32) Over-all loss coefficient
33) Darcy-Weisbach skin-friction coefficient (for given skin roughness and duct size)
34) Inlet-scoop cavitation margin at the takeoff-drag-hump, specified thrust condition

Outlet system parameters

35) "Equivalent" hydraulic radius (for skin-friction calculations)
36) Darcy-Weisbach skin-friction coefficient (for given skin roughness and duct size)
37) Velocity ratio at the "equivalent" section
38) Over-all loss coefficient (including elevation head loss)
39) Weight of outlet duct plus contained water in inlet and outlet systems above flying water line

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Pressure Hulls for Deep-Submergence Vehicles

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Deep-submergence vehicles should be small, highly maneuverable, and have high payload capacity. To attain these objectives, the pressure hulls for the vehicles must be the lightest possible structures that can withstand the pressures at operating depths. The efficiency of materials used in pressure hulls is expressed in terms of weight/displacement for a particular structure. Therefore, light, strong materials are at a premium. In addition, hull materials must be state-of-the-art, and stable in the marine environment. For moderate depths of about 6000 ft, tough, fail-safe metals such as HY 140 steel appear satisfactory. To achieve intermediate depth capabilities to 12,000 ft, higher strength metals such as the 18% nickel maraging steel or the titanium-6% aluminum $2\frac{1}{2}$% molybdenum are required. Some of these materials cannot meet the charpy impact or drop weight tear test criteria. For these materials, other toughness approaches, such as fracture mechanics, must be utilized. For the great depths, down to 20,000 ft, high-strength steels or titanium alloys, or nonmetallics such as glass, either in the solid or fiber form, can be utilized. To insure reliability with the latter materials, it will be necessary to develop proof-testing procedures. Two types of vehicles are planned for the Deep Submergence Systems Project—a 6000 ft rescue vehicle and a 20,000-ft search vehicle, to be operable by 1968 and 1970, respectively. The pressure hull for the 6000-ft rescue prototype will be fabricated from HY 140 steel. Advanced material technology will be required for the 20,000-ft pressure hull. The present concept calls for a manned metal capsule with buoyancy supplied by simple floatation spheres of glass or ceramics.

THE great depths of the ocean have been penetrated by large, relatively immobile submersibles known as bathyscaphs. In 1960, Trieste I reached the floor of the Challenger Deep, 35,800 ft down. To explore the depths fully, submersibles must have, in addition to depth capability, the mobility to explore and survey extended areas at a reasonable speed and the ability to perform useful work on the ocean bottom. It is intended that the new submersibles have these characteristics.

The bathyscaph is heavy and cumbersome because of its large buoyancy chamber. Trieste II carries 47,000 gal of gasoline in its float tanks. Since the compressibility of gasoline is significantly greater than that of seawater, a large amount of expendable ballast must be carried to maintain neutral buoyancy. For each 3000 ft of dive, 2000 lb of shot must be dropped. The over-all displacement of Trieste II is 220 tons.

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The pressure hull of Trieste II is a 7-ft-diam steel sphere that is heavier than the water it displaces by a factor of 2. The principal function of the pressure hull in the Trieste is to provide hotel space for the crew and control equipment. The vehicle size may be reduced considerably if the pressure hull, in addition to hotel space, provides buoyancy. Alvin is an example of the latter type of vehicle. The pressure hull of Alvin is a 7-ft steel sphere that displaces about 1.4 times its own weight of water and contributes substantially to the buoyancy requirements of the vehicle. The Alvin displaces about 15 tons over-all. It is a relatively shallow vehicle, with a 6000-ft operating depth, but it is hoped that the buoyant hull principle can be extended to great depths.

Consideration of power requirements, maneuverability, and surface support lends weight to the desirability of small, deep submersibles. In addition, mission constraints may impose limitations upon vehicle size and weight. In the Deep Submergence Systems Project, there is a requirement for a rescue vehicle that can be transported in a C141 aircraft. Hence, the following vehicle characteristics were established: size: 44 ft long, 8-ft diam; weight: approx. 25 tons in air; depth: 6000 ft; speed: 5 knots max, 3 knots for 12 hr; personnel:

Table 1 Sizing the rescue vehicle

	Weight, lb	Displacement, lb
Vehicle	50,000	50,000
External hull, machinery, payload	38,000	20,000
Pressure hull	12,000	30,000

3 crew and 12 rescuees. The buoyancy requirements for the pressure hull were approximated from the over-all vehicle weight and the known weights and densities of the non-pressure structure, as shown in Table 1. The more buoyancy (*D-W*) required for a given hull configuration, the lighter and/or stronger the material must be and the more difficult the material problems become.

