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AN EXPLORATORY STUDY OF THE FEASIBILITY OF GLASS AND CERAMIC PRESSURE VESSELS FOR NAVAL APPLICATIONS

by

Thomas J. Kiernan

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AN EXPLORATORY STUDY OF THE FEASIBILITY OF GLASS AND CERAMIC PRESSURE VESSELS FOR NAVAL APPLICATIONS

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ABSTRACT

An exploratory study was conducted to determine the feasibility of using glass and ceramic materials for deep-submergence pressure hulls. In general, the study confirmed the potential use of these materials in pressure hulls capable of withstanding pressures at the deepest part of the ocean with very little structural weight. However, the study also showed that very little is known about the behavior of glass and ceramic structures under high-compressive loading and that a great deal of basic data must be generated before this potential can be achieved. The use of simple spheres of glass and ceramic materials for providing buoyancy is considered to be the most promising near-future application.

ADMINISTRATIVE INFORMATION

The work described in this report was sponsored by the Special Projects Office under Subproject S-F013 01 02, Task 0222.

INTRODUCTION

The need for materials with high strength-to-weight ratios for possible use in structures at deep depth is becoming more and more important. As pressure hulls are required to withstand increasing hydrostatic pressures, the hull structure becomes heavier, and the percentage of the hull displacement that is available to perform some job or mission decreases. For some materials and depths, the pressure hull and payload become negatively buoyant. Such hulls require the use of external flotation devices which restrict mobility.

The Navy has been conducting extensive materials programs to meet this need. High-strength steels, titanium, and fiber-reinforced plastics are being investigated and developed for deep-submergence hulls. However, even some of these materials have limitations for near-future applications. For example, the most optimistic of materials forecasts from these programs indicates that the metallic pressure hulls for the Search Vehicle in the Deep Submergence Systems Project (DSSP) will be too heavy to be air transportable unless a lightweight flotation system is developed. In addition to those materials which are being studied in the programs mentioned, other materials exhibit extremely high ratios of compressive strength to weight--namely, massive glass, glass ceramics, and ceramics.

Under the sponsorship of the Special Projects Office, the Naval Ordnance Laboratory (NOL) and the David Taylor Model Basin conducted an exploratory investigation of the problems associated with the use of glass and ceramics in practical naval pressure vessels. NOL was responsible for the material aspects of the problem, depth-hardening effects, fabrication problems, and the use of shock-mitigating materials. The structural problems associated with the use of glass and ceramics were studied by the Model Basin and the results are presented and discussed in this report.

THE POTENTIAL

The compressive strength of monolithic glass-shell structures under external hydrostatic pressure was first demonstrated by Bridgman.[1] By subjecting glass cylinders with about a 3-to-1 ratio of external-to-internal radius to pressures of 400,000 psi, he achieved calculated compressive stress levels of 800,000 psi without fracture. Krenzke and Charles[2,3] at the Model Basin demonstrated that the collapse strength of unstiffened glass cylinders and hemispheres could be predicted by elastic theory even though the stresses in the shells were in excess of 300,000 psi. This strength combined with the low density makes glass attractive in paper studies as a potential material for deep-depth pressure hulls. In addition to glass, glass ceramics and ceramics also exhibit extremely high ratios of compressive strength to weight.

The potential of glass, glass ceramic, and ceramic materials for deep depth is illustrated in Figure 1. The configuration chosen for the illustration is the near-perfect sphere. The elastic buckling strength of this structure may be predicted by

$$\text{Collapse Depth} = 0.7 \times \frac{2E\left(\frac{h}{R_o}\right)^2}{\sqrt{3\,(1 - \nu^2)}} \times 2.25 \qquad [1]$$

[1]References are listed on page 26.

