc hull neutral position equal to $1/2[X + (S - Y)] + \ell$, where ℓ is the horizontal distance between the hull and any intermediate catenary support buoys. Figure 9 is a plan view of the excursion boundary for a four-point moor. This envelope is circumscribed by the maximum horizontal projection (X) of each mooring leg. The path of the relaxed leg ($S - Y$) is also shown. To prevent the mooring ropes from dragging back over themselves, X should not overlap $S - Y$ at any location. When an excursion force (F) is applied colinearly to any single mooring leg, the moor is holding in its weakest condition; the strongest condition occurs when an excursion force is at 45 degrees to the hull. The maximum excursion for a four-point moor was determined from the equation

$$e_{\max} = 2[X - (S - Y)]$$

Figure 7. Static mooring systems.

Figure 8. Elevation view of one plane of a typical four-point moor.

Figure 10 illustrates a three-point mooring system excursion envelope. The shaded area represents the slack rope in excess of $(S - Y)$ that can be laid on the bottom. This slack would cause the wire rope to foul, kink, and entangle. Accordingly, the three-point moor was not considered further in the study.

Forces Acting On Mooring System. The weight of the mooring system, which increases in proportion to the anchoring holding power and the depth, must be supported by the surface hull. If the hull is not large enough for supporting the weight, an intermediate catenary support buoy must be used to support the weight of each mooring leg segment. The support buoys must withstand sea pressures at depths corresponding to the 60-foot wave height expected. The forces acting upon a moored surface hull are created by wind, waves, and ocean currents. Surface conditions established for the study program were 150-mph winds, 10-knot currents, and 60-foot-high breaking waves.

Wind not only applies force to the hull structure above the surface but creates waves and currents as well. Model tests were conducted at the David Taylor Model Basin to estimate the force on a moored hull from wind at various velocities. These wind forces were extrapolated from the scale model to the full-size hulls used in the study.

Figure 9. Four-point mooring system excursion.

Figure 10. Three-point mooring system excursion.

The basic formulas used for wind and current are similar, but because of the higher specific gravity for water, the forces induced by even the slowest currents are significant. Surface plant hulls, which were established as symmetrical, exhibit an optimum aspect to any direction of the ocean current.

The wave forces that act on a moored surface hull fluctuate and are caused by three characteristics of a wave. First, the oncoming wave heave the hull upward. Second, the wave causes the hull to slide down its slope. Third, the wave subjects the hull to the increased velocity of the water caused by the orbital motion as the wave crest forms. Wave forces are periodic, causing the mooring leg and anchor system to react very much like a weight on a spring. The problem of analyzing the transitory force on the mooring leg when disturbed by the wave force is complex, and any solution is peculiar to a given sea-air condition. The possible conditions which may exist are infinite. For this reason, wave forces are usually neglected when moors are designed, but a sufficient safety factor is allowed for environmental conditions.

Anchor Holding Power. A fluke-shaped anchor was selected for use with the mooring system. The important parameter in the shape of the fluke is the moment of the fluke about the trunnion. The greater the first moment of the fluke area, the greater the anchor's holding power.

The maximum angle which the fluke makes with the shanks affects the holding power of an anchor in any type of ocean bottom. The optimum fluke angle is not the same for all types of bottom. Past tests have indicated that maximum holding power is attained in a mud bottom when the fluke angle is approximately 50 degrees, whereas in a sand bottom the optimum angle would be about 26 degrees. Figure 11 illustrates the effects of fluke angle on the holding power of an anchor.

The maximum anchor holding power is also developed when the pull extended is parallel to the bottom. If the anchor end of the mooring leg rises so that the angle of pull (that is, the angle of the mooring leg tangent at the anchor) begins to exceed critical values, the flukes of the anchor tend to break out of the bottom. Figure 12 illustrates the effect of the angle of pull on the anchor's holding power. 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. Figure 13 illustrates the effect of anchor drag upon holding power.

Mooring System Hardware. Conventional anchors are established pieces of hardware with proven reliability. Table 8 gives the holding power and weights of various conventional anchors. Development work is currently progressing to create new and better anchors. In the past, anchors have been pulled over the bottom to make them dig in; however, this method may not

suffice for surface plant mooring systems. Alternative methods would be to grout the anchor into the bottom or use explosives to drive it in. The advantages of these methods are high reliability and holding power that is not directionally dependent. However, the state of the art in deploying grouted pile anchors at depths of interest is not sufficiently advanced for use on the surface plant mooring system.

Table 8. Holding Power and Weight of Conventional Anchors

Type of Anchor	Weight (lb)	Maximum Holding Power in Sand (lb)
LWT	4,000	75,000
LWT wedge block	6,000	106,000
LWT wedge block	10,000	175,000
LWT wedge block	25,000	430,000
EELLS	8,000	80,000

Conventional anchors of the LWT wedge block design were selected for the surface plant mooring system. An electronic device that can be attached to the anchor is available to determine when the anchor has dug into the bottom.

Wire rope manufacturers and the petroleum industry are significantly advancing the state of the art of undersea wire rope. Stainless steel wire rope in underwater applications is susceptible to chloride stress corrosion. Stainless steel ropes have failed as early as 4 to 5 months after deployment. Programs to use plain steel and zinc-coated steel indicate that maximum deployment time for these ropes is 3 years. Cathodic protection for deep ocean applications is developmental and not available. For purposes of the study, a polyurethane-clad, three-strand, torque-balanced steel rope was selected for a 5-year deployment life. Swivels must be provided for terminating the ends of the wire rope so that end fixing can be avoided. Figure 14 is a conceptional sketch showing a method for attaching a wire rope to a terminal swivel socket. Many wire rope moorings are suspected of fatigue failure. Therefore, vibration dampers should be provided on the terminal swivel.

Figure 11. Effects of fluke angle on holding power.

Deep sea synthetic mooring rope, such as dacron, nylon, and polypropylene, is currently available in various types. All synthetic fibers creep under load. For a 5-year life, this creep will not present a problem if the working strength is kept below 25% of breaking strength for nylon and 30% for dacron. However, short-term loading equivalent to 90% 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 not be allowed to lie on the bottom or pass over jagged crevices. Synthetic rope failures usually occur near splices and connections. Therefore, care must be

taken in the proper design and application of juncture techniques. The elongation of synthetic rope is caused by the braiding and plaiting of the rope. New developments in synthetic fiber may soon eliminate the elongation problem. Polyurethane coverings on the rope would eliminate the problem of fish bites. Because synthetic ropes do not appear to be well enough advanced for deep sea mooring systems, they were not selected for use on the surface plant mooring system.

Two types of chains are feasible for use on surface plant mooring systems: 1020 carbon steel and 8620 high-strength steel alloy chain. The latter was chosen because of its high reliability. It was recommended that the chain be proof-tested at half the breaking strength and rated at half the proof-test value.

Figure 12. Effect of angle of anchor pull on holding power.

Figure 13. Effect of anchor drag on holding power.

Figure 14. Method of attaching wire rope to a terminal swivel socket.

Catenary support buoys should be manufactured from A-212 normalized steel plate, with internal structural members and ribs fabricated from A-36 silicone steel. The buoys' surfaces must be coated for protection from corrosion. The buoys should be provided with leak detectors having an alarm circuit connected to the surface plant alarm system. Automatic bilge pumps operated from batteries should be provided for support buoys. A circumferential pipe structure should be provided to protect the buoys from collision by ocean vessels. Navigational lights on suitable masts would be required.

Analysis of Surface Plant Mooring System. The sizing of mooring systems for the surface plant is determined by the mooring leg holding force required. Computed component drag forces for each power level at the selected depths are shown in Table 9. Wind and drag forces were combined into a total drag force for each condition. The required mooring leg holding power of 150,000 pounds was assumed. The difference between maximum holding power and the total drag force represents the wave force allowance. The ratio of wave force allowance to maximum holding power was established at 0.6 for the smallest hull-power-depth combination and 0.15 for the largest.

Once the required holding power of 150,000 pounds has been assumed, it is possible to trigonometrically compute the limiting angle and magnitude of the vertical component of force for standard wire rope sizes. A vertical component of force at any point in a catenary is equal to the total weight of the leg suspended beneath it. Thus, a smaller wire rope is required to support the leg below any given point. Use of a larger wire rope size for the entire length of the rope will increase the scope required.

In a compound catenary arrangement, the size of the mooring legs was determined by establishing nomographs and alignment charts to provide data which would otherwise be obtained from trial and error solutions.

It is characteristic of the catenary that for mooring legs of equal weight and bottom angle, the angle at the top will remain constant regardless of weight distribution along its length. The weight distribution will affect the scope, and accumulating leg weight into a clump will significantly change the scope. From a cost effective standpoint, wire rope at \$5 per foot can be replaced with equivalent clump weight worth \$0.35 per foot for developing the same holding power. The clump weight is limited by the capacity of the deploying winch and by the vertical force component of the wire rope tension.

A typical anchor-chain-clump configuration was elected for the bottom of each mooring leg based on the required holding power. It is comprised of a 25,000-pound LWT wedge block anchor, one shot of 1-1/2-inch chain, a clump ranging from 25 to 100 kips, two additional shots of 1-1/2-inch chain, and a scope of wire rope.

Table 9. Drag Force Profile for Surface Plant Mooring System

System Description	Depth (ft)	Thick-Disc Hull		Electrical Transmission Cable Drag (lb)	Mooring Cable Drag (lb)	Catenary Support Buoy Drag (lb)	Total Drag Force 1 + 2 + 3 + 4 + 5	Maximum Horizontal Force (lb)	Wave Force Allowance 7 - 6 (lb)	Ratio of Wave Force Allowance to Max Horizontal Force 8/7 (%)
		Wind Drag (lb)	Current Drag (lb)							
41 x 7-1/2-ft buoy, 30-kw plant	600	19,700	13,100	3,500	14,000	9,100	59,400	150,000	90,600	0.60
	2,000			4,200	16,800		62,900		87,100	0.58
	6,000			4,300	17,200		63,400		86,600	0.57
	10,000			4,400	17,600		63,900		86,100	0.57
	15,000			4,500	18,000		64,400		85,600	0.57
55-1/2 x 9-1/2-ft buoy, 100- and 300-kw plants	20,000			4,600	18,400		64,900		85,100	0.56
	600	35,000	24,600	3,500	14,000	38,000	115,100	150,000	34,900	0.23
	2,000			4,200	16,800		118,600		31,400	0.20
	6,000			4,300	17,200		119,000		31,000	0.20
	10,000			4,400	17,600		119,400		30,600	0.20
55-1/2 x 11-1/2-ft buoy, 1,000- and 3,000-kw plants	15,000			4,500	18,000		119,800		30,200	0.20
	20,000			4,600	18,400		120,200		29,800	0.19
	600	33,300	26,500	3,500	14,000	40,000	117,300	150,000	32,700	0.21
	2,000			4,200	16,800		120,800		29,200	0.19
	6,000			4,300	17,200		121,300		28,700	0.19
	10,000			8,700 ¹	17,600		126,100		23,900	0.15
	15,000			8,900 ¹	18,000		126,700		23,300	0.15
	20,000			9,100 ¹	18,400		127,300		22,700	0.15

¹ Values shown for 3,000-kw cable; half for 1,000-kw installation.

Figure 15 is a mooring leg selection chart showing depth versus the S/Y ratio for various wire and clump sizes considered. This chart will enable one to select a wire-clump configuration that results in the shortest scope at a selected depth. Figure 16 was plotted to show the total horizontal projection as a fraction of the vertical projection for the mooring system configurations considered. Figure 17 was plotted to illustrate mooring leg wire rope weight as a fraction of depth.

The results of the mooring system analysis indicate that the weight of each mooring leg will require catenary support buoys. Catenary support buoys should be located approximately 1,000 feet from the surface power plant to provide a constant holding force on the plant.

