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An Underwater Oceanographic Research Habitat

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AN UNDERWATER OCEANOGRAPHIC RESEARCH HABITAT - KILMER

B. A.

1969

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RESEARCH HABITAT

Windell H. Kilmer

May, 1969

"In partial fulfillment of the requirements for the degree of Bachelor of Architecture at The University of New Mexico, Albuquerque."

ACKNOWLEDGEMENTS

For my wife, Rosemary, who stood behind me in all the difficult times.

I would like to express my appreciation to Dr. D. R. Anderson, who provided the answers to keep this project going in the right direction.

I would also like to thank John Johnson IV, who helped me in a lot of my decisions, and who I believe could build this habitat.

PHASE ONE

program

program for an undersea habitat

w. kilmer jan. 17, 1969

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SECTION 1

STATEMENT OF PROBLEM

The purpose of this program is to set the goals, specify the requirements, and establish the limits for my involvement in the design of an Underwater Habitat which would be placed on a submerged continental shelf which borders one of the land masses. The habitat would serve an oceanographic research team who would be employed within a pilot program to ascertain the performance of the habitat for future human occupation in larger numbers.

The habitat shall be defined as all of the critical components (or systems) necessary to maintain a compatible environment for man's biological needs and human activities to exist in the hostile surroundings beneath the surface of the ocean. To meet the future occupancy requirements, the habitat shall have the ability to compensate for additional or reduced personnel. This expansion of the structure and/or related systems shall be accomplished in an orderly, efficient manner similar to the established pilot program.

The habitat shall be designed for a maximum operating depth of 600-800 feet beneath the ocean surface. This will allow the structure to be built on any continental shelf adjacent to a land mass that has properties similar to my typical site-the sea off the coast of southern California. The limitations on the physical size of the habitat shall be specified during the design process as there is a definite factor of positive bouyancy which cannot be exceeded or the habitat will not remain on the ocean bottom.

Various systems listed in this program shall be designed and specified according to type, size, capabilities, and working relationships. The exception to this rule is the structural system which must be detailed in all aspects as this system is the critical design determinant of the entire complex and its mission efficiency.

SECTION 2

BASIC MOTIVES

The twentieth century has propelled man into many realms never before open to his visitation due to the technological barriers which had to be overcome. Space exploration has set the tempo for countless masses to become excited over the possibility of man's extension beyond his planet. However, there exists a vast environment that man has not penetrated as a human being; discounting the possibility of his evolution from it. This world is that of the oceanic empire, the sea and all its depths. Let's take a look at some of the opportunities still available within this environment.

By the year 2000, the world's population will be approximately 6 billion people. A lot of the increased demand for energy, food supplies, and habitable space will undoubtedly be met from the sea. Man has already turned to the ocean and begun to explore the possibilities of this vast resource which physically occupies 70% of the earth's surface. This is evident primarily in the field of oceanography where new research vessels are probing the depths for new meaning of the oceanic environment which is available for man's uses,

> "Oceanography is the scientific study of that part of the earth which is covered with sea water. Its objective is to increase human understanding of all aspects of the oceans--the properties and behavior of the ocean waters, the nature of living creatures in the sea, the interactions between the waters, the air above them, and the solid earth beneath, and the shape and structure of the ocean basins."[1]

It is estimated that two-thirds of the people on earth suffer in a greater or lesser degree from deficiency diseases caused by the lack of animal protein in their food consumption. This protein deficiency

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[1] Draft of a General Scientific Framework For World Ocean Study, by the Scientific Committee on Oceanic Research of the International Council of Scientific Unions (France, 1964), p. 8.

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before long [illegible] [illegible] [illegible] [illegible] [illegible] barriers which had to be conquered. [illegible] [illegible] [illegible] [illegible] the [illegible] for scientists seemed to [illegible] [illegible] [illegible] the possibility of man's [illegible] [illegible] the [illegible]. However, [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] the possibility of his [illegible]-tion from [illegible]. This [illegible] is true of the [illegible] century, for the [illegible] all its depths. Let's take a look at some of the opportunities which available [illegible] [illegible] environment.

By the year 2000, the world's population will be approximately 7 billion people. [illegible] [illegible] [illegible] [illegible] demand for energy, food supplies, and habitable space will [illegible] [illegible] [illegible] [illegible] [illegible]. [illegible] [illegible] already turned to the ocean and begun to explore the possibilities of this vast [illegible] [illegible] [illegible] [illegible] 70% of the earth's surface. This is evident primarily in the field of oceanography [illegible] [illegible] [illegible] [illegible] for [illegible] [illegible] of the [illegible] environment which is available for man's uses.

> "Oceanography is the scientific study of that part of the earth [illegible] [illegible] [illegible] [illegible]. The objective is to increase man's understanding of all aspects of the [illegible]—the [illegible] [illegible] and [illegible] of the [illegible] layers, the [illegible] of living creatures in the sea, the [illegible] between the [illegible], the air above [illegible], and the [illegible] [illegible], and the shape and [illegible] of the ocean basins."[1]

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could be met by a 30% increase in the world fish catch, from 41 million tons to 53 million tons a year. However, the ocean has even more processing possibilities. The current declining land-based reserves, economic pressures, and rising consumption is already forcing organizations such as the oil industry to move to the sea. Moreover, the ocean floor is carpeted with nodules of manganese (used in making steel) and tin.

As, one can readily see, the importance of man's adaptations of his extensions to be compatible to an ocean environment is crucial to processing the ocean floors for ultimate human utilization. Moreover, man's obsession with bodily penetrating nature's barriers to him in his guest for knowledge and relevance of unknown places is reason enough for him to want to walk the ocean floor. The desirability of living on the ocean floor for purposes of research, ocean utilization, and recreation is evident by the accounts of Jules Verne's fictional Nautilaus at one extreme to the scientific study by the U.S. Navy's Sealab III project at the other.

As a potential dwelling place for future generations, the ocean has numerous possibilities. Perhaps in the near future, families could literally vacation in the sea, swimming out from pressurized dwellings for a day of fishing or underwater adventure. Within this ocean world, underwater habitats would support large city "sub"-burbs around seaports such as New York, San Francisco, Miami, and other congested metropolis's where land availability is a major problem. Eventually, a new Atlantis would take root somewhere in the vast oceans, expand into a mature city nation and link one land megapolis with another to create a unified earth habitat. Perhaps the land cities would even be leveled to re-create the natural setting so long ago aborted by man and his

machines. He would perform all of his work functions beneath the sea and take his leisure time on the vast land resources. These would be surface playgrounds which man could again enjoy as did his ancestors.

Many attempts have been made by various individuals and organizations to efficiently inhabit the ocean bottom. Most of these have been experimental programs that were successful in mission but costly to initiate and support. The vessels that were placed on the ocean floor were usually of a short occupancy duration and a "one-time" shot-meaning once the vessel had completed its mission, it had to be brought to the surface and outfitted for longer time durations and increased personnel.

It is my intent to create a habitat that can be economically fabricated, positioned on the ocean floor, and require a minimum of external support. I also hope to design a structure that can be used for a long time period at its working depth and expanded efficiently as required by additional mission parameters.

SECTION 3

ESTABLISH BASIC ISSUES

I. Oceanic Environment

A. Temperature

q - What is the temperature of the surrounding waters at the specified depth?

q - How often and to what degree does the temperature vary?

q - Is this temperature compatible to man or must it be compensated?

B. Pressure

q - What is the hydrostatic pressure at the depth of the habitat site?

q - Is the pressure constant in all dimensions?

C. Salinity

q - What is the salinity content of the water?

q - What are the effects of this substance in relation to submersible life?

D. Soil Conditions

q - What is the permissible soil bearing pressure?

q - What are the characteristics of the ocean bottom terrain?

E. Subsurface Currents

q - What are the velocities, magnitudes and direction of current flow?

q - What is the frequency and predictability of these flows?

F. Surface Waves

q - What effect does surface wave and tidal action have at lower depths?

q - What are the problems encountered when penetrating through this layer or layers?

G. Marine Organisms

q - What effect will micro-organisms and larger predators have on the habitat and its functions?

q - What are the chances and effects of impact by these organisms on the habitat?

H. Hazardous Conditions

q - What effects will be produced by earthquakes or other mantle faults?

q - What are the possibilities and effects of impact to the habitat by debris?

q - What are the effects of chemical corrosion on the habitat?

I. Visibility

q - What restrictions are placed upon seeing objects at distances through the ocean media?

q - Are objects as discernible in the ocean as on land?

II. Structural System

A. Structural Configuration Concepts

q - Will the pressure hull be designed for ambient internal pressure or saturation pressure similar to the surrounding waters at the specified depth?

q - What are the parameters to optimize for shape, operating depth, size, weight, safety factors, and buoyancy ratio of the habitat?

B. Material Properties and Performance

q - What is the yield strength and ultimate strength?

q - What is the strength-to-weight ratio?

q - What limits are placed by modulus and modulus-to-weight ratio?

q - What are the heat transfer characteristics?

q - What are the coefficients of thermal expansion and effects?

q - What are the properties of ductility, brittleness, impact strength, and notch sensitivity?

q - What is the moisture diffusivity?

q - What are the load cycling effects and fatigue strength?

q - What are the limits of corrosivity and protectability?

q - What is the failure criteria and its modes?

q - What is the onset of failure and propagation rate?

C. Construction

q - Will the habitat be composed of a monolithic structural material or composite materials?

q - Will the structure be made of conventional materials, materials of higher strength-to-weight ratios, or materials with high compressive strength and low density?

q - What methods of construction will be ulitized to form the structure?

q - How will future expansions to the structure be accomplished?

D. Availability

q - Are the materials and/or construction requirements readily available or must new materials and techniques be developed?

q - Are there existing structural systems that can be employed or does this project require new theoretical configurations?

E. Foundation and/or Anchoring

q - Will the structure be negatively, neutraly, or positively buoyant?

q - Will a foundation and/or anchoring be required?

q - Will this be integrated with the structural system or a separate system?

q - What are the requirements if a separate system is to be employed?

III. Life Support Systems

A. Environmental Control

1. Air Supply

q - How much air is required for various human functions?

q - What are the composition requirements of the air such as temperature, humidity, etc.?

2. Expended Gas Extraction

q - What is the allowable concentration of toxic gases in the habitat?

q - How and where will the excess toxic gases be vented?

3. Heating Cooling, and Ventilation

q - What temperatures and humidity levels must be provided in the habitat?

q - Are heating and/or air conditioning required?

q - What are the limits the systems must perform to?

q - To what extent must the air be circulated or re-circulated?

B. Energy Systems

1. Power Supply and Distribution

q - What and where will be the power source for the habitat?

q - What are the requirements of the power and its limits?

q - How will the power be distributed to the various systems requiring it?

2. Lighting

q - What level of artificial illumination will be required?

q - What natural illumination is available?

3. Comminication

q - What communication modes will require electrical power?

q - Is powered communication required throughout the habitat and/or between habitat and subsurface or surface stations?

4. Work Systems

q - What type of systems will be employed to provide physical magnification of human extensions (such as hydraulic door hatches or electrically powered elevators)?

C. Water Supply

q - What are the needs of the occupants in relation to fresh water supply and consumption?

q - How will the water be distributed throughout the habitat?

D. Occupant Nutrition

q - Will food products be prepared within the habitat or pre-packaged elsewhere?

q - How will these products be delivered and/or stored within the habitat?

E. Waste Disposal

q - What methods shall be used for collecting and disposing of organic and non-organic wastes?

q - Will these wastes be discharged directly into the ocean, transported to another place, or disentegrated?

IV. Circulation Modes and Paths

A. Internal

1. Habitat Complex

q - What are the mode and path requirements for movement throughout the total structure?

q - What areas are off limits or necessitate no human travel through them?

2. Unit Spaces

q - What are the activities and circulation within each component space of the habitat?

B. External

1. Surface to Habitat

q - How will travel between surface stations and the habitat be accomplished?

q - What restrictions are placed on this mode of travel?

2. Habitat to Surface

q - Will this circulation path be the same as surface to habitat?

3. Subsurface to Habitat

q - What are the requirements for circulation between the habitat and the surrounding ocean?

V. Fail-Safe Systems

A. Structural Safety

q - What are the material property variations?

q - What is the material performance probability?

q - What load variations are to be compensated for?

q - What are the oceanic temperature effects?

q - What limits are met as far as dynamic effects?

q - What hazards are prevailent due to adverse combinations arising from manufacturing processes and construction techniques?

q - What limits shall be specified for safety factors?

q - What time limits are placed on habitat submergence by the safety factor?

q - What monitoring must be provided for checking the behavior of the structure during its operational life?

q - What quality controls must be placed on manufacturing, construction, and placement of the structural system?

q - What factors must be taken into account when providing penetrations through the pressure hull for equipment service?

B. Life Support

1. Environmental Control

q - What design factors and/or support system will compensate for failure in air supply and exhaust?

q - Is there a critical time limit or performance of this back-up system for air supply and exhaust?

q - If there is a failure or reduction in the removal of toxic gases, how can this be alleviated?

q - To what degree could a breakdown in the heating, cooling, or air circulation systems be tolerated?

2. Energy Systems

q - What provisions will be made for emergency power supply and/or distribution provided in the event of a power failure?

q - What will be provided in the case of a lighting failure in the habitat?

q - How will a breakdown in communications be compensated for?

q - What emergency release circuits and/or mechanisms will support the work systems (such as manual over-rides)?

3. Water Supply

q - What provisions will be made for an emergency water supply?

q - Will there be provisions for servicing water distribution networks?

4. Nutrition Service

q - Will emergency supplies be necessary in event of a normal food supply breakdown?

5. Waste Disposal

q - What preventive measures or auxilary systems will be used in the event of failure in the waste disposal system?

C. Emergency Circulation Paths and/or Modes

1. Internal

q - Will emergency routes be established within the habitat complex for the occupants?

q - Will these routes be a directional path and must they be backed up by life-support systems?

q - What emergency provisions will be made for isolation of habitat spaces that have been subjected to catastrophic failure?

2. External

q - How will emergency escape from the habitat be accomplished?

q - What emergency support agencies will be needed to service the habitat in the event of disasters?

VI. Human Attributions

A. Physiological

q - What physical burdens or limits might be placed on the occupants of the habitat?

q - Will the environment of the habitat be compatible to human life functions?

B. Psychological

q - Will there be mental confrontations the inhabitants must adjust to living within the habitat?

q - What emotional stresses might arise from the "close" quarters?

C. Activities

q - What human activities may be hindered or not possible?

q - Will living conditions be similar as those available at surface environments?

VII. Feasibility Analysis

A. Economics

q - What is the economic base for supporting and living in the habitat?

q - What are the estimated costs of the various systems?

B. Construction

q - What steps must be undertaken to start and carry the project to completion?

q - What are the alloted times for completing the various stages of the project?

C. Future Expansion

q - What are the basic issues that require expansion to the habitat?

q - In what steps will expansion take place?

D. Ownership

q - What legal complications arise over claimed ownership of the ocean bottom by various land-based nations?

q - Can the ocean bottom and its materials be claimed by private parties, organizations, or nations?

E. Support Agencies

q - What various agencies must be employed to support the operations of the habitat?

q - Is the amount of work done by these agencies detrimental to the program's efficiency?

SECTION 4

ANSWER BASIC ISSUES

I. Oceanic Environment

Temperature

Referring to the Sealab II Project, temperatures at 200 feet depth off the shore of La Jolla, California varied from 52 degrees to 58 degrees Fah. with temperatures in the range of 53 degrees to 55 degrees predominating. It is assumed that temperatures at 600 feet depth will be approximately 42 degrees to 48 degrees Fah. Therefore, the habitat must be heated for human occupation. See Figure 1 for general oceanic temperatures.

Pressure

"Every foot in height of sea water produces an excess pressure of 0.445 (or 1/33 x 14.7) pounds..."[2] At 600 feet depth this would be 267 pounds per square inch and 356 psi at 800 feet. As can be seen, if a relatively long vertical body is submerged, there will be a pressure difference along its exterior. See Figure 2 for general hydrostatic pressures.

Salinity

Salinity increases directly with each foot of depth to a concentration of approximately 35 parts per thousand for the specified depth. See Figure 3 for these concentrations.

Soil Conditions

The sea floor off the coast of California is rather unique in its physiography for it has a complexity that has resulted in a concentration of environments of such a varied nature that it would require long cruises to find these conditions elsewhere. Detailed

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[2]Diving Manual - 1943, Dept. of Navy (Washington, D.C., 1943), p. 127.