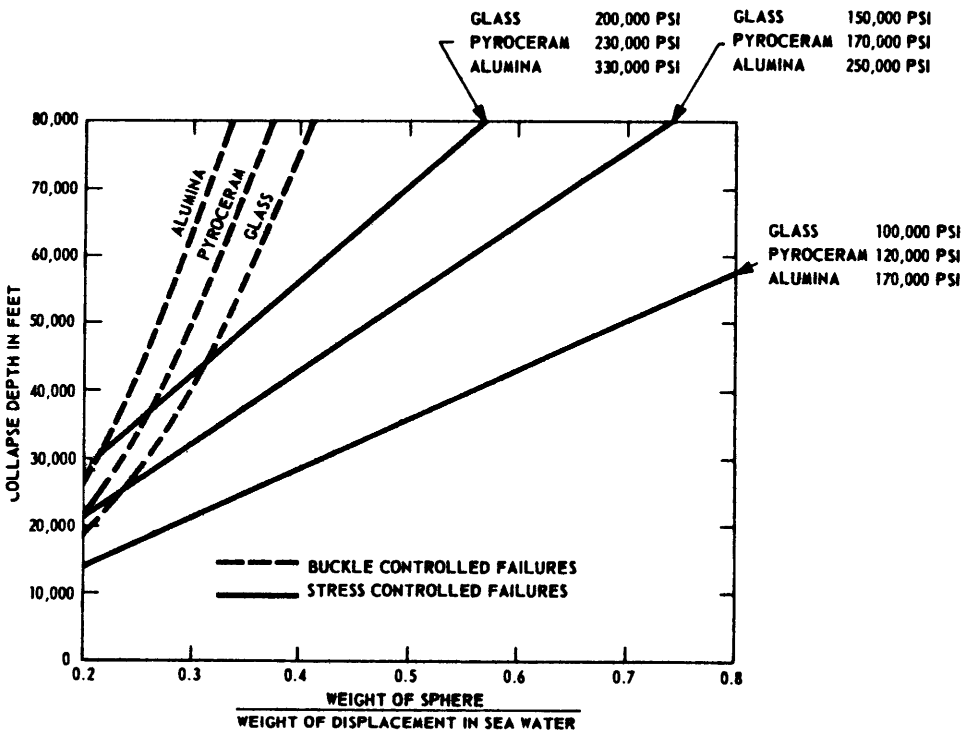


Figure 1 - Weight-Displacement Ratio versus Collapse Depth for Near-Perfect Spheres

where 0.7 is an empirical correction to the classical theory (this coefficient has been shown to predict the reliable strength of near-perfect spheres[4,5]),

$\dfrac{2E\left(\frac{h}{R_o}\right)^2}{\sqrt{3(1-\nu^2)}}$ is Zoelly's classical small deflection pressure for spheres,

E is Young's modulus,

h is the thickness of the sphere,

R_o is the outside radius of the sphere (in Zoelly's equation, the radius used is that to the midsurface of the shell),

ν is Poisson's ratio, and

2.25 is the conversion factor for changing pressure in pounds per square inch to depth in salt water.

The near-perfect sphere is defined as one in which initial deviations from sphericity are less than 2 to 3 percent of a shell thickness. When initial deviations exceed this value, the local radius R_{1_0} over a critical arc length[6] must be substituted for R_{1_o} in Equation [1].

The ordinate in Figure 1 is the collapse depth in feet, and the abscissa is the ratio of the structural weight of the sphere to the displacement of the sphere. The three dashed lines represent the depths which can be achieved with glass, Pyroceram, and alumina spheres of various weight-to-displacement ratios as determined by Equation [1]. Experimental verification of the curve for the glass sphere can be made to depths of 100,000 ft from the data presented in Reference 3, if corrections are made for the imperfections present in the test specimens. The three dashed lines represent buckle-controlled failures and even at collapse depths of 80,000 ft, the maximum stresses in the shell would be 270,000 psi for the glass sphere, 360,000 psi for the Pyroceram sphere, and 590,000 psi for the alumina sphere. It is apparent from the depths and stress levels indicated that theoretical compressive strengths of millions of pounds per square inch are of academic interest.

The three solid lines shown in Figure 1 represent stress-controlled failures. The stress levels associated with each of the three solid lines are indicated for glass, Pyroceram, and alumina. The cutoff point from the buckle-controlled failure to the stress-controlled failure depends on the stress level which could be achieved reliably in a practical full-scale structure. As will be discussed later, achieving even these apparently modest stress levels is not an easy task, for in structural configurations as simple as the sphere, the presence of a single circumferential joint degrades the strength of glass considerably. However, if the stress levels associated with the upper two lines can be achieved reliably, glass and ceramics will far surpass metallic materials on a strength to weight basis.

The same strength to weight advantages are indicated in paper studies of other structural configurations. However, investigation of these configurations logically follows the development of efficient, reliable joints for the sphere.

THE PROBLEMS

Even under the simplest of loading conditions, the designer cannot adequately predict the response of glass, glass ceramic, and ceramic structures. In simple bending tests of annealed glass, for example, the strength of nominally identical specimens may vary by a factor of at least 2 1/2. This scatter in tensile strength is attributed to the presence, size, location, and orientation of surface flaws that are not readily detectable. The designer can expect similar scatter in a structure under any loading condition for which surface tensile strength controls failure. In applications which require a high degree of reliability and in structural configurations or arrays where the weakest link in the chain controls the reliable strength, a careful interpretation of test results must be made. In addition to the problem of scatter, there are generally very few data available on the behavior of these materials under load, particularly under high-compressive loads and in a salt water environment. Data on the effects of chemical composition, defects, size, environment, loading rate, state of stress, and fabrication procedures on strength must be generated and disseminated to better understand the factors that influence strength and to evaluate feasibility properly. Such data are available in abundance on metallic materials that are being considered for deep-depth applications.

