AD 653094

An Investigation Conducted by
WESTINGHOUSE ELECTRIC CORPORATION
Westinghouse Deep Submergence
Systems Underseas Division
Contract No. N62399-67-C-0003.

CR 67.017

CONCEPT DESIGN FOR A MANNED UNDERWATER STATION (U)

March 1967

NAVAL FACILITIES ENGINEERING COMMAND

NAVAL CIVIL ENGINEERING LABORATORY
Port Hueneme, California

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CONTRACT N 62339 67 R 0003

U. S. NAVAL CIVIL ENGINEERING LABORATORY
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ABSTRACT

The results of a fifteen man-month conceptual design study for a Manned Underwater Station are presented, conforming to the requirement of a 30-day mission for 5 men at 6000 feet. The station is self-supporting when emplaced by using an isotope heat source with turbo-electric power generation, and a life support system to provide a comfortable one-atmosphere environment. The pressure hull is toroidal in shape, forty feet in overall diameter with a 10-foot tube diameter. HY-140 steel is recommended for construction of the internally ring-stiffened hull. The concept provides a stable platform with maximum viewing of the bottom in the limited visibility in the deep ocean. For bottom locations with sufficient bearing strength, the hemispherical foundation and toroidal hull act as a ball-and-socket joint with unique leveling capability. Where extremely low bearing strength materials are encountered, modifications are made to distribute the load on the bottom. Additional toroidal modules, mating in a vertical stack, permit expanding the station for larger operational missions.

Emergency power and life support provisions are included for a 5-day period beyond the 30-day mission requirement. However, with the recommended power system and the electromechanical life support equipment there is no reason why the mission time cannot be extended to 90 days when personnel interchange is undertaken. Crews may be exchanged by using small submersibles which have a mating capability with bottomed submarines.

A development plan presents cost and time estimates for the program through the prototype operations, and includes specific research and development problem statements for areas requiring investigation beyond the state-of-the-art.

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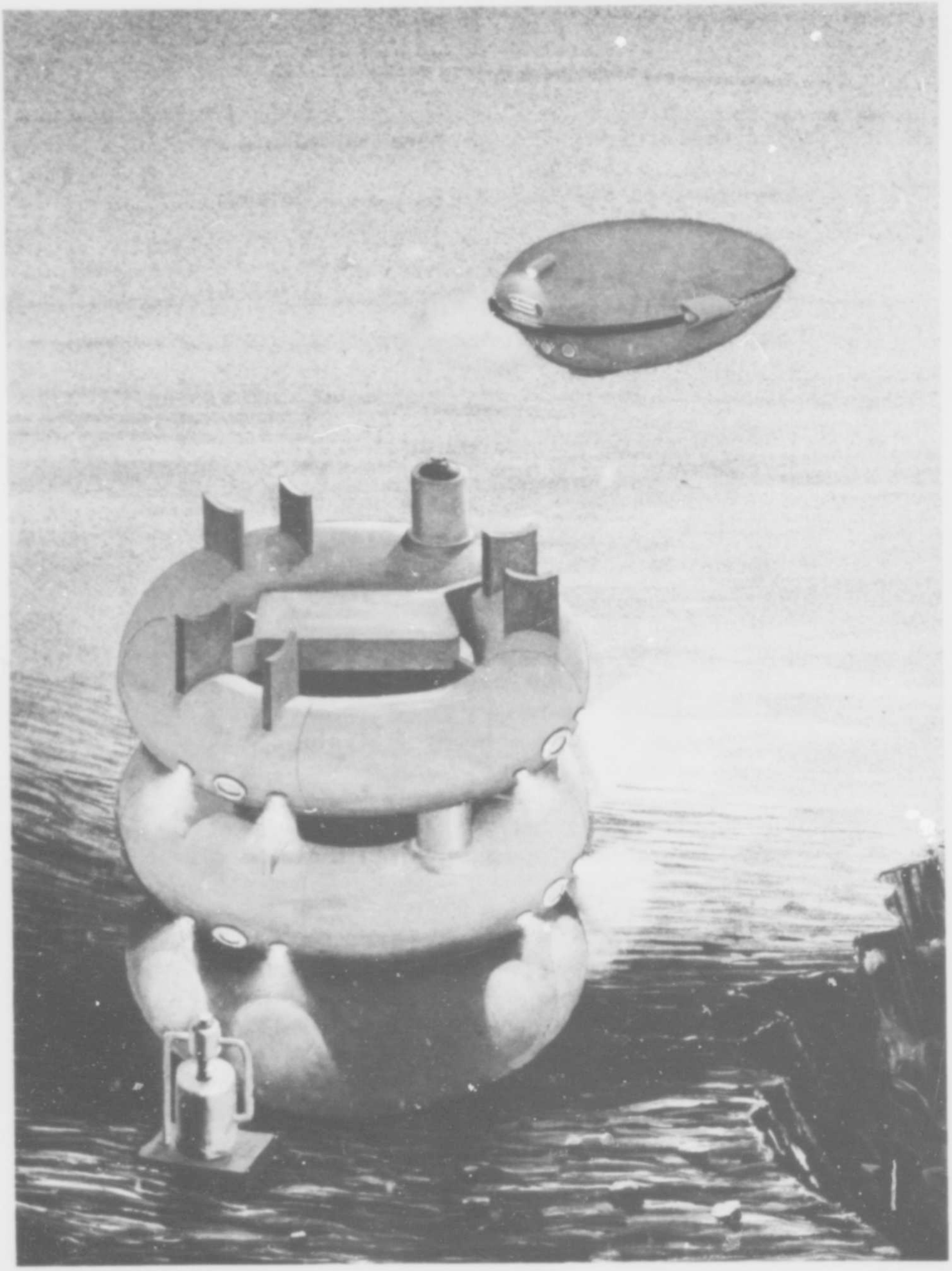

Figure 1-1 Manned Underwater Station - Artist's Concept

1.0 SUMMARY

The Westinghouse Manned Underwater Station concept was developed in a fifteen man-month study for the Naval Civil Engineering Laboratory. The toroidal station with hemispherical foundation is completely responsive to the Navy's requirements. It is suitable for deployment at depths to 6000 feet or greater with a 30-day mission and meets the specific requirements for space, electric power, mating of additional modules and foundation leveling. The majority of the techniques used are within the state-of-the-art needing only engineering development. An artist's concept is shown in Figure 1-1.

This conceptual design study includes system synthesis and examination of all of the major aspects of a Manned Underwater Station. Specified mission parameters and requirements have been reviewed, and a pattern developed for examination of other facets which influence the station utility.

- There are numerous potential civil engineering missions to be performed with the station in support of bottom hydrospace construction. The station will be of vital importance in support of the Deep Submergence Rescue Vehicle test and evaluation program. The system will permit implementation of our national claims to sovereign rights in the deep ocean as well as enhance our scientific knowledge and open avenues to commercial ventures. (Section 2.1)

- A reference environment describing bottom and surface conditions and a sequential plan of operational phases point up conditions to be met in transportation, emplacement, operation and retrieval of the station. (Section 2.2 and 2.3)

- Safety is the prime evaluation criteria. Other criteria are Cost, Development Risk, and Reliability - Maintainability - Operability. (Section 3.1)

- Candidate concepts for the Foundation, Structure, Power Plant, and Life Support are examined in evaluation of the available means for performing the task. Methods and materials for these major subsystems are discussed which lead to the selection of a design fully consistent with the study objectives and requirements.

- The foundation is a hemispherical reinforced concrete shell with a radius of 20 feet. Additional buoyancy or bearing area may be required on soft bottoms with extremely low bearing strength. With a permanent foundation, the structure is able to revisit the identical location to pursue long-term experiments. The hemispherical shape of the foundation permits the hull to maintain a level attitude even though the base of the foundation lands on a slope or settles into the bottom up to a 15° angle.

- The hull is a 40-foot outside diameter toroid with a 10-foot section diameter. This permits ample viewing access close to the ocean floor. HY-140 steel is used for construction with a 1.75-inch shell thickness and 6.75-inch by 4 1/4-inch internal "T" frames radially spaced on 21-inch centers on the mean circumference. This single level hull layout permits maximum utilization of space and eliminates the need for space wasting vertical ladders and hatches. (Sections 3.2.2 and 4.1.2)

- The electric power plant consists of four modular Cobalt-60 radioisotope heat sources with an air primary--steam secondary cycle to drive turbo-generators providing a total of 30 kilowatts of electric power. The modular power units provide redundancy for reliability and permit refueling using existing hatches without expensive hull work. (Sections 3.2.3 and 4.1.3)

- The closed cycle life support system permits a 90-day mission whereas more conventional methods are discussed should a 30-day mission cycle at minimum cost be paramount. (Sections 3.2.4, 4.1.4, 4.1.5, and 4.1.6)

- Communication requirements are developed and a section on External Viewing discusses the current state-of-the-art. The need for theoretical and empirical development of viewing port design is examined. The lack of long-term hydrostatic loading data on transparent ports of this size indicates a need for research and development effort. (Sections 4.1.7 and 4.1.8)

- Human factors are surveyed with recommendations for easing the psychological impact of confinement. The endless cylinder arrangement of the toroid provides the feeling of spaciousness. Provisions for part-time privacy for the individual are maintained by judicious interior layout. (Sections 3.2.5 and 4.1.9)

- The deployment system lowers the foundation on four cables and has the station ballasted to slight positive buoyancy, winch itself down to the foundation on a single cable. The single toroid station may be expanded by mating of additional modules in a vertical stack arrangement. Surface ship support for survey, emplacement, standby and retrieval are investigated. (Sections 3.3.1, 3.3.2, and 4.2)

- Drawings illustrate the various concepts throughout the report with external profile arrangement and interior division into five compartments by strength bulkheads shown in Section 4.3 Figure 1-2 is a cut-away view of a single emplaced station.

- The development plan presents a schedule for full-depth deployment of the station in early 1972. Budgetary cost estimates are shown for each Fiscal Year in various categories from design through fabrication and field support. The Power Plant costs are separated, since their effort may be partially supported by the Atomic Energy Commission.

- Many of the Research and Development tasks are oriented toward engineering smaller units of existing equipment for the life support system. Design and testing of large viewports for long-term exposure to high pressure loadings is another important R&D task.

- References used are listed at the end of each section. These and the discussions of concept evolution herein define the state-of-the-art for structures suitable for 6000-foot hydrospace deployment.

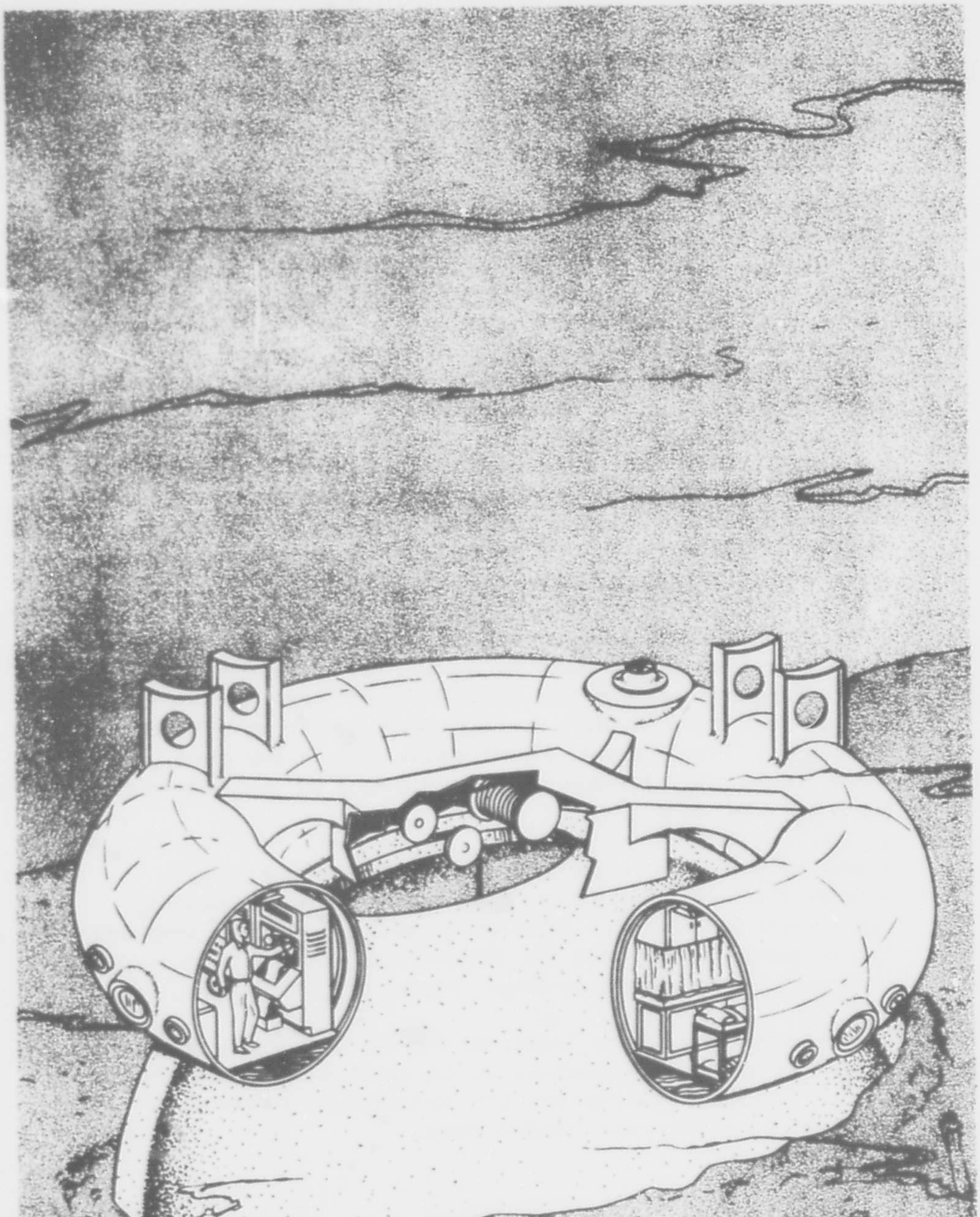

Figure 1-2 Sectional View - Manned Underwater Station Concept

PROBLEM DEFINITION
2.0 INTRODUCTION

In man's search for understanding of the world around him, he has in recent times extended the limits of this knowledge by positioning himself in previously untouched areas. The bottom of the seas have been but briefly examined by man. With scuba gear, he has looked at and felt the sea life and various components of the bottom interface at depths of about 300 feet. The hard hat diver has gone only slightly deeper. Man has gone to the deepest spot in the oceans in a protective sphere. However, these excursions have been brief and infrequent. Other techniques such as bottom core sampling and photography have added to the knowledge, but man has not yet been able to stay deep and observe for more than a very limited time.

The Manned Underwater Station (MUS) will serve to put five men on the bottom, or at some intermediate level in 1000 fathoms for a period of 30 or more days. It parallels the SEA-LAB and TRIESTE programs by enabling engineers and scientists to make in-situ observations over a period of time longer than that allowed by the other programs.

The Manned Underwater Station is planned as a versatile platform to be used for many missions, eventually including a combination of operational military missions, military test and evaluation missions and scientific and commercial missions. The versatility which is designed into the Westinghouse MUS concept readily satisfies a number of mission requirements. The approach used below depends upon a qualitative evaluation of some of the more significant potential missions with an attempt to prescribe requirements and constraints which are within the current state-of-the-art and yet will result in a system with high immediate and future utility on a reasonable time scale and at a feasible cost. Some of the potential missions are listed and described. Specific requirements for some of the missions are shown. Then the environment is described in sufficient detail to allow the design studies to proceed. The operational considerations include the derived constraints from operational deployment. The mission parameters and requirements for the initial concept study which are specified in the contract are shown in Table 2-1. Certain assigned definitions for the purpose of this study are shown in Table 2-2.

TABLE 2-1

Specified Mission Parameters and Requirements

Continuous manning by	5-man crew
Personnel replacement	30 days (maximum)
Life support endurance	30 days (minimum)
Emergency life support endurance	5 days
Working depth in ocean	to 6,000 feet
Undesignated operational space	200 square feet (6.5 feet high)
Electric power	5 KVA (continuous) plus 5 KVA (30%, 60%, 100% duty)

Must be capable of mating with additional modules.
Leveling technique to accommodate bottom slopes to 15 degrees.

TABLE 2-2

Definitions of Manned Underwater Station Components

Hull	The external pressure vessel.
Habitat	The hull and all elements of the construction exposed to an internal atmosphere that does not require decompression for personnel.
Structure	Assemblage of hull or hulls, habitat and all externally attached devices, machinery, appurtenances, etc.
Foundation	Components necessary to secure the structure to the sea floor and/or on which the structure will rest.
Station	The structure and all appurtenances necessary for the mission accomplishment.

2.1 MISSION ANALYSIS

The Manned Underwater Station (MUS) offers many possible missions beyond the obvious mission of affirming that man can be placed in a suitable environment on the ocean bottom 6,000 feet below the surface for extended periods of time. In itself, this demonstration is important, since all previous experiments with man on the bottom of the sea have been limited to either time periods much shorter than the 30 to 90 days envisioned for the MUS or to depth regimes much shallower than 6,000 feet. Specific useful missions are discussed. These range from those related to civil engineering to military missions which have not been previously considered because of the lack of an operational capability on the ocean bottom at this great depth. Some of the civil engineering aspects are almost prerequisite to the actual deployment of the Manned Underwater Station. As with many other tools, the applications will grow as more people become aware of the potential and after the operational demonstration of the prototype Manned Underwater Station.

2.1.1 Civil Engineering

The MUS application to undersea civil engineering is basically a "Boot Strap" operation since it would appear that much of the data to be generated from the station is desired for use in its design and planning phases. However, the MUS will utilize a conservative approach to many aspects of the station and foundation design and their subsequent deployment to assure successful demonstration of this extension of the civil engineers' capability. The data derived from emplacement and testing in itself will serve to allow improved designs for future bottom installations.

Existing data on underwater, in-situ soil mechanics is minimal with virtually no data from depths beyond diver capabilities. The station will be maintained close to neutral buoyancy and the large foundation footing will maintain low bearing stress on the bottom. This will provide good stability and minimal foundation settling. Thus the station will be an excellent platform for measurement of bottom characteristics. In-place vane shear testing can be conducted through direct observation. Plate bearing tests on the bottom soil can be performed using the station as a reference for displacement readings. Certain in-situ tests can be run on bottom cores in the water at ambient pressure followed by immediate comparison within the station at one atmosphere after a sample has been passed through the pressure lock. Since the bottom can be observed during testing and sampling, assurance can be given that successive tests used comparable bottom samples. Deep bottom cores may be taken, using power and support from the station, with immediate analysis of core sections performed inboard after passing through the pressure lock. In this way, it may prove possible to develop a meaningful correlation between tests made on bottom core samples at the surface and bottom characteristics that are important to civil engineering. Thus, data collection would begin to allow compilation of a handbook relating the vast store of oceanographers' data taken from bottom cores to that needed for ocean bottom construction operations. The oceanographers have collected thousands of bottom cores over a period of many years from many diverse locations. However, they have gathered mainly information on particle size and chemical composition of the cores. This has not been the handbook data needed by the hydrospace civil engineer for efficient design of foundations for underwater structures. With a single station deployed in two or three regions, a large step would be taken toward translation of the oceanographers' data to the handbook information required. Working data on the soil mechanics in these regions is in itself needed, but translation of a vast store of oceanographers' scientific data to a form meaningful to a civil engineer would be a most important step.

Much work has been done in recent years, at NCEL and elsewhere, on materials behavior at great depths. Observation from the MUS of test samples under various stress conditions will supplement the knowledge obtained from surface retrieval of test samples. Samples can be retrieved into the station and corrosion analysis performed immediately.

The station will also serve as a platform for investigation and advancement of underwater construction techniques including welding, riveting, drilling, pile driving and cable operated remote construction techniques. The Manned Underwater Station will serve for observation of these construction techniques to allow proper evaluation and improvement of the techniques as well as for observation of the long term results. The MUS and a small submersible for extending the radius of operation will provide a manipulator for work, electrical feedthrough for powering of equipment, direct observation through viewing windows and remote observation through closed circuit television. Even some of the most basic construction techniques have never been fully tested at the depths. The MUS will provide the platform for deep ocean testing with complete observation of performance and failure modes for both standard and advanced construction techniques.

The most immediate civil engineering result from the station is the demonstration of the underwater construction techniques used in the emplacement of the MUS itself. The very act of emplacement and observation from the habitat of the performance within its environment may be a most significant civil engineering result from the station.

2.1.2 Test and Evaluation

There are a number of test and evaluation applications for which the Manned Underwater Station will be used. Again perhaps the evaluation of the station itself is an important task, since the MUS is an extension of underwater construction and living, significantly beyond previous experience.

The Deep Submergence Rescue Vehicle (DSRV) or the Deep Submergence Search Vehicle (DSSV) may be used for crew changes and for resupply of the station since the mating hatches will be compatible. The DSRV evaluation itself, however, is best performed using the MUS since the DSRV mating hatch should be tested at depths down to full submarine crush depth. Obviously, a submarine cannot be taken to crush depth merely to test the rescue vehicle. Simulated testing at lower depths and in pressure chambers is indeed valuable. However, the actual performance of mating and hatch opening for complete evaluation of the performance of the mating hatch at depths below submarine test depth cannot be performed with any existing equipment. The station can serve as a platform for the DSRV mating hatch test and evaluation down to the full depth limits of the DSRV. Further, the MUS may be fitted with an adjustable mating connection to simulate the full range of submarine bottom attitudes. The MUS will have available within the station equipment and personnel to allow evaluation of the mating techniques under carefully controlled conditions. Following test and evaluation of the mating hatch and vehicle, operations instituted with the DSRV can provide operational experience with the vehicle and training for the DSRV personnel which cannot be simulated otherwise. The value of actual operations for the DSRV personnel as opposed to any possible simulation are obvious.

A very broad range of anti-submarine warfare equipment is presently under development. This equipment extends from sensors for submarine detection to various weapons for use against submarines. The Manned Underwater Station will allow fully instrumented and observed tests of this equipment through a comprehensive test and evaluation phase. The Manned Underwater Station instrumentation and personnel can collect data from underwater sensors and compare it with other available data as well as with direct observations. The station will be used to observe release of bottom located weaponry such as torpedoes and mines. Actual trajectories and hydrodynamics can be observed directly by personnel or by instrumentation in the station.

The June 1966 report of the panel on oceanography of the Presidents' Science Advisory entitled "Effective Use of the Sea" (reference 2-1) recommends provision of a test range equipped with standardized stations in which component systems, concepts and materials can be tested. This test range might consist of stations on the waters edge, at depths of 200, 600, 2400, and 6000 feet and the abyssal deep. The MUS is clearly optimal for the 2400 and 6000 station, with possible extension of the design to the abyssal deep regime. In order to achieve standardized stations the MUS could easily be used for all of the test range stations. The President's panel recommended that this range be made available to industrial and university groups in addition to Navy utilization.

2.1.3 Military Operation

The United States military forces have traditionally acted as one of the instruments of foreign policy. The Manned Underwater Station will serve foreign policy by simply demonstrating occupation of the bottom. The legal questions of territorial rights on the ocean bottom are many and complex. Without attempting to examine the legal ramifications, the MUS can serve to place men on the bottom and thereby demonstrate useful and "permanent" occupation of the bottom, for whatever policy ends that are desired This mission of the MUS can be served merely by the existence and deployment of the MUS without any other functions being provided.

Dr. John P. Craven of the Navy Deep Submergence Program has very carefully examined some of the problems of sovereignty rights in the sea bed. In developing the importance of the international challenge of the deep ocean, he calls out the ocean ridges and seamounts (6,000 to 8,000 feet) as the next geographic area of interest and predicts that man's "capability to deploy vehicles and to mount installations" in these areas is "virtually assured within the next decade". (Reference 2-2.) Admiral David L. McDonald as Chief of Naval Operations has publicly discussed similar matters. Reference 2-3 is one of his recent pertinent speeches.

With the establishment of men in a working environment on the bottom, a number of other military operational applications arise; a well camouflaged MUS could serve as a useful command post for command and control of various surface and underwater Naval forces. This might be extended to use of the MUS for Missile Launch Control, either with fixed, bottom deployed missiles or submarine launched missiles. The MUS may serve usefully as a relay station in a communications link since the habitat can be located at the center of the deep sound layer. There will be application for MUS as a secure navigation reference since having the crew available would allow easy change of interrogation codes to maintain security over an extended period.

The fixed, quiet, Manned Underwater Station has the capability for detection of submarines either at long ranges or for identification as they pass the station in the water column, thereby providing an underwater Distant Early Warning (DEW) line. Freedom from propulsion and wave noise in the station can provide extended range beyond that attainable with sensors mounted on a surface ship, and proper depth location will allow detection through the deep sound channel. Passive listening will provide detection of low level signals. However, active sonar or triangulation with other listening posts would provide target range and position information.

The potential use of the Manned Underwater Station for underwater DEW and a command post can be fully complemented by the addition of direct control of the ASW weaponry to provide a complete Anti-Submarine Weapons System station. Some development of weaponry suitable for deployment at depths with adequate control techniques may be required prior to utilization for this application.

In many of the military operational missions, the MUS requires a secure underwater communications link. Such communications links are already in use by the Navy for communications with the FBM submarines.

The MUS will act as a fixed site to support a deep submersible such as the DSSV. The large internal area for stores plus power for charging batteries would allow basing a submersible on the station for extended periods. By avoiding the air-water interface, the vehicle would be allowed many more working days per month since surface weather will not affect the

MUS support of the vehicle. Fixed station support of the DSSV would be valuable for extended operations on the bottom in a region where the transit time to the MUS would be significantly shorter than transit time to a surface support ship. This suggests the use of a MUS for operations in a typical circular area of not over five miles radius from the station. Within this range, the transit time to the support station would be roughly equivalent to the transit to a surface support ship; however, the major advantages to be gained are in the area of weather free operations. Detailed search by the DSSV of an area as large as ten miles square could be supported well by the MUS. For certain applications, it should be understood that an overall system might consist of several individual MUS structures.

2.1.4 Scientific

The number of scientific missions open to the MUS is large and the missions to be performed presumably will be a matter of assigned priority to the scientists once the station exists rather than preplanning prior to the MUS existence. Some of the missions which can be envisioned are quite obvious in that man on the bottom for an extended period of time can observe conditions on the bottom directly through the viewing windows. Examples of this type of observation are studies of marine life and the actions of the sediment. However, there are a number of more specific measurements which can be made. Time series data of the ocean environment is extremely limited. Much of the data which is needed for underwater work exists only in scattered bits and pieces.

A simple mechanism would allow the MUS to obtain water samples for analysis at regular intervals. These samples could be analyzed in the station or collected for later testing at the surface to provide time series data. The water samples may be related to underwater visibility studies with many possible variations. The optical properties of water at the depths have not been measured. Some of the studies would include visibility through and settling time of stirred sediments, methods of reducing settling time, visibility variations with altitude above the bottom and seasonal variations.

Simple sensors at the MUS would provide time series data on bottom currents beyond any available today. Additional sensors located remotely from the station and recording of the readings could provide data for profitable employment of several shore based oceanographers. Relation of the data taken on water currents to visual observation of the bottom and sediment analysis will provide new insight into the nature of the interface between the water column and the bottom.

Numerous biological observations could be made from the MUS. The degree of emphasis upon biological experimentation remains to be determined. Even the introduction of the MUS into the environment, and subsequent "casual" observation is an interesting biological experiment.

Sound propagation and bottom reflectivity measurements at the depths can significantly enhance our knowledge for various sonar applications as well as "pure science". A small submersible working in conjunction with the station will provide valuable data on underwater acoustics in both passive and active experiments.

Seismographic studies from this stable and quiet platform on the deep ocean bottom will afford significant scientific progress. Unmanned seismic measuring devices have been dropped to the bottom of the ocean but they eventually run out of power and must be periodically interrogated and the data read out by a support ship. Furthermore, the placement of the device is left entirely to chance. With the MUS carefully controlled emplacement, continuous powering and periodic data readout over a hard wire can be achieved.

The added capability of positioning the structure at any level from the bottom to just below the wave action zone offers an attractive extra with only slight changes in the basic requirement. Scientific observations from a stationary platform at various levels in a vertical water column will be very much desired by the oceanographic community.

2.1.5 Commercial

The commercial applications of the MUS are wide open since there has been little commercial utilization of the region of the ocean bottom below diver depths. The MUS can serve as an experimental location for many commercial or industrial applications. The station could be used for commercial recovery of the minerals on the ocean bottom through mining or collection. Oil exploration, drilling, production and storage require underwater capabilities provided by the MUS. The possibilities of using the deep ocean bottom for food production are also significant and have received virtually no direct exploration to date. For any underwater commercial and industrial application, the

MUS can support a small submersible similar to Deepstar 4000 in the same way as described for the Deep Submergence Search Vehicle. The advantages here are the same as for the DSSV in reduced transit time between work area and support platform and freedom from surface weather conditions.

2.2 ENVIRONMENTAL CONSTRAINTS

The environment at the air-sea interface, through the water column, and at the water-bottom interface will be of paramount importance to the MUS design and operation. For example, the air-sea interface environment is associated with constantly changing weather and surface conditions. These conditions will have a tremendous effect upon: 1) the operational planning for installation of the foundation, 2) the deployment of the bottom station to the foundation, 3) stores replenishment and personnel replacement, and 4) retrieval of the station at the end of the mission. The characteristics of the water column are of importance during all phases of the program from deployment thru retrieval since the water column will have a significant effect upon those phases involving travel through the water column and communications with surface ships. The interface between the water column and the bottom determines much of the physical characteristics of the foundation and structure to be selected. Since the overall mission is to be performed at the bottom, this interface will have gross effect upon any subsidiary missions to be performed.

In certain oceanographic regions, the environment may be described simply since stable conditions prevail throughout the year; but, in other regions, environmental factors are complex and variable.

A comprehensive study of the ocean environment is beyond the scope of the present study and has been performed several times under other auspices. Certain environmental factors have been described for the purpose of this study to allow informed decision in various systems and subsystem design items. These points of environmental description do not necessarily prescribe the final design of the bottom station nor do they necessarily indicate limits of performance. They have been selected to describe a major portion of the world's ocean. The bottom station would be clearly usable in any ocean during any season where the environment is within the limits described. Analysis of the results of the design studies may very easily allow operation outside of these prescribed environmental limits. The initial restriction of depth not greater than 6000 feet restricts the operation of the MUS to 24% of the world's open ocean areas, including peripheral seas. In the northern hemisphere, this increases to almost 33% of the water areas. However, there is little justification for use of the Manned Underwater Station in the shallow depths. Certainly depths of less than 500 feet can be more profitably utilized using ambient pressure housings such as the SEALAB or SEAHAB. The optimal depth range for the initial Manned Underwater Station will be from 1000 to 6000 feet in depth. The hull is designed to a 9000 foot collapse depth for safety and this concept is considered suitable for extension to greater depths in future applications. Similar restrictions are made for the other environmental parameters for ease in forming the proper concept for the Manned Underwater Station without limiting the area of operation too greatly. The depth restriction from 1000 feet to 6000 feet would allow operation in 15% of the world's water areas or 18% of the northern hemisphere areas. This restriction in the depth range allows much tighter specifications of water temperature and current velocities since the range of deep water currents and the temperatures is narrowed at the greater depths. Depth of 1000 feet is at the edge or over the edge of the shelf.

In the 1000 to 6000 foot spectrum, around the periphery of oceanic-continental slope--continental shelf areas, tidal currents, wind-driven currents and major permanent currents such as Gulf Stream and Kuroshio are found. Tidal currents are complex, rotary and significant at 1000 to 6000 feet as tidal flow passes from deep ocean region up the slope and across the shelf. Although not known in detail throughout ocean areas of our specific interest, in general, currents approximate 0.25 to 2 knots. In the Thresher wreckage area at 8400 feet, the tidal current was rotary and about 0.5 to 1.0 knots, such that the bathyscaph Trieste was at times unmaneuverable. Also large permanent currents like the Gulf Stream at depths of 1000 to 2000 feet have speeds of about 2-4 knots and these are significantly affected by the bottom topography. The selected maximum current of 2 knots may initially cause some restriction of site selection. It is probable, however, that higher currents may be accommodated as their effects become better understood. Bottom inclination on slopes of some atolls is greater than 15°, approximately 15°-25°. There is no reason for limiting the self leveling foundation concept to 15° since the base on which the hemispherical seat is built can probably be designed for greater angles, by use of anchors on the uphill side. A steeper angle will, however, require that the station site be surveyed and a "made to measure" foundation be constructed. Placement on steep slopes must be done with care to insure that the site is not chosen in a spot where underwater avalanches and turbidity currents are likely. A single design for the foundation base will probably be sufficient for angles of less than 15° bottom slope unless a very deep soft ooze dictates that a multi-unit foundation be constructed.

In high latitudes where glacial action was the generating agency in past ages, there may be significant large boulders, approximating 6-10 feet. In these areas, complex valleys and ridges exist whose profile could be in the order of some 1 to 10 feet. This complex and significantly rough topography is also prevalent in volcanic regions where again outcroppings of rock cause ridges up to 6-8 feet high. The 0-3 foot range is an approximation on a global basis, so that either careful selection of deployment site or some leveling of an area to get a foundation in a specific location may be required.

The bottom sediment at depths to 6000 feet is not as varied as would be expected in the basins. The depth limit of 6000 feet suggests tidal scrubbing removing the finer sediments and leaving a solid bottom, without thick sediment layers, thus the restriction on bottom sediment composition and thickness will not constrain site selection significantly.

Table 2-3 summarizes the reference environment on which the concept design is predicated.

TABLE 2-3 Reference Environment

Ocean Bottom	
Depth	1000 to 6000 feet
Temperature	-2 to +18°C
Current	0 to 2.0 knots
Bottom slope	0 to 15 degrees without special planning
Bottom smoothness	Rocks or peaks no more than 3 feet above average surface
Bottom sediment	Rock, coral, gravel, sand, mud, or red clay
Sediment thickness	0 to 10 feet (mud or soft red clay)
Visibility	Variable
Settling time	Variable
Surface (deployment, personnel replacement, resupply & retrieval)	
Air temperature	-10 to +35°C
Wind velocity	0 to 15 knots
Sea state	1 to 3 (wave height to 5 feet)
Water temperature	-2 to +30°C
Current	0 to 4 knots
Weather	Moderate (no operations during storms)

TABLE 2-4 Operational Phases

Transportation - Factory to Dockside
Final Assembly
Test
Loading and Transit
Foundation Emplacement
Station Emplacement
Mission Operations
Resupply and Personnel Replacement
Emplacement of Additional Stations
Station Retrieval
Return Transit
Overhaul

2.3 OPERATIONAL REQUIREMENTS

The Operational Requirements range from the need for transportation (possibly in several moves) from the point of assembly of the MUS to the deployment ship through the lowering to the bottom, retrieval and return for overhaul. These requirements are determined by, and derived from the various missions and the expected surface, water column and bottom environment. The MUS configuration and design interacts with the operational requirements, with a need for feedback between the design and the operational constraints.

The operational phases are listed in Table 2-4. Some of the more important considerations of each phase are listed below:

Transportation - Factory to Dockside. Choice between railroad, flatcar, truck, or barge will depend upon the station configuration, size and weight. The method of construction and the number of hull sections will also affect the selection of the proper mode of transportation.

Final Assembly. Final stages of assembly will take place at dockside.

Test. The final testing will include test of all internal equipment, inspection and air pressure testing of the hull.

Loading and Transit. The MUS will be transported to the deployment area by ship, either on deck, in tow or in a well. Shipment on deck requires structural rigidity and lifting points for loading and an adequate crane for offloading at the deployment site. Towing simplifies the on and off loading at the expense of additional structural requirements and hydrodynamic considerations during transit. The well of an LSD type ship provides an excellent conveyance for the components of the MUS. The hull may be "docked" on a cradle during transit and launched by ballasting down the ship and flooding the well. This method is also adaptable for handling the foundation. In fact, it is possible that one ship of this type may be modified to serve as a single unit support vessel. Alternately, one of the new catamaran hulled ASR vessels might be adapted for use as a MUS support ship.

Foundation Emplacement. Successful emplacement of the foundation will climax the most critical phase of the MUS program. Detailed site survey will precede emplacement using conventional hull mounted sonar for gross survey and a tethered unmanned vehicle or free manned search vehicle such as the DSSV for detailed bottom survey. Acoustic markers will be required for precise navigation to assure emplacement at the selected and surveyed site. The foundation will probably be prefabricated unless significant progress has been made on deep cast-in-place concrete construction techniques. Depending on the bottom soil mechanical properties, the emplaced foundation will have an adjustable buoyancy and may have anchors for permanent bottom attachment. The surface, water column and bottom environment will be of great significance during foundation emplacement. The environment is a vital factor in the selection of test and operational sites for the MUS requiring due regard to the seasonal weather variation and the time of year for planned operations.

Station Emplacement. Site and seasonal selection are again constrained by station emplacement. The station must be offlifted from or floated clear of the towing ship and the hauldown and any communication or buoy cables attached. It is envisioned that the crew will man the station during the lowering and positioning phase. Buoyancy must be adjusted and the descent started. A winch reeling in the cable is used to control the downward progress of the positively buoyant station. This assures a descent directly upon the foundation. The habitat will be halted a few feet above the foundation and adjustments made. The buoyancy, with the flotation material and the hull, will be controlled and the descent slowed prior to reaching the bottom. It is then winched down to the foundation. During portions of the emplacement, a crew shuttle submersible may be mated with the station to use its propulsion capability to assist in positioning the station.

Mission Operations. Potential missions were discussed in Section 2.1.

Resupply and Personnel Replacement. The mating hatch on the MUS or its special adapter will be compatible with the DSRV mating hatch. Any submersible with the requisite depth capability and the proper mating hatch can be used for resupply and personnel replacement. Submersible vehicle operations will not be considered here, since these are primarily a function of the submersible.

The mating operation will be performed exactly as that to be implemented for the DSRV. Resupply will include life support needs, added spare parts, mission consumables and fuel (if required) for the power source. The submersible carrying capacity will interact upon supply and manning philosophy. Personnel may be replaced entirely at 30 day intervals, or part of the personnel replaced at 10 or 15 day intervals. Availability of the large capacity DSRV or the need to use a smaller but available vehicle will determine the resupply philosophy as an operational development.

Emplacement of Additional Stations. The emplacement of addition stations above the first station is similar to the emplacement of the first station. It should be initially done at shallow depths. Assistance of sensors on the "under" platform is required. Accurate positioning and angular alignment during the final phase will assure mating of the hatches for transfer between the two habitats. The two stations may each be completely self-contained, or may be interconnected for such needs as mission power, food preparation, wet and dry laboratories and recreation, allowing optimal space utilization. The mating hatches will again be based on the DSRV mating hatch design.

Station Retrieval. The station must be brought back to the surface for return to port upon reaching the end of the mission or for overhaul considerations. Again the seasonal weather variations must be considered to assure successful performance of retrieval. The retrieval is essentially the emplacement operation reversed using buoyancy adjustment and winching on the buoy cable to achieve ascent. When on the surface, a hatch on the underside of the station will permit the crew to pressurize the structure and evacuate in the event of an emergency without the danger of swamping the station through an open top hatch.

Return Transit. Onlifting or placing the station in tow should be routine and involve no problems other than those found in initial transit.

Overhaul. The overhaul will be particularly significant on the initial operations since the station must be carefully examined for any deleterious effects of corrosion or stress. These early overhauls will be most informative.

The initial inspection period should be 30 or at most 60 days with accumulated experience allowing extension to 12 or 24 months. The ultimate overhaul cycle will probably approach the latter figure. The design of additional stations may be improved from the early inspection and overhaul data. A radioisotope power supply produces a relatively constant amount of heat and will require the application of an auxiliary cooling system during overhaul to remove decay heat during plant shutdown.

2.3.1 Prototype Test And Evaluation

The Test and Evaluation phase on the prototype station, including full certification for safety, will include several steps. Prior to hardware construction, there will be design approval and certification. Component and subsystem environmental testing will follow. Initial station operations will be in shallow water, with availability of external instrumentation and free divers to assess performance under water. The techniques for attachment to the foundation could be fully evaluated, and much of the mission and life support equipment checked out. Preliminary checkout of the mating hatch and support submersible vehicles can also be completed in shallow water.

Full pressure testing in a suitable pressure chamber is desirable, but the station size and pressure capability preclude this testing. An unmanned descent to 6600 feet of the completed hull, prior to outfitting, and utilizing surveillance from a free manned submersible could replace full pressure testing. In this event, the risk to the station is much greater than with the emergency capabilities provided with men aboard on a manned descent. Therefore, testing in a manner similar to submarine pressure hulls is recommended.

Initial deployment to the full depth of 6000 feet will be for a 30 day period, with minimal scientific or engineering mission, primarily to check out life support, power system, resupply and personnel replacement. The full depth site should be chosen with a view toward returning for an operational mission. It is expected that the prototype testing in increasing depths will occupy about one year and that the structure would be ready for a thorough inspection and overhaul after the initial manned deployment to 6000 feet. One of the advantages of this concept is that the same site can be revisited and the structure placed in exactly the same location as on previous visits. Also, inherent in the operational employment concept is the ability to predetermine a particular spot on the ocean floor for investigation and to insure that the station is emplaced in the desired location.

2.4 PROBLEM DEFINITION REFERENCES

References used in this section are:

2-1 "Effective Use of the Sea" Report of the Panel on Oceanography of the President's Science Advisory Committee - The White House June 1966.

2-2 Craven, John P. "Sea Power and the Sea Bed" United States Naval Institute Proceedings April 1966 Volume 92, Number 4, Whole No. 758.

2-3 McDonald, Admiral David L., U.S.N. Chief of Naval Operations - Remarks at the Navy League Seapower Symposium, Washington, D.C. 9 Feburary 1967.

CONCEPT EVOLUTION

3.0 INTRODUCTION

The previous section developed candidate missions for the Manned Underwater Station and an environment in which the station would be placed to perform its missions. Also discussed were operational phases from construction thru the deployment to retrieval and overhaul. In effect, the job is now defined so this section will examine the feasibility of various methods of doing the job. In some cases, the concept that evolves can be satisfied by any of several alternate methods. In these cases, tradeoffs will be examined either during concept evolution or later in the conceptual design phase. In any event, a concept will be recommended that is considered the best way of insuring that the mission is accomplished.

First, a set of evaluation criteria statements are presented. These form the background against which the major subsystems are examined. When put together, these major subsystems comprise the Manned Underwater Station.

Further discussions in this section are related to supporting the entire system and to the operational functions in which the system is the key element.

3.1 EVALUATION CRITERIA

The Manned Underwater Station along with the operational considerations in deployment, supply and retrieval comprise an entire system. The subsystems are various parts of the system including such elements as the power source subsystem, the pressure hull subsystem or the foundation subsystem.

3.1.1 Safety

In evaluation of the basic system configuration, the individual subsystems or the interface and interaction between subsystems, personnel safety must be the first consideration. Safety will be evaluated in three ways:

(1) Functional Safety: There are many functions which must be performed to assure the safety of the station personnel, such as protection from the ambient pressure, provision of a suitable atmosphere, food and water, control of the station during emplacement and retrieval, etc.

(2) Dangerous side-effects: The other aspect of safety is the introduction of dangerous factors into the environment due to failures in subsystems. These factors might include atmospheric contamination from spurious chemical elements, radiation hazard from a nuclear power supply, explosions from fuel or battery fumes, or excessive pressure from leakage of non-toxic pressurized gas.

(3) Environmental catastrophe: Earthquakes, Tsunami effects, tropical storms during deployment and other unusual natural environmental effects capable of exerting an influence upon the station beyond the normal and thereby endangering the personnel. The station must protect the crew during such catastrophe.

Each subsystem will be examined for any toxic elements, or any possibility of contamination of the station internal environment. Such obvious potential contaminants such as mercury, Freon in aerosol spray cans or air conditioning system and toxic chemicals for "in situ" sample analysis will be completely excluded. Pressure tanks of gases which can contaminate the atmosphere, or increase the pressure will be examined for their toxicity. Spurious chemical elements for example from "in situ" samples of biota or soil brought into the station through the pressure lock for detailed examination might pose atmosphere contamination problems.

Equipment which can lead to perilous situations will be excluded where possible, but where some hazard is inevitable, these hazards will be carefully examined. As a guide to acceptance or rejection of a particular equipment or component the following guidelines are stated for the station:

<u>Direct Hazard to life</u>: 10^7 hours between failures
<u>Hazard requiring evacuation or use of emergency equipment</u>: 10^5 hours between failures

To achieve these numbers, the individual equipments or components should be an order of magnitude better. In general, this magnitude of time to failure cannot easily be verified, however, the statement of the requirement will serve as a guide for design and evaluation.

3.1.2 Cost

The cost of the MUS is crucial since excessive cost can preclude the actual construction of the Station. Costs will be considered in several ways:

Non-recurring: those costs which are related to the development, or first time construction of the station will be segregated.

Recurring Costs: those costs which will be repeated for construction of additional stations.

Support Costs: those costs relating to maintenance and supply of the station including the cost of both short term expendables and long term maintenance and overhaul.

Indirect Costs: those costs relate to requirements placed upon other subsystems from interactions. These include electric power, cooling, etc. as well as size and weight which indirectly increase costs of the other subsystems such as power source, hull, foundation or emplacement. These costs will not be segregated, but will be considered qualitatively for the subsystem under consideration, and dollar costs will be developed only for the equipment or subsystem providing the direct function.

3.1.3 Development Risk

All equipment and subsystems are comprised of elements which are within the present state-of-the-art, however, the environment and requirements demand performance in some areas beyond previous work. In these areas, for example, with the power source, there will be some element of development risk. The development risk evaluation is qualitative, with any element representing excessive risk excluded from the recommended system and when possible, existing, or high confidence components used exclusively.

3.1.4 Reliability-Maintainability-Operability

These topics embrace the spectrum of requirements needed to have the station and all equipment on the station in good operating condition at all times. There is some duplication (particularly in life support) with the safety criteria above, but the overall needs for a reliable, easily maintained station properly operable by the men aboard is obvious. In particular, inaccessible external components such as a manipulator, sonar transducer, lights, and ballast release devices will have low maintenance engineered designs. The hatch design and emergency release devices will be easily operable and be configured for fail safe operation.

3.1.5 Deployment

Although deployment is considered as a subsystem in itself, there are large interactions on deployment from the other subsystems. Thus those effects are considered specifically for each subsystem where these interactions are present.

3.1.6 Growth Potential and Mission Versatility

There are many potential missions for the MUS; some possible missions are discussed in section 2.1. The breadth of missions leads to the set of requirements in an attempt to provide maximum station versatility. Future developments may demand significant changes in the mission profiles and the subsystem requirements. The sensitivity of the subsystem configuration to small (or large) changes in requirements is the measure of versatility. The likelihood of growth in subsystem (and system) capabilities with improvement in the state-of-the-art is the measure of growth potential.

While a formal system of weighting of these criteria is not provided, they are considered as factors in all subsequent investigations in this study.

3.2 MAJOR SUBSYSTEMS

The major subsystems of the Manned Underwater Station are foundation, structure, power, life support and personnel. These topics are examined in the following sections and various methods explored to determine a recommended concept for accomplishing the assigned task. Subsequent sections on conceptual design will develop the recommended major subsystem concepts and examine supporting areas in a combined concept evolution and design development.

3.2.1 Foundation

3.2.1.1 Discussion

The installation of a manned station on the ocean floor depends for its success on the emplacement of a foundation which meets the design criteria. Just as a structure on land must be completely supported by the ground in which it rests, an underwater structure must be supported by the ocean bottom. Architects and engineers use proven design techniques to transfer loads from the structure to the soil on land. They are required to use accepted building code allowable design loads for the soil or to establish these allowable loads by accepted test methods for obtaining data from soil samples, or driving and loading test piles at the selected building site. Extension of these testing, design and construction techniques has been made to shallow underwater sites for the Texas towers, Argus Island, and numerous oil-well drilling platforms located off shore on the continental shelf.

Structure loads on land are transferred to the soil by either direct bearing through a footing under the foundation or by shear through long piles driven vertically into the earth under the foundation. The selection of either of these designs is dictated by the soil design allowable loads and the magnitude of the load to be borne by the soil. In the same manner, the selection of a foundation design, and its emplacement at an underwater site, is governed by the allowable loading on the ocean bottom and sub-bottom. Core samples and driving tests of long piles on dry land have shown that the earth's stratified layers may have widely varying resistance to shear and bearing loads and the same phenomenon has been found on the ocean floor. Investigations through coring by oceanographic explorations have shown the ocean bottom to have many varied conditions dependent upon the location of the site. Soft oozy or slurry layers varying widely in thickness have been found to cover reasonably hard substrata of clay, sand or rock. In other locations, the reverse has been discovered - a relatively hard strata overlaying a soft sea of mud or ooze. It is therefore considered that prerequisite to the selection of a foundation design for the manned underwater station is a thorough investigation of the bottom and sub-bottom conditions at the selected site. The foundation design criteria found in Table 3-1 are selected as a reference frame for the design and represent a "worst case" bottom environment. It is expected, however, that the initial installation in deep water will be undertaken at a more favorable site and that these worst case conditions will not exist. Nevertheless, the design of the station must be able to meet these conditions.

3.2.1.2 Site Selection

The following are the recommended criteria for selecting the site of the manned underwater station.

(1) Consider only areas which fulfill the program requirements whether they be scientific, commercial, or military or a combination of these.

(2) Conduct a close survey of the bottom areas for topography, water currents, bottom soil physical

TABLE 3-1 Foundation Design Criteria

1. Maximum bottom slope of 15° assumed.*
2. Projections or depressions on bottom must be no greater than ±3 feet.
3. Maximum 2 knot bottom current assumed.
4. Target bottom soil bearing pressure is 0.5 psi.
5. Foundation must be resistant to corrosion and fouling by micro-organism and plant attack.
6. Foundation must be low cost with 1970 state-of-the-art.
7. Design for 10 year minimum life for reliability.

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* With special consideration, this can probably be extended to 45°.

and chemical properties and other pertinent data.

(3) Select potential sites located remotely from steep slopes or canyon-like floors to obviate possible safety hazards.

(4) Conduct a detailed examination of the bottom and sub-bottom at the potential sites to determine as accurately as possible the bottom soil physical properties and also the sub-bottom layers to an acceptable depth. This may be done by obtaining core samples or conducting seismic investigations.

(5) In place load testing may be required if the bottom investigations above prove to be inconclusive. Setting a statically loaded pile in the bottom, or resting a block of concrete on the bottom, and measuring its creep with respect to time is a means of obtaining some necessary engineering data on the soil.

Techniques for accomplishing the above named steps are well established. Topographic survey methods by sonar are well known and reasonably accurate. However, there is a need for a closer visual examination of the terrain at least for the initial installation. This can be accomplished through a towed sensor platform or by manned vehicles such as the Deepstar or the DSSV. These investigations will discern the local nature of the topography and be able to pin-point both desirable and undesirable features.

Test piles have been installed in the bottom at 6000' off the coast of California during the preparatory stages of the Mohole Project. In situ load tests were successfully conducted on these piles and are continuing. It is therefore recommended that similar tests be conducted on site as a final step in gathering data for the foundation design.

3.2.1.3 Types of Foundations.

A 40 foot outside diameter by 10 foot diameter cross section torus is the structure design selected for the manned underwater station as explained in section 3.2.2 of this report. Two types of foundations to support this toroidal shape are investigated - the hemisphere and the platform. Each of these general types is described and discussed in the following paragraphs along with its estimated cost, advantages, and disadvantages and a recommended selection is made. Foundation criteria are shown in Table 3-1.

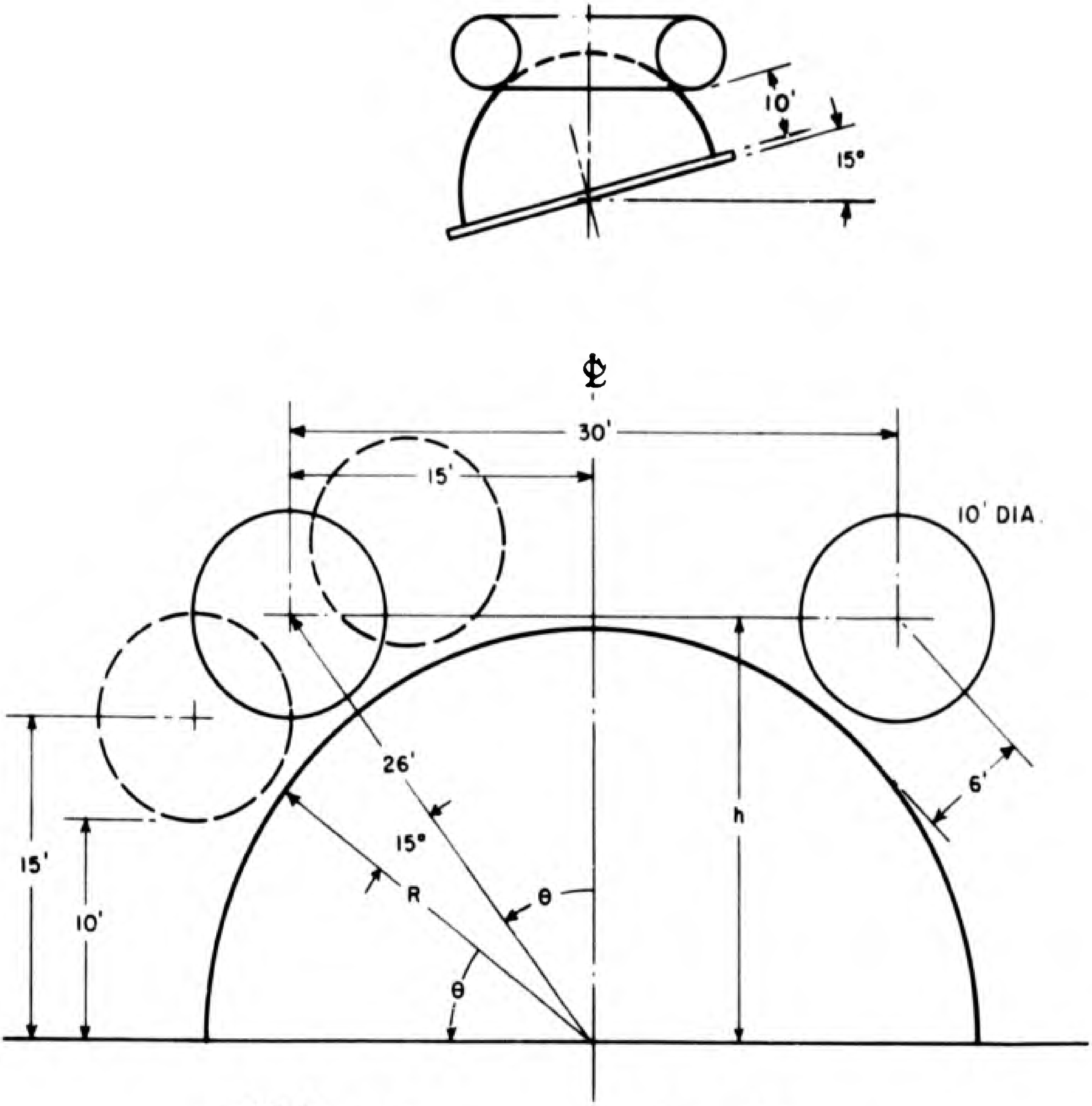
3.2.1.4 Hemispherical Foundations

A hemispherical foundation can be constructed with reasonable ease and within the present state-of-the-art techniques. It has the unique property of being able to support the structure in a level attitude off the ocean floor regardless of the direction of the bottom slope. Its dimensions are derived from the dimensions of the torus, the bottom slope of 15° maximum and the desire to maintain a 10 foot minimum distance between structure and bottom as shown in the sketch of Figure 3-1. From the geometry of the problem, it is determined that a 20 foot outside radius for the hemisphere is required to meet the desired conditions. Three alternate construction techniques are discussed below.