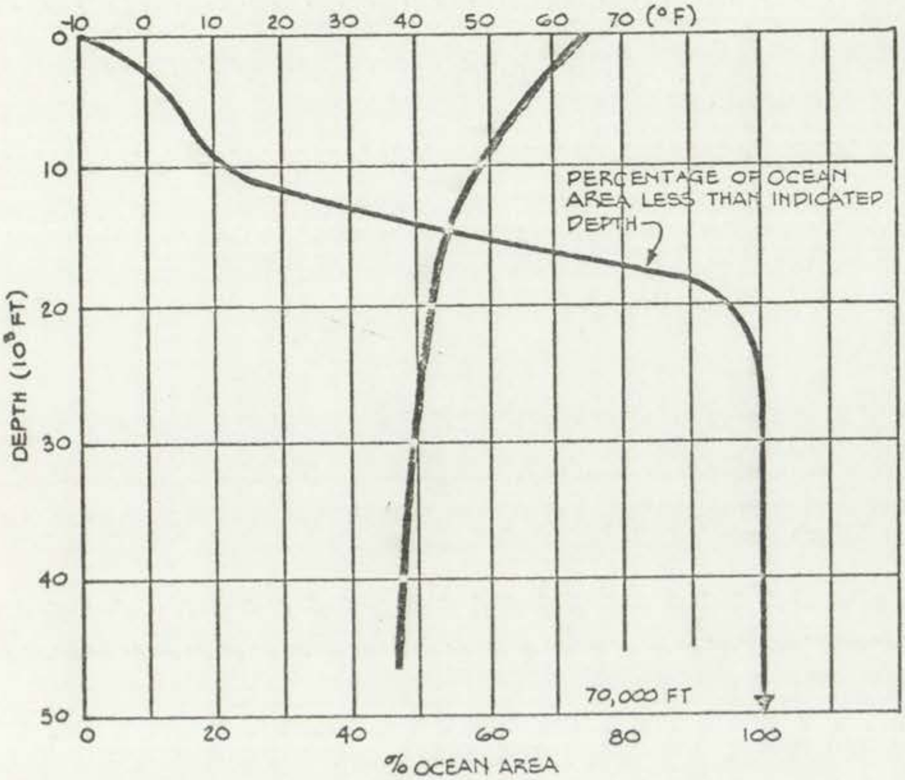

Figure 1. Temperature

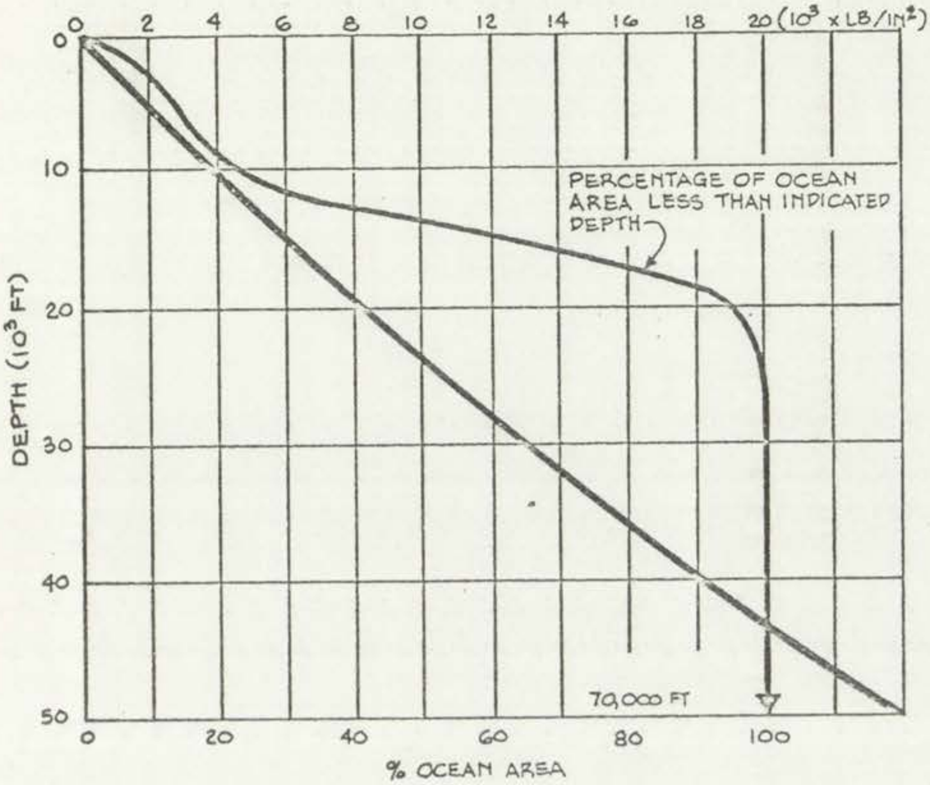

Figure 2. Hydrostatic Pressure

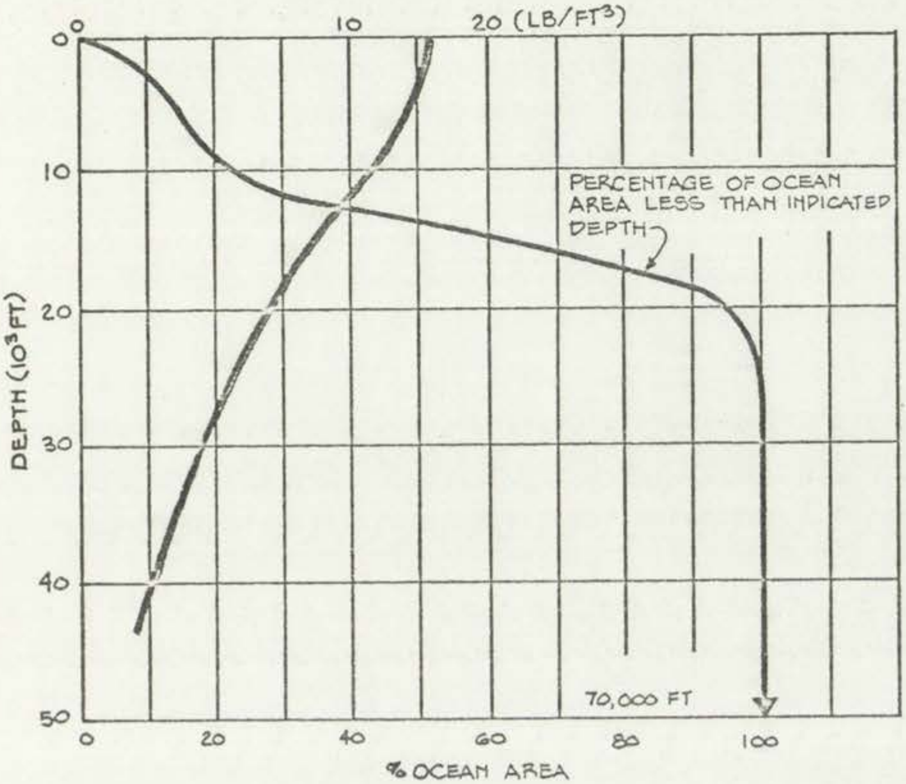

Figure 3. Salinity

knowledge obtained here can be extrapolated to more distant regions. The continental shelf here has both a rocky bottom and silty sand; the latter being the most common with an approximate bearing pressure of 300 psf and six or more inches of silt. There exists here a series of step-like terraces and terrain of zero degree slope to approximately twenty degrees slope which might be selected for habitat placement. See the Appendix for contours.

Subsurface Currents

Detailed information is not available to accurately predict the undersea currents in the area of the continental shelves due to the many unknown factors that affect the current flow. However, it may be assumed that a current flow of zero to two knots per hour could be encountered. See Figure 4 for more information.

Surface Waves

Referring to Sealab II Project, little effect was felt on the ocean floor from surface wave action. During the project's stay, horizontal amplitude motion never exceeded two inches. Therefore, it may be assumed that at 600-800 feet, there will be no apparent effect on the habitat from surface wave action. However, for surface support vehicles or penetrations through the air-sea face, wave motion is a critical item to functions requiring stability. Moreover, the open sea tides are not in a state of understanding due to lack of accurate tidal data forms from off-shore regions. It is assumed that this tidal action will have no adverse effects upon the habitat.

Marine Organisms

High concentrations of plankton and sediment greatly reduce

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[illegible]

[illegible]

[illegible]

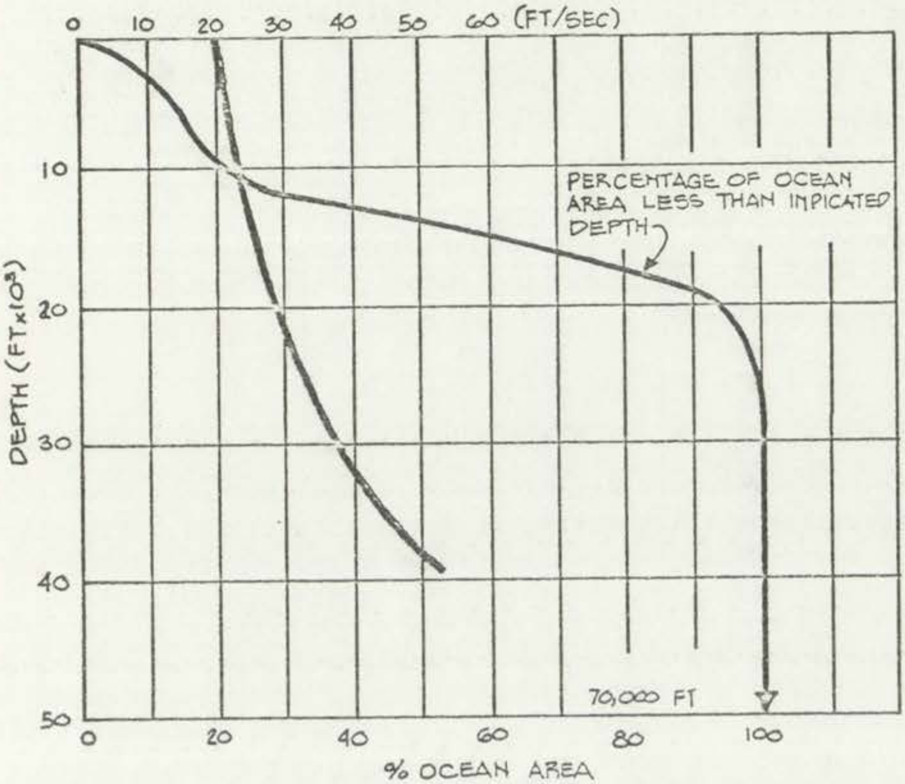

Figure 4. Maximum velocity of currents

the transparency of the ocean waters, making visibility poor. It has also been observed that much of the marine life have a tendency to crowd around habitat viewing ports, making sea observations difficult. As on ship hulls, barnacles will grow on the habitat's exterior unless preventive measures are taken. There is also danger of fouling by various species of hydroids, algae, calcareous worms, and sea squirts. Collision by large marine organisms is improbable, yet compensations in the design should take such impacts into consideration.

Hazardous Conditions

The effects of earthquakes on undersea structures go beyond that which is predictable from subaerial quakes. Underwater seismic shocks have caused a brief hydraulic overpressure on the sea floor. If vertical accelerations on the bottom in deep water approach the intensity and duration recorded near epicenters on land, a brief overpressure of almost twice the total hydrostatic pressure is feasible. Such an effect would be disastrous to an undersea habitat that was not designed to withstand this force. Debris impact to the habitat is a condition which must be theorized as to probable damage that could be inflicted by occurances such as this, since the actual probability of occurance cannot be accurately determined. Corrosion upon the habitat is not a major factor unless a chemical reaction occurs between the water and structural material when oxidous surfaces such as steel or iron are exposed directly to the ocean environment.

Visibility

Good visibility in the ocean media is affected by various factors such as sediment and plankton which tend to block vision and reflect light transmission. Visibility in the coastal waters off southern California is varied, ranging from five feet to one hundred feet at the specified depth. The visibility will range from day to day as do the currents which stir up plankton and sediment.

II. Structural System

Concept

The critical element in the design of an underwater habitat is the hull structure, for it must protect the occupants from the fatal environment. The ability of the structural system to resist the pressure load and the potential of the material to retain its properties in the extreme corrosive environment are the two basic requirements. The conventional approach to designing a structural shell capable of withstanding the high hydrostatic pressure and of suitable size for manned operations, is a cylindrical shell reinforced at intervals by stiff rings and/or bulkheads, as in the case of submarines. The cylinder is then closed with hemispherical ends. Various other studies have exhibited more suitable shapes for undersea vessels as seen in Figure 5.

The most efficient design for resistance to buckling is the sphere. This is primarily due to its double curvature and uniformity of generalized shell stress which require little or no stiffening. However, the size must be optimized to provide for internal volume utilization due to the poor efficiency of useable space.

1. Cylindrical:	With hemispherical ends With hemi-ellipsoidal ends With conical ends
2. Oblong shapes:	Cassinian Ellopsoid or Prolate Spheroid Ogive with spherical domes
3. Spherical:	Single sphere Two spheres-intersecting or barbell type Multiple spheres-intersecting or conjoined barbell

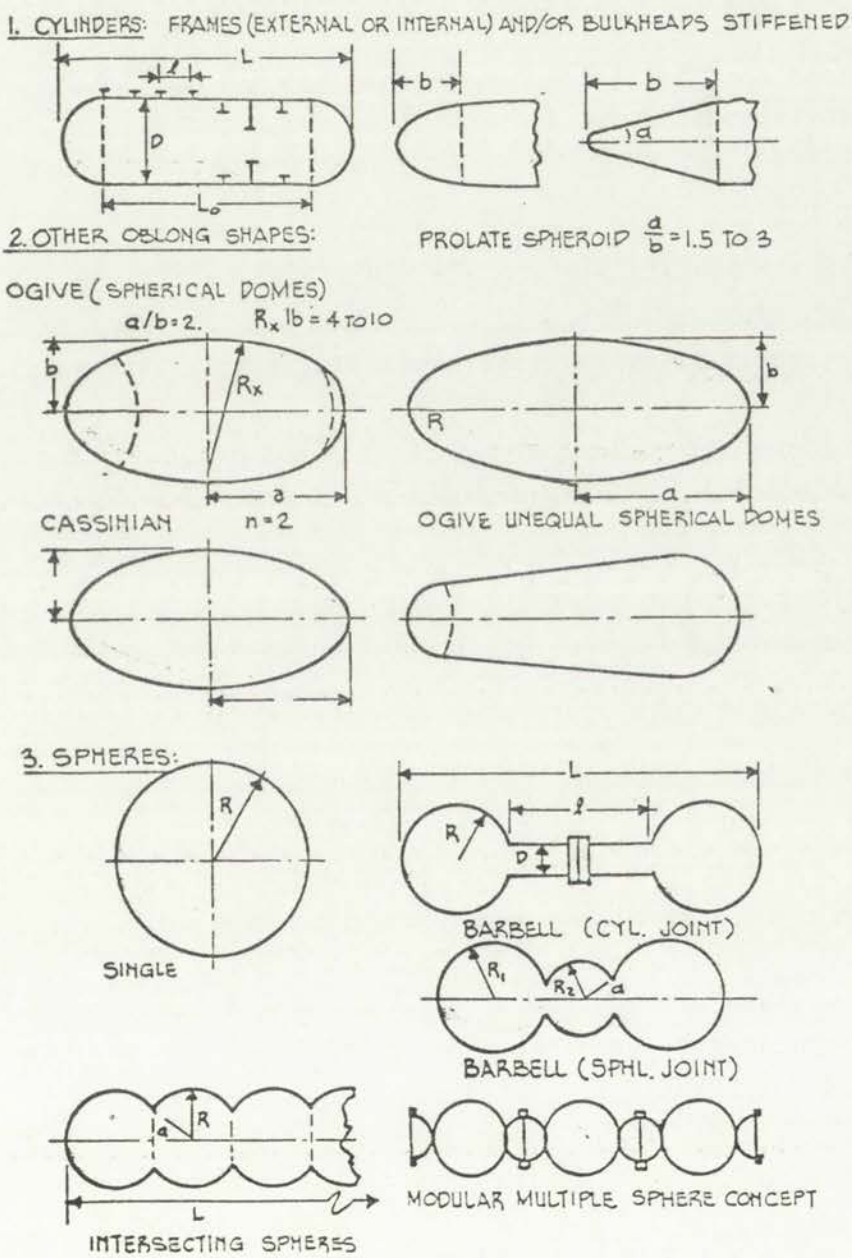

Figure 5. Structural Configurations [3]

[3] N. J. Shen-D'Ge', Structures/Materials Requirements and Considerations For Safety of Oceanic Deep Submergence Bottom-Fixed Manned Habitat (Pennsylvania, 1967), p.5.

Upon studying the configurations in Figure 5, it can be seen that segmented spheres yield about the lowest weight to displacement ratios. Prolate spheroids follow these with an aspect ratio of 2.0. Oblong shapes with two radii are subject to buckling as determined by one radius, which must be compensated with the other radius, reducing efficiency. Conventional cylinders with hemispherical ends are relatively efficient due to better utilization of internal volume, but are subject to buckling unless some stiffening is provided, thus adding weight.

The parameters that control the optimum design of a structural configuration could be grouped to produce significant quantities which would reflect their effectiveness as demonstrated below:[4]

a. Volume or Payload } ratio to { linear dimension (length or diameter) weight or area

b. Displacement ratio to volume, total weight, payload weight.

c. Ratios of geometric parameters of a configuration, e. g., length/diameter ratio for a cylinder, major to minor axis ratio for cassinian, or ellipsoid ratio of radii of ogives.

d. Strength to density ratios of materials.

e. Buckling/yield/ultimate criteria and safety factors

Possible structural composition are monolithic shell, ring stiffened/bulkhead stiffened, integrally stiffened, ring and intercostal stiffened, and a double wall with structural core such as corrugation or honeycomb.

When performing tasks in the ocean environment, it would be desirable for the diver/occupant of the habitat to dwell in a

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[4]Shen-D'Ge', p. 7.

saturated state of air which would be in pressure equilibrium with the ocean-floor conditions to avoid the necessity of undergoing decompression stages each time he re-enters the habitat from the ocean environment (if the habitat was at ambient pressure). Unlike diving from the surface, this diver must return to the pressurized habitat and cannot return immediately to the surface for it could mean certain death. This would result from the dissolved gases in his bloodstream expanding at too great a rate. Another disadvantage to living in this saturated atmosphere is that the helium required for this depth's atmosphere is both expensive and interferes with communications. This gas has an effect on man's vocal chords to the extent of giving his speech a "Donald Duck" quality. Furthermore, this saturated atmosphere would require the healthiest individuals to exist under this pressure. It can readily be predicted that many future occupants would be unable to live in the habitat due to their physical inabilities to withstand the gas mixture and pressure.

Therefore, the habitat shall be designed to maintain an atmosphere similar to that available on land, which is ambient or one atmosphere. However, it must be stated that there are drawbacks to maintaining an ambient pressure in the habitat. The hull design must be stronger to withstand the difference in pressure between the habitat atmosphere and the surrounding waters. Unless parts of the habitat are kept at a saturated pressure, a diver must undergo compression stages to leave and re-enter the habitat when adventuring into the ocean.

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the [illegible] the possibility of undergoing de-

compression, [illegible] from the

[illegible] ambient pressure), the

[illegible] return to the pres-

[illegible] to the surface for

[illegible] This would result from the

[illegible] a cost. Another

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between the habitat atmosphere and the surrounding [illegible]

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Material Properties and Performance

Modern organizations have done vast amounts of research and development to define material behavior under the oceanic conditions. At the time of this program, however, additional testing programs are necessary to accurately predict the effects on certain materials and their configurations at the specified depth of this habitat to reduce the unknowns and the currently high safety factors in design processes. Material considerations for the habitat should include conventional and new materials as well as composite materials to optimize on the characteristic properties of each. The properties of different types of materials proposed for oceanic use by various agencies are summarized in Figure 6. It may noted that the detailed questionaire established under the basic issues of this program is not fully answered by this chart. The reason for the lack of some of this information is that the amount of space required to answer all material property characteristics would be very space consuming and not relevant at this time. The intent of this program is an outline to follow for investigating materials, not an informative tabulation of possible materials. The answers to these specific questions will be supplied when a particular structural material has been selected during the design process.