The Navy's interest in pressure vessels ranges from microballoons embedded in a plastic matrix to military submarines with a diameter of 30 ft or more. At some point between these extremes, the production capabilities of industry dictate the presence of some type of joint. Fabrication with one circumferential joint appears feasibile for spheres up to 7 ft in diameter, but this remains to be demonstrated. The number and complexity of joints increase for larger structures, thereby increasing the likelihood of a weak link in the chain. Thus, the question of reliable joints in glass, glass ceramic, and ceramic pressure vessels limited the size of the pressure vessel under consideration in this study. If reliable joints for static loading can be developed, and if these joints prove reliable in cyclic and dynamic loading, the size and complexity of feasible pressure vessels will change considerably. Thus a breakthrough in the area of joints is required. Such breakthroughs were attempted with limited success in this study.

The problem of toughness is receiving considerable attention in the Navy and is common to all materials being considered for deep-depth pressure hulls. None of the materials which must be used to provide light structures for very deep depth operation meet today's toughness criteria which are based solely on material specimen tests such as Charpy. The reappraisal of the toughness problem focuses attention on three separate areas, which are as follows: (1) a definition of realistic dynamic loads for each particular application, (2) a definition of the structural response to these loads, and (3) a correlation of the response of the material in the structure with the behavior of the full-thickness material in laboratory tests. The feasibility of developing such criteria is being studied under the Model Basin Hull Toughness Program. The toughness problem is obviously more severe for glass, glass ceramic, and ceramic shells than for metallic hulls. The tensile strength of annealed, abraded glass, for example, is on the order of 2000 psi, several orders of magnitude below its theoretical strength. However, many techniques can be used to increase the effective tensile strength for instance, thermal and chemical tempering; prestressing the hull by mechanical means; and the use of surface treatments, coatings, and lubricants. In addition, the use of overlays of shock-mitigating materials can increase the dynamic strength of glass hulls. To properly evaluate glass, glass ceramic, and ceramics as structural materials, realistic hull toughness criteria must first be developed. Whether or not these materials meet or can be made to meet the criteria must then be demonstrated.

The permanence of glass has been under study for many years. Bending tests by several investigators have shown that the long-term strength of glass is considerably less than its short-term strength. This phenomenon is called static fatigue and is dependent on the testing environment. Cyclic tests of glass have shown that the behavior depends not on the cyclic loading but on the total time under load. In other words, the failure of a glass specimen under cyclic loading is really due to static fatigue. Very little experimental work has been done on the permanence of glass under strictly compressive loads and in a salt water environment. The permanence of glass and ceramic structures under compressive loads is possibly one of the strong features of glass and ceramic shells. This, however, must be demonstrated.

EXPLORATORY TESTS AND RESULTS

Because of lack of data on the behavior of brittle materials under high-compressive loads, a series of tests were conducted in an attempt to provide some of the information required for this feasibility study. Planned tests included the static, cyclic, and dynamic strength of compression joints and penetrations as well as exploratory tests of various hull configurations. Because of the exploratory nature of the study, a statistical approach was not used in many of the tests. The testing program encountered a major obstacle in the static strength of compression joints. Although limited success was achieved, a systematic, statistical approach to the problem appears to offer the only hope of providing an acceptable solution.

An attempt was made to minimize the variable materials in the program. All of the semitempered and annealed test pieces were fabricated from 7740 glass by the Corning Glass Works Co., all of the chemically strengthened Herculite-II test pieces were fabricated from 7265 glass by the Pittsburgh Plate Glass Co.; and all of the alumina (AD99C) test pieces were manufactured by the Coors Porcelain Co.

DEVELOPMENTAL TESTS OF SIMPLE COMPRESSION-JOINT SPECIMENS

In order to evaluate some of the variables which affect the strength of mechanical or bearing joints in shell structures, simple uniaxial compression tests were conducted. The effects of surface irregularities, gasket materials, and thicknesses of gasket materials on the bearing strength of various types of glass were studied. Approximately 300 glass rods were subjected to uniaxial compression in this series of tests. As shown in Figure 2, two types of tests were conducted. The first involved tests of single glass rods, one-half inch in diameter and three-fourths inch long. The second test involved two rods of the same dimensions (total length 1 1/2 in.) which were carefully aligned before testing. The specimens were subjected to uniaxial loads in a universal testing machine. Photoelastic techniques were employed to develop the test setups for the specimens and to ensure that bending was minimized. Hardened steel blocks were used to apply the load to the glass. Chemically strengthened, semitempered, and annealed glass with various surface preparations were tested. Gaskets of various materials and thicknesses were placed between mating glass surfaces and between the glass and hardened steel blocks to determine their effects on the bearing strength of glass. The purpose of this series of tests was to determine qualitatively the bearing strength of annealed versus strengthened glass under this particular loading condition, the effects of surface irregularities, and the characteristics of gasket materials that might improve the bearing strength of glass. Thus this series of tests was a screening process for determining the important variables in test of joints in glass shell structures.

