Structures/Materials Synthesis for Safety of Oceanic Deep-Submergence Bottom-Fixed Manned Habitat

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Safety considerations make it desirable to have a self-buoyant system capable of anchoring to the ocean floor and yet capable of delivering personnel to the surface without external assistance. This indicates a choice of lightweight structural concept with materials of high strength/weight ratio, a problem closely related to basic concepts in aerospace structural design. Using analytical techniques and computer technology to map a parametric study to include shape, size, weight, type of mission, structure, and material, the most suitable configuration is evolved with optimum design at minimum weight to satisfy the safety considerations. The effect of the choice of safety factors and failure criteria on the optimum weight is also investigated. The study indicates that a spherical modular configuration of not less than 10-ft diam is most advantageous for an ocean-bottom-fixed manned habitat, with critical structural design reduced to reinforcing of areas where hatches would be required. The method of estimating the reliability of such a structural configuration is indicated. The application of "fail-safe" and "safe-life" concepts is also considered so as to satisfy safety requirements. Various materials (conventional and newly developed, monolithic and composite) are screened for properties and performance critical for deep-submergence structural application.

Nomenclature

B = displacement (buoyancy), lb or ton
C = constant
d = ocean depth, ft
D = diameter, in. or ft
E = modulus of elasticity, psi
F = safety factor or load factor
L = length, in. or ft
P = design maximum pressure, psi
R, r = radius of curvature, in. or ft
t = thickness of shell, in.
W = total or structural weight, lb or ton
α, θ, ϕ = angles, deg
β = $[1 - (W/B)]$, i.e., excess buoyancy coefficient
γ = W/B, i.e., $\gamma + \beta = 1$
ν = Poisson's ratio
ρ = material density, lb/in.^{3}
σ = stress in material, psi or standard deviation

Subscripts

allow = allowable
b = buckling
c = core or critical
e = equivalent
f = face (skin)
i = inner
m = mean, middle surface
o = outer
R = ring
S = shell
y = yield
u = ultimate
1, 2 = numerals, sequence

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Introduction

THE spearhead of technologies is at present aimed at the race for extra-terrestrial or "outer space" exploration, whereas many aspects of terrestrial exploration have so far received only limited attention. Of some importance among the latter is deep oceanic or "inner space" exploration. All the reasons which make outer space a challenge (viz., adventure, scientific curiosity, military and commercial exploitation, and the consequent need for technological advancement) apply equally to deep oceanic systems. The similarity continues in various aspects, especially in manned habitat design and manned operations in either of the deep spaces, in spite of the fact that some features (such as environments) are opposite extremes. Indeed, the requirements become more severe and the challenge more exacting. Table 1 highlights some comparisons. The primary consideration in any manned operation is that of safety of the personnel, which must be achieved in both spaces in the face of environments which, in case of exposure, are equally hostile, become at once fatal, and exclude any chance of survival, unlike any system in the near earth (aerial or oceanic) space. This paper considers some design aspects for achieving inherent safety for a bottom-fixed, 1-atm manned habitat. It is interesting to observe that the structural designs for hulls of ocean surface ships were adapted for the first airborne ships and crafts that launched man into the air; now, it is the turn of aerospace technology concepts to make significant contributions in launching man to the ocean depths.

Environmental Requirements and Constraints

These will vary with the type of mission considered. An outline of some categories of missions is indicated in Table 2. The environments will depend primarily on depth and the longitude and latitude location of the habitat. In general, these still require further definition as scientific exploration progresses.

The critical features of the environment are high hydrostatic pressure and corrosive marine environment. Other environments for hull design safety considerations are maximum

Table 1 Manned habitat design requirements

Environment	Outer Space	Inner Space
Specified habitat conditions	Shirtsleeve conditions: 1 atm, 70°F, 46% RH	
External environment		
Pressure	Almost void, 10^{-14} atm	Increasing to over 1000 atm
Temperature	-10 to 110°F earth orbit to -300°F on dark side to $+200$° or over on sun side for interplanetary space depending on thermal sinks, etc.	Decreasing to near 35°F
Humidity	None	Submerged
Gravity	Weightless condition	Normal gravity
Shell loading	Tension, internal pressure	Compression, external pressure
Probable duration of human survival in case of exposure	None	None
Structural/material corrosivity	Radiation: α, γ, x-ray	Salinity and chemical corrosion
Detrimental conditions and hazards	Meteorites	Marine biology and debris

velocity of currents and their frequency distributions, and impact due to marine biology and/or debris. Others include temperature, illumination, and fungus growth rate.

Requirements for the Hull and Design Criteria for Safety

The ultimate aim of a deep-submergence system is to reach the deepest areas of the ocean. However, from the viewpoint of a development program, a gradual increase in depth will be achieved as the structures/materials technologies progress. The critical element in the design of a system for any deep-space manned operation, in this case oceanic underwater submergence, is the hull structure. The capability of the structure for resisting the increasing pressure load and the potential of the material to survive and retain its properties in the extreme corrosive environment are the two basic critical requirements.

A prime requirement for ultimate safety would be a naturally self-buoyant system capable of surfacing without assistance from a rescue mission, since forced buoyancy or supplementary buoyancy provisions depend on systems which themselves reduce the reliability of such an operation. The self-buoyancy requirements are correlated to failure criteria and minimum surfacing time. However, as the operating depth increases, for many types of structural construction and materials of fabrication, the hull weight required to attain the level of safety becomes too heavy to be self-buoyant. This primarily indicates choice of lightweight design in materials of high strength/weight ratio, using structural concepts that optimize safety and load capability, so as to meet the anticipated operational requirements for any given type of mission—scientific, commercial or military. Some details of a possible specification for a prototype habitat system are shown in Table 3.[11]

Structural Configuration Selection

Using analytical techniques and computer technology familiar in aerospace industry, structural design configurations are evolved to insure adequate safety by combining self-buoyancy and high design reliability. It is necessary to map a parametric study including shape, size, weight, structure type, and material as variants. Screening ranges for such a matrix would be established by a preliminary survey. This is dependent on better understanding of the environment and the material performance when subjected to these environments.

The conventional approach to structural design for a shell capable of withstanding high external pressure and of a size suitable for manned operations, as in the case of a submersible vehicle, is a cylindrical shell reinforced at appropriate intervals by stiff rings and/or bulkheads, and possibly also longitudinal intercostals. The cylinder is closed with hemispherical end closures, is relatively efficient because of better utilization of interval volume, and provides a shape easily fabricated. Although this is satisfactory from buoyancy considerations at moderate depths, with increasing depth, the ratio of weight to displacement of the shell increases rapidly, and it becomes necessary to investigate various other shapes and configurations. Those studied to date in various published and unpublished literature by various agencies[2,5,7] are shown in Fig. 1.