Construction

Structural materials and structural system configurations cannot be selected in this program for the design of the habitat. Selection of these items and format is impossible at this time without

Material		Aluminum Alloy		Titanium Alloy		Stainless Steel		Beryllium Alloy	Nickel Alloy	Ceramic Glass	Other Glass	Glass Reinforced Plastic	Quartz/ Resin	Boron/ Resin.	Concrete	
Specification		7079-T6	5456 -H323	6AL4V	Ti -155A	HY 100 HY 150	PH 15-7MO 5-CR-MO-V	Hot Rolled Sheet 4:1 at 1400°F	Rene 41	Pyroceram® 9606		143 Glass Fibre & Epoxy Resin	Carbon Coated Quartz & Epoxy	Boron Fibre & P.P.O.	Mix	Reinforced
Density	lb/in^3	.099	.096	.160	.163	.280 .283	.277 .281	.066	.293	.094	.089	.057	.074	.075		
Yield Strength (Tensile)	$10^3 lb/in^2$	64-56	35	126	135	100	200 240	64.5	130			59-55 150 $x10^3$				
Yield Strength (Compression)	$10^3 lb/in^2$	63-54	34	132			210 250		130	340 (ult.)	300	58.1	30	140		
Ultimate Strength (Tensile)	$10^3 lb/in^2$	73-66	48	134	145		225 280	83.5	170			85.0				
Modulus of Elasticity	$10^6 lb/in^3$	10.3	10.2	16.0	15.0		29.0 30.0		31.5	17.2			5	22		
Elongation	%	6-4	8	10	10		5/4	5.5	1.0							
Yield/ Ultimate (Tensile)	-	.877 -.848	.73	.940	.931		.889 .857	.772	.765			.684				
Yield/Density (Compression)	10^5 in	6.46-5.66	3.75	7.88	8.23		7.22	9.77	4.36	35.2 (compr).						
Ultimate/ Density (Tensile)	10^5 in	7.37-3.33	5.00	8.38	8.90		8.12 9.96	12.7	8.10	3						
Mod. of Elas./Density (Tensile)	10^7 in	10.4	10.6	10.0	9.62		10.5 10.7		10.8	15.3						
Poisson's Ratio	-	.33	.33			.3	.3			.24						
Notch Strength		Poor		Fair		V. Good	Good	V. Poor	Good	Pr		Good				Poor
Izod Strength																
Crack Propagation Rate		Moderate		Moderate		Slow		Rapid	Slow	Rapid						-
Welded Strength Deterioration		-		Low	Low	Low	Low			-	-	-				-
Weldability		Not Suitable		Fair to Good	Good	Excellent	Good/Good			-	-	-				-
Other Fabricability Characteristics		Fair		Good		Good	Fair	V. Poor	Fair	Poor	Poor	Fair				Good
Thermal Expansion Coefficient	in./in.°F	13.1 $x10^{-6}$	13.3 $x10^{-6}$	4.6 $x10^{-5}$	5.7 $x10^{-5}$		$5 x10^{-5}$ / 7.1 $x10^{-5}$			3.17 $x10^{6}$		6.7 $x10^{-6}$				
Thermal Conductivity Coefficient	Btu/Hr ft °F	74	68	3.8			9/16.6			1.95						
Low Cycle Fatigue in Marine Environment		Fair	Fair	Excellent		Good	Good		Good	Fair						
Corrosion Resistance in Marine Environment		Poor, Improved when Anodized & Painted		Excellent		Excellent			Good	Excellent						
Compressive Creep Resistance				Good		Excellent	Fair to Good		Fair	Fair						
Moisture Diffusion	$lb/ft^2/day$	-		-		-	-	-	-	-		$.9 x 10^{3}$				
Availability in Heavy Sections		Good	Good	Fair	Fair	Good to Fair	Fair	Poor	Fair	Fair		Poor				Good
Cost/lb Low / Med. / High	≤$1/lb / $1-3/lb / ≥$3/lb	Medium	Medium	High	High	Low	Medium	V. High	High	Medium		Medium				Low

Figure 6. Material Selection Data [6]

[6] Shen-D'Ge', p. 14.

a constant interaction between all of the determinants that affect one another and the design of the habitat. Therefore, this program shall leave the selection of the structural system and its construction peculiarities open until the design process can be initiated. This program will, however, specify the group of structural systems and their related materials which will be of prime consideration during the design process as evident in Figure 6.

Future expansion to the habitat shall be one of the governing structural considerations. The concepts and materials selected must yield readily and efficiently to imposed operating loads exhibited by component additions to the complex. Brittle materials must be respected with relation to impact forces resulting from the construction processes of mating of new components. The inefficient use of improperly selected connection mechanisms which do form a compatible link between existing and new spaces will be avoided. Allowances must be made in design tolerances and complex loading conditions created by the juxtaposition of new units on the habitat complex.

Availability

New structural designs or materials are often uneconomical in their applications to solving the problems of man's inhabitance in hostile environments. It is usually only after the unknown factors have been reduced and the manufacturing processes have been updated to efficiently produce the new systems and components that these items become readily feasible on a large scale. It is under these assumptions that the final design of the habitat shall optimize on the current materials and methods available with

uneconomical selections reduced to an absolute minimum in order to produce a feasible structure. All materials and construction methods shall be selected on the premisis that they are competitively produced items and not unique in their fabrication process or employment in the field.

Foundation and/or Anchoring

Various underwater habitation experiments have shown that transportation of the structure in the sea and its placement are difficult due to surface wave action and the varying ballast compensations that must be made to accurately lower and position the habitat. Moreover, after these obstacles have been overcome, buoyancy becomes a critical problem. A negatively buoyant structure will tend to sink into the soft ocean bottom whereas positive buoyancy creates the problem of constant surfacing of the structure. A neutrally buoyant structure will be at the mercy of the currents or other environmental features that cause drift, roll, or other undesirable effects. Therefore, buoyancy will be defined as a function of the project mission. As has been stated, the mission will be that of a habitat which is to remain in a fixed location for a long period of time. The efficiency of the project can therefore be measured by the ability of the structure to remain in its fixed location. This would tend to point to the fact that a negatively buoyant structure should be the most desirable over a neutrally or a positively buoyant one. However, positive buoyancy would facilitate surface maintenance and built-in safety features by raising the structure from the ocean depths to a more advantageous

place for repairs or rescue. In conclusion, the design of the habitat shall incorporate the facilities to give a varying buoyancy to meet the problems of transportation, placement, and surfacing for repairs or emergencies.

The foundation design must be capable of supporting the structure on a minimum 300 psf soil bearing pressure and securely maintain the habitat in its fixed location. It is preferable to design the foundation as an integral part of the habitat; however, if a separate system is employed, it should be incorporated as a part of possibly the placement system and not a monolithic pad that must be placed on the ocean bottom before lowering the habitat to it. The latter would tend to make an inefficient project due to the amount of time and construction needed each time the habitat is expanded.

III. Life Support Systems

Environmental Control

There are three ways to provide a breathable atmosphere for the occupants of the habitat. They are: (1) the open cycle where external air supply is exhausted and discharged directly into the sea; (2) the replenishable cycle where oxygen is added and CO_2, odors and/or contaminants are removed; and (3) the closed cycle where a completely ecological system is balanced by complementary organisms. A combination of the two latter cycles seems most advantageous to the habitat design. It is hoped that the closed system will be the final selection; however, the amount of space and service systems required to maintain this cycle must not be of such magnitude to directly deter the project's efficiency. The controlling factor over atmosphere systems shall be based on amount of work done by

each system versus the support agencies required. The minimum air supply shall conform with the requirement that "the average man at rest breathes about 0.25 cubic foot of air per minute...".[6]

It is noted that an average man at rest also produces about 0.014 cubic foot of CO_2 per minute or 0.045 cu/ft/min at moderately hard work. When the inspired air contains over 3 percent by volume of CO_2, it has a distressing effect on man. A concentration of 10% will produce unconciousness. The expended CO_2 gases must be removed from the atmosphere along with objectionable odors arising from waste disposal, cooking, etc. Any cabon dioxide filter employed shall conform to a design standard of 75 percent saturation based on the following formula:

$$100 \times \frac{\text{specified time period in days} \times 2.4\text{lb } CO_2/\text{day}}{\text{lb } CO_2/\text{lb of lithium hydroxide}} = 75 \text{ percent}$$

The 2.4lb CO_2 per day in the formula is the approximate rate of production of CO_2 gases by an average man.

Due to the cold surrounding ocean waters, no cooling of the habitat atmosphere is required. However, heating and humidity control must be introduced into the air. The internal atmosphere of the habitat shall maintain a temperature of 70-75 degrees F. with a relative humidity of approximately 40%. Moreover, the ventilation system should satisfy the following functions:

1. Atmospheric circulation and distribution
2. Removal of carbon dioxide (CO_2)
3. Removal of odors
4. Make-up oxygen mixing.

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[6] Diving Manual-1943, Dept. of Navy (Washington, D.C., 1943), p. 137.

Energy Systems

The power source for the habitat can be locally available or produced within the habitat complex. Voltage at the site shall be of a 3-phase 440-volt output. Distribution of power throughout the various units of the habitat shall be by conventional means such as wire conductors.

Since natural light at the specified depth is insufficient to maintain normal human activities, artificial lighting by commercially available fixtures shall be used throughout the habitat. Communication modes that require electrical power are:

1. Habitat - Support agency
2. Habitat - Swimmer
3. Swimmer - Swimmer
4. Support agency - National network
5. Personnel transfer unit - habitat - support agency.

Hydraulic, mechanical, and electrical systems should be included in the habitat design to facilitate placement of habitat units, securing of components, and personnel circulation throughout the system. This latter function could be in the mode of moving sidewalks, elevators, or gravity slides.

Water Supply

The purpose of the fresh water system shall be to obtain and distribute fresh water throughout the habitat for consumption, washing, cooking, and bathing at the specified rate of a minimum of 10-15 gallons per day per occupant. Distribution shall be by conventional means such as piping and storage septic tanks. Provisions should be made in the habitat for the heating of fresh

[illegible]

[illegible] [illegible] [illegible] [illegible]

[illegible]

[illegible]

[illegible]

[illegible]

1. Habitat - Support [illegible]

2. Habitat - Surface

3. [illegible] - [illegible]

4. Support agency - [illegible]

5. Personnel transfer [illegible]

Electrically, mechanically, and [illegible] [illegible] [illegible] in the habitat design [illegible] [illegible] safety of occupants, and personnel [illegible] [illegible] system. This latter [illegible] [illegible] walls, [illegible], or [illegible].

Water Supply.

The purpose of the fresh water [illegible] [illegible] [illegible] [illegible] [illegible] water through hot water tanks and distribution to the various fixtures. The use of salt water in the habitat shall be limited to sanitary flushing and machinery cooling systems.

Occupant Nutrition

It is desirable that food products be mostly processed on land establishments and delivered pre-packaged to the habitat. However, it is realized that some cooking will be performed within the habitat to make the living unit compatible with meal preparation found on land at ambient pressure. The habitat is therefore to contain full cooking facilities as realized in the average home. Freezing and refrigerated storage of food products are also required within the habitat.

Waste Disposal

Unlike submarine systems, the sanitary expulsion system cannot discharge directly overboard due to the proximity of the habitat to shorelines and large occupancy load of the complex. The waste disposal system for organic compounds must either store the waste in sanitary tanks for removal by the supporting agency; pipe the waste to shore facilities; or chemically break down the waste for re-use or expulsion into the sea water as harmless compounds. A central collection agency must be established for the removal of non-organic waste products to a selected processing area.

IV. Circulation Modes and Paths

Internal

Primary movement through the habitat in a two-dimensional planar direction shall be attained by walking. Due to the compactedness of the habitat, mechanical modes of travel are not

anticipated for travel distance between various points within the habitat. Movement in the third dimension, up and down, will require steps or mechanical devices such as escalators, hoists, or elevators. Circulation paths shall be specified to prevent public movement through private spaces or unnecessary routing to make transverse crossings within the habitat complex. Unit space circulation paths shall be similar to those found in dwelling units at surface land conditions. See the Spacerequirements (Section 5) and Relationship Diagrams (Section 6) of this program for further information on internal and external circulation.

External

Transportation between the habitat and ocean surface shall be via a self-contained support vehicle that has adequate systems for life support and mobility to efficiently transport the passengers. The transportation system shall be capable of mating up with the habitat at the pressurized depth in such a manner to guarantee ambient pressure transfer of the occupants.

V. Fail-Safe Systems

Structural Safety

Factors must be introduced into the design considerations to allow for effects of unknown principles as outlined in the structural questions (Section 3). Common practice in the aerospace field of structures has reduced the factor of safety as low as 1.25 or even 1.1. Manned space vehicles have a factor of 1.25 to 1.5. However, current practice in the field of oceanic structures is to use a much higher factor such as 1.5, 2.0, and higher in

the light of pressure loading and resultant catastrophic failure. A method should be derived to estimate reliability of a structure to predict the probability of failure which would arise from: (1) material property data and quality assurance, (2) structural configuration, components and their complexity, (3) loading characteristics and accuracy, (4) geometric and fabrication tolerances, and (5) failure criteria.

Catastrophic failure can be defined as a failure progressing at too rapid a rate to permit evacuation of personnel after incipient failure detection. Reliability requirements should be specified to retain this mode of failure. Therefore, probability of catastrophic failure shall be no greater than 1 x 10^{-4} for full system life; probability of non-catastrophic failure shall be no greater than 1 x 10^{-3}; and probability of repairable major structural failure shall be no greater than 1 x 10^{-2}.

Emergency Life Support

In the event of a pressure loss with flooding, it will be necessary to utilize damage control materials and procedures. An emergency breathing system is to be installed throughout the habitat to provide a minimum of one hours breathing time per occupant in the event there is a failure in atmosphere delivery or removal of toxic gases. A breakdown in the heating system is not a critical threat to the occupants. However, provisions should be made in the design for rapid repair of this system.

An alternate power supply must be provided in the habitat design to automatically take over power production in the event of the life support system, [illegible] failure. [illegible] failure should be no greater than [illegible] reliability, of a structure to [illegible] which would cause death: (1) material property data and quality assurance, (2) structural analysis, [illegible] (3) [illegible] testing and proof-testing, (4) [illegible] and fabrication tolerances, and (5) quality assurance.

[illegible] failure [illegible] as a failure [illegible] after accident failure [illegible] to reduce the rate of failure. Therefore, probability of catastrophic failure should be no greater than [illegible] for full system life; probability of non-catastrophic failure should be no greater than [illegible]; and probability of repairable major subsystem failure should be no greater than [illegible].

Emergency Life Support

In the event of a [illegible] power failure, it will be necessary to utilize design, control [illegible] procedures. An emergency operating system is to be installed throughout the habitat to provide a minimum of [illegible] hours operating time per occupant. In the event there is a failure in atmosphere delivery or removal of waste gases, [illegible] a sufficient [illegible] to the occupants. However, [illegible] would be made in the [illegible] of this system.

[illegible]

failure within the main power supply. The power distribution will be through the primary power lines and will be of sufficient level and duration to maintain all normal functions in the habitat.

Emergency water and supply shall be provided in sufficient quantity to allow for approximately 10 days consumption by the occupants until the main water supply can be restored.

Emergency rations shall be stored within the complex to allow for a week of breakdown in the normal delivery of food products.

Alternate procedures must be established in the possibility of a fouling or breakdown in the waste disposal system. This emergency alternate may be in the form of a central collecting agency.

Emergency Circulation Paths and/or Modes

Emergency evacuation routes shall be established within the habitat. They shall be direct routes of one-way flow to the evacuation point of departure from the habitat. An emergency mode of travel must be provided at this point to insure safety and speed of the occupants to the ocean surface, or to a staging area which will adequately contain all occupants until the support agency can reach them. Automatic mechanical devices shall be provided throughout the habitat for immediate isolation of spaces that are subjected to catastrophic failure.

VI. Human Attributions

Physiological

Physical burdens or limits on the inhabitants of the structure are not anticipated at the time of this writing. It is hopeful that the habitants will exhibit the features now found in dwelling places on the earth's surface. However, features such as natural failure of the emergency power supply. The power distribution will be through the primary power lines and will be of sufficient level and duration to maintain all normal functions in the habitat.

Emergency fresh water supply shall be provided in sufficient quantity to allow for approximately 10 days consumption by the occupants until the main water supply can be restored.

Emergency rations shall be stored within the complex to allow for a period of breakdown in the normal delivery of food products.

Alternate procedures must be established in the possibility of a failure or breakdown in the waste disposal system. This emergency alternate may be in the form of a chemical collecting system.

Emergency Circulation Within and/or Escape

Emergency evacuation routes shall be established within the habitat. They shall be direct routes of one-way flow to the evacuation point of departure from the habitat. An emergency means of transit must be provided at this point to insure safety and speed of the occupants to the ocean surface, or to a staging area which will adequately contain all occupants until the support agency can reach them. Automatic mechanical devices shall be provided throughout the habitat for immediate isolation of spaces that are subjected to catastrophic failure.

VI. Human Attributes

Physiological

Physical attributes or limits of the inhabitants of the structure are not anticipated at the time of this writing. It is hoped that the inhabitants will meet all the features now found in dwelling places on the earth's surface. However, features such as natural light will not be available at the ocean floor. Problems may arise in areas such as this where the human body is denied nature's environment.

Psychological

There is no question that the habitat may have distressing emotional effects upon the occupants. A lot of this will arise from living in relatively confined quarters and the ever-pressing thought that any catastrophic failure would result in a crushing death to the occupants. Other conflicts may arise due to the individual's concern with lack of certain items such as light, natural air, movement, etc. It is not the intent of this program to deliniate the numerous effects produced on man's mind during his stay in this habitat. Since the structure is to be radically different than conventional undersea vehicles, a study can only be made during the design stages of this project in the area of psychological confrontations. At this latter date, space allocations, textures, colors, and mobility of the occupant can be viewed in a more realistic manner than available at this time.

VII. Feasibility Analysis

Economics

The pilot program for the habitat shall be performed by a professional oceanographic research team. The team will follow the dictated program of an interested organization that shall assume the undertaking of the habitat occupational program. This agency shall bear the initial cost of outfitting the research teams. The economic breakdown of the habitat complex shall be estimated in the design process.

[illegible]

Psychological

[illegible]

VII. Feasibility Analysis

Economics

[illegible]

Construction

Primary construction of the habitat components shall be done at various land manufacturing points. The systems will then be shipped to the general coastal section for preparation and submergence to the site of the habitat. A time schedule should be set up in the design process to initiate the various stages and alloted times of construction activity.

Future Expansion

The initial pilot program of oceanographic researchers dwelling in the habitat will give way to a multiple expansion of the entire complex. Expansion will be dictated in various stages to ascertain the efficiency of the project. The first step shall be an increase in number of the pilot team at a rate of one, then double that figure- in consecutive steps. A maximum occupancy shall be stated in the design process which will be a governing factor in the decision to divorce the pilot program from the habitat occupation. At this time, a governing body must be established to regulate the complex growth; receive and dictate modifications; and insure the safety and welfare of the habitat occupants.