On the basis of a weight-displacement ratio of 0.4, materials that appeared suitable included maraging steel, a titanium alloy, and an aluminum alloy. In addition to weight displacement, materials had to be available, fabricable, tough, and permanent in the marine environment. The results of a material survey carried out at the David Taylor Model Basin are listed in Table 2.

The titanium 721 alloy was tentatively selected as the pressure hull material, even though there was some doubt as to its stress corrosion properties. The doubts arose from the results of the precracked cantilever test at the Naval Research Laboratory.[1] Subsequent tests at the Naval Applied Science Laboratory on full-size welded hull plate confirmed the results of the precracked cantilever test. Additional tests were scheduled to determine the effect of stress relief and removal of the weld bead. The plates were 22 in. square by 1 in. thick, welded by the metal inert process and tested by a combination of static loading and cycling in a sea-water environment. The nominal stress at the toe of the weld was 80,000 psi. Test data appear in Table 3.

The test data indicate that the weld bead was in fact acting as a stress raiser, and removal of the bead appreciably increased corrosion fatigue life. Stress relief apparently had no effect.

A number of remedies are applicable here. First, the design should minimize tensile stresses; second, all stress raisers such as weld beads should be removed; and third, the structure must be examined periodically during service life to discover flaws that could cause failure. From today's vantage point, the Ti 721 alloy appears suitable for use, provided these precautions are taken. However, at the time the weakness was disclosed, the remedies were not apparent and another material was selected. Since no other titanium alloy was available and maraging steels were not completely proven, the HY 140 steel was selected. The HY 140 steel pressure hull has a weight-displacement ratio somewhat greater than that required for the deep-submergence rescue vehicle

Table 2 Material survey for the rescue vehicle

W/D	Material	Compressive yield strength, ksi	Shell thickness, 8-ft sphere, in.	Maturity[a]
0.5 to 0.4	HY 150	140	1	4, 4, 4, 3, 3
	Maraging steel	180	1	4, 3, 2, 2, 2
0.4 to 0.3	Titanium (721)	110	$1\frac{1}{4}$	4.3.4, ?, 3
0.3 to 0.2	Aluminum (7079-T6)	60	$1\frac{3}{4}$	4, 4, 1, 0, 0
	GRP	60	$1\frac{3}{4}$	2, 2, 2, 1, —

[a] Maturity equals designability, producibility, toughness, permanence, weldability as of January 1, 1966; 4-excellent, 3-good, 2-fair, 1-poor, 0-none.

Table 3 Titanium stress cracking data

Condition	Prior to cracking hrs. static load	No. fatigue cycles to initiate crack	Min. static load to failure
1a) Weld bead intact	0	0	16.8
1b) Stress relieved	0	0	11.5
2a) Weld bead removed	88	8,890	165
2b) Stress relieved	72	5,267	70
3) Base plate	108	16,530	120

(DSRV) at 6000-ft operating depth. Therefore, the depth requirement was compromised. The operating depth was set at 3500-ft minimum with the HY 140 steel hull. It is anticipated that some of the depth will be recovered by precise control of the pressure hull contours during fabrication. Work at the David Taylor Model Basin has shown that the collapse strength of a spherical shell is based on local out of roundness rather than nominal geometry (Fig. 1). An increase in out of roundness from $\frac{1}{16}$ to $\frac{1}{8}$ in. in a critical arc length of 18 in. results in a 1000-ft loss of depth capability.

After it was discovered that the Ti 721 alloy was susceptible to stress corrosion, attempts were made at the Marine Engineering Laboratory to improve its resistance by altering composition. The sensitivity was believed to be related to the Ti-Al ordering reaction and was dependent upon aluminum content, isomorphous beta stabilizer content, and thermal history. A new composition was developed, which, in fact, was insensitive to stress corrosion, and had equivalent mechanical properties, as shown in Table 4.

Other titanium alloys that show promise are Ti-7Al-2$\frac{1}{2}$% Mo and Ti-6Al-4V at the 120,000-psi yield strength level. Steels of interest in the 180,000 to 200,000-psi yield range include the maraging steels and the 9-4-0.25 alloy. These metals are presently being proved out at Navy laboratories.