The criterion for structural design is the failure mode, such as buckling or general instability, static strength (both at yield and for ultimate failure), and fatigue strength. Also, these criteria must be satisfied throughout the structure, whether under monolithic shell forces or due to discontinuity loading. The discontinuities arise either due to intersections of shapes or due to operational requirements, such as a removable hatch or porthole, or incorporation of an operational or service penetrant. At shallower depths, general instability

Table 2 Mission analysis

Mission type	Scientific & exploratory	Military & engineering	Commercial exploratory	Commercial communal
Depth range	full range	up to 15,000	up to 10,000	up to 6000
Volume capacity	small	medium	large	large
Payload weight	2 tons	up to 50 tons	50 tons & over	50 tons & over
Total weight	up to 20 tons	20–250 tons	300 tons & over	300 tons & over
No. of personnel	3	3–20	5–50	10–100
Safety weighting	high	high	lowered, based on experience	
Duration on ocean floor	3–30 days	up to 1 yr	up to 1 yr	semipermanent
Location {near / on / below} ocean floor	near	on	near or on	below
Probable time scale	early 70's	late 70's early 80's	from mid 80's	from mid 80's

Table 3 Possible specification for a bottom-fixed, 1-atm, deep-submergence manned habitat

Item	Module	System
Capacity	3 men	14 men (28 for emergency)
Internal volume	12 ft diam $\approx$ 913 ft^3	>10,000 ft^3
Life		10 yr
Latitude		35° or less
Ocean current fixing	Max vertical 10,000 lb Max lateral, 50,000 lb	Pile emplacement
Weight	Displacement: 30 tons	300 tons
Buoyancy	Neutral buoyancy	Central $\pm$ 1000 lb/module
Nonstructural payload	10 tons	100 tons
c.g. position		1 ft below center of buoyancy
Ballast	Jettisonable 1000 lb^{3}module	Emergency ballast 10 tons
Failure	Probability of major repairable failure	10^{-2}
	Probability of noncatastrophic in situ failure	10^{-3}
	Probability of catastrophic failure	10^{-4}
	Using 3σ lower limits of property values	
Space	700 ft^3/man	
Ocean floor	15–20,000 ft, 2.0°C, 7–9000 psi. $\frac{1}{2}$ knot of max current velocity	
Hull strength	Safety factor = 1.5	
Impact strength	$\frac{1}{2}$ knot of contact of 75 ton DSRV with 300 ton habitat	
Joint moment	10 knot current when anchored Sea state 5 waves on surface	
Internal equipment	1.5 g limit in all directions	

due to hydrostatic pressure governs the shell thickness. With increase in depth, however, static strength or fatigue strength becomes critical. Although some hull shapes may have post-buckling strength, from safety considerations this is of little practical value, since secondary and local failures result and lead to total collapse of the shell.

A sphere is the most efficient for resistance to buckling because of its double curvature and uniformity of generalized shell stress in both meridian and hoop directions, and thus requires little or no stiffening. Unless the size is optimized, however, the internal volume utilization is poor. The sphere is inefficient from hydrodynamic considerations. However, for a fixed habitat, the latter is not critical. Results of a comparative study of a conjointed sphere of the "barbell" type with single sphere are given in Ref. 12. Segmented intersecting spheres yield the lowest weight-to-displacement ratios. These are followed by prolate spheroids with an aspect ratio of 1.5, cassinians, and prolate spheroids with aspect ratio of 2.0. With oblong shapes where, in general, two radii are involved, the onset of buckling is determined by one radius and a compromise has to be reached with the other, thus reducing the efficiency. Cylinders have poor resistance to buckling and require some stiffening to delay instability, thus adding weight. At intermediate depths (10–20 kft), oblong shapes would have certain advantages and may give sufficient excess buoyancy. At extreme depths, only spheres and combination of spheres would yield designs with only marginal excess buoyancy. Operating depth potential for hulls of various materials, prepared by M. A. Krenzke (Head, Design Analysis Submarine Structures Division, David Taylor Model Basin), are shown in Fig. 2. Depths were calculated for near-perfect, initially stress-free hulls with a safety factor of 1.5 on static collapse depth.

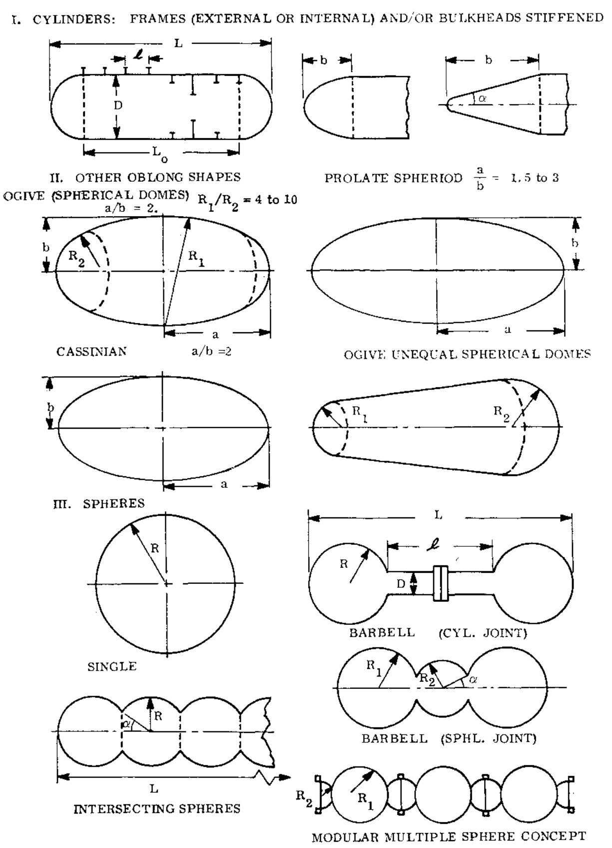


Fig. 1 Structural configurations.

The optimum structure for high external pressure loading is thus a shape of double curvature, and in particular the sphere. To increase the size and capacity by floor area or enclosed volume, the optimum structure is given by intersecting spheres; the size of the basic sphere, being chosen to suit the mission requirements and for a manned habitat, will derive from human factors (Fig. 3b).