Ownership

By tacit understanding, national control of coastal waters has been assumed to a distance of three statute miles from shore. Legal definition of the true edge of the continental shelf raised many difficulties, owing to the varied depth of the shelf-break from place to place. However, the Outer Continental Shelf Lands

Act in 1953 claims the subsoil and sea bed of the outer continental shelf as subject to the jurisdiction of the coastal nation. With respect to this law, the International Convention on the Continental Shelf gave sovereign rights to the adjacent continental shelf, slope, sedentary, and contained resources thereof to the coastal nations at the greatest depth at which they could efficiently exploit.

Support Agencies

During the design stage, various agencies should be called for and described as to their roles in the support of the habitat. These organizations, if not directly connected with the habitat employment, should not be dependent upon the economical base of the undersea project for their entire mission.

SECTION 5

SPACE REQUIREMENTS

VOLUME REQUIREMENTS

When considering volumetric requirements in a expandable habitat complex, we must first distinguish between total volume and free volume to accurately dimension the inhabitable space. Free volume refers to the space not occupied by internal hardware or instrumentation and which is actually available for occupant use. Figure 7 provides some typical comparative data on a number of volume limited systems. Upon examination of this chart, it appears that an allotment of 50-60- ft^3 volume per man is a reasonable value for long-endurance, deep submergence vehicles.

However, additional duration will require that increased volume be made available to the occupants. Over-restrictiveness adversely affects man's flexibility of performance, his activity, and his ability to adapt to his working environment. Mention should also be made, however, that excessive volume over the minimal functional needs of the occupants will penalize the total system by increasing weight and costs. Therefore, the following section of space requirements was based on a minimum cubic dimension to establish the initial size of the habitat. As the system expands or reduces in later stages, a proportional cubic content is based on a numerical occupancy, and not on system volume characteristics.

Figure 7. Comparison of Volumes of Undersea and Space Vehicles[7]

System	Mission (Days)	Est. Total Vol. (ft^3)	Crew Size	Free Vol. Per Man
Bathyscaphe	1	112	2	35
Bathysphere	1	33	1	25
Mercury	2	106	1	48
Gemini	14	175	2	53
Apollo	15	365	3	75
Polaris Sub	60	157,398	120	436

7 Transactions of the Symposium on Man's Extension into the Sea (Washington, 1966), p. 119.

WASHING, BATHING, AND PERSONAL HYGIENE SPACE

CRITERIA: There shall be a minimum of one WBPH space per living unit.

ACTIVITIES: Washing, bathing, voiding of body wastes.

SPECIAL CONDITIONS: Audio isolation and visual privacy.

RELATIONSHIP: Spaces for bathing and toilet shall bave visual contact only with private areas of the dwelling unit. Guests shall have access to washing and toilet facilities without passing through private areas of the unit.

SPECIAL SERVICES: Exhausting of odors, temperature control.

EQUIPMENT: Lavatory, tub/shower, water closet, storage of small items.

SIZE: Minimum size of the space shall be 130 cubic feet which will serve up to four occupants of a dwelling unit. Thereafter, 120 cubic feet will be required for every two additional people.

DRESSING AND STORAGE OF CLOTHING SPACE

CRITERIA: Storage and dressing space shall be provided for each occupant of the dwelling unit.

SPECIAL CONDITIONS: Dressing space is to have visual privacy.

RELATIONSHIP: Dressing space should be accessible to sleeping and hygiene spaces. Storage of outer clothing should be convenient to the entrance of the dwelling unit.

SPECIAL SERVICES: None.

EQUIPMENT: Provisions are needed for hanging and folded clothing.

SIZE: A minimum of 150 cubic feet per person for dressing. A minimum of 50 cubic feet for storage of clothing for each person.

EATING SPACE

CRITERIA: Eating space shall be required in each dwelling unit for every occupant to dine at one time. Additional space should be provided for guest eating.

ACTIVITIES: Eating.

SPECIAL CONDITIONS: The eating surface and floor shoul be easily maintained.

RELATIONSHIP: Eating space shall be adjacent to food preparation space. Storage space for linens, eating utensils, etc. shall be provided convenient to the space.

SPECIAL SERVICES: None.

EQUIPMENT: Eating surface and postural seating.

SIZE: Minimum of 35 cubic feet per person.

ENTERTAINING SPACE

CRITERIA: There shall be an entertaining space for a minimum of two people in each dwelling unit. The space, if larger, shall be designed to accomodate intimate conversation groups.

ACTIVITIES: Social conversation, entertaining, participation with medias (television, radio, phono, etc.)

SPECIAL CONDITIONS: Various lighting levels.

RELATIONSHIP: The space shall not conflict with circulation paths and shall have control of audio and visual privacy between it and other spaces of the dwelling unit.

SPECIAL SERVICES: Facilities for entertaining media hook-up. Storage is to be provided convenient to entertainment space for related equipment.

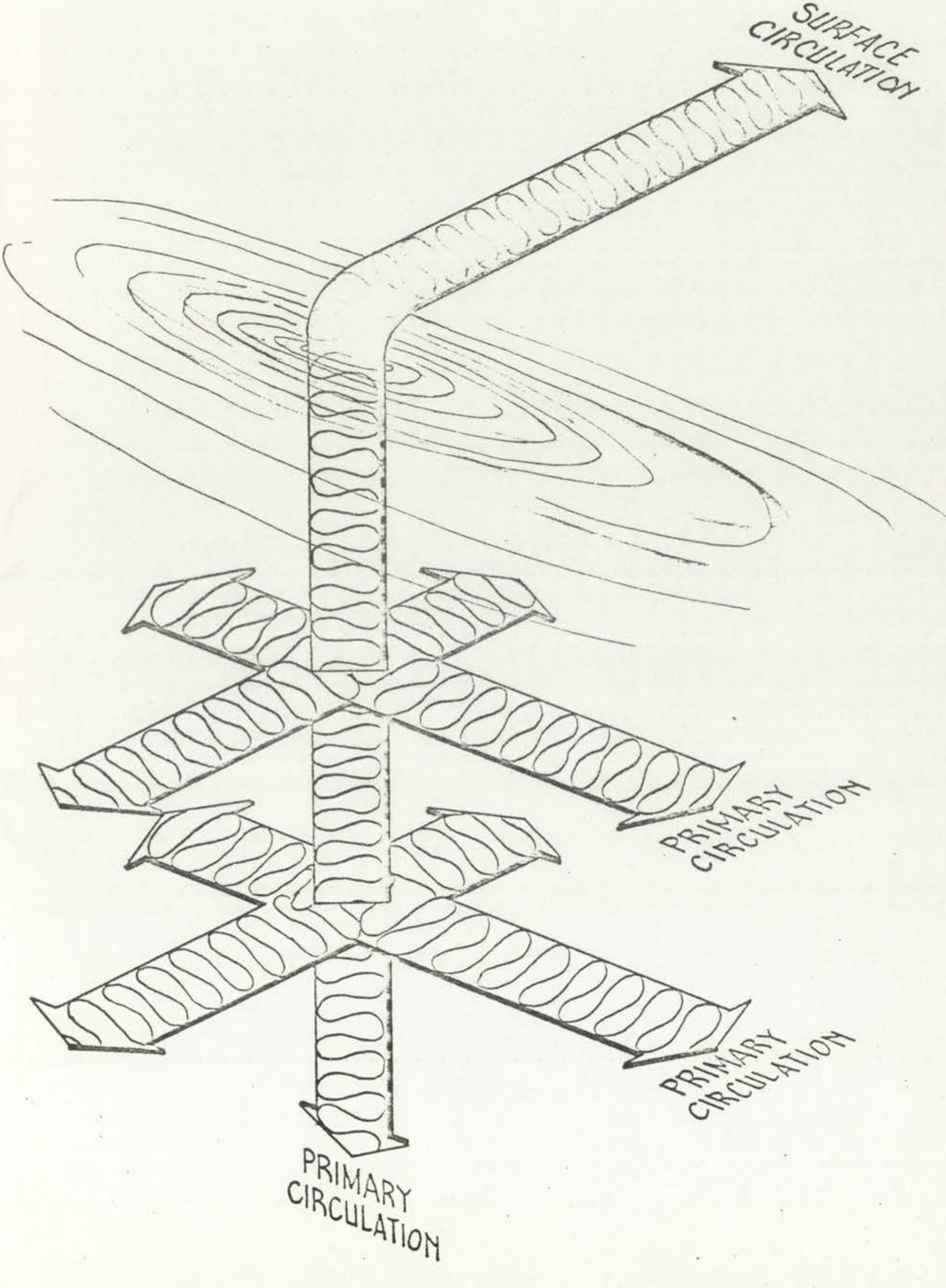
EQUIPMENT: Furniture of various seating characteristics.

SIZE: Minimum of 250 cubic feet for two people. Thereafter, a minimum of 55 cubic feet shall be provided for each additional person living within the dwelling unit.

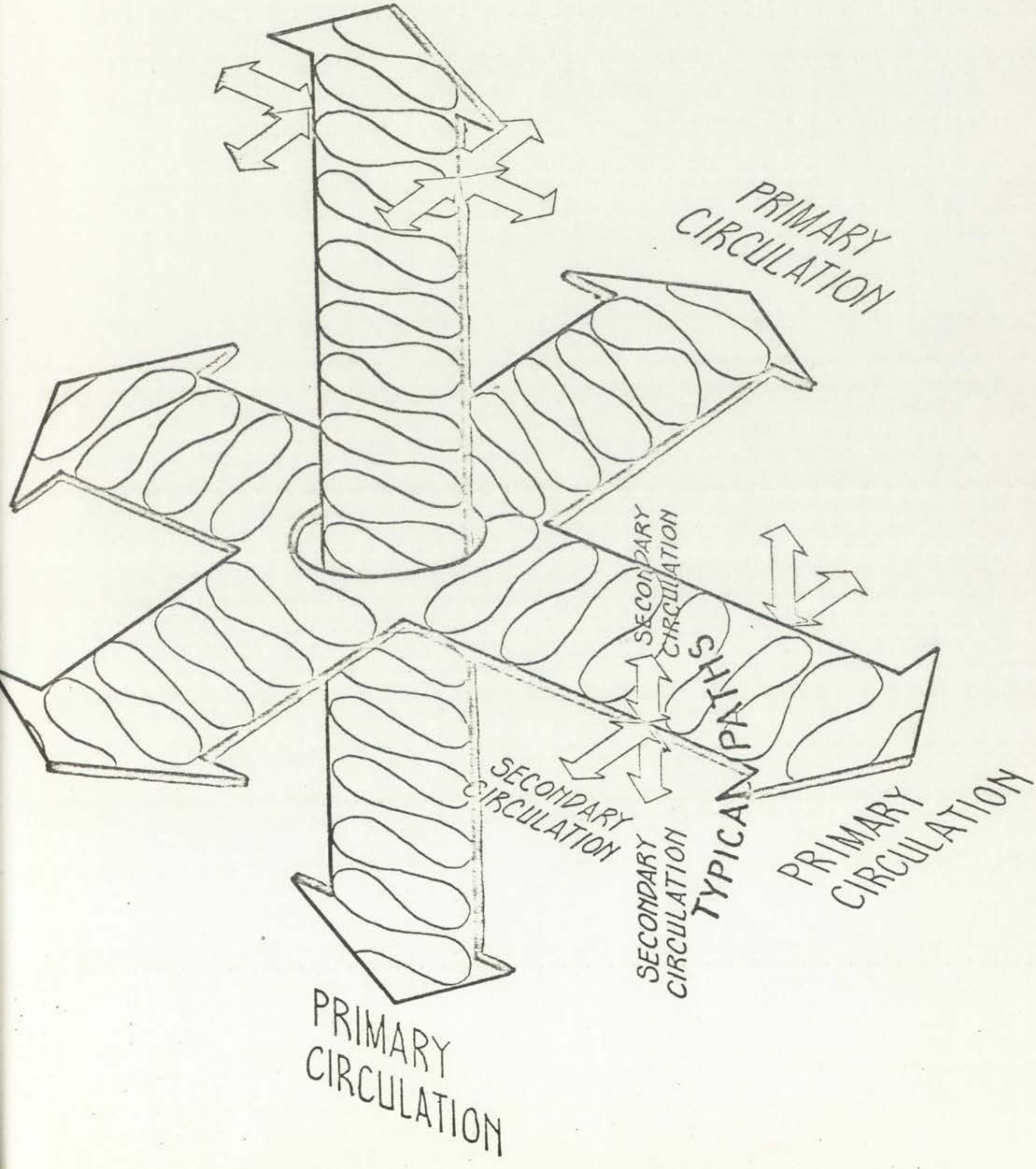
SECTION 6

RELATIONSHIPS

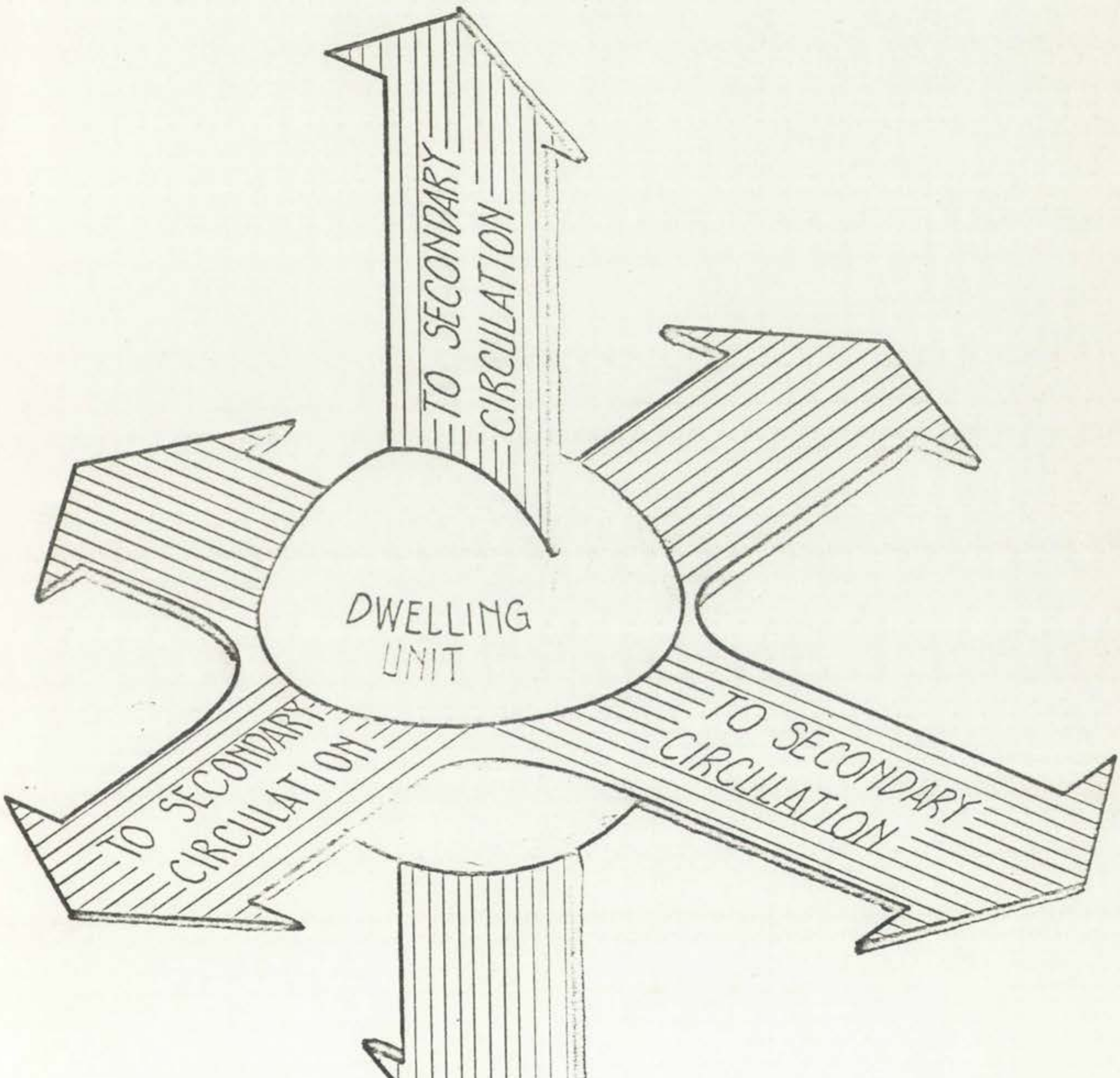
RELATION BETWEEN PRIMARY CIRCULATION AND SEA LEVEL CIRCULATION



RELATIONSHIP BETWEEN SECONDARY CIRCULATION AND PRIMARY CIRCULATION



RELATIONSHIP BETWEEN DWELLING UNIT SPACE AND SECONDARY CIRCULATION



SECTION 7

TYPICAL SITE

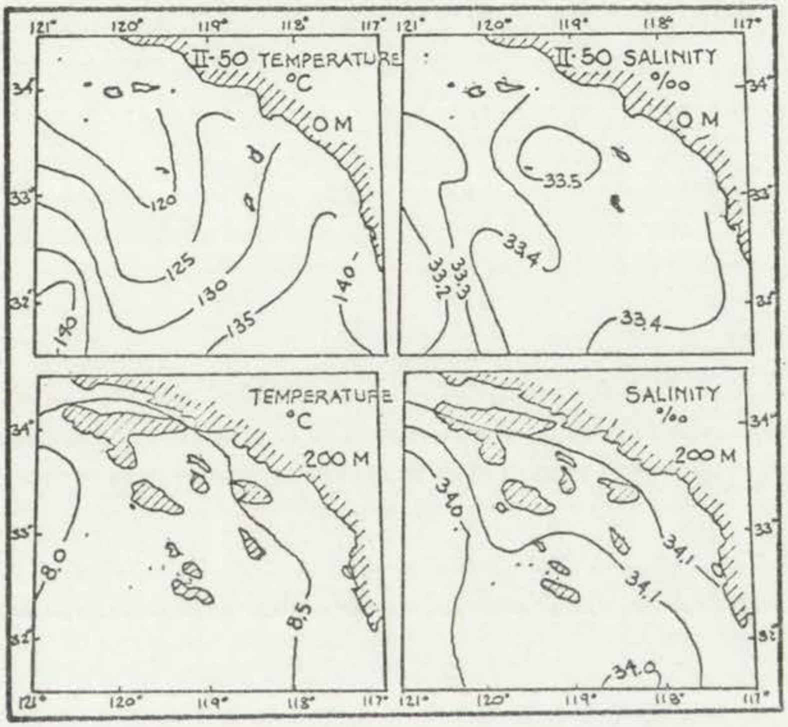
SITE PLAN INFORMATION

As previously stated in this program, the potential site for the habitat is a universal one. Its main parameters are that if lies on one of the continental shelves at an approximate depth of 600-800 ft.