Table 10 presents a summary of mooring leg data for the surface plant mooring systems at depths of 600, 2,000, 6,000, 10,000, 15,000, and 20,000 feet.

SHORE-BASED POWER SYSTEMS

Shore-Based Power Sources

The power sources discussed earlier for surface power systems are also suitable for use in shore-based systems. As in the case with surface systems, diesel engine generator sets were considered the most cost effective power plants for shore-based systems. The diesel engine generator sets would be self-contained at the 30-kw to 300-kw power levels, with conventional radiators for cooling and battery starting systems. Heat exchanger and cooling tower installations with compressed air starting would be required for diesel engine generator sets at the 1,000-kw to 3,000-kw power levels.

Shore-Based Generating Plant and Transmission System

The basic components of the shore-based power plants would be housed in a steel-framed, corrugated-steel-clad building. They include a diesel-electric generating plant, with all of the required auxiliaries, handling equipment, plant services, and monitoring and control equipment. Intermediate and high-voltage transmission cables would be used for transmission over distances of 10, 50, 100, and 500 nautical miles. In some cases, DC transmission is used. These DC systems require converters or rectifiers at the shore-based plant and the equivalent inverter at the load module end. 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 the blocking voltage

to stop the inverter if this becomes necessary. The static capacitors are pressure-compensated and are mounted outside the hull. Weights, volumes, and dimensions were not given for the shore plant, since these factors are not critical for this facility.

CABLE SYSTEM

The primary consideration in the selection of a cable system for use in an underwater power transmission system is the reliability of its elements. The cable, connectors, and support system must withstand the ocean environment—that is, must be resistant to corrosion, erosion, marine fouling, and water absorption—for the useful life of the power transmission system.

Cable Conductor Material

Two basic conductor materials were considered: aluminum and copper. The conductivity of aluminum is 60% that of copper and would, therefore, require a cross-sectional area approximately 1.6 times larger than copper for the same current-carrying capacity. The tensile strength of aluminum is 24,000 to 29,000 psi and that of copper 50,000 to 70,000 psi. The modulus of elasticity of aluminum is 10×10^6 and that of copper 17×10^6 . Aluminum has a high contact resistance due to the oxidation of its surface and exhibits a tendency to “creep” because of its high coefficient of thermal expansion. Because of these qualities, aluminum was eliminated as a conductor material from the study program.

Cable Insulation Material

The primary factors used in determining the selection of insulation material for underwater cables are voltage stability and life, resistance to moisture, resistance to temperature, dielectric properties, and flexibility. Resistance to ionization or corona and mechanical strength are of secondary importance.

Of the available materials, polyethylene combines excellent electrical characteristics with outstanding stability of both electrical and physical properties during long periods of exposure in seawater. Rubber and rubber-like insulation materials require tinned conductors to prevent a detrimental chemical reaction between the insulation and conductor. Rubber materials have a higher water absorption rate than polyethylene. Varnished cambric and impregnated papers have a long life, but require a continuous lead covering for underwater use. Lead coverings would make the total weight of the cable impractical for this installation. Polyethylene was, therefore, selected for the cable insulation material.

Table 10. Summary of Data for Surface Plant Mooring Systems

Depth (ft)	Clump Weight (lb)	Scope of Wire Rope						Total Scope of Wire Rope		Hoisting Weight ¹ (lb)	Catenary Support Weight (lb)	Total Mooring Leg Weight ² (lb)
		1-3/8-In. Diam		1-1/2-In. Diam		1-5/8-In. Diam						
		Length (ft)	Weight (lb)	Length (ft)	Weight (lb)	Length (ft)	Weight (lb)					
								Length (ft)	Weight (lb)			
600	57,000	1,590	4,040	—	—	—	—	1,590	4,040	86,700	67,000	92,000
2,000	48,000	5,400	13,700	—	—	—	—	5,400	13,700	83,200	67,000	92,000
6,000	85,000	—	—	10,400	31,600	—	—	10,400	31,600	133,400	122,000	147,000
10,000	58,000	1,575	4,000	17,925	54,500	—	—	19,500	58,500	117,700	122,000	147,000
15,000	89,000	—	—	8,900	27,000	15,100	54,700	24,000	81,700	167,600	176,000	201,000
20,000	56,000	2,000	5,100	18,000	55,000	15,000	54,300	35,000	114,400	146,200	176,000	201,000

¹ Hoisting weight = anchor weight (25,000 pounds) + chain weight (5,100 pounds) + clump weight + total wire weight
 — weight of wire retrieved before anchor is lifted from the bottom.

² To get the total mooring leg weight, add anchor weight of 25,000 pounds to catenary support weight.

Figure 15. Mooring leg selection chart.

Figure 16. Maximum horizontal projection of mooring leg.

Cable Sheaths and Coverings

Submarine cables usually have a water-resistant covering over their insulation as added protection. Neoprene or polyethylene may be used for this purpose. Where additional mechanical strength and abrasion resistance is required, the cable covering is wrapped with armor wire of bronze, copper, stainless steel, or galvanized steel. An additional covering is applied to protect the armor from the sea environment. High-strength galvanized steel with polyethylene covering was selected as the armor material.

Electrical Properties

The use of either three single-conductor cables or a single three-conductor cable is feasible for an underwater power transmission system. The costs involved in deploying three single-conductor cables are greater than those involved in deploying one three-conductor cable. In addition, three single conductors have a higher reactance than one three-conductor cable. Off-the-shelf three-conductor cables with standard conductor wires were considered in the study.

Figure 17. Weight and cost of mooring leg wire rope.

Electrical conductors must be shielded to provide symmetrical radial voltage stress distribution within the insulation and to eliminate tangential and longitudinal voltage stress on the insulation surface. Tangential and longitudinal voltage stress causes surface cracking and discharge to ground. Shielding maintains a zero potential on the surface of the cable for the safety of personnel and provides protection against lightning and switching surges. The shield should be of conduction tape or wire material for increased fault current capacity. Copper was selected for the shielding material, with the shielding applied to each conductor of the three-conductor cable.

Since each conductor of the cable would be shielded and grounded at both ends, the first order of faults, if they occurred, would be phase to ground. The important factor to consider in grounding a cable system is to detect ground faults and effectively clear the faulted section from the source of power. In the absence of an effective way to detect low ground currents, the system should be effectively grounded to provide faults of greater magnitudes for faster actuation of the system's protective equipment.

Splicing of the three-conductor power transmission cable was not considered necessary since the cable would connect directly to the power source and the load module. The splicing, if required, would be by special undersea connectors.

Mechanical Properties

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.

Table 11 illustrates the frequency of cable casualties as compiled by Bell Telephone Laboratories. Approximately 50% of the cable damage is attributed to breaks caused by fishing trawlers and a majority of these in depths less than 1,800 feet.

The fundamental requirement in cable laying is to deposit sufficient lengths of cable commensurate with the irregularities of the ocean bottom. The most detailed knowledge of the bottom topography and of cable-laying techniques is required to avoid introducing dangerous cable suspensions and laying excess cable slack.

Table 11. Causes of Cable Breaks

Cause	No. of Breaks		% of Total Breaks	
	a ¹	b ²	a	b
Trawler	127	96	47	47
Chafe-corrosion	95	61	34	30
Kink	18	—	7	—
Biological	9	2	3	1
No report	24	—	9	—
Electrical maintenance	—	20	—	10
Other (ship anchor, kink, etc.)	—	16	—	8
Unknown	—	8	—	4
Total	273	203	100	100

¹ Data derived from Western Union Cable History Study, British Continental Shelf (Allen, 1962) and includes break data for years 1930-1960.

² Data derived from a compilation of break history of telegraph cables at all depths in the North and South Atlantic Ocean. Period covered is 1959-1962.

Cable Configuration

The cable configuration defined by various trade-offs is a multiple cable, concentric-stranded copper conductor that is insulated with polyethylene, shielded, and protected by armor and jacket to meet the conditions of the ocean environment. A typical cross section of the marine cable selected is illustrated in Figure 18. Table 12 presents physical characteristics of selected marine cables.

Cable Connectors

There are several mechanical and electrical problem areas associated with underwater cable connectors and penetrations for the transmission of electrical power to loads encapsulated in a pressure hull. The mechanical problems involve watertightness, mating or connecting and disconnecting underwater, material compatibility, and strength. The ability to achieve the current-carrying capacity at the required voltage with minimum contact resistance through the connector is the major electrical problem to be resolved.

Table 12. Physical Characteristics of Selected Marine Cable

Wire Size	Three-Conductor Cable						3 Single-Conductor Cables					
	5 kv		15 kv		34.5 kv		69 kv		115 kv			
	Diameter (in.)	Weight (lb/ft)	Diameter (in.)	Weight (lb/ft)	Diameter (in.)	Weight (lb/ft)	Diameter (in.)	Weight (lb/ft)	Diameter (in.)	Weight (lb/ft)		
6 AWG	1.97	4.16	2.17	—	2.87	—	2.34	—	2.97	—		
4 AWG	2.05	4.7	2.27	—	3.01	—	2.45	—	3.12	—		
2 AWG	2.19	5.47	2.39	—	3.19	—	2.58	—	3.30	—		
1/0 AWG	2.35	6.36	2.61	7.5	3.53	8.1	2.84	2.94	3.67	3.20		
2/0 AWG	2.45	7.1	2.71	8.4	3.67	9.0	2.94	3.27	3.81	3.54		
3/0 AWG	2.61	8.0	2.83	9.3	3.85	9.9	3.08	3.57	4.00	3.84		
4/0 AWG	2.73	8.9	2.95	10.2	4.03	11.0	3.21	3.92	4.19	4.20		
250 MCM	2.89	9.9	3.05	11.1	4.19	11.9	3.33	4.22	4.35	4.50		
300 MCM	2.99	10.0	3.15	12.3	4.33	12.9	3.44	4.58	4.51	4.86		
350 MCM	3.09	11.9	3.33	13.5	4.61	14.1	3.65	4.96	4.81	5.25		
400 MCM	3.19	12.9	3.43	14.4	4.75	15.0	3.75	5.34	4.95	5.65		
500 MCM	3.43	14.7	3.59	16.2	4.99	16.8	3.93	5.92	5.19	6.23		
750 MCM	3.85	19.2	3.97	21.0	5.57	21.9	4.37	7.65	5.81	8.02		
1,000 MCM	4.17	23.6	4.35	25.2	6.13	26.1	4.79	9.02	6.40	9.36		

Note: 0.204-in.-diam galvanized steel armor wire was covered by a 0.35-in.-thick jacket

Figure 18. Typical cross section of selected marine cable.

One of the first devices used for sealing a cable penetration on a deep submergence pressure hull was a 1.1-inch-diameter, four-conductor cable sealed with a stuffing box design. The packing was composed of four or five layers of flax packing pressurized from both ends of the stuffing box with gland nuts. The seal was successful down to about 3,000 feet.

Primary and secondary cable seals are mandatory requirements for all submersibles. The primary seal is located outboard of the pressure hull and the secondary seal is located inboard of the hull. With respect to primary cable seals, the use of watertight connectors is recommended. The connectors would provide a positive water dam in case the cable is damaged or severed. Connectors also satisfy the secondary cable seal requirement by providing a positive water dam inboard of the pressure hull. The use of connectors for hull penetrations allows the testing of such fittings under pressure prior to deployment and provides junction points for the cable conductors. This eliminates the need for junction boxes and provides a test point for checking circuits served by the connectors.

Figure 19 shows a multiple-conductor hull fitting which has been used on Navy submarines. This fitting will withstand nominal shock loadings. As noted, the outboard watertight connectors are located radially around the body of the fitting to accommodate a maximum number of cables.

Figure 19. Multiple-connector hull fitting for submarines.

The approximate availability of dry electrical connectors for underwater power systems as function of voltage and amperage rating is presented in Figure 20. An extremely small power level area can be satisfied with presently available connectors. A significant program, therefore, will be required for the development of underwater connectors suitable for use at high power levels.