A habitat built below the ocean floor by excavating in the sub-benthic rock is also conceivable. For such a concept, primarily concrete and reinforced concrete-type structures would be most suitable; these are conceived as being relatively permanent structures and not just ocean-bottom-fixed habitats that are only tentatively anchored. However, utilization to any significant extent of this type of habitat at a reasonable depth would require, as a precursor, successful establishment of the bottom-fixed type of manned habitats discussed here. Thereafter, with suitable advancement in civil, mining, and/or petroleum well-drilling type technologies, the sub-benthic habitats would become feasible. The structural configuration of a hemispherical shell, with suitable hatch and passageway intersections, is best suited also for such a habitat.

Structural Concept Selection

The structural concepts used will vary with the shape, operating depth, and type and duration of mission, and will

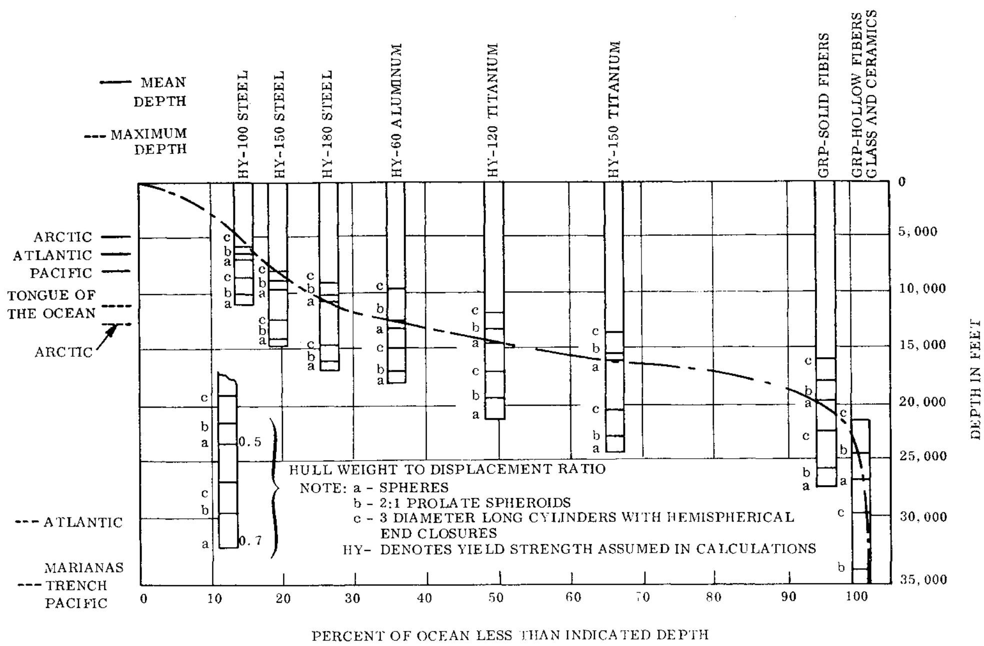


Fig. 2 Summary of operating depth potential of different configurations and various materials.

be required to be optimized. The various concepts include 1) monolithic shell, 2) ring stiffened/bulkhead stiffened, 3) ring and intercostal stiffened (internal or external), 4) integrally stiffened (internal or external), and 5) double wall with suitable core (honeycomb or corrugation).

Using analytical methods for buckling-design considerations, modified by experimental verification and computer techniques, the regimes defined by a parameter can be mapped for various operating depths. The typical parameters would be defined as shape, size, operating depth, mission, payload weight and volume required, buoyancy ratio, structural concept, structural material, failure criteria, and single cell or modular design. The parameters could be grouped to give significant (nondimensional or dimensional) quantities that reflect their effectiveness, e.g.,

1) volume or payload } ratio to { linear dimension (length or diameter) weight or area

2) Displacement ratio to volume, total weight, payload weight.

3) 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 an ogive.

4) Strength-to-density ratios of materials.

5) Buckling/yield/ultimate criteria and safety factors.

6) Single cell or multiple (modular) cells.

7) One mission to another, with varying size and weight of payload or free enclosed space required, displacement or excess buoyancy.

Finally, as the depth increases, critical design is based on strength, and the optimum shape is the sphere (with limiting maximum size for single cell design) and the design concept of a monolithic shell. With strength and not stability becoming critical, design is dictated by yield-failure criteria and material yield strength, and where a bimaterial design is used with matched elastic constants, the proportional limit governs. The selection of a material with high strength-to-density ratio is then of primary concern.

Variation of Shell Weight and Buoyancy

Variations, with operating depth, of shell weights and excess buoyancy coefficient for spherical and cylindrical hulls over a range of sizes and in different materials using monolithic construction were studied. Some results of such a typical parametric study are shown in Figs. 4 and 5. These indicate the transition from cylindrical to spherical shell as the more efficient structure with increasing depth. The analytical basis used is summarized below.

Shell Design Criteria

For shell design criteria, design operating depth is d, ft; design operating pressure, $P = 0.433d$ psi; design limit yield pressure, $P_y = 1.5P$; design stability pressure, $P_{cr} = 1.2P_y$.

Cylindrical Shell

For buckling, critical length is given, for example, by[9]

$$\text{Slenderness Ratio} = \left(\frac{(L/2R)^2}{(t/2R)^3}\right)^{1/4}\left(\frac{\sigma y}{E}\right)^{1/2} = 0.8$$

or

$$L = (1.28/\sigma y)ER(t/D)^{3/2}$$

For strength critical design, Lame's solution for thick shell gives

$$\sigma_{\max} = 1.155\sigma_y = -2P[R_o^2/(R_o^2 - R_i^2)]$$

Spherical Shell

Buckling critical: using Zolley's classical elastic buckling formula[9,10] for small deflections of sphere under pressure, with an empirical correction to allow for lower bounds of test data on near-perfect shells,