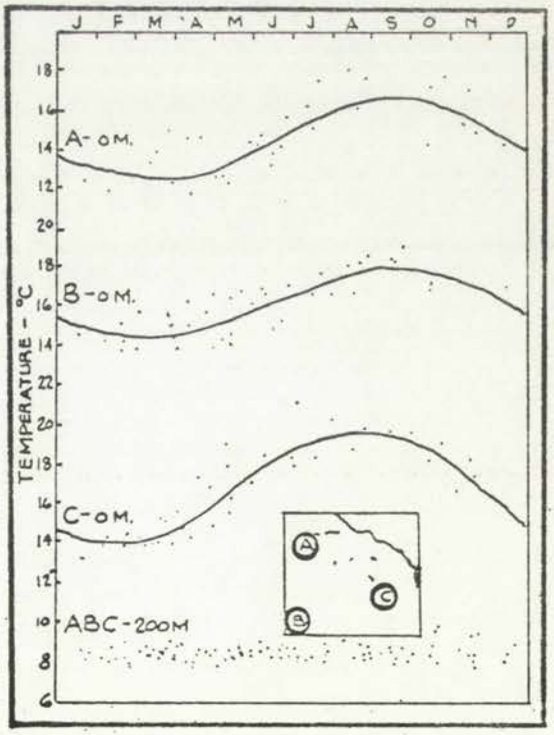
A typical site has been selected in this section on the coast of southern California to exhibit some of the particulars of the oceanic environment as reported form a detailed study. With the presentation of the following information, I hope to impress a few of the realistic conditions that affect the habitat. The characteristics of this real site are more appropriate determinants than a conceived site that has not been tested whether it exists.

TEMPERATURE AND SALINITY

Regional pattern of water temperature and salinity at the surface and at a depth of 200 meters during the Marine Life Research cruise of February 1950.[8]

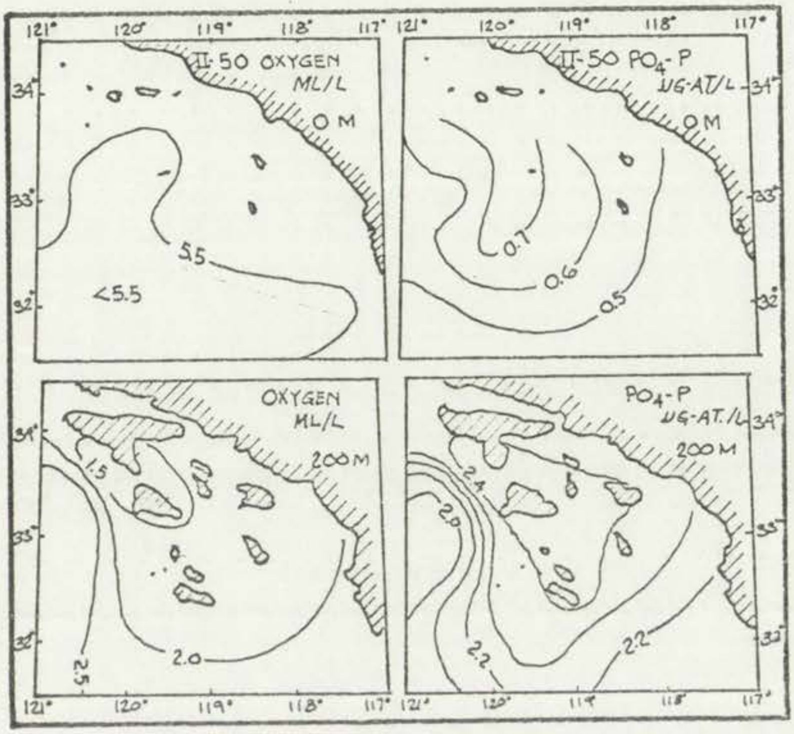


Annual variation of water surface temperature at three locations for 49 Scripps cruises during the years 1937-1941 and 1949-1952. Temperatures at 200 meters for all three localities are plotted together because of their similarity.[9]

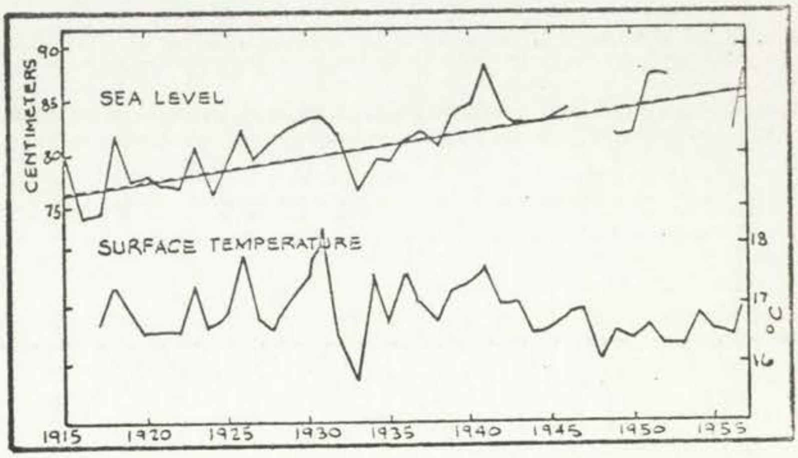


[8] K. O. Emery, The Sea off Southern California, (New York, 1960), p. 93.
[9] Ibid.

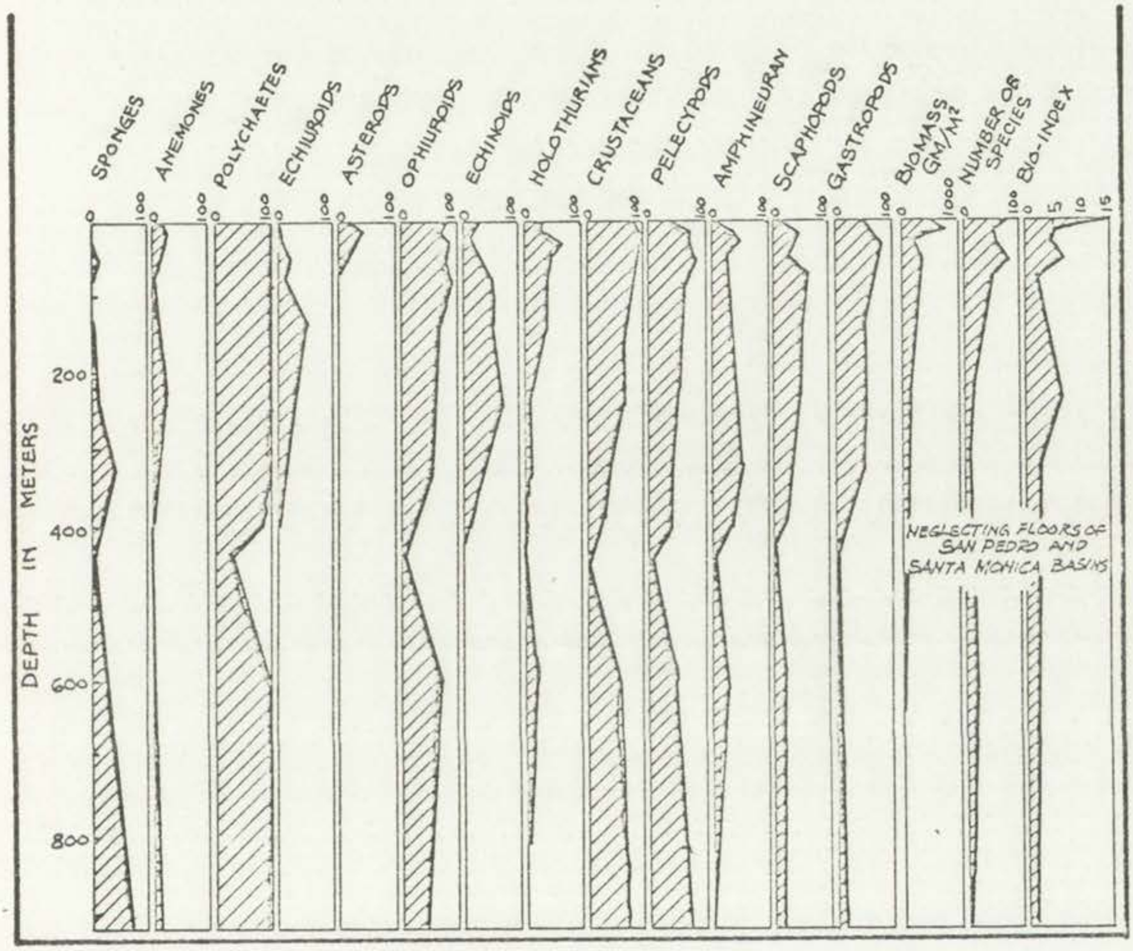
Regional pattern of contents of dissolved oxygen and phosphate-phosphorus at the surface and at a depth of 200 meters during the Marine Life Research cruise of February 1950.[10]



Yearly average sea level at San Diego(1915-1924) and La Jolla(1925-1957).[11]



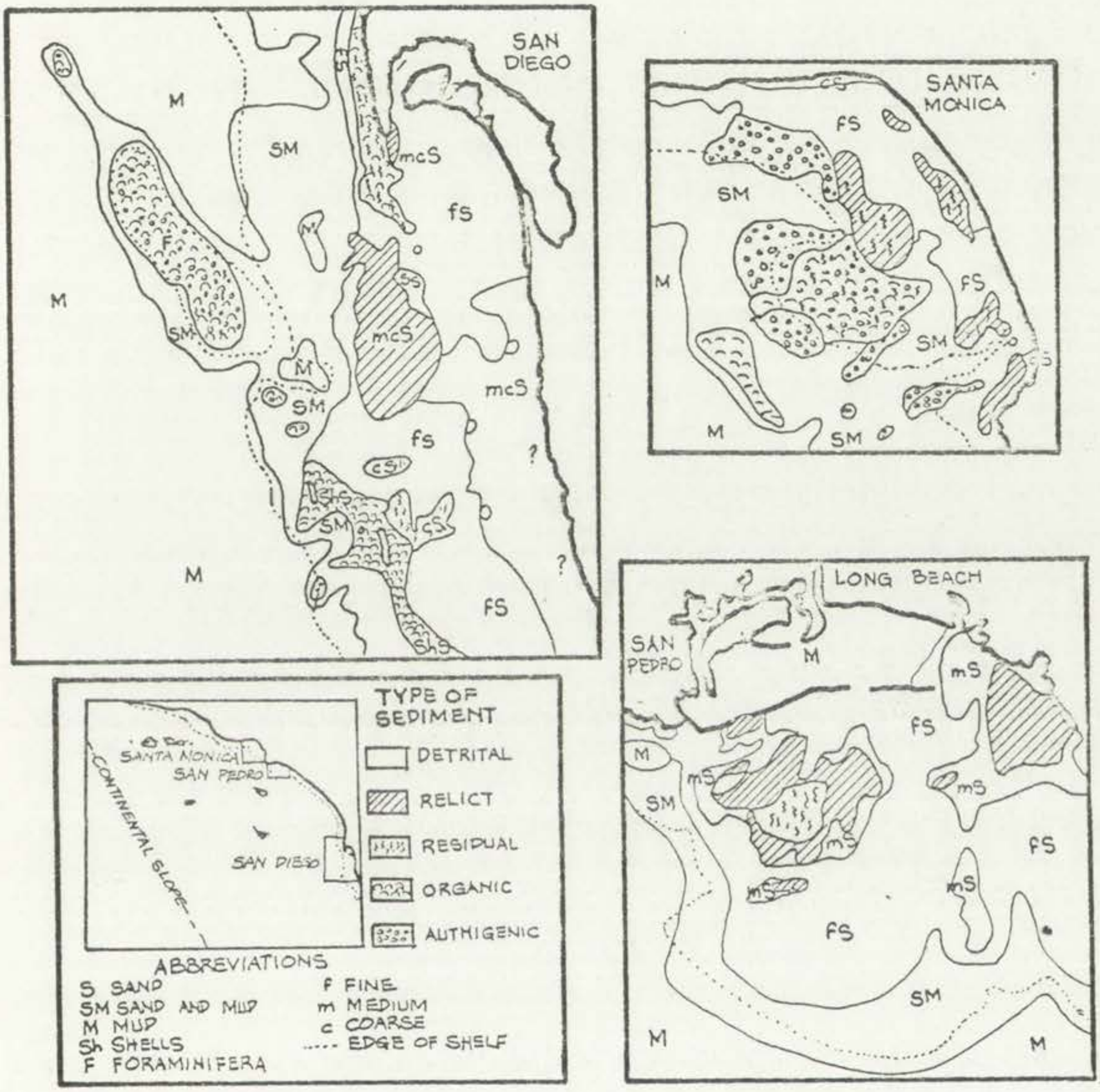
[10] Ibid., p. 99.
[11] Ibid., p. 133.



Graph showing percentage of 316 samples in various depth ranges which contain one or more specimens of silceous sponge, of anemone, and of other kinds of animals.[12]

[12] Ibid., p. 172.

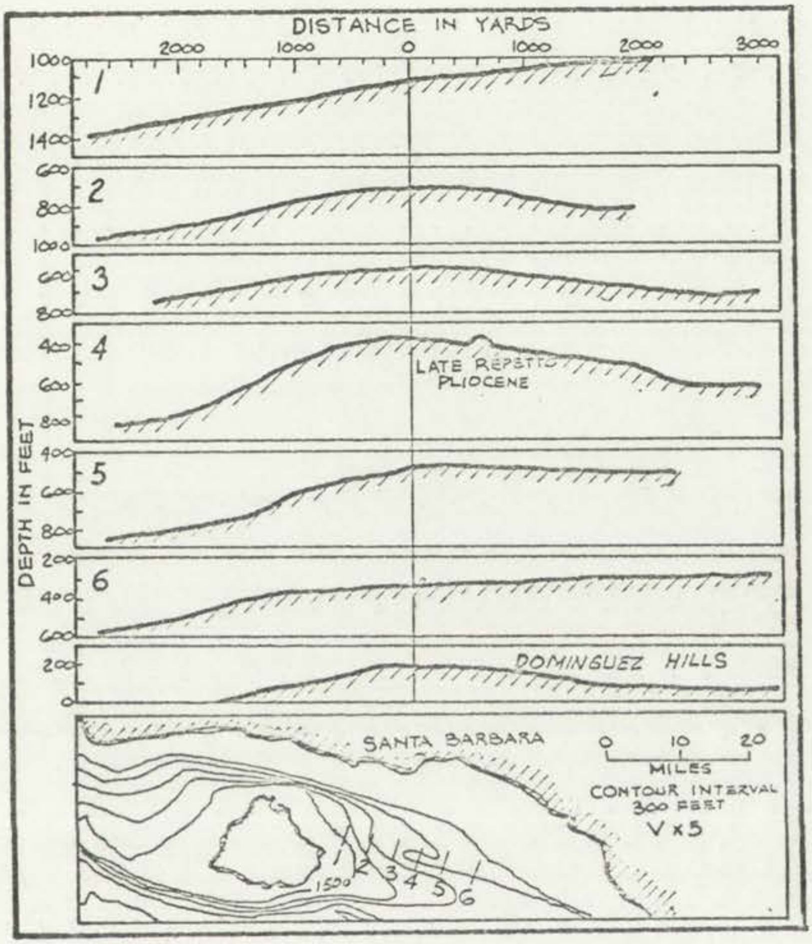
SOIL CONDITIONS



Sediments off San Diego, San Pedro, and Santa Monica classified according to origin.[13]

[13]Ibid., p. 204.

OCEAN BOTTOM TERRAIN



Profiles of probable small fold in Santa Barbara Basin as compared with one of Dominguez Hills.[14]

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[14] Ibid., p. 93.

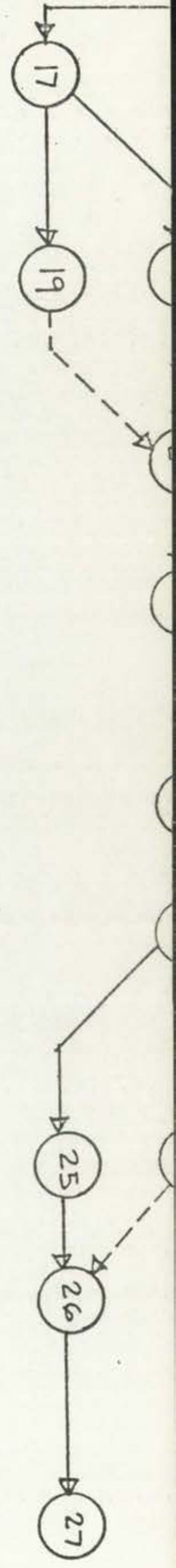
CRITICAL PATH

FOR DESIGN TIME FROM FEB. 6, 1969 - MAY 19, 1969

THIS CPM IS TO BE PERIODICALLY UPDATED

C. NT	SUCC. EVENT	ACTIVITY	DURATION	START	FINISH
	2	STUDY SITE	1	6 FEB	6 FEB
	3	STUDY CIRCULATION DIAGRAM	1	7 FEB	7 FEB
	4	STUDY REQ'D SPACE SIZES	4.	10 FEB	12 FEB
	4	DETAIL SITE CHARACTERISTICS	1	13 FEB	13 FEB
	6	DRW CIRCULATION FLOW CHARTS	1	14 FEB	14 FEB
	7	STUDY STRUCTURAL SYSTEM	2	17 FEB	18 FEB
	6	PRELIM SIZING OF SPACES	4	19 FEB	24 FEB
	7	DUMMY	0		
	8	STUDY LIFE SUPPORT SYSTEMS	6	25 FEB	3 MAR
	9	SELECT STRUCTURAL SYSTEM	2	4 MAR	5 MAR
	11	SELECT LIFE SUPPORT SYSTEMS	3	6 MAR	8 MAR
	10	SELECT STRUCTURAL MATERIAL	1	10 MAR	10 MAR
	12	STRUCTURAL SYSTEM SKETCHES	2	11 MAR	12 MAR
	12	LIFE SUPT SYSTEM SKETCHES	6	13 MAR	19 MAR
	13	STUDY AVAILABLE SPACES	1	20 MAR	20 MAR
	14	DRAW SYSTEMS TO SCALE	4	21 MAR	24 MAR
	15	BUILD ROUGH MODEL TO SCALE	3	25 MAR	28 MAR
	16	STUDY MODEL SYSTEMS	1	29 MAR	29 MAR
	17	REVISE SYSTEMS	3	1 APR	3 APR
	18	PRELIMINARY DRAWINGS	5	4 APR	7 APR
	19	WRITE SPECIFICATIONS	2	8 APR	9 APR
	20	BUILD PRELIMINARY MODEL	4	10 APR	15 APR
	20	DUMMY	0		
	21	PRESENT TO ADVISOR	1	16 APR	16 APR
	22	ADVISOR APPROVAL	2	17 APR	18 APR
	23	REVISIONS PER ADVISOR	2	21 APR	22 APR
	24	PREPARE FINAL DRAWINGS	5	23 APR	29 APR
	25	BUILD FINAL MODEL	14	30 APR	15 MAY
	26	DUMMY	0		
	26	DO PHOTOGRAPHIC STUDIES	3	16 MAY	18 MAY
	27	DELIVER PROJECT TO SCHOOL	1	19 MAY	19 MAY

S SCHEDULE IS THE END OF THE FIRST PHASE OF THE CRITICAL PATH
WILL BE UPDATED PERIODICALLY WITH RELATION TO ACTUAL PROGRESS



APPENDIX

CONCRETE HILLS FOR UNDERSEA HABITATS

CONCRETE HULLS FOR UNDERSEA HABITATS

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ABSTRACT

Exploratory experiments have shown that concrete is an acceptable construction material for hulls enclosing undersea habitats at atmospheric pressure. Models of spherical concrete hulls with and without penetrations have been built and tested to destruction in hydrospace. Test results indicate that positively buoyant concrete hulls of spherical shape are feasible for location to 3500 feet depth, while negatively buoyant hulls of the same shape may be able to be placed at depths to 10,000 feet. Both economical and military considerations seem to favor concrete hulls for permanent ocean bottom installations.