All concrete. Present day state-of-the-art reinforced concrete manufacturing techniques can be readily used to produce a hemispherical shell with cylindrical footing as shown in Figure 3-2. During the construction of such a shell, additional steel beams and fittings may be cast integrally with the concrete to provide a monolithic structure. The added steel is required for cable attachment, distributing loads through the structure and attaching buoyancy packages if desired.

Little data exists on deep ocean use of concrete though a great amount of data shows that dense concrete gives very satisfactory service in shallow water. Concrete installed at the water line, where it is exposed alternately to being wet and dry and to the effects of freezing atmospheres, has deteriorated. However, tests on 6 inch diameter by 12 inch long cylinders made by the Los Angeles Harbor Department after 20 years of submergence in sea water have shown an increase in the compressive strength of the concrete.

Using a high quality, high strength concrete provides a high degree of protection against sea water attack by the sulfates in the sea water solution and the leaching of lime from the concrete during exposure to sea water. On the contrary, the strength of the concrete should increase according to the test results indicated above. Corrosion of the steel reinforcing bars is not an anticipated problem if approximately 3 inches of high quality concrete, an alkaline medium, covers the steel bars. Exposed steel parts, such as the beams and fittings, will be protected by an organic coating a minimum of .015 inches thick. This type of coating has shown excellent results in protecting steel and other



$\theta = \frac{90-15}{2} = 37.5°$

$R + 6 = \frac{15}{\sin 37.5°}$

$R = 24.7 - 6$

$= 18.7'$ MIN

for $R = 20'$

$h = (R+6)\cos 37.5°$

$h = 20.6'$

Figure 3-1 Hemispherical Foundation Geometry

TABLE 3-2 Hemispherical Foundation Characteristics
(Without Added Buoyancy)

	Dry Weight (Pounds)	Wet Weight (Pounds)	Bearing Pressure (Lb/Sq.Ft.)
Concrete	210,000	126,000	251
Concrete and Steel	218,000	145,000	288
Steel	120,000	87,700	233

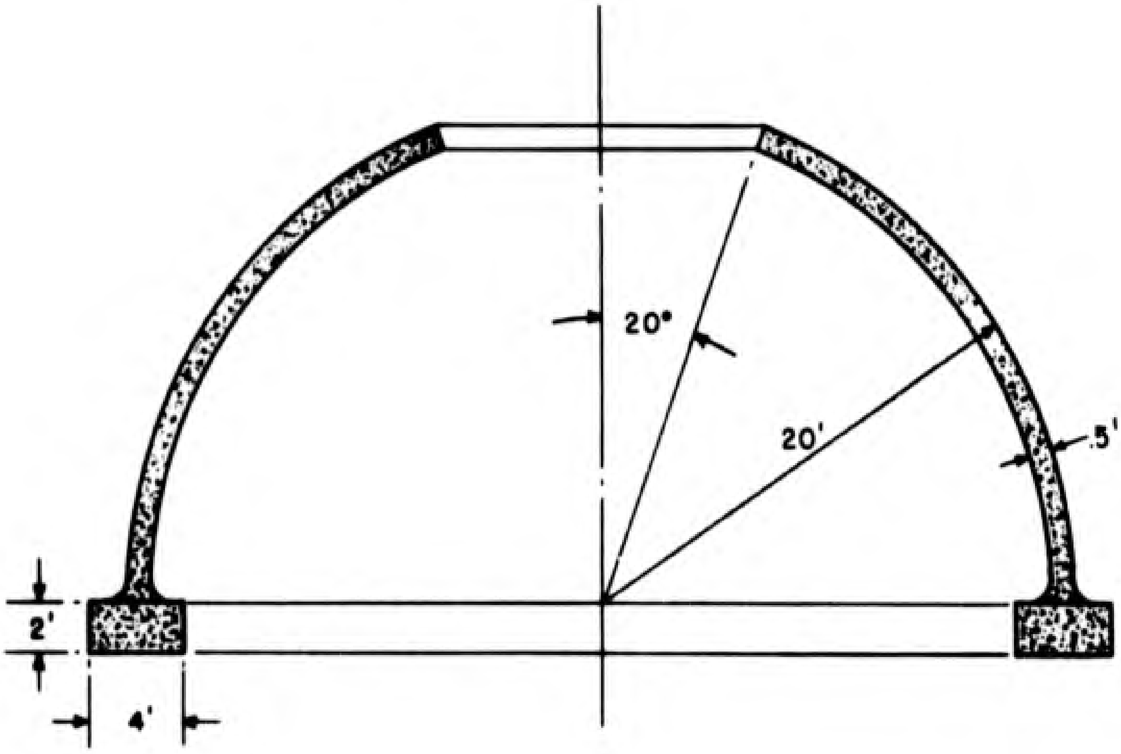


Figure 3-2 Reinforced Concrete Foundation (Section)

materials over a long period of submerged time in the STU I and STU II tests conducted by NCEL. These tests were conducted in water depths up to 5430 feet which approximates closely the maximum depth of the Manned Underwater Station.

A type I Portland Cement with sand and medium sized gravel aggregate to yield a density of 150 pounds/cubic foot is recommended. Reinforcing in the shell should be a welded wire fabric, symmetrically placed, with openings in the wire mat no smaller than 4 x 4 inches to allow free flow of the concrete. An estimated thickness of 6 inches for the shell and footing dimensions as shown in Figure 3-2 including an estimated 10,000 lbs. for the added steel beams, yields a foundation weight of 210,000 lbs. dry and 126,000 lbs. submerged. Neglecting the weight of the structure, the soil bearing pressure is 251 lbs/square foot which is far greater than the 72 lbs/square foot (0.5 psi) allowable bearing pressure given in the design criteria. Two means for solving this problem present themselves: (1) provide buoyancy in the foundation to limit the bearing pressure and (2) install piling under the foundation to distribute these loads into the bottom satisfactorily. It is also conceivable to use a combination of these but this will not be a subject for discussion in this report. A discussion of piling installation is contained in section 3.2.1.5.

Type I concrete reaches its maximum compressive strength and is considered cured after 28 days of hydration at a temperature no lower than 40°F. Hydration will occur below this temperature but reduced properties result and it is therefore recommended that the minimum temperature be observed. Because of this and the severe difficulties in pouring concrete in place under 6000 feet of water, it is recommended that a concrete foundation be poured on land. This foundation may be poured in sections and assembled prior to lowering in place or it may be constructed in the well of an ARD type ship at the dock, in transit, or at the site. Clean sea water, such as is found far off shore in the ocean, can be used to mix the concrete with no degradation of properties.

Concrete and Steel. Since the concrete foundation resulted in higher than allowable bearing loads, a composite structure of steel shell and concrete footing was investigated. With the concrete shell replaced by 0.5 inch thick steel plates welded together and reinforced by frames or stiffeners, the dry weight is computed to be 218,000 pounds and submerged weight is 145,000 pounds resulting in a bearing load of 288 $\#/ft^2$, which is higher than the all concrete foundation.

A design of this type presents no unusual problems beyond the present state-of-the-art. Shipbuilding techniques for forming steel plate to shape the hemisphere, welding these plates together and anchoring this assembly in a concrete footing are well known and no new development is considered necessary. Protection systems have been proved to prevent the corrosion of steel after long term submergence. It is therefore concluded that a composite structure is feasible and that the difference in bearing load from the all concrete structure is not significant. However, since it does exceed the design allowable pressure, some means such as piles are required to transmit the foundation loads to the soil.

All Steel. An all steel foundation was investigated with the result that its dry weight is estimated to be 120,000 pounds, its submerged weight, 87,700 pounds, and its bearing pressure 233 lbs/ft^2. Prior comments on steel construction and corrosion preventative techniques apply. It is concluded that piles are required. The selection of the foundation design from one of the above three would be governed by the unit cost of each since there does not appear to be any other definite, clear-cut advantage of one over the other. Table 3-2 summarizes the characteristics of the hemispherical foundations.

3.2.1.5 Platform Foundations

The second group of foundation types is the flat or the platform. These are thought to be a generally level, built-up area on the sloping bottom on which the structure would rest. Two methods for accomplishing the installation of this foundation type have been studied and are described below.

Fabriform. This is a patented construction technique for providing conformal, concrete mats either above or below the water surface. This invention uses a specially woven two-layer nylon fabric which has a specially designed porous weave. The two layers are woven together at intervals to form passageways in the shape of tubes or rectangular interconnected pockets. A reasonably fluid concrete slurry is pumped into these passageways, through suitable hoses and fittings, inflating the mattresses with the concrete mass. Excess water in the slurry is released through the nylon pores as pressure is applied while the fabric retains the concrete mixture under pressure. Since the nylon fabric is normally laid out on the ground, it conforms to the topography and once inflated with concrete, a firm conformal coating is provided. These "inflated mattresses" have provided erosion protection for river banks, bridge fenders and man-make islands. It is conceivable that this method would be able to provide a reasonably level platform for the Manned Underwater Station. The inflated mattresses would be applied to the bottom in stages, starting at the lowest point of the sloping terrain. Wedges of these mattresses are then built up after the previous layer has set until the desired level area is provided for the structure. A wedge shaped Fabriform foundation for a 15° slope weighs approximately 5,070,000 pounds dry and 2,900,000 pounds submerged resulting in a bearing pressure on a 60' by 60' area the bottom of about 800 lbs/ft^2. In order to use this foundation, the high load must be transmitted to the soil through piles. Since the platform discussed in the next section also requires piles but is less complex and lighter, there will be no further discussion of Fabriform at this point.

Steel. Another platform foundation type is a steel platform on piles. A technique for installing such a level platform has been developed and the platform now exists in the Gulf of Mexico in 300 feet of water. Global Marine Exploration, Inc. installed this platform during its work on the Mohole Project and engineers of the company have voiced assurance that this same installation technique can be extended to 6000 feet of water by the year 1970. This platform installation starts by setting one pile into the ocean floor to act as the key or starting point. The pre-fabricated steel platform is lowered so that it engages the key pile at the bottom. This platform is also a template. All remaining piles are then installed in the bottom with their locations governed by the template platform. Jacks raise the platform into a level attitude above the bottom and it is then attached to the piles. A maximum of 0.25° from true horizontal was attained for the Gulf platform, which is quite sufficient for the Manned Underwater Station structure. It is considered that even a 1° list could be tolerated by the personnel over a long period of time without ill effect. SEALAB II had a 6° up angle coupled with 6° list with no serious effects being experienced by the inhabitants.

All of the previous discussions on the protection systems used for steels underwater apply to this platform.

Installing piles in a particular location on the ocean floor, especially when it is required that these piles be located with respect to one another, requires that the drilling platform on the surface be accurately positioned. In the early stages of the Mohole Project, the National Academy of Sciences recognized this as a problem and set out to find a solution. Their experimental drilling of ten holes at the LaJolla Canyon and Guadalupe sites in deep water resulted in the conclusion that a dynamic method of station keeping for the drilling platform is entirely practical. The drilling barge, CUSS I, was modified to use a system of taut-wired buoys, sonar and radar sensing, and central maneuvering using computer outputs. This system held the CUSS I to a horizontal displacement of 2 percent of water depth from its desired location above the hole on this ocean floor. CUSS I achieved this '2%' position control in 11,672 ft. of water off Guadalupe while drilling a 1035 ft. deep hole in the bottom. A similar system can be practically employed for positioning a platform to set piles under 6000 ft. of water.

3.2.1.6 Recommendations for Foundation Design

From the above discussion, it is apparent that the site for emplacement of the Manned Underwater Station must be carefully selected. The cost of the foundation becomes the prime factor in selection of a design concept. Where bearing strength of the bottom is sufficient, a hemispherical foundation is recommended. It is anticipated that a concrete foundation with steel reinforcement will be the least expensive. In the case of low bearing strength bottom materials, the pile support platform foundation appears to offer the best success possibility. Anchoring a buoyant station just above the water-bottom interface is possible, but constant movement due to current action would appear to be disadvantageous. It therefore appears prudent to select a suitable "hard" bottom site for the first deep emplacements until more soil engineering data can be accumulated thru observation and testing with an emplaced station.

3.2.2 Structure

The present state-of-the-art in hull fabrication is restricted to the formation of ring stiffened cylinders and unstiffened spheres applied singly or in multiple units. Design methods have been developed to determine stresses and collapse pressures in ring stiffened cylinders and unstiffened spheres with initial imperfections with sufficient accuracy such that a collapse depth of 1.5 times the operating depth and maximum stress of 70% of the material yield strength may be permitted. Required dimensions of the ring stiffened cylinder can be established for a given material for a specific deployment depth by the use of optimization procedures that incorporate the stress and collapse pressure equations.

There are other alternatives for hull construction and configuration which may be considered, but require additional development effort before adequate design methods are established. These involve composite and sandwich construction. The composite construction consists of an inner layer of high compressive strength material such as glass held in place by a thin walled metal jacket. The inner segments provide the load carrying capability of the structure while the outer jacket provides a means of retaining the inner segments and acts as a watertight membrane. Sandwich construction consists of these plates separated by web material in the form of a sandwich. Although the plate thicknesses are easier to handle, this method of construction is more complex.

Other configurations that may be considered for this application are shells of double curvature such as the prolate spheroid and torodial shell. These shells have a structural advantage over the cylinder and provide better space utilization than the sphere.

To arrive at a design of a ring stiffened cylinder with hemispherical ends, optimization procedures incorporating the equations developed and generally accepted for collapse pressures and maximum stresses (References 3-1 through 3-6) are used. Curves of excess buoyancy may be obtained and a design established based on the space and buoyancy requirements of the pressure hull. Figure 3-3, for example, indicates the excess buoyancy as a function of hull dimensions for a ring stiffened cylinder design using 150,000 psi yield strength steel. However, other factors may dictate the size of the hull.

Penetrations in the pressure hull for accesses, view ports, and power lines result in stress concentrations which may result in local yielding and precipitate cracks as a result of low cycle fatigue combined with stress corrosion. A tapered reinforcement with machined mating surfaces for the closure results in the least stress concentration. Design of view ports is described in Reference 3-7 and in section 4.1.8. The details of the submersible mating hatch interface with the station are to be provided after the DSRV and DSSV designs are finalized. Thus, the reinforcement of the hatch opening will be an area for development effort as the detailed design phase progresses.

3.2.2.1 Configuration

The basic geometrical shapes that are considered for the pressure vessel are spheres, connected spheres, cylinders and toroids. In order to accommodate five men for a mission duration of 30-35 days, while allowing 200 square feet of floor space for unspecified equipment, it appears that a volume of at least 6000 cubic feet will be required. This is based on the SEALAB volume of 3500 cubic feet expanded to include additional work and relaxation area plus equipment space. A single sphere concept would require a diameter in excess of 22 feet, since its shape is generally suitable for efficient packaging of equipment.

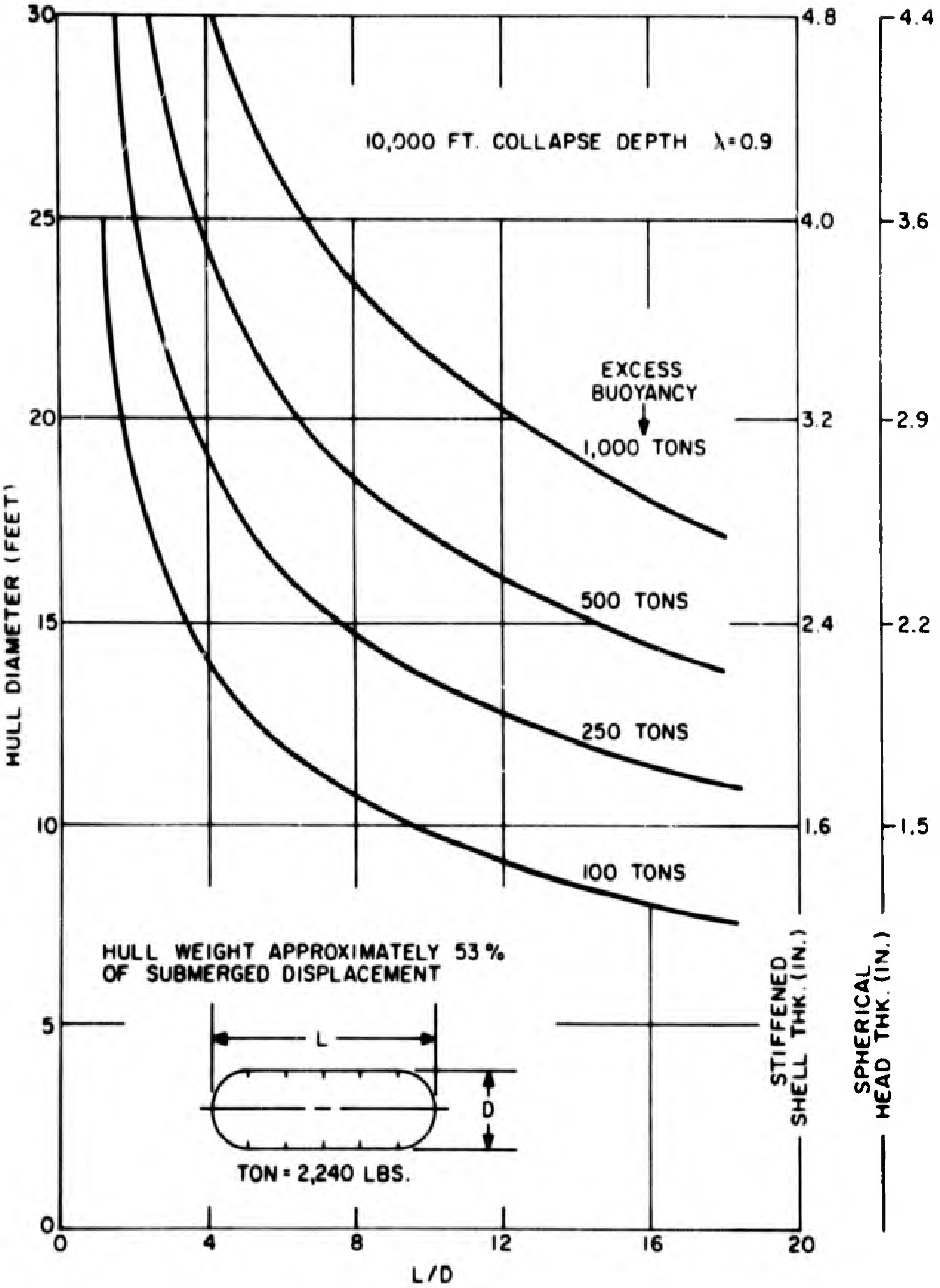


Figure 3-3 Excess Buoyancy for Various Diameters of HY-150 Cylindrical Hulls

Additional spheres may be connected to the main structure as pods to house power, stores and ballast. The disadvantages of this concept are:

(1) Mating of additional modules is restricted.

(2) Fabrication techniques for large-diameter spheres require considerable advancement to maintain acceptable sphericity.

(3) Available floor space within the sphere is limited.

(4) Sphere wall thickness for this diameter may be thicker than for a smaller diameter cylinder of equivalent volume. This can cause welding and other fabrication problems.

An adaptation of the spherical shape is possible by interconnection of smaller-diameter spheres. A linear connection of spheres has been employed for the Deep Submergence Rescue Vehicle. Such a concept solves only two of the disadvantages discussed previously for the large sphere concept, since floor space is still limited and the addition of flotation collars may still restrict viewing. The length of the interconnected spherical string also approaches prohibitive dimensions for the MUS. A further evolution of the interconnected sphere concept is shown in Figure 3-4. In this configuration, small diameter spheres are connected in a hexagonal manner. Additional modules could be added laterally to the structure to form a honeycomb arrangement, or could be added in a vertical stack. Problems still remain, however, in efficient use of floor space.

The use of cylindrical structures allows more lateral floor space while reducing the vessel cross sectional diameter. However, a cylinder with a diameter of approximately 10 feet (an acceptable size for state-of-the-art precision machining) would require a length of about 90 feet to supply the required volume to allow space for stores, ballast and life support equipment.

A compromise is possible by consideration of a toroidal structure - essentially a cylindrical configuration, but offering a desirable structural symmetry and continuity. The center of the toroidal structure could be filled with syntactic foam, thereby supplying necessary buoyancy volume without restricting perimeter viewing. Mating of similar modules is easily accomplished in a vertical stacking arrangement. Fabrication techniques are within the state-of-art. This concept is illustrated in Figure 3-5. Viewports can be included anywhere around the structural periphery. A mating hatch is planned atop the structure for vertical mating with additional toroidal modules or for use with both DSRV and DSSV. A deck is provided internal to the structure to provide level flooring for personnel. Ballast tanks, stores and waste

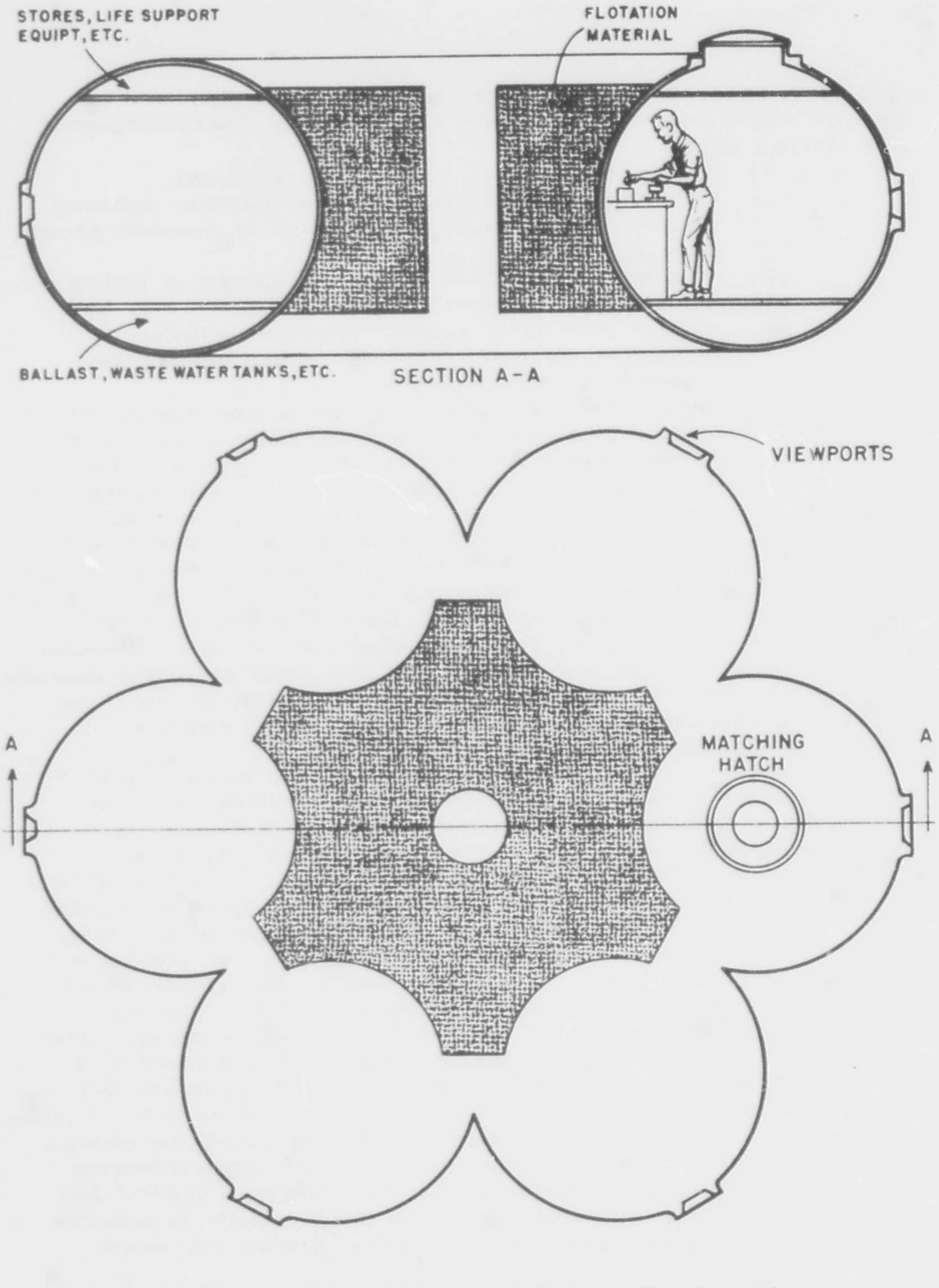


Figure 3-4 Hexagonal-Sphere Configuration

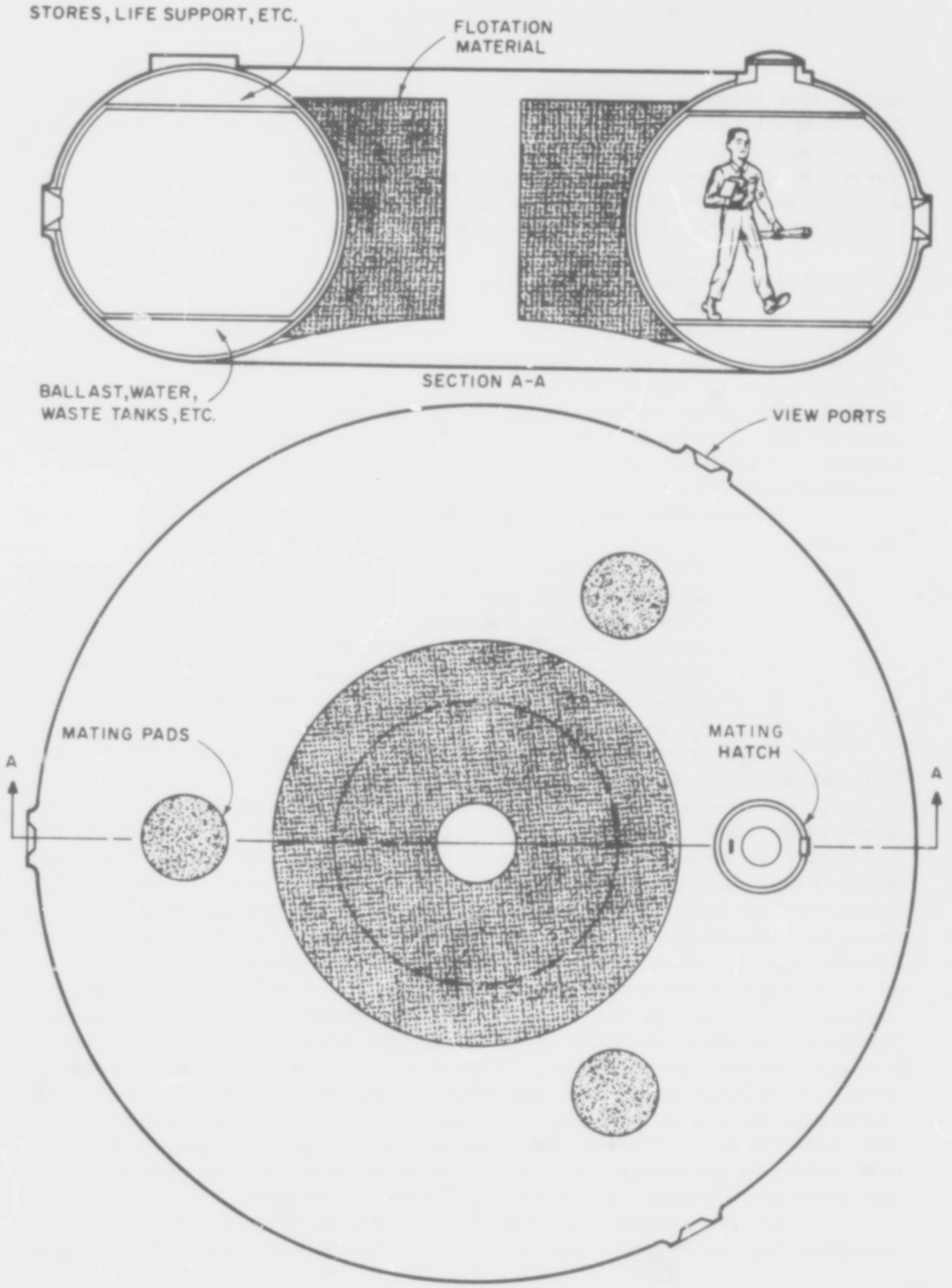


Figure 3-5 Preliminary Torus Configuration.

tanks are located under this deck. Life support equipment can be mounted near the ceiling of the pressure hull to maximize use of the cylindrical geometry. Bunks and other equipment can similarly be mounted along the side structure. The power plant can occupy either a portion of the toroid or be partially contained within an externally connected sphere.

3.2.2.2 Hull Material Selection

Emphasis placed on submarine construction in the past 10-12 years has led to increased knowledge of materials suitable for this type of construction. Also, expanding interest in oceanography and deep ocean vehicles has given added impetus to the search for improved materials, structures and fabrication techniques. Industrial and government laboratories have contributed considerable information in these areas.

Properties that are desirable in a pressure hull material include:

- Technological confidence
- Low material and fabrication cost
- Good fatigue, ductility, toughness, creep and corrosion resistance properties
- Compatibility with environment
- Retention of properties during fabrication
- Availability

Final selection of the hull material will be a compromise that takes these factors into consideration.

Metals have been used in the largest proportion of pressure hulls built to date. Construction with glass, including bridgmanities, is experimental state-of-the-art, but not yet proved in sizes required for the habitat. Also, glasses are suitable for compressive loading but tensile stresses must be avoided. In the complex structure required for this mission, it is not possible to insure against assymetrical loadings or to preclude the possibility of local stress reversals. Therefore, glasses have been excluded from the list of primary hull materials. Glass reinforced plastics including filament wound vessels show greater promise for submarine construction. However, the problem of interlaminate shear in fatigue tests has not allowed advance of this construction technique to a point where it is assured of 1970 readiness for this application. These non-metals may offer solutions to future hull material selection, but must be eliminated as candidates for the present Manned Underwater Station concept.

Of the metals, aluminum and titanium have received some attention for submarine construction. Aluminum has a light weight, but also possesses a low yield strength that causes it to be rejected for deep submergence use. Titanium has shown greater promise, but has also had problems. Stress corrosion tests in sea water have shown that new welding methods are necessary. Some definite progress has been made but the yield strength and ingot capacity is not yet attractive when compared to the high tensile steels, even though the weight would be less.

Many of the desirable properties are found in the high yield quench and tempered steels presently used in submarine construction. The HY-80 steel has been used very successfully for many years, whereas the HY-140 series is just beginning to receive full approval. It is confidently expected that HY-140 will be available by 1970 in quantity and fully suitable for this application.

Both the HY-80 and the HY-140 were developed by United States Steel for the U.S. Navy but can be made by others under license. Recent discussions with United States Steel representatives reveal that the properties and information contained in Reference 3-8 are current.

Another high yield steel that shows promise for Manned Underwater Station application is the Republic Steel HP-9-4 series. However, these steels are still experimental and do not have a definite specification. They are being tested with yield strengths from 180,000 psi to 205,000 psi and it is believed that by 1970 this material will be ready for use at least at its lower yield value. Current testing in welding and stress corrosion must be completed before qualification as a deep submergence hull material. The final selection of hull steel can be made when contract plans are drawn since either of the three steels discussed above will probably be suitable for this application. The current recommendation, however, is to use an HY-140 series steel. Tensile yield strengths of the three steels discussed are summarized below:

MATERIAL	YIELD STRENGTH (psi)
HY-80	80,000
HY-140	140,000
HP-9-4-25	180,000

3.2.2.3 Buoyancy Material

Syntactic foam offers several unusual features as a buoyancy material. It can be cast readily into almost any shape and withstands exposure to sea pressures without appreciable water absorption or loss in buoyancy. Additionally, it is compressed less than sea water under pressure and thus becomes relatively more buoyant as depth increases, and perhaps most important syntactic foam cannot lose buoyancy due to a puncture. (Ref.3-9) These desirable properties are currently exhibited by foams with a density of about 37 to 42 pounds per cubic foot and may be available in lighter foams by 1970. If additional buoyancy is necessary, the buoyant material will be contained within the center core of the toroid and might be assembled within open framework modules for ease of removal and access to other mechanisms in this area. Reference 3-10 covers many buoyant materials, and the choice of syntactic foam is supported by its use in deep diving research submersibles now in use and under construction.

True value of a buoyancy material is the ability to resist change in buoyancy during a lengthy exposure. This primarily means low water absorption and good strength retention. Preliminary tests to date have indicated that the syntactic foams consisting of glass microspheres in any epoxy resin matrix show very slight sea water absorption under pressure. The properties required in MIL-S-24154 can be equalled or exceeded so there is no lack of confidence in the material. However, in situ testing on water absorption and long term change in buoyancy will be a good job for the station personnel, since additional buoyancy is a probable requirement for similar structures suitable for operation at greater depths.

3.2.3 Power System

3.2.3.1 Concept Selection

Selection of a power supply for use in the Manned Underwater Station is one of the major efforts. This selection must consider mission and mission duration, power requirements, maintainability, reliability, seawater environment, performance characteristics, system life, and logistics as well as such factors as noise, pollution of the seawater and reaction products.

Safety and reliability are of prime importance in the design that employs a maximum of proven techniques and components. However, most conventional power supplies pose a considerable logistics problem. It is therefore considered that a combination of a conventional power conversion system with an advanced technology heat source will offer an attractive solution. One example is the use of a radioisotope heat source with a steam cycle power conversion. Power plants utilizing isotopic decay for heat generation offer the advantage of improved logistics supply over fossil or gaseous fuel systems. To realize this advantage in a practical sense, the inherent aspects of radioisotopes, such as continuous heat generation and shielding requirements, must be minimized. This can be accomplished by designing the power system in such a fashion that the heat output can be discharged (or used for internal heating) at all times regardless of the operating condition of the power system. The choice and location of the isotope will minimize the required shielding.

A nuclear reactor concept was examined briefly but rejected since a reactor would require more than five people for operation. Further, a single reactor producing 30KW would not provide the desired power system redundancy. However, this power source is attractive when several stations are grouped in a colony and there is need for more than 60KW of power. Reactors may be utilized as the Manned Underwater Station usage grows.

The fuel cell is another power source that was considered. An advantage is that some cell types produce potable water as a by-product. This eliminates the need for water storage or the requirement to use power for distillation from seawater. However, fuel cells have a logistics problem and a storage problem associated with the reactants. Cryogenic storage of the large quantity of hydrogen and oxygen is feasible, but costly. Work with these elements in a gaseous state at high-temperature also presents a greater safety hazard in a closed environment than does the isotope heat source. Further, and most important, the fuel cell will probably require development for the 1972-3 period to be used in a submarine application. Other fuel cell cycles may be ready earlier but present problems in cooling the cell during operation and handling the reactants as well as additional undesirable by-products (Reference 3-11). Other authorities predict longer development times for competitive commercial fuel cells (Reference 3-12) even though recent experiments (Reference 3-13) have proved the feasibility of the fuel cell for small submersible use in shallow water.

A battery system could be used for prime power, but weight and size are prohibitive. (Reference 3-14) Batteries also require recharging at the end of each 30 day mission and do not offer the advantage that is found in the isotope heat source of being able to extend mission time without major logistic support. However, a battery is desirable for an emergency power source and is incorporated in the station power system. A silver-zinc battery is chosen since the lead acid cycle produces undesirable gasses and the metal-oxygen battery is not expected to be ready by 1970.

Therefore, an air cooled radioisotope heat source coupled to a steam power conversion system using a turbogenerator is believed to offer the most practical method of providing basic power in the Manned Underwater Station. The rationale for the concept selection covers such major choices as the selection of cobalt-60, a steam Rankine cycle power conversion system and the use of a separate primary loop for gas cooling of the isotope.

3.2.3.2 Isotope Selection

The AEC has focused its attention on three radioisotopes for power conversion applications: strontium-90, cesium-137, and cobalt-60. Table 3-3 shows the significant characteristics of the three. Of these potential heat sources, cobalt-60 was selected for the following reasons:

- From the standpoint of availability, Co-60 is the only isotope now being produced in sufficient quantities to build a number of comparatively large isotope systems.
- From the standpoint of cost, Co-60 is the least expensive of the candidate isotopes. Subsequent reuse of the Co-60 in applications requiring lower specific activities will reduce the fuel cost even further.
- Cobalt 60 is produced by neutron irradiation while the others are fission products. Therefore, it can be reactivated for reuse in the station power plant if sufficient demand for the lower activity isotope does not develop.
- From a system design standpoint, the half life of Co-60 is sufficiently long to permit units to be designed for several years of operation without refueling.
- From a system weight standpoint, the high power density of Co-60 at a specific activity of 200 curies/gram provides a lighter weight, more compact heat source than the other isotopes which were considered. This is true even though Co-60 shielding requirements are greater than for other applicable isotopes, a disadvantage which is more than compensated for by the fact that the higher power density Co-60 provides a more compact source around which the necessary shielding is fitted.

TABLE 3-3 Characteristics of Radioisotopic Heat Sources

Characteristics	Co-60	Sr-90	Cs-137
Watts/g (Pure)(a)	17.7	0.95	0.42
Half-life, year	5.3	28	30
Compound form	Metal	$SrTiO_2$	Glass
Watts/g compound	1.7	0.23	.067
Density of compound, g/cm^3	8.9	4.6	3.2
Power density, w/cm^3 compound	15.5	1.05	.215
Availability, 1968--annual Kwt (b)	1500 Kw	200 Kw	100 Kw
Type of radiation (major)	$\gamma\beta$	βx	$\beta\gamma x$
Estimated future price \$/g (Pure)	570	18 (c)	9 (c)
Estimated future price \$/w	10 (d)	19	21
Curies/g (Pure)	1130	142	87
Curies/w	65	150	207
Minimum cost \$/Kwh_e (e) for mission (yr.)	36 (3)	5.6(10)	5.8(10)
Availability in 1980, Kwt (f)	--	720	720

(a) Includes contributions from daughters at equilibrium (thermal watts).

(b) Revised production capacities for Co-60 and fission products: Joseph, J. W., Allen, H., Angerman, C. L., and Dexter, A. H., Radioactive Cobalt for Heat Series, AEC Publication, 1965.

(c) From large civilian power reactor spent fuel processing and isotope recovery facility, after 1970 (see BNWL-25).

(d) Latest revised estimates: Fowler, E. E., and Sivering, N. F. Jr. Nuclear Power for Ocean Applications - Its Potential and Availability, AEC Publication, 1965.

(e) At terminal or lowest specific power (w/g) at 5% thermal to electrical conversion efficiency.

(f) From spent fuels from civilian power reactors; (80,000 Kwe in 1980).

A fourth radioisotope, cerium-144 was excluded from this comparison because its half-life was too short for the applications under consideration.

3.2.3.3 Power Conversion System Selection

Several types of dynamic power conversion systems were given preliminary consideration. Included in that evaluation were the Brayton and Stirling gas cycles, and Rankine cycles using steam, liquid metal, and organic working fluid.

Of these cycles, the steam Rankine cycle was selected for further study. Steam systems have a long history of development and use and, except for small turbines, their design is straightforward with most of the components requiring little, if any, development. In addition, most of the components are closely related to high volume commercial items and can be procured at reasonable commercial cost. While it is true turbine systems do present a problem in this small size range because of the low volumetric steam flow, the problem can be substantially alleviated by using a low pressure cycle (by steam standards) with many degrees of superheat and regeneration. Such a cycle gives reasonable volumetric flow rates at these low power levels and still provides overall efficiency levels of 15% or greater. In addition, the many degrees of superheat allows the cycle to drift with the isotopic power decay for a matter of months before correction become necessary. This is not true of other systems considered. It is also worth noting, that the high superheat eliminates the possibility of turbine moisture erosion.

Alkali metal cycles lack a developed technology and require higher temperatures than steam or Stirling cycles to operate. The liquid mercury and organic Rankine cycles boast substantial technology at reasonable temperatures, but there is no volume production base for components. Therefore, units like those required for this application will have to be specially manufactured and it is considered that the development costs outweigh any apparent advantage for application in the Manned Underwater Station.

Stirling plants are very efficient and have a good internal combustion engine related production base upon which to draw. However, substantial extensions in the technology of internal combustion engines (with respect to operating life between overhaul and gas to lubricant seal leakage) would have to be made to make this system competitive. Nevertheless, the Stirling engine could be developed for this operation.

Reference 3-16 is a broad comparative discussion of power conversion systems for underseas missions.

Brayton cycle design and production technology is well developed at larger power sizes than of those of interest to isotopic power plants. However, in the power levels of interest to this study, the Brayton cycle must be operated at substantially higher temperatures than either the steam Rankine or Stirling cycles to compensate for deterioration of component efficiency with size. This places an undue burden on the heat source without any real compensating advantages. Reference 3-15 reports on the status of the Brayton investigation effort.

3.2.3.4 Integrated System Selection

While the cobalt-60 isotope heat source can be cooled either directly by the steam cycle working fluid or indirectly through a separate primary loop, the latter procedure was selected because there are a number of advantages which result from the use of the separate primary loop. For example:

1. Because of its simplicity, the gas-cooled heat source requires a minimum of development effort. Furthermore, since it is relatively well developed, there is little uncertainly as to its operational characteristics.
2. Loss-of-coolant and general cooling problems encountered during transit are diminished when gas is used. (An emergency gas supply can be carried.)
3. The coolant loop is isolated from the working fluid loop.
4. The path of the coolant loop is minimized.
5. A loss of working fluid does not affect the heat source if an emergency heat rejection system is provided.
6. The heat source can be designed and developed separately.
7. Secondary system components are not subjected to radiation contamination.
8. The heat source may be coupled to alternate types of power conversion systems.

It must be pointed out that one advantage which the direct steam cycle has over the indirect cycle is that it gives 5 to 10% greater net electrical power output. Nevertheless, the other advantages offered by a gas-cooled heat source appear to outweigh the small loss in overall efficiency. It was concluded, therefore, that superheated steam cycle, used in conjunction with a gas-cooled cobalt-60 heat source, is potentially the best isotopic system for power generation in the submarine application.

3.2.4 Life Support

3.2.4.1 Introduction

The Manned Underwater Station mission requirement poses unique problems in management of the internal environment. Maintaining a healthful breathing atmosphere and providing food and sanitary services for the inhabitants will require a careful consideration of many factors. Furthermore, total life support includes creature comfort items such as berthing and recreation. Current experience with military submarines and small oceanographic submersibles provides a background against which the basic requirements may be developed. The station mission endurance of 30 days provides a challenge in that the power supply is relatively more expensive because it is not an auxiliary to a large propulsion power source. Further, the size of the structure must be controlled rigidly. The station components present a complex materials handling effort since self-propulsion is not available for transit between base and site. This lack of mobility imposes demands for an extensive logistic effort to support the maximum usage of the station. These and other constraints influence the selection between alternative life support methods when there is little technological basis for a clean-cut choice. Therefore, cost criteria may be applied as a basis of recommendation for equipment that is to prove the station feasibility in a limited evaluation program, while an extended development of the program would more logically demand use of different methods.

The crew of five is smaller than currently found in a closed atmosphere in a remote location for a period as lengthy as thirty days. This imposes demands of reliability and maintainability, ease of operation and maintenance and personnel safety. The latter consideration is of prime importance when it is realized that 6000 feet of overhead water separates the habitat from outside assistance other than that obtainable via a small submersible. The problems are not insurmountable, in fact the current state-of-the-art technology provides adequate methods for total life support. There is, however, a need for resizing of atmosphere control mechanisms from those on today's market. As the conceptual approach develops, it will be apparent that the sub-system recommendations are trade-offs between acceptable alternatives.

3.2.4.2 Atmosphere Management

Atmosphere management is concerned with the supply of oxygen, the removal of carbon dioxide, noxious gases, hydrogen, particulate matter, and the supply of makeup nitrogen to replace atmosphere lost in normal operation. For many years, the U. S. Navy has engaged in the investigation of these problems and the development of systems for atmosphere management. Systems for atmosphere management recently have been studied for space vehicles and bases.

In the study of atmosphere management, two general approaches can be considered--open and closed cycle. In the first, waste gases which are separated from the atmosphere are simply pumped into the surrounding seas. For the MUS such a pumping system could be objectionable because of the power requirements to pump gases over the side at the 6000 foot deployment depth. The second system provides for storing waste gases or converting them to usable products. Any conversion method must include provision for makeup oxygen.

Various alternatives are available for providing oxygen including electrolysis of water, reduction of carbon dioxide or water by a fuel cell and storage of compressed gas, to mention a few. On fleet submarines, the standard system is electrolysis of water; and the burning of chlorate candles is used as a supplementary source to stored gaseous oxygen. Compressed oxygen would require only mechanical devices for its distribution into the atmosphere and would produce no residue, eliminating the problem of recovery and disposal of unwanted gases associated with reprocessing.

Carbon dioxide removal from the air generally involves absorption by some medium. After absorption, the medium may or may not be regenerated. Systems available for removing carbon dioxide from the atmosphere include:

(1) Absorption in monoethanolamine,
(2) Absorption with a liquid or a solid inorganic base,
(3) Absorption on solid exchange medium (molecular sieve).

After removal of the carbon dioxide from the atmosphere, it may be compressed and stored or treated for oxygen recovery. Captain Cousteau planned CO_2 removal for Conshelf III by refrigeration. Mechanical difficulties caused him to fall back on another means but the principle is still valid.

The monoethanolamine (MEA) scrubber for carbon dioxide removal is the standard installation on fleet submarines.

There are drawbacks to this system in that MEA is toxic at the one part per million level in the atmosphere and degrades during use. To date there has been no known lethal exposure to MEA during a cruise.

The possibility of the use of solid exchange media for carbon dioxide removal appears to be good. Molecular sieve materials will remove water, organic contaminants, and carbon dioxide from the air, and they may be regenerated for reuse.

The control of hydrogen, noxious gases, and particulate matter can be effected by a combination of absorption and catalytic combustion. Catalytic combustion is in regular use aboard fleet submarines. Removal of noxious gas and particulate matter by absorption can be considered as a concurrent function with the removal of carbon dioxide. Consideration is given to small filters for particulate control in individual areas where high concentrations of dust may occur, and for removal of odor particles from the atmosphere.

In addition to the normal operating atmosphere, emergency equipment and procedures must be provided. Wall-mounted emergency breathing stations can be provided to adequately support the occupants for the time duration necessary to rescue them from the station or to bring the station to the surface. Such a breathing system must be closed-circuit to preclude the possibility of excessive internal pressure built up within the MUS, unless the anticipated rescue time is of reasonably short duration. Additionally, back pack breathing sets may be furnished for men to wear when entering contaminated areas of the station. This equipment must be independent of any tether so that the wearer may pass through a lock. In passing through a contaminated area and return, a small amount of that atmosphere will be brought into the unaffected area and provisions will have to be made to control such contamination.

3.2.4.3 Air Conditioning

The function of the air conditioning system is to remove heat and humidity from the air environment which receives heat from humans, power plant, electronic equipment and various auxiliary equipment. Control of the compartment temperature and relative humidity is necessary in order to insure comfortable conditions for the personnel and proper operation of internal equipment.

Factors which influence the design of the air conditioning system are the following:

(1) Low, relatively constant, outside water temperature.

(2) The desire to minimize the number and size of manned pressure hull penetrations for safety reasons.

Three different methods of air conditioning are available:

(1) Vapor Compression
(2) Absorption
(3) Thermoelectric

Vapor compression systems which are currently employed in submarines are subject to leakage of refrigerant vapors at seals, valves, pipe joints, and control connections. Absorption systems, such as the lithium bromide type generally used, are extremely heavy and bulky. They have a low coefficient of performance.

Both the vapor-compression unit and the absorption system use refrigerants which may prove hazardous to personnel. For example, freon becomes highly toxic at a concentration of 100 parts per million. These vapors, if not removed by the atmosphere control system can contaminate the atmosphere during the long periods of submergence. Furthermore, they also break down into more harmful gases in the presence of high temperature equipment such as galley ranges and pyrolytic burners.

In contrast, a thermoelectric system has no refrigerant to contaminate the atmosphere or equipment; it is quiet in operation; has no refrigerant or steam lines; is low in weight, and occupies much less space. Furthermore, a thermoelectric air conditioning system contains no moving parts (other than air-handling fans) and, hence, has an inherent high reliability. The operating history of thermoelectric air conditioning systems is relatively short compared to that of absorption or vapor-compression systems. However, a 27,300 BTU/hr thermoelectric air conditioning system has been operated by the Navy for 20,000 hours with no change in design performance. A comprehensive test program indicates that a reasonably unlimited life with no performance degradation may be expected. Production units rated at two tons cooling are being used on board Navy destroyers to cool radar equipment.

3.2.4.4 Heat Control

Utilization of energy by the various MUS internal systems results in conversion of this energy to heat which is rejected to the internal hull atmosphere. This, in turn, must be passed overboard to the sea. Since many of the heat sources may be localized, consideration can be given to heat removal devices which are also localized.

Fixed heat loads are defined as the quantities of heat rejected by internal systems required for performance of mission functions, and which are essentially independent of crew life support requirements. These will include radiation and conduction from hot piping and equipment, electrical losses from electrical motor-driven equipment, and heat associated with equipments such as sonar, communications and other instrumentation.

The variable heat loads are considered to be generated principally by life-support environment and control systems and associated processes. These include heat loads from hotel-type sources such as waste and water system, galley, food storage refrigeration, condensate from laundry and showers, metabolic water condensate and body heat. The major atmospheric management system heat loads are from the carbon dioxide absorbing and oxygen recovery and supply systems.

One approach to design of the heat rejection system is to reject all waste heat generated inside the pressure hull to the sea in a single heat exchanger. An intermediate coolant can be used to collect the waste heat from the various systems in which it is generated. Alternative locations of a heat rejection system heat exchanger inside and outside the pressure hull will be evaluated to determine the effect on system internal layout, cost and safety.

An alternate approach involves the use of thermoelectric devices which can be placed adjacent to the heat source. This eliminates the need to move large volumes of air with pumps, whose losses are converted back to heat.

3.2.4.5 Water Management

The 6000 foot operating depth has major impact on design of internal systems. A carefully planned system of water inventory management will be necessary because of the danger inherent in taking aboard large quantities of sea water at 6000 feet and the difficulty in discharging waste water at this depth. For example, in developing the pure water system design, use of a small, automated sea water distillation plant will be evaluated against the storage of fresh water with resupply from a support vessel at the beginning of each mission cycle.

As part of the water management plan, measures will be taken to minimize discharge water requirements. For example, consideration will be given to providing a system, similar in principle to that used in commercial airlines, whereby heads are flushed with water pumped at high velocity from a drain collecting tank. The drain collecting tank collects effluent from showers and other waste water sources.

In general, two basic water management concepts will be considered. The first of these is essentially closed, incorporating various forms of regeneration and reuse of waste water, and on-board storage of expendables and waste products. The second system is the conventional present-day system which is completely open, and rejects all waste water overboard or to storage in the form collected and utilizes storage tanks or sea water distillation as a fresh water source.

Water is required at different levels of contamination. Potable water is required for drinking and food preparation. A second supply of fresh water is needed in the life support area for personal hygiene and as rinse water in the area of sanitation, laundry and dish washing.

The closed system meets the requirements for water by reclamation involving various filter processes. Little or no make-up water will be required in an efficiently operating system. The open system is the one presently being used aboard submarines. Fresh water obtained from a distillation plant is stored in a central tank (or tanks) for the various onboard uses (drinking, food preparation, personal hygiene, etc.). Additional unprocessed water may be used for flushing urinals and toilet bowls. The pressure differential between the internal normal atmosphere and the sea ambient at 6000 feet depth provides strong impetus for selection of a closed system concept.

3.2.4.6 Waste Collection

Collection facilities must be provided for all the solid and liquid wastes generated in the MUS. There will be a direct interface with the water management system with respect to disposal of liquid wastes and consideration of closed and open system.

The discharge of sanitary wastes will require special attention. Blowing of sanitary tanks with compressed air, as is conventionally done in submarines, is not feasible because of the air resupply problem and the maximum operating depth. On the other hand, discharge of solid waste by eduction at 6,000 feet depth also represents a considerable advance over today's state-of-the-art. In addition, the sewage must be led away from the habitat, to avoid contamination of intake water, and to prevent further disturbing the scientific environment. One such system would employ low pressure eduction and high pressure pumping. The sanitary tank would be topped off with sea water, slowly, to avoid exceeding the capacity of the charcoal filters on the tank. When the tank is topped off, it would be isolated from the interior of the pressure hull and pressurized to sea pressure. A high volume, low head pump would then be used in conjunction with a sewage eductor to discharge solid material through an outfall which leads it away from the habitat. Finally, the liquid contents of the sanitary tank would be pumped overboard using a high head, low-flow pump of the positive displacement piston type.

A closed system concept would provide for all liquid wastes to be stored in a waste receptacle containing a chemical disinfectant for elimination of bacterial degradation. Garbage can be compressed, treated chemically, stored in drums, and packed in depleted refrigerator storage space with similar treatment for feces. Trash can be baled and stored in the trash collection area. With the proper use of depleted storage space, it is conceivable that little additional space and facilities will be required for a closed system.

3.2.4.6 Food Storage and Preparation

The design constraints require feeding five men for a minimum of 35 days of which five days may be on emergency rations. The crew will generally be young American males above average in physical fitness with attendant healthy appetites and tastes for good food. Considering the total cost of the mission, thought and money should not be spared in providing the very best food to suit the situation. Crew effectiveness and morale can be significantly influenced by the diet. Also in a closed atmosphere cooking odors can be offensive so it is important to develop procedures and techniques that will minimize air contamination problems. Also since power and space are high value items it is desirable to minimize waste and packaging material. Dry storage requirements can be reduced by making maximum use of ration-dense foods. A freeze storage refrigerator will enable essentially indefinite retention of frozen stores and completely inoffensive storage of solid waste matter in the volume vacated by the food. Electromagnetic cooking techniques can reduce the time required for food preparation and cooking odors. Utilization of high quality prepared meals alternating with meals "built from scratch" will impose a smaller burden of household chores on the crew. Since a full-time cook is not in the crew, the meal preparation needs to be as near "sailor-proof" as possible.

3.2.5 Personnel Psychological Considerations

The Manned Underwater Station is designed to accommodate five men for a period of thirty days. It is to be an enclosed habitat at depths ranging from 1000 to 6000 feet. The MUS will include a working area, sleeping area, toilet facilities, kitchen, recreation area and will provide approximately 1200 cubic feet per man.

Isolation and confinement can have serious effects on an individual's functional and emotional capabilities. Sensory deprivation studies (Reference 3-17), involving subjects placed in a chamber with a minimum of stimuli, showed that the subjects experienced visual and auditory hallucinations, depersonalization and minor intellectual impairment. The hallucinations, however, did seem to decrease with an increasing amount of mobility on the part of the subject. While environment in the MUS would not be completely devoid of stimulus, it would be repetitious and monotonous with a low level of variability. The semi-isolation of the MUS, as compared to the near complete isolation studies by these experimenters, could bring about mild decompensatory behavior with a possibility of mild hallucinations.

Several observational studies have been done concerning man's adaptation to isolated life in both large and small groups. Although the studies pertain to confinement in different environments and concern larger groups than the one of interest here, they are similar enough to provide much useful information. They can serve as a basis for setting up guidelines, predictions and designs for such a work environment as the MUS.