An impressive number of undersea research vehicles are in operation today or will be in operation shortly.[2] The vehicles range from the Aluminaut with a design operating depth of 15,000 ft to the Yomiuri, a Japanese submersible with a 1000-ft capability. Pressure hull materials vary from mild steel in the Soucoup to HY 200 maraging steel in the Deep Quest. The hull materials for the most part are extremely tough metals such as HY 80 and HY 100. These metals satisfy the requirements of the fracture-safe philosophy, i.e., the material can deform plastically in the presence of a through-the-thickness crack without catastrophic crack propagation and failure. The latter capability is demonstrated in the

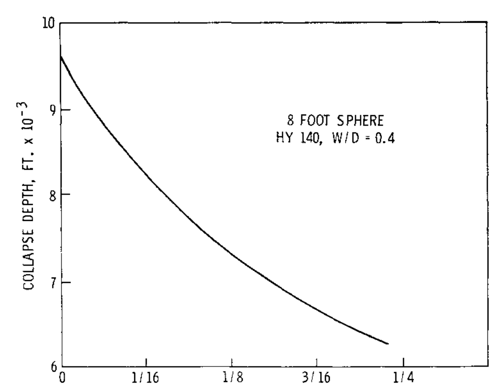

Fig. 1 Effect of out of roundness upon collapse depth of 8-ft sphere of HY 140 steel.

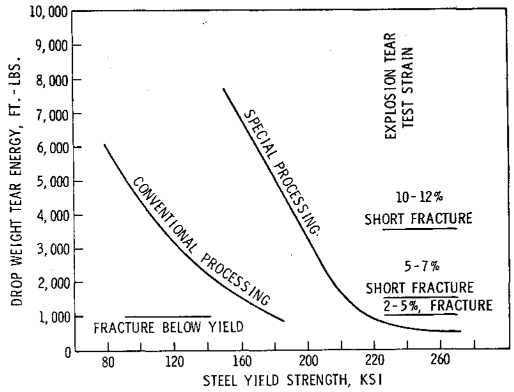

Fig. 2 Variation of drop weight tear energy with yield strength of high-strength steels.

Naval Research Laboratory explosion tear test and correlated with the drop weight tear test.

Figure 2 shows a spectrum of drop weight tear test data for high-strength steels plotted as a function of yield strength. The plastic strain overloads for fracture propagation in the explosion tear test are correlated with the drop weight tear test energy levels. The pressure hull materials for the Alvin and the Deep Star (HY 100, HY 80) fall into the area of 5 to 7% plastic strain in the explosion tear test and 2000–3000 ft-lb in the drop weight tear test. Large amounts of plastic strain overloads are considered necessary for deep-diving combatant submarines, but may be excessive for deep-submergence search and rescue vehicles. A figure of 1–2% plastic strain has been suggested for the latter.

The materials in the Aluminaut and Deep Quest do not exhibit the toughness characteristics demonstrated by the HY-80-type steels. At best, they exhibit limited plastic flow, possibly up to 2% prior to fracture. The pressure hull of the Aluminaut consists of a series of heavy forged rings of 7079-T6 aluminum, bolted together to form the cylindrical section, with spherical end caps. The design prevents the development of tensile stresses in the hull sections, and prevents the growth of cracks, if any. However, the bolted design is not adaptable to the complex, deep-submergence hull, which is best suited to a welded fabrication. The Deep Quest hull is fabricated from vacuum-melted HY 200 maraging steel, which may be somewhat tougher than the air-melted grade.

Although the toughness properties in Fig. 2 improved with special processing, such as vacuum melting, the diagram demonstrates a sharp decrease in toughness with increased strength. Above the 200,000-psi yield level, fracture will propagate under essentially elastic stresses. It is possible to utilize fracture-safe metals for buoyant hulls to depths of around 6000 to 9000 ft. Beyond this, for a limited depth span, the high-strength, relatively brittle metals can be used, provided that new toughness standards can be developed. In the case of the high-strength metals, fracture mechanics offers a solution.