INTRODUCTION

The conquest of hydrospace requires both mobile and fixed underwater structures capable of housing instruments and men for extended periods of time. There is a long history of research on the properties of materials and the design of hulls suitable for submarines; however, the research into materials and designs for static underwater hull structures is just beginning.

Although many materials developed for submarine or torpedo hulls are also applicable to fixed, ocean-bottom installations, there are materials which have not received careful study because of their manifest inapplicability to high-speed, deep submergence submarines or torpedoes. One such material is concrete.

The purpose of this paper is to describe several brief exploratory investigations into the applicability of concrete to the fabrication of structural hulls for deep submergence structures.* The scope of this series of experiments was limited to models of buoyant spherical hulls of 16 inch external diameter for 3500 feet depth cast from the same concrete mix. Variables were introduced into the study by varying the method of hydrostatic testing, as well as by incorporating into the hull different kinds of penetrations and inserts.

BACKGROUND

Concrete has been used in harbor installations for many decades, but it has not been used for the construction of underwater habitats. There are several reasons for this. Since concrete is not as desirable for submarine hull construction as other materials, no research was done on its properties under seawater hydrostatic pressure prior to the recent interest in fixed, ocean-floor installations. Furthermore, the impetus of research has been directed towards the discovery of new materials that would give buoyancy to a deep submergence hull even at greatest depths in the ocean. The most potent argument used against concrete in the past was that buoyant concrete hulls are limited by concrete's compressive strength to depths less than 5,000 feet and therefore cannot satisfy depth requirements that may arise in the future. Thus the philosophy appears to have been that since buoyant concrete hulls were definitely depth limited, there was no need to conduct research on structural characteristics of concrete as a stop-gap solution to the problem of finding suitable materials for deep submergence structures.

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*In this paper, "deep submergence" is used to refer to depths greater than 600 feet.

Recently, materials like glass and ceramics have been discovered[1,2] to possess such high compressive strength, modulus of elasticity, and resistance to corrosion that buoyant deep submergence hulls for fixed or mobile installations can be built for any depth. Unfortunately, although glass and ceramics have the potential of providing man with hulls of ultimate depth capability, the engineering problems to be solved are formidable, and the materials are too expensive for applications in shallow depths where their use is not mandatory. Since currently available glass and ceramic materials with the ultimate depth capability have been found impractical for general use because of their high costs of fabrication and yet unsolved joint design problems, the path has been cleared for other materials with limited depth capabilities, but with an attractive cost factor and ease of applicability to large structures. Such a material is concrete which is theoretically satisfactory for buoyant hulls with an operational depth requirement of 3,000 to 4,000 feet. In addition, engineering estimates indicate that it is more economical than other available metallic or nonmetallic materials when used in large ocean bottom habitat structures.

The depth capability of 3,000 to 4,000 feet of buoyant concrete structures which can be towed to location and submerged, permits the utilization of such structures over large areas of the continental borderlands. About 12% to 14% of the ocean floor can be explored and settled using concrete as the primary hull construction material for the ocean floor installations. While the portion of ocean floor that could be made accessible through the use of concrete hulls is small in comparison to the total ocean area, in terms of importance, it is a most critical part of the total. The reason for its importance is found in the presence of large continental borderlands made up of shelves, and submerged banks in zero to 3,500 foot depth range. Since these shelves and banks are generally flat to gently sloping, and since they are also in the general vicinity of land, they make ideal construction sites.

The areas of primary interest to the United States are directly accessible from this country without transversing ocean floors that are under another country's sovereignty. By occupying the shelves and banks adjacent to the United States in the 0- to 3,500-foot depth range, the land area of the United States could be extended approximately 23%.

In summary, it can be stated that although there is a need to develop materials and structures with ultimate depth capability, development of materials and structures for depths to 3,500 feet is more important in terms of national defense and natural resources. Since concrete has been in many cases the most economical construction material on land, it should be investigated early in the search for undersea construction materials. It may also turn out to be one of the most economical materials for ocean-floor construction on continental shelves and submarine banks in the 0 to 3,500-foot depth range.

APPLICABILITY OF CONCRETE TO OCEAN BOTTOM HABITATS

There are several very good reasons why concrete will find application for the construction of ocean bottom habitat foundations and pressure hulls containing atmospheric shirt-sleeve environment. The major reasons are low cost of material, ease of forming double curvature shells, strength to weight ratio (Figure 1) equivalent to steels with a 45,000 psi yield point, and excellent resistance to corrosion. Other reasons also important, but considered minor in respect to the previously enumerated ones, are high elastic stability eliminating the need for rib stiffeners in spherical habitats for depths beyond those 100 feet (Figure 2), excellent blending in with the ocean bottom making it difficult to detect the habitat by hostile personnel with standard submarine detection gear, and excellent resistance to underwater explosions or impacts created by hostile forces.

The thick walled concrete hulls for ocean bottom habitats make it relatively easy to incorporate window, hatch, and feed-through penetration flanges without additional thickening of concrete wall around the penetrations. The low heat and sound conductivity of concrete make it unnecessary also to insulate the interior of the structure against heat losses and noise emission which is helpful in detecting the habitat by hostile personnel. Properly formulated concrete serves also as an excellent radiation shield for nuclear power generators with which future ocean bottom habitats will be equipped.

The two drawbacks that concrete possesses is its permeability to sea water and tensile strength of less than 500 psi. These drawbacks can be overcome by taking them into consideration during the design of the habitat hull, and by the use of proper steel reinforcements and waterproof coatings during the fabrication process.

Although concrete will be also used in the construction of habitat foundations and columns supporting the pressure hull, all of the discussion in this paper and subsequent experimental work has been devoted only to pressure hulls, as they represent a more demanding application for concrete.

EXPERIMENT DESIGN

Literature search failed to disclose any previous experimental work with concrete pressure hulls under external hydrostatic loading simulating deep ocean environment. Therefore it was decided first to conduct an exploratory investigation into the use of concrete hulls for deep ocean pressure environment to determine the avenues along which it would be most profitable to direct future studies. Many avenues of investigation are open in such an exploratory study. Not only may different hull shapes be selected, but also the composition of concrete mix, the thickness of the walls and types of joints. In addition, once the hull shape has been select-

APPLICATIONS OF CONCRETE [illegible]

There are several ways in which concrete structures will find application for the construction of ocean bottom habitats. Foundations and pressure hulls constructed of concrete will [illegible] development. The major advantage may be that of economical ease of forming [illegible] structures [illegible] with its excellent resistance to [illegible] compressive strength [illegible] (Figure 2), excellent blending in with the ocean bottom making it difficult to detect the habitat by hostile personnel with [illegible] and excellent resistance to [illegible] explosions or impacts caused by hostile forces.

The three major concrete hulls for ocean bottom habitats made it relatively easy to incorporate windows, hatch, and feed-through penetrations through without compromising the integrity of the system [illegible]. The low heat and sound conductivity of concrete make it [illegible] to insulate the interior of the structure against heat losses and noise [illegible] which is helpful in [illegible] the habitat by hostile personnel. Properly reinforced concrete serves also as an excellent radiation shield for nuclear power generators with which future ocean bottom habitats will be equipped.

The two drawbacks that concrete possesses is its permeability to sea water and tensile strength of less than 800 psi. These drawbacks can be overcome by taking them into consideration during the design of the habitat hull, and by the use of proper steel reinforcements and waterproof coatings during the fabrication process.

Although concrete will be also used in the construction of habitat foundations and columns supporting the pressure hull, all of the discussion in this paper and subsequent experimental work has been devoted only to pressure hulls, as they represent a more demanding application for concrete.

EXPERIMENTAL DESIGN

Literature search failed to disclose any previous experimental work with concrete pressure hulls under external hydrostatic loading simulating deep ocean environment. Therefore it was decided first to conduct an exploratory investigation into the use of concrete hulls for deep pressure environment to determine the general lines along which it would be most profitable to direct future studies. Many avenues of investigation are open in which an exploratory study [illegible] not only may different wall shapes be explored, but also the composition of concrete and [illegible] thickness of the walls and types of joints. In addition, [illegible] the hull shape has been a largeed, it can be tested for different properties, depending on the requirements of the study. Since so many alternatives were possible the approach was chosen by which only buoyant concrete hulls of maximized pressure resistant shape of the simplest construction were to be considered first.

The pressure hull shape chosen for the experimental study was a sphere as it represents the optimum pressure resistant hull. The spherical hull is also desirable for its inherent uniform distribution of stresses. Because of this uniformity of stress distribution, the strains measured at any point of the sphere's surface can be considered representative of the strains on the sphere. Knowledge of the maximum compressive strain found in simple spherical concrete hulls is extremely useful in the evaluation of future concrete hull models where the presence of inserts and penetrations will create stress risers that may lower the critical pressure of the hull.

The spherical shape is also advantageous for the determination of concrete's permeability under different levels of hydrostatic pressure. Permeability of concrete is probably related to stress level, therefore uniformity of stress in the sphere eliminates those side effects that are associated with the nonuniform distribution of stresses. A spherical hull also eliminated any anomalies caused by edge effects of the test sample, as would be found, for example, in a flat specimen mounted in some sort of a flange. Furthermore, since in a spherical hull there is also continuity of curvature, a reasonable assumption can be made that the permeability of water through the walls of the sphere will be uniform throughout, and thus only the level of water in the sphere must be known in order to determine a nominal rate of permeability through the given concrete mix.

The actual dimensions chosen for the concrete hull models were 16-inch outside diameter and 14-inch inside diameter. The outside dimension was controlled by the inside diameter of the largest vessel available at NCEL, while the inside dimension of the concrete hull was based on the requirement that the resultant concrete hull possess at most a 0.75 weight/displacement ratio. This weight to displacement ratio was considered to be the highest allowable that would permit the fully equipped concrete habitat hull to be either positively, or at worst, neutrally buoyant.

SCOPE OF INVESTIGATION

The study of spherical concrete hulls was limited, to-date, to three major phases of experimental investigation.

PHASE I - Investigation encompassed the testing to destruction of twelve identical spherical concrete hulls of 16-inch outside and 14-inch inside diameters without penetrations (Figure 3): Six of the models were waterproofed and six were bare.

PHASE II - Investigation centered around the testing to destruction under hydrostatic pressure of six 16-inch external and

14-inch internal diameter concrete spherical hull models with penetrations (Figure 4) closed by inserts (Figure 5) of different ridigities. Only two sizes of inserts, and three kinds of insert materials were experimentally evaluated. All of the models were waterproofed prior to implosion testing in simulated hydrospace facility.

PHASE III - Investigation concerned itself with the design, fabrication, and testing of two concrete habitat models (Figure 6) with 16-inch external and 14-inch internal diameters. The models were equipped with operational windows and wire feed-throughs located inside penetrations of the concrete sphere (Figure 4) reinforced by annular penetration flanges (Figure 7).

OBJECTIVES AND PROCEDURES OF THE INVESTIGATION

PHASE I - The objective of the tests was to touch upon as many facets of concrete hull's behavior under hydrostatic pressure as possible, rather than research any one of them exhaustively. Thus the hydrostatic tests on the simple concrete spheres were employed to explore ultimate compressive strength of concrete under short-term and long-term loading, the latter at hydrostatic pressures approaching the critical pressure. Experiments were also conducted to investigate the leakage of water through unprotected concrete at different hydrostatic pressure levels. Because of the exploratory nature of these tests, only one to three spheres were tested in each type of experiment. Experimental data from such a small number of test samples are considered to be indicators of the general level of magnitude of the parameters studied, but not conclusive and final evidence of these parameters. Once the general magnitude of the parameters investigated is known, an accurate plan can be drawn up for future experiments to more thoroughly evaluate and define the physical and mechanical properties of concrete under the external hydrostatic pressure of seawater.

PHASE II - The testing to destruction of the spherical hull models had as its objective a quantitative evaluation of the relationship between the size and rigidity of the penetration insert, and the critical pressure of the whole concrete hull assembly under hydrostatic pressure. The concrete spherical hull models with solid penetration inserts of different rigidity had the same dimensions and were cast from the same mix as the models without penetrations. Since it is known that the stress concentration around a penetration in the hull is to a large degree dependent on the size and on the mismatch between the rigidity of the penetration insert and that of the hull material, two sizes of penetrations and three types of insert materials were selected that represented a wide range of rigidity properties. The two selected sizes of model penetration inserts were considered to be representative of penetration inserts required for full size spherical structure. The 32°30' size insert simulated a penetrathrough instrumented models. [illegible] with the models [illegible] different stiff- nesses, [illegible] of [illegible] the models were [illegible] be simulated [illegible] testing.

PHASE III - Investigations [illegible] the design, construction, and [illegible] of [illegible] models [illegible] with [illegible] and [illegible] were [illegible] located [illegible] of the [illegible] (Figure 4) [illegible] similar [illegible] (Figure 5).

SCHEDULING AND PROGRESS OF THE PROGRAM

PHASE I - The preparation of the [illegible] models [illegible] of possible, [illegible] one of [illegible] the [illegible] of [illegible] pressure [illegible] also [illegible] through [illegible] Because of the high costs, [illegible] of these [illegible] were [illegible] type of experiment. [illegible] of the [illegible] the general magnitude of the parameters [illegible] thoroughly [illegible] pressure of [illegible].

PHASE II - The testing [illegible] of the [illegible] models [illegible] relationship between the [illegible] and [illegible] of the [illegible] pressure. The [illegible] hull models [illegible] different rigidity [illegible] the [illegible] the models [illegible] large [illegible] the [illegible] of the [illegible] tion in the hull required for man-sized hatches or windows, while the 8° size insert simulated an electrical wiring or hydraulic piping feed-through on an underwater hull structure of ten to twenty feet in diameter with personnel transfer capability. The most rigid inserts selected were made of steel, while the least rigid inserts were made from polyvinyl chloride plastic; other inserts used were made from aluminum. During the hydrostatic testing to destruction of the insert-equipped models, strains were measured around the inserts and compared to strains existing in the same sphere away from the penetration inserts. In such a manner some quantitative measure of the stress concentration factors produced by inserts of different rigidities could be obtained. The comparison of the critical pressures of insert equipped spherical hulls with the critical pressures of identical hull without any penetrations would also be indicative of the effect that penetration inserts have on the overall strength of the spherical concrete pressure hull.

PHASE III - The design, fabrication, and testing of the spherical habitat model had as its objective proving the feasibility of concrete pressure hulls with usable windows, hatches, and wire feed-throughs for 3500 foot depth service. This concrete habitat model could be considered a typical example of first generation concrete habitats for ocean bottom location. The concrete hull model dimensions, concrete mix composition, and method of casting was selected to be the same as in the previous phases of concrete spherical hull feasibility study.[2] In this manner, the critical pressure of the model with penetrations reinforced by flanges could be directly compared to the critical pressure of models without penetrations. The difference between the critical pressure of the working model and of the concrete spheres without penetrations would serve as a quantitative indicator of hull strength decrease due to use of the particular type of window, hatch, and feed-through flange designs.

The pressure hull for the ocean bottom habitat was conceived as a monocoque concrete sphere resting on an aluminum cradle supported by three pad equipped legs. Three large window assemblies placed around the circumference, and one located at the bottom of the sphere would permit television or photographic cameras to observe and record the behavior of ocean floor, hydrospace, and its inhabitants. To make the habitat adaptable to different missions, it could be selectively equipped with an array of specialized subassemblies, fitting into typical large window penetrations. Such subassemblies, in the form of windows (Figure 8), a glass observation dome (Figure 9), diver transfer chamber, vehicle transfer hatch, or oceanographic instrument tower would make the basic concept of the concrete ocean bottom habitat adaptable to an almost unlimited number of mission requirements. The only requirement that would apply to all of them was that their mounting plates fit the penetration opening, and that the plate bearing lip matches the bearing lip on the penetration flange. In order to

maintain the effect of the penetration flange rigidity constant, all insert subassemblies that fit inside the penetration flanges were designed to fit with a known clearance between the exterior taper of the insert and the interior taper of the penetration flange. The only point of contact between the penetration flange and the insert subassembly was at the O-ring sealing surface located on the penetration flange lip.

FABRICATION OF CONCRETE SPHERES

Concrete hemispheres were cast in a mold and subsequently cemented together with an epoxy bonding agent. Depending on the type of test, the exterior and interior surfaces were either left untreated or coated with a waterproofing material. The concrete mix used developed after 250 days a strength of 10,000 to 11,000 psi as determined by uniaxial compression testing of solid test cylinders associated with spheres.

The treatment of the exterior surface depended upon the type of test for which the given sphere was intended. For the permeability tests, where the rate of water flow through concrete under hydrostatic pressure was under investigation, the exterior surface of the sphere was left untreated, the way it emerged from the mold. For the strain determination tests, on the other hand, where the prime objective of the test was to protect the electric strain gages from seawater, the external surface of the spheres was protected by a thin coat of epoxy resin.

HYDROSTATIC TESTING

INSTRUMENTATION - Two different types of instrumentation were employed on the concrete spheres. The permeability experiments required instrumentation designed to measure rate of permeability, while the short- and long-term stress investigations needed only strain measuring instruments.