The nuclear submarine offers a comparable situation to the MUS, but with a larger group of men. In 1954, a study was made on the confinement of 23 men for a period of fifty days (Reference 3-18). The results showed no significant decline in psychomotor or manipulative ability. However, there was a decline in personal motivation (and hence group morale), an increase in interpersonal irritability, and an increase in muscular tension together with sleeping difficulties. On the TRITON cruise of 1960, personal motivation and group morale showed a declining trend after ten days while homesickness rose concurrently. One interesting finding is that morale seemed to be an inverse function of the degree of regimentation imposed. Morale appeared highest on Sunday, which was a semi-free day for the crew (Reference 3-19).

During the shelter test experiments, the occupants were required to live in a much more crowded environment, about 100 cubic feet per person, but certain problem areas were pointed out by the tests which will have an effect on this project design (Reference 3-20). The shelter equipment and physical environment were ranked way above personal behavior as sources of psychological discomfort. During both the winter and summer tests, the main complaint was the lack of water for washing. Stress during the winter was emotional as opposed to physical, and as food is an important source of emotional gratification, the experimental crackers given the men received the most lengthy complaints. Struggle with the physical environment overshadowed the emotional stress during the summer test, and complaints of temperature and humidity, crowding, and dirt came above food. Adjustment was generally good among the submarine crews and shelter inhabitants. Only 2 or 3 of the 80 persons in TRITON in 1960 experienced anxiety reactions of a serious enough nature to require medication during the 83-day cruise. (Reference 3-19)

The Antarctic station studies involved groups of men varying in number from 15 to 150, isolated for periods of two to six months. No consistent trend was found indicating that small, medium or large stations showed a higher incidence of emotional symptons (Reference 3-21). However, the demand for an individual to adjust to the other station members is most intense at the small stations. The aspects of the immediate environment, such as work load and social boundaries, are more critical for emotional response variation than the fact of isolation from the world (Reference 3-22). The increased complaints of emotional and somatic nature during the winter appeared to be related to the reduction in work load and increased physical and social confinement. More frequent desire for privacy occurred than for greater social contact.

The recent SEALAB experiments with ten men living in a submerged habitat for two weeks involved the same environment, the sea. However, close control was maintained from the surface and the men were not completely confined. The morale and motivation were extremely high, probably due partly to the knowledge that the men were a part of a project with unlimited potential and great significance (Reference 3-23). Almost all the aquanauts had difficulty in sleeping. There was no evidence of a general slowing down of movement and thinking and the men did not experience any marked psychological breakaway from the surface (Reference 3-24). As there is a likelihood that the men will suffer some loss of sleep, the ability to do with less than normal sleep should be taken into account during selection.

Through all these reports, a type of general pattern can be evolved in which the possible complaints and disturbances of the men in an underwater station can be observed. The lack of privacy was a frequent complaint, although not the most serious. The MUS will provide more generous accommodations per man than the present submersible crews and much more than the shelter inhabitants. These quarters, including private bunks surrounded by curtains, should help to alleviate irritability and feelings of hostility. Hall (Reference 3-25), in his science which he calls "Proxemics," states that a man occupies a larger space than that bounded by his skin. In order to function without undue stress, he must have a surrounding "bubble" of space. In close, isolated quarters, providing enough room and privacy could make a difference between useful, fruitful work and apparent incompetence. In the space studies, 125 to 150 cubic feet per man is acceptable for small groups for 7 to 30 days under circumstances of good habitability and working conditions (Reference 3-26). The 1200 cubic feet provided each man in the MUS is about nine times as generous.

The most serious physical complaints found in the shelter tests will be alleviated in the MUS by an ample supply of water for washing and excellent kitchen facilities with one or more of the crew experienced in food preparation. The temperature, humidity and atmosphere purity will be closely controlled.

Although the physical well-being and comfort of the crew will be assured, there remains a necessity for adequate stimulus to combat the inherent boredom and monotony of such a mission. The small crew size may increase the task load of each individual. More time spent at meaningful work, which has been designed to be as variant as possible, should reduce symptoms of anxiety, indifference, regressive behavior and eliminate hallucinations. It was found that "feedback" as to the preliminary results of repetitious activity was very useful in maintaining vigilance (Reference 3-19). This could even involve a work-up of any data obtained. Some jobs should be kept complex, as the interest value is related to the task complexity throughout a period of time.

Leisure time amounts to voids in a work situation which must be filled in by activity or inactivity which will negate rather than increase boredom. An area is set aside for recreation activities including physical exercise. Physical exercise is a very good stimulus and may ease the problems of depression and soreness of muscles. Motion pictures or canned TV and radio will be available as well as a comprehensive library. As no one would consider painting the interior of their house a drab gray or green, the station's interior will not be drab and depressing but of a gay light nature with several paintings on the walls.

Wheaton (Reference 3-27) has suggested the following as a possible pattern of the mental attitude of an isolated man. First, the individual feels an emotional shock which may be followed by either apathetic surrender accompanied by mental deterioration, or resistance, self-help and recovery. Next is the feeling of loneliness which seems inescapable, but which can be neutralized by the structuring of activities on a rigid time schedule throughout the day. The third step involves a turning into oneself for the requirements of social and emotional stimulation. This situation can deteriorate and involve delusions and hallucinations. It is believed that the environment and stimuli involved in the station is of a type sufficient to modify these steps and to aid the individual crew member in avoiding mental pitfalls.

Limited capability exists to predict the interactions of two or more personalities exposed to an environment with a large number of variables. Little is known on the relationship of personality to symptom susceptibility or whether group characteristics modify individual reactions to restricted stimulation. In spite of these shortcomings, certain recruitment standards have been set which have reduced failure in the submarine service for psychological reasons to less than 10% as compared to over 40% in a non-controlled population (Reference 3-19). The selection is made based on the following criteria:

(1) Each man must be a volunteer.
(2) Each must meet aptitude criteria - verbal, arithmetical, and mechanical.
(3) Intensity of motivation.
(4) General psychiatric status.
(5) Assessment of his somatosychological nature.

It does not seem to matter much if a person is withdrawing or outgoing toward others as long as he does not annoy, irritate or cause dissention (Reference 3-22). There seems to be a tendency for persons closest to the median age of the group to adapt better to isolated conditions, as did single men from rural background with previous work experience outside the United States.

Through a number of years, some significant variables of personality have been isolated which appear to be important in the assessment of personnel for Antarctic station duty (Reference 3-28). They are discussed below with the thought that they will be valuable in selection of a crew for the MUS.

Positive motivation such as saving money, possible rate advancement, and the challenge of an unusual experience is not as important a criteria as it once was. However, unhealthy or negative motivation including escape from marital conflict, transfer from an undesirable duty station, and immature search for adventure, is disqualifying.

One of the most important variables is the history of a man's past personal effectiveness. Incompetence poses a threat to the group's well-being and is a source of interpersonal conflict. In a very real sense, every man is dependent upon every other man.

Evidence of potential or suggestive history for emotional decompensation is disqualifying. The adequacy of the defense mechanisms is considered more important than their nature. Therefore, neurotic mechanisms are not in and of themselves disqualifying with the exception of extreme rigidity. The rigid individual, without the ability to be flexible in the face of group needs becomes a source of disruption to the group.

Little attention has been given to the structure of the small isolated group, which now is considered to be very important. In terms of preventative psychiatry, the greatest future gains will probably be found in evaluating the individual in terms of the group.

It is interesting to note that the characteristics listed by the divers of SEALAB, as being most important for a man to live and work in that environment, follow the assessment data above very closely (Reference 3-23). Highest on the list was diving experience and competence in his job specialty. The person's congeniality and willingness to do his share of general work were also high on the list.

Criteria for crew selection should also involve some word on the leadership of the group. The most esteemed leaders of the small Antarctic stations were those who assumed the democratic orientation of leadership and used a relatively personal and participatory style (Reference 3-29). They were closer to their men and seemed more capable of making impartial decisions.

The participation of group members in the development of the basis for general station policy is usually very conducive to support of the final decision. This has the added advantage of facilitating self-discipline but leaves no doubt as to who is in charge. As no leader is usually technically competent in all the logistic and scientific fields represented, it follows that recommendation should be requested from the expert member. The leader then can weigh as much relevant information as possible before making a technical decision.

The personal type of leadership facilitates a psychological distance between the leader and crew and yet is compatible with the group situation. This arrangement seems to provide better solutions and decisions which are personally supported by the crew.

It has been shown that the possibility of emotional difficulties occurring in such a situation as a small group isolated in a manned underwater station is ever present. The possibilities of auditory and visual distortions due to stimulus deprivation should be kept minimal with the provision of a variety of leisure activities and meaningful job activities. Some sensory stimulus is available by means of viewing ports and exterior lights incorporated in the station design. The individual's understanding of the mission and its present and future importance is necessary for good morale. The lack of social stimulus due to the small number in the group could present a problem over a period of time. However, communications facilities can be set up to enable the men to carry on long distance telephone conversations as appropriate. The provision for as much privacy as possible should alleviate the social situation to some degree.

In summary, isolation and confinement may cause delusions and hallucinations. This is unlikely if the subject has mobility or if there is a group of three or more. Symptoms such as tension, irritability, headaches, depression, insomnia, and muscle soreness are common and tend to increase with time. Selection criteria have been developed and are being refined which can substantially reduce human failure. Leadership abilities and methods are important factors in group stability. Areas needing serious study include the relationship between group characteristics and an individual's personality. The station is designed with the mental and physical comfort of the crew members in mind. Sensory stimulation, privacy, personal comforts and emergency provisions will make the station a habitable environment.

3.3 SYSTEM CONCEPT EVOLUTION

Sections immediately preceeding have discussed the evolution of the major subsystem concepts. This section treats the overall system concept in connection with the deployment of a station and the surface support required. Also included are sections listing requirements for various missions and a discussion of operational capabilities of the MUS concept with respect to several potential missions.

3.3.1 Deployment and Retrieval

In the discussion of the deployment of the habitat, the following factors must be considered:

(1) Transporting the foundation and the structure to the selected site.
(2) Station keeping or dynamic positioning of the surface ships over the selected site.
(3) Emplacing the foundation on the ocean floor.
(4) Lowering the station structure onto the foundation.
(5) Retrieval of the station structure.

Each of the foregoing considerations are discussed in the paragraphs following.

3.3.1.1 Transportation

Hemispherical foundations which are wholly prefabricated may be transported to the site by an LSD, ARD or similar vessel which has a reasonably large center well. Both the ARD, which is a floating drydock, and the LSD have a floodable center well and an aft gate which can be lowered. This type of transport would allow a buoyant foundation to be floated out of the ship. Dry weights of the three foundation constructions range from an estimated 100,000 pounds for the all steel to 218,000 pounds for the steel and concrete, without any buoyant packages or handling fixtures attached. These weights are acceptable in either vessel. A disadvantage of the ARD type, however, is the lack of a self-contained propulsion system, which requires that it be towed whereas the LSD is self propelled.

Transporting a 40-foot diameter, 22-foot high object, similar to the foundation, any great distance overland is a sizeable problem and it is therefore recommended that the construction site be a shipyard. This site has the advantage of being situated on the waterfront and of having the handling capability for such an object. A completed foundation could therefore be lifted aboard the transport vessel using standard shipyard heavy lift such as travelling cranes.

A platform foundation of prefabricated steel presents much the same problem as the hemisphere. Its estimated weight of 30,000 pounds dry and its 40-foot by 6-foot dimensions also require the heavy lift capabilities of a shipyard. Standard shipyard assembly techniques will be used for fabricating the platform which further points up the advantage of constructing the platform at such a site. This foundation will also be carried in the well of the LSD or the ARD to the installation point. All of the steel piles required with the flat platform foundation are transportable aboard the vessels of the pile setting contractor.

The flat concrete "Fabriform" foundation type discussed previously would be poured at the site which requires only that the materials be transported. Sufficient space is required aboard one of the vessels for the contractors mixing and pumping machinery. No new ship requirements are foreseen for the capability since the LSD center well area has sufficient open deck space to accommodate this machinery.

Shipyard techniques and machinery are required to fabricate the toroidal station structure and, therefore, the discussion above applies equally well. The estimated weight of the completed structure with all equipment is 475,000 pounds. Since the completed unit will be transported with little of its equipment removed, the same LSD or ARD ship which transports the foundation will be used. These two components will load the ship by 280 to 325 long tons which is well within the ship's capability.

Transporting both the foundation and the structure from the same shipyard allows a trial dry mating prior to their leaving dry land. This preliminary step will be taken with the full scale prototype prior to shipment to satisfy all observers that the components will assemble on site.

3.3.1.2 Station Keeping

A prerequisite to the station emplacement is site selection and survey as stated in Section 3.3.2. During the detailed bottom survey part of that phase of the program, the dynamic positioning or station keeping of the survey vessels is of paramount importance. Experimental deep ocean drilling operations off La Jolla and Guadalupe have resulted in a method for accurately positioning and maintaining this position, for a drilling platform on the surface. By selecting sufficiently long life, reliable transponders and other sonar equipment for planting during the survey phase, station keeping for the installation vessels becomes less a problem and more important, the location of the selected bottom site is pin-pointed. The installation vessels now use the same positioning techniques and equipment as was used by the survey group.

3.3.1.3 Foundation Emplacement

Lowering the massive foundation into place requires the selection of a cable and winching system which can withstand high dynamic loads. Although the foundation will have a negative buoyant force of approximately 60,000 pounds, its mass and the hydrodynamic mass associated with it while submerged are large. Therefore, the static load of 60,000 pounds on the suspension system is a small part of the total load when compared to the inertia loads induced in the cables as the ship responds to the sea. A mathematical investigation of the problem of raising and lowering loads in the ocean and a design procedure for the suspension system is presented in NCEL Technical Report 433 (Reference 3-30). To properly use this analytical procedure, however, requires that the response of the ship to the ocean swell and the sea state be known or taken into account by other factors since the ship may either amplify or attenuate the ocean input oscillations. Since the response characteristics of the surface vessel are not known for this report, the following analysis was made in conformance with the procedure of reference 3-30. It must be understood that different ships have different response characteristics in a seaway and that the analysis presented herein is only to demonstrate feasibility.

Reference 3-31 states that the wave heights in a sea state 3 averages 2.9 feet, 10% of the waves reach 5.8 feet, and the period of the waves varies between 2 and 8.8 seconds. Let it be assumed that the wave height varies directly as the period; that is, the higher waves have longer periods. Designating the wave height by h, the period by T, and using the symbol U_o from reference 3-30 as the wave amplitude

h ft.	1.0	2.0	2.9	3.5	4.0	5.0	5.8
T sec.	2.0	3.42	4.69	5.54	6.25	7.67	8.80
U_o ft.	.5	.1	1.45	1.75	2.0	2.5	2.9

A galvanized plow steel 6 x 19 wire core bridge rope having the following properties is used as a starting point for the analysis:

$d = 2.0''$ diameter
$P_{al} = 186$ tons $= 372{,}000\#$
$W = 6.85$ lb/ft
$S = 1.92$ in^2
$E = 15 \times 10^6$ psi

The concrete foundation weighs 206,000 pounds dry and 122,200 pounds submerged. By providing buoyancy to the foundation, it can be made to weigh 60,000 pounds submerged. This can be accomplished through the addition of four 9-foot diameter spheres under the dome of the foundation.

The buoyant force required:

$$W_b = 122{,}200 - 60{,}000 = 62{,}200\#$$

The displacement $\nabla = 62{,}200/64 = 972$ ft^3

One sphere of this volume would be 12.3' in diameter which is too large to be easily used in the foundation and therefore a number of spheres of smaller diameter will be used. Dividing the required displacement by four yields a required sphere diameter of 7.8 feet which is more easily manufactured and handled. Since the weight of these spheres must be compensated for, assume 9 feet for the diameter.

Using HY - 100 steel and allowing a safety factor of 1.5 on the critical buckling pressure for a 9 foot diameter sphere, the thickness of the shell can be computed from the relationship:

$$P_a = .84E\left(\frac{t}{R_o}\right)^2$$

where t = shell thickness
E = Young's modulus = 30×10^6 psi
R_o = outside radius of shell
P_a = critical buckling pressure

This formula has been derived from test results and is a modification of the theoretical buckling pressure formula for ideal spheres:

$$P_a = 1.21E\left(\frac{t}{R}\right)^2$$

in which R is the midsurface radius. Imperfections in manufacturing have caused collapse of the tests spheres at pressures lower than that determined by the classic equation, resulting in the empirical formula noted previously. Further tests have shown that both sphericity and out-of-roundness manufacturing tolerances further lower the predicted collapse pressure and therefore an additional 1.5 factor is arbitrarily incorporated in the formula to calculate the required skin thickness thusly:

$$P_a = \frac{.84\,E}{(1.5)\ (1.5)} \left(\frac{t}{R_o}\right)^2$$

$$\left[\frac{(6000)(.434)(1.5)(1.5)(54)^2}{(.84)(30 \times 10^6)}\right]^{1/2} = t$$

$$.825'' = t$$

Additional factors of safety are not required for this design since the spheres are not occupied by personnel nor will these spheres be subjected to cyclic stresses for any large number of cycles or any high rate.

The estimated weight of these spheres is 34,600 pounds, however, their displacement offsets this weight to givean excess buoyancy of about 64,000 pounds.

From reference 3-30, the allowable dynamic stress in the cable can be computed by the relation

$$\Sigma_d = \frac{\Sigma\ \text{ult}}{F} - \Sigma\ \text{static}$$

Allowable dynamic load can be similarly computed:

$P_{static} = 60{,}000\#$

$F = 4$

$P_{ult} = 372{,}000\#$

$$\therefore\ P_d = \frac{372{,}000}{4} - 60{,}000$$

$P_d = 33{,}000\#$

This resulting allowable dynamic load for the cable is too small when considered in relation to the large foundation mass which suggests the investigation of a multiple cable suspension system. Although it is possible for the wire rope manufacturers to make large diameter ropes, their machinery capacity limits the length of some diameters to less than 6000 feet. According to Reference 3-32, a 4-inch diameter rope is available in 2700 foot lengths and the 3.75-inch diameter in 3100 foot lengths. Special handling equipment exceeding a 40 ton capacity is required to manufacture a length longer than shown above. A 3-inch diameter rope of the same 6 x 19 galvanized plow steel construction as previously considered has the following properties:

$d = 3.0$ diameter

$P_{al} = 412$ tons $= 824{,}000\#$

$W = 15.11$ lb/ft

$S = 4.25$ in^2

$E = 15 \times 10^6$ psi

Six thousand feet of 2.0-inch diameter rope weighs 41,100 pounds while 6000 feet of 3-inch rope weighs 90,700 pounds and 6000 feet of 1.5-inch rope weighs 23,900 pounds. Because the handling chore would be reduced with reels of smaller diameter of cable, except when the number of reels becomes excessive, it is recommended that multiple lines of 2.0-inch diameter or less be used in the lowering system.

Let it be required to have an allowable dynamic load in the cable which is 5 times the static load of 60,000 pounds plus have a factor of safety, F, of 4. Then, from:

$$P_d = \frac{P_{al}}{F} - P_{static}, \text{ in which } F = 4$$

$$(300,000 + 60,000)4 = P_{al}$$

$$14.4 \times 10^5\# = P_{al}$$

which requires that a minimum of four 2-inch diameter cables be used to lower the foundation. Investigating this system in accordance with the design procedure in NCEL Technical Report 433 (Reference 3-30) results in the following analysis:

Load Parameters:

$M = (206,000 + 34,500)\ 1/32 = 7520$ slugs

$W = 60,000$ lbs

$A = 1225$ ft^2

$C_D = 1.2$ = coefficient of drag

$C_m = 1.5$ = coeficient of virtual mass

Cable Parameters:

$d = 2.0''$ (4 cables to be used)

$L_{max} = 6000$ ft

$w = (6.85)4 = 27.4$ lbs/ft

$E = 15 \times 10^6$ psi

$a = (1.92)4 = 7.68$ in^2

$P_{ult} = 14.88 \times 10^5\#$

Velocity of Sound in the Cable:

$$C = \sqrt{\frac{E}{\rho c}} = \sqrt{\frac{15 \times 10^6 (12)(1.92)(386)}{(6.85)(144)}}$$

$$C = 1.162 \times 10^4 \text{ ft/sec}$$

Damping Parameter:

$$\beta = \frac{4C_D\ \rho c A}{3\pi C_m M}\left|u_o\right| = \frac{4(1.2)(2)(1225)}{3\pi(1.5)(7520)}\left|u_o\right|$$

$$\beta = .1108 u_o$$

ω , the induced circular frequency of the input oscillation of the sea varies with the wave height and its period is

$$\omega = \frac{2\pi}{T} \quad \text{and} \quad \omega' = \frac{\omega L}{C}$$

Table 3-4 assists in the computation of ratio of cable weight to load virtual weight.

$$\mu = \frac{WL}{W_a} = \frac{(27.4)\ L}{(240,500)(1.5)}$$

$$\mu = 7.6 \times 10^{-5} L$$

TABLE 3-4
Induced Circular Frequency for Various Wave Heights & Ocean Depths

h	1.0	2.0	2.9	3.5	4.0	4.5	5.0	5.8
$\lvert U_o \rvert$	0.50	1.0	1.45	1.75	2.0	2.25	2.5	2.9
T	2.0	3.42	4.69	5.54	6.25	6.96	7.67	8.80
ω	3.14	1.84	1.34	1.132	1.005	0.902	0.818	0.713
β	0.0554	0.1108	0.1608	0.194	0.2216	0.249	0.277	0.321
ω' 6000	1.620	0.948	0.692	0.585	0.518	0.475	0.422	0.368
ω' 4000	1.080	0.633	0.461	0.390	0.346	0.310	0.282	0.246
ω' 2000	0.540	0.316	0.230	0.195	0.1730	0.155	0.141	0.123
ω' 1000	0.270	0.158	0.115	0.0975	0.0864	0.0776	0.0704	0.0613
ω' 500	0.135	0.0781	0.0576	0.0488	0.0432	0.0399	0.0352	0.0307
ω' 200	0.0540	0.0316	0.0230	0.0195	0.0173	0.0155	0.0141	0.0123

Substituting for L in the above equation,

L	6000'	4000'	2000'	1000'	500'	200'
μ	.456	.304	.152	.076	.038	.015

Allowable dynamic load in the cable,

$$P_d = P_{ult} - P_{static}$$

$$= \frac{(372,00)4}{4} - 60,000$$

$$P_d = 312,000 \text{ pounds}$$

Allowable dynamic stress $\Sigma_d = \frac{312,000}{7.68} = 40,700$ psi

Determine dynamic stress in cable for wave height 2.9', $\lvert U_0 \rvert$ = 1.45 and 200' depth. Therefore, β =.1608, ω'= .0230. The design curves in Reference 3-30 have $\lvert \Sigma' \text{max} \rvert$, the normalized dynamic stress, plotted against ω' for various values of β and μ . In preliminary analysis, a close approximation of $\lvert \Sigma' \text{max} \rvert$ can be obtained by using the curves for a value of β close to the one derived from the problem. In this instance, the curves for β = .25 over the range $0 \leq \omega' \leq .1$ and $.005 \leq \mu \leq .10$ are used since plots with lower values of β are not shown.

It can be shown that the effect of β on the value of $\lvert \Sigma' \text{max} \rvert$ is reasonably small by considering the values for β = .25; .50; 1.00 for a value of ω' =.02 with μ = .01 and .03. Setting these in tabular form:

β	μ = .01, ω' = .02			μ = .03, ω' =.02		
β	1.00	.50	.25	1.00	.50	.25
$\lvert \Sigma' \text{max} \rvert$	0.063	.049	.049	0.026	.026	.026

shows that as β is reduced, its effect on the magnitude of $\lvert \Sigma'_{\text{max}} \rvert$ decreases. It is, therefore, reasonable to assume that the curves pertaining to β = .25 can be used to find $\lvert \Sigma'_{\text{max}} \rvert$ when β = .1608 and that the results are conservative.

Using this procedure to determine the stress in the cable system for the hypothesis

$$
\begin{aligned}
L &= 200' \\
\lvert U_0 \rvert &= 1.45' \\
\beta &= .1608 \\
\omega' &= .0230 \\
\mu &= .015
\end{aligned}
$$

Σ'_{max} = .02 from the design curve. (Figure 2 of NCEL Technical Report 433) The dynamic stress is computed from

$$\Sigma'_{\text{max}} = \frac{L \, \Sigma}{\lvert U_0 \rvert E}$$

$$\frac{(.02)(1.45)(15 \times 10^6)}{200} = \Sigma$$

$$2175 \text{ psi} = \Sigma$$

Margin of Safety:

$$
\begin{aligned}
MS &= \frac{\Sigma_d}{\Sigma} - 1 \\
&= \frac{40,700}{2,175} - 1 \\
&= 17.7
\end{aligned}
$$

for

$$L = 6{,}000'$$
$$U_\circ = 1.45'$$
$$\beta = .1608$$
$$\omega' = .558 = .178\,\pi$$
$$\mu = .456$$

Σ'_{max} = 3.8 from curves for $\beta = .10$ (Figure 15, Reference 3-30).

Dynamic stress in the cable:

$$\Sigma = \frac{\Sigma'_{max}\, U_\circ E}{L}$$

$$= \frac{(3.8)(1.45)(15 \times 10^6)}{6000}$$

$$\Sigma = 13{,}750 \text{ psi}$$

and

$$MS = \frac{40{,}700}{13{,}750} - 1$$

$$MS = 1.96$$

For intermediate depths, the stress in the cables can be found by the same procedure. A curve of cable maximum stress and margin of safety plotted against depth for one wave input amplitude is plotted in Figure 3-6. It can be seen that the maximum dynamic stress occurs when the foundation is suspended at 3,000' and that a positive Margin of Safety exists under these conditions. In a similar manner, the dynamic stresses can be computed for other sea wave input heights to verify that the allowable cable loads will not be exceeded during the lowering operation. The above assumes that all cables act in unison. Increased stresses are possible should there be phase displacements between cables. A ram tensioning device similar to that used with FAST replenishment-at-sea system hi-line can probably be adapted to equalize loading of the cables. Also precautions will be required to insure that the lowering cables do not become self-entangled. Lightweight spreaders attached at intervals could resolve this problem.

3.3.1.4 Structure Emplacement

One of the environmental conditions affecting the emplacement of the structure is the maximum predicted current of 2 knots which produces a lateral drag force. This force must be absorbed by the foundation and thence transmitted to the ocean bottom. Let it be assumed that a final station configuration will consist of 3 toroidal modules stacked one on the other as shown in the sketch.

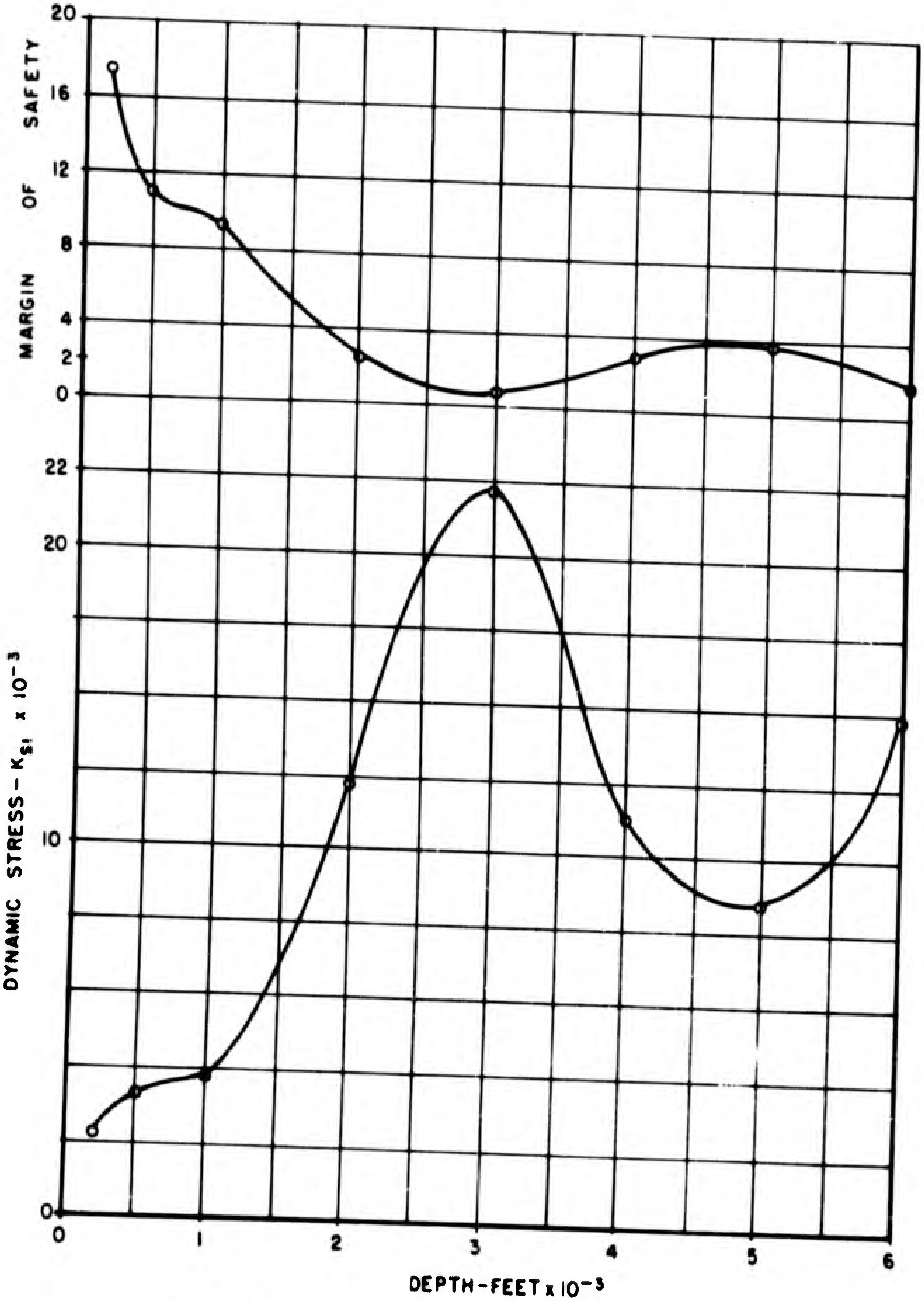


Figure 3-6 Dynamic Stress & Margin of Safety vs. Depth for Sea State 3 Example

For equilibrium:

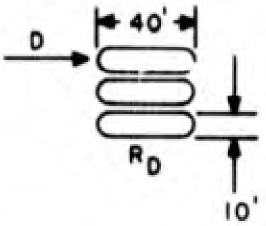
$$\Sigma H = 0$$

$$D - R_d = 0$$

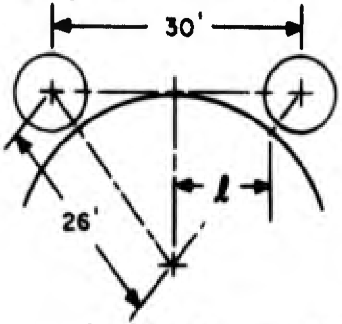
$$C_D \frac{\rho A V^2}{2} = R_d$$

$$\frac{(1.5)(2)(10)(40)(3)(200)^2}{(2)(3600)} = R_d$$

$$20{,}000\# = R_d$$



This reaction must be provided by friction between the concrete foundation and the steel structure at their faying surfaces. Three such surfaces are provided equally spaced 120° apart on the structure. The angle of contact between the hemisphere and circular cross section remains constant and is calculated from the geometry as follows:

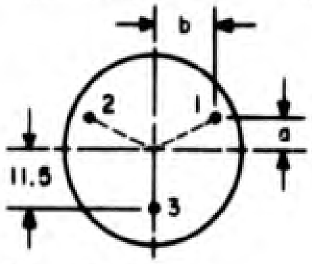


$$A = \sin^{-1} \frac{15}{26}$$

$$A = 35.2°$$

$$\ell = 20 \sin 35.2°$$

$$\ell = 11.5'$$



$$a = 11.5 \sin 30° = 5.75'$$

$$b = 11.5 \cos 30° = 9.96'$$

In order to keep the station in equilibrium, the drag load of 20,500 pounds, which is assumed to act as shown in the diagram below, is transferred to the foundation in accordance with the equilibrium equations.

$$\Sigma H = 0 = 20{,}000 + R_H$$

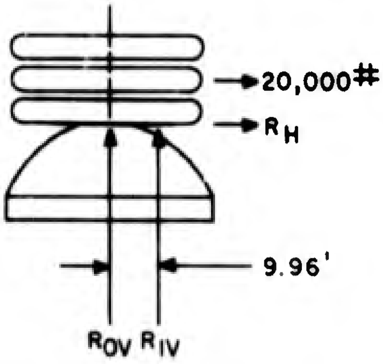
$$R_H = -20{,}000\#$$

$$\Sigma M = 0 = 20{,}000\ (18) + R_{0v}\ (9.96)$$

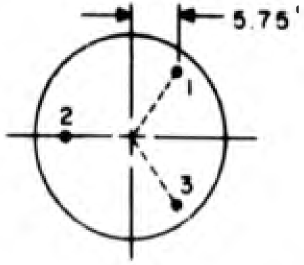
$$R_{0v} = -36{,}100\#$$

$$\Sigma M = 0 = 20{,}000\ (18) - R_{1v}\ (9.96)$$

$$R_{1v} = 36{,}100\#$$



In the case shown, one of the bearing pads supplies the reaction of 36,100 pounds, (#1), which is a maximum, two bearing pads are under no load from the moment. A minimum load on the pad occurs when two of them react the moment equally, and the summation of moments yield:

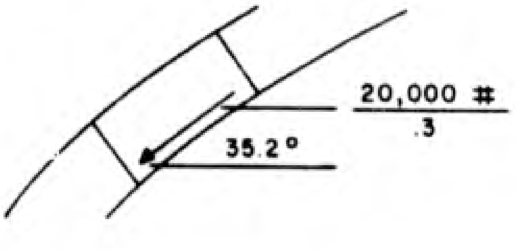


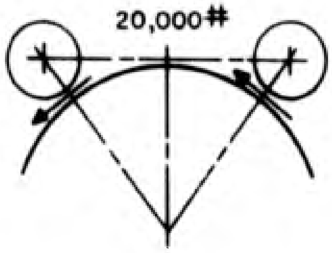
$$\Sigma M = 0 = 20{,}000\ (18) + 2\ R_V\ (5.75)$$

R_V = -31,300# and

$R_{1v} = R_{3v} = -15{,}650$

The coefficient of static friction between steel and wet, reasonably smooth concrete is taken as 0.3, which is the value for iron on sandstone from Reference 3-33. The friction force is generated between the three bearing pads and the hemispherical foundation which contact each other at an angle of 35.2° with the horizontal. Once seated on the foundation, the structure radius by the action of the cable and therefore the required static friction reaction vectors will be tangent to the foundation at the bearing pads as indicated in the sketch.

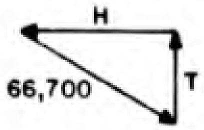




The normal force at these pads is: $N = \dfrac{20{,}00\#}{.3}$

$N = 66{,}700\#$

To generate this force, the cable tension is found from the following force triangle:



T = 66,700# sin 35.2
= 38,500#

The minimum cable tension required to stabilize a 3 module structure in a 2 knot current is:

$$T = 36{,}100 + 38{,}500 = 74{,}600\#$$

A 2.0 inch diameter, 6 x 19, steel wire core, galvanized plow steel cable has a breaking strength of 372,000 pounds which yields a factor of safety of:

$$F = \frac{372,000}{74,600} = 4.99$$

which is within the accepted limits for cable loads. A maximum positive buoyant force of 10,000 pounds will be maintained for the station structure by taking on sea water ballast as required. The 10,000 pound value is slightly greater than 2% of the total displacement of the structure, and is chosen as a value which should not be exceeded by salinity and thermal effects on buoyancy at gradient interfaces. This buoyant force is reacted by the cable giving a maximum cable tension of 88,600# required for equilibrium and a safety factor of 4.2.

This analysis leads to the conclusion that a mechanism for applying a tensile load to the central cable is required.

The original concept for structure emplacement was that the toroid would slide or pull its way down a cable anchored to the foundation and supported by a buoy at the near surface. Although this seems to be a feasible means for station emplacement, a number of disadvantages exist and among them are:

(1) The cable offers a hazard to the operation of the submersible work boat at or near the station.

(2) The station and station personnel are in danger of disaster if a non-buoyant cable should break and sink entangling the station on the bottom.

It is therefore recommended that the station structure include a winching mechanism and storage drum to hold up to 8,000' of steel cable. Since it is required that the high tensile load in the cable be exerted only at the foundation, it is proposed that a smaller diameter cable be used except at the foundation since the small diameter cable will not be as highly loaded. A maximum positive buoyancy of 10,000 pounds has been recommended for the structure and a 1.00 inch diameter 6 x 19 wire rope can be used. Its breaking strength is 91,400# which gives the cable a safety factor of 9.14 for a 10,000# tensile load.

Descent of the structure will therefore be accomplished by hauling in cable and pulling the structure down to the foundation, ascent will be by controlled release of the cable. Once the structure and foundation are engaged, the required added tension is put into the cable to provide the necessary normal force between the two bodies.

Initially one structure module will be located on the ocean floor and emplacement of additional modules will require that the first module ascend to the surface. Each succeeding module must be securely fastened to the preceeding one in order to maintain the station in equilibrium on the foundation. This attachment is more readily done at the surface where the attachment points are more accessible and inspection is easier. In addition, testing of the completed assembly near the surface is easier. Access hatches and trunks between the modules are checked for operation and leaks without endangering personnel to the degree which would exist under 6000' of water.

An advantage of this method of raising and lowering the station structure is that the bearing pressure on the bottom soil is minimized. It can be seen from the discussion of the foundation that the desired allowable bearing pressure of 0.5 psi for the reference bottom soil is exceeded in all cases by the foundation weight alone. Any additional load on the foundation which must be reacted by the bottom further complicates the emplacement problem. By applying the normal force required between structure and foundation by tension in the cable, the bottom is relieved from reacting this load. In addition, since the structure is buoyant, it obviates the need to take on ballast weight equivalent to the normal force which relieves the structure of the need to dump ballast for ascent.

The ascent-descent cable will be installed on the foundation before it is lowered and it is possible to use this cable as one of the multiple cables required in the lowering operation. It must, however, be held at the surface and attached to a buoy when the foundation is seated so that it may be retrieved when the structure is ready for lowering.

Two general types of cable material which can be considered are synthetic fiber and steel wire rope. Natural fiber such as hemp can be eliminated because of the rapid deterioration during prolonged submergence in sea water.

Of the synthetic fibers, only polypropylene is buoyant and this factor makes it most attractive for this project. Parting of this cable presents a safety hazard to the underwater station if a non-buoyant cable should fall and tangle in the structure. Such a disaster may be brought on through loosening of the cable fittings or weakening of the synthetic fibers by fish bite. If the structure descends to its foundation by pulling itself down along a taut line polypropylene cable, buoyed beneath the surface, then the cable remains suspended above the emplaced station as shown in Figure 3-7.

Both Woods Hole Oceanographic Institute and Scripps Institution of Oceanography have encountered the problem of fish attacking deep mooring lines in the Atlantic and Pacific Oceans.

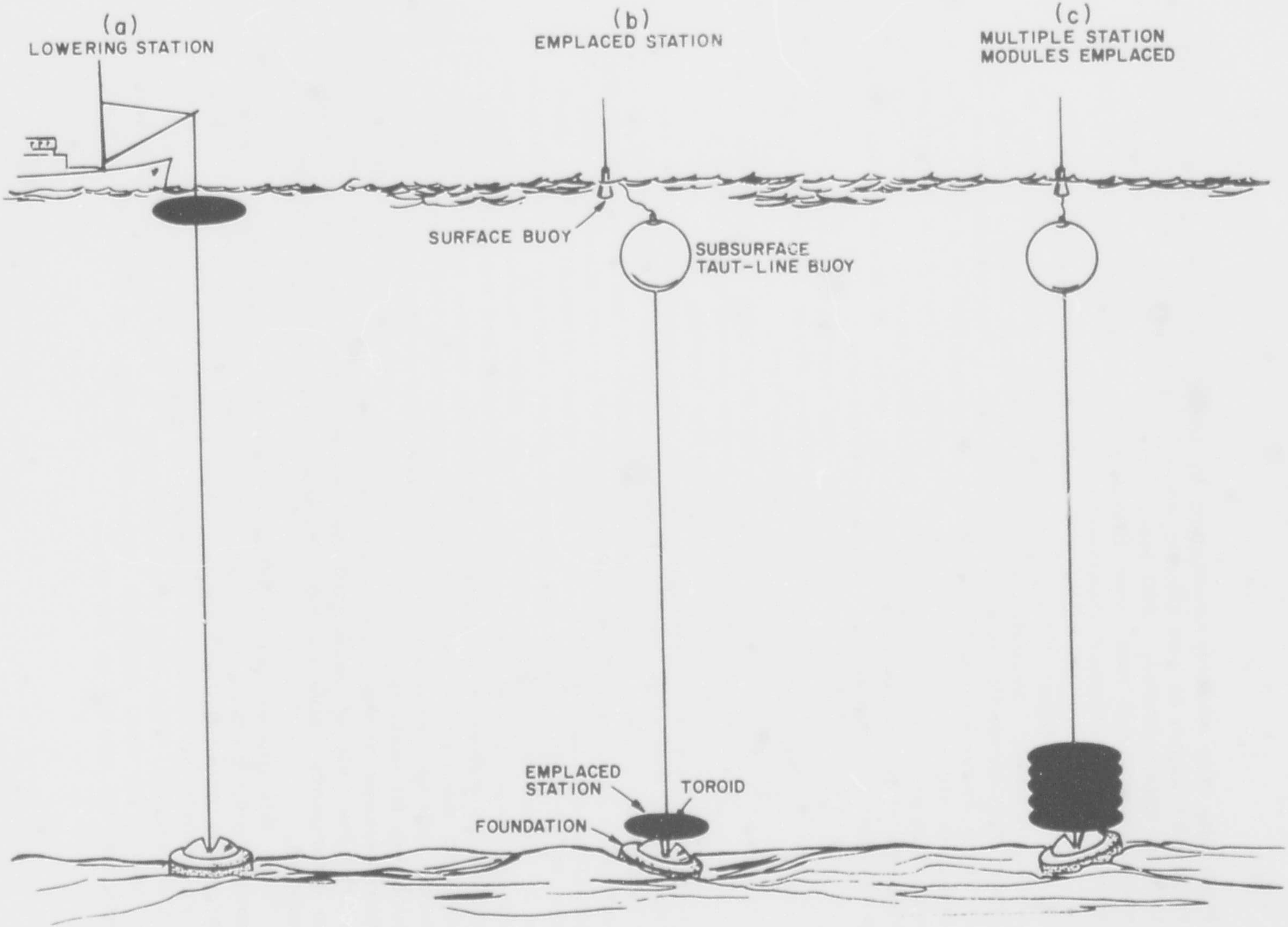


Figure 3-7 Taut Line Buoy Concept

Fish bite has severly weakened synthetic fiber lines so that Woods Hole has begun to use plastic encased steel cable from the surface to approximately 1800 feet. Below this depth, fish attack has been minimal and nylon braided line has been spliced to the steel cable for deeper moorings.

To avoid the hazard of entangling the station structure in a length of fallen cable, a buoyant polypropylene line may be used, however, because of its vulnerability to attack, a cable of other than synthetic material is required. The satisfaction of both of these requirements leads to the consideration of a steel cable which is stored on a drum on the habitat. Thus, the structure would descend by hauling in the cable and ascend by controlled release of the cable from the storage drum. Such a method has a number of advantages, some of which are:

(1) A steel flexible cable has significantly higher allowable loads and much lower creep rate than a comparable diameter synthetic line.

(2) Storing the cable on the structure lessens the danger of entanglement to the submersible work boat as it navigates around the habitat.

A one-inch diameter 6 x 19 plow steel wire rope rerequires a minimum tread of sheave or drum of 26 inches (Reference 3-32). Since the final nesting of the structure on the foundation is accomplished by a length of 2-inch diameter cable to withstand the tensile load, the winch drum miminum tread diameter is 52 inches while the storage drum minimum tread diameter is 26 inches for 1-inch cable. As an added factor of safety, the storage drum will be 30 inches in diameter and the winch drum will be 60 inches in diameter. A locking device will be incorporated into the mechanism to hold the cable under tension. This device will be designed to have a low power consumption and an unlocking fail-safe feature if the primary power is interrupted. Upon release of the lock, a friction clutch built into the winch will control the rate of cable release and therefore the rate of ascent. An emergency cable cutting or cable release device will be installed.

Six thousand feet of the 1-inch 6 x 19 cable will weigh about 10,000 pounds when dry (Reference 3-32). Weight submerged is about 8,700 pounds. Ten layers of cable on a storage drum initially 30 inches in diameter by 5 feet long will be 6300 feet in length. The final drum diameter in this case is 50 inches; by making the final diameter about 55 inches, up to 8,000 feet of cable can be stored on the drum.

3.3.1.5 Retrieval of Structure

Recovery of the station structure entered the discussion of structure emplacement in Section 3.3.1.3. Since the structure is buoyant, it will rise to the surface once released from the foundation and ascent will be controlled by release of the cable from the storage drum on the structure. The locking and holding mechanism for the winch, which will maintain the required tension in the cable for equilibrium at the bottom, will be a fail-safe design. In the event of power loss, the lock will be released and the station will ascend paying out the cable. Such an ascent will be reasonably controlled by friction designed into the cable storage system. In the event of emergency, the personnel may leave by way of the submersible work boat leaving the station to ascend when power has run down. A timing mechanism can be included in the holding circuit as an alternate so that the holding power will be interrupted if the timer is activated. Since the structure has taken on ballast to limit its buoyancy to 10,000#, a means for releasing this ballast is provided if it becomes necessary and therefore the structure should always be capable of rising to the surface of its own accord.

As the structure ascends, either controlled or in emergency, a pinger is activated to alert any of the support ships standing by and to provide a means for these ships to determine their range to the ascending structure thereby allowing all ships to stand clear of the broaching point.

3.3.2 Surface Support

Site selection is a key element in the emplacement of the station. This is the beginning of surface support and will be accomplished by a series of surveys that will enable the program manager to pinpoint a location for the mission site. These surveys will range from land based review of nautical charts to surface or submarine oceanographic studies, to a close up look at the bottom. Ability to choose a precise location indicates that accurate, all weather ultrasonic navigation aids must be emplaced in the area surrounding the site. These aids will enable both surface ship and submersibles to visit and revisit specific locations during the site selection investigations. The surface support ship during emplacement must also be accurately positioned.

Previous discussions have suggested modification of a Navy LSD for surface handling of the station components. Knowledge of the precise position of the ship and ability to maintain that position are required. This includes a navigational system compatible with the survey navigational aids and a propulsion system able to maintain the ship accurately on station. If all operations are conducted in calm weather, the ship's boats might be sufficient for the position maintenance, but a system of bow and stern thrusters is more dependable. Other details include such items as sufficient personnel accommodations aboard for the extra personnel involved in the station program to assurance that storage room for the handling tackle is properly arranged. Some modifications in capstan and sheave arrangements will probably be necessary. A study of surface ship requirements should evolve in the detail station design phase of this program.

Because of the large dry weight of the station components, avoidance of over-the-side handling is desired. It is envisioned that the foundation and structure will both be docked in the well of the LSD. The initial unloading step will be to flood down and float the foundation clear of the well using auxiliary buoyancy devices as necessary. While this is being done, the structure will be made negatively buoyant and clamped into its cradle. A step-by-step plan for handling each component of the MUS should be developed during the detail design phase.

A few, possibly up to four, small tugs may be required. These will be used to pay out cables as needed, and to control the buoyant foundation assembly when it is afloat. Other uses may evolve, including the hauling of cables to lower a buoyant foundation to the desired spot. This method of deployment envisions 3 or 4 bottom anchors with sheaves so that the foundation can be positioned where desired by controlling pull-down cables; however, the recommended method is to lower a lightly negatively buoyant foundation to the bottom.

A number of services will also be required in the operation. A small submersible and its support ship will be needed in the initial deployment to check on progress of the operation. Small boats will be needed to support the shallow water divers during their work and check out with the station components near the surface. One ship in the task group must be capable of handling a helicopter for supply support and other liaison work. In addition to publishing notification in the Notice to Mariners, some shipping and pleasure boat control vessels will be necessary to keep sightseers and merchantmen clear of the operation.

After emplacement, surface support during the mission will be limited to communications and an emergency rescue capability. It is envisioned that one ocean going tug or salvage vessel would provide sufficient accommodations for the personnel and equipment required. This vessel would remain in the immediate vicinity of "surface zero" and maintain communications with the station. A small submersible with mating capability would serve for logistics support in the event of unforeseen requirements and for crew exchange or emergency evacuation and replacement.

During the retrieval phase of the operations, a smaller support group will suffice since the MUS structure can surface itself. In this operation, only the "mother" ship and the small submersible support will be required, unless shipping control is again desired.

Techniques developed during the first year of operations may allow reduction in the task group for emplacement. Further, the Westinghouse Toroidal Support Submarine concept can be developed for covert placement of the Manned Underwater Station. Development of a submersible deployment concept can probably reduce the ship involvement to one submarine and a small submersible based on the submarine.

3.3.3 Station Functions

Maintenance of the station on the ocean bottom is a prime task and a certain portion of the crew effort must be devoted to this function. However, there is a second group of station functions which will be of greater importance when the station operation becomes routine. These functions are the various missions which will be performed, either singly or in a multimission deployment. This section briefly considers these mission derived functions. Table 3-5 lists many of the missions with some of the specific requirements for each.

TABLE 3-5
Specific Requirements for Various Missions

- Vane Shear Testing
  - Exterior Power
  - Manipulator
  - Observation
- Plate Bearing Testing
  - Exterior Power
  - Manipulator
  - Observation
- Bottom Cores
  - Exterior Power
  - Manipulator
  - Pressure Pass Through
  - Observation
  - Internal Chemical and Mechanical Analysis
- Material Testing
  - Pressure Pass Through
  - Manipulator
  - Observation
- Construction Techniques
  - Exterior Power
  - Manipulator
  - Control
  - Direct Observation
  - Remote Observation
- Anti-Submarine Warfare Testing
  - Exterior Power
  - Control
  - Pressure Pass Through
  - Direct Observation
  - Remote Observation
- Command and Control
  - Exterior Power
  - Control
  - Secure Acoustic Communications
  - Hard Wire Communications
  - Underwater Sensors
- Underwater Distant Early Warning
  - Underwater Sensors
  - Secure Communications

Table 3-5 (Continued)

- Weapon Deployment
    - Pressure Pass Through
    - Control
    - Secure Communications
- Submersible Support
    - Mating
    - Power
    - Consumables Storage
    - Relief Crew Berthing
- Water Sampling
    - Pressure Pass Through or Sampling Penetration
    - Analysis Laboratory
    - Storage Facility
- Hydrospace Weather Measurements
    - Temperature and Salinity Sensors
    - Pressure and Current Sensors (3 Dimensions)
    - Visibility and Turbidity Sensors
    - Recording
    - Data Reduction
- Sound Propagation
    - External Hydrophones
    - Drivers and Receivers
    - Recording
- Mining or Exploration
    - See Construction Techniques and Submersible Support

3.3.4 Operational Capabilities

A description of the operational procedure for performance of several potential missions is an indication of the capabilities of the MUS. This section provides brief descriptions of 4 missions and is not intended to be a comprehensive treatise on all the varied possibilities of the MUS concept.

3.3.4.1 In-Situ Vane Shear Test on Bottom Sediment

The vane shear test requires the following operations:

(1) Vane Emplacement (and Penetration)
(2) Vane Torquing and Torque Measurement
(3) Vane Rotation Measurement

The vane shear tester is a minor development item including the vane, torque motor, and synchro transmitter as a unit on the manipulator arm. The tester will be sent through the pressure pass through and affixed to the manipulator. The manipulator will be extended and lowered to the bottom region to be tested. The manipulator will then press the vanes to the desired bottom sediment penetration. Voltage will be applied to the torque motor while monitoring current (to determine torque) and rotational displacement. The voltage will be increased slowly until rotational displacement is observed on the synchro receiver. Voltage can then be increased further and rotational displacement recorded along with applied voltage and current.

Initial torque can be computed from locked rotor torque curves taken on the torque motor. After the vanes have broken free and are rotating steadily, torque can be derived from the torque-speed curves.

3.3.4.2 In-Situ Plate Bearing Test on Bottom Sediment

The plate bearing test requires the following operations:

(1) Plate Emplacement
(2) Weight Application
(3) Displacement Measurement

The plate bearing tester will require two separate units which will be joined outside the pressure hull. Several plates of different sizes if desired will be stowed where they are accessible to the manipulator. These plates will have a levelling rod attached to their center to allow observation of vertical displacement. The combination of plate and levelling rod will have a slight negative buoyancy. The weight application will be performed by releasing a series of floats attached to weights placed on the plate. The manipulator will put the weight and float units (again slight negative buoyancy) on the plate and take the entire assembly and place it on the bottom sediment. Sediment stirring from this movement may cause clouding of the water thus obscuring visibility. The plate, weight and float assembly will be left in place until the turbidity has subsided and normal visibility returned. The levelling rod will be observed from the MUS through one or two viewports using a theodolite. A float will then be released allowing the weight to bear on the bottom, and the vertical deflection observed by sighting the levelling rod. Additional floats will be released increasing loading to determine ultimate bearing strength, through checking vertical displacement of the assembly.

Visibility through the water will restrict the distance from the station at which the test can be performed. Normal visibility using floodlights may be from ten to fifty feet. This may be extended significantly using a back lighted levelling rod. The back lighted levelling rod can be constructed from a sealed pyrex cylinder and a single fluourescent tube. The tube will be roughly centered in the cylinder and the inside surface of the cylinder silvered to provide a good reflective surface. The silvering would be cut at accurate intervals (i.e., one inch) and identified with suitable markings to provide a graduated scale. The internal scale lighting should provide a 2:1 range improvement over normal visibility in water.

The range from the MUS at which the plate bearing readings can be taken is quite significant since (1) the MUS foundation may disturb the bottom sediment for a distance of 20 feet or more from the edge of the foundation, and (2) a single plate bearing test using a plate area of 0.5 square feet may disturb the sediment over a region five feet or more from the test point. Thus, to get significant readings, testing should start 20 feet from the edge of the foundation, and successive test points should be 10 feet apart. Both emplacement and visibility at distances to 50 feet is desirable to obtain tests at several points. It is expected that the internally illuminated levelling rod will be visible at 50 feet. Emplacement of the tester may utilize the small manned submersible but can be performed with an extended reach manipulator. A 50 foot tracked arm with the manipulator adjustable along the arm should be considered as an optional accessory for extended reach.

3.3.4.3 Acoustic Properties Testing

The acoustic properties of both the water and the bottom sediment are of interest. Measurement of the water attenuation requires the following operations:

(1) Reference reading attenuation vs. frequency
(2) Increased distance attenuation vs. frequency

Measurement of the bottom reflectivity requires the following operations:

(1) Reference readings signal strength vs. frequency
(2) Reflectivity signal strength vs. time at frequencies of interest

The water attenuation measurement can be performed simply using two transducers (hydrophones), one as the transmitter, the other as the receiver. The signal level received can be recorded with the transmitter energized at various frequencies. The distance between the transducers will then be increased to increase the water attenuation, and the measurement repeated. To obtain significant results, the distance should be sufficient that the attenuation (as opposed to spreading loss) increase is over 10 db, since measurement accuracy better than 0.1 db is difficult to achieve and 1% accuracy of attenuation measurement is desired. This will require the use of the submersible, since at 50 kc a distance of 1000 yards, and at 5 kc a distance of 10,000 yards provides roughly 10 db attenuation. A hardwire link between the submersible and the MUS will be desired to allow precise calibration of instability in the transmitter and receiver unless adequate accuracy can be obtained using stable monitors on transmitter output and receiver gain. Range measurements can be performed using pulsed transmission and measuring delay time.