$$P = C2E\,(t/R_m)^2/[3(1-\nu^2)]^{1/2} \qquad R_m = R_o - (t/2)$$

with $C = 0.25$ and $\nu = 0.3$, and

$$t = R_m\,(P/0.3E)^{1/2}/1 + 0.5\,(P/0.3E)^{1/2}$$

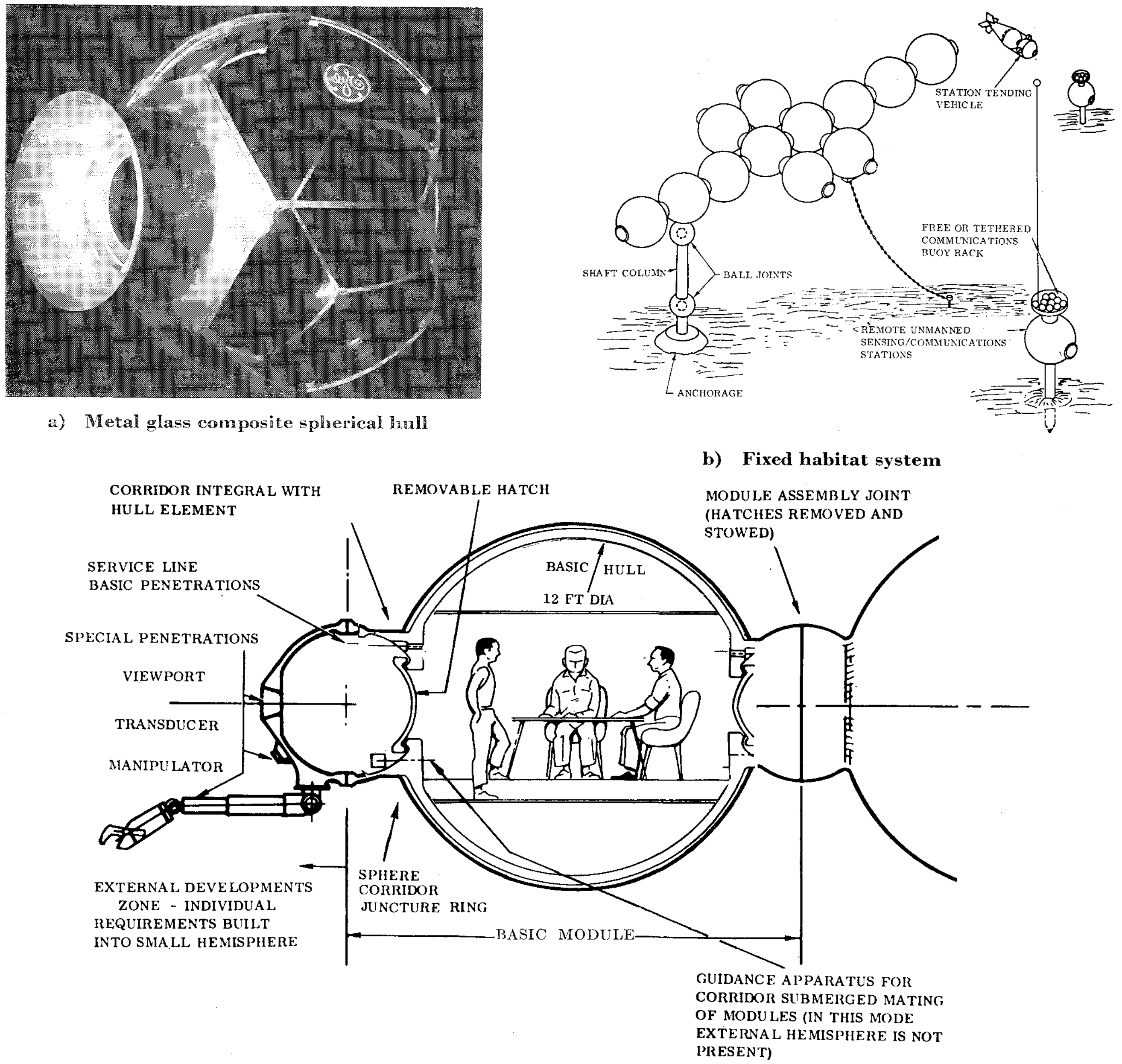
yielding critical:

$$P = (2t/R_m)\sigma_y \qquad \text{or} \qquad t = P\cdot R_o/2\sigma_y\,[1 + (P/4\sigma_y)]$$

For spherical segment type hatch,

$$P = C\,\frac{2E_s t^2}{R_m^2(1-\nu^2)^{1/2}} = 0.3E_s\left(\frac{t^2}{R^2}\right)_m$$

For juncture ring with two spheres of radii R_1 and R_2, the



a) Metal glass composite spherical hull

b) Fixed habitat system

c) Modular configuration and components

Fig. 3 Schematic details of General Electric Company's "Project Bottom Fix": a possible concept for deep-submergence, 1-atm manned habitat.

ring area is given by

$$A_R = \frac{R_1 \sin\phi_1 \cos\phi_1 E_1 t_1}{E_R(1 - \nu_1)} + \frac{R_2 \sin\phi_2 \cos\phi_2 E_2 t_2}{E_R(1 - \nu_2)} = C_1 R_1 t_1 + C_2 R_2 t_2$$

Effect of Criteria of Failure

To study the effect of failure criteria on weight and buoyancy coefficients for spherical shells, the following considerations apply.

Buckling critical:

$$d = 0.7\ [2E(t/R_o)^2 \times 2.25]/[3(1 - \nu^2)]^{1/2}$$

for a given material and R_o, $d\alpha t^2$, $W\alpha t$, $d\alpha W^2$, B = const. If $W/B = \gamma$, $d\alpha^2\gamma$

Yield critical:

$$d = 2.25 \times 2 \times t\sigma_y/R_2$$

for a given material and R_o, $d\alpha t$, $d/(W/B)\alpha\sigma_y$.

Figures 5 and 6 show the interrelationship of depth of submersion with yield stress for yield criteria and with modulus of elasticity and instability stress for buckling criteria. For a given material, the transition from buckling to strength design at various depths and hull sizes is shown in Fig. 5.

Table 4 shows[13,14] results of the study of different concepts for a spherical hull structural design, using various materials, both conventional and those that show promise of future application. Both yield and instability criteria were considered. A safety factor of 1.5 was required for either criterion for failure.

Composite Spherical Hull Concept

Composite type of structures using either integral laminar or grid and panel type of constructions are also feasible, so as to combine characteristic properties of each material. A possible conceptual design is indicated in Figure 3a. This attempts to combine the high compressive strength and low density of ceramic glass with fabrication flexibility of a