Cable Suspension Systems

In the study program, the analysis of cable suspension systems was based on the assumption that the cable is affected by its own weight and the trace configuration it assumes when deployed. The suspension system was primarily studied for use with surface-tendered power units.

The length of cable, which determines the cable weight, is a function of the depth of the load module and the excursion of the surface unit. The excursion of the surface unit depends, in turn, on the environment in which it is placed. Since the environment could not be predicted, the cables were chosen to include those lengths which might be required to reach depths of 600, 2,000, 6,000, 10,000, 15,000, and 20,000 feet.

To limit the length of cable required, the center of excursion for the surface unit should be placed directly over the load module. However, 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 causes a

wrap-up of cable because both ends of the cable are fixed. To avoid this cable wrap-up, the excursion of the surface unit should be beyond the centerline of the load module. Thus, the surface unit should never pass above the vertical centerline of the module.

Two methods can be used to provide the cable with added strength. The first is to provide armor or wire wrapping. The second is to provide a separate cable to which the power cable is attached. If in each case the material used for strength is the same and an equivalent area can be applied, then it is advantageous to use armor. Armor can be placed on the cable during manufacture. Original estimates were made for a standard, available submarine cable with galvanized steel armor. Such a cable would have an ultimate strength of 60,000 to 70,000 psi. A higher strength armor with an ultimate strength of 250,000 pounds can be used, but the cost rises sharply. The added cost of this armor is reduced for extended depths because the high-strength armor reduces the amount of support which must be supplied by buoyancy devices.

A safety factor of 2, based on the ultimate strength for the standard armor and for the high-strength armor, was used in determining the unsupported cable length. This provides an allowable working stress of 30,000 psi for the standard armor and 125,000 psi for the high-strength armor.

There is a restriction on the weight that a surface plant can support which, for the purpose of the study, was established at 50,000 pounds. Therefore, even if the supporting strength of the cable can exceed this loading, some system has to be employed to reduce the cable load below 50,000 pounds. Buoyancy devices can be added either completely throughout or at discrete points in the cable system. Adding buoyancy material to the cable during manufacture or during deployment is not considered a practical solution to the provision of natural buoyancy for cables in the undersea environment. Therefore, the use of the discrete buoyancy system was preferred.

Optimizing a cable support system requires definite knowledge of the actual techniques used for the installation of any given number and type of buoyancy devices. The number of buoyancy units can be kept at a minimum by so placing them along the cable length that the weight of the cable hanging below results in a maximum allowable working stress in the cable. A factor of 1.3 was used in determining the effective net buoyant force necessary to maintain the cable in a generally vertical attitude, resist ocean current drag forces, and account for the load component of the surface cable between the surface unit and the first buoy.

Figure 20. Availability of dry electrical connectors.

Two basic types of buoys were investigated for the cable support system: hollow buoyancy spheres and homogeneous buoyancy materials. Various materials with acceptable weight-to-buoyancy ratios, such as glass-reinforced plastics, glass, and titanium, are considered to be in the development stage and were eliminated. Of the readily available materials, aluminum alloy 7079-T6 was selected because of its high yield strength, lightness, and suitability for the marine environment. The sphere buoys must be fabricated with a mechanical joint at the equator because the material has poor welding characteristics. Hemispheres with a diameter of up to 84 inches are presently available. This size was used as maximum to avoid unnecessary development costs. At all depths multiple spheres must be used to support the selected cable sizes.

A syntactic foam material weighing 44 lb/ft³ in air was considered for buoyancy floats. This foam is available and has well-established properties.

Typical buoy configurations used in the study are shown in Figure 21. Each of the configurations is shaped like a clam shell to minimize drag forces on the buoyancy units.

Figure 22 shows the support requirements for a representative number of cables at their respective depths. The number of aluminum spheres required for each float device is noted in Figure 22.

Both the syntactic float and aluminum sphere float are considered to be within the present state of the art and can be procured in a reasonable time. Aluminum spheres were considered the most cost effective buoys for the cable support system.

There are two cable suspension configurations suitable for an underwater power transmission system—namely, a taut line configuration and a normal catenary configuration. A taut line configuration is shown in Figure 23. One or more buoys are suspended along the cable length. The total buoyancy of the buoys 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 is attached to the surface unit. The uppermost buoy was placed at a 2,000-foot depth for all concepts evaluated.

When the surface unit excursion is at its minimum point, it was assumed that the pendant cable is hanging essentially vertical, with one end supported by the surface unit and the other end by the upper-most buoy at 2,000 feet. For a load module at a 20,000-foot depth, the length of the pendant cable was postulated to approach 20,000 feet. With this length the pendant cable would hang to about 11,000 feet when the surface unit is above the load module. The minimum excursion point in an actual design must be displaced a horizontal distance from the vertical centerline of the load module to prevent the cable from entangling with the mooring legs or wrapping around itself.

A catenary configuration is shown in Figure 24. As noted, the buoyancy units are spaced along the cable at discrete points to maintain safe tensile levels in the cable armor. The surface unit excursion poses no serious problem in catenary configuration. However, as the surface unit moves from its maximum excursion point, the cable will abrade on the bottom. To prevent this, a buoyancy unit must be installed so that at the innermost portion of the excursion the total depth of cable is less than that of the load module. With a load module at 20,000 feet, the surface excursion is approximately 18,000 feet. Allowing the innermost portion of the excursion range to be directly above the load module, the buoyancy unit would be placed some 7,000 feet above the bottom.

(a) Aluminum sphere.

(b) Homogeneous material.

Figure 21. Buoyancy support configurations.

Figure 22. Cable support requirements.

Figure 23. Taut cable support system.

The above configurations are based on the assumption that the total cable suspension system is slightly negatively buoyant. If it is made positively buoyant, the cable system will probably broach the surface during the excursion of the surface unit and be subjected to surface conditions as well as to the possibility of becoming entangled with the mooring system.

Both the taut line and the catenary system suffer from the fact that if the cable is lost at any point below the attachment to the last support buoy, the cable complex will descend to the bottom. The cable would have a higher probability of falling on the load module with the taut line system. Suspension systems for underwater cables will require careful analysis during system design.

ELECTRICAL SYSTEMS

Surface Power Systems

The electrical system for each load at each depth considered for analysis in the study program included the generated voltage, step-up primary transformer, transmission line, and protective equipment. A load power

factor of 0.85 lagging was selected for analysis. 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 no load to full load and vice versa. To establish circuit protection requirements, loads under steady-state voltage and transients caused by a fault condition were evaluated.

Early in the study it was established that overall electrical characteristics could not be clearly defined that would be suitable for all lengths of transmission cable under consideration. Therefore, an analysis was initiated for moderate cable lengths of 600 to 30,000 feet which would be applicable to surface power sources.

Alternating Current Versus Direct Current. The design constraint established for the study program required the delivery of 480-volt, 3-phase 60-Hertz AC power to the load module. For a DC transmission system, this constraint would require additional transformation, conversion, or inversion equipment at each end of the transmission cable. The primary advantage of using DC is the reduction in cable size for an equivalent power level. In addition, transmission cable losses are substantially reduced with DC. For loads over the distance of 600 to 30,000 feet, it was determined that the savings in transmission losses and cable size would not be offset by the additional cost of DC terminal equipment at each end of the transmission cable.

For each voltage level, AC costs were found to be less than DC for cable lengths of 600 to 30,000 feet. Therefore, an AC transmission system was considered optimum for moderate cable lengths because of simplicity, reliability, availability of hardware (including control devices), and low acquisition cost.

Frequency. Transmission frequencies above and below 60 Hertz were evaluated in the study. As frequency increases, the impedance of the transmission cable also increases, requiring a larger and heavier cable for a given power level and cable length. In addition, frequency conversion equipment would be required.

The total impedance of the transmission cable decreases with decreasing frequency down to the DC resistance at zero (DC) frequency. A reduction in cable sizes is possible, but this advantage is quickly offset by limited availability of low-frequency equipment for the load module. The requirement for conversion equipment at the load module results in added costs for a hull to house the equipment. Consequently, the 60-Hertz frequency was selected as the optimum AC power transmission frequency for cable lengths of 600 to 30,000 feet.

Figure 24. Catenary cable support system.

Voltage Regulation. A voltage variation limit of plus or minus 5% was established as a design constraint to obviate the need for additional voltage regulation equipment in the load module. In case of constant power demand, voltage regulation equipment can be added at the power source end. However, this criterion is not practical since any load module will have an average load and a peak load, either of which may vary as much as 50%. The allowable voltage drop for a circuit depends on the required regulation or the current-carrying capacity of the cable. The required voltage regulation would be obtained by limiting the voltage drop in the cable system to 5%.

AC Distribution System. The selection between single-phase and three-phase power was 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.

The same pulsations take place in a three-phase system in each of the phases, but each phase of a three-phase circuit is separated by 120 electrical degrees. When one phase is delivering zero power, the other two are supplying the power requirements. Line losses are less in a three-phase circuit than in a single-phase circuit. Three-phase circuits may be as much as 40% more efficient. Conductor size and weight would be less for the three-phase circuit for the same power level and cable length. A three-phase system was therefore selected as the most cost effective for distributing AC power.

Transmission Voltage. Transmission voltage is the most significant electrical characteristic to be resolved since it will produce the most variation in the cost and versatility of the basic electrical system. Incremental transmission voltages of 480, 600, 2,400, 4,160, and 13,800 volts were considered appropriate for the study for cable lengths of 600 to 30,000 feet. Higher voltages were only considered appropriate for long transmission cables in excess of 10 miles, as required for shore-based plants.

At each selected transmission voltage, the components and equipment of the basic electrical system were added to the cable to arrive at an acquisition cost. The acquisition cost was then compared for each possible combination of transmission voltage, power level, and cable length. The acquisition cost was used in this trade-off on the assumption that engineering and deployment costs were the same for each voltage selected. The 5% maximum voltage drop in the transmission cable created limitations in the cost analysis of the selected voltage levels.

Cable Connectors. The availability of connectors with respect to voltage level and pin sizes was investigated in the selection of the most cost effective transmission voltage. Wet connectors suitable for underwater mating are nonexistent, and only a limited number of dry connectors are available for underwater use at the power levels of interest.

In an effort to reduce the number and types of connectors required for the power transmission system, a study was conducted on the effects of combining the secondary transformation and distribution equipment within the load module. This concept would require high-voltage connectors and hull fittings on the load module but would eliminate multiple sets of connectors and hull fittings required on a separate hull for transformation and distribution equipment. The separate pressure hull would also be eliminated. Consequently, it was determined that it is most cost effective to transmit the higher voltages directly to the load module. With this concept, additional weight and volume requirements would be imposed on the load module.

Electrical System Cost. A cost analysis was conducted on the acquisition cost of the basic electrical system versus transmission voltage. The costs of engineering, packaging, and protective circuits were considered

constant for the analysis. In addition to the costs of electrical equipment, the cost of cable support systems was considered. This cost, a direct function of the size of the cable and its overall length, favors the selection of higher voltage. For cable lengths of 600 to 2,000 feet, the cost of the suspension system must include additional buoyant support to maintain the cable in a vertical orientation. Therefore, a cost constant was assigned to the cable suspension systems.

An analysis of the two armor strengths included in the study indicates that the 125,000-psi armor costs about twice as much as the 30,000-psi armor and provides a cable load capability four times greater than that of the 30,000-psi armor. The results of the analysis indicate that the most cost effective cable support system would be 30,000-psi armor for cable lengths of 600 to 10,000 feet and 125,000-psi armor for cable lengths of 15,000 feet or greater.

Table 13 presents the most cost effective transmission voltages selected as a function of power level and cable length. The voltages indicated in Table 13 are acceptable for applications requiring long-term usage at a specific power level and installation. However, for general utility purposes, a block of power level conditions at various cable lengths can be selected and satisfied by one or two specific transmission voltages.