Bottom reflectivity can be measured from the manipulator, or the extended manipulator arm. Again, a calibration run is desirable, here using a rigid steel or concrete surface of known reflectivity as the reference. Reflectivity can then be measured over the bottom prior to soil mechanics testing. One desired result would be sufficient data to establish a correlation between the bottom reflectivity and the later soil mechanics testing.

3.3.4.4 Submersible Support

Supporting a small manned submersible will require the following operations:

(1) Mating
(2) Battery Charging
(3) Consumables Loading
(4) Waste Unloading
(5) Maintenance
(6) Personnel Hotel Facilities

A small manned submersible (SMS) will be launched from the surface and descend to the MUS, homing on a sonic beacon on the station. The SMS will maneuver into position on the mating hatch, attach to the station and check for proper mating, including opening the hatches. After the SMS personnel have affirmed readiness for operations, hatches will be shut, and the submersible will proceed with the next phase of its mission.

Upon approaching end of endurance, the SMS will return and mate with the station. The SMS operators will enter the station, and connections will be made for battery charging. After operator refreshment and debriefing, the used containers and waste from the SMS will be unloaded. Fresh supplies of consumables will be loaded aboard the SMS. If a fuel cell using ambient pressure fuel storage is used on the SMS, external connection will be made with external storage tanks for pumped refueling. A maintenance check will be performed to assure proper operation of all SMS equipment. The SMS will be ready for the next mission by the time the operators have had a rest period. The MUS personnel may include a crew trained as SMS operators to allow faster turnaround time. In a small station, this would require that the SMS operators were also capable of relieving the MUS crew.

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CONCEPTUAL DESIGN

4.0 INTRODUCTION

Previous sections have explained the environment in which the station must operate and commented on the operational phases that are expected. Also, broad evaluation criteria have been developed that are constraints in the concept evolution. The major subsystems have been examined and recommendations made for the method to be used in the station development. This section is devoted to the design concept for the prototype Manned Underwater Station.

4.1 DESIGN CRITERIA AND ANALYSIS

The design agency should have a definite requirement with specific objectives in order to prepare a preliminary design. Since the MUS concept is applicable to so many potential operations, it is considered necessary at this point to choose a reference base against which the conceptual design is to be developed. This base should not be construed as limiting the concept or its application. It is only chosen to enable a realistic approach to the design development within the scope of this contract.

REFERENCE DESIGN BASE

Prototype Station for Initial Test and Evaluation
Suitable for bottom operation to 6000' - may be equipped for off the bottom positioning at later date
Foundation to be selected after investigation of bottom conditions at site(s)
Power and Life Support Subsystems to be developed for possible 90 day mission
Initial operation is overt
The 200 square foot undesignated internal area and 10 kw additional power will be provided
Special arrangement considerations for scientific and commercial application are not currently included
Station will be built in early 1970's

In addition to the criteria in the reference base, there are several other factors which are considered. These factors are of a nature that they would be included in the development of any station incorporating good engineering practice and are not peculiar to the prototype design within the above reference base.

A principal consideration in the systems approach is the intercompatability of the various subsystems. Each of the subsystems must not only do the job for which it is intended; it must also work with the other subsystems rather than against them. The overall design must consider the safety of the personnel as well as the station and its chemical and electrical subsystems and components. Since the crew is so small, the ease of operation of the various subsystems is of vital importance as is their reliability and maintainability. In preparing the designs, the designer must continually consider the state of the art and its probable extension into the reference time base.

One further consideration is the life cycle cost of the chosen approach. It is obvious that some systems can be specified with a lower initial cost but that logistics and maintenance will require a large total dollar outlay over the useful life of the station.

The above factors are important considerations in the following design sections describing the major and minor subsystems.

4.1.1 Foundation

Section 3.2.1 contains the discussion of a number of alternate foundation designs and results in the recommendation that the final design of the foundation be made subsequent to a bottom survey of the site selected for the station. Use of the reinforced concrete design for the foundation would give the lowest cost, but in order to reduce the bearing load and moments on the ocean floor some additional avenues must be explored. Earlier computations for the bearing pressure exerted on the bottom by the foundation were based only on the submerged weight of the foundation itself and did not take into account the additional load of the three module stations. Preliminary calculations using the foundation design concept shown in Figures 3-1 and 3-2 result in an excessively high bearing pressure. Removal of the lower eight feet of the hemisphere as shown would place the hull within two feet of the bottom at a 15° tilt, assuming no foundation settlement. On a hard, level bottom the height (h) of the centerplane of the lowest toroid becomes 12.6 feet. The estimated weight reduction in the foundation is 77,000 pounds when dry or 44,000 pounds when submerged. This reduces the bearing pressure to about 170 psf, which is still considerably in excess of the desired value of 72 psf.

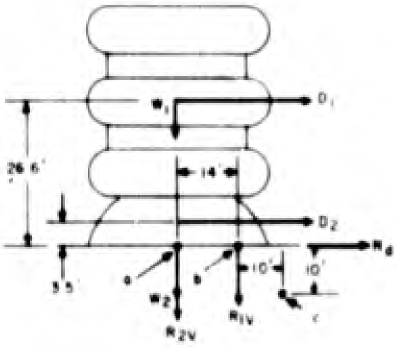
A further reduction in bearing pressure may be obtained by extending the outer radius of the foundation by means of a flat steel skirt backed up by radial 'T" bars. One twelve foot long 3" x 3" 'T' weights 80.4 pounds; fifty of these evenly spaced around the foot of the foundation would support an annular plate of steel to enlarge the foundation bearing area. Using a maximum diameter of 54' and a minimun diameter of 32' would result in a total bearing area of 1486 square feet, of which 1034 square feet would be steel plate. The weight of the added steel, assuming use of ten pound plate with an allowance for welding and bolting of the skirt to the foundation is 18,000 pounds. Total weight of the submerged foundation now becomes about 100,000 pounds. This results in a bearing pressure of 67.5 psf which is within the value desired. One disadvantage is that because of the larger diameter, the skirt would have to be attached after removing the foundation from the well if an LSD type ship were used.

In preparation for calculation of the loads, current drag forces on the structure and foundation are determined assuming a coefficient of drag (C_d) of 1.5.

	Foundation	One Toroid	Two Toroids	Three Toroids
1KT	975#	1,675#	3,350#	5,000#
2KT	3,900#	6,700#	13,400#	20,000#

An investigation of the equilibrium conditions for the three module stations with a 2KT current follows:

A free body diagram of the station is as shown:



D_1 = 20,000#

D_2 = 3,900#

W_1 =-10,000#

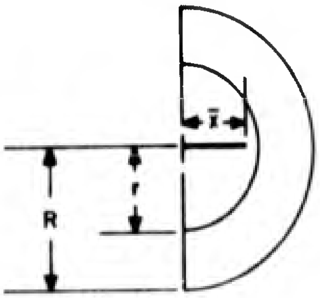
W_2 =100,000#

The submerged weight (W_2) assumes that the flotation spheres in the foundation are flooded. W_1 is adjustable, however a value as shown appears reasonable to permit rapid start of ascent in case of emergency. The drag forces D_1 and D_2 are taken from the listing above. A sample calculation was shown in Section 3.3.1.4. D_2 is assumed to act at the center of the exposed foundation which is 5' above the base. The bearing load R_{1V} under the footing due to the overturning moment is assumed concentrated at the centroid ($\bar{x}$) of the hollow semicircle. This value is determined from the formula:

$$\bar{X} = \frac{4(R^3 - r^3)}{3\pi(R^2 - r^2)} \qquad R = 27' \quad r = 16'$$

$$\bar{x} = \frac{4\ (19683 - 4096)}{3\eta(729 - 256)}$$

$$\bar{x} = 14'$$



In equilibrium:

$$\Sigma M_a = 0 = D_1\ (12.6 + 14) + D_2(3.5) + R_{1v}\ (14)$$

$$R_{1v} = -\frac{2 \times 10^4\ (26.6) - .39 \times 10^4 (3.5)}{14}$$

$$R_{1v} = -\frac{(53.2 + 1.37)}{14} \times 10^4 = -3.90 \times 10^4$$

$$\Sigma Mb = 0 = D_1(26.6) + D_2(3.5) - W_1(14) - W_2(14) - R_{2v}(14)$$

$$R_{2v} = \frac{(53.2 + 1.37) \times 10^4 + 14 \times 10^4 - 140 \times 10^4}{14}$$

$$R_{2v} = \frac{71.4 \times 10^4}{14} = -5.1 \times 10^4$$

$$\Sigma H = 0 = D_1 + D_2 + R_d$$

$$0 = 20{,}000 + 3900 + R_d = -23{,}900\#$$

$$\Sigma V = 0 = W_1 + W_2 + R_{1v} + R_{2v}$$

$$0 = -10{,}000 + 100{,}000 - 39{,}000 - 51{,}000$$

From the above, it is seen that three loads must be supported by the bottom material. (1) R_d - the horizontal reaction is countered by the frictional shearing force of the soil over the contact area of the foundation. (If this soil property is inadequate, a series of skegs extending vertically below the foundation in a radial pattern could provide sufficient flat plate area to prevent lateral movement of the station along the ocean floor.) (2) The R_{2v} load acts vertically through the centroid of the foundation. The bearing stress (P_{2b}) for this component is R_{2v} divided by the total footing area. $P_{2b} = 51{,}000/1486 = 34.3$ psf. (3) The R_{1v} load acts vertically through the centroid of the down stream half of the foundation bearing area. The actual loading distribution on the bottom is a function of the contact area distribution about this centroid. Assuming a triangular distribution over the down stream half of the foundation results in a higher than actual maximum loading and thereby provides a conservative approach to the bearing stress. The maximum ordinate of the triangle is twice the average load imposed by one half of the foundation due to the overturning moment. It thus becomes: $P_{1b} = 39,000 \times 2/743 = 105$ psf. Adding P_{1v} and P_{2v} we obtain about 140 psf for the maximum bearing stress when 3 modules are emplaced in a 2 knot current. A similar calculation for a single module produces a requirement for 65 psf bearing strength material. It is reasonable to assume that the ocean bottom will have a higher than minimum (72 psf) bearing strength when the current is on the order of 2 knots.

In a stiff foundation, the downward reaction of P_{1b} would be offset by an upward lift at the extreme opposite edge of the foundation. At first glance, this might appear to produce a condition which could cause the station to upset. However, taking moments of the entire station as a free body about an isolated point not in the action line of any on the forces demonstrates that the sum of the moments is zero and that the station will not overturn. For example, point C is chosen 10 feet downstream of the point B and 10 feet below the bottom plane. (See previous sketch.)

$$\begin{aligned}\Sigma Mc &= D_1(10+26.6) + D_2(10+3.5 - W_2(10+14) - W_2(10+14)\\ &\quad - R_{2v}(10+14) - R_{1v}(10) + R_D(10)\\ &= 20,000(36.6) + 3900(13.5) - (-)10,000(24)\\ &\quad -100,000(24) - (-)51,000(24) - (-)39,000(10)\\ &\quad + (-)23.900(10)\end{aligned}$$

$$\begin{array}{rcr} + & \qquad & - \\ 73.2 \times 10^4 & & 240.0 \times 10^4 \\ 5.3 \times 10^4 & & \underline{23.9 \times 10^4} \\ 24.0 \times 10^4 & & -263.9 \times 10^4 \\ 122.4 \times 10^4 & & \\ \underline{39.0 \times 10^4} & & \therefore \Sigma M_c = 0 \\ +263.9 \times 10^4 & & \end{array}$$

Since the free body moments on the station are in equilibrium, the station is stable.

There are many potential variations of the method of distributing the load of the station on the bottom. The above should demonstrate the feasibility of this concept. As previously discussed, the final design of the foundation will be made when bottom conditions at the selected sites are defined more precisely.

Section 3.3.1.4 contains a preliminary investigation of the stresses in the lowering cable system. A more precise analysis in conformance with the procedure of Reference 3-30 would require more definition of the foundation design and would be required before the design of the lowering system could be completed. In addition, the determination of the virtual mass coefficient and the drag coefficient of the hemisphere is required for the cable design. Although the specifications require that the system be designed for a sea state 3, it is expected that the weather conditions would be carefully researched so that a relatively calm sea can be selected for the initial installation.

4.1.2 Structure

4.1.2.1 Introduction

The object of this section is to determine the optimized dimensions of a toroidal shaped hull which is reinforced with intermittent frames on the inside of the hull. Since there is no available solution for the stability of toroidal shapes reinforced with intermittent frames, the design of the toroidal hull is based on the requirements of a ring-reinforced cylinder with parameters to suit the design conditions. A general study of cylinders reinforced with rectangular frames is first made to establish some general boundaries; then a more specific study with tee-shaped frames is made. Dimensions are established as a function of critical pressures and vice versa, considering the three modes in which a reinforced cylinder might fail; axisymmetric collapse, asymmetric collapse and general instability collapse.

Preliminary data indicate that the significant modes of failure are axisymmetric and general instability collapse and these are therefore used as the parameters for the hull design.

The results of the study indicate that a 10 foot diameter cylindrical hull made of 140,000 psi yield strength steel will have a shell thickness of 1.75 inches and an excess buoyancy of 2400 pounds per lineal foot of hull.

In considering concepts for the hull design of the Manned Underwater Station, the requirement of optimum utilization of interior space as well as an efficient pressure resisting configuration is a prime factor. The toroidal shape is selected as possessing the most compatible combination of characteristics since it has the advantage of the cylindrical configuration and a critical pressure greater than a cylinder of the same diameter and thickness (Reference 4-1). The problem of this study is, therefore, one of designing a continuous cylinder, within the parameters needed for efficient design, which will resist the hydrostatic pressure (2670 psi) encountered at operating depth of six thousand feet.

Extensive work has been done on the structural analysis of frame reinforced cylinders and cylindrical pressure hulls and reports of this work as listed in References 4-1 through 4-6 are drawn on for methods of analysis of various modes of failure. In order to obtain an optimum design, the design calculations for the pertinent modes are programmed in Fortran II and computed for a wide range of possible design dimensions. From these results, an optimum design having the most favorable combination of weight, frame spacing, frame dimensions and shell thickness can be selected.

The following section consists of an explanation of the computer programs used and the method of optimizing the design dimensions to suit the criteria. Emphasis will be placed on the formulas used, the reason for using them, their source and results.

4.1.2.2 Discussion of Programs

Under the action of external hydrostatic pressure, failure of a ring stiffened cylinder may be precipitated by any or a combination of three basic modes. The three distinct possible modes with which we will be concerned are:

(1) Axisymmetric collapse of the shell between adjacent ring frames.

This is a combination of yielding and axisymmetric buckling, or rather inelastic axisymmetric shell instability between frames. This mode is characterized by an accordion-type pleat which may or may not occur in more than one bay of the cylinder. From the theory of Salerno and Pulos (pp 18-36, Reference 4-1) the maximum stresses occur in the circumferential direction on the outside surface of the shell plating midway between adjacent ring frames, and in the longitudinal direction on the inside surface of the shell plating at a frame. The Salerno and Pulos equation for yielding on the outer surface of the shell plating, which is the critical collapse pressure, is:

$$P_{CR} = \frac{\sigma_y h/R}{\left\{\frac{3}{4} + a^2\left[F_2^2 + F_2 F_4(1-2\nu)\sqrt{\frac{.91}{1-\nu^2}} + F_4^2(1-\nu+\nu^2)\times\left(\frac{.91}{1-\nu^2}\right)\right] - \frac{3}{2}a\left[F_2 - \nu F_4\sqrt{\frac{.91}{1-\nu^2}}\right]\right\}^{\frac{1}{2}}}$$

where:

$$a = \frac{(1-\nu/2)\alpha}{\alpha+\beta+(1-\beta)F}$$

α = frame area/area of one bay of shell

β = ratio of ring-frame faying to frame spacing

$$F_1 = \left(\frac{4}{\theta}\right)\left[\mathrm{COSH}^2\,\eta_1\theta - \mathrm{COS}^2\,\eta_2\theta\right]\Big/ D_1$$

$$F_2 = \left[\frac{\mathrm{COSH}\,\eta_1\theta\;\mathrm{SIN}\,\eta_2\theta}{\eta_2} + \frac{\mathrm{SINH}\,\eta_1\theta\;\mathrm{COS}\,\eta_2\theta}{\eta_2}\right]\Big/ D_1$$

$$F_3 = \sqrt{\frac{3}{.91}}\left[-\frac{\mathrm{COSH}\,\eta_1\theta\;\mathrm{SINH}\,\eta_1\theta}{\eta_1} + \frac{\mathrm{COS}\,\eta_2\theta\;\mathrm{SIN}\,\eta_2\theta}{\eta_2}\right]\Big/ D_1$$

$$F_4 = \sqrt{\frac{3}{.91}}\left[\frac{\mathrm{COSH}\,\eta_1\theta\;\mathrm{SIN}\,\eta_2\theta}{\eta_2} - \frac{\mathrm{SINH}\,\eta_1\theta\;\mathrm{COS}\,\eta_2\theta}{\eta_1}\right]\Big/ D_1$$

$$D_1 = \left[\frac{\cosh \eta_1\theta \ \sinh \eta_1\theta}{\eta_1} + \frac{\cos \eta_2\theta \ \sin \eta_2\theta}{\eta_2} \right]$$

$$\eta_1 = \frac{1}{2}\sqrt{1-\gamma} \qquad \eta_2 = \frac{1}{2}\sqrt{1+\gamma}$$

$$\gamma = \frac{P}{2E}\sqrt{3(1-\nu^2)}\left(\frac{R}{h}\right)^2$$

$$\theta = \sqrt[4]{3(1-\nu^2)} \quad \frac{L}{Rh}$$

P = hydrostatic pressure

L = frame spacing

A derivation and explanation of the above equations can be found in Reference 4-1, pages 18 to 34.

(2) Asymmetric collapse of the shell between adjacent ring frames.

This is usually referred to as shell or lobar buckling, and since the shell is designed to be stressed beyond the elastic limit at design collapse, it is in reality, inelastic asymmetric shell instability between frames. This mode is characterized by inward-outward lobes which may or may not develop around the entire periphery, and which may or may not occur in more than one bay of the cylinder. The basic difference between modes 1 and 2 is in their collapse patterns and which is the more critical of the two is governed by the ratios of their physical dimensions. An analytic solution for the collapse pressure in the asymmetric mode was developed by Windenburg and Trilling (Reference 4-2) and is:

$$P_{CR} = \frac{2.42E}{(1-\nu^2)^{\frac{3}{4}}}\left[\frac{(h/2R)^{\frac{5}{2}}}{L_e/2R - 0.45\,(h/2R)^{\frac{1}{2}}}\right]$$

(3) Overall asymmetric collapse of the shell and frames together, or general instability collapse, which may extend over the entire length of the ring-stiffened cylinder.

In addition to the parameters mentioned above, the occurence of this mode is strongly influenced by the moment of inertia of the ring frames and the ratio of the overall length to the radius of the cylinder. Imperfect circularity of the ring frames plays an important role here since it can precipitate a premature overall instability of long cylindrical hulls. It is this mode of collapse that is of prime concern in designing an adequate hull.

Tokugawa (Reference 4-3) was the first to develop a theory to predict general-instability behavior. His approach was essentially based on a method which has come to be known as the "method of split rigidities." Much later, Bryant (Reference 4-4) arrived at the same result but from a different point of view.

For our purposes, it suffices to give the final Tokugawa-Bryant formula which has the form: (See Reference 4-6)

$$P_{CR} = \frac{Eh}{R}\left[\frac{\lambda^4}{(\eta^2 - 1 + \lambda^2/2)(\eta^2 + \lambda^2)^2}\right] + (\eta^2 - 1)\,\frac{EI_e}{R^3 L_f}$$

where: λ = thinness ratio (see Program B following)
η = harmonic mode at which failure takes place
I_e = moment of inertia of frame plus an equivalent length of cylinder shell
L_f = frame spacing

It should be pointed out that Tokugawa's original equation was somewhat more complicated, however, calculations for a wide range of interest indicate that the additional terms included by Tokugawa were insignificant.

(4) Finally, a semi-empirical connection, based on results of column buckling analysis, was made to the simple hoop-stress collapse pressure ($P = h\sigma y/R$) for structures in the plastic buckling range and the resulting critical collapse pressure calculated. This equation, which is used to determine the plastic-instability collapse, is referred to as Modified Equation (92 a). Reference 4-5 and 4-6. The equation is:

$$P_{CR} = \frac{2h/D\sigma y}{\left[1 + H\,\dfrac{\left(1 - \dfrac{\nu}{2} - B\right)}{(1+\beta)}\right]\left[1 + 0.148\,(\lambda^2 - \xi^2)\right]}$$

where:

$$H = \frac{-2\left[1 + \left(\dfrac{3\nu^2}{1-\nu^2}\right)^{\frac{1}{2}}\right] \text{SINH}\,\dfrac{\theta}{2}\ \text{COS}\,\dfrac{\theta}{2}}{\text{SINH}\,\theta + \text{SIN}\,\theta} + \frac{\left[1 - \left(\dfrac{3\nu^2}{1-\nu^2}\right)\right] \text{COSH}\,\dfrac{\theta}{2}\ \text{SIN}\,\dfrac{\theta}{2}}{\text{SINH}\,\theta + \text{SIN}\,\theta}$$

$$\xi = \frac{.9R\sigma_y}{Eh}\left(\frac{1-\nu^2}{.91}\right)^{\frac{3}{4}}$$

$$\beta = 2NLB/b\theta$$

$$\theta = \frac{[12(1-\nu^2)]^{\frac{1}{4}}\ L/D}{(h/D)^{\frac{1}{2}}}$$

$$N = \frac{\cosh\theta - \cos\theta}{\sinh\theta + \sin\theta}$$

$B = bh/A_f + bh$

A_f = frame area

b = flance width

By comparing the pressures obtained from each formula, it can be determined which are more critical and which dimensions give satisfactory pressures.

The parameters for this design are that the hull withstand the pressures encountered at an operating depth of 6000 feet and a collapse depth of 9000 feet. The maximum pressure on the hull will therefore be set at 4000 psi. The general instability pressure (Mode 3) is set at 6000 psi, a minimum of 1.5 times the axisymmetric collapse pressure (Modified Equation 92a) as a safety factor. Two types of steel are studied, 180,000 and 140,000 psi yield stress. A preliminary computer run with 80,000 psi yield material indicated a shell thickness greater than 3 inches would be required. No further studies were made with this material.

4.1.2.3 Computer Program Description

The following programs are executed in the design study:

a. Program A

Program A is designed for computing critical collapse pressures for the three modes of failure of a cylinder reinforced with rectangular shaped frames. A general outline of the program is as follows:

(1) Pertinent data is read into the program including shell diameter (D), shell thickness (h), a

thinness ratio (λ), bulkhead spacing (BS), frame thickness (t), yield stress of material (σy), modulus of elasticity (E), Poisson's ratio (ν), and the material density (ρ).

(2) Using the given data, the Windenburg-Trilling equation for the critical collapse pressure in the asymmetric mode is solved.

(3) The Salerno-Pulos equation for axisymmetric collapse pressure is then solved.

(4) The Tokugawa-Bryant equation for the pressure at which collapse by general instability takes place is solved.

(5) Finally, the Modifed 92a equation is solved to determine the plastic instability collapse pressure.

By varying the hull dimensions and comparing the pressures obtained from each formula, the critical pressure is obtained and the corresponding dimensions are established.

b. Program B

Program B is an extension of the work of Program A. The frames reinforcing the cylinder are changed from rectangular to tee-shaped and relations established for the ratio of web thickness, flange thickness and flange width are specified. The results of Program A indicate that neither the results of the Windenburg-Trilling equation or the Salerno-Pulos equation are significant compared with the general instability equations (Tolugawa-Bryant) or the modified axisymmetric equation (Modified 92a). Only the latter two equations, therefore, are used as design criteria. A description of this program is as follows:

(1) The following data are read into the computer.
   (a) Outside diameter of cylinder (D)
   (b) Shell thickness (h)
   (c) Frame spacing (L)
   (d) Ratio of flange width to web thickness
   (e) Web thickness
   (f) Flange thickness
   (g) Yield stress (σy)
   (h) Modulus of elasticity (E)
   (i) Poisson's ratio (ν)
   (j) Hydrostatic pressure (P)
   (k) Density (ρ)

(l) Bulkhead spacing
(m) Inside diameter of cylinder

(2) An equivalent effective length of the outer shell, to be used with each frame for the moment of inertia of each frame area, is found by calculating F_1 of the Salerno-Pulos equation and solving equation 22 from Reference 4-1.

$$L_e = LF_1 + b$$

(3) The thinness ratio is calculated from:

$$\lambda = \left[\left(\frac{Le}{2R}\right)^2 \Big/ \left(\frac{h}{2R}\right)^3 \right]^{1/4} \left[\frac{\sigma_y}{E} \right]^{1/2}$$

(4) The moment of inertia of one frame and an equivalent length of shell about its centroid is calculated.

(5) The Tokugawa-Bryant equation is solved for the critical pressure for general instability collapse. A DO loop is used to solve the equation for the first six harmonic modes and select the lowest pressure as the critical pressure.

(6) The general instability pressure is then compared with the desired 6000 psi in an IF statement. If it is less than 6000 psi, the frame dimensions are increased and the entire calculation is re-run using the new frame dimensions. The frame spacing and shell thickness are held constant.

(7) When the pressure from step 5 exceeds 6000 psi, the IF loop is ended and the program goes on to solve the Modified 92a formula for axisymmetric collapse at 4000 psi.

(8) The entire program is set within two DO loops. The initial shell thickness is set and the inner loop changes this in selected increments with the frame spacing held constant. The outer loop increases the frame spacing in slected increments and the calculations are repeated. Thus, data is obtained for a series of shell thicknesses for each frame spacing and also a series of frame spacings. In a modification to Program B, the inner loop was changed to vary the flange width while the shell thickness was held constant throughout the program.

(9) The inner DO loop contains a calculation for the weight per linear foot of cylinder of the hull and the weight of the water displaced by each linear foot of hull. The excess buoyancy of each design is determined from the difference between the displacement and the weight of the cylinder.

(10) The output data from this program is the following:
   - (a) Frame spacing (in)
   - (b) Flange width (in)
   - (c) Web thickness (in)
   - (d) Flange thickness (in)
   - (e) Shell thickness (in)
   - (f) Weight per linear foot of toroid hull in lbs/ft
   - (g) Excess buoyancy per linear foot of hull in lbs/ft
   - (h) Modified 92a axisymmetric buckling pressure in psi
   - (i) General instability pressure (Tokugawa-Bryant) in psi
   - (j) Harmonic mode of failure

4.1.2.4 Computer Program Tabulation and Results

a. The following data is used:
   - (1) Outside diameter of cylinder = 120 inches
   - (2) Clear inside diameter of cylinder = 108 inches
   - (3) Bulkhead spacing = 240 inches
   - (4) Constant added to web thickness to allow for 1/4 in. welds each side = .33 inch
   - (5) Yield stress = 140,000 psi and 180,000 psi
   - (6) Modulus of elasticity = 30,000,000 psi
   - (7) Poisson's ratio = 0.3
   - (8) Density = 0.284 lb/in^3
   - (9) Hydrostatic pressure = 4000 psi

b. The output data is given in the following tables:
   - (1) Table 4-1. This represents the original Program B using a yield stress of 140,000 psi and the following ratios: Flange width = 20 times web thickness and flange thickness = 2 times web thickness. The frame spacing and shell thickness are held constant and the web thickness varied to suit the needed resulting pressures.

Frame Spacing (in)	Shell Thickness (in)	Flange Width (in)	Flange Thickness (in)	Web Thickness (in)	Weight (lb/ft)	Excess Buoyancy (lb/ft)	Mod. 92A Pressure (lb/in^2)	Gen. Inst. Pressure (lb/in^2)
16.0	1.75	6.0	0.6	0.30	2625	2407	4227	6428
17.0	1.75	6.0	0.6	0.30	2603	2429	4192	6124
18.0	1.75	7.0	0.7	0.35	2686	2345	4190	7122
19.0	1.75	7.0	0.7	0.35	2663	2368	4151	6810
20.0	1.75	7.0	0.7	0.35	2643	2389	4144	6521
21.0	1.75	7.0	0.7	0.35	2624	2408	4079	6252
22.0	1.75	7.0	0.7	0.35	2607	2425	4045	6001
23.0	1.75	8.0	0.8	0.40	2683	2349	4015	6813
24.0	1.88	8.0	0.8	0.40	2822	2209	4304	6632
25.0	1.88	8.0	0.8	0.40	2806	2226	4271	6389
26.0	1.88	8.0	0.8	0.40	2791	2241	4240	6161
27.0	1.88	9.0	0.9	0.45	2863	2169	4201	6846
28.0	1.88	9.0	0.9	0.45	2847	2185	4171	6610
29.0	1.88	9.0	0.9	0.45	2832	2200	4143	6387
30.0	1.88	9.0	0.9	0.45	2818	2214	4117	6178

Table 4-1 Program B - Yield Strength 140,000 psi

Frame Spacing (in)	Shell **Thickness** (in)	Flange Width (in)	Flange Thickness (in)	Web Thickness (in)	Weight (lb/ft)	Excess Buoyancy (lb/ft)	Mod. 92A Pressure (lb/in^2)	Gen. Inst. Pressure (lb/in^2)
16.0	1.38	7.0	0.7	0.35	2270	2762	4229	6448
17.0	1.38	7.0	0.7	0.35	2240	2791	4160	6306
18.0	1.38	7.0	0.7	0.35	2214	2818	4093	6175
19.0	1.38	7.0	0.7	0.35	2190	2841	4028	6053
20.0	1.50	7.0	0.7	0.35	2327	2705	4403	6300
21.0	1.50	7.0	0.7	0.35	2308	2724	4346	6106
22.0	1.50	8.0	0.8	0.40	2387	2645	4291	6496
23.0	1.50	8.0	0.8	0.40	2367	2665	4233	6388
24.0	1.50	8.0	0.8	0.40	2349	2683	4178	6288
25.0	1.50	8.0	0.8	0.40	2332	2700	4125	6097
26.0	1.50	9.0	0.9	0.45	2407	2625	4057	6430
27.0	1.50	9.0	0.9	0.45	2389	2642	4008	6333
28.0	1.63	9.0	0.9	0.45	2531	2501	4407	6383
29.0	1.63	9.0	0.9	0.45	2515	2516	4363	6159
30.0	1.63	10.0	1.0	0.50	2588	2444	4296	6688

Table 4-2 Program B - Yield Strength 180,000 psi

(2) Table 4-2. This is the same program as Figure 4-1, except the yield stress has been changed to 180,000 psi.

(3) Table 4-3. This is Modification #1 of Program B and it is given for a yield stress of 140,000 psi, a flange width of 15 times the web thickness and a flange thickness of 1.5 times the web thickness. The frame spacing and shell thickness are held constant and the web thickness varied to suit and parameters.

(4) Table 4-4. This is the result of Modification #2 of Program B. The shell thickness was held a constant 1.75 inches and the flange thickness and web thicknesses made equal. The frame spacing and flange width are set at various dimensions and the web thickness varied to suit the parameters.

The results indicate that any frame spacing, within the limits used for the calculation, is adequate provided the frame dimensions and shell thickness are adjusted to suit the boundary conditions. From the initial runs at 140,000 psi yield stress, it was seen that only shell thicknesses of the order of 1.75 to 1.88 inches were suitable and in the final run, a constant shell thickness of 1.75 inches is used and the flange width optimized. If the maximum excess buoyancy is considered the deciding factor, an optimum design can be selected from the final run (Modification #2), as the results of this run give the highest excess buoyancy figures (see Table 4-4).

It should be noted that frame spacing beyond about 22 inches becomes inefficient because of the increasing importance of the axisymmetric collapse pressure. Necessary increases in the shell thickness at this point adds considerably to the weight.

Bulkhead spacing is not critical in this calculation. Initial arrangement of the structure interior was determined to be either a 4 or 5 sector toroid, so the 240" bulkhead spacing is compatible with either the 282" or 226" respective spacing. The arrangement shown in Figure 4-6 has 5 sectors.

The recommended hull design is summarized in Table 4-5.

Frame Spacing (in)	Shell Thickness (in)	Flange Width (in)	Flange Thickness (in)	Web Thickness (in)	Weight (lb/ft)	Excess Buoyancy (lb/ft)	Mod. 92A Pressure (lb/in^2)	Gen. Inst. Pressure (lb/in^2)
16.0	1.75	6.00	0.60	0.40	2654	2377	4239	6563
17.0	1.75	6.00	0.60	0.40	2630	2401	4203	6254
18.0	1.75	6.75	0.67	0.45	2688	2344	4192	6922
19.0	1.75	6.75	0.67	0.45	2665	2367	4154	6620
20.0	1.75	6.75	0.67	0.45	2644	2388	4117	6340
21.0	1.75	6.75	0.67	0.45	2625	2406	4082	6080
22.0	1.75	7.50	0.75	0.50	2679	2353	4054	6649
23.0	1.75	7.50	0.75	0.50	2660	2372	4018	6389
24.0	1.88	7.50	0.75	0.50	2800	2232	4307	6222
25.0	1.88	8.25	0.82	0.55	2852	2180	4274	6724
26.0	1.88	8.25	0.82	0.55	2835	2197	4242	6483
27.0	1.88	8.25	0.82	0.55	2819	2213	4211	6256
28.0	1.88	8.25	0.82	0.55	2804	2227	4182	6043
29.0	1.88	9.00	0.90	0.60	2853	2178	4144	6465
30.0	1.88	9.00	0.90	0.60	2838	2193	4117	6253

Table 4-3 Modification 1, Program B - Yield Strength 140,000 psi

Frame Spacing (in)	Shell Thickness (in)	Flange Width (in)	Flange Thickness (in)	Web Thickness (in)	Weight (lb/ft)	Excess Buoyancy (lb/ft)	Mod. 92A Pressure (lb/in^2)	Gen. Inst. Pressure (lb/in^2)
16.0	1.75	8.50	0.35	0.35	2596	2435	4215	6048
17.0	1.75	8.00	0.40	0.40	2606	2425	4194	6052
18.0	1.75	8.50	0.40	0.40	2600	2431	4165	6007
19.0	1.75	8.25	0.45	0.45	2615	2417	4142	6081
20.0	1.75	8.75	0.45	0.45	2611	2421	4111	6048
21.0	1.75	8.50	0.50	0.50	2623	2409	4083	6085
22.0	1.75	9.00	0.50	0.50	2620	2411	4050	6061
23.0	1.75	8.75	0.55	0.55	2630	2401	4020	6066
24.0	1.75	8.50	0.60	0.60	2638	2393	3988	6035
25.0	1.75	9.00	0.60	0.60	2638	2394	3955	6027
26.0	1.75	9.00	0.65	0.65	2653	2379	3922	6085
27.0	1.75	8.75	0.70	0.70	2658	2374	3891	6012
28.0	1.75	8.75	0.75	0.75	2669	2362	3859	6027
29.0	1.75	8.75	0.80	0.80	2680	2351	3828	6026
30.0	1.75	8.75	0.85	0.85	2690	2341	3798	6011

Table 4-4 Modification 2, Program B - Yield Strength 140,000 psi

TABLE 4-5 Hull Structure Summary

Sectional Outside Diameter	10' 0"
Clear Inside Diameter	9' 0"
Shell Thickness	1.75"
Material HY-140 Steel	140,000 lb/sq in. yield
Frame Spacing (Mean Circumference)	21.0"
Flange Width	6.75"
Flange Thickness	0.67"
Web Thickness	0.45"
Weight	2625 lb/ft
Excess Buoyancy	2406 lb/ft
Axisymmetric Buckling Pressure	4082 lb/sq in
General Instability Pressure	6080 lb/sq in
Depth of Critical Pressure	>9000 ft
Overall Toroid Diameter	40' 0"
Overall Hull Weight	247,400 lb
Overall Excess Buoyancy	221,600 lb

4.1.2.5 Structural Weights

The computer program used in the hull design was initially configured for rectangular frames. Modification of the program was undertaken to provide 'T' frames for lighter construction. The use of about 50 identical frames and 5 identical bulkheads is one of the advantages of the toroidal hull shape. This simplified the construction and weight estimates. Weight of a 10-foot outside diameter cylinder suitable for this application is about 2600 pounds per foot. This implies an excess buoyancy of about 2400 pounds per foot. For the hull of 15' mean radius, the dry weight of the hull is approximately 248,000 pounds. The excess buoyancy must then be balanced either by (1) internal outfitting on a pound for pound basis, (2) external attachment on a difference of weight versus displacement basis or (3) ballast. In this conceptual design it is deemed appropriate to develop assurance of feasibility of buoyancy control rather than make a detailed weight and moment report because of the unknowns in mission hardware. It is not intended to minimize the importance of proper weight distribution, but rather to point out that expenditure of engineering effort is not currently justified. Most assuredly, very careful attention must be directed to the weight and balance of the station in the detailed design phase.

Principal weight groups (less hull) are currently estimated (in pounds) as follows:

Isotope Power Plant	60,000#
Life Support (including crew)	38,000
Emergency Equipment (including batteries)	15,000
Interior Non-structural Dividers & Outfitting	25,000
Mission Equipment	15,000
Structure Reinforcement for Penetrations and Hatches	20,000
External Attachments	42,000
Total Estimated Weight	215,000#

This total weight is believed conservative and indicates that additional buoyancy material will probably not be required. Further refinement will be mandatory in the next phase of the design program and final adjustment of buoyancy will necessarily be undertaken after the structure is completed. Even though the various components will be weighed during construction, the overall station weight will again be checked with the completed station suspended from a crane. The balancing adjustments completed during this operation in air will be refined during the first waterborne buoyancy checkout at the building activity. Final buoyancy adjustments will be a portion of every preemplacement operational plan for the station because of the variations in loading inherent in different missions.

4.1.2.6 Balance

The balance of the station also requires specific attention. In shipbuilding, the designers take steps to develop the desired trim for the ship and to avoid a permanent list by close attention to distribution of weights in the structure. It will be necessary to choose a set of mutually perpendicular axes in the horizontal plane to which the moments of structure and outfitting weights are balanced. It will also be necessary to place the ballast tanks for variable weight adjustment in locations within the structure which take into account the moments of added, shifted or deleted weights including consumables for expenditure during the mission cycle. A detailed analysis of these variables is beyond the scope of this study.

4.1.2.7 Buoyancy Control

The structure will be positively buoyant on the order of 10 tons and therefore will require taking on of weight to achieve near neutral buoyancy for descent on the hauldown cable. The cable tension will be directly proportional to the buoyancy of the station and a design limitation of 10,000 pounds is called for when using 1 inch 6 x 19 cable with a 9.14 safety factor. . The weight added to the station will be in the form of droppable ballast or internal liquid. The droppable ballast weights and the peaking battery (Section 4.1.3.7) are emergency ascent weights in the event that internal liquids cannot be pumped overboard. Thus, the external weight excess over displacement must be greater than the weight of the disposable internal liquids in order to provide a fail-safe ascent arrangement.

The structure will become less buoyant as it descends as a result of hull compressibility and reeling in the downhaul cable. This will necessitate discharging ballast on the descent to maintain a near constant buoyancy. Likewise, weight must be taken on during the ascent to prevent development of an excessive strain on the downhaul cable. Changes in temperature and salinity will also affect the buoyancy so sensors for measuring these quantities, in addition to depth and cable tension, are necessary for on board calculation and control of ballast compensation.

For added safety, the internal liquid will be taken on in small quantities into a pressure chamber designed to prevent flooding of the station. It will be possible to open only one end of the chamber at any time so that only a discrete amount of seawater may be admitted against an air bubble. Following admission of the water, the sea valve is closed and the water allowed to flow to an unpressurized internal tank while venting the air bubble. Overboard discharge at depth is likewise accomplished by pumping from the internal tank into the pressure chamber and build-up of an air bubble pressure greater than the sea pressure head. The tank is then isolated from the pump and internal tank by valving and the air bubble allowed to expel the water into the sea. An arrangement similar to this is employed on some small manned submersibles.

4.1.2.8 External Hatches

Because of the water depth involved, it will be necessary that all hatches seat with sea pressure. With the hatches for access between structures opening in opposition, a mating trunk between any two structures is required. The study contract specifies that "Details of this hatch are being developed by the Government and are not to be studied under this contract." This section, therefore, is devoted only to the mechanism and procedures for mating between modules.

A design featuring an internal trunk for the lower hatch is a potential variation. Placing the lower hatch inside and clear of the shell outline would permit the modules to mate closer together in a vertical stack. However, this concept requires a detailed study of the effect of inserting a 'hard' floodable trunk as a discontinuity in the toroidal structure. Some internal space would be lost, but this can be recovered by a slight increase in overall size. It is recommended that this feature be explored in more depth in the detail design phase.

A trunk external to the hull precludes the toroidal hull surfaces being used in direct contact for a seating surface, but simplifies the hull design. In order to keep the lowest structure close to the bottom, the built up mating cradle and trunk have been placed on top of each hull. The cradle serves the additional purpose of containing the attachment points for lifting the structure when on the surface. With the trunk above the upper hatch, small waves will be kept from swamping the hull when the top hatch is open on the surface. Even though the pressure hull is extremely stiff, the problem of alignment of two structures with the cradle and the hatch trunk in mating will be difficult. Early conceptual formulations considered two access trunks between each hull, but this is no longer believed suitable.

Initial mating of the modules should be done near the surface with divers available for checking alignment and attachment. The hulls will be roughly aligned by using an external water jet thrusting system and optical viewing. Positive final alignment will be insured by means of conical pins. After a mating, an external hydraulic system will be used to clamp the two hulls together. Thus, relative movement between the two hulls will be prevented. The upper hull will be cradled in a series of pads or saddles built on open framework attached to the top surface of the lower hull. Successive modules will mate in a similar manner.

After mating, the hatch trunk must be freed of water. This can be done relatively easily at shallow mating depths but would require considerable power at the operating depth to discharge the several hundred gallons of entrapped water against ambient pressure. The mating trunk design will probably use detailed seal techniques similar to those being developed for the DSRV.

Safety considerations at operating depth makes the simultaneous opening of both upper and lower hatches to the mating trunk undesirable. Therefore, the trunk must be large enough to permit a man to open either hatch from inside the trunk with the opposite hatch shut. The mating trunk will also be large enough to permit handling of supplies during replenishment since there will be dry access only to the upper module either on the surface or from a submersible. A four foot inside diameter and four foot height is probably sufficient for the trunk.

The detailed design of the mating trunk is not attempted in this report since it will be largely determined by the hatch design being developed separately. Likewise, the design of the cradle between two structures will be governed by the distance a hatch opens as this will control the vertical spacing between two stations when mated. Since the distance between two adjacent hulls is expected to be on the order of 4 feet, no problems are envisioned in designing an open framework cradle support which will also contain the lifting points for surface handling of the structure. A series of vertical webs could also be used to separate two modules. The mating cradle will be configured to clear the hatches and mating trunk as well as the bearing pads on the inner portion of the hull discussed in Section 3.3.1.4.

A modified trunk will be used on the upper hull module for mating with the DSRV or other submersible. This modified trunk will be closed at the upper end with a standard type hatch. For routine operations, the upper seat will be parallel to the plane of the hull. However, for advanced training operations with DSRV crews, the upper seat will be constructed at an angle simulating a submarine heeled over on the bottom. Future developments in seals may permit the upper seat to be fitted to a swivelling upper section so that a single modified trunk will serve to exercise the DSRV at any desired angle within its design limitations.

4.1.2.9 Corrosion Protection

In a complex structure such as the Manned Underwater Station, there will be many different materials used. Some of these are metallic and all will share the sea water environment. In this situation, it will be necessary to take precautions to prevent electro-chemical action and resultant corrosion. The galvanic series in sea water fortunately provide a suitable method of cathodic protection. A paint film will be of great assistance, but cannot be 100% effective due to nicks and scratches from various sources. This does not mean that paint will not be used. It's application will be discussed in subsequent paragraphs.

Cathodic protection recommended is the patented "Cathanode" which uses 40 pound magnesium bars in an interconnected passive array. The system roughly corresponds to the circuit of a battery in that the "Cathanode" may be considered as one plate of a battery, the hull and its associated equipment as the other plate and the sea water as the electrolyte. A similar system has proved very successful in use on the TRIESTE since 1959 and is described in Reference 4-7. It has virtually prevented all external galvanic deterioration of the craft below the waterline.

The paint system recommendation is based on data in Reference 4-8. It is particularly noted that the samples for testing were prepared under the direction of application specialists. The importance of proper coating application with respect to surface preparation, temperature, humidity, drying time, and total film thickness cannot be overemphasized in construction specifications.

A zinc inorganic system should be used for the base coat and overcoated with the proprietary coating specified by the base coat manufacturer. The activity responsible for the protective coating on the Manned Underwater Station should be given a choice between the two leading systems discussed in Reference 4-6. These are the Devoe and Raynolds Catha-Coat 300 base overcoated with Devran and the Plas-Chem Zinc-ite B topcoated with Cevanite. The trade names may differ at the time the station is constructed so the specification should be worded to insure equivalent composition to those systems previously tested. It is noted that the coal tar system performed well in the deep ocean environment, but because of its soft character its use in areas susceptible to abrasion is not recommended.

The cathodic protection and protective coating systems will be applied to metallic areas of both the hull and the foundation. A November 1965 NCEL Report (Reference 4-9) indicated that "it will be some time before a comprehensive treatment of the evaluation of all specimens can be made and a report issued" on material corrosion in bottom environments. The results of these studies should be carefully reviewed in preparing detailed design specifications for the station. The state-of-the-art will handle the situation, but possible improvements and cost savings can be affected by application of new developments.

4.1.2.10 Toroidal Hydrodynamics

The toroidal hull will be inherently stable when submerged because the center of gravity can assuredly be placed below the center of buoyancy. There should be no problem associated with a controlled slow descent or ascent through the water column. There may be some slight pitching or rolling action due to shearing current structures but these will be of short duration as the structure is winched through the current strata. Drag forces due to horizontal current action can easily be determined from a model test in a towing tank or tunnel.

A controlled traverse to or from the bottom should pose no hydrodynamic problem. However, if the vertical drag forces are significantly unbalanced so as to cause rotation of the station about any of its axes, it may be necessary to employ an external water jet system for control and roll stabilization. This system utilizes a pump moving sea water through a series of rotable discharge nozzles. The effect is analogus to the thruster system employed in space capsules for attitude control. The system is normally used for fine positioning of the structure during the last few inches of descent to the foundation and for small altitude changes in the event of foundation settling. These small changes could be accomplished by shifting weights but the jet system is more responsive to demand and is also highly desirable for possible use in the ascent and descent phases. A secondary use of the jet pump is forcing filtered sea water over the observation viewports and hatch seating seats to remove sediment. A series of electrically controlled valves would serve to divert the pumped sea water in the proper direction.

The real uncertainty is the hydrodynamic behavior in an uncontrolled buoyant ascent. This emergency situation will probably never occur but is a credible accident should the hauldown wires be severed during an ascent. The question becomes a matter of the attitude assumed by the hull. It will certainly take the path of at least hydrodynamic resistance. Determination of this least drag attitude can be done in model testing after the detail design is prepared. This determination should be considered a requirement of the next phase of the program and not separate R&D development.

4.1.3 Power Plant Description

The 30 Kwe modular power plant described is designed for installation in the Manned Underwater Station. In particular, high reliability, safety of isotope containment, and minimum maintenance were prime design goals. In addition, the system was chosen on the basis of a reasonable compromise between high efficiency and minimum development requirements.

The power plant for the station consists of four completely separate power plants (for redundancy), each consisting of a two-loop system which uses cobalt-60 as the heat source and providing 7.5 Kwe. Air is used as the primary coolant with the heat source being cooled by forced circulation. A superheated steam Rankine cycle of low pressure level is used for power conversion. A schematic diagram of a 7.5 Kwe power plant is shown in Figure 4-1. A typical set of operating conditions is also shown so that it can be seen that heated air leaves the heat source at 1300°F and enters the superheater, where saturated steam is superheated to 1200°F. The air then enters the steam generator, and returns to the heat source at a temperature of approximately 300°F.

The steam exhausted from the turbine is still in the superheated state. It is, therefore, used in a heat exchanger (feed preheater) to preheat the boiler feed. The saturated steam then enters the condenser, where the remaining heat is rejected to the sea water through the hull.

Two sets of operating conditions were investigated. The first one corresponds to a turbine back pressure of 1 psia, and the second to that of 1/2 inch mercury (0.245 psia). The overall electrical power conversion efficiencies are 15.2% and 16.7%, delivering 7.6 and 8.3 Kwe, respectively. Operating data for these two systems are summarized in Table 4-6. It should be noted that a 5% heat loss from the heat source was assumed.

A conceptual view of the complete plant is shown in Section 4.3.2.1. The overall 30 Kwe package, exclusive of control equipment, fits into a space approximately one eighth of the total toroidal volume. It is estimated that the necessary control equipment can be fitted into the consoles required for general operation of the station. A weight breakdown of the 30 Kwe power system is shown in Table 4-7.

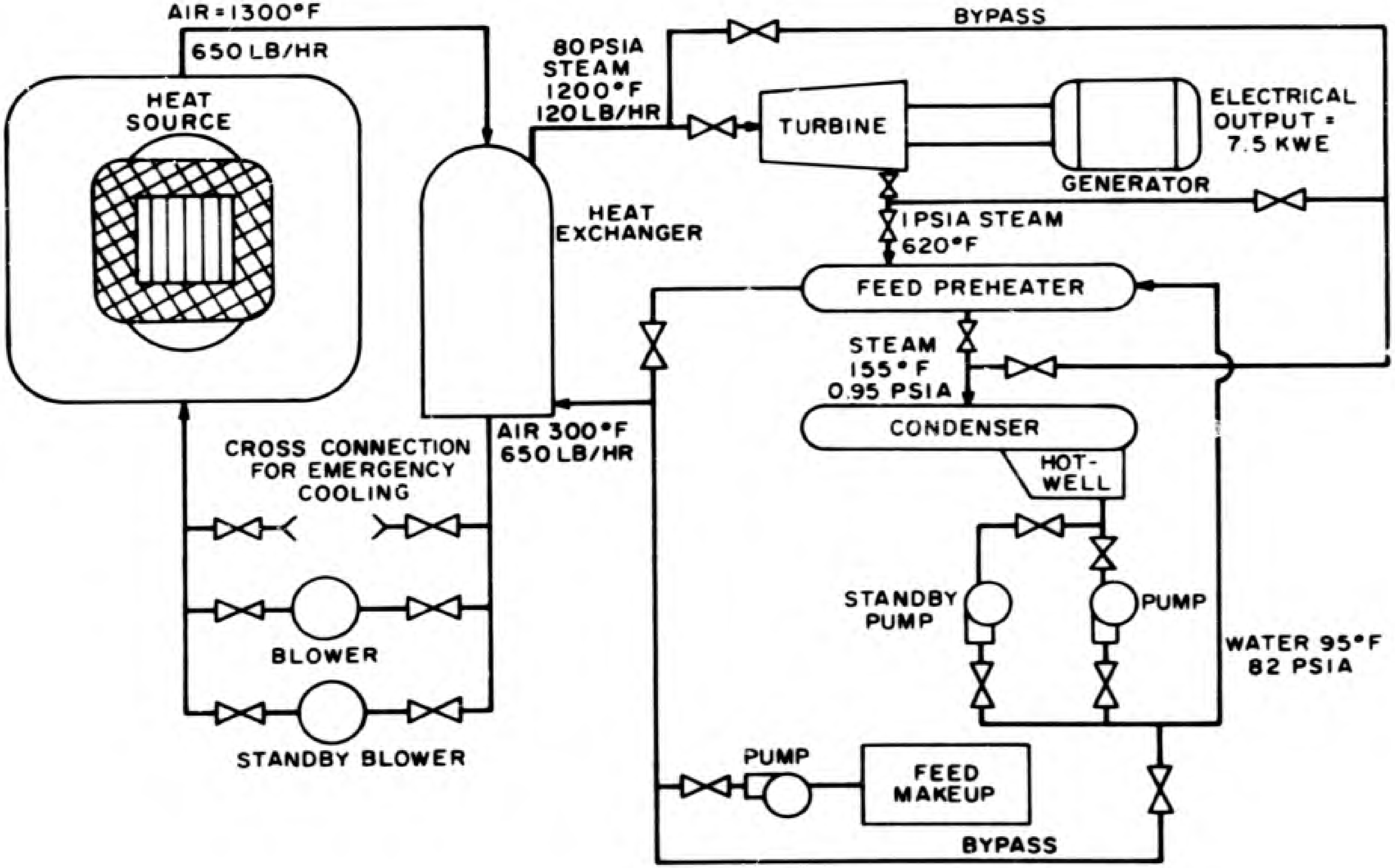


Figure 4-1 7.5 Kwe Power Plant Module Schematic

TABLE 4-6

Summary and Comparison of System Operating Conditions

Characteristics	Turbine Exhaust Pressure 1 psia	 (.245 psia) 1/2-Inch Hg
Inlet Steam Pressure, psia	80	80
Inlet Steam Temperature, °F	1,200	1,200
Total Heat Source, Kw	50	50
Heat Loss	5%	5%
Net Available Power, Kw	47.5	47.5
Air Inlet Temperature, °F	314	314
Air Inlet Pressure, atm.	1	1
Maximum Air Temperature, °F	1,300	1,300
Maximum Core Temperature, °F	1,470	1,470
Air Flow Rate, lb/hr	650	650
Steam Flow Rate, lb/hr	120	120
Turbine Exhaust Pressure	1 psia	1 in. Hg
Turbine Efficiency, %	57	57.7
Generator Efficiency, %	77.5	77.5
Overall Electrical Output, Kw	7.60	8.34
Overall Efficiency, %	15.2	16.7
Power Consumption for Operation, Kw	0.45	0.45
Net Useful Electrical Power, Kw	7.15	7.89
Net Efficiency, %	14.3	15.8
Heat to be Rejected, (BTU/hr)	142,780	140,000
ΔP Heat Source, psi	0.45	0.45
ΔP Primary Loop	1.5 psi	1.5 psi

TABLE 4-7

30 Kwe Co-60 Power Supply Weights in Pounds (Four 7.5 Kwe Units)

	Unit Weight	Plant Weight
Heat Source with Depleted Uranium Shield	11,000#	44,000#
Turbogenerator Set	510	2,040
Heat Exchanger	1,150	4,600
Preheater	170	680
Condenser H_2O Cooled	170	680
Pumps (6 per unit)	400	1,600
Blower (2 per unit)	100	400
Piping and Valves	1,250	5,000
Total Weight	14,750#	59,000#

4.1.3.1 Components

Heat Source. Cobalt-60 is primarily a gamma emitter, and a significant amount of ionizing radiation shielding is required for a biologically safe heat source using this isotope. Therefore, in order to minimize the weight of the overall system, the heat source volume must be minimized. On the basis of calculations for several possible configurations, it is apparent that a packed bed design will satisfy all three conditions. The packing material must be relatively small in volume to provide the necessary heat transfer area, i.e., to minimize temperature gradients. Ideally, the radioisotope should be in the same shape and size as the packing material but from an economic standpoint this would be impractical. A study of various possible configurations indicates that a core with encapsulated Cobalt-60 strips or rods distributed in a matrix of spherical metal packings would most nearly approach the ideal design. Due to the immediate availability of Brookhaven National Laboratory (BNL) strips, the fuel configuration was chosen for the conceptual design although stacked wafers, encapsulated in the form of rods, may serve the same purpose and provide more uniform heat generation. A conceptual design of the heat source with this array is shown in Figure 4-2. The heat source is essentially a simple two-pass heat exchanger in which the gas enters the inner shield near the top of the core, as shown in the figure, and picks up heat as it flows downward. Near the bottom of the core, the gas turns around and flows upward through the central section, exiting at the top. Additional data on the heat source are included in Table 4-8. The heat source is 30 inches in diameter but has a 3 inch removable shield so that a 24 inch diameter cylinder may be lowered thru a standard submarine hatch. Portable shadow shielding will be necessary during this part of the operation.