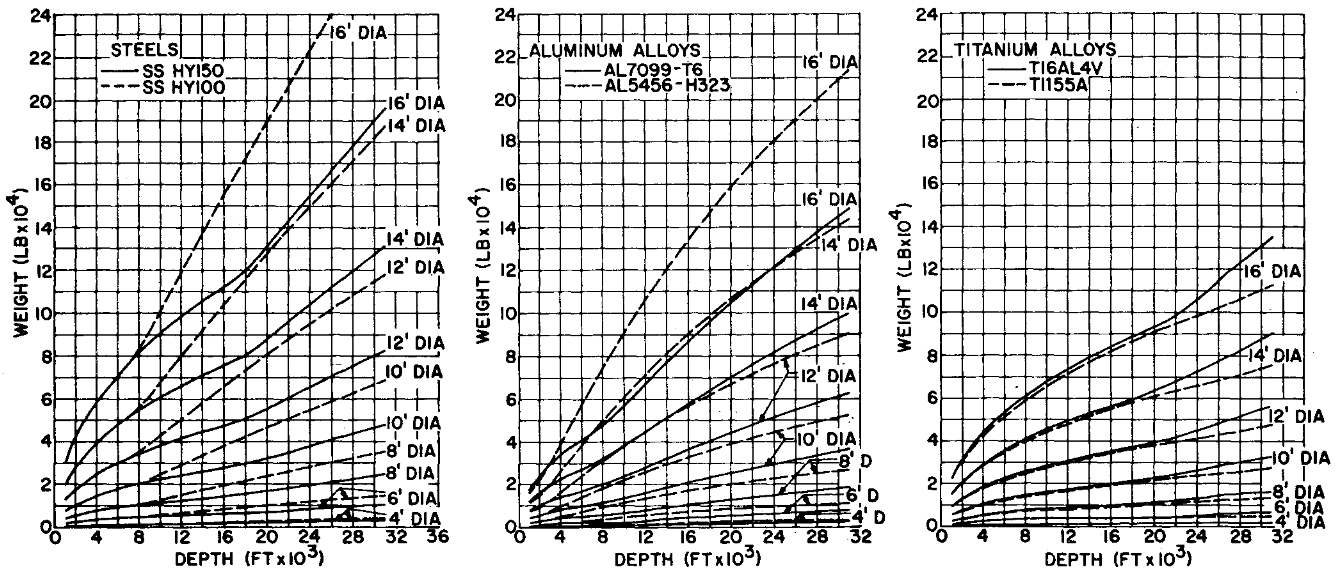


Fig. 4 Spherical hull weight vs depth.

metallic grid. Such a design would maintain excess buoyancy at near-extreme depths to include more than 80% of the ocean area.

The design consists essentially of a sphere deliberately segmented in the interest of handling the materials from which it is made. The individual elements are then formed with precision so that the assembled unit will have favorable structural properties or characteristics of a continuous one-material sphere. The Pyroceram used in the design has $\frac{1}{3}$ the weight of steel, 3 times its compressible strength, and $\frac{2}{3}$ of its elastic modulus. The metal parts of the design are of titanium, which was selected for compatibility with the Pyroceram, relatively low weight, and outstanding characteristics when exposed to the marine environment.

Determination of Standard for Required Margin of Safety or Factor of Safety

Factors are introduced into design considerations to allow for the effects of unknowns in the following areas: load variation; material property variation; material performance probability; repeated or cyclic loading; temperature effects, both on loading and material properties; effect of environment on material (corrosion and deterioration); dynamic effects; and hazards due to adverse combinations arising through manufacturing processes. For the aerospace structures, accent is placed on eliminating the "unknown" nature by determining as many or all of these considerations; factors for safety can be then reduced to as low as 1.25 or even 1.1. For manned space vehicles, the factors vary from 1.25 to 1.5. Current practice in the oceanics field is to use much larger factors than these, 1.5 to 2.0 and higher, in view of the pressure loading and its attendant catastrophic failure. Also, this is because unknowns are as yet insufficiently investigated and determined.

As will be discussed later, considerable efforts are required to define material behavior under the operating load and environment conditions. Extensive test programs are necessary at various levels, such as material specimen, coupon, structural component, subsystem and complete structure, so as to reduce the unknowns and the high safety factors, while maintaining satisfactory reliability.

The effect of variation of load and safety factors based on assumed material properties for a given structural configuration (viz., spherical) have been studied; results[14] are shown in Fig. 7. It must be noted that for elastic materials, yield-to-ultimate strength ratios are inherently obtained when one or the other is used as a design condition.

Material Considerations

The structural considerations must go hand in hand with material selection. It is necessary to screen carefully ma-

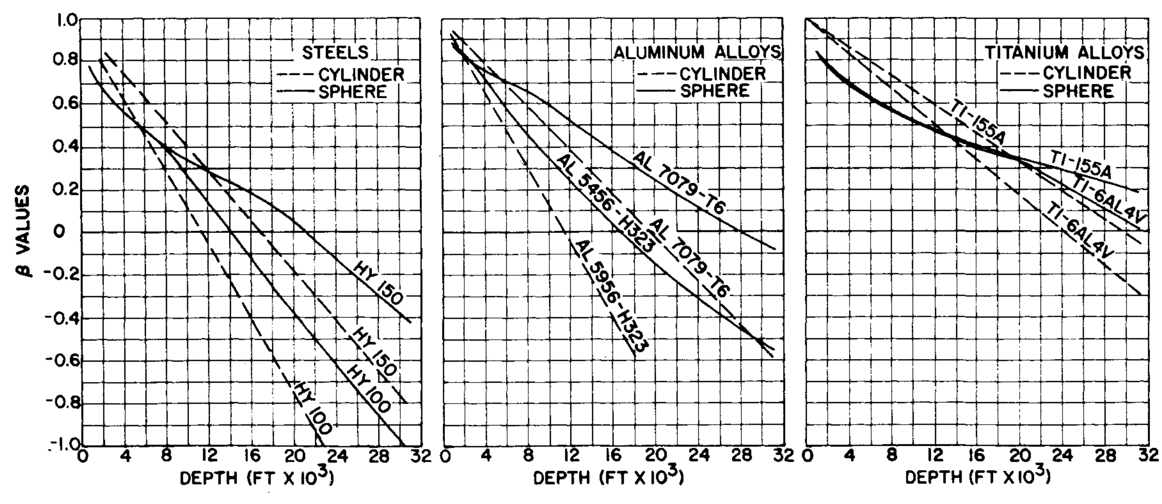
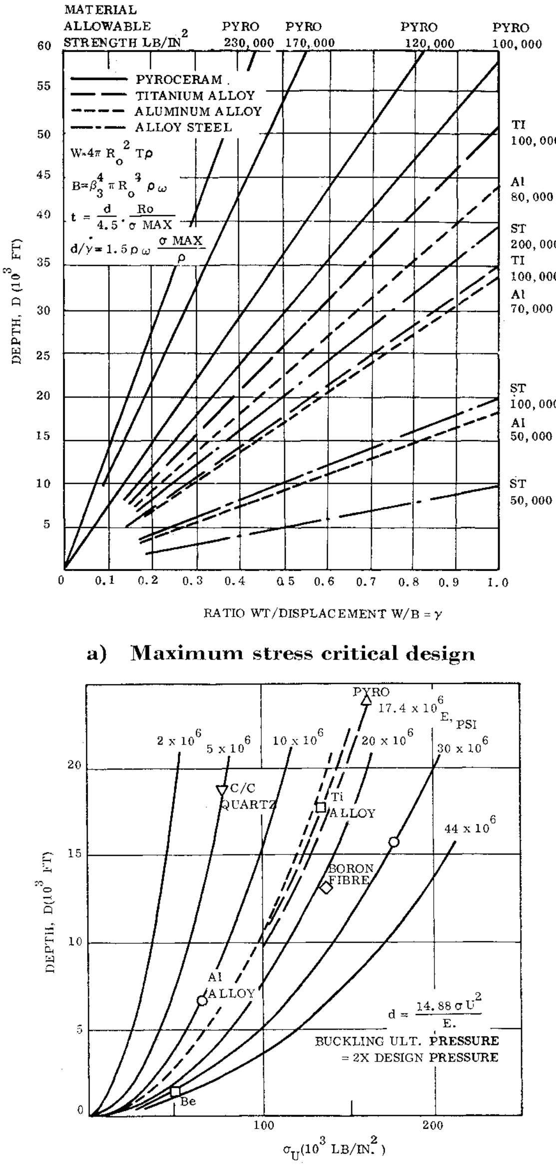