Table 13. Selected Transmission Voltages for Various Cable Lengths

Power Level (kw)	Cable Lengths (ft)							
	600	1,000	2,000	6,000	10,000	15,000	20,000	30,000
30	480	480	480	600	4,160	4,160	4,160	4,160
100	480	480	600	4,160	4,160	4,160	4,160	4,160
300	480	480	600	4,160	4,160	4,160	13,800	13,800
1,000	4,160	4,160	4,160	4,160	4,160	13,800	13,800	13,800
3,000	4,160	4,160	4,160	13,800	13,800	13,800	13,800	13,800

Protection System. The protection of electrical systems can be extremely complex. For this study, a constraint was established which limited the electrical protection to the underwater power transmission systems, excluding the load module or the specific safety needs of the mission.

For faults within the generation area, such as a generator or prime mover failure, it was determined that the generator plant would shut down while at the same time the emergency power system would be activated if available. All other faults on the transmission cable or at the load module

would be referred to the main reclosing circuit breaker at the power generating plant. The circuit recloser would complete one, two, or three reclosures before lockout to allow for transient conditions. The generator would be kept in operation during the reclosing operation but would be shut down at the time lockout occurs. The plant would also shut down on loss of control power. Standard differential and overcurrent relay protection would be provided for the generator plant. The transmission cable and load module faults would be referred by a carrier current scheme to the main reclosing circuit breaker for isolation.

The two modes of operation considered for the protection system were cascade and selective tripping. The selective system was not considered beyond a preliminary stage because of the added weight and space requirements.

A cascade protective scheme was therefore selected for the transmission system. Faults in the cascade system would be detected anywhere in the power transmission system up to and including the load module transformer. Loads connected on the secondary of the load module transformer would be provided with adequate protection with automatic, multiple-state reclosers. Both the load protection and reclosing equipment have to be coordinated with the transmission system for proper operation.

An unattended load module and generating plant, as envisioned in the study, would constantly display their condition and have a provision for periodic inspection. Some form of control is also necessary to allow an inspector or operator to operate (close or open) a circuit breaker remotely, depending on conditions noted on the display board. An alarm system connected to an established monitoring point is also required to alert plant operators of trip functions and problem indicators (high water temperature, low lubricating oil, etc.). A carrier system would be employed for this purpose.

In addition to providing a transfer trip function and indication, the carrier system would provide an overall differential circuit around the entire transmission line. Any faults in the cable would be detected by this differential zone which would, in turn, trip a differential relay located at the generator plant. Differential relays would be provided for the generator and transformer at the generator plant. Activating the differential relay would trip the main reclosing circuit breaker independent of the carrier system.

Control power would be provided by a control power transformer which would be connected ahead of the main breaker on the generator output. Thus, control power would always be available regardless of fault conditions, providing the generator is operating normally. The control system would automatically switch to emergency control power source should loss of the primary control power occur. A loss of both power sources would cause the generator plant to shut down.

A power transformer would be required for the plant auxiliary services and a rectifier for battery charging. The batteries provide emergency control power for relays, instrumentation, and tripping power for the main breaker.

The generator prime movers would have a full complement of mechanical and electrical indicating and protective devices.

In-Situ Power Systems

The preceding discussion on the electrical power transmission system for the selected power levels and cable lengths concerns surface plant facilities. In the in-situ facilities, the power module and the load module may be separated by less than 100 feet because wet connectors do not exist. As a result, the in-situ power module and the load module must be electrically connected prior to emplacement.

The operational philosophy of the protection system for in-situ plants is similar to that described earlier for surface plants. On a permanent fault, the load module is electrically isolated from the in-situ power module. The reactor then goes through a controlled shutdown. When the primary source fails, power for the load module is derived from batteries. In an in-situ facility, there is no external station to which fault information can be monitored, nor are there means to provide a remote corrective capability.

The mode of operation selected as the most cost effective for the in-situ system is to provide protective devices, instrumentation, and main circuit breaker in the power module, with redundant protective and control devices located in the load module for corrective action performed by an operator. The power module for all power levels and ocean depths would also contain the reactor, steam turbine, and generator. Only critical mechanical problems and electrical failures will shut down the in-situ plant by energizing various protective relays. All relays, main breaker, switchgear, and monitoring devices are located in the power module. All functions and ability to close or open the main breaker are carried back to the load module by a control cable.

Shore-Based Power Systems

For the shore-based system, the maximum length of circuit that could be tolerated while maintaining a 15% maximum voltage drop was considered for loads of 30, 100, 300, 1,000, and 3,000 kw at nominal voltages of 5 kv, 15 kv, and 34.5 kv, with a brief evaluation at 69 kv and 115 kv. The maximum incremental distances of 10, 50, 100, and 500

nautical miles were chosen as representative distances to reach the depths selected for the study. Table 14 presents the selected AC or DC voltages and includes all electrical costs, including costs for transformers, switchgear, and conversion and inversion equipment. No system is shown for the 3,000-kw power level at 500 miles. This distance and power level must be reached at a voltage level not considered practical with the present cable technology.

Table 14. Selected Voltages

Power Level (kw)	Cable Lengths (miles)			
	10	50	100	500
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
1,000	13,800 AC	34,500 DC	34,500 DC	34,500 DC
3,000	13,800 AC	34,500 AC	34,500 DC	—

For shore-based plants, the available cable sizes are limited. The maximum size of a three-conductor cable is determined by the maximum diameter of the three conductors, the insulation requirements for the voltage level, and the limitations of the cable manufacturing process. The minimum cable conductor size required for each voltage level would be dictated by voltage stress considerations.

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 thickness. The average value of voltage stress was determined by dividing the voltage across the insulation by the insulation thickness in mils. Voltage stress is not uniform in all parts of the insulation wall and is greatest at the conductor-insulation interface. Voltage stress in any point of a cable may be found by

$$S_v = \frac{\text{Voltage}}{2.303 \tau \log \left(\frac{D_1}{D_2} \right)}$$

where S_v = stress in volts per mil at a point in the insulation τ mils from the cylindrical axis of the cable

D_1 = outside diameter of insulation in mils

D_2 = inside diameter of insulation in mils

τ = point in the cable insulation measured from the cylindrical axis of the cable

Using the above formula, the maximum stress will occur at the conductor surface ($\tau = D_2/2$), or

$$S_{vmax} = \frac{0.868 \text{ Volt}}{d \log \left(\frac{D_1}{D_2} \right)}$$

The voltage levels considered for transmission of power from shore-based plants were 5 kv, 15 kv, 34.5 kv, 69 kv, and 115 kv. At 69 kv and 115 kv, single-conductor cables are recommended. The three-conductor cables rated for these voltage levels at the selected power levels and cable lengths exceed current manufacturing capabilities. Further, the single-conductor cables for 69 kv or 115 kv require a cable separation from 90 to 600 feet, depending on retrieval, maintenance, and repair requirements. This would require multiple passes with a cable-laying vessel, resulting in excessive deployment costs. For the larger cable lengths (500 miles), the inductive and capacitive reactances would cause a changing current of many times the load current. In addition, the size and weight of transformers at 69 kv and 115 kv required in the load module would be prohibitive when related to the added size and cost of the load module. Therefore, the 69 kv and 115 kv were eliminated from the study.

A trade-off analysis was made of AC versus DC power transmission systems for shore-based plants. The cost of engineering and deploying the AC and DC systems was assumed to be equal for purposes of this analysis. The three items considered to have a major influence in a cost effective analysis of the two systems were cable costs, DC conversion and inversion equipment, and the cost of the containment hull needed to house the DC inversion equipment in the load module.

A DC transmission system has distinct advantages over an AC system when related to transmission cable requirements at the voltage and power levels considered in this trade-off. The DC transmission cable has practically no changing current, no ionic motion in the insulation, no induced current

in the cable sheath, and no skin effect, all of which are prevalent in an AC transmission cable. Further, the DC transmission system may require only one cable if the sea is used as a return circuit; however, the hazards involved with so using the sea must be thoroughly investigated. Thus, the effective power transmitted in a DC cable is greater than that transmitted by AC for the same circuit conditions, resulting in reduced cable costs.

A DC transmission system does have some restricting factors. There is no easy way of transferring DC voltages except by AC methods at the converter and inverter ends of the transmission system. Inversion equipment requires a leading power factor which must be supplied by AC static or synchronous capacitors. Mercury arc valves have been used as conversion equipment for DC; however, this equipment requires clean room housing, degassing facilities, and rebuilding approximately every 5 years. The mercury arc equipment is expected to be replaced by high-voltage DC solid-state conversion equipment in the near future.

The DC transmission system has a lower cable cost than an equivalent AC system but requires special transformers and converter-inverter equipment at each end. A careful trade-off was therefore required before appropriate transmission systems from shore-based plants could be selected for the given circuit requirements.

Figure 25 shows a preliminary system selection and indicates that DC is the most cost effective system for cable lengths of 50 to 500 miles for the given power levels. AC is the most cost effective for all loads up to 10 miles and for a 3,000-kw load at 10 and 50 miles.

Figure 25. AC-DC system selection.

Voltage regulation of selected power transmission systems for shore-based plants is of major importance because of the long cable lengths. Voltage regulation for AC systems is affected the most by changing currents. Normally, the AC voltages at each end of the system are kept within desired limits by automatic tap changers on the transformers provided.

DC high voltage is normally regulated by controlling the rectifier firing angle to produce the required DC current and by operating the inverter with the maximum firing angle necessary for safe commutation.

The protection system for shore-based generator plants will be similar to that of the surface plant system. Where DC transmission is required, the protection system must also protect the DC equipment, which includes converter, DC transmission cable, and inverter. The AC transformers at either end of the DC system are protected with a differential relay circuit similar to the surface plant arrangement. The inverter equipment would have failure detectors, voltage sensors, and monitoring and control devices to cover such conditions as commutation failure, pulse synchronization, and fire-through. The converter or rectifier would also be similarly protected. All DC faults are referred to the AC systems at both ends of the DC link. The protection system should provide a means to differentiate between DC cable faults, inverter faults, and load module faults.

DEPLOYMENT CONCEPTS

The deployment of the three underwater power transmission systems, in-situ, surface-tendered, and shore-based, involves unique problems in the emplacement of cable in the deep ocean. Some of the major problems include induced cable oscillations due to ship or hull motion, high cable loading on storage drums, twist induced in long cables, and the placement and recovery of the large modules and associated components.

A route and site survey is of utmost importance in obtaining data for the design and deployment of an underwater power system. A bottom survey should be conducted to determine topography, sediment characteristics, temperature, and current profiles. Sediment information would also be required to determine the correct anchoring configuration. Temperature and current profiles are necessary to define the temperature effects on structures and materials as well as the current forces which cables and structures may be subjected to.

In-Situ Power Plant Deployment

The emplacement of the in-situ plant includes two modules, the power plant and the load module, which are rigidly coupled to a common base with either negative or positive buoyancy, depending on the mission. However, each module is positively buoyant and is provided with a safe method of separating from the base or from the other module in an emergency. The base has provisions for a ballast system. A wire rope and winch-down system are also included in the base for controlled descent and ascent.

The power plant and the load module would be connected together with the power and control cables at the surface prior to submergence. The in-situ plant is emplaced on the bottom by towing the preassembled system to the work site. The anchor is lowered to the bottom by heavy-lift ship, and the plant complex is trimmed out to the required buoyancy. Descent of the plant is accomplished by winching down against the positive buoyancy. A system of leveling legs and minor anchor blocks may be used for leveling when the system nears the bottom. In an emergency, the power unit may be shut down and the power cable disconnected (by explosive or mechanical means) to allow the power module to ascend upon release from the base. Retrieval of this power plant would involve the reversal of the deployment steps.