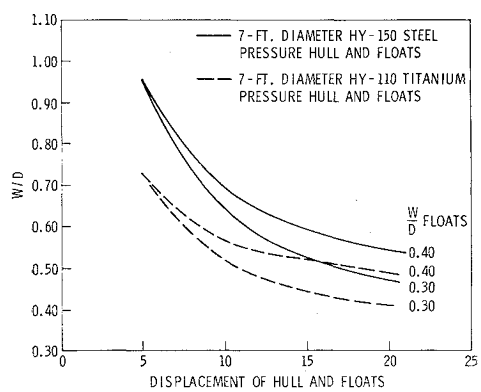

Fig. 3 Effect of floats upon pressure hull buoyancy and displacement.

Table 4 Mechanical properties of Ti 721 and Ti 621 + 0.8 Mo, metal-intert-gas welded

	Ti 721	Ti 621 + 0.8 Mo
Tensile strength	121,000 psi	122,000 psi
Yield strength	106,000 psi	106,000 psi
Elongation	10%	9.5%
Reduction of area	25%	26%
Charpy V-32°F	35 ft-lb	46 ft-lb
Drop weight tear test, 32°F	3000 ft-lb	2100 ft-lb

In the Polaris program, fracture mechanics helped in the development of high-strength, high-reliability motor cases fabricated from AMS 6434 steel at the 200,000-psi yield strength level.[3] A means of determining toughness was provided, and of relating flaw size to working stress. A table of data (Table 5) has been worked out for the Ti 721 alloy, based upon the stress corrosion intensity parameter of Kiscc.[1]

The intermediate depths such as 12,000 to 15,000 ft theoretically can be reached with pressure hulls fabricated from ultra-high-strength steels or titanium alloys with a W/D of 0.5 or less. However, at 20,000 ft, the W/D factor of hulls fabricated from the same materials varies between 0.6 and 1.

The Deep Submergence Systems Program has a requirement for a deep search vehicle, with the following preliminary characteristics: size: 10 by 30 ft; weight: 25 tons in air; depth: 20,000 ft; speed: 5 knots max, 3 knots for 10 hr; crew: 2 plus 2 relief or observers. For a vehicle to operate at 20,000 ft, under a weight limitation of 50,000 lb, the pressure hull must have a weight displacement of 0.5 maximum. The only materials that meet this 0.5 maximum requirement are fiberglass-reinforced plastic, glass, and alumina. A survey of materials for the search vehicle appears in Table 6.

The development of pressure hulls with hatches and penetrations from these brittle materials is a formidable job that will require considerable effort. The first application of these materials, therefore, will probably be as simple flotation spheres. In conjunction with a heavy, metallic pressure hull, they can reduce weight displacement and over-all weight to acceptable levels. The effect of nonmetallic floats upon these parameters is illustrated in Fig. 3.

Although fiberglass-reinforced plastic has been successfully used as the structural material in the Polaris motor case program (and others), its application to pressure hulls, even in the form of simple spheres, presents problems. Tests on 6-in. spheres fabricated by the H. I. Thompson Company have yielded satisfactory collapse pressures at a W/D of 0.5, but showed a lack of fatigue strength. These results are presented in Table 7.

The fatigue test confirmed earlier data on 6-in. cylinders furnished by the Illinois Institute of Technology Research Institute. The mechanism of fatigue failure in biaxially stressed, fiberglass-reinforced plastic appears similar to that observed in metals, i.e., the development and growth of microstructural defects that progressively weaken the composite until failure occurs. The defects are believed to be interlaminar in nature. Improved design, fabrication techniques,

Table 5 Data for Ti 721 alloy

Critical flaw depth ($L \gg D$), in.	Working stress, psi
0.45	26,000
0.11	52,000
0.05	78,000
0.02	105,000

Table 6 Material survey for the search vehicle

W/D	Material	Compressive yield strength, ksi	Shell thickness, 8-ft sphere, in.	Maturity[a]
0.6 to 0.5	Titanium	180	$2\frac{1}{8}$	4, 1, 2, 2, 1
0.5	Fiberglass-reinforced plastic (GRP)	75	$4\frac{1}{2}$	3–2, 2, 2, 2, —
0.5 to 0.2	Fiberglass-reinforced plastic (GRP)	100	3	3–2, 1, 2, 1, —
	Glass	150	$2\frac{1}{4}$	2, 2, 1, 3, 2
	Alumina	300	$1\frac{1}{4}$	2, 2, 1, 3, 1

[a] Maturity equals designability, producibility, toughness, permanence, weldability, as of June 1, 1968; 4-excellent, 3-good, 2-fair, 1-poor, 0-none.

and matrix materials (stronger and stiffer resins) may improve fatigue life.