A detailed report on the test procedures and results is being prepared at the Model Basin. Figure 3 summarizes very briefly some of the early findings. In the tests of the glass rods, nominal stresses ranged from 25,000 to 350,000 psi. The following observations have been made:

1. Under uniaxial compression, the bearing strength of the chemically strengthened glass was on the average much higher than that of the semitempered or annealed glass. About half of the 80 chemically strengthened rods failed at stress levels in excess of 200,000 psi. Only 15 percent of

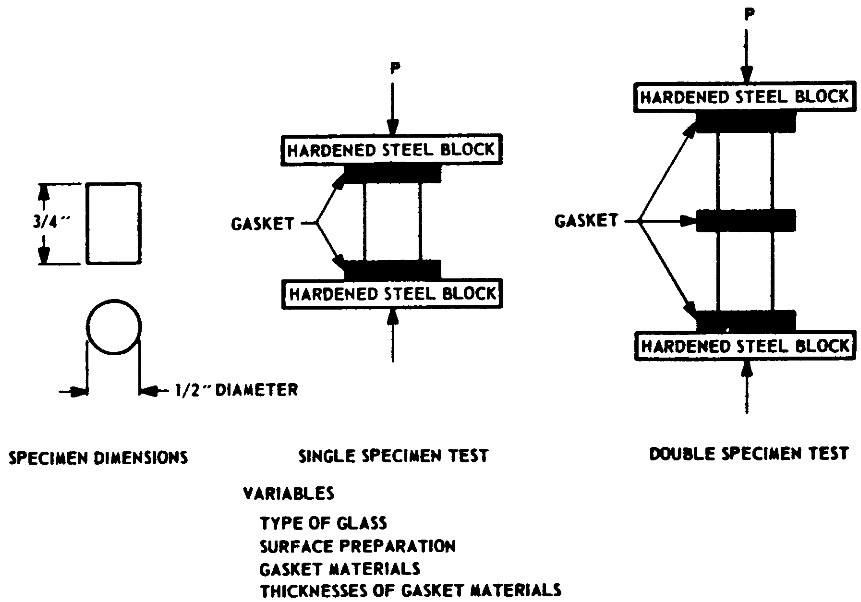


Figure 2 - Simple Compression Joint Specimens

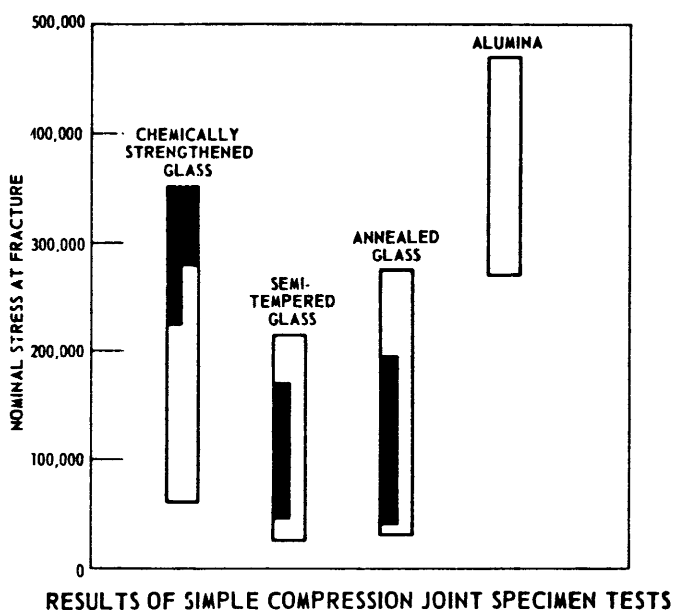


Figure 3 - Results of Simple Compression-Joint Specimen Tests

Shaded areas indicate results of tests of specimens with rounded corners.

the 137 annealed and semitempered specimens failed above 200,000 psi. This is particularly surprising in view of the fact that the corners of the bearing surfaces of the chemically strengthened rods were chipped. The manufacturer was reluctant to provide these specimens because of the condition of the edges. Because of the need for test data, however, the specimens were furnished, and the condition of the edges is here noted.