Instrumentation for the determination of strains consisted of electric resistance strain gages attached to the concrete sphere, and an automatic strain switch and read-out unit. Two different approaches were used to measure the rate of permeability through concrete in the experimental spheres. One approach relied exclusively on electronic transducers and read-out equipment, while the other utilized only mechanical or hydraulic components. The electronic water detector, specially designed for this study, operated on the principle that a rising water level in the sphere would markedly change the resistance between two separated rods placed inside the sphere cavity. As the water rose in the sphere, it would wet more and more of the two vertical rods, decreasing the resistance between them. This voltage change could be amplified, measured, and recorded to provide a resistance versus time record. The other approach used in the measurement of permeability rate consisted of tubing inserted into the sphere, through which accumulated water in the sphere's interior could be ejected at desired

time intervals.

TESTING PROCEDURE - The testing of the concrete spheres under hydrostatic pressure was conducted in the pressure vessel of the Deep Ocean Simulation Laboratory. The spheres were either placed in a retaining cage prior to testing or were attached to end closure (Figure 10) so that they would not float in the vessel and strike the end closure when the vessel was filled with water. The vessel was pressurized by air-operated, positive-displacement pumps that raised the pressure inside the vessel at a predetermined rate until implosion occurred. Pressure and temperature sensors located inside the pressure vessel permitted recording of these two parameters on a strip chart recorder. Upon implosion of the concrete spheres, manifesting itself by a loud noise, the end closure was removed and the fragments of the concrete structure were inspected. (Figure 11).

DISCUSSION OF TEST RESULTS

PHASE I

SHORT-TERM STRENGTH OF DRY CONCRETE SPHERES - The average ultimate compressive strength of the concrete spheres under hydrostatic loading has been found to be approximately 48% higher than for the 3 x 6-inch solid control cylinders tested under standard conditions (Table 1).

Table 1. Implosion Pressure, Calculated Maximum Stress in Dry Concrete Spheres; and Average Compressive Strength of Test Cylinders Associated With These Spheres.

Item	Sphere 1	Sphere 2	Sphere 3	Sphere 8
Implosion pressure	3,100 psi	3,050 psi	3,200 psi	3,600 psi
Compressive stress1/ on the interior of the sphere	14,080 psi	13,860 psi	14,540 psi	16,350 psi
Compressive stress1/ on the exterior of the sphere	12,530 psi	12,330 psi	12,940 psi	14,550 psi
Average compressive strength of 3x6-inch dry test cylinders under uniaxial compression	8,990 psi	9,750 psi	9,930 psi	11,200 psi

1/ Stress calculated with Equation 1 (Figure 2).

SHORT-TERM STRENGTH OF WET CONCRETE SPHERES - The average ultimate compressive short-term strength of concrete spheres permeated by seawater has been found to be approximately 18% higher than the compressive strength of identical dry concrete in 3 x 6-inch solid test cylinders under uniaxial compression (Table 2).

Table 2. Implosion Pressure, Calculated Maximum Stress in Wet Concrete Spheres and Average Compressive Strength for the Dry Test Cylinders.

Item	Sphere 5	Sphere 12	Average
Implosion pressure	2,850 psi	2,750 psi	2,800 psi
Compressive stress 1/ on the interior of the sphere	12,950 psi	12,500 psi	12,720 psi
Compressive stress 1/ on the exterior of the sphere	11,550 psi	11,100 psi	11,320 psi
Average compressive strength of 3 x 6-inch dry test cylinders 2/	10,500 psi	11,060 psi	10,780 psi
Wetting period at 1,500 psi hydrostatic pressure	4 days	13 days	

1/ Calculated stress with Equation 1 (Figure 2).
2/ Under uniaxial compression.

TIME DEPENDENT BUCKLING OF CONCRETE SPHERES - Long term pressurization of wet and dry concrete spheres has shown that wet concrete spheres are more susceptible to static fatigue than dry concrete spheres loaded to the same fraction of their short-term implosion pressure (Table 3).

Table 3. Hydrostatic Pressure and Duration of Loading of Wet and Dry Concrete Spheres in Static Fatigue Test; and the Average Compressive Strength of the Corresponding Dry Test Cylinders

Item	Sphere 11	Sphere 6	Sphere 8
Condition of concrete in sphere	wet	wet	dry
Hydrostatic pressure	2,000 psi	2,500 psi	3,000 psi
Percent of their short-term critical pressure	71.5%	89%	83.5%
Compressive stress1/ on the interior of the sphere	9,089 psi	11,361 psi	13,633 psi
Duration of loading prior to implosion	6 days	10 minutes	3 days2/
Average compressive strength of 3 x 6-inch dry test cylinders	10,890 psi	10,610 psi	11,200 psi

1/ Stress calculated with Equation 1 (Figure 2).
2/ No implosion occurred during 3-day test.

PERMEABILITY OF CONCRETE SPHERES TO SEAWATER - The rate of seawater seepage into sphere at 750 psi has been measured to be approximately 2.5 milliliters per hour, while for a sphere pressurized to 1,500 psi the rate was approximately 5 milliliters per hour. When the leakage rate is divided by the surface area of the sphere, it can be expressed as 6×10^{-3} milliliters per hour per square inch of area per inch of thickness at 1500 psi hydrostatic pressure. In both cases the salinity of water siphoned from the interior of the sphere was about 20% lower than the salinity of the pressurization medium.

From this rather sparse data, it would appear that permeability of concrete to seawater under high hydrostatic pressure is quite low, and that some chemical or physical phenomena, which occurs in the concrete, results in a decrease in the salinity of the water that passes through the concrete sphere wall.

DEFORMATION OF CONCRETE SPHERES UNDER LONG-TERM LOADING - The measured strains (Figures 12 and 13) showed that dry concrete on the sphere's interior has a time-dependent strain rate, which is very large immediately after load application, but which decreases with time. That the time-dependent strain is a function of both

[illegible]	[illegible]	[illegible]	[illegible]
[illegible]			
Hydrostatic pressure	5,000 psi	[illegible]	[illegible]
Percent of depth ... than implosion pressure	77.5%	[illegible]	[illegible]
Compressive stress ... the interior of the sphere	5,000 psi	[illegible] psi	[illegible] psi
Duration of loading prior to implosion	4 days	[illegible]	[illegible]
Average compressive strength of ... specimens ... dry cylinders	[illegible] psi	[illegible] psi	[illegible]

1/ Stress equivalent ... [illegible] (Figure 3).
2/ To implosion ... [illegible] during ... [illegible] test.

[illegible] ... approximately 1.5 milliliters per [illegible] ... at 1,000 psi ... [illegible] hours. Thus the leakage rate ... [illegible] the sphere. It can be expressed as ... [illegible] per square inch of area per inch of thickness at 5,000 psi ... static pressure. ... [illegible] from the interior of the sphere was about 20% ... [illegible] of the permeability of the ... [illegible].

From this simple experiment, it ... [illegible] of concrete ... [illegible] ...

[illegible]

the compressive stress level as well as time was shown by the difference of time-dependent strain rates measured on the exterior and interior surfaces of the sphere. The interior surface of the sphere, which was under a higher stress, showed a considerably higher time-dependent strain rate than the exterior of the sphere, which was under a lesser stress.

The long-term hydrostatic loading was conducted for only 3 days, and thus it is not known how much the time-dependent strain rate decreases after loading duration of several months, or years. The data generated indicates that even at the 6,700 foot depth level to which the waterproofed concrete sphere was subjected, the time-dependent strain rate of dry concrete decreased to 0.01 microinch/inch/minute after 3 days. This would lead one to believe that at lower stress levels, corresponding to 3,500 foot operational depth, time-dependent strain would not pose any serious engineering problems for concrete spheres with a 0.0625 wall-thickness to diameter ratio.

Upon depressurization, a time-dependent relaxation strain was observed whose rate decreased to a very small value after only 3 days. The difference between the strain level at the beginning of pressurization, and the strain after 3 days of relaxation at zero pressure shows that a nonrecoverable deformation of concrete in the sphere occurred.

TANGENT MODULUS OF ELASTICITY UNDER SHORT-TERM LOADING - The tangent modulus of elasticity of concrete under short-term uniaxial compression (2,100 psi/minute loading rate) was found to decrease with increasing stress level. The axial strains on the exterior surface of solid dry concrete test cylinders under uniaxial compression show that the average tangent modulus of elasticity for concrete mix employed in the casting of spheres is 3.68×10^6 psi in the 0 to 4,500 psi stress range, but decreases rapidly at higher stress levels (Figure 14). What the magnitude of change is in the tangent modulus of elasticity under biaxial or triaxial stresses, as found in the sphere, is not known. The slope of the strain curve for the interior of the spheres shows, however, positively that a decrease in the tangent modulus of elasticity does take place. This makes it necessary to treat E_t in equation (1) as a variable, and not as a constant. Since curves for E_t of concrete under different biaxial and triaxial stress levels do not exist at the present time, E_t as determined under uniaxial compression must be used in the meantime. Since E_t under uniaxial compression appears to be larger than E_t under biaxial and triaxial stress combinations, use of E_t under uniaxial loading is a conservative assumption.

PHASE II

EFFECT OF PENETRATION INSERT RIGIDITY ON CRITICAL PRESSURE OF SPHERE - It was found that there is no significant difference between critical pressures of concrete hull models with solid penetration inserts (Spheres No. 15, 16, and 17) and model without penetration (Spheres No. 18) as long as the rigidity of the insert was equal to, or larger than, the rigidity of the concrete hull

model. When the rigidity of the penetration insert was considerably lower than the rigidity of concrete (0.5×10^6 psi for polyvinyl chloride versus 3.65×10^6 for concrete) the sphere equipped with such inserts (Sphere No. 17) imploded at a significantly lower pressure than the sphere without penetrations (Table 4).

Table 4. Implosion Pressures of Concrete Spheres With Solid Penetration Inserts.

Sphere No.	Type of Inserts	Type of Test	Implosion Pressure	Age of Concrete	Strength of Concrete*
15	Solid steel inserts	Short term implosion test; 100 psi/minute pressurization rate	3485 psi	330 days	11,205 psi
16	Solid aluminum inserts	Short term implosion test; 100 psi/minute pressurization rate	3400 psi	335 days	11,165 psi
17	Solid polyvinyl chloride inserts	Short term implosion test; 100 psi/minute pressurization rate	2675 psi	330 days	11,150 psi
18	No inserts	Short term implosion test; 100 psi/minute pressurization rate	3375 psi	320 days	11,480 psi

* Strength of concrete was determined by subjecting 3 x 6 inch test cylinders of the same mix and age as the associated concrete sphere to compression testing in an uniaxial test machine. The compressive strength shown is the average of 18 test cylinders loaded to destruction at 2100 psi/minute rate.

THE EFFECT OF PENETRATION INSERT RIGIDITY ON STRAINS AND STRESSES IN THE SPHERE - The strains at the small penetrations in the concrete were not significantly different from strains measured at locations in the sphere away from penetrations. The strains at the large penetrations in the concrete, however, were significantly higher than strains measured at locations in the sphere away from penetrations only in the sphere No. 17 containing plastic inserts in the penetrations. The strains measured there one half of an inch away from the edge of the penetration with a plastic insert were approximately 40 percent higher than the strains in the same sphere not in close proximity to the penetrations. When the strains on the

interior of the concrete hull away from penetrations are translated into stresses, the measured stresses at locations remote from the penetrations are found to be of the same magnitude as stresses derived analytically for the interior of a thick sphere.

The strains on the interior surface of the solid inserts varied inversely with the modulus of elasticity of the particular insert material (Figure 15). Stresses, calculated on the basis of the strains in insert materials, were higher than in concrete for materials with modulus of elasticity higher than of concrete. Conversely, the stresses in inserts with modulus of elasticity less than of concrete, were less than in concrete itself (Figure 16).

PHASE III

CRITICAL PRESSURE OF OPERATIONAL HABITAT MODELS - The critical pressures of the two identical habitat models were approximately the same as of the concrete sphere with identical dimensions without any penetrations (Table 5) even though one of the models was subjected prior to destructive testing to its operational depth for 200 hours.

Table 5. Implosion Pressures of Ocean Bottom Habitat Models

Sphere No.	Type of Inserts	Type of Test	Implosion Pressure	Age of Concrete	Strength of Concrete
13	Functional windows and hatches	Held at 1500 psi for 8 days, then pressurized to implosion at 100 psi/min rate	3300 psi	350 days	10,840 psi
14	Functional windows and hatches	Short term implosion test; 100 psi/minute pressurization rate	3300 psi	310 days	9,640 psi
18	No inserts	Short term implosion test; 100 psi/minute pressurization rate	3375 psi	320 days	11,480 psi

STRAINS AND STRESSES IN HABITAT MODELS - The strains and stresses in the interior of the concrete habitat models were not significantly different from those found in spheres with solid steel ($E = 27 \times 10^6$) or aluminum ($E = 10 \times 10^6$ psi) inserts, even though the rigidity of the annular steel penetration flanges was approximately the same as of a rigid insert with a 5×10^6 psi modulus of elasticity. The experimentally determined meridional and equatorial stresses on the interior of the model were in the

4400 to 4600 psi range at 1000 psi exterior pressure.

The time dependent strain rate of the model's interior under 3350 feet operational depth submersion (Figures 17 and 18) decreased from 100 microinches/hour, one half hour after submersion to 0.15 microinches/hour after 200 hours of submersion at operational depth indicating that only very little additional time dependent strain would take place in the future if the model was left at operational depth permanently.

OPERATIONAL PERFORMANCE OF HABITAT MODELS - The operational performance of the habitat models was successful. No leakage occurred through the four window assemblies, three wire feed-throughs, and the single instrumentation tower assembly. Inspection of the penetration insert assembly components after implosion of the models showed that no yielding took place in any of the components.

CONCLUSIONS

Findings based on experimental data resulting from testing to destruction of spherical concrete pressure hulls show that concrete is a reliable material and that buoyant external pressure hulls with a safety factor of two can be built from it on land that will perform successfully undersea at 3350 foot depth for at least one to two week periods of time. Whether concrete hulls with a safety factor of two will perform successfully at 3500 feet design depth for periods of time measured in years will have to be experimentally established. Indications exist that they will be able to do so successfully.

In view of the fact that concrete is a very economical material whose composition is well known, and that construction techniques of large concrete shells on land are well developed, more emphasis should be placed by the U. S. Navy on utilization of this material to permanent, or semi permanent ocean bottom installations in the 0 to 3500 foot depth range.

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PHASE TWO

design

design of an undersea habitat

w. kilmer may 20,1969

The purpose of this project is to design an underwater habitat to serve an oceanographic research team of 22 personnel working on a submerged continental shelf at a depth of 600-800 feet. Six of these people are aquanauts who will dwell in a portion of the habitat designed for saturated pressure corresponding to the specified depth. The remaining number of occupants will be the support personnel who exist in the habitat at a normal pressure. They will be divided into two teams of eight and will operate on a twenty hour work day. The research team will be replaced at various time intervals of approximately sixty days by a new team from the land base.

The habitat complex is designed to be of a modular system that will permit construction of a repetitive structure that can be "plugged into" the nucleus as need dictates. In this manner, the structure can be expanded or reduced at a later stage to meet new mission requirements.

The saturated pressure is restricted to the diver area due to the critical atmospheric control that must be maintained. This environment is composed of approximately 80% Helium, 15% Nitrogen, and 5% Oxygem. The helium in this mixture has many drawbacks that make this saturated atmosphere very expensive and restrictive to permit this mode of breathing throughout the habitat. Helium has an adverse effect on the human vocal chords to the extent of raising the pitch of the voice to an un-communicable level. Helium is also six times as conductive as air, which would necessitate more thermal insulation for the habitat. Moreover, a saturated pressure could restrict the placement of the habitat at deeper depths in the future due to the greater pressures that must be tolerated by the human occupants.

A sphere represents the optimum shape for a pressure vessel for underwater purposes. This is due primarily to the double curvature of the shell which reduces the need for rib stiffeners such as is required with a cylinder. A variable ballast placed within this sphere would facilitate transportating, lowering, positioning, and raising of the structure. By designing the ballast within the pressure shell, it would not be subjected to the hostile oceanic environment or be in the way of future structural additions to the habitat. The ballast is water which is placed in a reservoir at the "bottom" of the sphere to stabilize the vessel in the ocean waters.

The advantages to using concrete as the pressure vessel are many. Concrete is economical, easy to form into double curvature shells, highly resistant to marine corrosion, and has a low heat and sound conductivity. However, there are a few drawbacks to the use of concrete. These are that it is somewhat permeable to seawater and has a low tensile strength. An epoxy coating could eliminate the water problem and proper engineering specifications would allow for possible tensile loading of the structure.

By investigating the various diameters and wall thicknesses of concrete spheres, an optimum size can be calculated. Theoretically, the spheres in the vicinity of 14 to 18 feet outside diameter with a wall thickness of one to one and a half feet can be designed as a neutrally buoyant structure. Larger spheres are expensive to construct due to the required shell thickness to maintain the proper buoyancy. Smaller spheres do not allow enough interior space for mission functions or proper surface area for hatchway connections.

The buoyancy tank within this vessel will provide approximately 15,000 pounds of water ballast. By using fresh water, the ballast

can serve a dual purpose as weight and for drinking purposes in a closed re-usable system as controlled by a master ballast regulator.

A removable flooring is placed above the ballast tank, allowing a clearance for mechanical systems. Connections of the mechanical systems are performed beneath the floor assembly between spheres in the steel mating cylinders. These cylinders are anchored into the concrete shell to provide positive watertight connections between various spheres.

The concrete spheres would be cast at a controlled shop area in re-usable forms. After the concrete had cured, the top half of the outer form and the inside forming assembly could be removed. The latter would be a break-apart system that would be taken out through the formed hatchway. The structure would be supported by the lower outer casting form due to the possibility of a collapse in the shell wall if it were placed on a horizontal bearing surface. The interior would then be finished out with the various mechanical systems and other internal facilities. The hatchways of the sphere would be outfitted with the steel mating unit as a integral of the formed sphere. This cylindrical assembly would be then sealed shut with a water and pressure resistant door.

The finished sphere is then launched from drydock as though it were a ship. With the ballast tank empty, the sphere will be positively buoyant and float out of the lower form which is lowered into the ocean. The lower casting form is then pulled back to the shop area for construction of the next sphere. The sphere is towed to the upper staging vessel which is located above the selected habitat site.

This staging vessel would serve as a lowering and placement platform, a supply base, and a monitor of the habitat operations below.