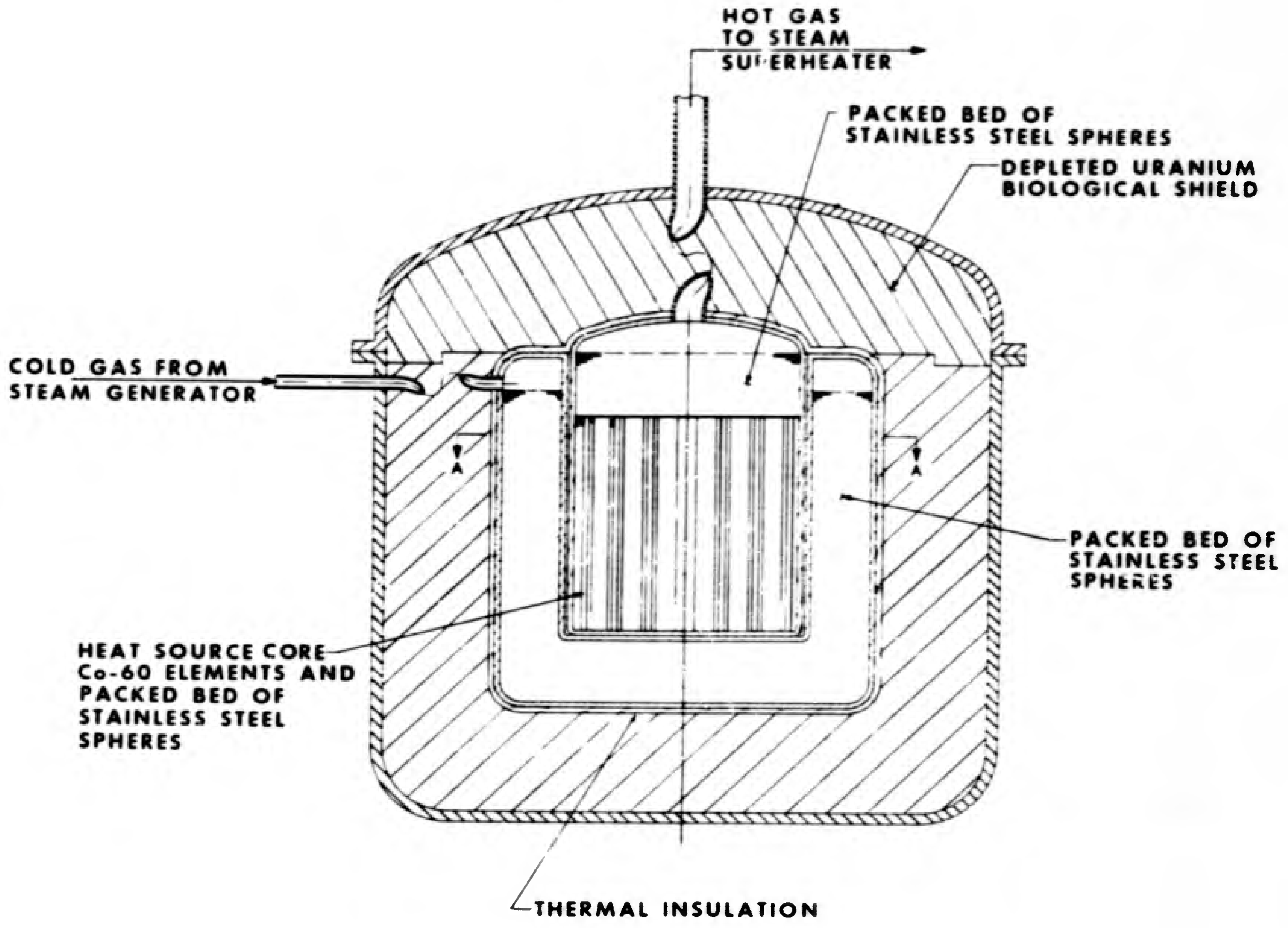


Figure 4-2 Conceptual Design of a Cobalt-60 Heat Source

TABLE 4-8
Basic Data for Conceptual Heat Source Design

Co-60, Kwt	50
Co-60, Curies	3.3×10^6
Form of Fuel	BNL Strips
Specific Activity, Curies/gm	200
Dimensions of BNL Strips	
Width, Inches	0.80
Thickness, Inches	0.0625
Length, Inches	10.0
Dimensions of Nickel Coated Strips	
Width, Inches	0.84
Thickness, Inches	0.1025
Length, Inches	10.04
Dimensions of Co-60 Capsules (Two Strips per Capsule)	
Width, Inches	0.88
Thickness, Inches	0.245
Length, Inches	10.20
Number of Co-60 Capsules	112
Diameter of SS Spheres, Inches	0.125
Core Inner Diameter, Inches	10.00
Overall Core Void Fraction	0.40
Overall Weight (Including Depleted Uranium Biological Shield), Pounds	11,000
Radiation at Shield External Surface	2 mr/hr

Turbogenerator. A conceptual design of a turbogenerator for the 7.5 Kwe system is shown in Figure 4-3. The steam turbine uses partial admission in a single impulse stage. The rotor is overhung from a ball bearing assembly at the exhaust (cool) side of the rotor. Between the rotor and bearing assembly is a combination of dynamic slinger seal and carbon face seals. This arrangement minimizes oil leakage into the steam system during operation, startup, and storage.

A gear box uses helical gears to provide a two-step reduction from 48,000 to 12,000 to 3600 rpm. The gears are organically lubricated by a forced flow system utilizing an integral pump with gravity return to the gear box sump. The gear box and bearings are vented through filters to the interior of the powerplant enclosure.

The generator provides a 60-cycle output. Speed of the rotating combination is controlled by varying a parasitic load on the generator output in response to external power demand. The generator is a standard wound rotor, 3600 rpm, inductor-type alternator with a 12 Kva capacity. The alternator, which uses permanent grease lubricated ball bearings, has an integral cooling system.

4.1.3.2 Selection of Steam Cycle Design Conditions

The following section presents the results of a parametric study on superheated steam cycles. The design was based on a 50 Kwt heat source and four independent systems, designed to provide the total required power and conservative redundancy. An additional factor in the 50 Kwt heat source selection was elimination of the requirement for cutting the hull when annual refueling is carried out. The thermal source can be handled through a 25 inch hatch incorporated into the station design.

Turbine Efficiencies. For the 50 Kwt heat source stipulated, it can readily be shown that the steam mass flow rates must be small in size in order that the blading will have a reasonable height. This implies high rotational speeds so that the turbine tip velocities are sufficient to do a significant amount of work per expansion. Such a turbine would closely approach aircraft-type gas turbines. The efficiencies of various types of re-entry gas turbines are compared in Figure 4-4, where the turbine efficiency is plotted as a function of the specific speed, N_s, defined by the equation:

$$N_s = \frac{n\,Q^{1/2}}{H^{3/4}}$$

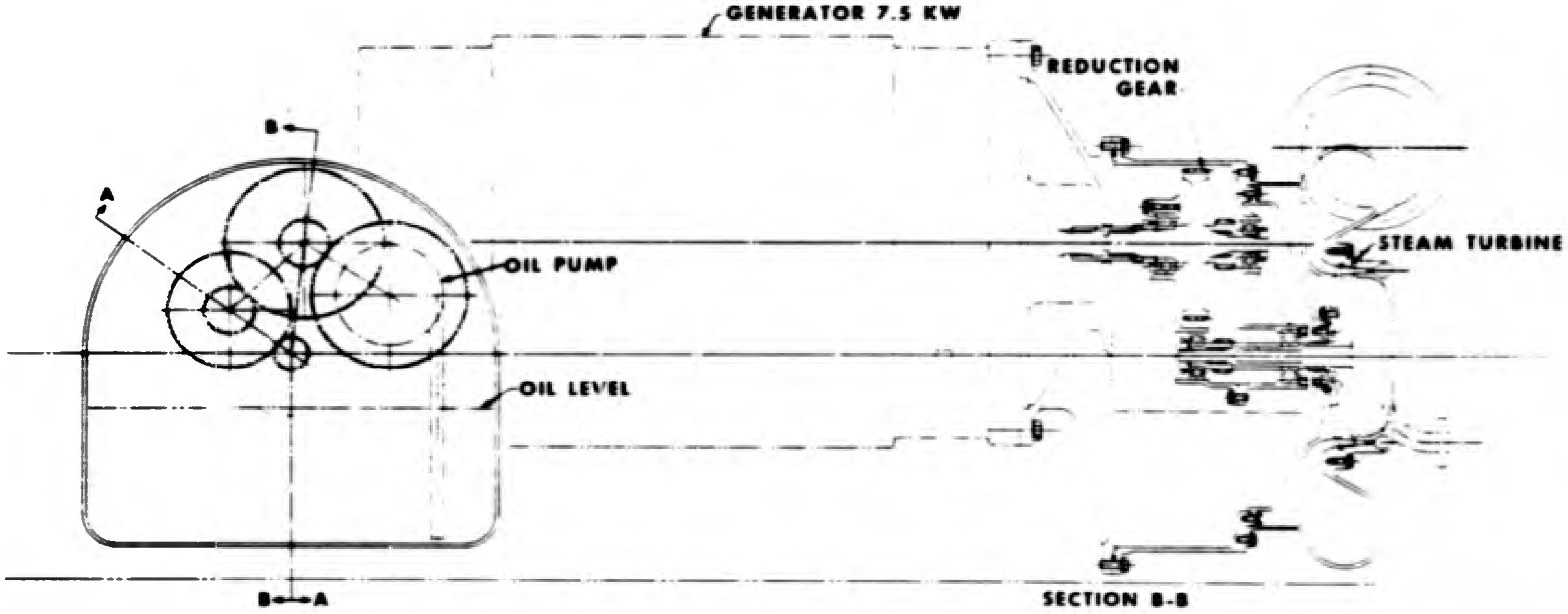


Figure 4-3 Turbogenerator Conceptual Design for a 50 Kwt Heat Source

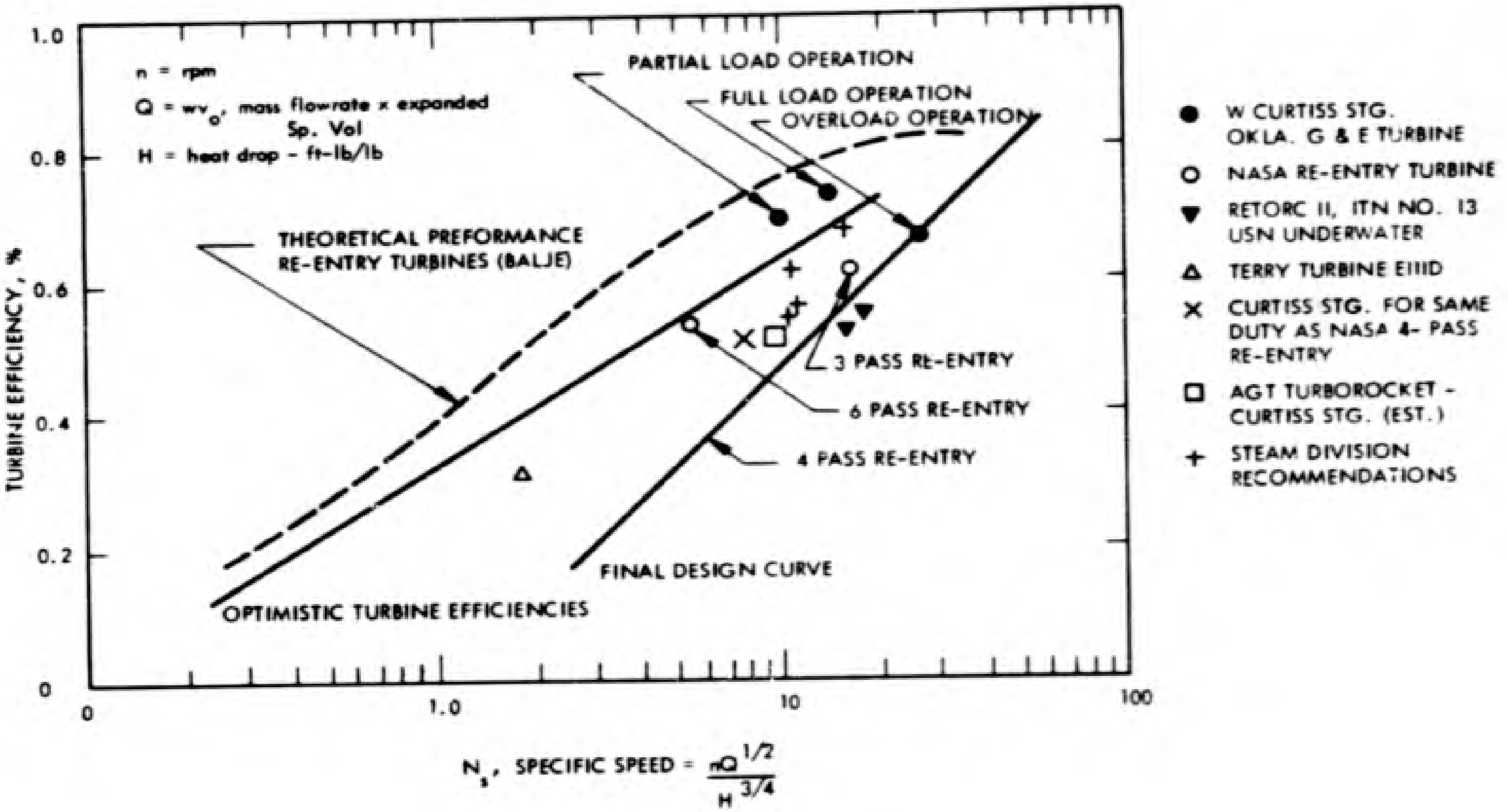


Figure 4-4 Efficiency of Various Types of Re-entry Systems

where n is the turbine speed in rpm, Q is the expanded volumetric flow rate in cu. ft/sec, and H is the heat drop in ft-lb $_F$/lb$_m$. The theoretical relation derived by Balje is also shown on the figure. Two straight lines were drawn through the data points as shown. The upper line represents the more conservative efficiencies which were used in the final conceptual design. It should be noted that these efficiencies are somewhat lower than those recommended by the Westinghouse Steam Division. The turbine speed was set at 48,000 rpm. While 48,000 rpm is high, it is still within the range of commercial technology with respect to bearings and seals for the 7.5 Kwe size.

The effect of inlet steam temperature, steam pressure, and the turbine exhaust pressure on the turbine efficiency was studied and the results are presented in Figures 4-5 and 4-6. It is evident from the two figures that the turbine efficiency can be increased by lowering the back pressure and by increasing the inlet steam temperature. However, the heat source must be limited to a temperature of approximately 1500°F, which is within the metallurgical capabilities of stainless steels. For higher temperatures, more expensive materials would have to be used. This fact coupled with the temperature gradients required in the heat exchangers sets a limit on the maximum turbine inlet steam temperature. A temperature of 1200°F was chosen because this represents a realistic, attainable value. The effect of inlet and exhaust steam pressure on the net electrical power generated was calculated by assuming a generator efficiency of 77.5%. The results are presented in Figure 4-7, and do not take the possibility of feed preheating into consideration. If this factor were included, the overall efficiency can be somewhat improved.

Heat Exchanger. The heat exchanger consists of two basic parts (a) the evaporator and (b) the superheater.

(a) The evaporator includes the supply tank at the bottom of the heat exchanger, six rows of 5/8 inch × .030 coils of 17 turns each, enclosed in an annular space, a vapor drum at the top of the evaporator and a downcomer, connecting the vapor drum to the bottom supply tank at the center of the system.

The water coming from the preheater which is collected in the bottom tank flows upwards in the coils where its energy is increased by the hot air flowing in the annular space.

The discharge from the coils empties into the vapor drum where the vapor separates the liquid droplets and rises into a steam dome which also acts as a separator.

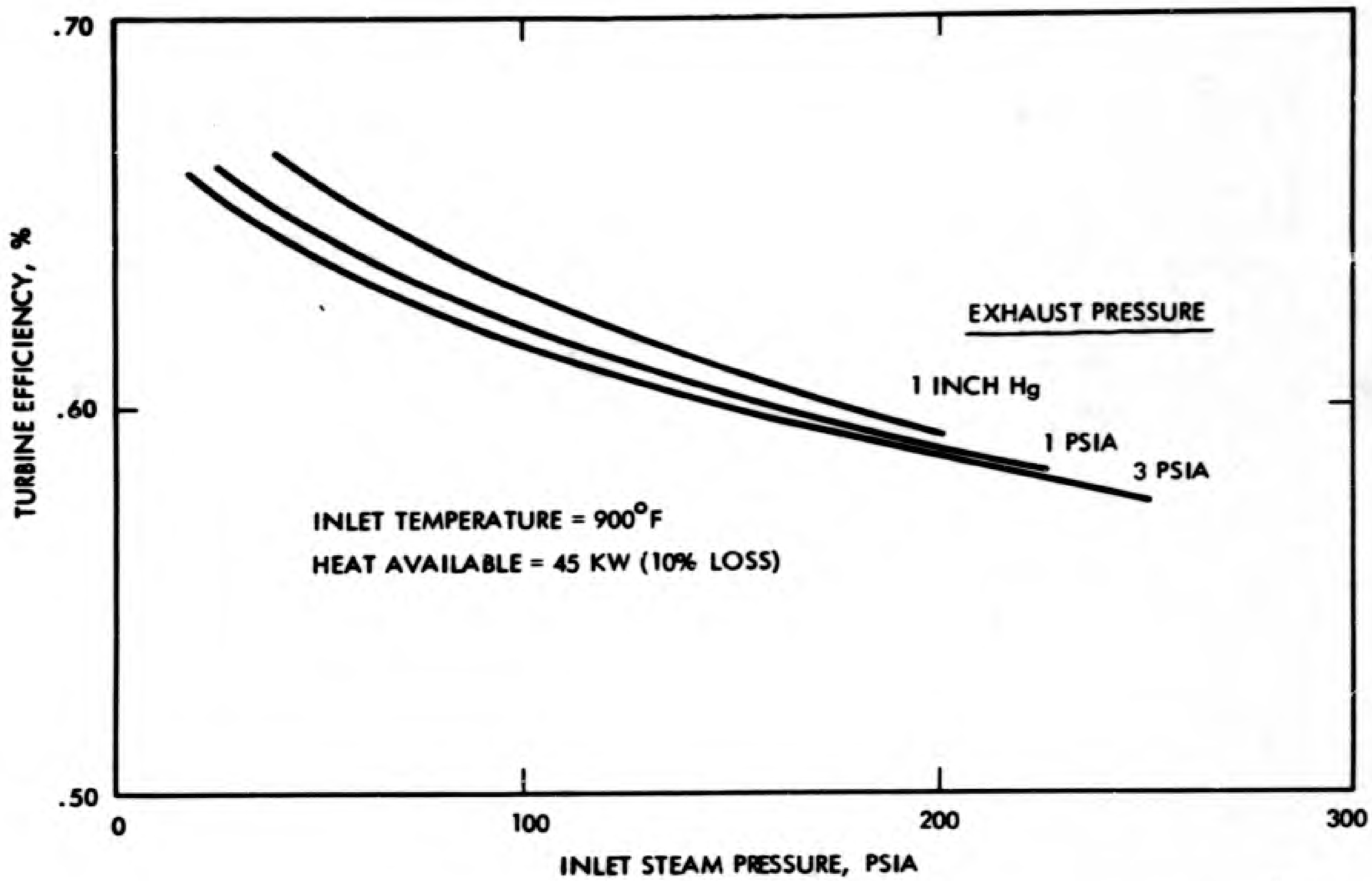


Figure 4-5 Effect of Inlet Pressure at Various Exhaust Pressures on Turbine Efficiency

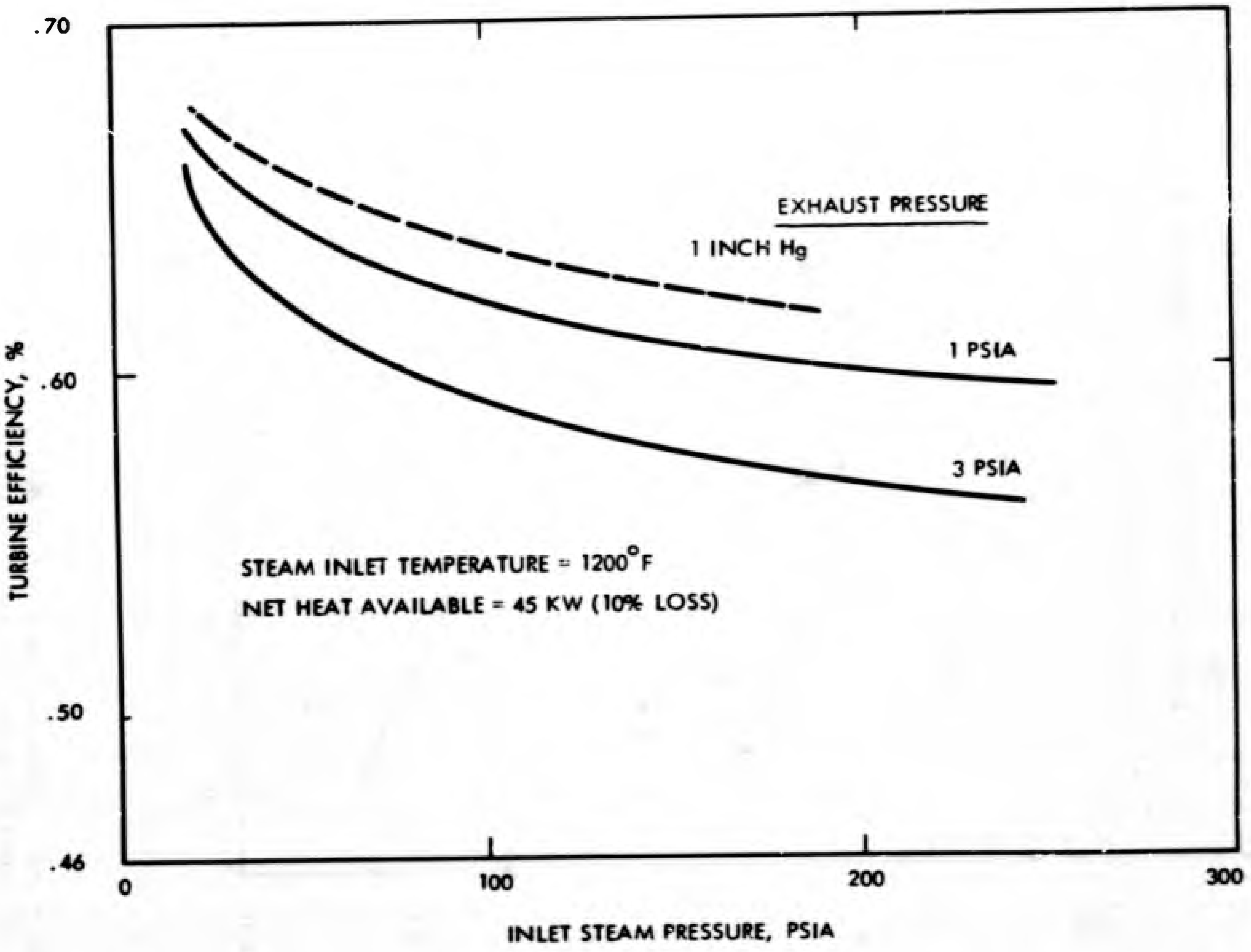


Figure 4-6 Effect of Inlet Pressure at Various Exhaust Pressures on Turbine Efficiency

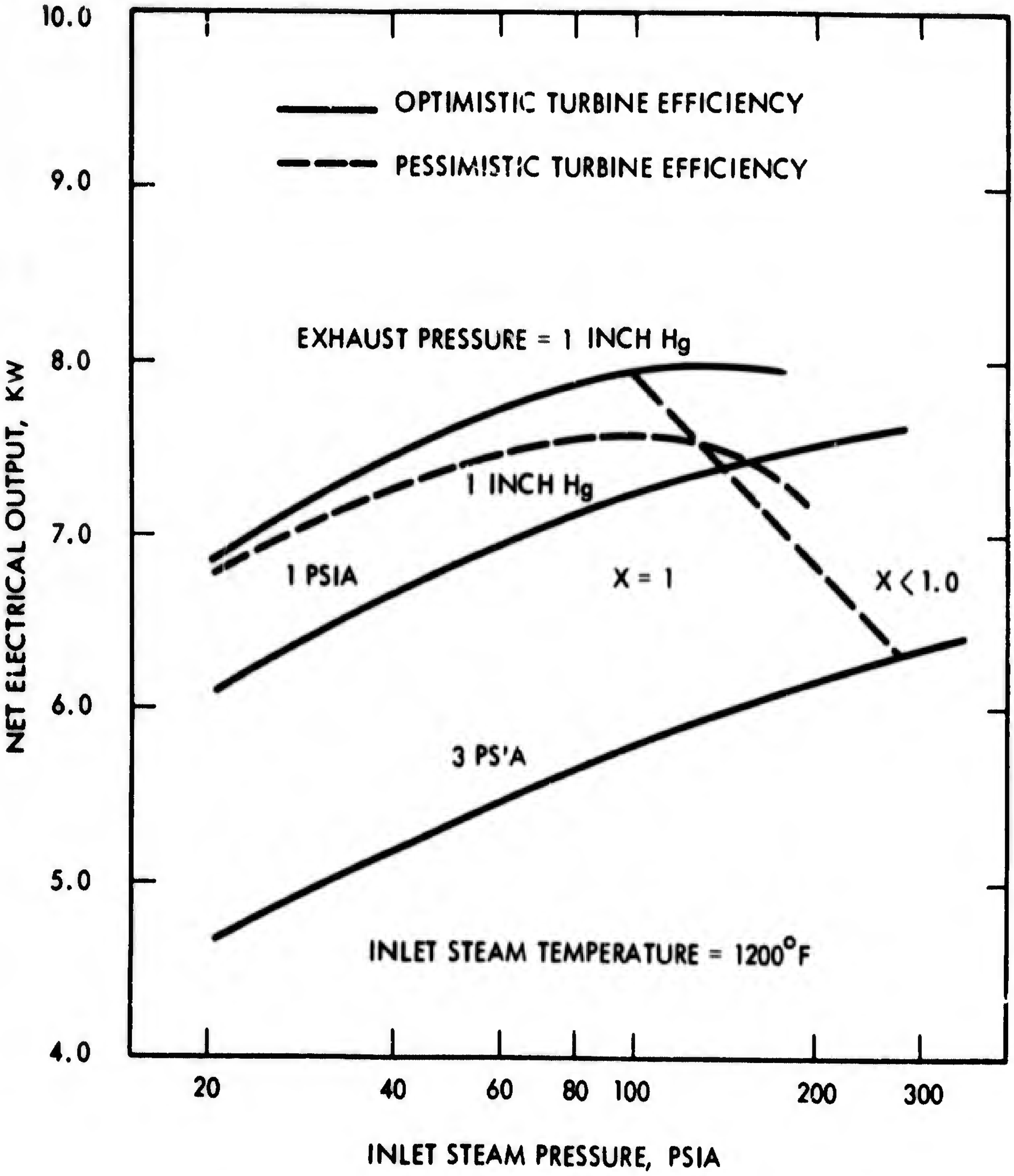


Figure 4-7 Effect of Inlet and Exhaust Steam Pressure on Electrical Output (Feed Preheating Not Considered)

The energy deficient water is returned to the bottom tank through the downcomer. The latter is a 1.5 inch standard pipe.

(b) The superheater picks up the saturated vapor from the top of the evaporator at a temperature of 312°F and increases the temperature of the vapor to 1200°F. It consists of six rows of 5/8 inch x .030 coils of 15 turns each, enclosed in an annular space. It is mounted in the same enclosure as the evaporator. The air temperature is decreased from 1300°F to 986°F in the process. The six coils are connected via a header to the main steam piping.

Preheater. The preheater serves to increase the temperature of the water leaving the condenser at 92°F to 312°F entering the boiler. In the process, it reduces the temperature of the steam leaving the turbine from 620°F to 155°F entering the condenser. The preheater consists of three rows of coils of 1/2 inch diameter tube of 16 turns with a total tube length of 56 feet.

Condenser. The condenser serves to condense the steam at 155°F and discharges condensate at 92°F. Two designs were considered: (a) The condenser is cooled by seawater at 1 atm which enters at 60°F and leaves at 120°F. The condenser design is identical to the preheater design discussed above. The pressure of the seawater is reduced from the environmental pressure to 1 atm in a reducer valve in order to avoid a bulky condenser at high pressure. (b) The other design is to reject the waste heat by the use of heat exchanger bonded to the inside of the pressure hull and utilize the natural conduction of heat through the hull into the surrounding seawater. The hull area required for these condensers was determined to be approximately 500 square feet. The latter concept is recommended because of problems associated with the handling of high pressure seawater.

Development Efforts Required by the Concept. With the exception of the heat source and possibly the turbine, the conceptual design consists of conventional, readily available components. With respect to the heat source, packed beds are commonly used in chemical processing industries and a number of "pebble bed" nuclear reactors have been proposed. The Brown, Boveri-Krupp reactor is actually under construction. However, it is believed that this would be the first application of a packed bed to the design of a gas-cooled radioisotopic heat source. Since the design is quite simple and extensive data exists on similar heat transfer components, it is expected that relatively little development effort will be required.

The turbine development problem even at 7.5 Kwe is not so much one of technical development as of cost relative to the unit's power output. Similar high rpm technology is well defined for aircraft auxiliary turbines and centrifugal separators. However, since this relatively well developed technology cannot be directly applied, a substantial testing program will be required to demonstrate performance and reliability and to reduce manufacturing costs. Modern noise reduction techniques will be utilized to reduce structure-borne and airborne noise to acceptable levels.

4.1.3.3 Heat Source Replacement

Replacement of the heat sources can be performed with the aid of the tender, however, the procedure is not recommended due to difficulties created by ship movement afloat. It is, therefore, recommended that the source is replaced in a shipyard where calm waters are found, or where the station may be docked or lifted clear of the water. Compressed air for source cooling during the operation must also be available. Frequency of source replacement is a function of mission power requirements and general overhaul schedule. Partial replenishment of the Co-60 in the heat sources at sea is not recommended since it will be difficult to provide adequate hot cell facilities on a tender. Therefore, the heat sources should be shipped to a hot cell facility for refueling. Since a short based refueling facility is used, partial replenishment of the Co-60 is not advisable since the savings in fuel cost is partially negated by the handling charges. A better method would be to have the Co-60 returned to the manufacturer for reactivation to full strength at each regular overhaul of the structure.

4.1.3.4 Power Plant Heat Rejection

Two separate methods of rejecting the waste heat from the power plant were considered during the program. One method required hull penetration in order to obtain seawater for cooling of a standard surface condenser. The seawater pressure is reduced to station interior pressure at the hull inlet and pressurized back to exterior environmental pressure at the hull exit end. The other scheme relies entirely upon depositing the waste heat onto the interior of the hull and natural convection of the heat into the surrounding seawater. A compromise of this method would be to utilize part of this waste heat (290,000 BUT/hr to heat the interior of the station). The total heat rejection area required

(500 sq. ft.) is much greater than the hull area adjacent to the power supply, which necessitates the use of part of the living/working area for heat rejection purposes. Inasmuch as the steam pipes will already be located in this area, the proper use of insulation would provide interior heating at no additional cost.

4.1.3.5 Power Plant Safety Considerations

The general purpose of a safety analysis involving any nuclear power source is to insure that the design of the system provides a maximum degree of safety and to assess the radiological consequences associated with the operation of the power source. In order to perform a meaningful safety analysis, it is necessary to (1) consider malfunctions or accident situations to which the system may be subjected, (2) define the possible environment in which these accidents may occur, and (3) examine the response of the system to these accident situations. With a knowledge of these factors, it then becomes possible to insure maximum safety by incorporating pertinent design and operating features into the system which will prevent the development of serious radiological consequences as a result of accidents and malfunctions.

The safety criteria for the Co-60 power system requires complete containment of the fuel under all credible conditions which may exist during fabrication, assembly, transportation and operation of the system. To insure that these criteria can be met, it is necessary to consider the accident conditions which may lead to fuel release and to consider the environments in which these accidents can occur. However, a detailed study of these conditions are beyond the scope of this program. Therefore, the conditions which may lead to accidental isotope release and the steps taken to prevent it are listed below:

(1) Fires and loss of primary cooling.
An emergency cross connection gas cooling system is provided.

(2) Explosions, shock overpressures and impact.
System and components such as coolant line, source capsules, etc. will be analyzed from a point of view of the most credible accident and designed to meet these maximized stresses.

(3) Water Immersion.
The emergency gas cooling system will provide adequate cooling for a short period. In the case of the flooding of the MUS power compartment, the heat

source vessel will be subjected to large pressure differentials and thermal shock. However, the radioisotope proper within the vessel is contained in separate sealed capsules specifically designed to minimize corrosion in sea water.

(4) Loss of secondary coolant or pump and turbine failures. Redundant pumps are provided as standby in the system. The turbine can be bypassed and heat rejected to the sea. Emergency gas cooling is provided.

However, not only accidents must be considered. The radiation levels associated with normal operation and the interactions with the crew duty cycles must be considered since this greatly affects the design of the habitat. Therefore, the shielding requirements for the 50 Kwt Cobalt-60 heat source for this application were determined on the basis of Title 10CFT20, Standards for Protection Against Radiation. The Cobalt-60 heat source conceptual design used in sizing shield requirements is shown in Figure 4-2. The heat source block containing the Co-60 radioisotope is a right circular cylinder of diameter of 11 inches and length to diameter ratio of 1.0. The structure and vessels, which contain the heat source block, steel ball packed bed, and the uranium alloy biological shield were assumed to provide 3.0 inches of steel shielding. The packed bed region was assumed to have a packing fraction of 0.8 and a thickness of 3 inches, hence a total of 5.4 inches of equivalent steel shielding (ρ = 8.0 g/cm^3) is provided in the design. On this basis, the biological shield requirements for a single source were sized using the Title 10CRF20 criteria of radiation levels less than 200 mr/hr at the accessible surface or 10 mr/hr at one meter from the accessible surface. Design shielding requirements were based on the 10 mr/hr level and the uranium alloy thickness required is 4.75 inches. The uranium alloy shield material was assumed to have a density of 17.0 grams/cm^3. At the design point, 10 mr/hr at 1 meter from the accessible surface, the thickness of uranium alloy or steel required to reduce the radiation level by a factor of two for a single source is 0.25 and 0.75 inches, respectively.

The radition environment in the habitat was determined on the basis that four 50 Kw thermal Co-heat sources were placed at the outer periphery of the power and machinery room. The grouping of the four sources resulted in excessively high dose rates in both the equipment compartment and beyond the bulkhead. Therefore, an additional one inch of uranium alloy (U-5Mo)

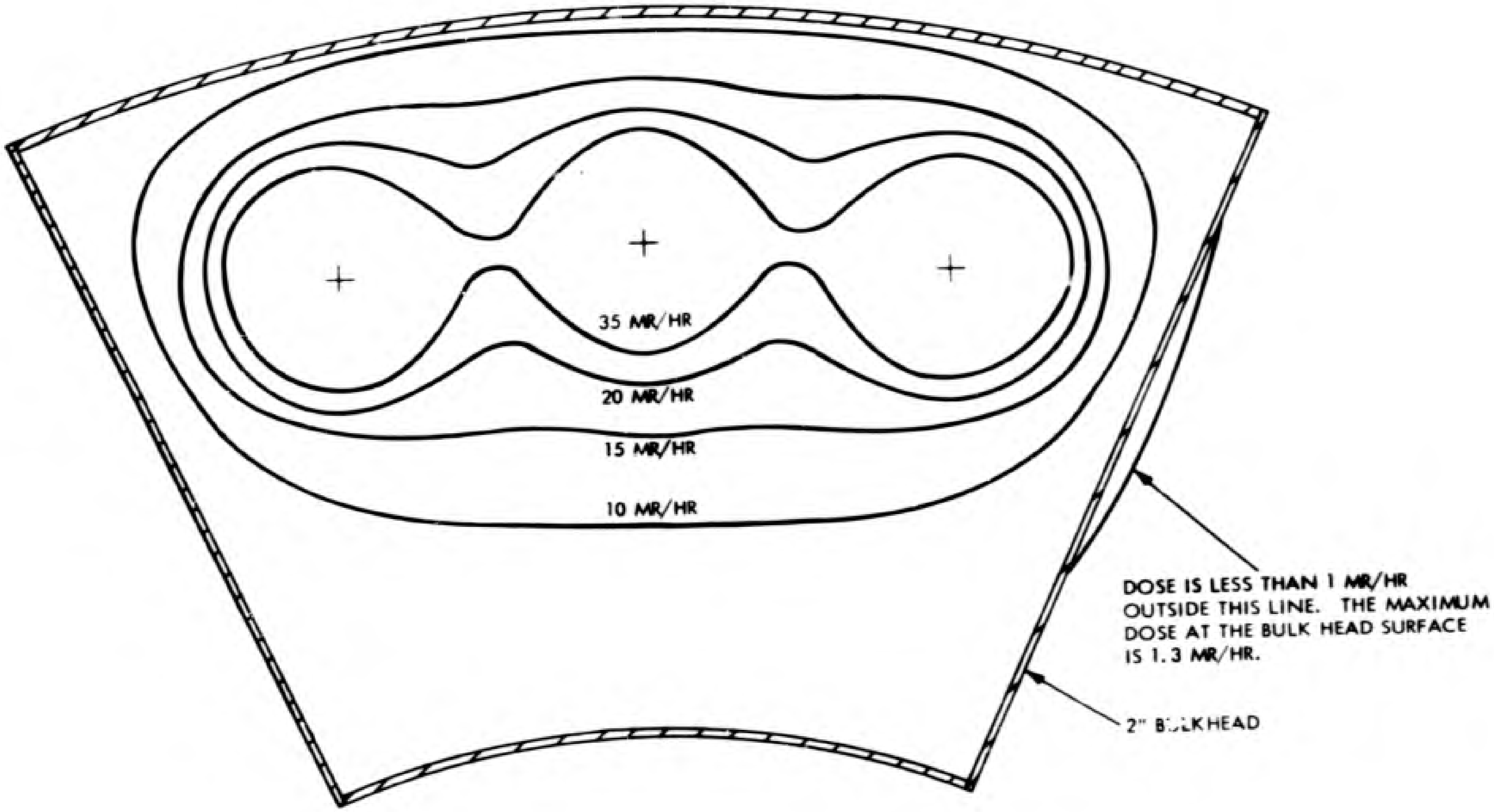


Figure 4-8 Isodose Contours About Four Co-60 Heat Sources

shielding was necessary, resulting in a shield thickness of 5.75 inches, in order to reduce the dose rates to a level which would permit daily servicing and maintenance of the power generating equipment and 8 hours daily staytimes adjacent to the bulkhead outside of the power and machinery compartment. Isodose contours were determined for the immediate area surrounding the sources and are depicted in Figure 4-8. If the original shielding of 4.75 inches of U-5Mo had been considered, the dose rates shown would have been one order of magnitude greater than those shown. The dose rate at the surface of an isolated heat source is 3.5 mr/hr. For the purpose of calculations, the bulkhead thickness was assumed to be 2 inches of steel. Calculations were made for the mid-plane of the three lower sources as shown in the arrangement drawing (Figure 4-26).

Federal regulations (Title 10CRF20) states that a permissible dose is 33 mr/day. Therefore, using this as a basis, service personnel can stay a total of one hour per day in the power and machinery compartment in addition to remaining in the vicinity of the bulkhead for the remainder of the day (8-16 hours) without receiving a dose exceeding the 33 mr/day maximum.

Exterior dimensions of the fully shielded heat source are 30 inches diameter x 32 inches high. This, of course, is too large to fit through a standard 25 inch Navy hatch. Therefore, the source container is so designed that a 3 inch layer of shielding can be removed prior to the loading operation and reinstalled afterwards. The loading operation must therefore be performed using adequate shadow shielding of the personnel. Remote handling equipment must be used both to protect the personnel from radiation as well as protection from the heat since the heat source is a thermally hot object. It must also be borne in mind that the heat source cannot be shut off, hence, in order to avoid meltdown of the Co-60, it is necessary to cool the source with forced air curculation at all times until the heat source system is operating.

4.1.3.6 Power Distribution System

The success and safety of the mission depends upon a highly reliable power distribution system as well as the power source. A preliminary conceptual design of the power distribution system is presented in this section with a block diagram of a typical distribution system for the MUS illustrated in Figure 4-9. An explanation of the system with considerations on the choice of system parameters follows.

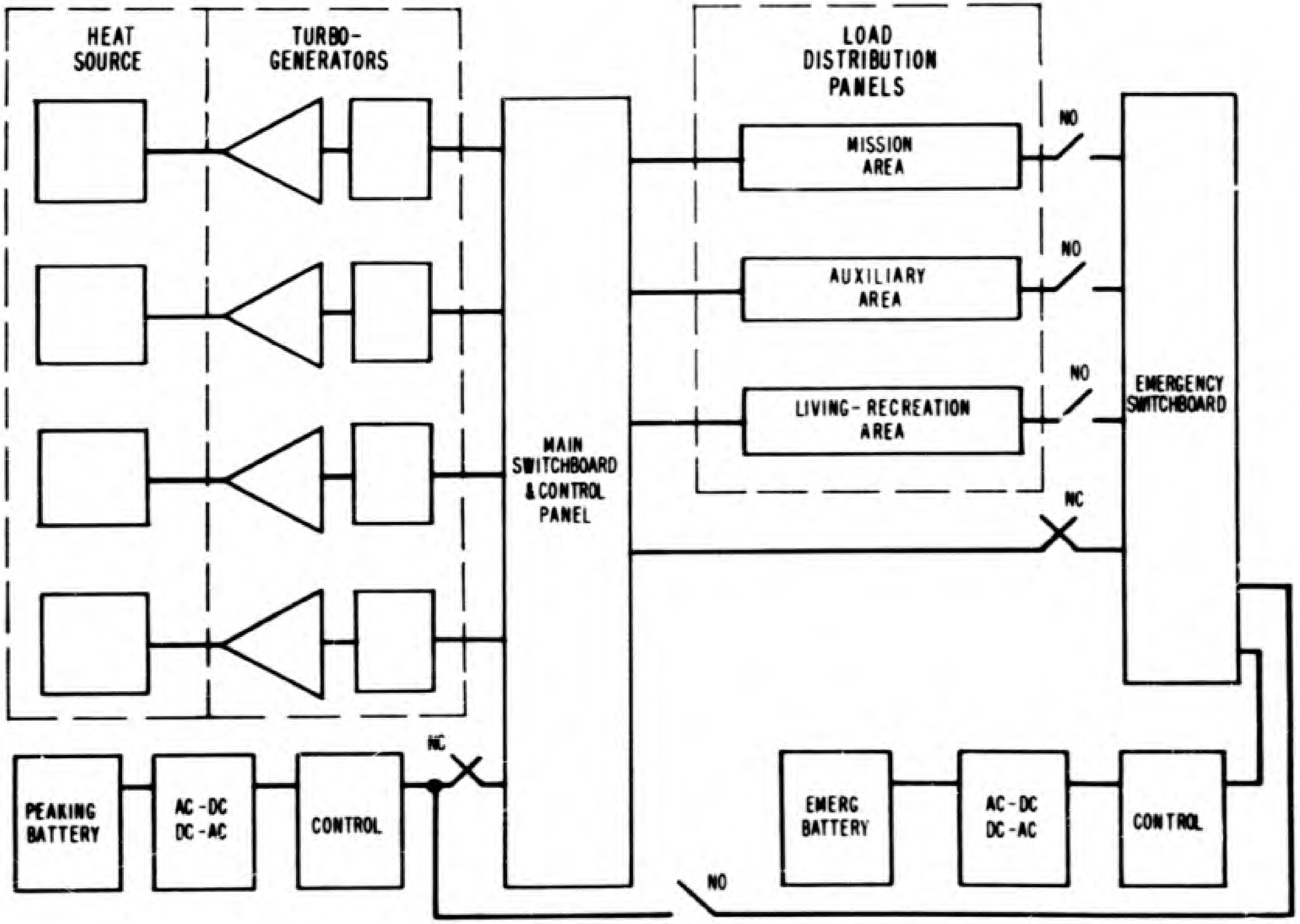


Figure 4-9 Typical Power Distribution System Block Diagram

Four turbo-generators convert thermal power to three-phase, 60 cycle, alternating-current output. Three-phase generation of power as compared to single phase provides a more constant power output and is more economical. In view of the limited scope of this study, 60 cycle power generation was chosen to fully utilize the results of previous design technology. Recent developments in electrical power systems indicate potential advantages with higher frequency systems. Therefore, the power plant design and systems integration tasks will include in the early phases a requirement to re-examine this area to assure optimal power frequency selection.

Control and synchronizing circuits are contained in a main switchboard supplying either 120/240 volts, three-phase power to the load distribution centers. These systems offer maximum flexibility for the requirements of the station since 208 or 240 volts, three-phase power for motors and 120 and 208 or 240 volts, single-phase power for lights and appliances are available. The choice of the voltages will be made in the final design depending upon the requirements of the auxiliary equipment for the station.

Load distribution centers are located in the mission area, auxiliary area and living-recreation area. The motors are not fed from the same circuit as the lights and appliances since overloads and short circuits are more common in motors.

Careful planning will insure equal or near equal distribution between the phases of the three-phase system with circuit breakers provided to redistribute the loads in the event that conditions arise which result in unblanced phase loading.

With the power output of the four turbo-generators limited to 30 Kwe, there will be certain periods when more power is needed. Therefore, lead-acid batteries under ambient conditions outside the habitat are used for the peaking periods. The peaking battery system is designed to supply the necessary power at peaking periods and to be charged during low demand periods, as explained in Section 4.1.3.7. Control equipment regulates the charging and discharging of the batteries. The batteries are kept fully charged by means of a trickle-charge current when not in use. After the batteries have been used during peaking or an emergency, they are given a normal charge to maintain peak efficiency.

A separate emergency back-up for the turbo-generators and lead-acid batteries is provided by silver-zinc batteries, carried inside the habitat. These batteries are of sufficient size for the five day emergency period. Critical circuits are segregated, and an automatic circuit breaker connects this battery in the event of total failure of the normal power supply.

Power for charging both the lead-acid and silver-zinc batteries is supplied by AC to DC converters. Typical types of converters are motor-generator sets, synchronous inverters, or silicon controlled rectifiers. Rectifier converters and silicon controlled rectifiers were selected on the basis of high reliability, efficiency and ease of maintenance.

The overall design of the power distribution system will include all necessary protective devices for maximum safety of the personnel. Redundancy in the various parts of the system is included where necessary to insure maximum reliability of the power distribution system.

4.1.3.7 Power Demand Profile for MUS

The purpose of this section is to define the power requirements of the station and thereby establish the size of the power plant and any auxiliary power equipment which may be necessary. Power demands may be conveniently classed as follows:

Class I: 5 kw continuous power is to be available. The method in which this power is to be utilized has not been specified However, external lighting has been tentatively allocated to this class and also to class II.

Class II: Percentages of an additional undesignated 5 kw continuous power are required as follows:

30% of this additional 5 kw is required 1/3 of the time
60% of this additional 5 kw is required 1/3 of the time
100% of this additional 5 kw is required 1/3 of the time

The above time requirements have not been specified to any greater extent. It is not specified if these are requirements per day or requirements per mission. The latter case may imply ten consecutive days of 100% demand.

Class III: 17.2 kw continuous power is required for life support functions. The general breakdown of this requirement is as follows:

(a)	atmospheric management	12.8 kw continuous
(b)	food preservation	1.4 kw continuous
(c)	water and waste management	3.0 kw continuous

The atmospheric management power requirement may be reduced by 4.5 kw by employing alternate temporary procedures. The maximum time considered for this reduction is six consecutive hours in any 24 hour period.

Class IV: The internal lighting demands for the habitat require that 1.5 kw continuous power be available.

Class I to IV specify the continuous power demands of the station. The main plant must be prepared to supply:

5 kw	class I
5 kw	class II (worst case)
17.2 kw	class III
1.5 kw	class IV

for a total of 28.7 kw continuous power (24.2 kw continuous with the temporary life support reduction). These requirements are indicated in Figure 4-10. For illustration purposes, the reduction due to a temporary shutdown of the atmosphere management facility is indicated as a permanent reduction. Total continuous power demands are indicated under a worst case assumption for the class II demand, i.e. 10 consecutive days of 100% demand followed by 10 consecutive days of 60% demand. Note that the non-continuous power demands of the hotel appliances have not yet been considered. Since the basic generating module is 7.5 kw, a 30 kw plant is illustrated. This is the minimum plant consistent with station design which will satisfy the worst case continuous power demands. The magnitude and distribution of the non-continuous demands will specify whether a larger plant is required or whether batteries can be used to handle the peak loads.

The non-continuous demands of the MUS may be classed as follows:

Class V: The magnitude of the main appliance demands are conservatively estimated as follows:

washer	0.4 kw
dryer	5.0 kw
iron	1.0 kw
percolator	1.2 kw
microwave oven and burner	8.0 kw
recreation facilities	0.3 kw

Figure 4-11 below illustrates the distribution of the hotel appliance demands under the assumptions that:

(a) meal cooking and laundry are NOT done simultaneously
(b) the iron and dryer are NOT run simultaneously.

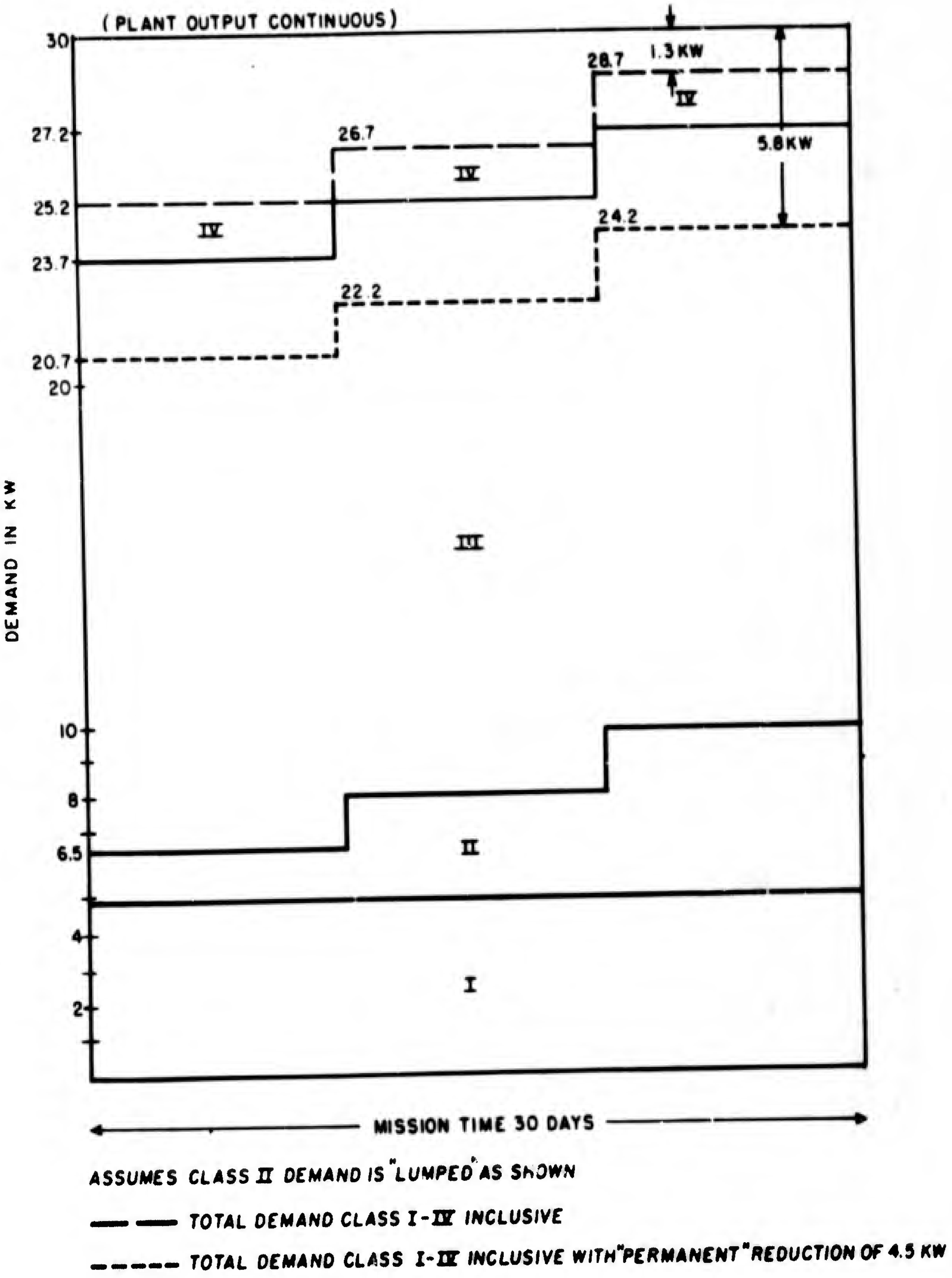
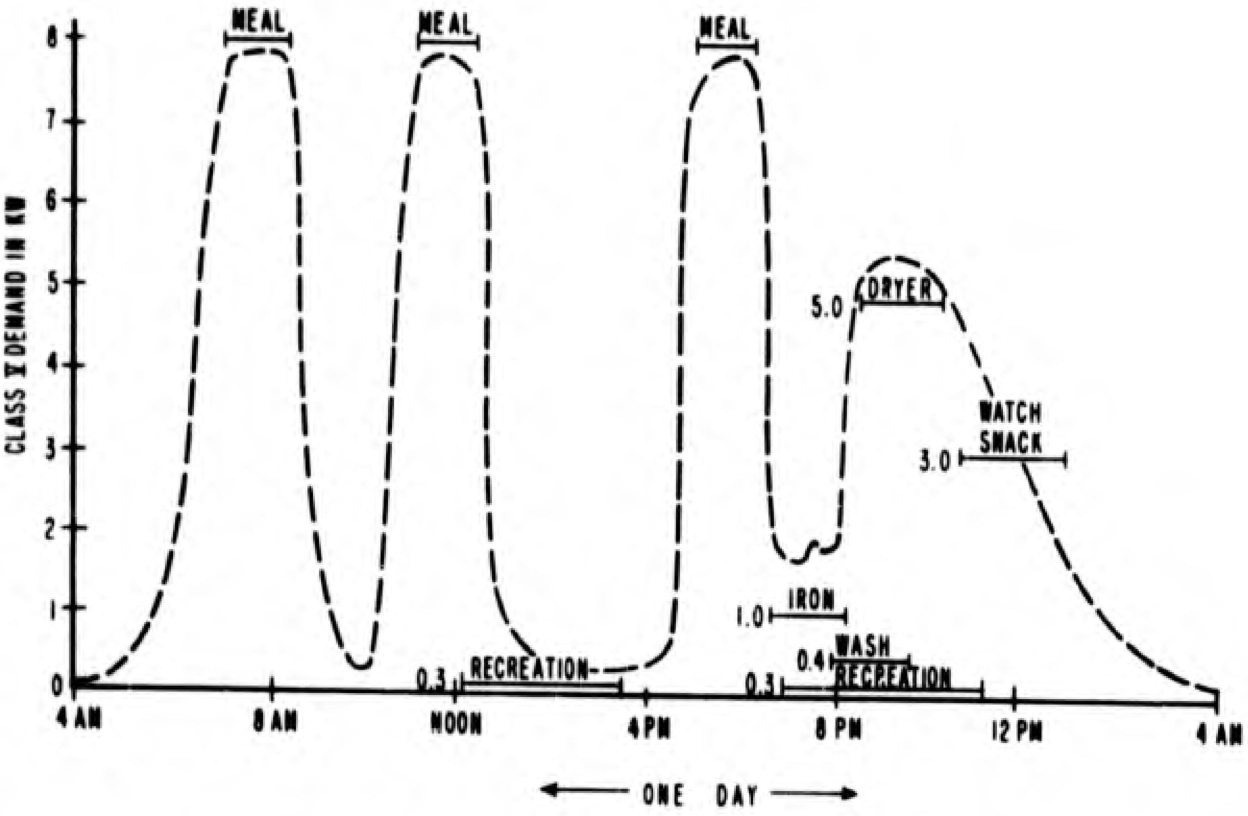


Figure 4-10 Mission Power Demand by Classes



DEMAND SUMMARY:

for 6% of the day, there will be a 8 kw demand (meals 1.5 hrs.)
for 6% of the day, there will be a 5 kw demand (dryer 1.5 hrs.)
for 16% of the day, there will be a 2.5 kw demand (laundry-4 hrs.)
for 72% of the day, there will be a 0.7 kw demand (miscellaneous)

Figure 4-11 Class V Power Demand Profile

Class VI: The power requirements during descent and ascent are as follows: 5.4 kw (7.5 hp) is required to power the hydraulic equipment during descent. During ascent, the primary requirements are for pumping (to change buoyancy) and hydraulic braking; the 5.4 kw (provided for a relatively short period of time, ~6 hours) is sufficient to accomplish this.