2. In an attempt to improve the edge conditions, a corner radius was ground on the chemically strengthened specimens. For comparison purposes, the corner of the annealed and semitempered specimens were ground in the same manner. The test results of these specimens are indicated by the shaded areas in Figure 3. It is apparent that the highest bearing stresses were achieved in the tests of chemically strengthened glass rods with a radius on the edges; in 11 tests of both single and double specimens, bearing strengths ranged from 225,000 to 350,000 psi. The use of a radius did not appear to have any effect on the strength of the semitempered or annealed specimens.

3. Of the gasket materials tested, tin, aluminum, steel, and titanium gave the best results on the average. However, no gasket materials gave results that were consistently higher than those obtained in tests of glass on glass or glass on the hardened steel blocks.

4. No significant variations in bearing strength could be attributed to varying the thickness of gasket materials from 0.010 to 0.030 in.

5. The use of oil, grease, or Teflon on the bearing surfaces appeared to increase the strength of glass slightly.

Six tests of single alumina rods of the same dimensions as the glass specimens were also conducted to determine the relative bearing strengths of glass and ceramics. Teflon and/or grease were used on the ends of the specimens. Average stress levels at failure ranged from 270,000 to 470,000 psi. On the basis of the limited number of tests conducted, the joint problem would appear to be less severe for ceramics.

Tests of annealed and strengthened glass, Pyroceram, and alumina rods with diameters ranging from 1/2 to 1 1/2 in. are continuing under the sponsorship of DSSP. The effects of size, environment, loading rate, and magnitude of surface compression are being explored. Testing techniques have been developed and refined, and test results are indicating definite trends. A detailed report of test procedures and results will be published in the near future.

The simple uniaxial compression test is proving to be a useful and economical tool for evaluating qualitatively the variables which affect the strength of compression joints. These variables might include the influence of composition, defects, size, environment, loading rate, surface preparation, bearing configuration, flaws, surface compression, gasketing, and joining techniques. The test setup was developed not to achieve the ultimate bearing strength or the theoretical compressive strength of the materials but to provide a common loading condition by which the variables could be evaluated economically.

DEVELOPMENTAL TESTS OF COMPRESSION JOINTS IN SHELL STRUCTURES

In order to evaluate the strength of compression joints in shell structures, tests were conducted on two hemispheres placed together to form a complete sphere. Some of the joints were simple mechanical butt joints, and others were fusion sealed. The sphere with a single circumferential joint was chosen as a simple model configuration for the study of compression joints in shell structures. When acceptable and reliable static, cyclic, and dynamic strengths were obtained, tests of more complicated joints which might be more representative of prototype structures were to be conducted. Reliable stress levels associated with the upper two solid lines shown in Figure 1 constituted the goal for this series of tests.

Mechanical Joints

The first tests of mechanical joints in glass shell structures were conducted by Krenzke and Charles.[2,3] In these tests, the highest stress levels for joints were obtained in tests of annealed Pyrex hemispheres placed against hardened steel blocks. Although compressive stress levels of approximately 300,000 psi were achieved in the shells of these hemispheres, the demonstrated bearing strength of the joint was on the order of 240,000 psi due to an increase in thickness at the bearing surface.

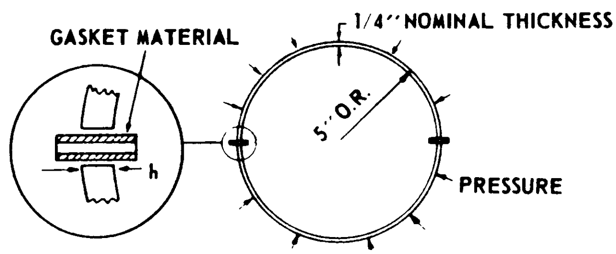
In order to determine the static strength of compression joints in a shell structure, two 10-in.-diameter glass hemispheres were placed together to form a single circumferential joint, as shown in Table 1. The complete sphere was then subjected to external hydrostatic pressure, using oil as the pressurizing medium in all tests. In early tests, the corners of the mating surfaces of the hemispheres were not rounded or beveled. In aligning the hemispheres, extreme care was taken to minimize mismatch between mating surfaces. Annealed, semitempered, and chemically strengthened glass spheres were tested in this manner. The effects of various surface preparations, gasket materials, and thicknesses of gasket materials were studied.

The dimensional tolerances achieved for the chemically strengthened models were quite different than for the annealed or semitempered models. The chemically strengthened models were ground all over and the annealed and semitempered models were pressed. (The difference in the costs of the models was, obviously, appreciable.) Based on minimum measured thicknesses and measured deviations from sphericity, the calculated stress levels associated with the elastic buckling strength of monolithic glass spheres were in excess of 200,000 psi for the chemically strengthened spheres and 170,000 psi for the semitempered and annealed spheres. A Poisson's ratio of 0.2 and a Young's modulus of 10.2×10^6 for the chemically strengthened glass and 9.1×10^6 for the semitempered and annealed glass were assumed.