Another interesting material in the composite family is edge-oriented fiberglass, developed by the U.S. Rubber Company. Spheres are fabricated from mosaic blocks of fiberglass with the fibers oriented in the radial direction. The blocks are cut from cured unidirectional plates prepared from prepreg tape (MMM 1009-265). The cut blocks are placed in a hemispherical mold, impregnated with resin, and cured. Two hemispheres are then bonded together with epoxy cement to form a sphere. All spheres had thin resin coatings (0.020 in.) on the exterior. Test results are listed in Table 8.

The cracks are believed due to process variables, i.e., cure temperature and pressure. In spite of the cracks, performance of this material to date has been very promising. Additional tests will be carried out to determine the effects of scale up, the resin coating, permanence in the marine environment, and protection from impact.

As with fiberglass-reinforced plastic, the technological aspects of structural glass are rated fair to poor. Because glass is almost perfectly elastic, i.e., completely brittle, one faces formidable problems in design, fabrication, and testing. Although the theoretical strength of glass is on the order of 1,000,000 psi, the tensile strength of massive glass is very low. This apparently contradictory situation is believed to be due to flaws on the surface of the glass which effectively reduces its strength. Surface removal experiments by Proctor of Rolls Royce[4] have confirmed the surface flaw theory. The removal of 0.03 cm from the surface of soda-glass rods 6–8 mm in diameter increased the tensile strength from 12,000 psi to over 400,000 psi (Fig. 4). In order to retain the strength, the pristine surface must be carefully protected. Another technique for increasing the tensile strength of glass is to place the surface in compression by chill-tempering or by an ion-exchange process. In this way, the material can withstand tensile loading, the amount depending upon the process and depth of the surface layer.

Today's methods of fabricating glass spheres from hemispheres are fairly crude. The David Taylor Model Basin made a study of the collapse strength of 38 10-in.-diam spheres, formed by fusion-welding hemispheres of Corning 7740 glass. The data are plotted in Fig. 5 as percentage of the spheres which failed above the indicated depth and stress. The maximum and minimum stresses at collapse were 203,000 and 83,000 psi, respectively. The scatter in test results was 2.5, which is attributed principally to joint strength variations, mismatch, and flaking of the weld bead.

Table 7 Test results on 6-in. fiberglass spheres

No.	W/D	Failure pressure	Remarks
1	0.504	11,000 psi	Titanium bosses
2	0.526	12,000 psi	Filament build up at poles
3	0.495	13,500 psi	Improved #2
4	0.495	14 cycles at 8900 psi	Like #3

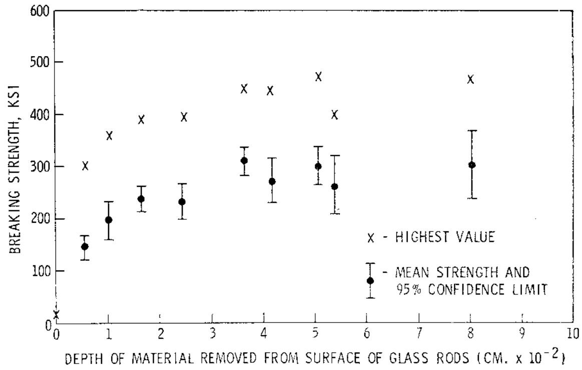

Fig. 4 Improvement in strength of soda-glass rods by surface etching.

A limited number of tests has been conducted on 10-in. alumina spheres, fabricated by the ceramic technique by the Coors Porcelain Company. The results, listed in Table 9, show high strength and little scatter. However, six of the eight spheres failed at constant pressure. The first four spheres were one piece. The last four were butted hemispheres.

Alumina has considerable potential on a strength-weight basis, but more testing is required to determine its fatigue strength and corrosion resistance, and firmly establish strength characteristics. The use of alumina, as in the case of glass, depends upon the successful application of a proof test. The problem is how to test a brittle material in order to guarantee reliability in the finished product. This problem is under investigation at the Naval Research Laboratory. One approach is described below.

Proof-Test Procedure for Brittle Materials

The procedure is as follows: 1) test simple specimens at proof pressure (greater than service pressure); 2) test survivors of 1 at service pressure for N cycles; 3) determine strength of survivors; 4) subject small numbers of structures to 1, 2, and 3. The proof test is designed to eliminate those samples containing flaws that can cause failure during subsequent service life. The behavior of the survivors of the proof test depends on the stress level and the rate of flaw growth in the subsequent cyclic testing phases. After N cycles, the survivors should have a strength equal to the service stress plus the factor of safety, with a high confidence level.