When it is impractical to deploy the two modules together on a common base, precaution must be taken in the handling of the power cable. If the two modules are deployed without a common base and are connected with a short link coupling, inherent cable fouling problems may occur. If the mission requires the two modules to be separated by a working radius greater than the depth of submergence, then deployment is greatly facilitated since the emplacement techniques used for the surface-tendered plant could be utilized.

Surface Power Plant Deployment

The sequence of deploying a surface-tendered power source and its related power cable is the establishment of the moor, emplacement of the surface power plant, and the connection and emplacement of the load module. Equipment and components required include a winch, specialized heavy lift equipment or modifications to a ship for the winch, and sensing and control devices. Flotation devices may also be used, particularly for the deeper depths. The mooring deployment vessels and equipment should have the capability of installing one leg of the moor without having to be resupplied with cable during the installation. A minimum of three deploy-

ment ships are envisioned, with one ship having heavy-lift capacity, one ship acting as a termination and collection point of the mooring legs, and one ship acting as a wire rope or cable supply and assist ship. A fourth ship, such as a seagoing tug, may be required for moor tensioning and intership transfer.

On arrival at the mooring site, the three ships take a position over the site of the first mooring leg anchor. Then the anchor is lowered in a controlled manner, keeping a constant rate of tension on the wire rope to place the anchor as opposed to dropping it. The use of a battery-operated bottom-sensing device attached to the anchor serves to indicate depth and anchor position relative to the bottom. A scheme using a different frequency for the sensing device on each anchor would provide an accurate positioning system.

An example of an anchoring system is shown in Figure 8. The anchor, a single shot of chain, a clump, and at least two additional shots of chain are attached to steel wire rope and deployed the full scope length. The wire rope is then connected to the terminal swivel socket and to the catenary support buoy. A nylon mooring line is attached to the terminal rig. This nylon mooring line is connected to a second ship at the central position of the moor, which would also be the location of the surface plant. Tension is kept by the second ship while the mooring legs are deployed 180 degrees apart. An estimate of mooring time per leg is 1 day to depths of 6,000 feet and 2 or 3 days per leg to depths greater than 6,000 feet. On completion of the deployment of the mooring system the surface plant hull is towed to the ship at the plant site. The nylon mooring lines are transferred from the ship to the hull by divers. This involves passing the lines through hawsepipes to the termination points (bits) on the deck of the hull. If required, a winch is used to pretension the lines.

The load module is deployed by positioning it relative to the bottom and slightly off-center along a bisector of the mooring legs. The ship that lays the power cable is brought alongside and the power cable is connected to the load module. The submergence of the load module and the paying out of the power cable from the ship storage drum are synchronized. On completion of the deployment of the load module the power cable is transferred and connected to the surface plant.

Two basic modes of load module emplacement are available: the free-fall technique and the tethered concept described earlier for the in-situ plant emplacement. The free-fall technique was not considered suitable for this emplacement. The second scheme involves tethering at the surface or at the bottom and winching down from the deployment ship. A surface-tethered emplacement uses a cable attached to the deployment vessel and is winched

down with negative buoyancy. This method provides a controlled and precise method of placement but is hazardous should the tethering cable fail. A module tethered at the bottom and winched down against positive buoyancy provides the best controlled mode with maximum safety. A nylon or polypropylene rope should be used for the winching operation because of the neutral buoyancy.

Shore-Based Power Plant Deployment

The emplacement of a shore-based power plant for an underwater power system involves three phases of effort—namely, construction of the power site, deployment of the power cable, and deployment of the load module. Deployment of the cable would be initiated at the power site and would end at the load module site at sea. Emplacement of the load module at the bottom would be accomplished last. The power cable would be connected to the load module while the module is on the surface over the deployment site. This would enable the complete check-out of the power system before the load module is submerged. Further, this method would assure that the proper amount of cable had been deployed to place the load module at the operational site.

The cable-laying procedure is basically the same as used for submarine power cables, except in deep water where a cable not capable of supporting itself must be deployed using buoyancy devices. A bottom topography survey is required to establish a cable route, to determine the correct cable length required, and to locate hazardous areas. A cable-laying ship having the required cable storage and handling capacities would be used for cable emplacement. The cable would be laid seaward from the shore with the surf and tidal zone section of the cable buried or placed in ducts 6 feet below the low tide level. Bottom cable laying may be done from a ship having spinal-wound cable tanks, providing the recommended cable tension is maintained by the winches on the ship. Table 15 lists the cable-laying capacities of ships which can be used for the cable emplacement.

When the cable becomes so long that it can no longer support its own weight, cable buoyancy must be provided. A state-of-the-art buoyancy system that could be used to give maximum buoyancy control is 42-lb/ft³ aviation gasoline. Syntactic foam increases net buoyancy by 2% due to its relative incompressibility and temperature independence. Aviation gasoline decreases in buoyancy by about 8% at a depth of 20,000 feet due to compressibility and temperature effects.

Table 15. Cable Ship Data

Ship ¹	No. of Cable Tanks	Volume of Cable Tanks (ft ³)	Nautical Miles of 1.25-Inch-Diam Cable ²
<i>LCV</i>	1	6,937	80
<i>LSM</i>	2	10,395	125
<i>LST</i>	2	15,777	200
<i>USS Neptune</i>	3	30,116	415
<i>USS Aeolis</i>	3	43,385	610
<i>USS Thor</i>	3	43,385	610
<i>USACS A. J. Meyer</i>	4	48,000	615
<i>SS Saleumum</i>	3	22,354	315
<i>SS Long Lines</i>	7	139,000	2,000
<i>SS Mercury</i>	3	106,740	1,200
<i>SS Neptune</i>	5	222,500	3,000
<i>SS Marcel Bayard</i>	4	77,333	1,000

¹ All the ships except the *LCV*, *LSM*, and *LST* are equipped with automatic tensioning devices to compensate for sea conditions.

² Ship loaded at 80% cable capacity.

Varying ratios of syntactic and aviation gasoline can be used to achieve negative, positive, or neutral buoyancy. The floats may or may not have release mechanisms to enable them to return to the surface. A retrievable flotation system would use rubberized fiber bags containing a mixture of aviation gas and syntactic foam; upon reaching the bottom the bags would be released by an imploding glass ball or spring-loaded trip mechanism.

It is important that the power cable be allowed to relax as the load module is emplaced. Cable stored in the tanks twists as it is deployed. The twist is tolerable when the cable is laid on the bottom, since the surrounding friction forces tend to secure the cable. However, in open water, the cable would tend to coil. One way which could be used to solve this problem is to unwind the cable from the tank in a tangential manner. Proper techniques in applying cable armoring would also relieve the problem. The cable twist problem during cable-laying operations must be investigated thoroughly in the final design of underwater power systems.

Figure 26 illustrates two methods of submerging the load module from the surface. An untethered descent requires an outward force through the arc of deployment, as shown in Figure 26a. Figure 26b illustrates a precisely positioned, self-submerged (by winching) load module emplacement.

SELECTED POWER SYSTEMS

The evaluations, analyses, and optimization processes described heretofore provide the basis for selecting the most cost effective concepts of the following underwater power systems:

1. 30-, 100-, and 300-kw in-situ power plants for load modules deployed at depths of 600, 2,000, 6,000, 10,000, 15,000, and 20,000 feet; 1,000- and 3,000-kw in-situ power plants for load modules deployed at depths of 600 and 2,000 feet.
2. 30-, 100-, 300-, 1,000-, and 3,000-kw surface-tendered power plants for load modules deployed at depths of 600, 2,000, 6,000, 10,000, 15,000, and 20,000 feet.
3. 30-, 100-, 300-, and 2,000-kw shore-based power plants for load modules deployed at distances of 10, 50, 100, and 500 miles from shore; 3,000-kw shore-based power plants for load modules deployed at distances of 10, 50, and 100 miles from shore.

The preliminary designs for six of these power systems are given in the Appendix.

The cost estimates presented for the recommended systems are for engineering, construction, and testing. Cost of development programs or advanced engineering for the power cable connectors, system deployment, property acquisition for shore-based plants, transportation, and site preparation are not included. Likewise, the cost of the common base for the in-situ plant is not included.

In-Situ Power Systems

A reactor power plant was chosen for all the selected in-situ power systems. This plant will provide an in-situ power system with a reasonably long life. Cost data for the in-situ power systems are presented in Table 16. Operational costs are difficult to define without more complete data on operating schedules and power profiles, both of which influence refueling

costs. Investment and maintenance costs range from \$150,000 to \$500,000 per year for 30-kw to 300-kw plants, and estimated yearly fuel costs range from \$25,000 for the 30-kw plant to \$1,000,000 for the 3,000-kw power plant. Maintenance and investment costs are related to power level and operating depth, whereas fuel costs depend primarily on the core size or energy available, refueling operational costs, and core costs.

Table 16. Estimated Costs of In-Situ Power Sources

(Values are in millions of dollars and include the cost of syntactic foam for flotation.)

Power Level (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	—	—	—	—
3,000	13.3	14.2	—	—	—	—

Note: Dashes indicate that the power plant concept was not defined because of the major developmental effort required.

For loads of 30 to 300 kw, a 3-phase, 60-Hertz, 480-volt transmission link was selected between the in-situ power and load modules. A 3-phase, 60-Hertz, 4,160-volt transmission link was selected for loads of 1,000 and 3,000 kw. A transformer would be required in the load module at the higher transmission voltage.

Table 17 summarizes the cable and connector requirements for the recommended in-situ power systems. As indicated in the table, there is no restriction on connectors for loads of 30 and 300 kw. However, at the 300-kw power level, two 1/0 AWG conductors would be used in lieu of the 4/0 AWG shown since no connectors are available with 4/0 AWG pin size. A connector is available for the 4,160-volt and 1,000-kw load but requires some engineering and testing prior to use. For the 4,160-volt and 3,000-kw load, connectors are not available; therefore, three 1/0 AWG conductors per phase are recommended.

(a) Surface tethered.

(b) Bottom tethered.

Figure 26. Load module deployment.

Table 17. Cable and Connector Requirements
for In-Situ Plants

Transmitted Voltage	Load (kw)	Conductor Size	Connector Available	Recommended Transmission Method
480	30	6 AWG	yes	optional
	100	4 AWG	yes	optional
	300	4/0 AWG	no	two 1/0 AWG cables
4,160	1,000	4 AWG	yes	requires engineering
	3,000	300 MCM	no	three 1/0 AWG cables

The hull of the in-situ power plant would serve as a heat transfer area. The internal equipment of the plant includes a typical pressurized water-cooled reactor and shielding as a primary system. The secondary system includes the steam turbine generator system. The turbine steam exhaust would be condensed and the waste heat removed by contact with the steel pressure hull for loads up to 300 kw. For loads of 1,000 kw and above, standard condensing techniques would require the use of hull penetrations to provide seawater cooling for the condenser.

Surface Power Systems

A 3-phase, 60-Hertz, AC electrical system was selected for each of the surface-tendered power plants. A diesel generator was selected as the power-generating equipment for surface-tendered plants. Control and instrumentation signals from the load module would be transmitted by carrier over the power cable. A 24-kw/hr manhex plante battery complete with battery charger was selected for the emergency power source.

The cable system selected included a three-conductor power transmission cable, cable support system, watertight connectors, and pressure hull penetrations. High-strength galvanized steel wire armor was selected for the cable. Conductor sizing was based on the smallest size that would transmit the required power at no greater than 5% voltage drop. A maximum cable load to be supported by the surface plant hull was established at 50,000 pounds.

The budget cost estimates for the surface power systems are given in Table 18.

Table 18. Estimated Costs of Surface Power Sources

(Values are in thousands of dollars.)