For a number of reasons, the lower bound limits on buckle-controlled failures are considered conservative. First, the use of the empirical correction factor of 0.7 for the classical theory is considered conservative. This value could approach 1.0. For thin shells, the factor of 0.7 provides a reliable estimate of collapse strength. For thicker shells, such as the models tested in this program, there is reason to suspect that this coefficient may be higher. Second, a minimum measured thickness was used for all models. The thickness used for the annealed and semitempered models was 0.253 in. Average measured thicknesses were approximately 0.29 in. Third, the maximum measured deviation from sphericity indicated that the maximum local radius was 5 percent greater than the nominal radius for the chemically strengthened models and

TABLE 1

Test Results for Compression Joints in Glass Spheres



Gasket	BEARING STRESS AT COLLAPSE, PSI [1]						
	Chemically Strengthened Glass			Semi-Temp. Glass	Annealed Glass		
	Polished Mating Surf.	Hand Lapped Mating Surf	#150 [2] Grit	Hand Lapped Mating Surf [3]	Polished Mating Surf.	Hand Lapped Mating Surf.	#220 [2] Grit
No Gasket	84,000	147,000	157,000	118,000	140,000	143,000	117,000
.010 Teflon				80,000			
.032 Titan.			101,000	89,000		88,000	83,000
.010 Teflon. .032 Titan. .010 Teflon.		98,000		95,000		82,000 75,000	160,000
.010 Teflon .032 Lead .010 Teflon			114,000	56,000		78,000	42,000
.010 Teflon .032 Alum. .010 Teflon		198,000 [4] 119,000 118,000		191,000 [4] 62,000		166,000 [4]	94,000
.001 Alum. Foil						88,000	53,000

[1] Based on minimum measured thickness, h, at joint and nominal radius.

[2] Grinding wheel used on mating surfaces.

[3] Because of warping during tempering, as much as 0.020 in. of glass had to be removed from mating surfaces to true up hemispheres. Thus, part of the surface compression layer was removed.

[4] This stress level could indicate elastic buckling of shell rather than failure at the joint.

15 percent greater for the annealed and semitempered models. These local radii were used to determine the lower bounds on elastic buckle failures. Fourth, it was assumed that the location of the area of minimum thickness coincided with the location of the maximum local radius.

The results of the tests are shown in Table 1. Those stress levels which may be associated with elastic buckling of the shell are indicated. All of the lower stress levels are attributed to the strength of the joint. In the limited number of tests conducted (as was the case in the uniaxial compression tests), no gasket materials gave results that were consistently higher than the results obtained in tests of glass on glass. Although stress levels approaching 200,000 psi were obtained, no reliability could be placed in these values as evidenced by subsequent attempts to repeat the test.

In the uniaxial tests, the highest values of bearing strength were achieved in tests of chemically strengthened glass specimens with rounded edges. All of the results shown in Table 1 were obtained in tests of specimens without rounded edges. The corners of the chemically strengthened glass hemispheres with the polished mating surfaces had a sharp tip. Measurements made by the manufacturer during all stages of fabrication indicated that after strengthening, the hemispheres had a sharp pointed edge which extended approximately 0.0002 in. beyond the plane of the bearing surface. The hemispheres were tested in this condition and failed at a stress level of only 84,000 psi. Since this condition may have existed on the other hemispheres, and because of the results of the uniaxial specimens, additional tests of chemically strengthened glass hemispheres were conducted to determine the effects of rounded corners on bearing strength. In addition to the 10-in.-diameter hemispheres, tests were conducted on 5 1/2-in.-diameter hemispheres with a nominal thickness of 0.131 in. The corners of the hemispheres were rounded after strengthening. Tests were conducted in oil with two glass hemispheres placed together and also with glass hemispheres placed on hardened steel blocks.

The results of these tests are shown in Table 2. It appears that the bearing stresses achieved are on the average higher for the specimens with the rounded corners. In addition it appears that the results of the tests of glass on glass and the glass on the hardened steel blocks are approximately equal. Again, these observations are based on a limited number of tests and require verification. One of the 5 1/2-in.-diameter models failed at a stress level of 240,000 psi. Using the same approach as that used for the 10-in.-diameter spheres, the minimum stress level which could be associated with elastic buckling of the shell rather than failure of the joint was 185,000 psi. This indicates that the approach used in determining lower bound limits for buckling failures was conservative.