The steel footing assembly is attached to the sphere if it is designated as a lower unit. The transfer unit then controls the ballast tank of the sphere thru a line from the supply tanks located on the staging vessel. The transfer unit then transports the sphere to the ocean floor via four drive units traveling down the cable assemblies. Once the sphere is positioned on bottom, the transfer unit then returns to the surface for the next unit.

The first sphere is equipped with a universal footing that serves four spheres. The cable assemblies are attached to an eyelet on the footing for accurate positioning by the transfer unit. When a new sphere is attached, its steel supporting unit is places on the existing unit and secured in position by a locking device.

The footing arrangement allows for an accurate positioning of the steel mating assemblies. When the second sphere is brought within contact of the first, the mating assemblies are connected with a minimum outside securing. The entrapped water is pumped from within the two mating assemblies, creating a pressure seal via the neoprene gasket between the units. An access hatch is opened from the existing sphere, enabling the occupant to step into the mating units and secure them with a series of locking devices along the interior circumference of the mating units. When this operation is complete, the pressure resisting hatchways can be disassembled and transported back to the surface for positioning on new spheres. The occupant can then make

the proper mechanical and electrical connections between the spheres and move into the new sphere. This is the established procedure for attaching new units.

The habitat arrangement for the initial research program shall be constructed in two levels of twenty-seven spheres. By stacking the vessels, footing assemblies can be reduced and transient time between points within the habitat can be lessened. A reinforced, semi-rigid cup assembly of approximately six foot in diameter would be placed between all spheres. This would distribute the loading of upper spheres on the lower ones and provide a cushioning effect to any movement that may occur between spheres throughout the total structure. These cushions would also have embedded sensors in them that would detect variable loading weights of the upper spheres. This means that if an upper sphere became positively or negatively buoyant, the sensor would detect this condition through a variance from the initial weight setting on the sensor when the vessel was first positioned. This change would be reported to the main ballast regulator system which would then translate this factor into an addition or reduction in the water ballast of that particular sphere. Spheres on the lower level would be monitored by similar sensors in the footing assemblies.

The diver portion of the habitat is on the lower level to facilitate the entry and operations in the immediate area. These three spheres are operated at a saturated pressure as supplied and monitored by the support lab. Between these two areas is the decompression complex which enables transfer of nutrients, aid and work operations between the habitat support personnel and the divers. The critical atmosphere has dual monitoring by both areas to permit a backup check on the system. The support lab is the principal physical link and support to these divers.

Directly above these areas are the main laboratories. They are located on the upper level to provide a better view over the divers performing work and experiments in the immediate area. The command sphere is placed on an axis with these labs and the primary circulation route. This sphere contains the major control functions of the habitat. An upper hatchway in this sphere is provided to mate up with the pressurized transfer unit from the staging vessel above. All items and personnel are brought through this entry to and from the surface to permit logging of weight changes, distribution of equipment, and supply or outgoing items. Gas tanks are taken to the lower level by way of a small, open elevator platform located directly outside of the command area. The gas cylinders are plugged into the proper gas banks to replenish the expended gas tanks which are taken to the surface by way of the same routing.

All bathing facilities are located in one sphere for the support personnel. In this manner, more rigid control of the humidity and water cycles can be maintained through a direct hook-up to the mechanical sphere below. Hygiene areas are arranged into personal compartments to provide for the possibility of women occupants using the facilities at the same time as the men. The remaining upper level contains the quarters for the support personnel. Two people are assigned to each vessel for their duration of stay in the habitat. Each sphere is equipped with private storage space, two bunks, conversation couches, a study area, and washing facilities. A pressure door connects each sphere to the primary circulation and mechanical spheres. This door is kept closed at all times to insure safety to the occupants in the event of a catastrophic failure somewhere in the

total habitat. In the event of this disaster, rescue divers could save these individuals by removing the locking devices between the spheres and blowing the ballast tank of the quarters to raise it to the surface.

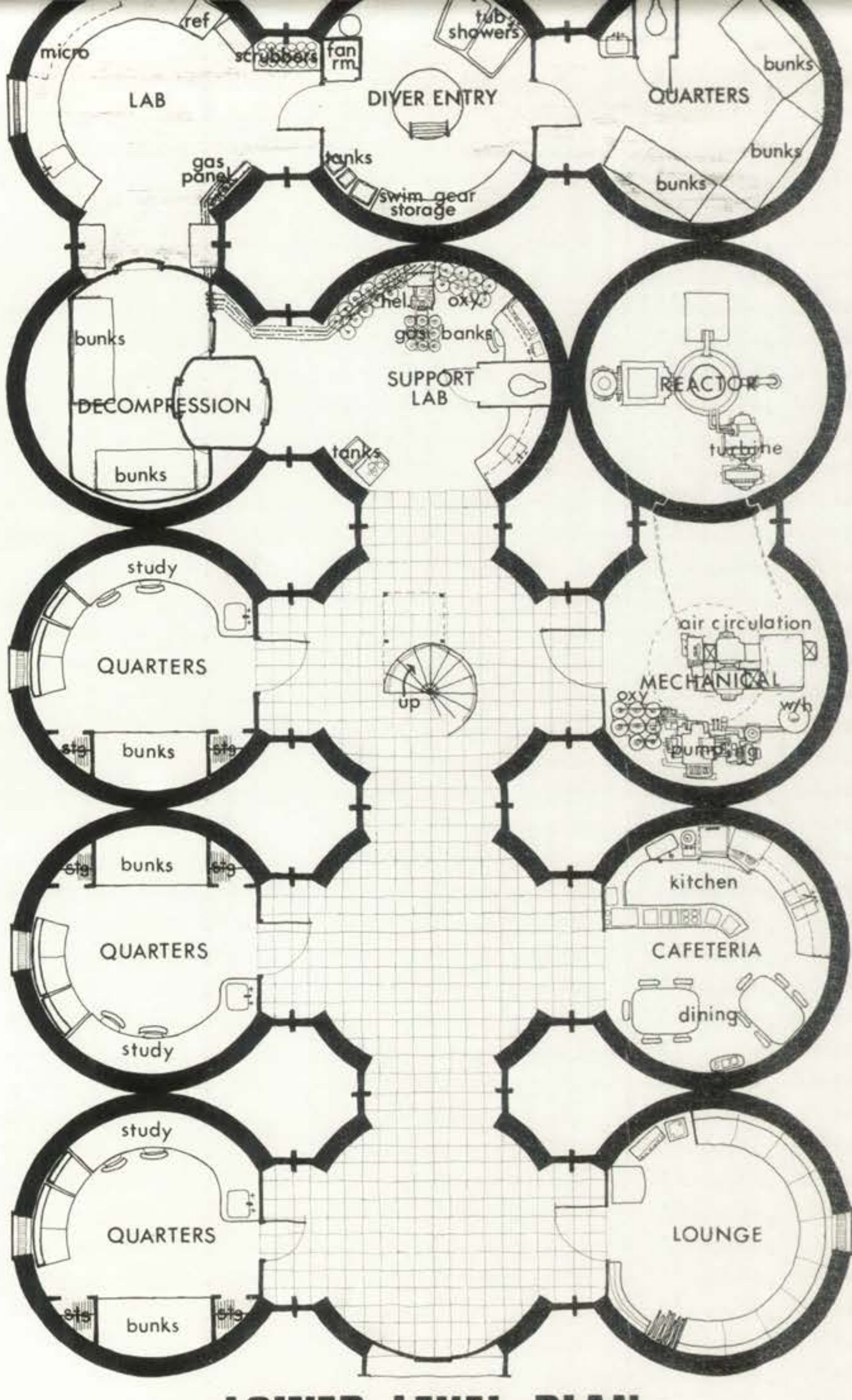
The mechanical and reactor spheres are located on the lower level directly off the vertical connector between levels. The equipment contained in the mechanical sphere would be the air circulation machinery, the gas scrubbers, the replenishable gas banks, the water distilling units, and the master ballast regulator. Directly accessible to the mechanical room is the reactor area which is sealed off by a radiation-proof door.

The lower level also houses the cafeteria, which is designed as a small galley area to prepare the meals for the support personnel and the divers. The dining area will seat a maximum of ten people or one shift of the personnel. The lounge is primarily a "wasted" space in the habitat. It is used for recreation, reading, entertainment, or group meetings. This sphere is to provide the kind of space needed to break the closeness and monotony of the other vessels.

Both levels are designed with an open-ended circulation and mechanical connector. The last "corridor" sphere is fitted with a pressure hatch that can be utilized in future stages for additional growth of the habitat complex.

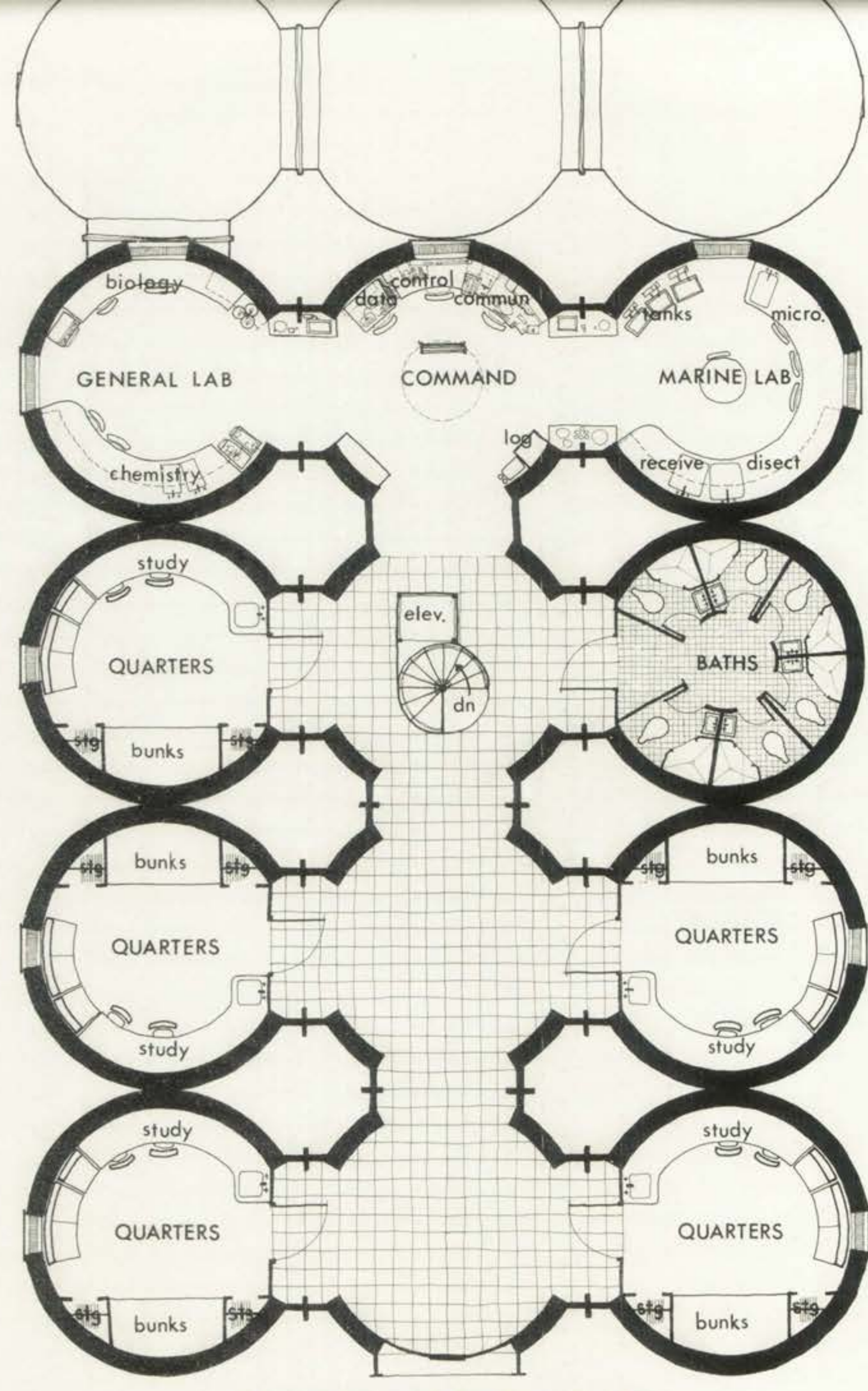
ASPECTS OF CONCRETE SPHERES

[O]UTER [S]PHERE [DI]AM. IN FEET	INNER SPHERE DIAM. IN FEET	SHELL THICKN'S IN FEET	SHELL WEIGHT POUNDS	DISPLACEMENT IN SEA WATER POUNDS	BUOYANCY POUNDS
18	17	.5	72,000	196,000	+124,000
	16	1.0	137,000		+ 59,000
	15	1.5	193,000		+ 2,500
	14	2.0	244,000		- 48,000
17	16	.5	64,500	165,000	+101,000
	15	1.0	123,000		+ 42,000
	14	1.5	171,000		- 6,000
	13	2.0	214,000		- 49,000
16	15	.5	57,000	137,500	+ 80,500
	14	1.0	106,400		+ 31,100
	13	1.5	150,000		- 12,500
	12	2.0	186,000		- 48,500
15	14	.5	49,500	113,000	+ 64,500
	13	1.0	93,000		+ 20,000
	12	1.5	129,000		- 16,000
	11	2.0	161,000		- 48,000
14	13	.5	43,500	92,000	+ 48,500
	12	1.0	79,500		+ 12,500
	11	1.5	111,000		- 19,000
	10	2.0	137,000		- 45,000



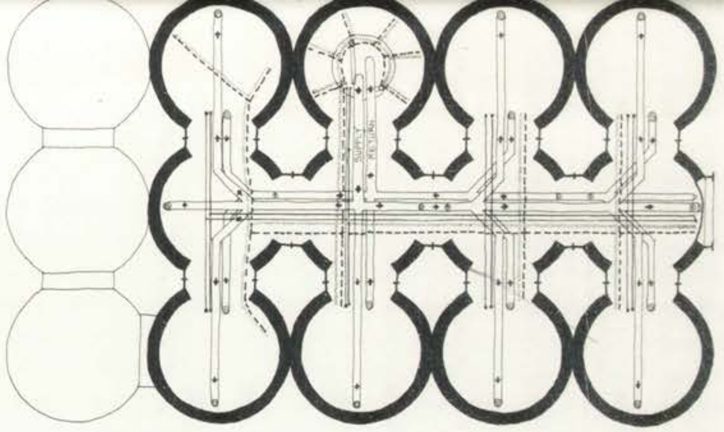
LOWER LEVEL PLAN

1/4"=1'-0"



UPPER LEVEL PLAN

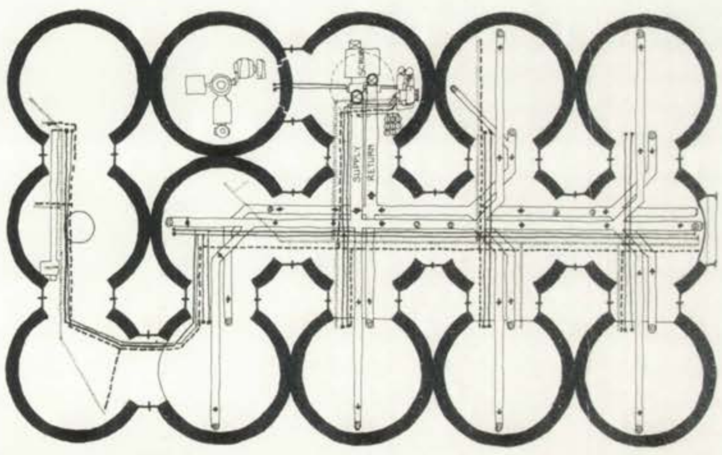
1/4"=1'-0"



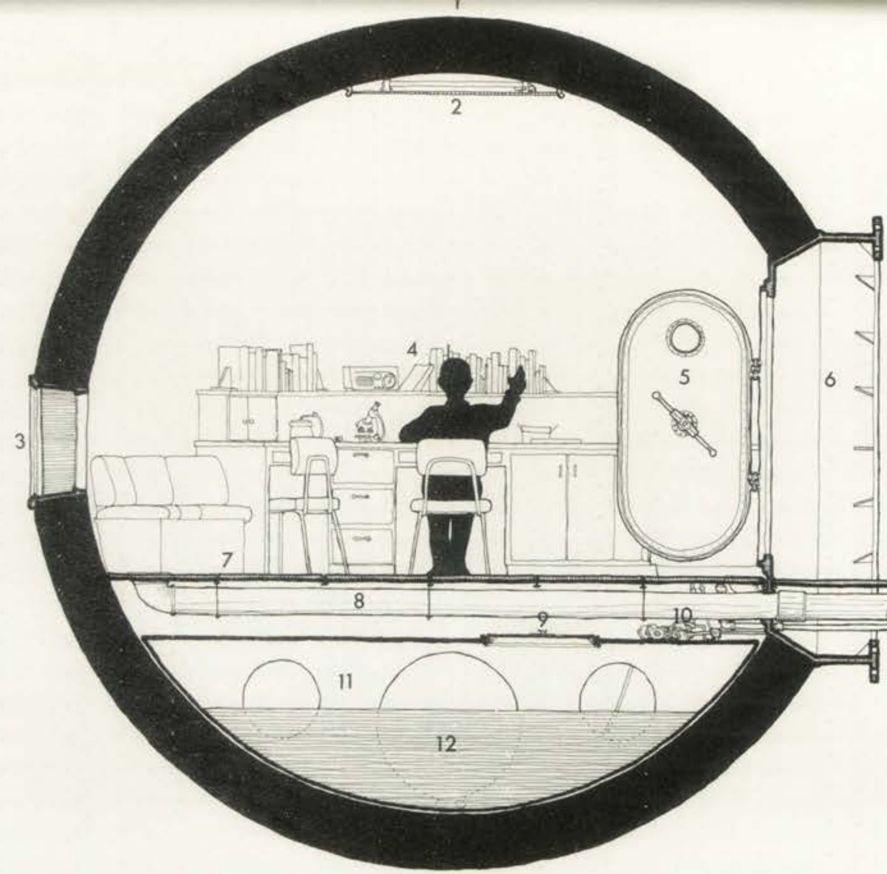
UPPER LEVEL PLAN

LEGEND

— ballast water supply
— ballast water return
= air circulation duct
▬ sewage return line
--- utility water supply



LOWER LEVEL PLAN



1 concrete pressure hull
2 electrical light unit
3 exterior view porthole
4 individual work area
5 pressure tight door
6 steel mate assembly
7 removable flooring
8 air circulation duct
9 access hatch to tank
10 ballast regulator unit
11 water baffles in tank
12 water ballast tank

MECHANICAL SYSTEMS
1/8"=1'-0"

TYPICAL SECTION OF SPHERES
3/4"=1'-0"