Power Level (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	1,535.0	1,708.1	1,961.2	2,268.4	2,783.9	3,445.9
1,000	2,155.7	2,297.4	2,553.7	2,883.8	3,362.4	4,019.8
3,000	2,619.0	2,775.3	3,010.2	3,423.3	3,824.5	4,660.6

Shore-Based Power Systems

In most cases, a DC electrical system was selected for the shore-based power systems. A DC system requires conversion or rectifiers at the shore-based plant and inversion equipment at the load module end. Shore-based power systems require the same load module subsystems as surface-tendered plants, with the addition of the DC inversion equipment and a bank of capacitors. The capacitors would provide blocking voltage to stop the inverter if this becomes necessary and would be mounted on the outside of the module in a pressure-compensated configuration. Table 19 presents the voltage levels, loads, frequency, conductor sizes, and losses for the shore-based power systems.

Physical characteristics of the shore plant were not investigated since those factors are not critical for this facility. The diesel generators are self-contained in the 30-kw to 300-kw power levels. The 1,000-kw and 3,000-kw diesel generators require cooling tower and compressed air starting systems. No system was selected for the 3,000-kw load at 500 miles. The protective system for the shore-based power system would be similar to that of the surface plant system. Cost estimates for the shore-based power systems are given in Table 20.

A power generating plant was purposely included in the shore-based power systems to provide a "worst case" cost effectiveness analysis. Electrical power services available at the shore sites should be utilized if sufficient power is available.

Table 19. 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 AWG	1.39
	100	4.16	AC	4 AWG	12.00
	300	13.8	AC	2 AWG	5.1
	1,000	13.8	AC	2 AWG	66.0
	3,000	13.8	AC	4/0 AWG	202.0
50	30	13.8	DC	2 AWG	1.3
	100	13.8	DC	2 AWG	15.3
	300	13.8	DC	1/0 AWG	85.5
	1,000	34.5	DC	1 AWG	202.0
	3,000	34.5	AC	1 AWG	204.0
100	30	13.8	DC	2 AWG	2.7
	100	13.8	DC	1/0 AWG	19.2
	300	34.5	DC	1 AWG	36.0
	1,000	34.5	DC	2/0 AWG	246.0
	3,000	34.5	DC	350 MCM	280.0
500	30	34.5	DC	1 AWG	1.8
	100	34.5	DC	1 AWG	20.0
	300	34.5	DC	4/0 AWG	69.0
	1,000	34.5	DC	600 MCM	231.0
	3,000	— ¹	— ¹	— ¹	— ¹

¹ A 3,000-kw load at 500 miles cannot be reached at the voltages considered.

Table 20. Estimated Costs of Shore-Based Power Sources

(Values are in thousands of dollars.)

Power Level (kw)	Cable Length (miles)			
	10	50	100	500
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
1,000	1,700	2,990	5,421	44,837
3,000	2,140	4,232	11,339	—

CONCLUSIONS

1. The most serious problem associated with the development of underwater power systems for power levels of 30 to 3,000 kw at depths of 600 to 20,000 feet is the limitation of watertight cable connectors.
2. In-situ power plants can supply 30 to 300 kw of usable AC power at depths of 600 to 20,000 feet and 1,000 to 3,000 kw at depths of 600 to 2,000 feet within the current state of the art.
3. Surface power plants can supply 30 to 3,000 kw of usable AC power to depths of 600 to 20,000 feet within the current state of the art and, except for underwater connectors, without technical limitations.
4. Shore-based power plants can supply 30 to 1,000 kw of usable AC or DC power to depths of 600 to 20,000 feet and 3,000 kw at depths of 600 to 10,000 feet within the current state of the art and, except for underwater connectors, without technical limitations.
5. In-situ power plants are not economically competitive with either shore-based or surface-tendered power plants except for restrictive undersea missions.
6. Surface-tendered power systems are most cost effective for all selected power levels and ocean depths more than 50 miles from shore.
7. Shore-based power systems are most cost effective for all selected power levels and cable lengths of 10 to 50 miles.

8. The water-cooled nuclear reactor is the most cost effective power plant for the in-situ power system that operates at power levels greater than 30 kw.
9. The diesel engine generator is the most cost effective power plant for both the surface and shore-based power systems.
10. AC power transmission is more cost effective for distances up to 10 miles between power source and load module; distances from 10 to 500 miles involve trade-offs; and beyond 500 miles, DC power transmission is more cost effective.
11. The most cost effective generated voltage is 480 volts, 3 phase, 60 Hertz for loads of 30, 100, and 300 kw and 4,160 volts, 3 phase, 60 Hertz for loads of 1,000 to 3,000 kw.
12. An armored, polyethylene-insulated and jacketed, three-conductor cable provides the most reliable transmission cable for all deep ocean power systems.
13. A four-point mooring system is the most reliable method of mooring a surface plant.

RECOMMENDED DEVELOPMENT PROGRAMS

As a consequence of the study program on underwater power systems, several development or "high risk" areas were identified. These development areas are necessary to complete the preliminary design of selected power systems (see the Appendix). The establishment of a development program for the "high risk" areas would greatly improve the cost effectiveness of the selected systems.

Cable Connectors

The surface-tendered and the shore-based underwater power systems require two different connectors for each system—one at the power plant and one at the load module. For the in-situ power systems, two connectors are also required, but both would be identical.

Connectors can be characterized as two basic types, wet and dry. The dry connector is essentially an electrical device that provides the necessary continuity between a cable and a particular module. In a dry connector, water or moisture are not allowed to enter the connection point. Therefore, the connection must be made in a relatively dry atmosphere and, in the case of underwater systems, connections must be made prior to emplacement of the cable or modules. A wet connector has the same capabilities as the dry

connector, but it enables an electrical connection to be made in the ocean. This feature offers a tremendous advantage in the emplacement of underwater power system elements.

A wide range of connectors are available so that power levels up to 1,000 kw can be handled. However, this is not true for connectors to be used with the higher voltages selected in the study program. Figure 20 illustrates the availability of dry connectors for underwater power systems. Connectors suitable for a power level of 100 kw could be made available by preliminary engineering and limited testing. Connectors in the 3,000-kw range are not available and would require substantial development effort.

The recommended development program was divided into a series of phases. A milestone chart, program schedule, and budget costs for the connector development program are given in Figure 27. Phase I of the connector development would encompass concept formulation and trade-off analysis. Four types of connectors suggested for development were pressure-compensated and not-pressure-compensated connectors for both the dry and wet connector designs. The connectors would be suitable for 4,160 volts and loads of 300, 1,000, and 3,000 kw and for 13,800 volts and 3,000 kw. Final design approaches would be studied to evaluate the most cost effective connectors and to establish the validity of specific connector concepts developed. Phase II would involve the design, fabrication, and testing of prototype dry connectors for the selected designs established in phase I. A 4,000-volt, 50-ampere connection would be developed for depths as great as 20,000 feet. In phase III a prototype 4,000-volt, 50-ampere wet connector and a prototype 4,000-volt, 160-ampere dry connector would be developed and tested. Phase IV is the same as phase III except that the prototype connectors would be for higher power levels. A 4,000-volt, 200-ampere wet connector and a 4,000-volt, 500-ampere dry connector would be developed. In phase V a prototype 13,800-volt, 150-ampere dry connector and a prototype 4,000-volt, 500-ampere wet connector would be developed and tested. Phase VI would produce the final design of the entire family of connectors for underwater power systems.

Heat Rejection Systems

An in-situ reactor power plant using a secondary steam turbine generator as the energy conversion system requires a significant heat removal capability. Heat removal could be accomplished by the use of circulating seawater through appropriate hull penetrations or by condensing the steam on the normally cooler pressure hull. The advantage of the first method is that a theoretically unlimited heat removal capability would be provided.

However, such a method suffers from such significant disadvantages as the requirements for hull penetrations, high pressure piping systems, and internal heat exchangers, as well as the excessive weight of transition forgings for the hull penetrations. There is also the possibility of sediment clogging with the plants resting on or near the ocean bottom. At present pressure hull penetrations 3 inches in diameter have the capability of withstanding pressures as great as those found at 3,000-foot depths. The second method of heat removal—condensing steam on the pressure hull—would reduce the high risk design of hull penetrations and the sediment clogging problems, but its limited heat removal capability would make necessary an oversized hull or the provision of finned surfaces with external or internal circulating techniques.

Figure 27. Milestone chart for cable connector development program.

A three-phase development program was suggested to advance the state of the art in heat rejection systems for in-situ reactor power plants. A milestone chart, budget costs, and program schedules for the heat rejection systems development are shown in Figure 28. Phase I would entail a concept formulation and trade-off analysis to develop criteria for the selection of the most promising heat rejection designs. Two concept approaches to be evaluated would be circulating seawater through hull penetrations and heat removal through the hull structure. Effective ranges of both concepts would be established to show the feasible upper limit of the hull transfer and the lower limit of the seawater circulating systems.

Figure 28. Milestone chart for heat rejection system development program.

Phase II would include concept development studies for the most promising hull heat rejection system selected in phase I. Sufficient stress analysis would determine the adequacy of hulls with thermal stresses applied. In addition, the upper limit of effectiveness of this approach would be established, with sufficient details developed to initiate the final design process.

Phase III is similar to phase II except the most promising seawater circulating system and hull penetration schemes would be analyzed. A stress analysis of the transition forgings for the hull penetrations and a pipe stress analysis would be conducted to minimize the weight of the high pressure piping and forgings. The parameters developed would define cost effective limits of the hull penetration—seawater-circulation concept. Here, as in phase II, the goal would be to extend the state of the art of in-situ power plant heat rejection systems and to provide sufficient details for initiation of the final design process.

General Utility Power System

A development program for an underwater utility power transmission system was recommended as a result of the underwater power systems study program. The development program would involve three phases. The estimated budget costs and a milestone chart for the general utility underwater power systems are shown in Figure 29.

In phase I concepts of a 30-kw to 100-kw general utility power transmission system would be developed for depths of 600 to 10,000 feet. The concepts would provide a secondary power distribution module to serve several dissimilar loads and the necessary primary power conditioning equipment for adaptation to either the surface or the in-situ power plants.

In phase II additional concepts for a 100-kw to 300-kw general utility power transmission system would be developed. The concepts would provide primary conditioning equipment and a secondary power distribution module to serve several dissimilar loads from an in-situ reactor plant only. A maximum transmission cable length of 6,000 feet would be considered.

The adaptation and modification of the recommended systems to the available power sources constitute phase III of the development program.

The recommended development program for each system described above would include 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, the underwater general utility power transmission systems would provide the current needs of underwater load modules with total power requirements of 30 to 300 kw down to 10,000 feet.

Figure 29. Milestone chart for general utility power system development program.

Development of the secondary power distribution module, including pressure containment hull and penetrations for cable connectors, would be assigned the highest priority of all the elements associated with the development of the general utility power system.

In-Situ 3,000-kw Power Plant

It became apparent during the course of the study that reactor power systems with a 1,000-kw to 3,000-kw electrical power output could not be readily adapted to depths of 6,000 to 20,000 feet. There are numerous problems associated with the physical size and weight of large reactor plants, such as hull design and materials, buoyancy, heat transfer techniques, place-

ment and recovery, and logistics. A separate study was therefore considered necessary to formulate concepts for large in-situ reactor plants when an application becomes apparent and defined in greater detail. Sufficient definitive information was not available in this study to establish cost and time schedules for the development program.

PRELIMINARY DESIGNS OF SELECTED UNDERWATER POWER SYSTEMS

SELECTED SYSTEMS

The underwater power systems selected for preliminary design were:

1. 100-kw in-situ power systems emplaced on the ocean floor at depths of 600 feet and 6,000 feet.
2. 30-kw surface-tendered power systems for supplying power to ocean depths of 600 feet and 6,000 feet.
3. 300-kw shore-based power systems for cable lengths of 10 miles and 50 miles.

100-kw Nuclear Reactor In-Situ Power System

The in-situ plant selected for a preliminary engineering analysis consists of a power module, a load module, a foundation, and auxiliary equipment, as illustrated in Figure A-1. Trim and ballast components, as well as winches, would be provided as the required auxiliary equipment.