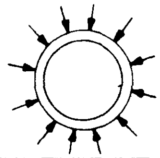
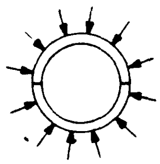
Fusion-Sealed Joints

In order to evaluate the efficiency of fusion-sealed joints, 38 spheres were tested. The spheres were formed by placing two pressed 10-in.-diameter hemispheres of 7740 glass together and applying heat to the equational joint until the hemispheres were fused. A typical weld configuration resulting from this operation is shown in Figure 4. The spheres had an average thickness of 0.296 in. Stress levels which could be associated with elastic buckling of the shell were, again, on the order of 170,000 psi. Stress levels significantly below this value are attributed to the efficiency of this type of joint. The spheres were subjected to external hydrostatic pressure with oil as the pressure medium. The results of the tests are shown in Figure 4. The ordinate is the collapse depth and the corresponding average stress level in the shell at collapse using nominal radius and average thickness. The abscissa is the percentage of the models which failed above the indicated depth and stress level. The maximum and minimum average stresses in the shell were 203,000 and 83,000 psi.

These values are conservative estimates of the compressive strength of a fusion-sealed joint since they do not take into account the bending stresses and the reduction in the area of the mating surfaces due to mismatch between the hemispheres. In addition, the local radius at the joint was higher due to distortion during fabrication. Nevertheless there was a scatter in test results of approximately 2.5. Careful measurements were made on 30 of the models in an unsuccessful attempt to correlate mismatch with collapse strength. The maximum mismatch ranged in shell thickness from approximately 5 to 15 percent. The two spheres which had a maximum

TABLE 2

Strength of Chemically Strengthened Glass Hemispheres

DESCRIPTION OF TEST	WEIGHT TO DISPLACEMENT RATIO	COLLAPSE DEPTH (FT)	AVERAGE STRESS IN SHELL AT COLLAPSE * (PSI)
MONOLITHIC ALUMINA SPHERES 	0.23 0.24 0 26 0.28	28,100 24,800 31,500 33,800	300,000 260,000 300,000 300,000
ALUMINA HEMISPHERES 	0.21 0.22 0.25 0.26	21,400 21,200 28,000 27,100	240,000 210,000 270,000 250,000

*Based on shape and thickness measurements, it is estimated that the maximum stress in the monolithic shells and the bearing stress across the joint in hemispheres was 10 to 20 percent higher than the average stress shown.

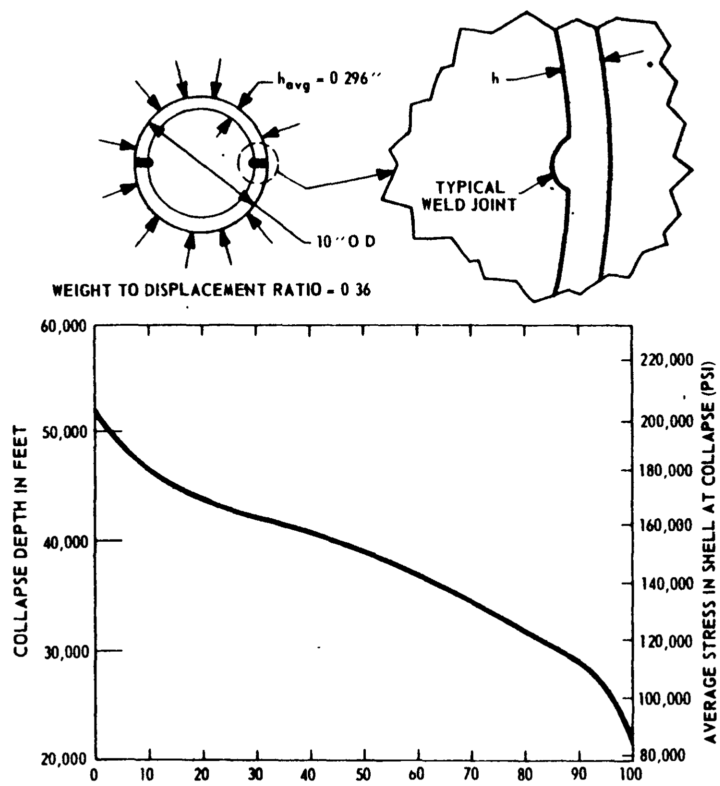


Figure 4 - Experimental Results for Fusion-Sealed Annealed Glass Spheres

mismatch of 5 and 15 percent of the thickness of a shell failed at stress levels of 149,000 and 142,000 psi, respectively.

During the tests of these spheres, sharp fluctuations occurred in the pressure gage prior to failure. Inspection of the models indicated that these fluctuations were caused by flaking of the glass bead formed in fusion sealing; see Figure 5. This process was random and may have contributed to the scatter. Industry is attempting to improve the reliability and efficiency of the fusion-sealed joints.