Class VII: Provisions for emergency power require that an independent source provide:

5.4 kw intermittently to run the pumps, heater and fans
0.5 kw continuous for emergency lights
0.5 kw continuous for communications.

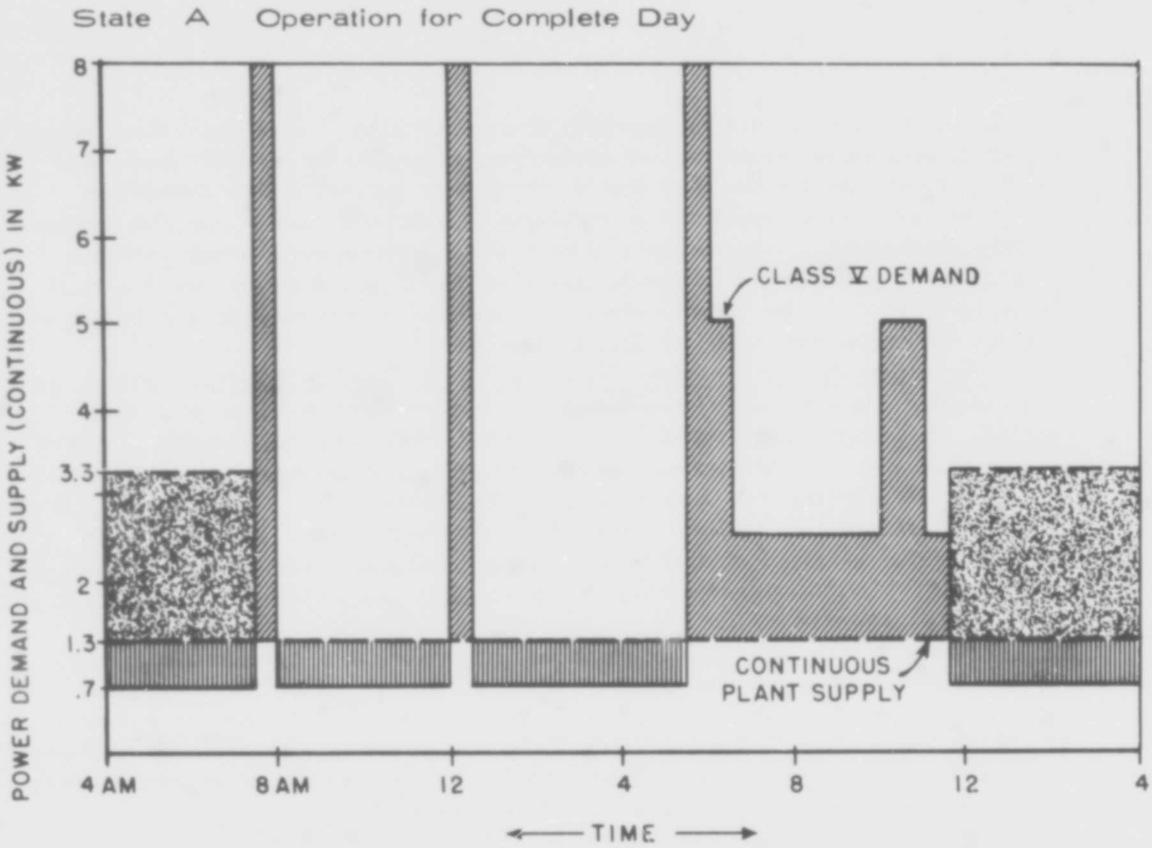
The emergency lights and communications are required for a continuous period of 5 days. The remaining power is required for a maximum of three consecutive hours per day for five days. If an operational reserve of batteries is used to handle both the peak power demands and the emergency power, the batteries must at all times maintain a reserve sufficient to handle the emergency demands. However, since the peaking batteries will be useful as an emergency droppable ballast if positioned on the hull exterior, it may be preferable to maintain the emergency batteries as a separate source inside the hull.

<u>System A - Minimum Power Plant Configuration</u>: As previously stated, a 30 kw plant is the minimum size that will satisfy the continuous station demands. With some modification of the worst case operational requirements, a reserve battery can be used to satisfy the class V peaking demands. In addition, a descent/ascent procedure may be specified which allows these functions to be performed with primary station power. Finally, a silver-zinc battery provides a completely separate emergency power reserve.

Worst case operation is present when ten consecutive days with 100% of class II demand (referred to as state A operation) occurs. In this case, only 1.3 kw continuous power is available to meet the class V demand. This situation is illustrated in Figure 4-12. The energy requirements in excess of that which may be supplied by the plant are (from Figure 4-10)

1.2 kw for 4.0 hrs. = 4.8 kwh/day
3.7 kw for 1.5 hrs. = 5.5 kwh/day
6.7 kw for 1.5 hrs. = <u>10.1 kwh/day</u>
for a total of 20.4 kwh/day

The charging capability for this same day is 0.6 kw for 17 hours = 10.2 kwh which has a converted value (conversion factor 1.25) of 8.16 kwh/day. The conclusion is that 12.24 kwh per day must be supplied from batteries which cannot be charged during that day. In the worst case operation, this situation may persist for ten consecutive days. Two alternatives exist in this situation. First, the required energy (at least 122 kwh) may be provided from a battery which is depleted as needed during the ten days without recharging (the recharging capabilities of the remaining mission time may be used to charge battery for next mission). Although weight considerations may not be critical, the large capacity will be costly. Secondly, the battery can be designed on a per day basis with the requirement that a less demanding state of operation be maintained for a daily period of time sufficient to recharge the auxiliary batteries. The average charging capability per day may be increased to meet the class V demand (on the average) by running the station with the class


State A Operation for Complete Day

▥ Energy available for battery charging: 10.2 kwh/day (converted value of 8.16 kwh/day).

▨ Energy demand which must be satisfied by battery: 20.4 kwh/day

CONCLUSION: 12.24 kwh/day must be supplied from batteries which cannot be charged during that day.

▒ Additional charging capability to meet daily demand (on average) obtained by 8 hr. operation per day in state B (60% of 5 kw) condition.

Figure 4-12 Worst Case Operation - Additional Power from Battery

II demand reduced to 60% of 5 kw for approximately 8 hr/day (see Figure 4-10). In this case, ten consecutive days of 16 hour state A operation per day and 8 hours state B operation per day can be realized with a lower capacity battery that is recharged each day.

For ten consecutive days of state B operation (60% class II demand), there is no problem on the average since the charging capability for any day is 38 kwh converted value, while the energy demand from the battery is only 9.6 kwh per day. Similarly for state C ten day consecutive operation, the charging capability per day is 63.2 kwh converted value, while the energy demand from the battery is only 5.1 kwh/day. In the last two instances, the same battery pack--designed to handle the peak demands of worst case state A operation--can be used satisfactorily.

During worst case operation, the station descent/ascent power requirement is in excess of the continuous power normally available from the 30 kw plant, even though the class V demands are not present during this time. The excess energy required may be designed into the battery source discussed above. An alternate recommended procedure is to terminate temporarily some of the continuous demand of the life support system during station placement. As previously noted, an additional 4.5 kw continuous power from the primary source can safely be made available for a period up to six hours by temporarily modifying the atmospheric management procedures. With this reduction, the 20.6 kw continuous power required during placement or ascent can be supplied directly from the 30 kw plant.

First Approximation for Peaking Battery Sizing: The power distribution for charging and discharging the peaking batteries are given in Figure 4-13. On the average, there is sufficient energy available per day to completely recharge the batteries. Since the battery is augmenting the primary power source, the class V current and voltage loadings--as specified by the actual demands of the various appliances--are not used in sizing the battery; otherwise, no allowance is made for the energy contribution from the plant. In addition, the battery is not directly feeding the load so that actual load demands will not be reflected to the battery. An initial estimate of the size and volume of a lead acid battery can be made as follows:

Consider that the demand upon the battery is concentrated into a 7 hour period (5:30 to 11:30, Figure 4-12) and that the battery is recharged during the remainder of the day. Consider the average battery voltage to be constrained to 120 volts. The

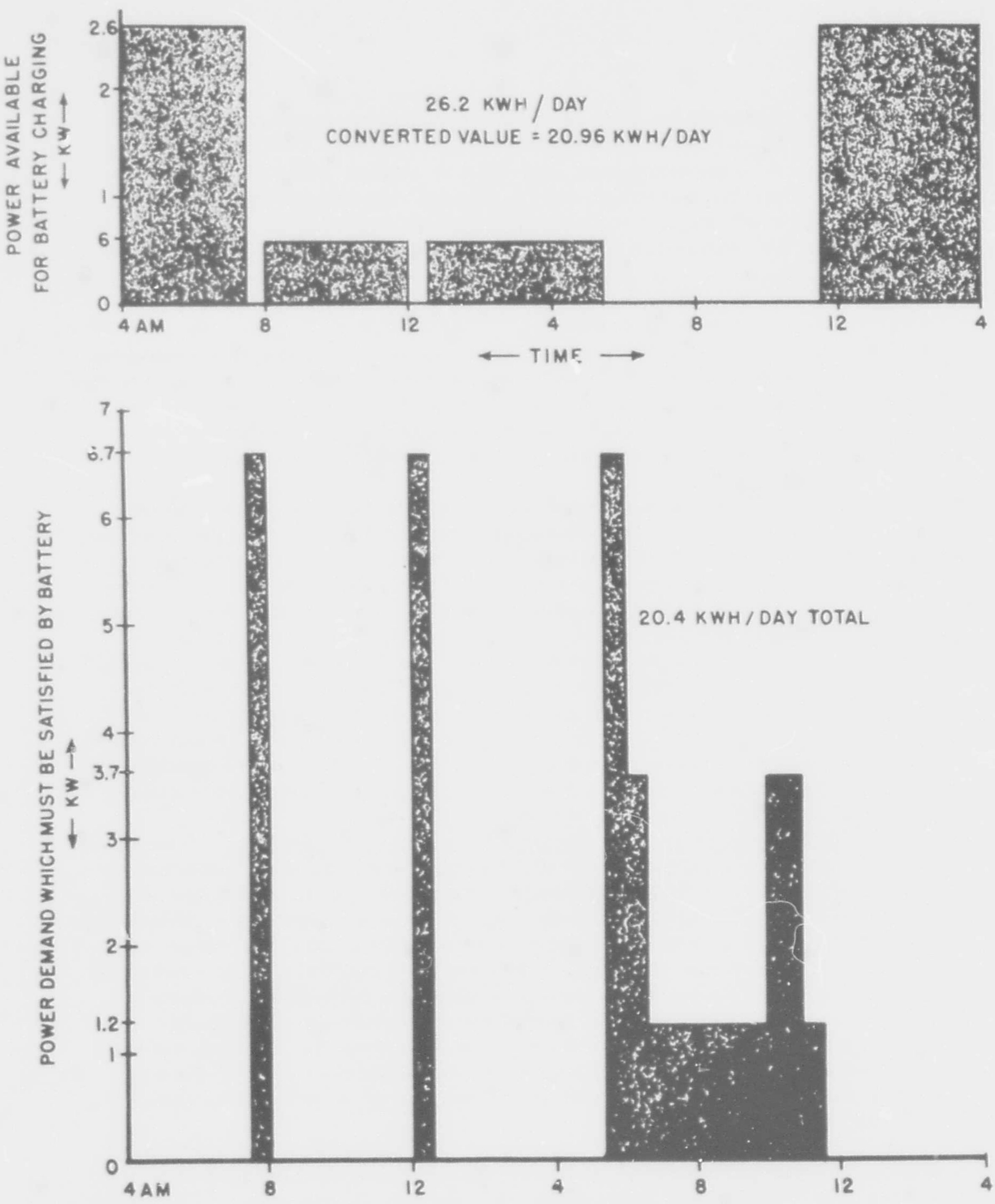


Figure 4-13 Charging or Discharging Power Distribution During Worst Case Operation

energy required from the battery is 20.4 kwh/day which can be supplied with an average battery current of I_{ave}, where

$$(120)\ I_{ave}\ (7) = 20400 \text{ wh so that}$$

$$I_{ave} = 24.3 \text{ amps}$$

Including a 1.5 safety factor, the capacity required is:

$$(24.3)\ (7)\ (1.5) = 250 \text{ amp - hr}$$

Since the seven hour discharge period is considered as low discharge, the single cell weight is:

$$W_1 = \frac{250}{5} \text{ or } \sim 50 \text{ lbs}$$ (see table I of Reference 4-10) (5 hr rate at 30°F)

and the single cell volume is:

$$V_1 = 50 \text{ lbs} \times \frac{15 \text{ in}^3}{\text{lb}} \text{ or } 750 \text{ in}^3$$ (Table III of Ref. 4-10)

The above cell will provide the desired amp-hr capacity. The desired voltage may be obtained by a series connection of N_s such cells where

$$N_s = \frac{120 \text{ volts}}{1.9} \text{ or } \sim 60 \text{ cells}$$ (Table IIA of Reference 4-10) (5 hr rate at 30°F)

Therefore, the total battery weight is:

$W = 50 \times 60 = 3000$ lbs and total volume is

$V = 750 \times 60 = 45{,}000 \text{ in}^3 \text{ or } \sim 27 \text{ ft}^3$

The above estimate does not include corrections for either cell volume or container volume and weight (as recommended in Reference 4-10).

The battery required is primarily low discharge (≥ 5 hrs). Although three high discharge periods do occur (Figure 4-13), no single high discharge removes more than 35% of the watt-hour capacity of the battery. The estimated cost of this battery is (see table V, Reference 4-10) $5,700.

Emergency Battery Sizing: In the interests of safety, it is recommended that the emergency battery be positioned on the interior of the habitat. This will give maximum assurance that the battery will not be damaged by collision and allow for constant surveillance and for easy accessibility in case it is desired to rearrange the wiring configuration. In this case, the gassing associated with lead-acid batteries must be avoided. Silver-zinc (Ag-Zn) batteries are recommended because of their low weight and volume which will ultimately be reflected in a lower cost.

The emergency energy required is:

5.4 kw × 3 hr/day × 5 days = 81 kwh

$$2\ (.5\ \text{kw} \times 24\ \text{hr/day} \times 5\ \text{days}) = 120\ \text{kwh}$$

or a total of 201 kwh over a five day period. Under the same assumption used for the peaking battery computation, the average battery current (@120 V average) I_{ave} required from a Ag-Zn battery is (5 day discharge)

$$I_{ave} \sim 14\ \text{amps}$$

With 1.5 safety factor the required capacity is

$$14\ (1.5)\ (24)\ (5) = 2520\ \text{amp-hr}$$

The single cell weight and volume are

$$W_1 = \frac{2520}{34} \text{ or } \sim 74\ \text{lbs}$$

(Table I of Reference 4-10)
5 hour rate at 60°F

$$V_1 = 74 \times 15 = 1110\ \text{in}^3$$

The number of series cells required is:

$$N_s = \frac{120}{1.48} = 81$$

so that the total battery weight and volume is:

$$W = 74 \times 81 = 7{,}178\ \text{lbs}$$
$$V = 1110 \times 81 = 89{,}910\ \text{in}^3 \text{ or } \sim 63\ \text{ft}^3$$

The estimated cost for the emergency battery is (Table V, Reference 4-10) $162,000. Comparative figures are shown for other battery types.

Type	Total Wt. (lb)	Total Vol. (ft^3)	Est. Cost ($)	Comment
Lead Acid	30,240	267	33,000	Not acceptable
Ni-Cd	22,213	196	211,000	
Ag-Zn	7,178	63	162,000	Low wt., vol.,cost
Ag-Cd	12,535	110	338,500	

4.1.4 Atmosphere Management

4.1.4.1 Introduction

The requirements for atmospheric gasses are based on a habitat size of about 6000 cubic feet. A toroidal arrangement provides a circular airflow pattern which simplified the ventilation system. The activity level and heat output of each occupant ranges from 250 BTU/hour during sleep to 650-750 BTU/hour for light work and walking. There will be an occasional excursion into the area of vigorous exercise expending 1400 to 2000 BTU/hour per man. Commensurate with these energy expenditures, oxygen consumption of 1.95 lb/man-day is taken as a median from United States and Russian sources.

Respiratory quotients (volumetric ration, CO_2/O_2) are quite variable, depending on diet, activity and age. A normal range is 0.75 to 0.95 with the higher value for rest and sleep. An average value of 0.85 indicated a CO_2 output of 2.28 lb/man-day.

Nitrogen is an obvious choice for the inert gas since the total pressure within the hull will be maintained within five percent of the standard atmosphere of 760 mm. Hg. For special missions, a different atmosphere may be required. The atmosphere circulated counter clockwise in the habitat at about 800 cubic feet per minute gives a mean velocity of 12 feet per minute. An air particle thus makes a trip around the mean circumference of the toroid in about nine minutes. This geometry provides an ideal arrangement for life support.

4.1.4.2 Carbon Dioxide

The normal operating point for CO_2 in the atmosphere will be 0.35% by volume with a requirement that the CO_2 concentration remain below 0.75% (5.7 mm. Hg. pCO_2) by volume. Two independent detection devices are recommended. A CO_2 detection cell of the type developed for Project Mercury will be used for hourly checks. It consists of a glass and silver electrode and a permeable membrane which allows CO_2 to diffuse through it and dissolve in a potassium chloride gel containing bicarbonate. The cell is quite small and covers the range of one to fifty millimeters of mercury partial pressure of CO_2 with a stability and accuracy of approximately one mm. Hg. at the 'ALERT' point of 5 mm. Hg. pCO_2.

The second detector is a suitcase size commercial Beckman Model IR215 Infrared CO_2 Analyzer. It consumes 500 watts electrical power when energized. A suggested setting of the adjustable range is 0-2.5% CO_2. At the 'ALERT' point, the accuracy is ±0.2 mm. Hg. pCO_2. This instrument should be turned on once every 8 hours since the increase of pCO_2 is quite slow and although an excess of CO_2 in the atmosphere can be injurious, the buildup is not likely to become critical rapidly. From Figure 4-14, it is noted that 30 or more hours would elapse before crew effectiveness would be significantly degraded.

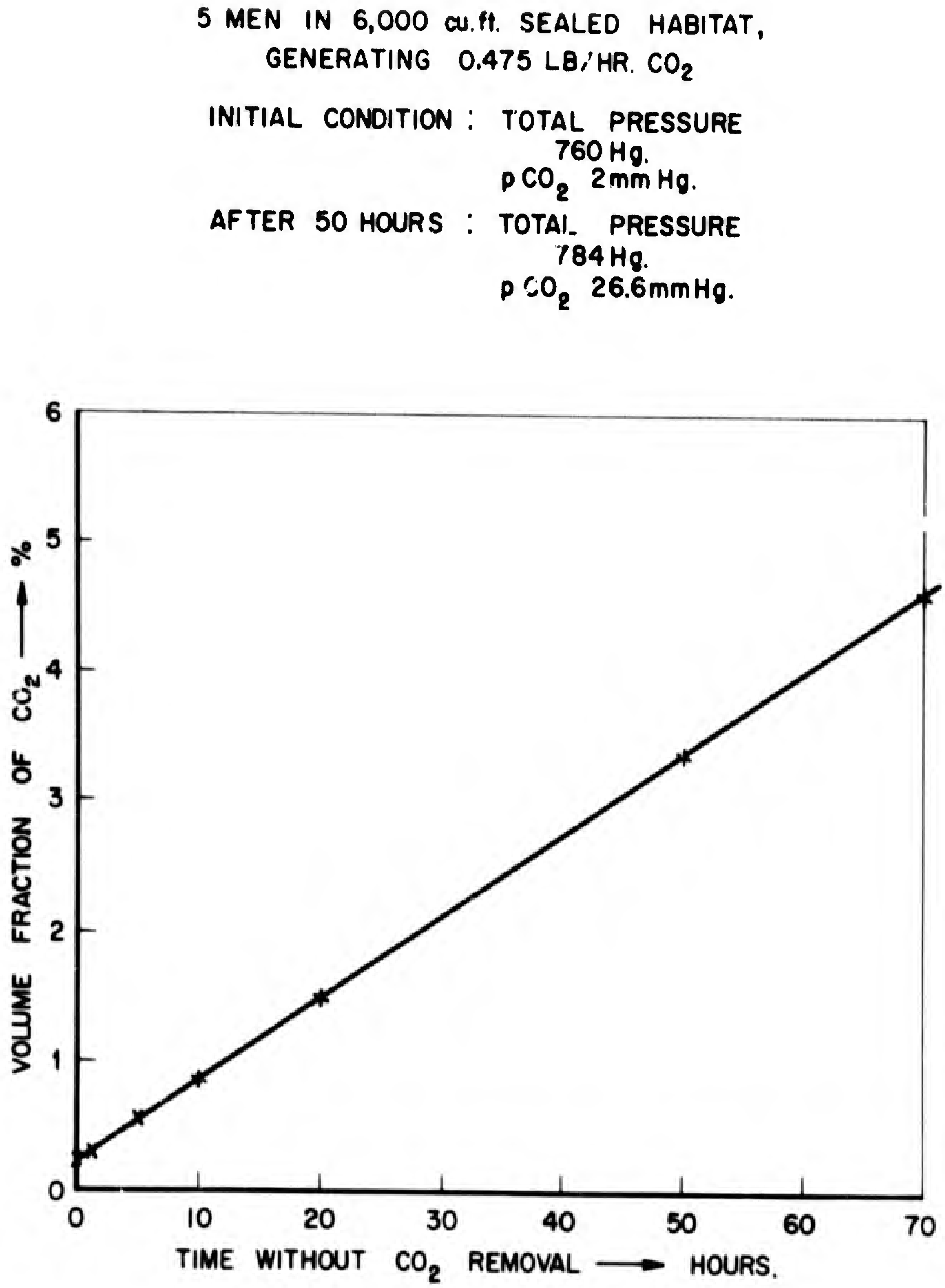


Figure 4-14 Predicted CO_2 Buildup Rate for Habitat

About 400 pounds of CO_2 must be removed during a 35 day mission. This figure is based on a five man crew producing 2.28 lb/man-day or a total of 0.475 pounds/hour. Three methods of removal are feasible:

(a) absorption by lithium hydroxide granules
(b) scrubbing with monoethanolamine (MEA)
(c) separation by refrigeration

The first method is the cheapest since no engineering costs are involved. Only a small fan is required to circulate the atmosphere through the LiOH canister and remove the heat. The chemical reaction is exothermic and produces approximately 605 BTU/hour. If this system were used exclusively, approximately 667 pounds of LiOH would be required for the mission. This would occupy 26.7 cubic feet of storage space. The reliability of the system is exceptionally high. The noise generated would be quite low and the system can be switched off for three to six hours without harm or difficulty.

The second system employs a regenerative cycle using an MEA and water solution. The basic machine is used widely in Naval Nuclear power submarines but is too large for the MUS, and would require substantial engineering to reduce its size. The MEA solution degrades very slowly in use and may last as much as six months. However, it is recommended that change be made about every 30 days. The solution does produce toxic vapors in very minute quantities, but these have not proved to be a problem in submarine operation. For make-up or recharging, the low iron MEA concentrate is mixed with potable water to form the working solution. Plastic containers are required for the mixing operation. Storage of the MEA concentrate does not present a problem. The scrubber itself is designed for continuous operation processing 20 cubic feet per minute of atmosphere. The CO_2 extracted must be pumped overboard or stored. If the latter approach were taken, the 35-day mission would require six 240 cubic foot cylinders weighing 1150 pounds and occupying 18.2 cubic feet. This appears simpler than pumping overboard but the overboard discharge system may be connected to that required to remove hydrogen produced in the oxygen generation process.

For the initial testing of the MUS concept, the LiOH system would be the least expensive approach. However, the MEA scrubber method of CO_2 removal is recommended for engineering development when consecutive missions are planned. For emergency use, a 5-day supply for LiOH should be carried.

4.1.4.3 Oxygen

In a one atmosphere environment the 'NORMAL' point of 21.7% by volume of oxygen is not critical. A ±3.3% variation in partial pressure is suitable and will be used for the 'ALERT' limits of 140 mm and 190 mm Hg. abs. The monitoring and control will be by two independent Krasberg oxygen sensors. These are polarographic cells with reliability and sensitivity easily adequate for the task. They are battery powered and connected to the station power busses through a charger in order to maintain the batteries in a fully charged condition for emergency use. Both units will display partial pressure of O_2 (pO_2) on a voltmeter graduated to read in millimeters of mercury (mm. Hg.) and thus act as a check one on the other. The control cell will also activate the oxygen supply system when pO_2 has fallen from the normal 165 to 155 mm Hg. absolute. Westinghouse has miniaturized the Krasberg cell to a point where a diver can wear it like a wrist watch. The amplifier needed would fit into a cigar box. For calibration and as a further back-up unit, a Beckman Model F3 Oxygen Analyzer will be provided. This instrument makes use of the fact that oxygen is strongly paramagnetic, displacing a glass dumbbell suspended in the field of a permanent magnet. This type of instrument has been in service for many years and will perform reliably to ±1% accuracy of full scale deflection. The size is 15.5" x 18.38" x 11.06" and power drain when in use amounts to 150 watts. If desired, the instrument may be left switched on continuously.

The main oxygen supply calls for 0.406 pounds per hour (4.55 cubic ft./HR) or a total of 341 lb. (3,820 cu. ft.) of oxygen in 35 days. There are two basic ways of supplying this gas: from pressure vessels and by electrolysis of water. The first method is simple commercial practice. Sixteen cylinders each containing 240 cubic feet of O_2 at 2400 psi must be stored inside the habitat and dispensed via suitable regulators, valves and restrictors. This quantity would weigh 2660 pounds and occupy 50.5 cubic feet of space. Additionally, unless a hull penetration and charging from the supply vessel are envisaged, this means handling steel cylinders weighing 118 pounds and measuring 51 inches long through the station supply hatch every 35 days. Storage of pressurized oxygen external to the hull appears attractive at first sight. Points on the 'minus' side would be: (a) a hull penetration is required; (b) submerged recharging of cylinders by the supply vessel is a delicate task akin to in-flight refueling; (c) supply via the hatch means long high pressure lines; (d) an external hydrostatic pressure of 2,670 psi acts on the empty cylinders. This precludes the use of a light structure such as fiberglass.

The recommended source is a Treadwell Electrolytic Oxygen generator built in a size adequate for five men. It would be a little larger than a five drawer filing cabinet, weigh less than 1,000 pounds and provide oxygen as long as it received 2.5 kw of electrical energy and a trickle of fresh water. It also produces two volumes of hydrogen for every volume of oxygen which will have to be pumped overboard against the ambient pressure of 2,670 psi. Neither the oxygen generator as a whole nor the hydrogen dumping need be active at all times and the hydrogen dumping may be done by the same pump as the CO_2 overboard discharge. Temporary shut down to suit military, scientific or other needs is quite feasible. As with the scaled-down MEA scrubber, the scaled-down Treadwell oxygen generator will require an engineering effort and consequently cost several times as much as follow on units.

To provide a back-up system and allow for comfortable extension of a temporary shutdown of the electrolytic oxygen generator, three 240 cubic feet 2400 psi oxygen cylinders will be required together with a regulator, manifold and suitable valving to permit discharge to the habitat or to oral/nasal masks on flexible extension hoses. This would sustain the crew for 150 hours. The bottled oxygen will be located remote from the electrolytic oxygen generator for additional security.

4.1.4.4 Carbon Monoxide (CO), Aerosols and Other Trace Contaminants

On nuclear powered submarines (SSN's), the bulk of the carbon-monoxide in the atmosphere (75-80%) is produced by smoking, which also produces a large portion of the aerosols. Hydrocarbons originate from cooking and lubricating oils, except for methane which stems largely from the sanitary tanks. Organic sulphur compounds and a trace of CO are produced by various body processes. Freon-12 has been found up to 50 ppm where refrigeration circuits containing Freon-12 are in normal repair. Table 4-9 below shows some of the more prevalent contaminants encountered in the atmosphere of a nuclear submarine. Oil base paints, battery gassing and unsuitable bonding cements on furniture can also play a part in atmosphere contamination.

TABLE 4-9 Some Trace Contaminants Found in SSN Atmospheres

	Material		Highest Concentration Normally Found ppm
Hydro-carbons	Methane	CH_4	118
	Acetylene	C_2H_2	0.5
	Pseudocumene 1,2,4 -	$(CH_3)_3\ C_6H_3$	0.57
	m, p - Xylene	$(CH_3)_2\ C_6H_4$	0.95
Non-hydrocarbons	Carbon Monoxide	CO	30
	Ammonia	NH_3	2
	Freon-12	CCl_2F_2	50
	Methyl Alcohol	CH_3OH	6
	Methyl Chloroform	CH_3CC2_3	6
	Nitrous Oxide	N_2O	27
	Vinylide Chloride	CH_2CCl_2	2

It is quite certain that the living pattern in the station will be influenced by submarine experience up to the point when the first unit goes into service. In the ensuing three or four years, a pattern will evolve in the light of direct operating experience. At this stage, one can stipulate the following: (a) smoking will be permitted at certain times; (b) the menus will be geared to avoid frying in an open pan and make maximum use of an induction oven; (c) no oil base paints will be supplied during normal station operation; (d) space cooling, food refrigeration and deep freeze will all be thermoelectric without the need of Freon; (3) personal hygiene, extending to clothing and food preparation, must be maintained at an exceptionally high level.

Carbon monoxide and most organic contaminants can be handled by a catalytic burner. A type widely used by fleet submarines was known as the Desomatic CO/H_2 Burner and is now made by the Mechanical Products Division, Atlantic Research Corporation, Alexandria, Virginia. Air is preheated in a recuperator and then boosted to 600°F by an electrical heater prior to entering the catalyst bed. The Hopcalite catalyst at the elevated temperature oxidizes and burns hydrocarbons to CO_2 and water end products. In the standard model, ship cooling water returns the air temperature nearly to room temperature prior to leaving the unit. A short fresh water loop to a hull mounted heat exchanger can perform the same function in the habitat. A disposable, 50 micron filter is placed in series with the air intake. Depending on the operation of the electrostatic precipitator, this filter may have a 1,000 hour operating life. The unit is smaller than a one foot cube, weighs about 120 pounds and draws 2.2 kw of electrical energy. The logistic load would be 2.5 pounds of material for a 30 day mission.

Hopcalite can be restored to its original effectiveness by 'airing' it in the habitat atmosphere at normal temperature for a few hours. No harmful fumes are given off during this rejuvenitation process. The burner unit also serves to keep the hydrogen content of the atmosphere well below the 3 percent danger point. Body generated organic sulphur compounds and other odor causing organic contaminants will be removed by an activated carbon filter. Space allocation for this should be approximately 3 cubic feet. An electrostatic precipitator will remove aerosols resulting mostly from smoking. This piece of equipment is suitcase size and draws less than 1 kw of electrical energy. It becomes essential if smoking is permitted.

4.1.4.5 Inert Gas and Summary

For the vast majority of conceivable missions, nitrogen will be the most suitable inert gas. Regardless of the type of gas used, there will be a small loss, caused by activity such as mating with the supply ship or providing make-up for station based excursion vehicle. It is proposed that 1,650 cubic feet of inert gas in six steel cylinders at 2,400 psi be carried aboard the MUS, weighing 1,150 pounds and occupying 22 cubic feet of space. An atmosphere management summary is tabulated in Table 4-10.

TABLE 4-10 Atmosphere Management Summary

	Wt(lb)	Volume(cu ft)	Power(kw)	Cost($)
CO_2 Detection	60	1.6	0.6	3,600
CO_2 Scrubber and Storage*	4,600	69.8	2.0	26,400
O_2 Detection	81	1.1	0.3	3,000
O_2 Generation*	1,100	33.0	2.7	62,000
CO/H_2 Burner	150	4.0	2.2	7,500
Precipitator	255	8.4	1.0	7,000
Thermoelectric Heat/Cool Units	472	8.8	4.0	20,000
TOTALS	6,718lb	126.7cu ft	12.8kw	$139,500

*May be supplied by other means; see below.

Use of stored oxygen gas and Lithium Hydroxide for CO_2 absorption gives a net saving of 2350 pounds, 26 cubic feet, 4.7 kw and an estimated $80,000 in the station outfit, but the 90 day mission capability is lost. This arrangement may be potentially attractive in the early phases of the station development since missions are not expected to exceed 30 days. However, for extended mission duration with crew replacement by submersible or when resupply is more expensive, the mechanical O_2 generation and CO_2 removal are more efficient. In any event, the engineering development of the smaller size mechanical life support equipment should be undertaken concurrently with the detail design oi the MUS.

4.1.4.6 Emergency Life Support

To allow mobility during an emergency which impairs normal breathing, it is planned to provide five portable closed circuit breathing rigs. These will permit the crew to act on the emergency at source and possibly restore normal operation. The portable breathing rig will be a modified Min-O-Lung with a three hour (9.50 cubic feet) oxygen supply. In a smoky atmosphere, speed in donning is of primary importance and this need will govern the design of the harness and method of storing the rig. Because the wearer may be facing a fire, the oxygen flask and breathing bags will be on his back. The front of the vest will be of a fire resistant fabric. Carbon dioxide absorption will be handled in a fiberglass lithium hydroxide cannister mounted on the wearer's back. Since this is a closed circuit breathing rig, all the oxygen goes to satisfy metabolic needs and no gases are exhaled to the environment. Quick disconnects will permit the use of the closed circuit rigs connected to the emergency oxygen supply and carbon dioxide absorption systems.

The emergency breathing system is provided with oxygen from 2400 psi cylinders. 600 manhours for men who may be under a nervous strain, although relatively inactive, calls for 0.10 pounds per hour per man or a total of 60 pounds (672 cu feet) of oxygen. This will be dispensed manually via a regulator and high flow and low flow restrictors in parallel. A flow meter will indicate the rate of discharge and a battery operated Krasberg oxygen sensor will slow pO_2 in the atmosphere.

Carbon dioxide will be generated at the rate of 0.11 pounds per hour per man, or a total of 66.0 pounds (540 cubic feet) in 120 hours. Lithium hydroxide is proposed as the absorbant; three cannisters will be provided containing 32 pounds of LiOH each, for a total volume of 2.0 cubic feet. Battery operated fans will provide air circulation.

As previously indicated, the emergency oxygen supply and carbon dioxide absorption systems have T-pieces with valved quick disconnects to permit five closed circuit breathing rigs to be coupled to them.

Hot food will not be available in the emergency situation. Emergency rations for five men for 120 hours weighs 38 pounds and occupies 3 cubic feet. A water allowance of 2.5 liters/ man-day requires a total of 62.5 liters, weighing 32.5 pounds with containers and occupies 2.6 cubic feet. A fifteen gallon capacity emergency toilet with a hermetically sealed cover and a quick action latch will be provided.

Emergency lights from four light fixtures will require a total of 30 w, supplied from a silver-zinc battery. In addition, there will be a four hand flashlight, again powered by silver zinc batteries. A small battery charger will be available. Emergency communications are explained in Section 4.1.7.

4.1.5 Space Heating and Cooling

4.1.5.1 The Environment

At the vast majority of locations, the deep ocean is a few degrees above the freezing point. A reference of 36°F as a maximum and 28°F as a minimum bottom water temperature with a current velocity of 0.2 ft/sec is assumed for a 6,000 foot maximum operating depth. The inside air in the station will be held to the following conditions:

Sleeping Compartment	64°F	66% RH
Work and Recreational Spaces	72°F	50% RH
Machinery and Spares Storage	82°F	38% RH

All relative humidity figures correspond to 0.0085 pounds of moisture per pound of dry air, a vapor pressure of 10 mm Hg. absolute and a dew point of 52.4°F. To simplify calculation, it is assumed that the 72%F, 50%RH figure pertains to the whole of the internal atmosphere. For the shape and size of habitat shown in Section 4.3.2, the gross internal hull area is 2,950 square feet. Except for areas covered by hull heat exchangers, the inside walls will be covered with 1/2" RUBATEX "R321V" bonded to the hull with "FAST BOND 30", a water soluble bonding cement made by the 3M Company. RUBATEX is a silicone rubber. It will not sustain combustion nor produce toxic fumes should a fire occur in the habitat. RUBATEX is pleasant to touch, durable and easy to handle. It is normally supplied in a light beige, can be painted and will effectively reduce the condensation problem. Thermal insulation is inherently provided where the hull rests on a concrete foundation and in areas where flotation material touches the hull. As a rough figure, it is assumed that 3% of the hull area is completely insulated to allow for these two factors.

4.1.5.2 Heat Balance

Thermal conductivity for RUBATEX "R321V" is 0.028 BTU/HR × °F × ft^2/ft. Though a two inch thickness for the steel hull is assumed, a 50% variance in this value is negligible for heat balance. The overall transmission coefficient for the hull and insulation is:

$$u = 0.325 \text{ BTU/HR} \times {}^\circ\text{F} \times \text{ft}^2$$

Estimated heat transfer area:

Total internal hull area	2,950 sq. ft.
15% for heat exchangers	443 sq. ft.
3% for foundation and flotation contact	89 sq. ft.
Net hull area for direct heat loss	2,418 sq. ft.
Estimated minimum heat loss T = 36°F	28,300 BTU/HR
Estimated maximum heat loss T = 44°F	34,600 BTU/HR

Cooling loads attributable to various sources are summarized in Table 4-11. Some allowance has been made for systems which are not active continuously. For unit conversion, the following may be noted:

1 ton of refrigeration = 12,000 BTU/HR
1 HP = 2,545 BTU/HR
1 kw = 1.340 HP = 3,410 BTU/HR

TABLE 4-11 Cooling Load Attributable to Various Sources

SYSTEM	COOLING LOAD BTU/HR	TONS
Main Power Unit	10,000	0.8333
Hydraulic	4,000	0.333
Battery Charging	1,500	0.125
Electronic Equipment	9,000	0.750
"Unspecified" 200 sq. ft. area	6,000	0.500
Internal Lighting	2,500	0.207
Water, Stills, Waste Management	13,000	1.080
Atmosphere Management	16,000	1.333
Galley	3,500	0.297
Food Storage	2,200	0.183
Condensate; Laundry and Showers	3,500	0.297
Metabolic Heat, Crew of 5	5,500	0.457
Total Cooling Load	76,700 (22.5 kw)	6.39

Completing the heat balance for normal operation on-station in the deep ocean yields these values:

	BTU/HR	TONS
Total Internally Generated Cooling Load	76,700	6.39
Heat Loss Through Hull	28,300	2.36
Maximum Cooling Load	48,400	4.03

While this would easily suffice even for an active crew and much of the equipment switched on simultaneously, there could be circumstances when either more cooling load or the need for space heating is called for.

The thermoelectric cooling system recommended will switch to heating merely by operating a polarity reversing switch and duct baffles. About 1.8 kw of heat energy is obtained for each Kwe input. Short periods during launch in the tropics pose no special problems. For prolonged functioning in water above 60°F, thermoelectric cooling systems can readily be expanded by adding an additional module. The wide variety of conditions which may be encountered necessitate a certain degree of flexibility in the equipment of the station and may understandably require modifications in outfit when site conditions differ drastically between successive emplacements of the same structure.

4.1.5.3 Dehumidifying

Water vapor will enter the habitat atmosphere from a variety of sources. Each man exhales roughly 1.10 lb/day and looses an equal amount from his skin surface. Food preparation, showering and laundry put moisture into the atmosphere. Vapor will be condensed from the atmosphere by chilling to the dewpoint of the desired end state (52.4°F) and then reheating to approximately 60°F before discharge to the habitat. This reheat would be supplied by passing the air through the hot side fins of an air-to-air thermoelectric module. This method gives considerable flexibility through series heating and a by-pass. Condensed water will be returned to the station storage system, described in a later section.

4.1.5.4 Cooling System Slection and Location

Three methods of air conditioning the station are feasible:

- Direct cooling in a heat exchanger using 36°F seawater
- Vapor compression systems, similar to those in use in homes and offices
- Thermoelectric cooling

Using the cold ocean appears attractive at first glance, but there are several drawbacks. A simple hull contact heat exchanger would be too large and unwieldy. Hull penetration and power are required to pump sea water through an internal heat exchanger. Cold sea water is of no use when space heating is required.

Vapor compression systems use fluids which can generate toxic vapors and even with extreme care, recent experience in submarines indicates that substantial atmosphere contamination may occur. The design approach providing even partial safeguards leads to a system more bulky and heavier than the one recommended. The vapor compression system also requires compressors and fluid control devices which generate noise and give rise to reliability and maintainability problems.

A thermoelectric direct transfer cooling system made up of two identical units is recommended. The habitat air itself is the heat transfer fluid in this system, so that water circuits and associated pumps, make-up tanks and piping are entirely eliminated. There are standardized one ton modules for this type of application. Each unit will have its own power conversion and controls, so that only electric power need be brought to the equipment. All allowance of 100 watts per ton of cooling has been made for control and conversion losses in the habitat cooling load.

A schematic of the system is shown in Figure 4-15. It will be seen that the arrangement is symmetrical, identical hotside ducts being located on either side of a central cold side duct. For ease of reference, the squares have been numbered.

Air enters a hull heat exchanger, square 1, and gives up heat to the ocean. Air thus cooled goes into the hot fin side of an air-to-air thermoelectric heat pump element, square 2, where heat is added. This sequence is repeated through squares 3, 4 and 5. The air stream through each side is now turned and combined in square 6. It is then lead into the cold fin side of a thermoelectric element, square 7. It is further cooled in the cold fin side of the lower thermoelectric element, square 9. The air is now at the dew point of the final desired condition and ready for reheat. This can be accomplished for example by taking the right side out of the main stream, omitting the hull heat exchangers in squares 1, 3 and 5 and letting the hot fin side of the thermoelectric elements at 2 and 4 serve as air reheaters. In practice, there would be many such elements and great flexibility is possible by series and parallel combinations. The temperatures shown in Figure 4-15 are meant to be illustrative only.

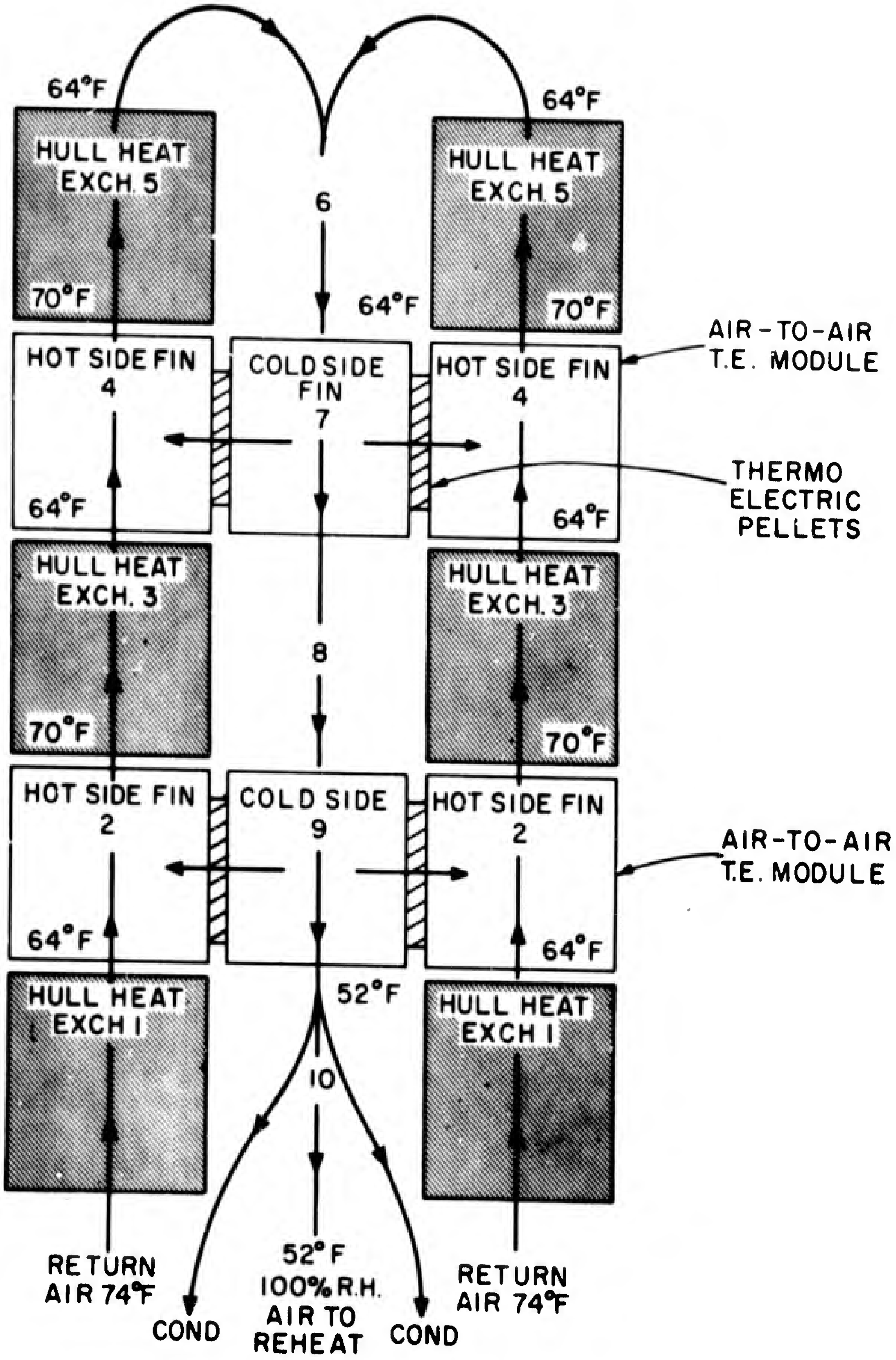


Figure 4-15 Thermoelectric Direct Transfer Cooling System Schematic

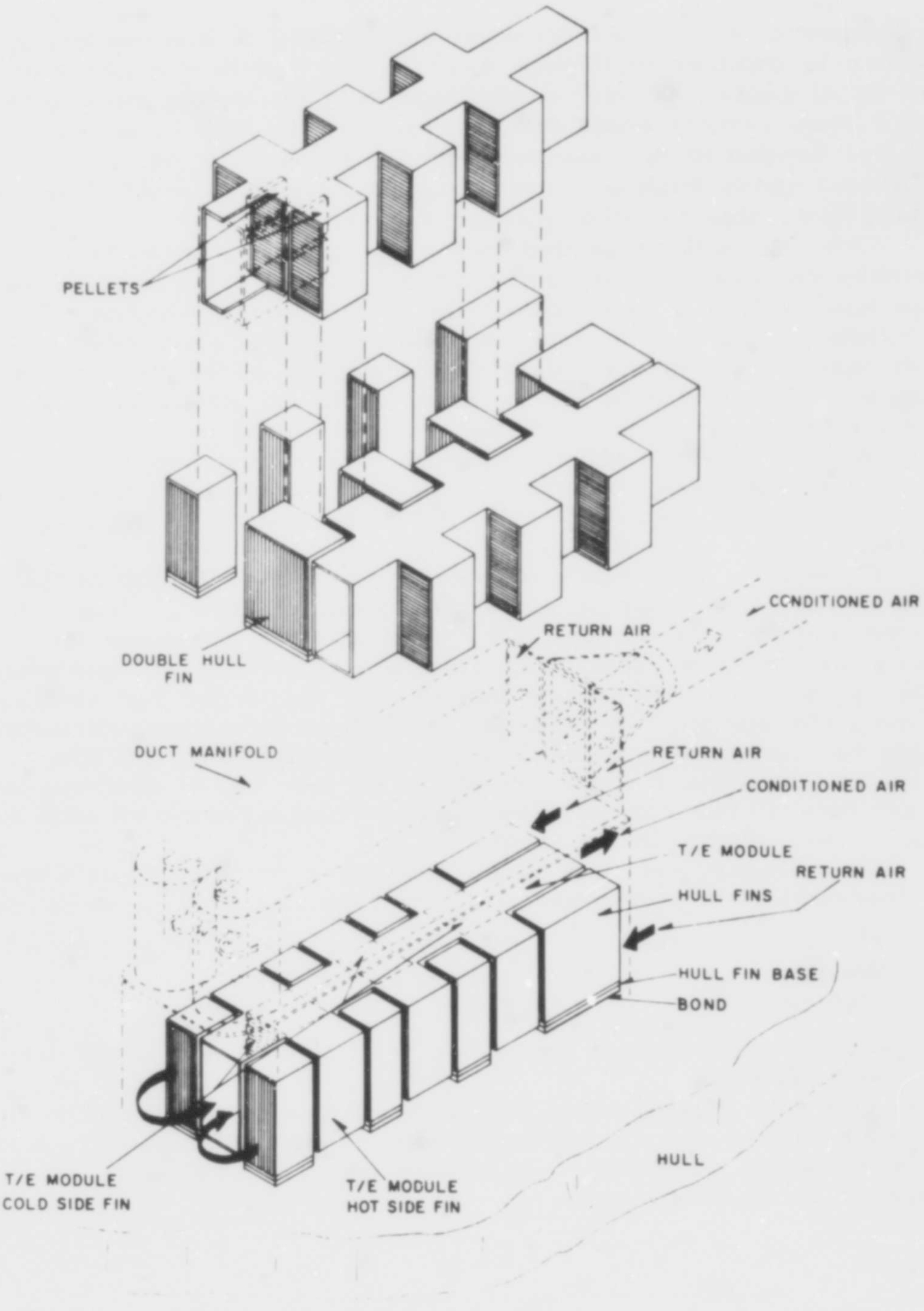


Figure 4-16 Air to Hull Fin T/E Air Conditioning Unit

An isometric view of an arrangement utilizing 3 thermoelectric modules is depicted in Figure 4-16. The hull heat exchangers may be of copper or aluminum, depending on weight considerations. They project about two inches from the hull inner surface and are bonded to this surface with an epoxy. A bonding technique and epoxy thickness have been developed to give a satisfactory joint, able to accommodate thermal cycling.

One unit will be located in the "Unspecified" area and will normally remove the heat and moisture input from the crew and hotel type activity. In keeping with the counter-clockwise air circulation in the toroid, one unit will be located downstream of such heat producing equipment as the oxygen generator and MEA CO_2 scrubber and followed by a stores area, producing neither heat, moisture or noise. In this way, the sleeping crew members would receive a quiet supply of the cleanest and coolest air. Both hull heat exchangers and thermoelectric modules can be located in the segmental ceiling of floor spaces of the toroidal habitat.

Generally, hull heat exchangers can transmit 1200 BTU/ square feet, with a temperature differential of 20°F. (i.e. 10 square feet per ton of cooling.) Making some allowance for fouling and using a value of 12 square feet per ton refrigeration calls for a total of 48 square feet of heat exchanger for air conditioning the station. A separate fan will be provided with each of the two ton cooling units. Using a rule-of-thumb air flow figure of 400 cubic feet per minute (cfm) per ton of cooling gives an air flow of 800 cfm for each unit. This agrees well with the desired air velocity in the toroid.

In making power and space allocations for the direct transfer thermoelectric cooling system, the following figures were used:

Power Required	1.00 kw/ton of cooling (i.e. COP=3.5)
Weight	118 lb/ton of cooling
Volume	2.2 cubic ft/ton of cooling

The above values include fans, heat exchangers and power conversion equipment.

The only moving parts associated with a thermoelectric system such as the one recommended are fans to pump low pressure air at moderate velocities. In consequence, the reliability of such a system is unusually high.

4.1.6 Food and Sanitation

4.1.6.1 Food

The station is self-sufficient for a period of at least 90 days with no appreciable increase in size or weight beyond that required for 30 day capability if provision is made to pump hydrogen and carbon dioxide overboard. It would thus be undesirable to limit the mission time by food supplies planned for a 30 or 35 day period. For this reason, when quantities are mentioned, they are called out for both 35 day and 90 day mission duration.

Storage for food will be split up as follows by volume:

"A" 15% deep freeze at -40°F
"B" 20% zero storage at 0° to +4°F
"C" 10% chilled storage at 36° to 40°F

The remainder is shelf storage at 50° to 60°F

Cooling will be done thermoelectrically, with cabinets so arranged that "A" will pump heat to "B" from whence it will be pumped to "C". Final heat rejection from "C" will be through the hull to the ocean. Cool shelf storage will be provided simply by having cupboards close to the hull, with very light thermal insulation on both hull side and room side.

The pre-packed meals and other frozen foods will be stored in the deep freeze and zero storage. Those in the zero storage will be used first and replacements moved up from the deep freeze several days before planned usage. Suggested menus and an associated operating plan will provide a basis for a logical stowage of food so that minimum time access to the low temperature areas is required. The zero storage will safely hold ice cream in airtight wrappings and naturally, the ice cube trays. The chilled storage is provided for items stored for short periods, such as fresh vegetables, and fruits and items not fully consumed requiring cool storage for a day or so.

Dry storage on cool shelves covers all the stable items like sugar, salt, tea and coffee. Dried soups and other food requiring reconstitution with water would be kept here. Though frozen or "instant mashed" potatoes are most practical, if fresh potatoes are stored on board, they would be kept in this cool shelf area.

Beverages would include a wide range of fruit juices, stored at 0°F, tea and coffee and chocolate made with dried milk blended with plain water. No special storage problems are posed. From a logistic aspect, water for drinking and cooling is covered under the water system.

Assuming a varied diet of high quality food with only a small fraction provided in the freeze dehydrated form, the following intake should be used per man per day:

Food, 2.8 pounds - 0.2 cubic feet
Water, 3.4 pounds - 0.05 cubic feet (1.54 liters)

The requirements for a five man crew as shown in Table 4-12 below:

TABLE 4-12
Food Storage, Five Man Crew, 35 Day and 90 Day Mission

Item	Weight, lb.		Gross Vol. Cu. Ft.		Power Continuous KW
	Mission Duration, Days				
	35	90	35	90	
1. Food and Wrapping	500	1280	36.0	92.0	----
2. Deep Freeze, -40°F	165	396	8.1	19.4	0.8
3. Zero Storage, 0°F	150	360	8.0	19.2	0.5
4. Chilled Storage, 38°F	82	197	5.2	12.5	0.06
5. Shelf Storage, 55°F	305	733	21.6	51.8	----
Total, 2 through 5	702	1686	42.9	102.9	1.4

Arranged as a countertop unit, the deep freeze, zero storage and chilled storage would make a module 33 inches high, 30 in. deep (average) and 90 in. long. As the deep freeze unit is depleted of food, the following substances would be stored there in hermetically sealed tins:

(1) Human feces in sealed plastic bags.
(2) Wet, objectionable garbage, e.g. acid or toxic residue from equipment, again in sealed plastic bag.
(3) Any moist food residue after dewatering in centrifuge or hand press.
(4) Space permitting, any small discarded items not ideally suited for dry/garbage storage bin. These can be stored in zero storage also, if desired.