Fig. 5 Excess buoyancy ratio vs depth.



a) **Maximum stress critical design**

b) **Buckling critical design**

Fig. 6 Material capabilities of monolithic shells.

terials currently available and those that show future promise before final choice is made for a material suitable for a light-weight construction of the structure, either in single monolithic shell or composite structure, or even using composite materials to optimize properties of each material. In addition to conventional materials (such as steel and aluminum alloys), some of the newly developed materials (e.g., titanium, ceramic glass, reinforced ceramic materials) would be considered.

Table 4 Weight/buoyancy ratios for various constructions and materials[a]

Construction	Monocoque	Waffle	Honeycomb
Steel	1.08	1.15	0.96
Beryllium	0.73	1.07	0.73
Pyroceram*	0.42	0.30	(0.19)
Carbon coated quartz	0.66	0.67	0.54
Boron fiber	0.30	0.37	0.28
Aluminum alloy	0.96	2.22	...
Titanium alloy	0.78	0.89	...

[a] 12-ft internal diam, spherical hull; bouyancy of 25 tons (50,000 lb); operating depth, 12,000 ft.

From the material viewpoint also, a progression is noticeable from conventional materials to materials of higher strength-to-weight ratios, leading finally to materials, such as massive glass or ceramic, which combine extremely high compressive strength with low density. Certain composite materials with high-strength fibers such as glass, and boron fiber or whisker-fiber products, in conjunction with plastics or synthetic resins, show promising characteristics.

Desirable characteristics for a material for deep submergence application are

Properties: yield strength in compression; ultimate strength (compressive in particular), and directional variation; strength-to-weight ratio; modulus and modulus-to-weight ratio; compressive creep, static fatigue, compressive stress corrosion; ductility, brittleness, and embrittling—notch sensitivity, impact strength or, in general, toughness; coefficient of thermal expansion and thermal effects; and heat-transfer characteristics.

Performance: failure criteria and modes; onset of failure/crack and propagation rate; load cycling effects and fatigue strength; corrosivity and protectability; moisture diffusivity; reliability of material data; weldability and/or fabricability; manufacturing and quality control considerations; and cost and cost effectiveness. Properties of different types of materials are summarized in Table 5.

In addition to high compressive strength-to-weight ratio and resistance to marine corrosion, for safety requirements another critical consideration is the mode of failure. This is governed by the toughness or ductility, brittleness or embrittling, which in turn is indicated by both elongation and the yield-to-ultimate-strength ratio, in tension, of the material. For a less ductile material, and in particular for brittle materials such as ceramics and glass, and for some of the high-strength steels with low ultimate-to-yield-strength ratios and elongation, it would be necessary to design for working stresses well below material strength, i.e., for higher safety factors. Consequently, structural weight would be increased and excess buoyancy would be reduced without necessarily decreasing the probability of failure. The choice of such materials must, therefore, be made most judiciously and with sufficient data generated by exhaustive testing for material behavior and performance.

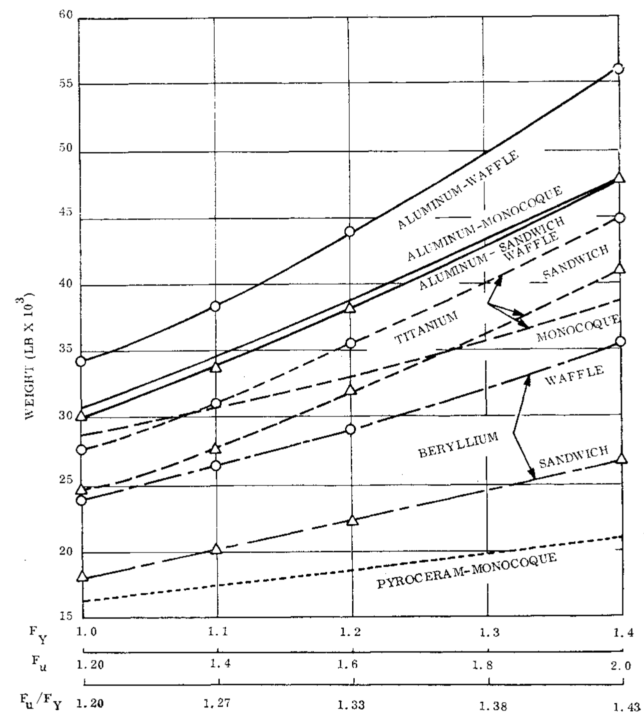


Fig. 7 Variation of hull weight with design factors.