In view of the difficulties involved in developing high-reliability flotation spheres from glass, ceramics, or fiberglass, it is prudent to consider an alternate buoyancy material, syntactic foam. Syntactic foam is a suspension of hollow glass microspheres in an epoxy resin. The spheres vary in diameter from 22 to 68 μ. The spheres and resin are mixed and cured in simple shapes that can be machined to fit into

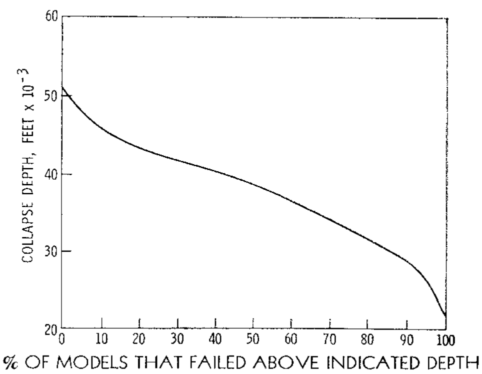

Fig. 5 Collapse behavior of 10-in. glass spheres.

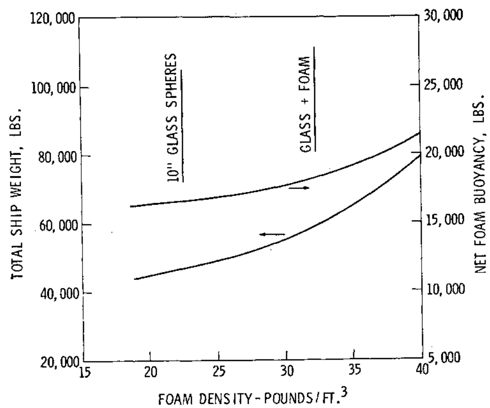

Fig. 6 Effect of foam density upon vehicle weight.

convenient spaces between the pressure hull and outer hull. The cured blocks must withstand static and cyclic exposure to pressure without loss of strength or water absorption.

In the Alvin, syntactic foam weighing 43 lb/ft^3 (W/D of 0.7) was used for supplementary buoyancy. By means of tight quality control, the density was reduced to 37 lb/ft^3 in the Deep Quest, for approximately the same depth range. For increased depths (to 20,000 ft) it is anticipated that the higher density foams of the present materials on the order of 40 lb/ft^3 will be required to resist the increased pressures. One way to attain lighter density foams for the great depths is to combine macrospheres with syntactic foam. Macrospheres of various diameters are under consideration.

Table 8 Test results on edge-oriented fiberglass spheres

Diameter, in.	W/D	Pressure, psi	Medium	Remarks
3	0.50	25,500 (c)[a]	Oil	Fatigued 5000 × at 8900 psi
3	0.50	25,000	Oil	Cracks in structure
11	0.39	20,500	Salt water	Hairline cracks
11	0.39	11,550	Oil	Held 20 hr

[a] (c)-Collapse. No collapse in others.

Table 9 Test results for 10-in.-diam alumina spherical shells

Weight to displacement ratio	Collapse depth, ft	Average stress in shell at collapse, psi
0.23	28,100	300,000
0.24	24,800	260,000
0.26	31,500	300,000
0.28	33,800	300,000
0.21	21,400	240,000
0.22	21,200	210,000
0.25	28,000	270,000
0.26	27,100	250,000

The effect of foam density upon total vehicle weight is shown in Fig. 6. With a 40-lb foam, a total ship weight of 80,000 lb results, assuming a 7-ft pressure hull sphere, with a W/D of 0.8. Of the total ship weight, about 40% or 30,000 lb is syntactic foam. If the foam density can be reduced by the addition of macrospheres to 32 lb/ft^3, the ship weight is reduced to 60,000 lb. With 10-in. glass buoyancy spheres, the weight falls below 50,000 lb.

In summary, the most important aspect of the development of underwater vehicles to explore the great depths is the achievement of a high-strength, low-density pressure hull, or buoyancy material. The attainment of this goal requires the use of new structural materials such as glass and ceramics. The use of these new materials poses challenging problems ranging from design to reliability testing.

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