4.1.6.2 Sanitation and Water Management

To pump 100 gallons of water overboard against an ambient pressure of 2,670 psi requires the expenditure of 9,000,000 foot pounds 11,600 BTU or 3.4 KW.HR) of energy. With average care, this would last five people almost half a day. Using shower and laundry water to flush toilets, which is not demanding in terms of engineering and equipment, can bring the per capita consumption down to 6 gal/day. Such an open system, relying on fresh water brought to the station, poses very substantial logistic problems for a 90 day mission. Sea water can be taken in and distilled, supplying a system much as described above. This requires the additional power for distillation but eliminates a massive supply problem. For a 30 day mission, there are a number of variants possible, using a combination of sea water distillation and retreatment of used water, leading eventually to an almost completely closed system. Recovery of the small amounts of water in feces and some wet garbage is neither necessary nor practical for such an underwater station.

Supplying the habitat with fresh water by submersible vehicle at 6 gal/man day could only be entertained if a severe limitation of power existed aboard the station. For interest, system requirements would be as shown in Table 4-14.

TABLE 4-14 Open System, Fresh Water from Shore

Item	Weight, lb.		Vol., cu. ft.		Power KW
	Mission Duration, Days				
	35	90	35	90	
Water, Liquid Only	8770	22520	140	361	---
System Full	10050	25000	156	402	0.5

Using a sea water still to generate fresh water aboard and relying on drain water from shower and laundry facilities to flush toilets will eliminate the need for any water brought from shore. This is the system presently used aboard our submarines. Very rough estimates indicate the system power requirement as 5.5 kw. Weight and volume of the system would be determined by redundancy requirements. An allocation of 2,500 pounds and 85 cubic feet should be made.

Arrangements where very nearly all water aboard is treated and recycled have been described for use in space stations. A system of this kind has been proposed for a submersible vehicle. In this instance, three separate subsystems, each at a different level of contamination, were used in cascade fashion. Urinals are included in the system, but feces were collected and stored separately. To minimize carry over of volatile organic matter to the distillate, vapor-compression vacuum distillation units are offered. A further advantage of this type of distillation unit is that it only requires electrical power to operate. Activated carbon beds treat distillate for taste and odor. Filters and settling tanks remove large contaminants. The system considered most promising for the station is shown schematically in Figure 4-17. Size and weight would depend very much on the degree of redundancy desired in items such as filters, pumps and stills. It is anticipated that it would not be very much larger than the system using a sea water still and pumping waste overboard. Power requirement would be less, probably of the order of 3 kw.

The mountain of garbage normally generated in a home or aboard a surface ship can be vastly reduced by advance planning. The most difficult problem is presented by the collection and disposal of feces and wet garbage from the galley. By suitable design of an appliance, separate collection of feces and urine is readily possible. Feces will be collected in plastic bags and sealed. The plastic bags will then be placed into tin cans, which are hermetically sealed with a small crimping machine. Wet garbage from the galley sink can be dewatered in a small handpress, dropped into plastic bags, and sealed in tins. Both feces and wet kitchen garbage will ultimately be stored in the deep freeze compartment at -40°F. This treatment precludes the risk of a health problem and metal containment should satisfy the aesthetic need. Dry waste, ranging from empty spare cartons to broken combs, can be compressed, baled and stored in a trash bin. Logistics of waste material as finally packaged are estimated as follows:

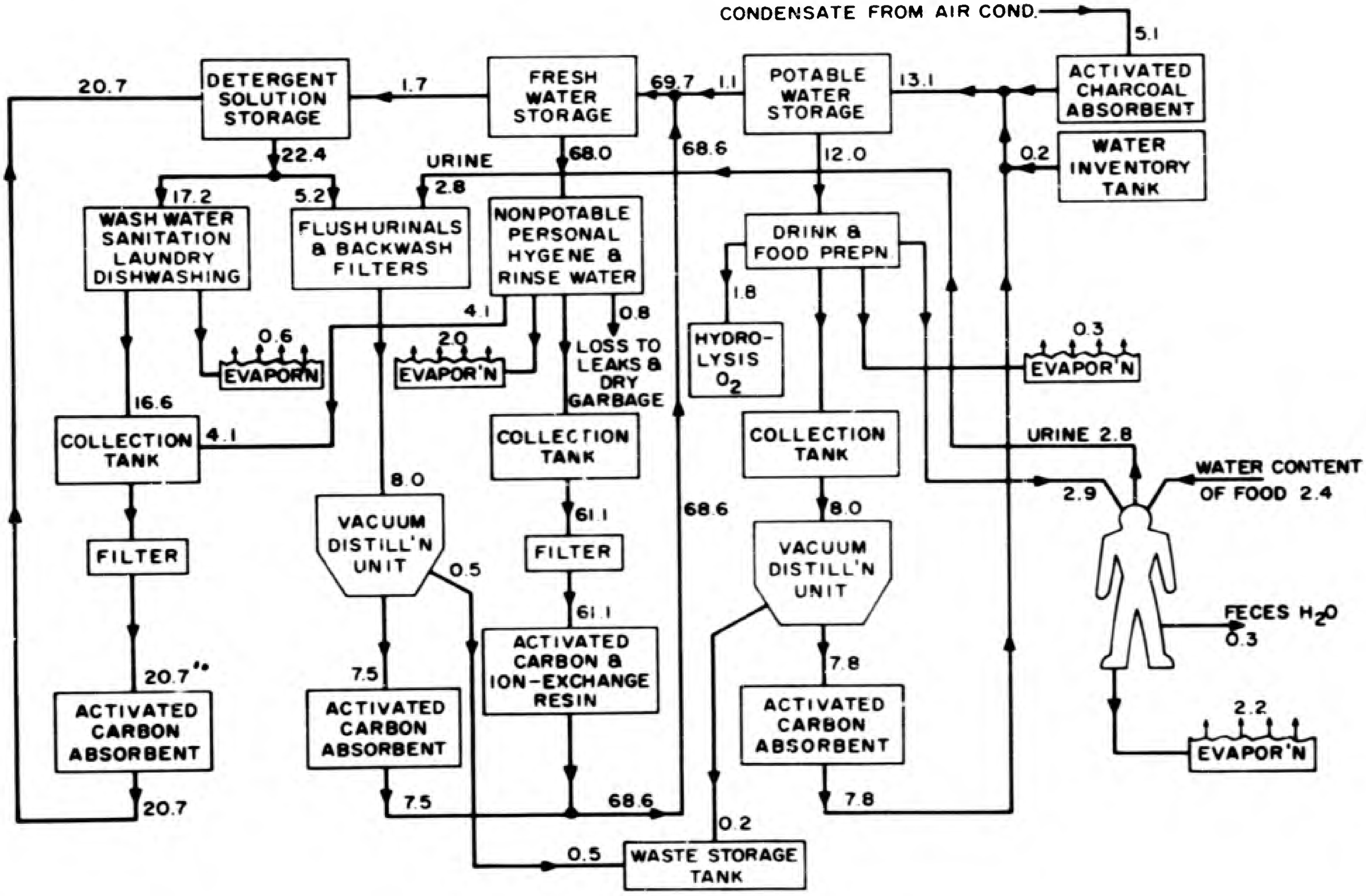


Figure 4-17 Water Re-use System Schematic (quantities in pounds per man-day)

	35-Day Mission	90-Day Mission
Feces	144 lb., 1.9 cu. ft.	370 lb., 4.9 cu. ft.
Wet Garbage	98 lb., 1.2 cu. ft.	251 lb., 3.1 cu. ft.
Dry Garbage	87 lb., 1.6 cu. ft.	224 lb., 4.0 cu. ft.

For an extended series of missions with "surfacing" every thirty days, the less expensive alternative of an open water system may be desired. There is room and weight capacity within the structure design for a one-time water use system with either pumping overboard or internal storage, depending on the electric power availability and buoyancy conditions. However, development of the triple use water management subsystem is recommended to support missions in excess of thirty days or those where submersible resupply is required. In a larger station complex with abundant electric power, sea water distillation coupled with a one time fresh water usage is recommended. Operational constraints should therefore be the basis for final determination of the water system specified for a particular mission or series of missions.

4.1.7 Communications

Two way communications between the station and the surface support vessels are vital to successful maintenance of the MUS on the bottom. Information from the surface ranges from reassurance of the presence of assistance to news of current events. Experience with SEALAB has indicated that constant communications are invaluable to the crew. The MUS completely self contained life support will reduce the men's need for constant manifestation of the surface support, without eliminating that need. A high bandwidth (video) down link would provide the further advantage of televisions transmission for more varied recreation. Adequate communications from the MUS to the surface are a safety requirement to provide information as to the need for assistance under emergency conditions, and for assurance to the surface of satisfactory conditions within the station.

Data transmission from the MUS could include automatic or manual monitoring of various station internal environmental parameters and equipment status, plus any mission data that may be desired.

A sonic voice communications link, compatible with the AN/UQC-1 underwater telephone will be the primary communications link between the MUS and other vessels. This will provide fairly reliable communications through the water column, with a choice of conical or toroidal transducers, depending upon the location of the surface ship. The hardwire is the secondary communications link.

The hardwire link will be co-axial cable to allow high bandwidth video signals. These may be multiplexed with the two-way radio, or may be used on an alternate basis of either two-way radio, single direction video, or single direction high data rate digital code.

CW transmission (code) will be provided for the sonic data link for use during propagation anomolies (or at long ranges) which reduce the signal-to-noise ratio beyond that required for reliable voice communications. The reduction of bandwidth will improve range performance by 20 db, or more, thereby allowing communications to continue except in the most severe conditions.

The sonic communications link will also serve for communications with the support submersible (DSRV or DSSV) or with the work submersible supported by the MUS.

For emergency situations, several other provisions should be made for communications:

(a) An external, self-powered pinger, turned on automatically in the event of power failure (or other failures) within the MUS.

(b) A buoy containing a self-powered UHF transmitter, automatically released from the station under certain emergency conditions.

The required equipment and technology for the prototype station is current state-of-the-art. Future developments in the station operational concepts that include covert missions may require development coordination with Naval communications specialists.

4.1.8 Outside Viewing and External Attachments

4.1.8.1 Viewport Arrangement

The complement of the Manned Underwater Station has many reasons for viewing the surrounding ocean ranging from the necessities of observing the station foundation for stability, settling or undercutting, through many scientific and mission requirements, to the recreational value of observing the life in the sea. The toroidal shape allows extensive regions for free and unobstructed vision but a variety of viewports, peepholes, lighting and viewing aids are required to take full advantage of the shape.

Several large viewports will be the primary means of exterior viewing supplemented by peepholes to fill in blind spots and to provide coverage for regions of special but only occasional interest. The viewports will probably be 10 inch diameter flat plate acrylic plastic yielding coverage of about a 90° (full angle) cone. The critical angle due to index of refraction limits the coverage to an absolute maximum of 96° for a single flat plate viewport. "Bubble" shaped viewports could yield larger angular coverage, however, there is little or no history of performance on bubble viewports at any significiant depth. It is considered necessary to develop and carry out a testing program to determine the effects of long term pressure on acrylic windows to insure the safety of the habitat. Short term tests of windows and operations with small submersibles have proved the suitability of using acrylic windows under high hydrostatic pressure loading. (References 4-11 and 4-12.)

However, no reports of long term loading tests or experience have been found that would establish a high confidence level in specifying an acrylic or for that matter any transparent material with suitable optical properties for other than short term usage. A secondary aim in a test program of this type would be to examine the pressure capabilities of "bubble" type windows. As an additional safety feature, water-tight covers may be provided to be hydraulically positioned in place outside unmanned viewports, at least until adequate experience has been gained on long term pressure and creep effects of the window materials.

Five large viewports will provide the desired primary coverage in the horizontal plane. Three of these, will be located in the mission or work area. Two will be spaced 70° apart with their axes pointed 20° below the horizontal. This line of sight along the viewing axis intersects the bottom at about 35 feet from the station which is a normally expected range of vision. This angle also provides some view of the bottom from almost directly below the viewport out to the limits of vision. The third mission area viewport will be approximately centered between the first two with its axis 15° above the horizontal to provide a better view out into the sea. The remaining two viewports will be spaced clear of the bulkheads in the berthing and recreation areas with their viewing axes 20° below the horizontal. Large viewports are not planned for the power plant or life support areas.

Cleaning of the external surfaces of the viewports may be required in turbid water, and particularly at the shallower depths. Accumulation of silt and sediments will be kept to a minimum by the downward orientation, but there still may be some accumulation over a long mission. Marine life attracted to or sustained by the interior lights may also agglomerate on the outer window surfaces. A completely external flushing system using filtered high velocity sea water to wash contaminants from the viewport surfaces will be provided. Mechanical wiping of the viewports is not initially specified, even though a "windshield wiper" attachment for the external windows and lights would warrant consideration if the flushing system should prove inadequate.

The viewports will be supplemented by several peepholes, each covering a 70° cone. The peepholes have a reduced light gathering ability as compared to the viewports, and the inconvenience of bringing the eye to the optics limit their use. However, for short period special purpose use, the peepholes provide vision at a much lower cost than viewports. A peephole will be provided on each side of the mating hatch to assist the support or work submersible in proper mating and to evaluate the performance of the mating system. Some peepholes will have external rotatable prisms and lights to examine the hull surface. One will allow observation of the lowering and raising winch system, and three will observe the regions of contact between the hull and the foundation. Others will be positioned to insure that those inside can observe any necessary external operation or surface contact. An alternate to the peephole is the "fisheye" periscope built by Kollmorgen for submersible use and these will be specified if proven successful. With the five large viewports and numerous smaller devices, there will be complete visual coverage of the ocean surrounding the structure and all vital portions of the habitat exterior.

The viewports will be further supplemented by four external television cameras. Two of these will be placed symmetrically about the mission area and will have pan and tilt control to provide maximum coverage. One will be directed at the winch system and one will observe the mating hatch.

Photography will depend upon "hand held" cameras operating through the viewports. Many of the users of today's submersibles such as DEEPSTAR prefer internal, hand held cameras. In the MUS, the film reloading problems virtually rule out external cameras. Use of cameras inside the habitat will allow greater versatility with a choice of still or moving pictures, color or black and white and various focal length lenses. It is anticipated that exposed film would be retained on board or sent to the surface with the support submersible rather than developed on board.

4.1.8.2 Lighting

Lighting for exterior viewing requires a cumulative power load which will exceed the total power generation capabilities of the station. Thus, each external light will be individually controlled, with a power status indicator showing the available electric power. Two short arc modified mercury vapor lights, well matched to the light transmission window in water, will be positioned to illuminate the field of each viewport. A single light will be provided for each peephole and television camera. The lights for the mission area television cameras will be on the pan and tilt platform to follow the cameras.

A pair of incandescent lights will be located at each of the mission area viewports. These lights will have a broader spectrum suitable for color photography, and useful in viewing certain colored objects (such as red against a black background) which have poor contrast when viewed under the narrow spectrum mercury vapor lights. A smaller light will be provided for each of the peepholes.

Despite the one year period for which the MUS is designed, the life of the lights will range from 1000 to 2000 hours. Development and fabrication improvements of the high efficiency mercury vapor lights should yield a life expectancy of 2000 hours by the time of station deployment, with adequate light output for their full life. The quartz-iodine incandescent lamps are designed to maintain their light output over their full life. The light output of normal quartz lamps gradually drops off with length of service because of a film deposited on the quartz inner surface. The iodine chemically combines with the elements responsible and effectively prevents the formation of the light absorbing film. The inherent nature of a high efficiency incandescent lamp results in a limited lifetime but a 1000 hour capability is expected. These short life times are compatible with the station bottom endurance since no one light will be burning as much as 20% of the time, and the incandescent lamps will not exceed 10% duty. (30 days x 24 hours/day = 720 hour mission; 1000 hours = 46 percent of a 90 day mission.) Defective or overage lights would be changed at the surface. The power consumption figures for the various lamps are shown in Table 4-14.

TABLE 4-14 Exterior Lighting Power Consumption

Modified Mercury Vapor 1000 Watts 2 per Viewport 5 Viewports	10,000 Watts
Quartz Iodine Incandescent 500 Watts 2 per Viewport 2 Viewports	2,000 Watts
Modified Mercury Vapor 250 Watts 1 per Peephole 12 Peepholes	3,000 Watts
Modified Mercury Vapor 1000 Watts 1 per Television Camera 5 Television Cameras	5,000 Watts
Combined Power Requirement	**20,000 Watts**

4.1.8.2 Viewport Design Introduction

Although a detailed design is beyond the scope of this study, a few important considerations are pertinent. A large flat window of 10 inch diameter on the inner surface would probably require an acrylic material thickness greater than the 4 inch maximum plate currently available. This can be solved by employing a laminated technique similar to that used on the TRIESTE since the maximum thickness is expected to be less than eight inches. Thus, the viewport, except for possibly long term pressure effects, is state-of-the-art. Piccard in Reference 4-13 gives criteria for window design which are conservative.

Glass or quartz materials were also briefly considered. To date glass has not proved suitable because of problems with crazing and less than adequate optical properties. Quartz could be used if the design shape insured that no tensile stresses acted on the window. A shape with this property may be achieved by using a curved rather than flat window. Again test data is lacking but it is believed that tests on a reduced size model would suffice to prove the concept. This assumption is based on successful results in DEEPSTAR window design with a four tenths scale model. Additional advantages of the curved window are an increased angular field of view and the possibility of optical correction through proper lens design. This latter feature would permit the viewer to observe features in the water outside the station in normal size rather than at reduced size as seen through a flat window.

Further detailed design and testing will be necessary to prove the window to frame compatibility in the configuration chosen for the hull. This phase of the testing should be combined with the long term window pressure tests in order to certify both concepts in one effort. Design of viewing windows has not progressed much beyond Piccard's original design for the TRIESTE. The same configuration and materials are being used in the windows of the present deep submergence vehicles as in the TRIESTE. As a result, the diameters of the windows are small with D/h in most cases less than 1.0.

4.1.8.4 Design Discussion

A review of the literature indicates that viewing window design for deep submergence applications has received very little attention since Piccard conducted some studies on plexiglas windows in the form of truncated cones with an apex angle of 90° (Reference 4-13). His experiments consisted of model tests varying the parameter, D/h (D = minor diameter of truncated cone, h = height of cone), for several different pressures. The test results were plotted on a graph of pressure vs. D/h. A curved line separating the tests in which models sustained permanent deformation from those in which the models did not exhibit any permanent deformation was drawn on the plot. Based on this data, Piccard selected an interior diameter to thickness ratio of two-thirds. This ratio would not result in any permanent deformation of the plexiglas up to a pressure of 1500 kg/cm^2 (2130 psi). The results of Piccard's tests leave much to be desired as it is not clear how the permanent deformations were determined and what the magnitude of stresses and the stress pattern in the plexiglas window would be for different pressures.

In 1963, a photoelastic investigation of stresses at windows and hatches in spherical pressure vessels was conducted at Allied Research Associates (ARA) by H. Hamilton and H. Becker (Reference 4-14). This study resulted in inconclusive findings with a recommendation that further study be conducted to obtain a theory for accurate analysis and design. Their major conclusions in this study were:

(1) For 15 degree edge angles, no reinforcement appears to be required for a hatch, or for a sphere in the region of a hatch.

(2) Reinforcement may be required on a sphere in the region if a window with a 45° chamfer seat. However, the amount of reinforcement apparently could be minimized by reducing the seat angle. Furthermore, the effect of friction is not clear. Until it is clarified, optimization of the shell geometry in the window region cannot be undertaken.

A further study was conducted on openings in spheres at Allied Research Associates (ARA) and the results of this study were reported in Reference 4-15. In this report, reference is made to the work by Piccard and states that "no further data have appeared in the literature either to define the stresses in windows or to show how window strength is related to stresses and basic material properties". (Reference 15) This indicates the status of window design to this data. From several tests on models with 45° chamfer angles, the significant findings were that in the range $0.5 < D/h < 1.0$, the windows act as conical plugs and for $1.0 < D/h < 2.5$, the transition to plate behavior takes place. It should be noted that in the years since Piccard's tests, the ARA results represent the additional increase in knowledge of the behavior of deep submergence windows. Furthermore, these studies have been on windows in spherical vessels and there have been no tests or analyses of windows for cylindrical or toroidal hull shapes.

Viewing windows have been designed for deep submergence vehicles such as the Aluminaut and Alvin as well as for the DTMB proposed oceanographic vehicle with a titanium sandwich pressure hull (page 17, Reference 4-16). These designs have been based on simplifying assumptions to permit a theoretical stress analysis of the viewing window and reinforcement. The windows are basically the same as those employed in the TRIESTE by Piccard. They are made of plexiglas with 45° chamfer angle and differ only in the D/h ration.

4.1.8.5 Review of Some Viewing Window Designs

<u>DTMB Window</u>: (Reference 4-16) The basic approach in the design method developed at DTMB is to provide a ring

reinforcement that would eliminate all moments at the reinforcement spherical shell juncture such that membrane radial deformation would result under load. In designing a viewing port ring, the deflection and rotation are calculated using thin ring formulas in lieu of Lame's formulas for thick rings because of the asymmetric cross-section of the ring reinforcement. Also, the assumed distribution of loads through the plexiglas window is based on engineering judgement. With the use of equations (1) and (2), the proper geometry of the ring reinforcement of a viewing port can be computed by iteration since the initial value of z (distance from the center of gravity of the ring reinforcement to the centerline of the spherical head at the reinforcement head junction) must be assumed. (See Figure 4-18 and 4-19).

$$A = \frac{(R_{CG})^2}{R_{SO}\,R_{SM}} \quad \frac{2F_R h}{p(1-\nu)\,\mathrm{SIN}\,\theta} \qquad (1)$$

where:

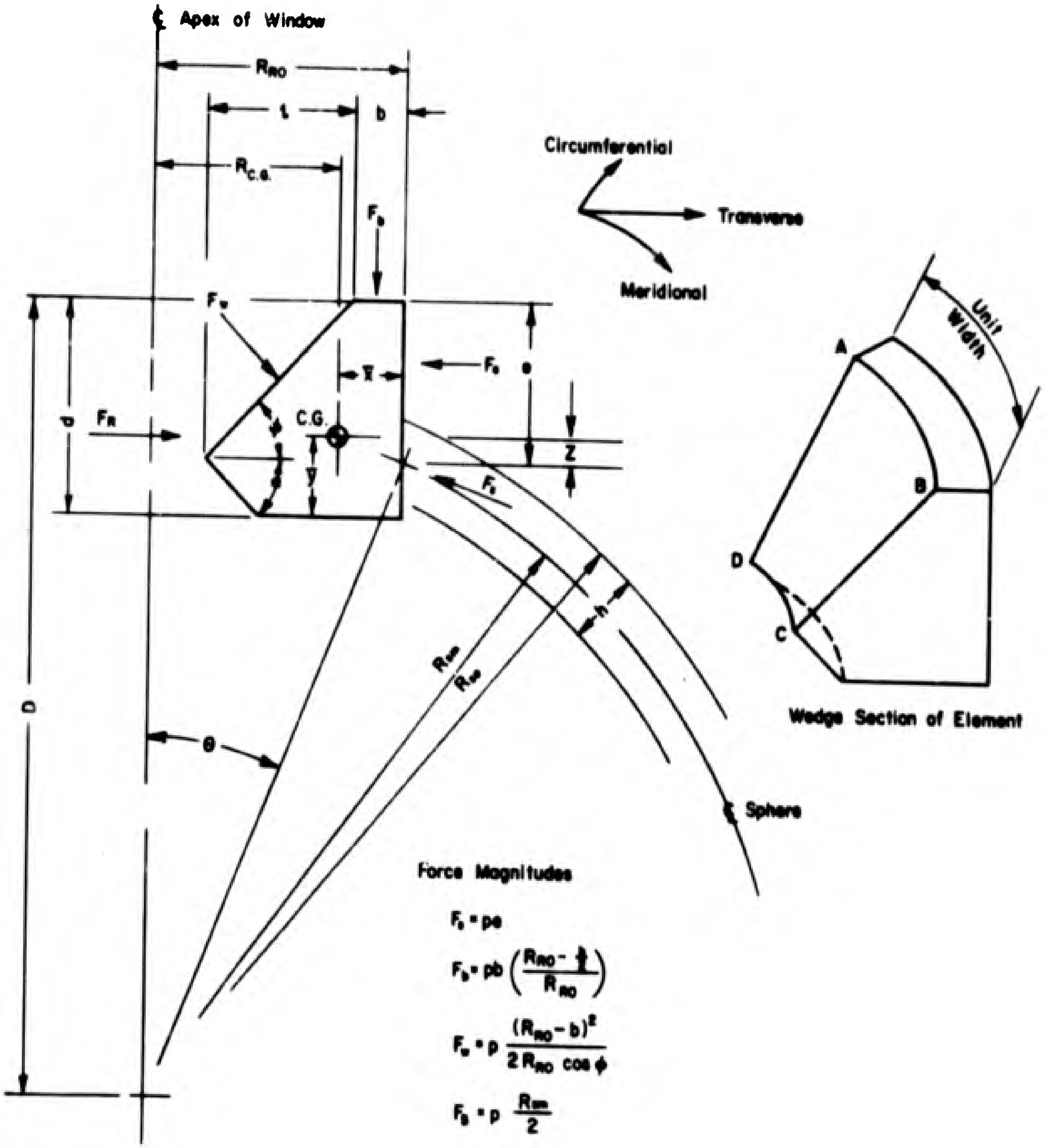
$$F_R = \frac{R_{RO}}{R_{CG}} \left(F_S \cos\theta + F_e - F_W \,\mathrm{SIN}\,\phi \right)$$

$$z = \frac{F_e\left(d - \bar{y} - \frac{e}{z}\right) + \bar{x}\,F_e\,\mathrm{SIN}\,\theta - F_b\left(\bar{x} - \frac{b}{z}\right)}{F_S \cos\theta} +$$

$$\frac{F_W\left[\cos\phi\left(\frac{\ell}{z} + b - \bar{x}\right) - \mathrm{SIN}\,\phi\left(d - \bar{y} - \frac{\ell\,\mathrm{TAN}\,\phi}{2}\right)\right]}{F_S \cos\theta} \qquad (2)$$

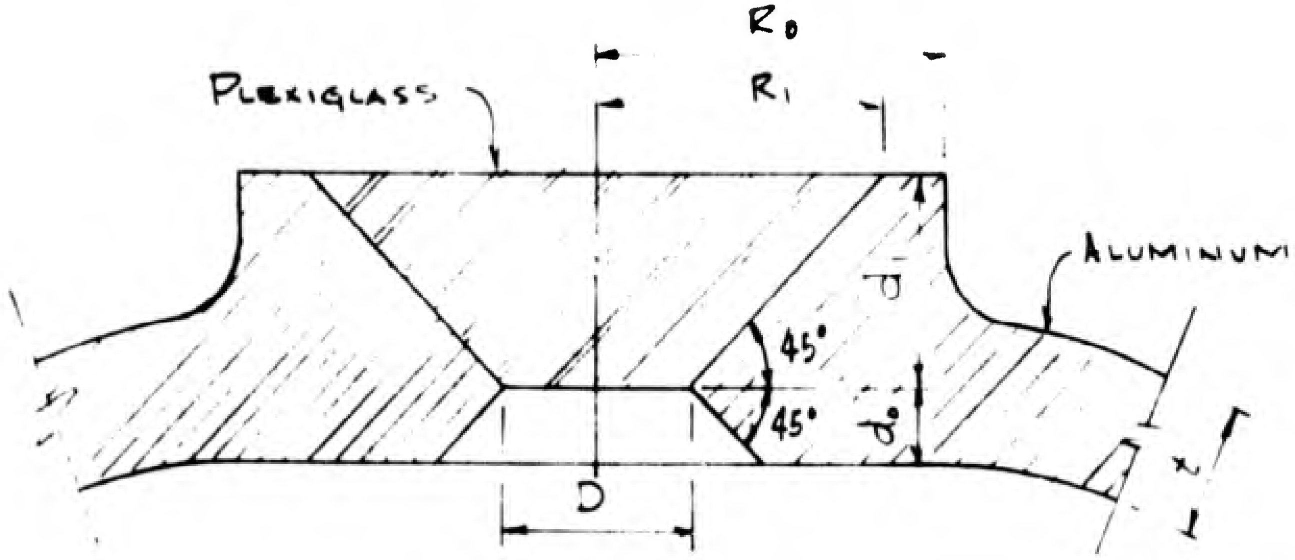
DTMB conducted a test on a small hemispherical model (inside radius = 1.785 in.) and concluded that no significant bending occurred in the area of the viewing port-hemispherical head juncture with a reinforcement designed by the foregoing method. The results indicated that the assumptions of membrane deflection and zero rotation were satisfied. Since this was a pilot study on a small model, DTMB recommends a model test of any new design be made to substantiate the assumptions in the analysis.

Alvin Window: (Reference 4-17) The Alvin pressure hull contains inserts at openings to provide gradual transitions to the hatch which is thicker than the pressure hull. The viewing window is mounted in a hole in the hatch as shown in Figure 4-20a. The stress distribution through the hatch insert-hatch transition is determined by compatibility of slope and deflection at the transition. To simplify the analysis, the hatch and hatch insert are



(From DTMB Report No. 1737 - Reference 4-16)

Figure 4-18 Resultant Forces on Viewing Port Ring Reinforcement

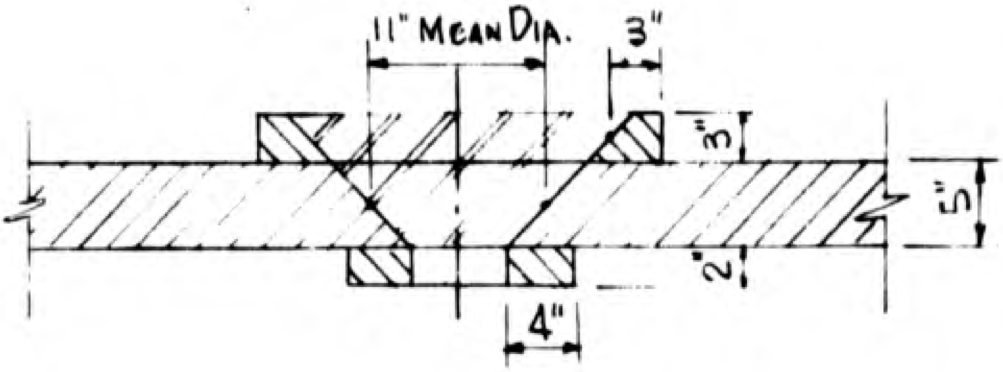


FROM P. 15, REF. No 4-16

<u>DTMB VIEWING PORT</u>

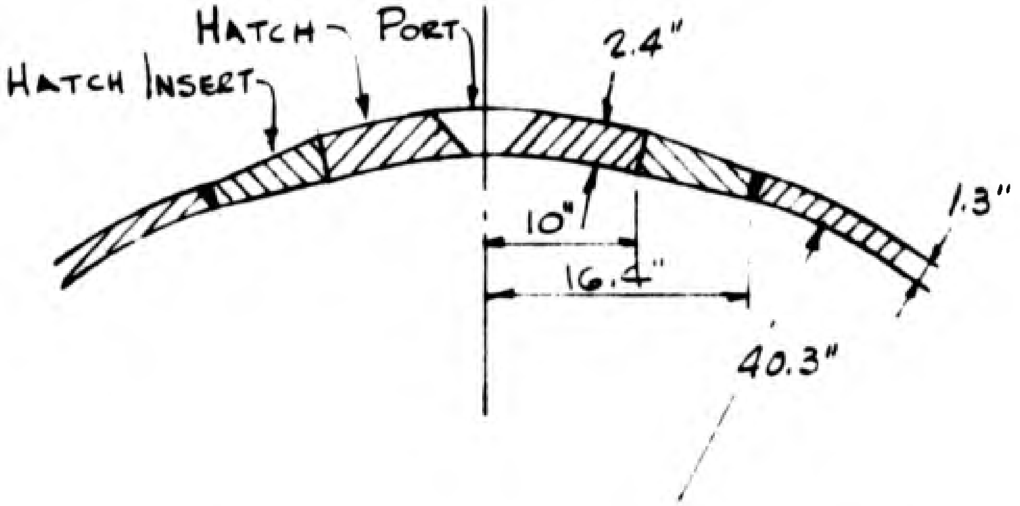
MODEL : SPHERICAL RADIUS = 1.785" (INSIDE)
SHELL THICKNESS = 0.135"
D = 0.200"
d_1 = 0.200"
d_0 = 0.080"
R_1 = 0.300"
R_0 = 0.370"

Figure 4-19 Sketch of DTMB Viewing Port



FROM P. 9, REF NO. 4-17

a. ALUMINAUT VIEWING WINDOW



FROM P. 22, REF. NO. 4-18

b. ALVIN VIEWING WINDOW

Figure 4-20 Aluminaut and Alvin Viewing Windows assumed to form a solid shell of constant thickness with the mean diameter same as the diameter of the hull. The effect of the port on the edge coefficients is neglected. Based on these assumptions, it was found that the stress resultants arising from the discontinuity in the shell thickness was small relative to the membrane stress due to the external pressure.

To determine the stress at the hole, the effect of the low-modulus plastic window was first determined. The window was assumed to conform to the hole in the hatch such that a uniform pressure was exerted on the window seat and no frictional shear stress was present. With this assumption, it was found that the stress resultants radial and tangential to the pressure hull were negligible relative to the pressure stress. Therefore, the port was treated as an unstiffened opening in a flat plate subjected to edge loads. The circumferential stress at the hole for a plate under equal biaxial stress is twice the applied stress, which, in this case, is twice the membrane stress due to pressure loading. The effect of the hole on the stresses diminishes rapidly and the applied stress is restored at about one diameter away from the hole. Results from model tests indicated that theoretical results fall near the mean of the values for the inner and outer surfaces.

Aluminaut Window: (Reference 4-18) The stress analysis of the Aluminaut windows was made by determining the stress concentrations at the penetrations. The stress concentration was found by considering the spherical shell to be a flat plate under the action of membrane stress. The method for determining the stress concentration of a reinforced hole is outlined in "Stress Concentration Factors in Design" by R. E. Peterson (p. 79). Results from model tests did not provide good correlation with the theoretical results. The installation is shown in Figure 4-20b.

4.1.8.6 Design for MUS

The 10-inch diameter window that is required for the MUS is larger than any of the windows presently in use. In addition, it is planned to be inserted in a toroidal hull which results in a non-uniform stress distribution around the window in contrast to a window in a spherical hull which has uniform stress resultants around it. Therefore, present design methods are not adequate for this application. In order to obtain efficient reinforcement for the opening a method of analysis needs to be developed and substantiated with model tests of proposed design.

Reference 4-19 reports on the preliminary phase of a test program to produce design criteria for conical acrylic windows for short-term hydrostatic loading. This testing should be continued and integrated with theoretical analysis efforts to develop design parameters for additional types of viewing windows and mounting flanges. A plexiglas window 10 inches in diameter would require a thickness of 10 inches or greater ($D/h < 1$) in order to act like a conical plug. However, this appears to be rather thick for this application, in which case, an analysis of the window as a plate must be made. Since there is little experimental data of plexiglas windows in the region of $D/h > 2$, additional development tests of these windows would be required. A preliminary design based on circular flat plate analysis could be made to determine the dimensions of the window. Then some basic designs must be tested before an efficient final design can be established. The following is recommended:

(1) Test of window materials in a cylindrical hull should be made for $1 < D/h < 3$. Stress pattern at the edge and on the surface of the window should be determined.

(2) A design method for windows in a cylindrical hull should be developed for deep submergence applications.

4.1.8.7 External Attachments

The crew within the habitat will be able to observe the surrounding ocean and to take water samples through a piping penetration. Other areas of interest not adjacent to the hull can be investigated by remote sensors electrically connected to read-out equipment inside the hull. The electrical penetrations may either be similar to the pin connectors found on submarines or to the sphere electrical penetrators on TRIESTE II (Reference 4-7). In any event, electrical penetrations are state-of-the-art and difficulties are not anticipated.

Other external attachments require hydraulic piping penetrations for operations such as downhaul winching, clamping when mating, camera and light pan and tilt. This type of penetration is also state-of-the-art with modern welding techniques. All piping penetrations are fitted with flow limiting devices which shut off the flow in event of a large leak on the low pressure side.

A pass through device for material specimens is also desirable. This would be in the mission "unassigned" area and would be similar in operation to a submarine signal ejector except that the external door would be hydraulically operated without a mechanical shaft penetration. Testing of a prototype pass through in a pressure chamber should be completed before installation in an operational MUS.

An external manipulator may be used for taking samples or test readings in the visual field of the viewport and returning the sample to the pass through. Typical manipulator designs are found on modern small submersibles (Reference 4-20). If a small submersible operates in conjunction with the station as planned, the manipulator on the station itself may be redundant since the submersible will cover so much more area with its manipulator. However, for some missions an external manipulator might be attached to the structure. It would be hydraulically powered and would require about 3 horsepower. The electric load to provide the hydraulic power and manipulator lighting is considered to be within the 10 Kva "unspecified" requirement. This manipulator should be able to reach the outside of the pass through and the ocean floor. The pass through should be located such that the manipulator on a submersible can deposit or retrieve items in the pass through when the submersible is mated to the MUS. It is not desirable to have the submersible maneuvering in the vicinity of the MUS while attempting to operate the manipulator in conjunction with the pass through device.

4.1.9 Personnel

4.1.9.1 Environmental Factors

The habitat environment is one of isolation and confinement. Under these conditions, there is a very definite degradation in the performance of man. In the extreme, regressive behaviour patterns and feelings of hostility can be produced. Selection, training, and motivation play a large role in this area. The feeling of isolation can be lessened by frequent and varied contacts with the world above. Though war time conditions can severely restrict outgoing signals, in peace time some or all of the following might be considered:

(a) Monitoring passing surface ships and submarines.

(b) Pick up radio news and weather broadcasts, either from shore stations or satelites.

(c) Send and receive telephone messages on selected occasions - Christmas, graduations, weddings, etc.

(d) Using microfilm and a small messenger buoy, it may be possible to receive and transmit the written word and pictures once a week. This could conceivably include mail service.

(e) Hydrophone contact with submarines in the area.

Although crew size will be small, staggered crew changes may provide a variance in personnel atmosphere and increase contact with the outside. However, care must be taken not to cause group disrupture. The change will depend on the operation of the supply vessel. One criterion of confinement is how far the eye can see. A toroidal station is quite advantageous from this point of view, since a man can follow his line of sight, stepping from room to room in the process. The color, feel, texture, and temperature of walls and ceilings will have a bearing on the feeling of confinement. A man shut up in a dimly lit, cold, moist steel shell will not be at ease for long. Apart from using two or three pastel shades on large surfaces, the main wall covering will be textured and applied in some kind of panel pattern. The "RUBATEX" selected for hull insulation may be formed with a pleasing pattern. Further, there is no intrinsic reason why the front panels of any electronic racks should not carry out the pattern established by the wall covering.

The light level in work and recreation areas should be higher than normal. No large area should remain in complete darkness for more than 0.3 seconds, even if a main circuit breaker trips. A low general noise level is mandatory for military needs and self-noise would hamper a number of scientific objectives. Also, man is not happy in a noisy environment, especially if the noise pattern is repetitive, steady, cyclic or inescapable. Big surfaces, such as the ceiling panels and sides of large cabinets, should be sound absorbers while resonators should be avoided.

It has been established that a definite need exists in isolated small posts for the ability to avoid social contact. This need to be alone is augmented by the fact that each man has only a limited number of social contacts. Retreating to a quiet area allows a man to "recharge his emotional battery" and restore balance. Each man will have a bunk with a curtain enabling him to read, write or sleep without being disturbed or disturbing others. There will be light, removable partitions, perhaps blended with equipment modules, which will allow at least the suggestion of privacy in two or three separate areas. This does not mean that the crew members will be hermits and live in isolation from each other. There is only a requirement for the ability to select privacy when not at work. Recreation can take many forms such as a hobby or physical exercise. Hobbies may be combined with the scientific interest or role of the individual. Consideration of space and noise suggest items such as chest expanders, high parallel bars and a pedalcycle fixture to provide physical exercise for the men.

4.1.9.2 Crew Training

The functions required of station crew members will fall under one of the following main headings:

(a) Power Plant Operation
(b) Life Support Equipment Operation
(c) Communication and other Electronic Equipment
(d) Damage Control
(e) Maintenance
(f) Hotel-type Functions
(g) Special Operations
(h) Station Control (Launch, Retrieve, etc.)
(i) Command

The crew members selected will be highly skilled in the fields covered by their service designation. This will permit the use of an accelerated schedule. A training program will be implemented so each man can develop proficiency in combined skills and familiarization with the station systems and operation. Certain functions not directly connected with the mission will require training of the men. For example, two members of each team should receive medical training.

In the basic day-to-day business of living in close confinement, there will be much give and take on the part of all hands in the matter of hotel type functions. In the limited crew, there just is not room for one billet encompassing all the pick-up, clean-up, and dirty work. Every member will have to take care of his personal housekeeping and perform some of the common labor type tasks in the habitat. The routine cleaning will be minimal and should be equally shared by the three junior crew members as a portion of the watchkeeping routine. The meal preparation and clean-up tasks must be shared and may involve additional training for the crew.

Four basic steps will be followed in developing a specific program for training:

(1) Organization of the position tasks into training segments and preparation of a training outline. Each segment will consist of a small group of related tasks around which the training program can be organized.

(2) Breakdown of the training segments into phases of instruction or related units dealing with some common objective which will encompass several days or weeks of instructions.

(3) For each of the training units, specification of the goal of the unit, the instructional presentation of the student's activity, and provisions for evaluating the performance and feeding this evaluation back to the student.

(4) Description of the characteristics of the training aids and devices which will be needed.

It is important that selected crews work together as a team for much, though not all, of their training. Some of this team work should be done in conditions of isolation. If an interim exchange cycle is adopted whereby 2 or 3 of the crew are relieved on station before the mission is completed, the teams will encompass larger groups. This should help prevent the five man crew from becoming too closely associated so that they cannot work effectively with others when exchanges are made. Though support and maintenance personnel are not treated in detail here, it is vital to recognize that they are an essential part of the overall team. They should share some of the training sessions of the crew and be given the chance to identify with the overall effort. It is a psychological advantage for the crew to know that qualified men are topside, ready to aid them in an emergency.

4.1.9.3 Billets

The emplacement of the first station by an operational activity will almost certainly use a crew more senior than is normally expected. The billets suggested below are recommended for normal operation.

BILLET TITLE	NOBC/NEC	GRADE/ RATE	NUMBER ALLOWED
Commanding Officer	9222	LCDR	1
Scientific Observer (Oceanographer/ Engineer)		Civilian or LT	1
Sonar Technician	0426	STC	1
Nuclear Power Electrical Technician	3353	EM1	1
Auxiliary Equipment Technician	4356	EN1	1

The following discussion will develop the principal duties and qualifications for the billets listed above:

Commanding Officer - LCDR: Serves as senior officer of Manned Underwater Station. Serves as Control Officer during movement of station. Responsible for the operation and maintenance of crew proficiency and readiness. Assists project authorities in the preparation and evaluation of station. Assigns personnel to duties and exercises military control of the station. Insures safety, checkout and maintenance procedures of station.

Qualifications: Submarine qualified volunteer
Completion of specialized Manned Underwater Station Training Program

Scientific Observer (Oceanographer/Engineer): Civilian or LT. Assists in the preparation and evaluation of station experiments. Directs use of scientific instruments for experimental purposes. Evaluates results of experiments and initiates any changes to collect the maximum amount of scientific information. Responsible for maintenance and repair of scientific instruments.

Qualifications: Submarine qualified volunteer (if military)
Broad scientific experience in oceanography
Completion of specialized Manned Underwater Station Training Program

Sonar Technician - STC: Serves as senior enlisted crew member and junior control officer of station. Supervises the complete maintenance and checkout of the station as directed by the Commanding Officer. Maintains all scientific instruments, sonars, communications equipment and other electronic equipment, operates all electronic equipment as directed. Responsible for general housekeeping functions.

Qualifications: Submarine qualified volunteer
Completion of specialized Manned Underwater Station Training Program based on required skills outlined previously
Demonstrated ability in operation and maintenance of various fleet sonar systems
Advanced course in emergency medical techniques

Nuclear Power Electrical Technician - EM1: Operates and maintains nuclear power plant. Responsible for station lighting circuits, electrical fixtures, electric motors, electric circuitry, and wiring. Operates scientific equipment when required.

Qualifications: Submarine qualified volunteer
Completion of specialized Manned Underwater Station Nuclear Power Training Program

Advanced course in emergency medical techniques
Completion of specialized Manned Underwater Station Electrical System Training Program

Auxiliary Equipment Technician: Operates and maintains all hydraulic equipment aboard Manned Underwater Station. Responsibilities include heating, air-conditioning, water and other systems such as plumbing, waste disposal, etc.

Qualifications: Submarine qualified volunteer
Completion of specialized Manned Underwater Training Program based on required skills outlined above

The designation as "qualified in submarines" is not a mandatory requirement. This background was selected since it is considered that personnel experienced in submarine operations may need less training than others. Basically, each crew member should have a high mechanical aptitude and be intimately familiar with the principles of buoyancy and stability. He also should have experience swimming underwater in event an emergency exit has to be made near the surface.

It should also be noted that all the crew members will be able to give some support to the scientific observer. The crew will be able to record regular readings while on watch, but their primary job is station operation. They should not be expected to set up experiments or perform lengthy observations when on duty. However, some of their off-watch time will be available to directly support the scientific phase of the mission. The Commanding Officer in particular may spend a considerable portion of his time in mission support. He can be expected to continue experiments for the scientific observer while the latter is sleeping.

4.1.9.4 Duty Rosters

Duration and cycling of activity will be mission-oriented. In the early stages, it will not be prudent to have all crew members asleep simultaneously. The Commanding Officer is considered "on duty" at all times. The Auxiliary Equipment Technician should not be on duty alone. This suggests the following duty roster:

Watch "A"	Scientific Observer Auxiliary Equipment Technician	Commanding Officer 24-hr. duty
Watch "B"	Sonar Technician	
Watch "C"	Nuclear Power Technician	

If a supply vehicle of the size of the DSRV is used, the simplest crew change schedule would be a complete change every 30 days. In the event that one or two crew members are required to stay aboard for substantially longer periods, it may be advantageous to change the remainder of the crew in pairs, staggering the duty periods at 14-day intervals. Some flexibility will be possible in the early stages of the operation.

The allocation of duties requires careful planning, with much informal flexibility in the implementation, since with only 5 men, a close and friendly working relationship must be developed. Table 4-15 illustrates a suggested sequence of watches; each man shown with a total of 24 hours watch standing in every 72 hours. The Mission Officer and Commanding Officer will relieve the men of their regular watches for special duties, or in the event of minor illness. The isolation of this small group demands great flexibility in the work schedule. The Commanding Officer must maintain his command role, yet he will be called upon to perform duties which are not normally considered within his scope. There will not be a large group of enlisted men to do all the "dirty" jobs.

The regular watches will include communications monitoring, preventive maintenance, equipment monitoring and mission duties plus cooking and sanitary tasks. Repairs and major mission tasks will require additional efforts from the men outside of the regular watches. Meals will be at the normal times of 0800, 1200, and 1800, with sufficient leeway to allow the men ending and starting watch at mealtime to eat. The watches will be on the standard four hour schedule with the evening watch dogged. This will rotate the three watch standers through the cycle every three days to insure variety.

TABLE 4-15 Suggested Sequence of Watches

	First Day	Second Day	Third Day
00-04	1	2	3
04-08	2	3	1
08-12	3	1	2
12-16	1	2	3
16-18	2	3	1
18-20	3	1	2
20-24	1	2	3

4.2 SUPPORT

4.2.1 Deployment

Station emplacement requires a minimum force of surface ships and a submersible vehicle which have the combined capabilities to insure the success of the mission. During the initial shallow and deep water emplacements, many of these ships will stay on station to continually monitor communications and generally assist in the "prototype test" programs conducted to gain experience with the station operation. The number and types of ships required for these operations will probably remain fluid to some extent and is not a topic for this report at present. However, the minimum force of surface ships required to establish the initial Manned Underwater Station is discussed in the following paragraphs.

It has been agreed that the initial step to be accomplished in the successful establishment of the station is a detailed survey and selection of the site during which time a grid or network of sonar transponders shall be accurately positioned surrounding the site on the bottom. This same network is used by the ships in the emplacement force to relocate the site and to serve as benchmarks for dynamically positioning these surface vessels--particularly the LSD which lowers the foundation and launches the structure.

It is assumed that the site selected for the first station is highly advantageous to the mission, that it is relatively level, that its soil has a high bearing capacity, that it is removed from any underwater hazards and surface shipping lanes, and that it shall be assumed that the weather conditions will be somewhat ideal with low winds and sea state. Once the experience has been gained from establishing and maintaining the initial station, future stations may be placed at less ideal locations and under less ideal weather conditions. A description of the proposed task force is contained in the following paragraphs.

4.2.2 Task Force

The task force shall consist of the following ships:

(a) Survey Ship
(b) LSD (modified)
(c) Submersible Support Ship
(d) Submersible
(e) Ocean Going Tug (2)

4.2.2.1 Survey Ship

Functions:

(1) Explore in detail certain selected sites for the MUS.
(2) Plant and survey in a network of underwater transponders for navigation and positioning.

Capabilities Required:

(1) Modern surface navigation facilities such as Shoran, Ray Dist, etc.
(2) Underwater sonar ranging and tracking facilities.
(3) Complete bottom survey and exploration facilities including soil sampling, bottom coring, water temperature and current measurement devices, bottom and sub bottom profiling, etc.
(4) Laboratory for chemical and physical analysis of soil and water.
(5) Electrical and electronic repair facilities.
(6) 'Fish' towing facilities including recording and instrumentation equipment.
(7) Surface and underwater communication and recording facility.

4.2.2.2 LSD (Modified)

Functions:

(1) Transport foundation and structure to the site.
(2) Lower foundation and launch the structure.
(3) Task Force command.

Capabilities:

(1) Minimum load capacity 1000 tons.

(2) Minimum winching capacity 250 tons.

(3) Surface and underwater communication for station keeping and normal command network.

(4) Forward, aft and lateral accurately controlled propulsion system centrally coordinated with station keeping system.

(5) Electrical and electronic repair and test facilities capable of supporting the structure systems.

(6) Quarters for all scientific and other personnel required for the mission other than the ship's crew.

(7) Helicopter deck and handling.

4.2.2.3 Submersible Support Ship

Functions:

(1) Transport the submersible.

(2) Launch, retrieve, and replenish the submersible.

(3) Replace and repair the submersible's systems.

(4) Quarter and support divers and the submersible crew in addition to the ship's complement.

(5) Stow, launch, and support small boats used by divers.

Capabilities:

(1) Provide for the above functions.

(2) Surface and underwater communication with submersible and the command network.

4.2.2.4 Submersible

Functions:

(1) Close inspection of the habitat site prior to emplacement.

(2) Close inspection of the foundation emplacement in progress and upon completion.

(3) Close inspection of the structure during descent and in place.

(4) Visual inspection provisions such as view ports, lights, cameras, etc.

(5) Underwater communications with surface and station.

(6) Mechanical manipulator arm to assist inspection if required.

(7) Mating with structure escape hatch if desired.

4.2.2.5 Ocean-Going Tug

Functions:

(1) Assist the LSD and other vessels when required.
(2) Assist in lowering the foundation and launching the structure.

Capabilities:

(1) Normal ocean-going tug capabilities.
(2) Communications with command network.

4.2.3 Logistics

The initial station operating period is limited to 30 days with a crew of five men. It is expected that future missions will continue for much longer periods of time as more is learned about the capabilities and the possibilities of the Manned Underwater Station. As the mission time changes from the originally required 30 days, the logistics problem also changes but not as a direct function of time for all logistics items. Each planned mission must therefore be examined to accurately determine the elements of support required. Since this is beyond the scope of this report, this discussion of logistics will be confined to the initial emplacement period and the first 30 days of operation.

4.2.3.1 Initial Emplacement

Section 4.2 contains a discussion of the task force required to accomplish the initial site selection and station emplacement, and each of the ships requires its normal complement of officers and crew for its operation. In addition to these personnel, there will be a number of people assigned to the program to accomplish its various phases and these will be quartered aboard the task force vessels as required. However, these added personnel are not all required in residence throughout the emplacement period since many functions will not be required in all phases. At the present, it is a difficult task to determine the number of people required on site since the location of the site with respect to the shore-based depot is not known and the distance between these two places has a direct bearing on the number and type of people required on site. In order to provide some guidance in this area, however, let it be agreed that the site and depot are sufficiently close so that only 24 hours are required to ferry personnel and supplies between the two. In such a reference frame, the resupply of the task force becomes a relatively small problem and larger than normal stocks of supplies need not be stored on board the ships. As each phase of the program advances, the special personnel required can be brought to the site and those who have finished their tasks be returned to port.

In this study, it would be presumptuous to attempt a detailed list of all items of supply that might be required for emplacing the station. Quantities and supply scheduling of items such as the length of steel wire cable, air bottles for scuba gear, recording tape, etc., are not easily determined without a detailed schedule of the operations and detailed data of the site location. After the development plan and schedule has been established for emplacing the station and for its first 30 days of operation, the personnel, supplies and re-supply can be readily determined.

4.2.3.2 30-Day Mission

The station operation for the first 30 days is assumed to be in conjunction with a submersible which does not have a mating capability with the structure. It is also assumed that the station will remain in place on the bottom for the entire 30 days, and that it will surface at the end of this time to complete the initial phase of operation. As a result of these constraints, the station must receive its full complement of supplies such as food, clothing, life support, etc., prior to its first descent to the bottom and no resupply of station commodities is required during this time. Surface support during this time is limited to the LSD command ship, the submersible, and its support ship with a minimal additional complement of program personnel. Since the site is assumed to be within 24 hours travel of the depot and since the supplies required by the task force should be limited to supporting personnel and test equipment on board, the logistics problem is considered to be relatively small.

4.3 ARRANGEMENT AND DRAWINGS

This section contains a description of one possible layout of the station. Exterior structural provisions for mating with additional modules and small submersibles are described in Section 4.1.2.8 and are not shown in this section. Preliminary internal arrangements are presented, since a detailed study of equipments and outfitting in the next phase of the design program may dictate changes in space utilization.

4.3.1 General Arrangement

The hull of the Manned Underwater Station has been described in Section 4.1.2 and the principal exterior dimensions are shown in Figure 4-21. The interior of the structure is separated into five equal sectors by strength bulkheads. Each of these 72° sectors has physical dimensions shown in Figure 4-22. The rectangle height was chosen because of the contractual requirement for 200 square feet of floor area with a 6 1/2 foot clear height. It is not anticipated that the overhead or sides of this rectangle would normally be closed in by non-structural bulkheads. In fact, one object of the interior design will be creation of an illusion of maximum spaciousness. This will be assisted by judicious use of lighting and color and avoiding narrow passages to the maximum extent possible.

In this conceptual study, only a preliminary layout is attempted in order to insure that there is enough room in the hull. A more detailed layout will be required when the mission equipment is defined for the prototype station.