Table 5 Material selection data

Material		Aluminum Alloy		Titanium Alloy		Stainless Steel		Beryllium Alloy	Nickel Alloy	Ceramic 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 6:1 at 1400°F	Rene 41	Pyroceram® 9606	Other Glass	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	.298	.094	.069	.067	.074	.075		
Yield Strength (Tensile)	$10^3\ lb/in^2$	64-56	36	126	135	100 150	200 / 240	64.5	130			58-85				
Yield Strength (Compression)	$10^3\ lb/in^2$	63-56	34	132	150	100 150	210 / 260		130	340 (ult.)	300	58.1	80	140	4000	
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	16.0	30	29.0 / 30.0	42	31.6	17.2			5	22		
Elongation	%	6-4	8	10	10		5/4	5.8	1.0							
Yield/ Ultimate (Tensile)	-	.877 .848	.75	.940	.931		.889 / .857	.772	.765			.684				
Yield/Density (Compression)	10^5 in	6.46-5.66	3.75	7.88	8.28		7.22	9.77	4.36	36.2 (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	63.6	10.6	18.3						
Poisson's Ratio	-	.33	.33			.3	.3			.24						
Notch Strength		Poor		Fair		V. Good	Good	V. Poor	Good	Poor		Good				Poor
Izod Strength																
Crack Propagation Rate		Moderate		Moderate		Slow		Rapid	Slow	Rapid		Moderate	Moderate	Moderate		-
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	10^{-6} in./in.°F	13.1	13.3	4.6	5.7		5 / 7.1 $\times 10^{-6}$	5.5		3.17		6.7				
Thermal Conductivity Coefficient	Btu/Hr ft °F	74	68	3.8	4		9 / 16.6	110		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						Good
Compressive Creep Resistance				Good		Excellent	Fair to Good		Fair	Fair						
Moisture Diffusion	$lb/ft^2/day$	-		-		-	-	-	-	-		$.9 \times 10^3$				
Availability in Heavy Sections		Good	Good	Fair	Fair	Good to Fair	Fair	Poor	Fair	Fair		Poor	Very Poor			Good
Cost/lb Low Med. High	$\leq\$1/\text{lb}$ $\$1\text{-}3/\text{lb}$ $\geq\$3/\text{lb}$	Medium	Medium	High	High	Low	Medium	V. High	High	Medium		Medium	Very High			Low

The phenomenon variously described as static fatigue, compressive creep, and stress corrosion is of some significance. A phased program of wide-scale testing is required to cover the parameters such as stress level, time, temperature, variation or cycling of stress level, corrosive environment, size and shape of specimen, and combined loading, e.g., flexure or shear combined with compression. Study of material behavior subsequent to the onset of failure is also necessary. This would define the interval available for rescue or surfacing and also, consequently, excess buoyancy requirements. The significant parameters in this respect are lower limit of yield stress for onset, rate of yield or crack propagation, local yielding or generalized yielding and transition from local to general yielding.

Structural Reliability Analysis

This can be defined alternately as safety estimation. Having conceived a structural configuration concept and chosen a suitable concept and material that is optimum from the viewpoint of design considerations, manufacture, cost, and effective operation (all of which considerations involve compromising or lowering of standards from those ideally desired), it is necessary to obtain the effect of these on the

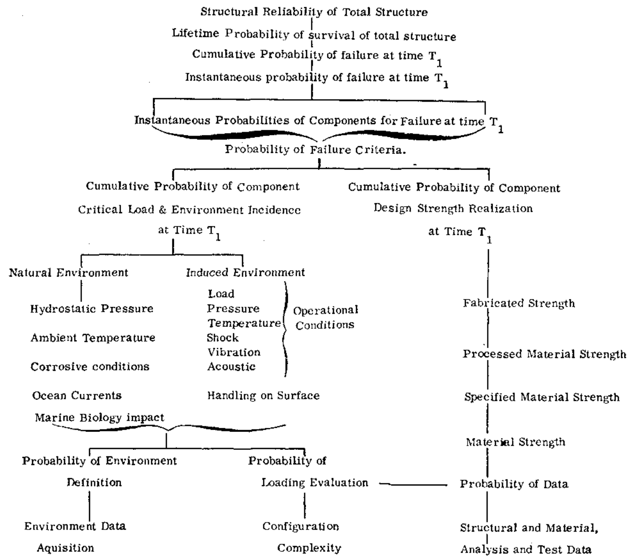


Fig. 8 Structural reliability analysis interrelation flow diagram.

integrity of the structure. Using analytical and computer techniques, a method is derived to estimate reliability of a structure or to predict probability of failure, taking into account parameters such as 1) structural configuration, components, and their complexity, 2) loading evaluation and accuracy, 3) material property data and quality assurance, 4) geometric and fabrication tolerances, and 5) failure criteria. A flow diagram (Fig. 8) details the interrelationship of these parameters. A comparison of estimated reliabilities of the matrix of structural shape, size, and construction would then indicate the optimized safe and reliable structure. The estimation must incorporate data obtained from tests of various types. Experimental techniques with regard both to ultimate failure testing and to nondestructive testing methods (such as brittle lacquer, photoelasticity, and strain gages) must be used to develop a structural test plan for both shell analysis and discontinuity analysis. Analysis is required (in addition to data obtained from already published material) to establish criteria for practical levels of geometric tolerances and their effect on reliability of structural integrity. These would include ovality and out-of-sphericity, local deformities, and surface and interface irregularities during manufacture and fabrication.

Catastrophic failure is defined as a failure progressing at too high a rate to permit evacuation of personnel after incipient failure detection. As a typical approach, reliability requirements for safety could be specified as follows. Probability of catastrophic failure shall be no greater than 1×10^{-4} for full system life; probability of noncatastrophic failure shall be no greater than 1×10^{-3}, and probability of repairable major structural failure shall be no greater than 10^{-2}. Margins of safety computed to demonstrate compliance with these requirements shall be based on theory of failure for the selected material. Computed results shall reflect experimentally determined numbers for both materials properties and fabricated structural failure. Three-sigma lower limits of property values can be used where singularly applicable; where combinations of properties influence performance, probabilistic combinations of 3σ limits shall be used only where there is a time or position randomness superposing on basic materials influence. Where such is not the case, worst 3σ combinations may be employed in demonstrating compliance with the requirement.

Spherical Modular Configuration

The preliminary survey[11] indicates that a spherical modular concept of not less than 10-ft diam is most advantageous at depths in the region of below 10,000 ft for manned habitat primarily intended for anchoring to the ocean floor and has the capability of adjoining with other modules, allowing for variations in available space and payload. The main advantage of the spherical module is that a single continuous integral structure can be obtained, except where access or joint hatches are required for two primary purposes (which are equally necessary for other configurations): 1) attachment of modules to provide continuity of structure and seal, with adjacent module or passageway, and for juncture between modules; 2) penetration for a hatch and transfer chamber to provide access for functions external to the module, and penetrations for functions and services shared with other modules. This gives a structure that is free of other joints, discontinuities, and associated stress-raisers and weak links, thus contributing to the structural system reliability.

A cylindrical configuration with spherical ends requires development of both techniques, whereas a spherical configuration needs only one. For other shapes with double curvature, not only analytical but also manufacturing problems become more complex. Structural components of a typical modular configuration (shown in Fig. 3b) include a basic hull shell and a passageway shell with a juncture ring between, a hatch cover, and, hatch and penetrant reinforcements.