A design concept of a 100-kw in-situ power plant module is shown in Figure A-2. The plant consists of a nuclear steam generator and a Rankine cycle turbine generator system rated for 100-kw net power. The steam generator selected was based on General Atomics TOPS-300 power supply. It 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 would be geared to a 60-Hertz electric generator.

Figure A-1. In-situ nuclear reactor power plant.

Figure A-2. Preliminary design of a 100-kw in-situ power plant.

The pressure hull for an in-situ power plant would be cylindrical, with external frames and hemispherical heads on each end. External frames allow smooth internal surfaces for use as a heat exchanger. The top hemispherical head would be used for all the electrical penetrations and an access hatch. Main power, plant monitoring and control, and battery cable penetrations would be required, with a number of spare or blank penetrations provided for power and instrumentation. The access hatch would be large enough to accept a small submersible for underwater servicing or maintenance of the power plant. An alternative to the access hatch could be a bolted hemispherical top, which would make it easier to replace large equipment and refuel the reactor. However, a more complete analysis of these two methods in terms of equipment size would be required if replacement or refueling was defined as a plant requirement.

The pressure hull for the 600-foot depth has been estimated as 1/2-inch HTS steel plate and for the 6,000-foot depth as 1-5/8-inch HY 130 steel plate. Typical hull designs are shown in Figure A-3. These hull estimates allowed for factors of safety of at least 1.5 on yielding and 2.0 on buckling. An increased hull weight of 10% was included in the plant design to allow the use of the hull as a heat exchanger. The hull would be used for condensing steam.

The arrangement of the power plant is the same for both operating depths, 600 and 6,000 feet. The characteristics of the load module were undefined. Preliminary characteristics of a 100-kw plant are listed in Table A-1. The plants would normally operate with the axis oriented vertically. However, full power could be obtained with the plant at 15 degrees from the vertical. The plant could be transported in nearly the horizontal position.

Table A-1. Characteristics of Preliminary In-Situ Power Plant

Operating Depth (ft)	Outside Diam, Less Frames (ft)	Overall Length (ft)	Hull Material	Weight (lb)			Displacement (lb)	Buoyancy (lb)
				Hull	Machinery	Total		
600	10	36-1/2	HTS	34,000	122,000	156,000	166,500	+10,500
6,000	10	36-1/2	HY 130	93,000	122,000	215,000	166,500	-48,500

Figure A-3. Typical pressure hull designs.

The lower portion of the plant would contain the reactor, its auxiliary systems, shielding, the secondary system condensate and feed pumps, and the freshwater cooling system. The midsection would contain the turbine generator and its auxiliary systems. A shield deck separates the midsection from the lower compartment, through which there is limited access while the plant is operating. The upper level would contain all the electrical and electronic equipment, the power plant control equipment and enclosures, the primary distribution equipment, and the transmission control and instrumentation circuits. An air conditioning unit would be provided for temperature and humidity control of the upper compartment. Cable penetrations through the hull and the access hatch would be located in the upper compartment.

An inner cylinder would be provided in the lower reactor compartment to form a steam condenser. This cylinder supports nearly all the equipment in the midsection and meets the hull only through a flexible skirt at the upper end of the inner cylinder. The bottom end of the cylinder would be fastened to the shield tank structure. This arrangement would prevent pressure hull deflections from disturbing the equipment. The deck above the cylinder is connected to the shield deck by stanchions.

The inner cylinder provides a structure on which the complete plant may be assembled, tested, and installed within the pressure hull without disassembly. Prior to installation, the reactor operating time and power level should be limited to the amount of residual radiation which would not prohibit handling during installation. For subsequent refueling or maintenance, the inner cylinder with the two deck levels may be detached and removed as a unit.

The maximum radiation levels established for the in-situ plants are presented in Figure A-4. These levels would allow limited personnel access to the area above the shield deck for servicing the plant while it is operating at full power. Since occupancy times can only be predicted, the maximum permitted radiation levels established may be lower than necessary. A primary shield would be provided by lead and shield water tank. This would allow limited access to the exterior of the pressure hull after the reactor is shut down (30 days). Dose rates during operation would be high in the water surrounding the reactor compartment. A protective screen would be required around the reactor compartment at shallow depths where divers may have access.

Requirements for a special containment vessel for this power plant were not firmly established. Such a vessel would protect the pressure hull from overstress due to thermal gradients resulting from secondary steam, primary coolant relief valve lifting, or primary coolant system leakage. The containment vessel would also provide additional protection against the

release of fission products. The thermal stress gradient across the hull was not calculated, but if a containment vessel were required, the inner cylinder could be closed off at the upper end. This would result in increased fabrication complexities. Even without the containment vessel, there would be three barriers to the release of fission products: fuel element cladding, primary coolant pressure vessel, and pressure hull. Therefore, a special containment vessel would not be required.

Figure A-4. Maximum radiation levels for in-situ power plants.

The power conversion system would have a single turbine generator with a main steam system, condensate and feed system, auxiliary steam equipment, make-up water system, and purification system. The power conversion

system flow diagram is shown in Figure A-5. Superheated steam would be obtained from dual, full-capacity, once-through steam generators. Steam would flow through a stop valve and would be controlled by a throttle valve which is governor-regulated to control the turbine speed. The stop valve would be closed automatically to protect against overpressure, overspeed, or loss of lubrication. Exhaust steam would be condensed by an annular hull condenser and recycled through a full-flow demineralizer to maintain purity for the once-through steam system. Power conversion system data for the preliminary design are shown in Table A-2. Figure A-6 shows the full-power heat balance for the power conversion system.

Table A-2. Data for Preliminary Power Conversion System

General	
Electric power (net), kw	100
Overall efficiency, %	11.4
Thermal power, kw	880
Steam Cycle	
Turbine inlet pressure, psia	262
Turbine inlet temperature, °C	235
Turbine inlet superheat, °C	10
Turbine exhaust pressure, psia	3.3
Turbine steam flow, lb/hr	2,560
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	3,600
Power, kw	115
Voltage, volts	480
Frequency, Hertz	60
Phases	3

Figure A-5. Preliminary power plant conversion system.

Figure A-6. Preliminary full-power heat balance.

The annular condenser would be formed by making a space between the pressure hull and the inner cylinder. A 3/4-inch annular condenser would allow for pressure hull deflections of 5/32 inch. The lower end may be rigidly attached, but the upper end should be attached with a flexible seal to the hull to avoid loading the inner cylinder with sea pressure deflections of the pressure hull. The hull condenser would be adequate sized for plants at depths of 600 and 6,000 feet where the ambient seawater is 24°C. However, for 29°C seawater, the plant at 6,000 feet would have to operate at about 2/3 of full power, and the plant at 600 feet would provide full power at 29°C.

The freshwater cooling system, shown in Figure A-7, would provide cooling for the air ejector and gland exhaust condenser, air and lubricating oil cooler for the turbine-generator set, reactor plant auxiliary systems, and machinery spaces. Freshwater would be circulated through a water cooler heat exchanger and then circulated to the various coolers. Heat would be transferred from the freshwater to the shield water by a shield water circulating system and then finally rejected from the shield water through the pressure hull. The total freshwater heat load was estimated to be less than 250,000 Btu/hr. The shield water heat load was estimated to be less than 300,000 Btu/hr.

Figure A-7. Preliminary freshwater cooling system.

A relatively warm interior is possible when the pressure hull is used for heat transfer. However, humidity would be high because of the water and steam systems. The upper level would be thermally insulated from the rest of the plant to maintain a reasonable temperature and humidity for the electronic and control equipment. An air conditioning unit that uses a forced convection cooler with water circulating against the hull could be used for the upper level area.

A pressure-compensated battery supply located outside the pressure hull would supply power for plant start-up, monitoring and standby, deployment and recovery operations, and emergency power. Batteries would provide power for navigational lights and signalling devices during deployment and recovery. The total battery power requirement was estimated not to exceed 15 kw-hr, with about 5 kw-hr allowed for plant start-up. A battery charging system was included to automatically maintain the batteries at full charge.

The turbine generator plant would deliver 100-kw, 480-volt, 3-phase, 60-Hertz power for the 600- and 6,000-foot depths. The transmission cable between the power module and the load module of the in-situ system would be a three-conductor, shielded, grounded, neutral, armored cable. Conductor size would be 4 AWG. Duplicate monitoring and control of the power plant would be provided in both the power module and in the load module. A multiconductor control cable would be provided between the two modules.

The protective system for the in-situ power system would include standard differential relay circuitry for the generator, a differential zone for the cable transmission between modules, and circuit protection for the control power as well as the generator exciter circuits. The philosophy of operation would be to keep the system in operation until loss of equipment is inevitable, at which time it will shut down. Loss of control power would also shut the plant down.

A forced descent-ascent concept was selected for emplacement of the in-situ power system. The anchor would be located on the bottom by using soundings in conjunction with a leveling device or by the more elaborate method of using a remote television camera mounted on the anchor cable. The camera method would probably be used at the 600-foot depth; the bottom leveling device and surface soundings at the 6,000-foot depth.

Once the anchor has been set on the bottom site, deployment of the in-situ plant would begin by placing the plant's primary and secondary systems in a remotely actuated start-up mode. Final ballast and trim adjustment would be made, and descent stabilizers would be rigged for descent. The descent may be initiated by flooding the main ballast tanks, but the winch-down method would be used for the actual descent. A bottom-sensing weight would begin to decelerate the descent velocity 150 to 200 feet above the bottom. When the plant is on the bottom, a triggering device would trip the winch switch to stop the winch operation.

Emergency ascent is based on retrieving as much of the in-situ plant as possible. The winch would also be used for ascent. However, if the batteries fail or the winch becomes inoperative, the free ascent method, described earlier, would be made. In the preliminary design, the power module would be jettisoned for free ascent, leaving the load module and base in situ. The ascent rate of the power module must be controlled to avoid having the module jump out of water when it surfaces. Figure A-8 illustrates the emergency ascent method selected.

The major milestone chart and budget cost estimates for the 100-kw in-situ power systems are shown in Figure A-9. The milestone schedule would be the same for both depths of 600 and 6,000 feet. The costs of transportation deployment and common base for the power and load modules are not included in the estimates.

Extensive engineering effort is anticipated for solving heat transfer problems and for protecting the hull surfaces against the environment. Some testing may be necessary to evaluate the heat transfer characteristics of selected protective coatings.

30-kw Diesel Electric Surface Power System

A standard commercial 30-kw diesel electric power plant would be installed in a surface hull similar to the General Dynamic monster buoy. The hull (buoy)—41 feet in diameter and 7-1/2 feet high overall—would be equipped with a 20-foot-high, 5-foot-diameter mast and stack. The buoy would have a double hull, the outer hull being circular and the inner hull being square. An egg-crate structure between the inner and outer hulls would serve to stiffen the hulls and provide a baffled fuel storage area with a minimum of fuel agitation. Four vertical hawsepipes would traverse the fuel storage area, allowing passage of the mooring lines.

Figure A-8. Emergency ascent.

Figure A-9. Milestone chart and budget cost estimates for 100-kw in-situ power system.

The surface plant hull would use a modular arrangement of the power plant and components. Three compartments would be provided in the power plant module. The largest would contain the power plant, a separate compartment would contain the electrical and electronic equipment, and the third compartment would contain the oil handling and filtering equipment. Any of the major units could be hoisted out of the buoy or surface hull without disturbing the mooring system. The provision was made to avoid abandoning the moor for equipment replacements. The generator plant could be replaced with a 100-kw unit if needed in the future. The only difference as the result of this exchange is that a shorter refueling cycle is required. This eliminates the need for establishing a new moor. Existing cables would have adequate capacity to serve the higher load. Figures A-10 through A-12 show the surface plant hull arrangement.

Figure A-10. Surface power plant hull.

Figure A-11. Cutaway of surface power plant hull.