The five sectors are allocated for use as shown in Figure 4-23. The mission requirement of 200 square feet with a 6.5 foot overhead is satisfied by using one 72° sector and 50° of an adjacent sector. The remainder of the sector is allocated to atmosphere management and heating equipment. Following in counterclockwise order, come the berthing space, the pantry and recreation area and the power plant area. Preliminary arrangement sketches of these areas are shown in Figures 4-24, 4-25, and 4-26, respectively.

The mission "area with undesignated functions" is not included in the preliminary sketches. The initial layout of this area will be governed by the mission assigned to the prototype. The life support equipment is contained in a 267 cubic foot portion of one sector. With 75 cubic feet alloted for a passageway, this leaves 192 cubic feet in which to house the 126 cubic feet of atmosphere management machinery. No engineering problems are expected in arranging the chosen suit of life support equipment in the assigned space.

The berthing area (Figure 4-24) contains five bunks provided with individual lights and ventilation control. Each bunk can be enclosed with a privacy curtain. Between the two outboard bunk tiers is one of the large viewports. This area also can be curtained off from the remainder of the compartment to prevent reflections in the viewport and secondarily to serve as a private

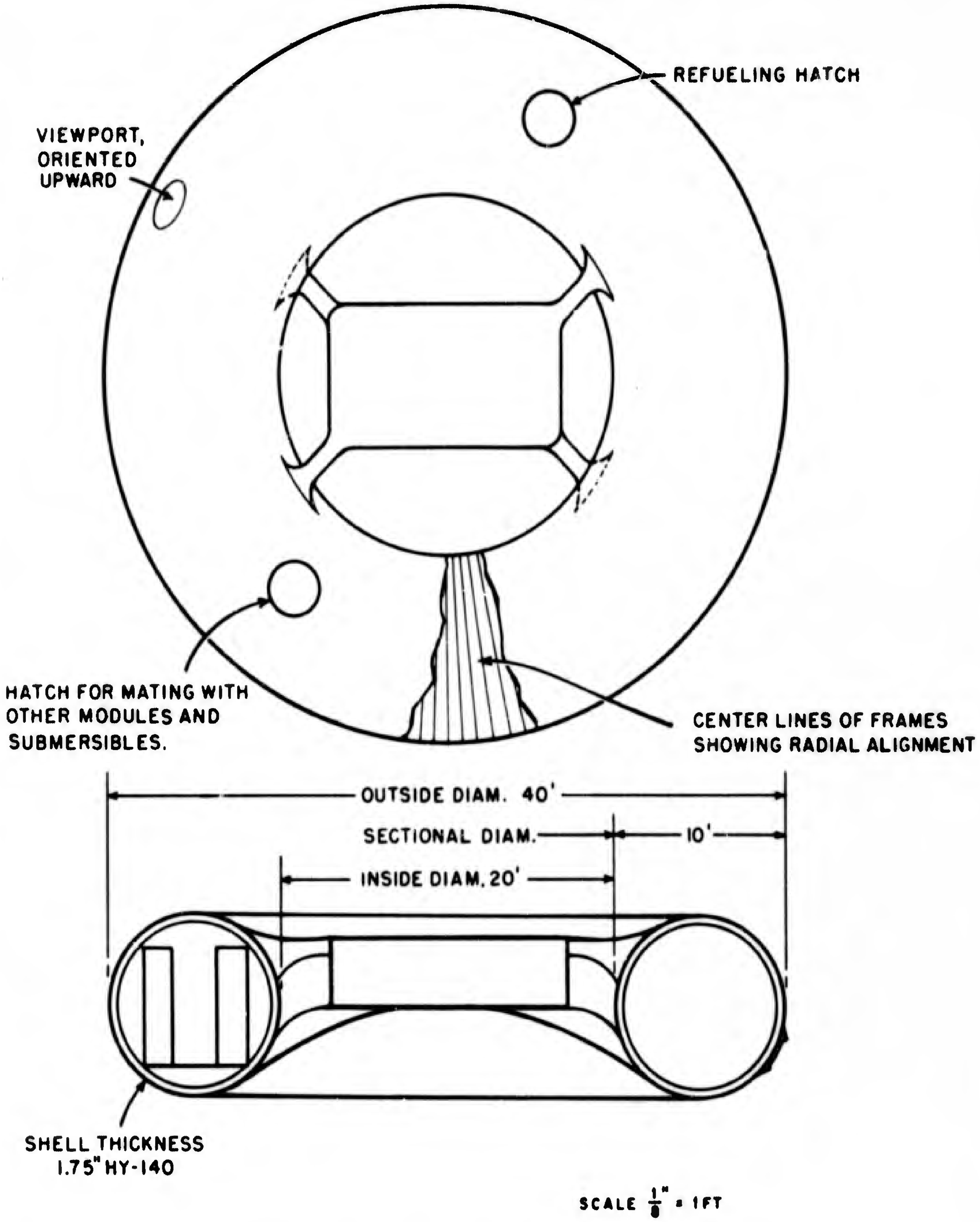


Figure 4-21 Outboard Profile of Manned Underwater Station

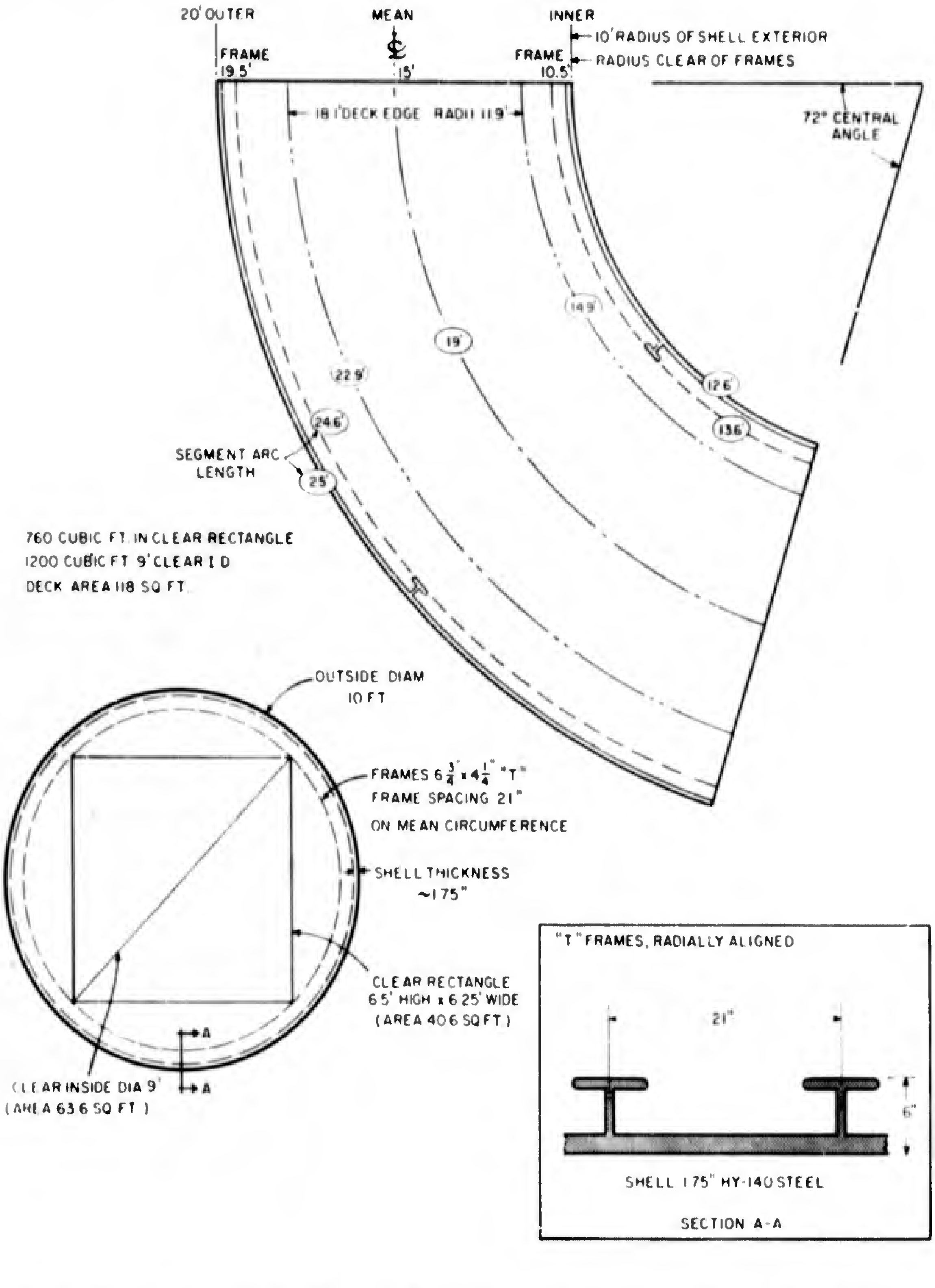


Figure 4-22 Physical Dimensions of Habitat Interior Sector

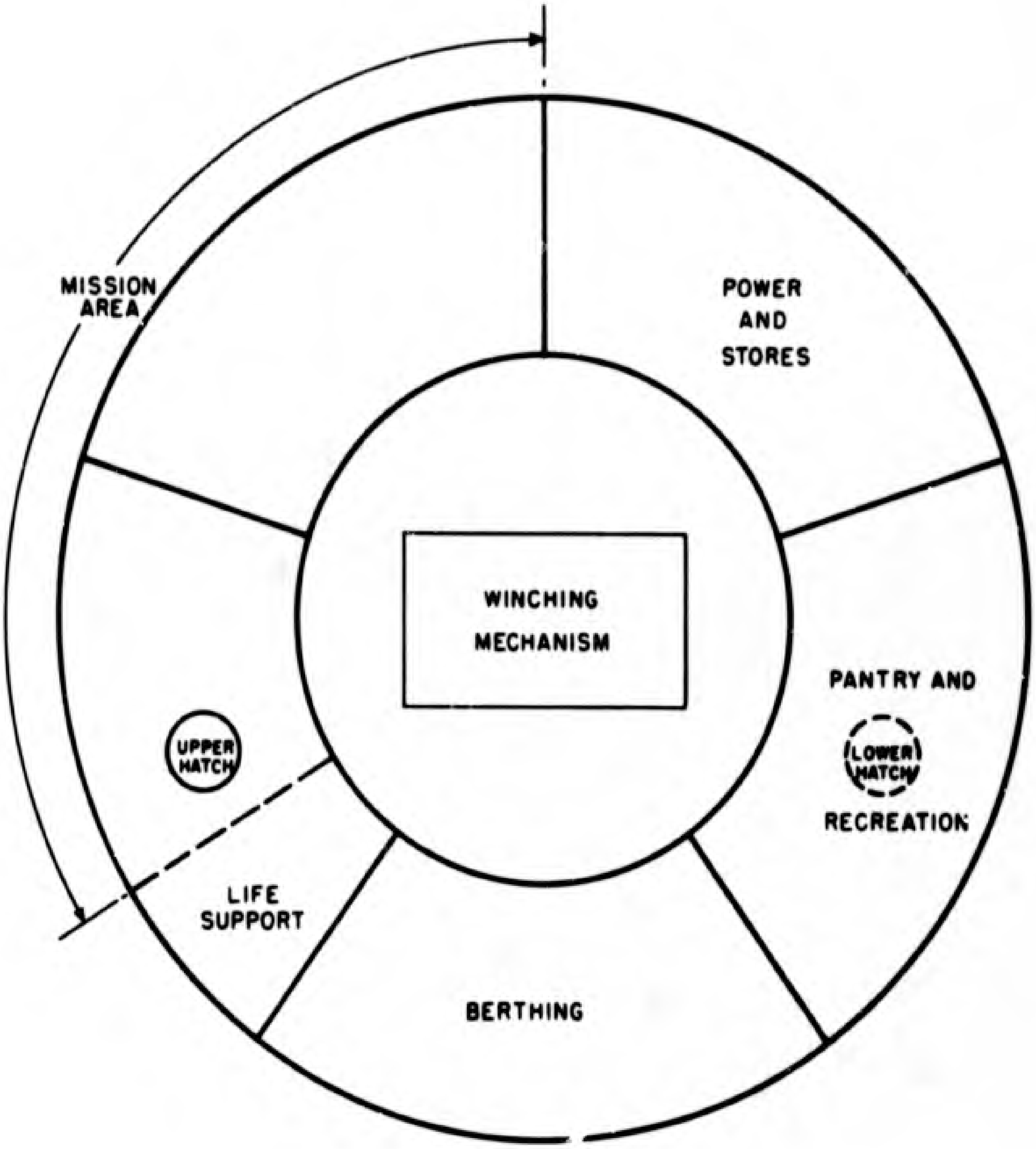


Figure 4-23 Habitat Sector Allocation

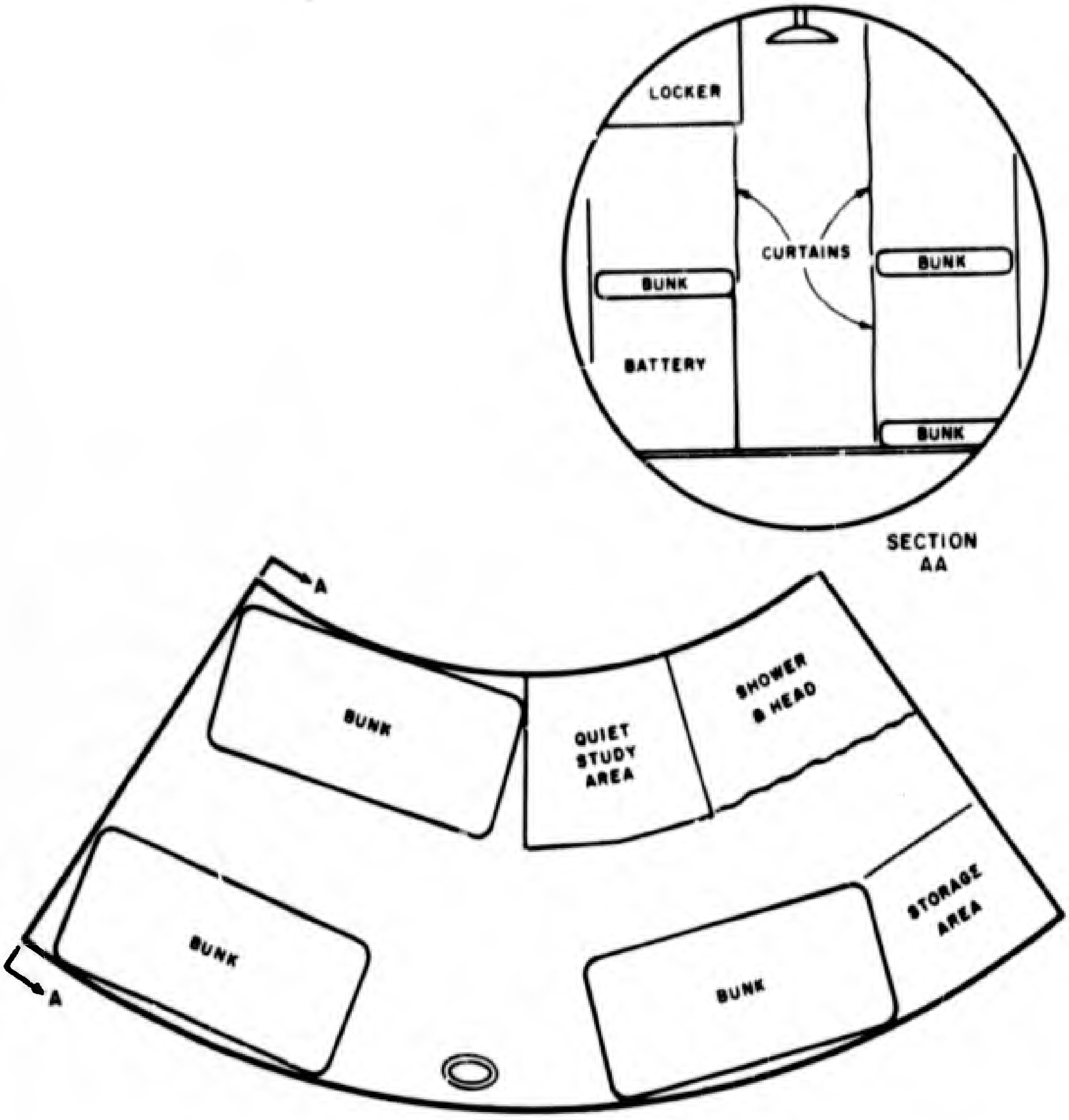


Figure 4-24 Berthing Sector Preliminary Arrangement

standup dressing area. A quiet study booth is provided and it is anticipated that a stereo headset for tape recorded entertainment will be included in this space. In addition, it will have a small TV monitor to observe the view of the station cameras that are in use, or for watching taped TV entertainment programs brought down in a resupply submersible. The shower and head occupy one corner of the room and storage areas are included where-ever practicable. The emergency storage battery is located under the inboard bunk.

The pantry and recreation area is more spaciously arranged (Figure 4-25) than any of the other spaces. A folding table and chairs are used for eating and recreation. Floor space is provided for an exercise machine. A large downward oriented viewport is centered in the area. One corner is occupied by the food storage and preparation areas. The food preparation space is at right angles to the traffic pattern to allow maximum unobstructed floor space. On the power plant bulkhead are located the station controls and communications panels.

4.3.2 Power Plant Arrangement

Several ways and methods were considered for integrating the power system with the station. Of prime concern during the selection of the location were the considerations of serviceability, source replenishment, and space requirements. Locations, both internal and external to the habitat, were considered, and the in-vehicle appeared to be the most favorable. Locating the complete power supply in an exterior pressure shell mounted on a boom protruding from the toroid was deemed undesirable from both the point of serviceability and the point of denying a clear field of view from the viewports in the structure. Locating the complete system in a separate pressure shell within the boundary created by the torus was also considered undesirable from the viewpoint of serviceability.

It was felt that although some shielding advantage is realized by locating the source only in an exterior pressure shell, the difficulty in source replenishment and maintenance far outweighed the shielding gain.

Therefore, the entire power supply is located within the pressure hull. About one eighth of the toroidal volume is occupied by the power system as shown in Figure 4-26. However, it should be noted that there is ample space leftover in this sector for inclusion of other machinery necessary to operate the station and for additional storage.

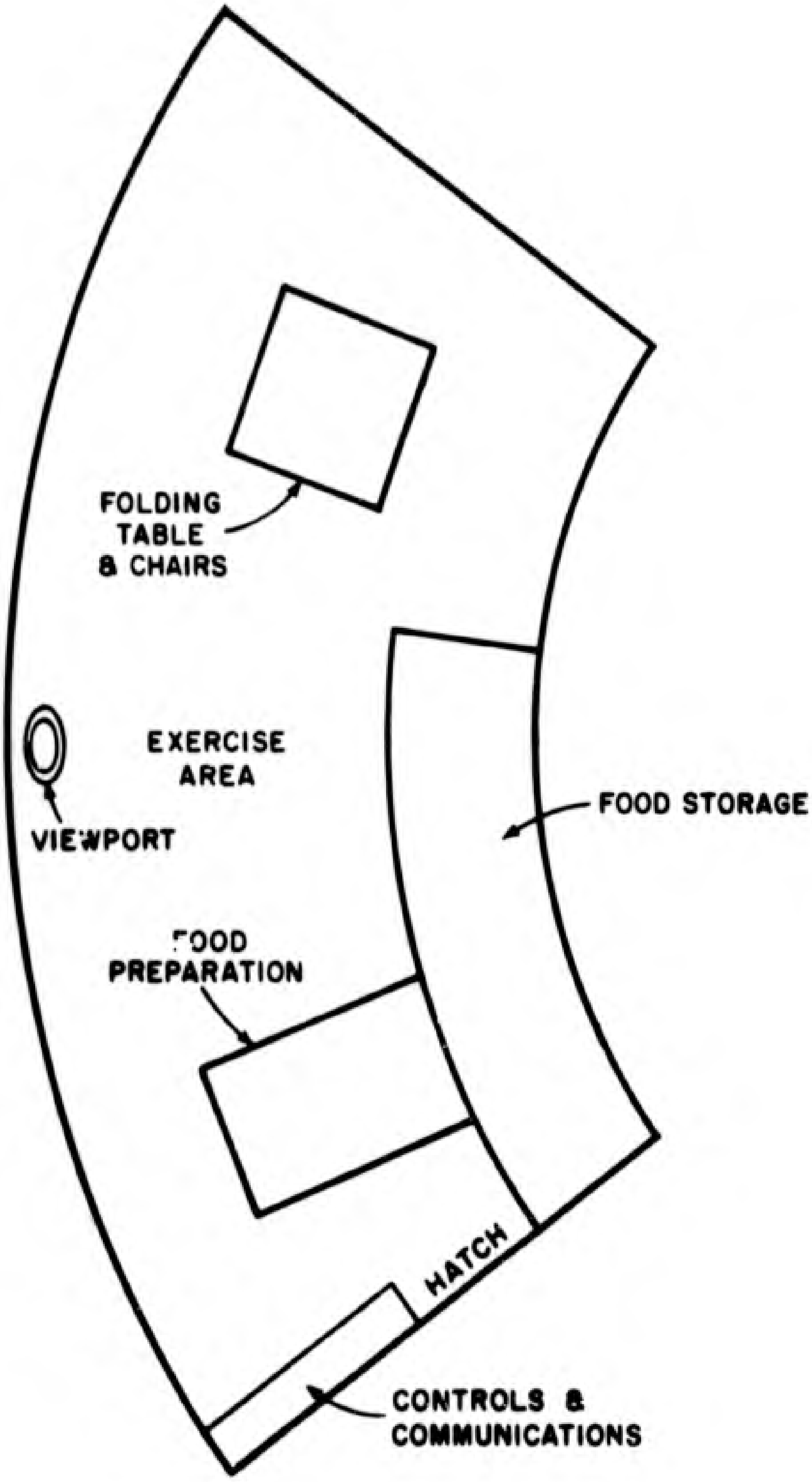


Figure 4-25 Pantry-Recreation Section Preliminary Arrangement

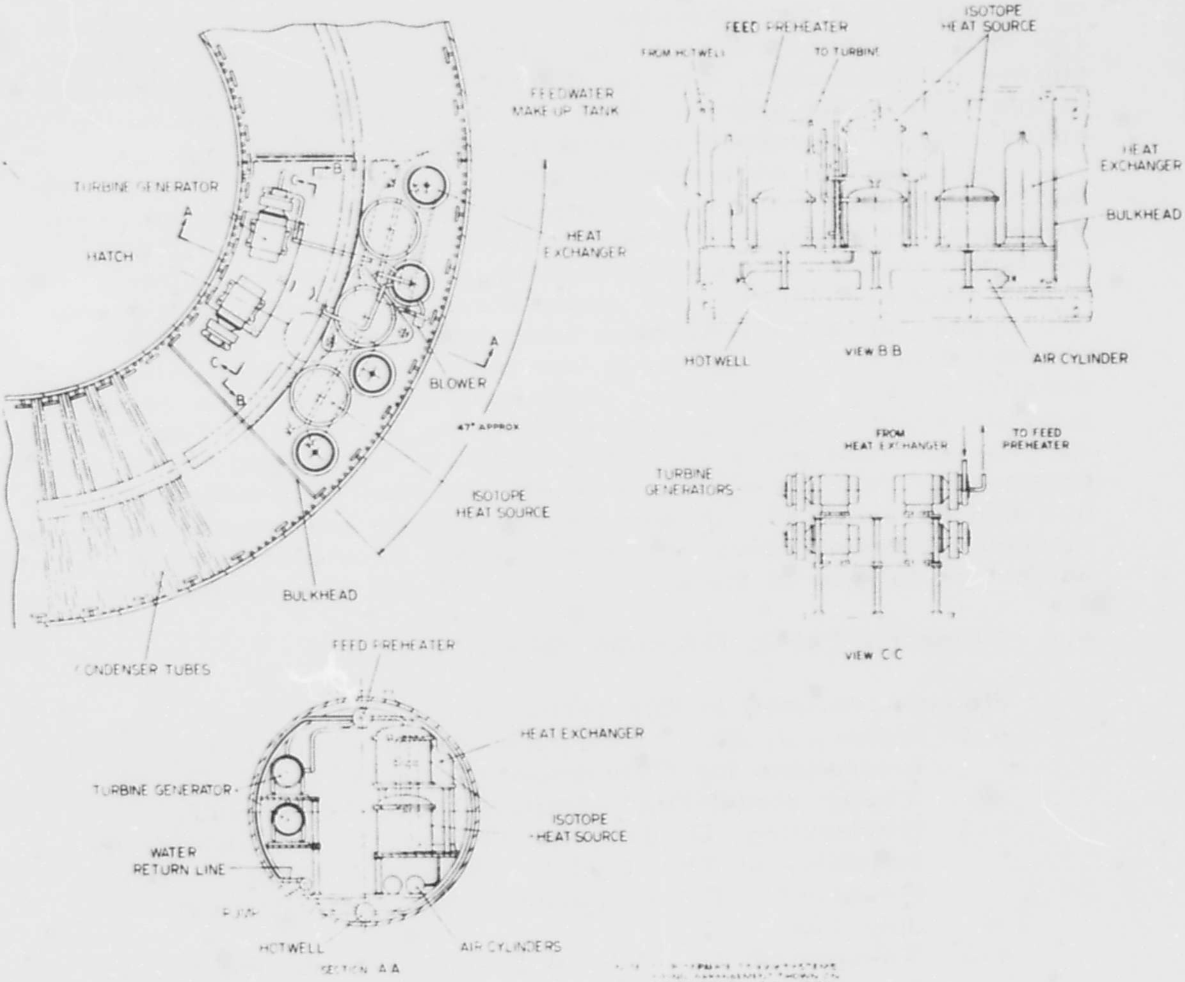


Figure 4-26 Power Plant Arrangement

The components that make up the power system can all be installed by standard ship building techniques, i.e., prior to welding the hull closed. However, the four Co-60 heat sources, although 30 inches in diameter, they are manufactured in such a fashion that during installation, part of the shielding can be stripped off in order to lower the sources through a standard Navy hatch (25 inch diameter), during which time manipulators and shadow shields must be used, and the shielding remounted inside the hull. In this fashion the sources need not be installed until the entire structure and associated systems have been checked out.

Although the equipment is installed prior to hull closure, all the rotating machinery will fit through the 25 inch hatch and can, therefore, be replaced. Four completely separate 7.5 Kwe systems provide complete redundancy and emergency power. Where possible failure could cause disaster, standby components and bypass arrangements have been included. All pumps and blowers that are in continuous use have been provided with a parallel standby unit, making continuous operation of the equipment possible while a pump or blower is being serviced. This type of service can take place while the station is submerged. If a turbogenerator fails, a bypass for heat rejection is provided until the unit can be serviced. Minor repairs can be performed in submerged condition, however, major repair or replacement is easiest performed at the surface with the aid of a tender.

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5.0 DEVELOPMENT PLAN

In order to provide a potential station at 6000 feet housing a crew of five men for 30 days or longer, certain equipment identified in this section will require special development planning. As there is no present comparable facility, this program will be the forerunner of certain critical elements. These are summarized in listings immediately below and discussed in more detail in the sections referenced:

Research and Development Items	Section
Isotope Power Plant Module	5.4.1
Large Acrylic Windows	5.4.2

Directed Engineering Development Items	Section
Smaller Size Oxygen Generator	4.1.4.3
Smaller Size Carbon Dioxide Scrubber	4.1.4.2
Water Management Subsystem Components	4.1.6.2
Pass Through for Samples	4.1.8
Deep Ocean Piling Emplacement	3.2.1.5

These latter items are also tabulated in Section 5.4

As an aid to formulation of a Technical Development Plan, certain summary statements are included in this section with attendant table and figure suggestions.

Technical Development Plan Statements: The Manned Underwater Station is to provide a bottom station at ocean depth to 6000 feet in which a crew of five men can live and work for extended periods of time. (Various specific missions to be performed by the crew are discussed in Section 2.1 of this report.)

There is no present Navy facility or capability comparable to the Manned Underwater Station.

The station will have a life of over twenty years with overhaul and refueling at regular intervals. There are no present prospects for a competitive system which will fulfill the same missions.

The conceptual phase of the MUS is fulfilled by the results of this study. Following Navy evaluation, parallel programs will be initiated for the MUS design and the power plant module development. The equipment of the station will be included in the design program for the MUS; however, the power plant justifies a separate effort.

The MUS design will be followed by procurement of the prototype station. The scheduling of fabrication, evaluation and deployment of the prototype will be coordinated with development and fabrication of the four power plant modules to assure prototype deployment on schedule.

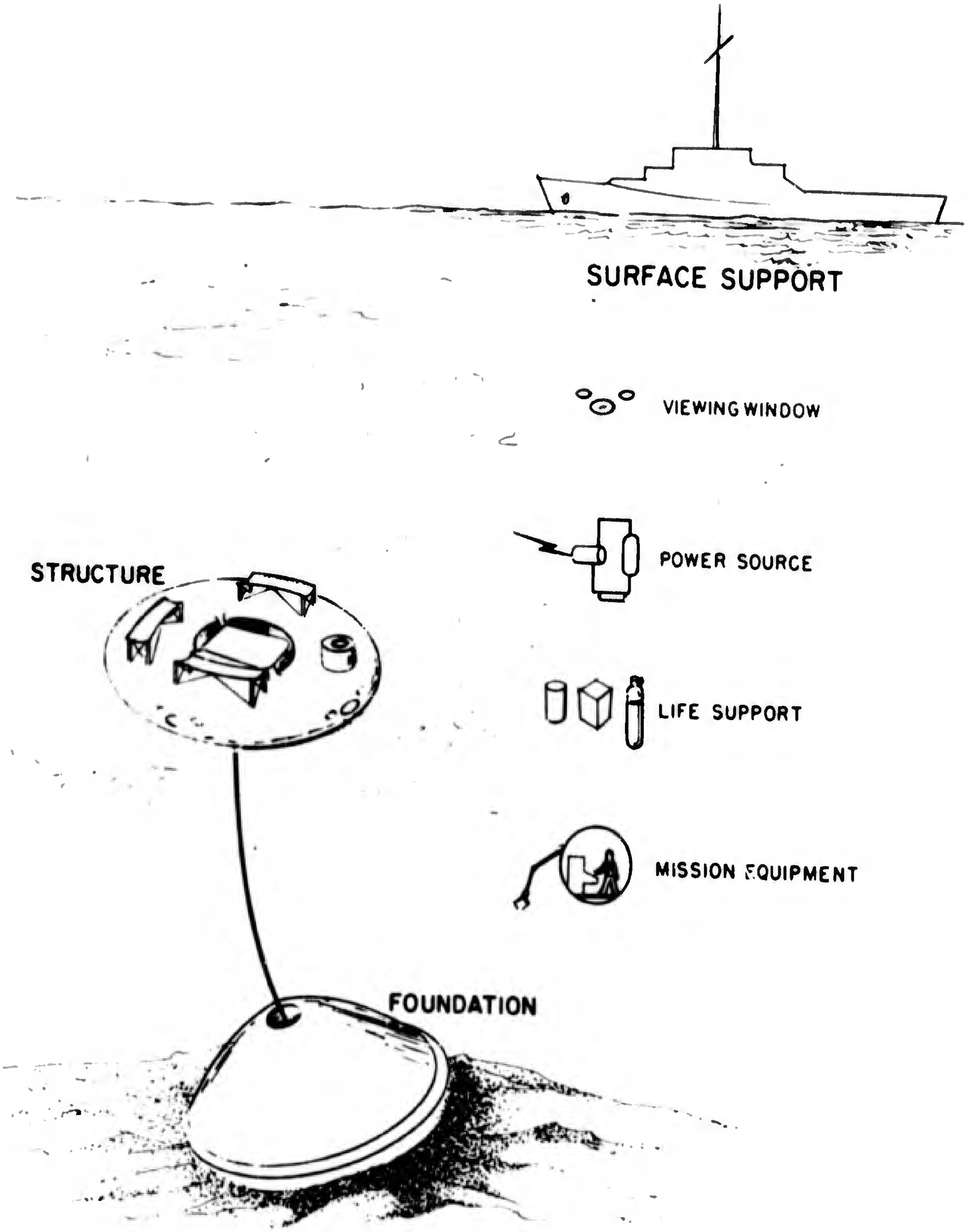

Figure 5-1 Manned Underwater Station - Identification & Picture

Successful operation of the MUS is dependent upon the mating hatch design planned for the Deep Submergence Rescue Vehicle (DSRV) and the Deep Submergence Search Vehicle (DSSV). The DSRV mating hatch is well advanced and is not considered as a likely obstacle to the MUS program.

There are no high risk elements in the MUS program, however, several items require design and/or testing to assure success. The power source is the major item. In addition, the life support equipment requires scaling from existing designs, and long term pressure testing of the viewing windows is desirable. These areas and others relating to optimal station design are fully described in the R&D problem statements.

A line drawing of the Manned Underwater Station, identifying the major elements is shown in Figure 5-1.

The major milestones in the program are listed in Table 5-1.

TABLE 5-1 Major Milestones

Milestone	Date
Concept Study Contract Awarded	October 1966
Concept Study Final Report Submitted	March 1967
Modular Power Plant Design RFP Issued	June 1967
Station Design RFP Issued	June 1967
Station Design Contract Awarded	August 1967
Power Plant Design Contract Awarded	August 1967
Heat Source Connected in Test Cell	January 1968
Pressure Window Test Units Complete	January 1968
Power Plant Optimization Complete	May 1968
Pressure Window Long-Term Test Compl.	June 1968
Power Plant Design Complete	August 1968
Station Design Completed	August 1968
Prototype Power Plant RFP Issued	September 1968
Prototype Station Fabrication RFP Issued	October 1968
Prototype Power Plant Contract Awarded	December 1968
Prototype Station Fabrication Contract Awarded	January 1969
Additional Power Plant Fabrication Started	December 1969
Prototype Power Plant Fabrication Compl.	December 1969
Life Support Fabrication Complete	January 1970

Milestone	Date
Structure Fabrication Complete	January 1970
Viewing Subsystem Fabrication Complete	January 1970
Mid-Depth Site Survey Complete	January 1970
Prototype Power Plant Setup Complete	March 1970
Subsystem Installation Complete	June 1970
Prototype Power Plant Test and Evaluation Complete	July 1970
Dry Test Complete	August 1970
Shallow Test Foundation Complete	October 1970
First Power Plant Installation Complete	October 1970
Full Depth Site Survey Complete	November 1970
Shallow Test Complete	December 1970
Delivery of Remaining Power Plant	January 1971
Delivery of Remaining Heat Sources	Febuary 1971
Refurbishment Complete	May 1971
Mid-Depth Foundation in Place	May 1971
Power Plant Installation Complete	May 1971
Mid-Depth Test Deployment	June 1971
Mid-Depth Test Complete	September 1971
Full-Depth Foundation in Place	October 1971
Full-Depth Deployment	January 1972

5.1 FINANCIAL PLAN

Design will be accomplished on design funds from a Naval Facilities activity. Procurement of the prototype will be funded as a Major Construction activity. Special missions will not be defined until later and these will be funded by the specific user. It is assumed that the AEC will be interested in this approach to the isotope power usage and that reduced price isotopes may be obtainable. The financial plan, therefore, as shown in Table 5-2, identifies the years in which programs require certain funding.

5.1.1 Description of Cost Items

5.1.1.1 Design

The design costs represent the effort in prescribing the design and fabrication techniques in sufficient detail to allow meaningful cost predictions and to provide further assurance of the practicality of the techniques required for the MUS. The individual items include:

Systems Integration: This is the synthesis of the various component and subsystems into a working MUS. The requirements of each major element must be prescribed and each interface must be controlled to assure proper assembly, interconnection and operation. Various parameter variations will be considered to arrive at optimal values. As the design progresses, the function of systems integration includes review of the design for performance and ease of manufacture. Various subsidiary considerations of standardization, maintainability, reliability, and value engineering are also included. Production scheduling will precede procurement, fabrication and installation. During the later phases, quality control and test of the equipment plus the operational considerations become the major Systems Integration tasks.

Foundation: The hemispherical concrete foundation concept will be continued to achieve detail drawings of the foundation suitable for fabrication. The characteristics of the sites selected for the shallow, mid-depth and deep tests will be examined to allow further refinement of the foundation concept.

Hull: The preliminary design will be further extended, and the effect of various fabrication techniques on strength and cost examined. The fundamental stress analysis of the toroidal hull under compressive stress will be extended. The effects of the mating hatches, windows, other penetrations, interior loading, foundation contact, etc., will be further explored.

Life Support: Scaling of the design of existing equipment to that required for the MUS is the major consideration for the life support area.

Communications and Control: This area includes internal and external communications, and the internal control of the various functions of the MUS not specifically covered in the other design areas.

Viewing and Lighting: Fabrication and long-term pressure testing of the viewports is the major design effort. The selection of a proper set of lighting equipment and assessment of available accessories and peephole optics is also required.

Mission Equipment: The manipulator and the pressure pass through are the mission equipments clearly prescribed for the MUS. Additional design tasks may be required by the specific missions selected for the prototype station.

Power Plant Module: The early design efforts for the power plant include setting up a test cell for selection of optimal design

TABLE 5-2

Preliminary Manned Underwater Station Budgetary Cost Estimate

	FY 1968	FY 1969	FY 1970	FY 1971	Item Totals
	(Thousands of Dollars)				
Design					
Systems Integration	250	250	250	150	900
Foundation	50				50
Hull	200				200
Life Support	100				100
Communications & Control	50				50
Viewing & Lighting	150				150
Mission Equipment (manipulator & pass through)	100				100
Power Plant Module (including isotope)	600	2400			3000
Site Survey		100			100
Design Sub-Total	1500	2750	250	150	4650
Fabrication					
Foundation & Cable			100		100
Hull		2000			2000
Life Support		200			200
Communications & Control		150			150
Viewing & Lighting		200			200
Installation & Checkout			850		850
Power Plant Modules (3)			420		420
Isotope for Heat Source			1500		1500
Training			50		50
Field Support			100	100	200
Fabrication Sub-Total		2550	3020	100	5670
Yearly Total	1500	5300	3270	250	
MUS Design (exluding AEC, Mission Funding and Prototype Procurement)					
Estimated AEC supported effort (prototype test 3000; production units 1920)					4920
Prototype procurement					3500
Mission related costs					750
GRAND TOTAL					10320

parameters and detail design of the steam generation, power generation, power conversion, control and safety equipment. The later efforts include fabrication and assembly of a complete module. This module would be completely tested and evaluated, including AEC licensing. After the evaluation is completed, the heat source will be refueled and furnished as one of the four modules for the prototype MUS.

Site Survey: The site survey for the prototype MUS includes three sites: the shallow, mid-depth and deep test sites. The survey will be performed using a conventional oceanographic ship supplemented by actual examination of the bottom with a small manned submersible.

5.1.1.2 Procurement

Procurement is defined as the cost of acquisition of the hardware and service necessary to provide the prototype MUS. Design and development programs are not included. The following items are expanded to further amplify the unusual aspects of the procurement activities of this program.

Installation and Checkout: Each piece of equipment must be installed in the hull and checked out separately and together with the other equipments. Various minor items such as cabling, internal lighting, etc., will be supplied as part of the installation and checkout phase.

Training: Special training is required for the MUS crew, as described in section 4.1.9.

Field Support: Field Engineering and Service personnel from the equipment and subsystem contractors are required for proper field support.

5.2 PROGRAM CONSIDERATIONS

Several aspects of the program to attain an operational Manned Underwater Station warrant further examination. These aspects are explored in this section.

5.2.1 Pre-Production Planning

Following the completion of the conceptual designs, it is necessary that the initial mission of the prototype Manned Underwater Station be defined. Included in this definition will be several alternate programs which may be supported within the habitat "operational area with undesignated functions.' The conclusive study, resulting from this detailed analysis; including further mission definition, will serve as a basis for proceeding with a definite design. The next logical step is preparation of a set of detailed contract plans and specifications which will be the basis for construction of the prototype station. This plan preparation should be undertaken by an organization intimately familiar with systems considerations, the mission and user requirements.

Concurrently, with the detailed design preparation, there will be engineering development and testing as outlined in the R&D problem statements. Additional considerations and equipment development problems may evolve as more comprehensive investigations of the chosen concepts are undertaken. Resolving these may require further study or testing. The work statements for the R&D problems should be assigned or contracted for study and resolution. With the broad base of experience in the Navy, certain R&D work could be done "in house," however, the time schedule and relative priorities may dictate that a well-qualified industrial source should conduct the necessary development study and testing phases.

The result of this phase of effort will be primarily plans and specifications which will serve as a basis for a realistic bid for the fabrication of the prototype station. The R&D effort concurrent with the detail design will provide the program manager with the necessary technical evaluation and assurance to properly interface and integrate the various components within the hull. Thus, it is recommended that a single organization be placed in charge of the overall construction of the station. This organization should be given responsibility for the MUS from the design development through the completion of the prototype testing. It should be stressed that the one project management group in working for the Naval Facilities Engineering Command will provide services which may include talents and hardware from many different existing organizations.

5.2.2 Fabrication and Operational Evaluation

5.2.2.1 Hull Construction

The pressure hull will be the first unit of the station to be fabricated. It will be made at an activity familiar with submarine standards and shipbuilding practices and government quality control standards will be imposed to insure that the hull is constructed in accordance with specifications. The latter are primarily materials identification, tradesman qualification and rigid inspection. By 1970, the HY-140 hull steel currently specified and the alternate HP-9-4 series will most probably be covered by a numbered MIL-Spec. The HY-140 interim specification at this time does not have a number. If the selected hull material has not been used in the building activity within a few months of start of the construction, a requalification program will be necessary to insure that the welders are prepared for the high quality workmanship necessary on a project of this nature. Current radiographic, magnetic particle and ultrasonic inspection techniques will suffice for the nondestructive testing of the hull during fabrication. Following completion of the hull, a standard submarine hull tightness test of 15 psig air will be sufficient before the initial submergence to about 100 feet. No pressure chambers of sufficient dimensions exist which can handle the full size toroid. Although a seven-tenths size model could be tested, the pressure capability of the Portsmouth Naval Shipyard test facility cannot currently exercise the model to the required operating depth.

5.2.2.2 Initial Emplacement

Since the first emplacement is in shallow water, and primarily for checkout of the habitat, construction of a foundation may not be required. This initial submergence of the hull will probably be made using a clump or driven pile for an anchor. A low current site should be selected to facilitate the employment of scuba divers in checking the hull. A trunk may be placed on the lower access hatch and the habitat pressurized to ambient pressure after the integrity testing of the hull and the final ballasting adjustments have been completed. This pressurization would allow the checkout of escape procedures for near-surface emergencies.

If currents become a problem at this shallow depth, a series of anchors could be laid out around the structure and guy lines attached to the station to hold it steady. This would save the expense of a foundation of limited value, yet avoid having to settle the station on the bottom for stability. Testing at this shallow depth should be complete in about 30 days after emplacement. However, a second or third excursion will probably be utilized for crew training.

5.2.2.3 Intermediate Emplacement

The next logical step is emplacement at a depth clearly in reach of small submersibles. By 1970, it is expected that a submersible capable of mating with the MUS at 2000 feet will be available. This depth also will provide a realistic checkout of foundation emplacement techniques. A site will be chosen which will permit use of a hemispherical seat type foundation. The structure will initially be placed in the foundation ashore or in shallow waters alongside a crane of sufficient lifting capacity. This will insure that the structure and foundation are compatible at various angles and that no unforeseen contact interface problems exist. By proper instrumentation, a measure of stresses resulting from the foundation contact can be obtained. Duplication of the stress pattern when emplaced on the bottom will assure that positive contact is achieved. It is possible that the stress pattern analog will indicate the structure loading on the foundation and thus be of use in interpreting the results of settlement of the station after emplacement.

Several operational missions will be run at 2000 feet for a "shakedown" of the life support subsystem and other equipment plus crew training. Significant engineering results will be obtained from this series of tests. However, the full capability of the MUS will not be exploited until the 6000 foot operating depth is reached. "Out-of-the-water" hull inspection will be performed between the shallow and intermediate emplacement. Interim inspections will be made by divers each time the structure is brought to the surface for resupply or crew change.

5.2.2.4 Design Depth Operation

The hull of the Manned Underwater Station is built to submarine standards and will be used in a similar manner. It will be instrumented for strain measurement and taken to the operating depth of 6000 feet by the crew. The initial emplacement will be on a site of interest for future deployments, since at the end of this thirty-day operation, thorough inspection of the hull and machinery will be conducted at an overhaul facility. The hemispherical type foundation at the site should allow immediate reuse of this site. During this first deep emplacement, long term experiments external to the habitat should be positioned for future observation during the return visits to the same location.

5.3 GROWTH POTENTIAL

The prototype Manned Underwater Station, as presented envisioned will serve many of the missions discussed in Section 2.1. Changes in the mission equipment and area will adapt the station to various mission combinations. However, the station may be desired for concurrent use for several missions, or for more complex missions, requiring more area, power, or personnel. Stacking of two or more toroidal hulls will provide a combined structure which can be handled as a single unit. The hulls will be joined at the mating hatches, to provide personnel interchange between structures, and with additional mechanical connections. The joined hulls will allow specialized functions in each hull, perhaps added power plants in the lower hull for a high power consumption mission, or additional space for food preparation or recreation in the upper hull, releasing mission space in the lower.

The joined hulls may require improvement in the downhaul system to handle the larger forces, but careful ballasting should preclude excess cable tension. Horizontal forces during downhaul require careful current profiling to determine positioning methods. Current drag forces on the combined structure when in place and in the water column may require some use of auxiliary positioning devices.

The use of the station to provide a platform for lengthy experiments in the deep sound channel, for long term sea life observation at various depths, and for deep scattering layer measurements and for current and tidal measurements is an attractive extension of the MUS concept. This would permit the mission profile to be split into several phases so that a multitude of experiments could be performed during a single deployment. The ability to deploy at various levels is further enhanced by the mating capability afforded between the station and small submersibles. Since the crews can be partially or completely interchanged by submersible and without necessity for surfacing the MUS, the various scientific missions can be observed by experts in each study area, even on a short term interchange. For example, the descent to the deep sound channel might be observed by a biologist while the sound channel experiment could be conducted by a physicist. After several days and at the conclusion of his experiment, the physicist might be replaced by a bioluminescence expert for the descent to the foundation. He in turn will depart after a short period on the bottom and be relieved by a civil engineer who will conduct the major portion of the bottom experiments before interchange by submersible with a sonar engineer who will conduct a bottom sound survey and sonar mapping project until received by an ichthyologist who will observe for a short period on the bottom and during the ascent. The hypothetical profile is intended to illustrate potential in the Manned Underwater Station for use in combination with a submersible and an auxiliary winch system for multi-level positioning.

Hull improvements for station use at depths to 20,000 feet are clearly feasible. Improved stress analysis with materials of the near future should allow a 20,000 foot hull requiring a minimum of external flotation to achieve positive buoyancy.

The basic MUS with some significant changes in configuration could be used to serve as a nuclear reactor power plant with a multimegawatt capability. The five man crew is sufficient for reactor operation, if no other duties are prescribed. This reactor with suitable power transmission could service a number of bottom stations and other installations.

5.4 ENGINEERING DEVELOPMENT

The Manned Underwater Station, as described in this study, is regarded as feasible and within the state-of-the-art of the time phase of the program. There are several areas in which directed engineering development is required to provide suitable equipment and/or optimal design. This section presents several problem statements for additional R&D efforts which would be profitable in achieving the station at the earliest possible date. Detailed design of the mating hatch is a government responsible item prerequisite to development of the station.

In addition, several components are used in the station that are state-of-art but require further efforts to scale them to the size desired for the MUS. These components are discussed in the respective conceptual design sections but are grouped here for convenience.

Component	Section
Smaller Size Oxygen Generator	4.1.4.3
Smaller Size Carbon Dioxide Scrubber	4.1.4.2
Water Management Subsystem Components	4.1.6.2
Pass Through for Samples	4.1.8.7
Deep Ocean Piling Emplacement	3.2.1.5

5.4.1 Isotope Power Plant Module (See Section 4.1.3)

The Research and Development requirement associated with the modular isotope power plant is primarily engineering developmental work with the heat source. Most of the other power plant items such as turbogenerators, condensers, valves and controls are off-the-shelf hardware. Every new design isotope power supply must undergo a certification program including licensing and formal testing by the Atomic Energy Commission (AEC).

To meet these requirements, a prototype 7.5 Kwe unit requires detail design before assembly as a complete unit. The design work including a demonstration of the heat source concept in a hot cell (radiation shielded) would take about one year from the award of a contract. Coupling with a 'breadboard' secondary power conversion system would be demonstrated at about this time. However, the assembly of a full-size unit of the final configuration would require an additional year for delivery to the test installation. This test installation will probably be on the customer's property in order to provide convenient crew training in plant operation and maintenance. By utilizing the prototype for training and insuring that the crew is checked out in operation of all subsystems, valuable operational time is saved by enabling deployment of the station immediately after completion of outfitting. In addition, demonstration of a single modular unit is tantamount to stimulating other potential users so that ultimate system costs may be reduced as a result of quantity production.

Following the delivery of the prototype modular plant, a 6 to 8 month period is needed to erect the units in a MUS simulator and to complete the required power plant optimization and testing program. In effect, a three-year R&D program is required for completion of an optimized isotope power unit module. Feasibility of the modular power sources will be assured within the one-year design period by the heat source demonstration. The cost estimate for the prototype, including fabrication, tests and licensing and crew training, is 3 million dollars.

Production hardware costs are estimated at $150,000 per module, less fuel cost, but including heat source assembly. The fuel charges are subject to AEC production availability which in turn is understood to be subject to user demand. Discussions with AEC representatives have indicated that the AEC is interested in developing isotope power units so that some cost sharing may be possible. For the reasons cited above, the best fuel investment figures obtainable are only estimates. This initial investment for Co-60 for 50 Kwt is estimated at $500,000. After use in the power plant, the isotope would be returned for reactivation or possible resale to other isotope users. It is expected that the power consumption costs are only about 15% of the initial investment.

In summary, the work statement includes:

a. Design of the 7.5 Kwe power plant module.
b. Demonstration of the heat source concept in a hot cell.
c. Development, engineering, fabrication and optimization of a prototype power plant module.

d. Licensing and testing as required by the AEC.
e. Assembly of the module and training services at the contracting facility.
Estimated time - 36 months
Estimated cost - $3,000,000

5.4.2 Viewport Research and Development Program (See Section 4.1.8)

The three separate problems found in viewport design are (1) long term creep strength of acrylic plastics under continuous loading, (2) design method for deep submergence windows in non-circular mounts and (3) the feasibility of a lens shaped window. These situations must be examined under (non-spherical hulls) high hydrostatic load of cold sea water on the exterior and a one atmosphere man-inhabited interior. A single series of tests and a less than full-size model should prove adequate, after a period of engineering research.

The work statement includes: design, construct and operate a pressure testing facility to check the creep properties of one quarter to one half size viewing window for possible application to the MUS. Determine stress patterns at edge and on surface of windows during test in cylindrical hull for $1 < D/h < 3$. Develop theoretical or empirical method for design of deep submergence windows in cylinder hull. Full size window desired is 10" inside diameter with a solid angle of 90°. It should be designed to withstand 3000 psi for not less than 500 days. Initially apply pressure for a 100 day period to check flexure, creep properties and compatibility with the frame. During this test, determine whether a shorter period will suffice or whether a longer test is required for future testing. An additional objective would be to design and test an optically corrected curved window for similar service. Prepare report stating test and study results.
Estimated time - 12 to 15 months
Estimated cost - $100,000

5.4.3 Toroidal Shell Theory (See Section 4.1.2)

It is recognized that a critical element of the concept is optimization of stiffened toroidal bodies under high external hydrostatic pressure. A number of papers are available that treat thin shell unstiffened toroids under internal pressure; only one treatment of toroids with external pressure has been located.

(Reference 5-6) The analysis used in the conceptual design uses a cylinder bent to close on itself and there is a sound basis for the theoretical treatment in this manner. The possibility of using thinner shell on the inside of the torus with thicker shell on the outer surface should be investigated since this may lead to lighter structures. This effect is particularly interesting for toroidal structures at very deep depths and may not be important for the 6000 foot structure.

References 5-1 through 5-6 were consulted and did not provide information for this specific application. A theoretical treatment may or may not be obtainable, however, a series of model tests could develop a sound understanding of the stresses in a ring stiffened toroid under external pressure. David Taylor Model Basin has a low priority study of this nature underway. It is recommended that this project be aggressively pursued.

Pages 44 to 46 of Reference 5-5 report on a test of a tube bent to a "U" shape. In both the external and internal pressurization, the cylindrical sections failed at a significantly lower value than the toroidal bends. The stabilizing effect of the double curvature in the torus region is credited with increasing the pressure required for deformation in this area. The toroidal hull is believed to have important advantages over more familiar shapes.

The toroidal hull concept offers a unique opportunity for man's extension into hydrospace. It provides a means for locating numerous viewports very close to the ocean bottom. The unobstructed field of view allows maximum utilization of the short range of underwater visibility permitted by even the most powerful illumination. The toroidal concept further provides a simple means for mating additional modules in a vertical stack. The hull is tightly held to a bottom sitting foundation and becomes an extremely stable structure eminently suited for test and evaluation of the mating capability of submersibles. The excellent internal accessibility provides for efficient space utilization.

Development of a theoretical stress analysis backed by model testing will be an extremely valuable step in advancing the technology of structures suitable for very high external pressures. The torus has served for many years as an internally pressurized vessel in such a simple application as pipeline expansion joints. This extension of man's ingenuity provides a most interesting and rewarding challenge for the future. A study contract to optimize the design will most probably produce significant progress toward the impending deep ocean installations.

5.5 DEVELOPMENT PLAN REFERENCES

References used in this section are:

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UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Deep Submergence Systems Department Underseas Division Westinghouse Electric Corporation Baltimore, Maryland 21203	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP

3. REPORT TITLE
Concept design for a Manned Underwater Station

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

5. AUTHOR(S) (Last name, first name, initial)
Westinghouse Deep Submergence Systems Department

6. REPORT DATE March 1967	7a. TOTAL NO. OF PAGES 222	7b. NO. OF REFS 62

8a. CONTRACT OR GRANT NO. N62399-67-C-003 b. PROJECT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
c d	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. AVAILABILITY/LIMITATION NOTICES
Distribution of this document is unlimited

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY U. S. Naval Civil Engineering Laboratory Port Hueneme, California

13. ABSTRACT

The results of a fifteen man-month conceptual design study for a Manned Underwater Station are presented, conforming to the requirement of a 30-day mission for 5 men at 6000 feet. The station is self-supporting when emplaced by using an isotope heat source with turbo-electric power generation, and a life support system to provide comfortable one-atmosphere environment. The pressure hull is toroidal in shape, forty feet in overall diameter with a 10-foot tube diameter. HY-140 steel is recommended for construction of the internally ring-stiffened hull. The concept provides a stable platform with maximum viewing of the bottom in the limited visibility in the deep ocean. For bottom locations with sufficient bearing strength, the hemispherical foundation and toroidal hull act as a ball-and socket joint with unique leveling capability. Where extremely low bearing strength materials are encountered, modifications are made to distribute the load on the bottom. Additional toroidal modules, mating in a vertical stack, permit expanding the station for larger operational missions.

Emergency power and life support provisions are included for a 5-day period beyond the 30-day mission requirement. However, with the recommended power system and the electro-mechanical life support equipment there is no reason why the mission time cannot be extended to 90 days when personnel interchange is undertaken. Crews may be exchanged by using small submersibles which have a mating capability with bottomed submarines.

DD FORM 1 JAN 64 1473

UNCLASSIFIED
Security Classification