Engineering Analysis of Selected Structural Design Configuration

The objective of the analysis is to explore, delineate, and effect proper structural design of the shell, taking into account various parameters for structural integrity. The prototype will be designed for various requirements of a mission and must be capable of withstanding, in addition to pressure effect, the handling or maneuvering and anticipated operating load conditions typical for a bottom-fixed manned habitat:

1) When both the shell and junction passageway are subjected to external pressure.

2) When the passageway is flooded and shell only is subjected to pressure.

3) Transition from 1 to 2 and vice versa.

4) Anchoring loads to include dynamic effects due to ocean bottom current, ocean floor/sediment disturbances, impact during transfer from other submersible vehicles, impact of ocean creatures, debris, etc, and shock consideration.

5) Handling on surface during submergence with no external pressure, resting on flat surface, and resting on wave crest.

6) Residual stresses due to temperature changes between fabrication and operating conditions.

The approach will be characteristically iterative. First, the candidate configuration will be analyzed according to basic shell theory to limit generalized shell stresses to 75% yield stress, with capability for resistance to buckling at a collapse depth of, say, 1.5 times the operating depth, coarse consideration being given to discontinuity stresses due to shell junctures, hull penetrations, and hatches. Secondly, discontinuity stresses will be evaluated in detail using computer programs to minimize ring strain, ring roll, and deflections relative to membrane due to loading, including asymmetric loads, based on analyses similar to Refs. 1 and 6. Effect of initial imperfections and residual stresses on collapse strength would also be minimized.[2] Ring reinforcing for penetrations would be designed to keep the stress concentrations to minimum, and to eliminate strains and moments relative to the shell.[3] Structural design of any hatches would be accomplished by methods similar to Ref. 4, such that there are no large relative deflections between hatch and hatch-juncture ring which would affect sealing. Analysis must also take into account secondary structural requirements such as exterior and interior impact shields, sealing, and corrosion protection. Finally, using experimental techniques (such as photoelastic and brittle lacquer models for nondestructive testing and strain-gaging for ultimate-failure tests), appropriate physical models of the promising configurations and assembled model structures will be tested under critical loading conditions to qualify the design and to obtain experimental coefficients to verify analytical methods.

The structural concepts and configurations would be reviewed for their characteristic response to dynamic effects due to ocean current, impact, and shock, as well as random and acoustic vibratory excitations. The analysis would be carried out to ascertain that there are no adverse effects on structural integrity of the hull.

Subsystem Correlation

Subsystems to be studied in relation to hull structure are impact protection, foundation, and anchoring. Others having secondary bearing on safety are power and distribution, environmental control, communications, life support, and surface and external support. These must be accounted for by providing sufficient redundancy margin. Effective sealing is also most critical for safety.

Fail-Safe Design

From the safety consideration, it is vital to ascertain that, in case of load and environmental conditions causing stress levels where failure would initiate, the failure would occur progressively and not catastrophically. This would require both structural and materials considerations, such as whether the failure is due to lack of strength or to stability and stiffness, as well as whether either the crack or fracture is propagated throughout the material. The safety factors could be reduced without reducing safety if a fail-safe design is considered, allowing for either redundancy of a structure or a mode of failure that is not catastrophic. Methods of achieving these under the arduous conditions of deep ocean environment must be investigated.

One of the methods is redundancy of load paths, with each path capable of resisting the operating load with the alternate or multiple paths together capable of providing integrity under ultimate load conditions. Application of this principle to a monolithic hull can be achieved in two ways: 1) by using a double shell design, as, for instance, in the case of a sandwich core construction, with each wall capable of resisting the operating pressure to its full yield strength while the two walls together are capable of the ultimate strength required for the shell; or 2) by using a stiffened wall design, with some of the shell loading transfered to stiffeners when yielding occurs, and with the stiffener and skin combination capable of resisting ultimate loading. Other approaches based on preventing progressive failure and redistribution of loads when initial failure occurs, so that complete or catastrophic failure is delayed, include plasticity considerations, postbuckling strength estimation, and crack stoppers.

Safe-Life Design

"Safe-life" considerations would allow further reduction in safety factors. Loading, temperature and dynamic effects, material performance, and behavior must be investigated to estimate their effect on the safe life of the structure. For a bottom-fixed manned habitat, the cycling of loads and stresses is limited. However, the effect of the compressive creep or static fatigue phenomenon discussed earlier must be accounted for in establishing safe life of the hull, for maximum duration on the ocean floor as well as for safe number of submersions. The effect of rate of unloading of the shell during surfacing must also be considered, as well as the loads due to thermal effects and residual stresses.

Malfunction Monitors

Finally, the structural design must provide for monitoring the behavior of the structure during its operational life, so as to gage constantly the state of the hull and to verify the behavior against that conceived by the design. The monitors should be able to give an indication of onset of any failure or to provide data that would enable prediction of the future behavior of the structure. This is particularly essential as inspection of the hull on the ocean surface must, of necessity, be limited, both in frequency and scope. Some methods of achieving monitoring are load cells, strain gage coupons, crack detectors, photo stress coupons, sonic methods,[8] and seal failure detectors.

Conclusions

To achieve maximum safety in a bottom-fixed, deep-submergence manned habitat, a self-buoyant system is desirable for utmost reliability. By mapping a parametric study, it is possible to choose an optimum structural configuration in shape, size, and weight for given operational mission requirements, the operating depth, and environment. Judicious choice of suitable structural concepts and materials must be made, so as to combine minimum weight with high reliability and to exclude catastrophic failure. Safety and reliability can be obtained without necessarily resorting to higher safety margins. Approaches to structural design, such as fail-safe and safe-life, methods of analysis of shells and discontinuities, and use of computer techniques currently familiar in the aerospace technology can be successfully applied to oceanic systems, in spite of differences in extremes of loading and environment.

At increasing depths, a spherical modular concept is evolved as the most suitable optimum structure for a bottom-fixed habitat. Such a conceptual design for manned fixed habitat represented by the General Electric Company's "Project Bottom Fix," is shown in Fig. 3. For this concept, the structural components become less complex, and developmental problems are reduced to a minimum. From material considerations, there is still need for generating data on environmental conditions to which materials would be subjected and—of even more importance—on behavior and performance of the materials subject to these environments. In particular, areas such as compressive creep/static fatigue, onset and propagation of failure, and postfailure behavior require concentrated and exhaustive efforts by testing methods, before some of the promising materials can be applied successfully to deep ocean manned habitats.

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