The power plant is a turbocharged diesel generator. The unit is self-contained, with necessary engine accessories and protective devices. A shell-and-tube-type heat exchanger is provided for the diesel engine, with seawater in the tubes and freshwater in the shell. The freshwater system cools the engine. Engine intake air is taken from the engine room at ambient conditions. An additional 3,000-cfm fan is provided to ventilate the engine room. An exhaust muffler is provided between the engine and a plenum leading to the exhaust stack. Batteries are used for starting the engine.

Figure A-12. Cross section of surface power plant hull.

The generator is rated for 50-kw continuous or 60-kw intermittent, 60-Hertz, 480-volt, 3-phase, AC power output. Voltage regulation was established at 1% bandwidth of steady-state voltage, with a maximum steady-state frequency variation of 0.5%. The no-load to full-load recovery time was set at 4 seconds with an isochronous governor. The same generator plant is used for the 600-foot-deep and the 6,000-foot-deep transmission systems. Table A-3 lists the characteristics of the diesel generator.

The electrical systems selected for the surface-tendered power system were 480 volts, 3 phase, 60 Hertz for 600-foot depths and 4,160 volts, 3 phase, 60 Hertz for 6,000-foot depths. The 480-volt generator plant output will be transmitted directly to the load module. The 4,160-volt system will generate power at 480 volts, which will be stepped-up to 4,160 volts with a dry transformer; the power will then be transmitted to the load module at 4,160 volts.

Both the 480-volt and 4,160-volt systems will utilize the same type of cable, with the insulation level at 5,000 volts. The conductor size selected for both systems is 6 AWG. The 480-volt system at 600 feet will require 915 feet of cable, and the 4,160-volt system at 6,000 feet will require 11,790 feet of cable. These cable lengths would limit the voltage drop to within 5%.

Table A-3. Characteristics of 30-kw Diesel Generator for 600-Foot-Deep and 6,000-Foot-Deep Surface Power Plant

Diesel Engine (Turbocharged and Aftercooled)	
Rating	50 kw at 1,800 rpm, continuous 60 kw at 1,800 rpm, intermittent
Approximate volume	6 feet long x 3 feet wide x 3-1/2 feet high (63 ft ³)
Approximate weight	2,400 pounds
Governor	0.5% speed control
Heat exchanger	single-pass shell and tube
Capacity	5,000 Btu/min
Generator (Splash Proof)	
Voltage	480 volts at 60 Hertz, 3 phase
Rating	50 kw at 70°C, continuous, with 25% overload capability for 2 hours
Regulation	1% steady state
Attached Accessories	Detached Accessories
Turbocharger and aftercooler	Heat exchanger
Generator and exciter	Heat exchanger pump
Air filter	Exhaust muffler
Lubricating oil pump and filter (self bypassing)	Alarms and gages
Fuel oil pump and filter (self bypassing)	
water pump	

A cascade-type protection system was recommended because of savings of weight and volume in the load module. The carrier system was provided for transfer of trip functions, data recordings, and system-condition displaying. Communications to the surface could also be provided by carrier.

A four-point moor would be provided for the surface plant hull. The four wire rope moorings enter the bottom of the hull close enough to the center to retain the desirable characteristics of a single-point moor but far enough outboard to prevent rotation and the consequent twisting of the power cable. A four-point moor reduces the excursion limits of the surface hull and therefore reduces the length of power cable required. The moors entering the bottom of the hull would prevent the hull from towing under in high sea states. Figure A-13 illustrates a four-point mooring attachment to the surface hull.

Three ships would be required to set the four-point mooring system: a heavy lift ship (HLS), a supply ship (SS), and a station-keeping ship (SKS). The HLS or the SS could be used to tow the surface plant hull to the site. On arrival at the site, the SKS would establish and record the site geography for comparison to a prior site survey and would position itself at the center of the moor. The SS would take a position at 90 degrees to the SKS while the HLS would position itself over the first leg. The HLS would first lower the anchor slowly. When the anchor has bottomed, the HLS would then proceed slowly toward the SKS to bottom the anchor clump. When the clump bottoms, the HLS proceeds to the location of the catenary support buoy, paying out the remaining mooring leg. The anchor would then be set and the support buoy emplaced. The HLS then continues toward the SKS to lay the synthetic mooring line for the first leg. This procedure would be repeated for the other three mooring legs. On completion of the mooring system emplacement, the mooring lines would be transferred from the SKS to the

Figure A-13. Four-point moor accommodations on surface buoy.

surface plant hull by transferring one mooring line at a time. The mooring lines would be pretensioned from winches in the surface hull. It is estimated that each mooring leg could be set in 1 day.

Requirements for the four-point moor are shown in Figure A-14. As noted, the excursion limit, vertical and horizontal components, and scope developed for each leg, are given for the 600-foot depth and for the 6,000-foot depth. The moor geometry for the two depths is shown in Figures A-15 and A-16. Installation details of the catenary support buoy and mooring leg riser are shown in Figure A-17. The anchor, clump weight, and mooring leg details are shown in Figure A-18.

A major milestone chart and estimated budget costs for installation of a 30-kw, surface-tendered power plant system for 600-foot and 6,000-foot depths are presented in Figure A-19. These cost estimates do not include cost of development programs, transportation, and deployment, since the load module mission and site are undefined.

Figure A-14. Basic configuration of four-point moor.

300-kw Shore-Based Diesel Generator System

The 300-kw shore-based power plant selected for preliminary design is illustrated in Figure A-20. The selected transmission distance was established at 50 miles. This system includes a diesel generator plant and auxiliary

support facilities. The diesel generator is housed in a corrugated steel building equipped with a 10-ton bridge crane for installation and maintenance requirements. All equipment associated with the diesel generator system is housed in the same building. The switchgear and transformer equipment are located in a single location and oriented to facilitate surveillance during plant operation.

Figure A-15. Moor geometry for 600-foot depth.

Figure A-16. Moor geometry for 6,000-foot depth.

Figure A-17. Installation details for the catenary support buoy.

Figure A-18. Details of the mooring leg.

The shore-based facility could also include a water tower and, if remote monitoring of the plant is necessary, a microwave link. This link would transmit plant conditions and could provide a voice channel. A closed circuit television system could also be incorporated to monitor the plant conditions.

Diesel fuel would be stored underground adjacent to the diesel generator building. The fuel pump, filter, and day tank would be located inside the building in one shallow drain basin area.

Power would be transmitted to the load module by cable. This cable would originate at the generator building and extend to the sea via an underground duct. A carrier system would be provided for monitoring, communications, and control functions between the load module and the shore-based plant.

The self-contained diesel generator would be rated for 300-kw continuous operation. The engine would be equipped with supercharger or scavenging blower for reduced operating temperatures and higher efficiencies. Engine sensors would be provided to indicate cooling water temperature, lubricating oil pressure, and engine overspeed. A freshwater cooling system would be provided with a forced convection radiator requiring a minimum air flow of 29,000 cfm. Radiant heat from the engine and generator was expected to approximate 7,500 Btu/min.

Figure A-19. Milestone chart and budget cost estimate for 30-kw surface-tendered power system.

Figure A-20. Shore-based power plant.

Fuel consumption necessary to transmit 300 kw 50 miles was approximated to be 7% higher than that necessary to transmit 300 kw 10 miles.

The drip-proof generator would have a remote alarm to indicate overtemperature conditions. The generator output rating would be 300 kw continuous, 4,160 volts, 3 phase, 60 Hertz. A steady-state voltage regulation of 0.25% was considered possible with a generator of this capacity. The diesel engine generator characteristics are listed in Table A-4.

The shore-based plant could supply a load of 300 kw at distances of 10 to 50 miles at 13,800 volts. For the 10-mile distance it was recommended that a 13,800-volt AC system be used, but for the 50-mile distance a 13,800-volt DC system was preferred. Since a 300-kw plant for a 50-mile load was selected for preliminary design, a transformer for stepping-up the generated voltage of 4,160 volts to 13,800 volts, as well as conversion equipment to provide DC transmission power, must be provided at the shore plant. Inversion equipment would be required in the load module. A two-conductor, shielded, armored cable with 1/0 AWG conductors would be used for the power transmission cable.

Table A-4. Characteristics of Shore-Based 300-kw Diesel Engine Generator

Diesel Engine	
Rating	500 kw at 1,200 rpm, continuous 550 kw at 1,200 rpm, intermittent
Approximate volume . . .	14 feet long x 5 feet wide x 7 feet high (490 ft ³)
Approximate weight . . .	21,000 pounds
Governor	0.25%
Cooling	Radiator, forced convection, 29,000 cfm
Generator (Drip-Proof)	
Rating	500 kw at 70°C, continuous
Voltage	4,160 volts at 60 Hertz, 3 phase
Regulation	0.25% steady state
Attached Accessories	Detached Accessories
Supercharger or scavenging blower	Air filter and silencer
Generator and exciter	Radiator
Lubricating oil pump and filter (self bypassing)	Exhaust muffler
Fuel oil pump and filter (self bypassing)	Alarms and gages
Water pump	
Cooling fan	

The deployment and emplacement of the 10-mile, three-conductor, 15-kv power cable from a shore-based power source to a load module on the ocean floor involve many factors, such as bottom conditions, depths, and tide and current data, which have an effect on the type and size of the cable ship required. An intermediate landing craft was selected as an excellent vessel for an emplacement of the 10-mile cable.

The diameter of the cable is approximately 3 inches and the weight of the cable is estimated at 7 lb/ft. 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. The cable would be loaded at the manufacturer's plant and the cable ship dispatched to the emplacement 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. The cable would then be hoisted on board and the necessary electrical connections made.

The load module would then be placed overboard 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 is slipped and retrieved and the cable ship then proceeds 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 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 of the cable. For installing a 50-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, to adequately cope with the increased weight of cable involved.

A major-milestone chart and budget cost estimates for the 300-kw, 50-mile, shore-based power system are presented in Figure A-21. Costs for transportation, deployment, property acquisition, site preparation, and development programs were not included in the estimates.

Worst-case conditions were assumed for the preliminary design of the shore-based power system. The availability of electrical power at the shore site would, of course, reduce budget costs for this system.

Figure A-21. Milestone chart and budget cost estimates for 300-kw shore-based power system.

LIST OF SYMBOLS

a	Nominal outside shell radius, in.	S_v	Stress in volts per mil at a point in the insulation τ mils from the cylindrical axis
B	Buoyancy	t	Temperature
D_1	Outside diameter of insulation in mils	V	Volume, in. ³
D_2	Inside diameter of insulation in mils	V_o	Initial volume at zero pressure
d	Density, lb/ft ³	ΔV_p	Change in volume due to pressure, $\Delta P/K_o$
Δd_p	Change in density due to pressure	ΔV_t	Change in volume due to temperature
Δd_{ts}	Change in density due to temperature and salinity	ΔV_{ts}	$\alpha_{ts} \Delta t$
E	modulus of elasticity	v	Specific volume
E_S	Secant modulus of elasticity	X	Horizontal projection of mooring leg, ft
E_T	Tangent modulus of elasticity	Y	Vertical projection of mooring leg, ft
e	Excursion, ft	α_{tv}	Volumetric coefficient of thermal expansion for the hull and its material
F	Excursion force, lb	σ_y	Yield stress, psi
h	Shell thickness, in.	μ	Poisson's ratio
I	Moment of inertia of shell frame	τ	Point in the cable insulation measured from the cylindrical axis of the cable
K_o	Effective bulk modulus of the hull = $P/(V/V_o)$		
L	Effective length of cylinder, in.		
ℓ	Horizontal distance between hull and any intermediate catenary support buoys, ft		
m	a/L		
n	Number of lobes		
P	Pressure		
P_b	Lobar buckling pressure, psi		
P_{cb}	Critical buckling pressure, psi		
P_{cy}	Critical yielding pressure, psi		
R	Radius of frame-shell section, in.		
R_{LO}	Local outside radius of a spherical shell, in.		
S	Scope of mooring leg, ft		

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