Joints in Alumina Spheres

Tests of 10-in.-diameter alumina spheres and hemispheres were also conducted. The description of the models, tests, and the test results are shown in Table 3. The hemispheres were carefully aligned prior to test, and no gaskets were used between bearing surfaces. Weight-to-displacement ratios based on average measured thicknesses ranged from 0.21 to 0.28, and corresponding collapse depths ranged from 21,200 to 33,800 ft.* The table also shows the average stresses in the shell based on nominal radius and average measured thickness. On the basis of a limited number of shape and thickness measurements, it is estimated that the maximum average stress in the shells and the average bearing stress across the joint in the hemispheres were 10 to 20 percent greater than the average stresses shown. There was no appreciable scatter in results for the eight tests and no reduction in strength was attributable to the presence of joints. On the basis of the limited number of tests conducted, it appears that the joint problem is less severe for alumina, and that stress levels higher than those associated with the upper two solid lines of Figure 1 may be attained.

Tests of joints in glass and ceramic shells are continuing under the sponsorship of DSSP. The possible use and effectiveness of a proof test

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*Six of the eight spheres tested failed while the pressure was being held constant. The spheres withstood the pressure from 12 to 58 sec prior to failure. Only two of the spheres collapsed while the pressure was being increased.

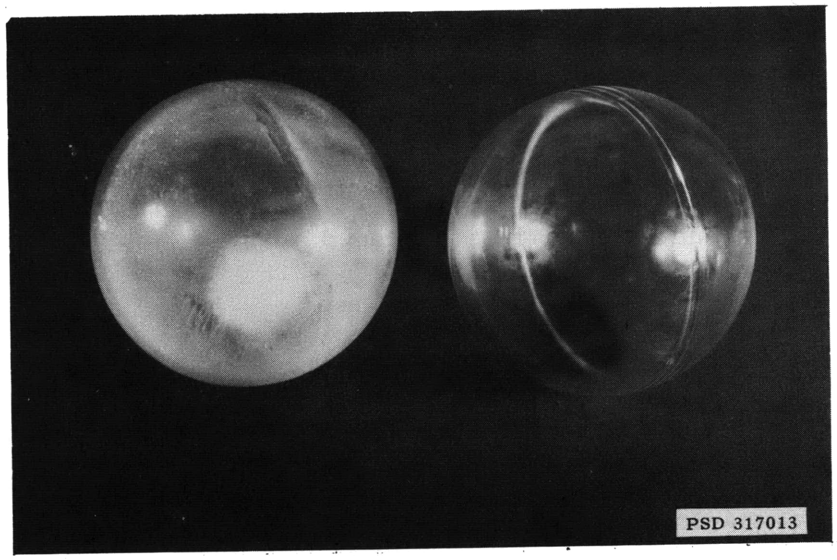
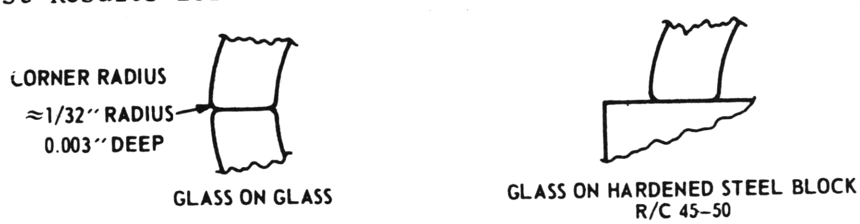


Figure 5 - Flaking of Fusion-Sealed, Annealed, Glass Spheres

TABLE 3

Test Results for 10-Inch-Diameter Alumina Spherical Shells



DESCRIPTION OF TEST	BEARING STRESS AT COLLAPSE (PSI) [1]			
	10″ DIAMETER HEMISPHERES		5 1/2″ DIAMETER HEMISPHERES	
	WITHOUT RADIUS	WITH RADIUS	WITHOUT RADIUS	WITH RADIUS
GLASS ON GLASS	84,000 [2] 147,000 157,000 [3]	162,000 170,000 176,000	139,000 189,000	183,000 195,000 240,000
GLASS ON HARDENED STEEL BLOCK (R/C 45–50)		173,000		213,000

[1]Bearing stress was calculated using nominal radius and minimum measure thickness at joint. With the exceptions noted, all bearing surfaces were hand lapped.

[2]Mating surfaces were polished.

[3]Mating surfaces were ground. (# 150 Grit)

approach was explored by Nishida,[7] using fusion-sealed, annealed Pyrex spheres. The results indicated that the long-term hydrostatic strength of these particular models in a salt water environment was equal to its short-term strength and that cyclic loading had no apparent effect on static collapse strength.* These tests were exploratory and do not apply to structures of other materials (e.g., chemically strengthened glass) or joining techniques (e.g., mechanical joints) where the mechanism of failure may be completely different.

DYNAMIC TESTS

Because of the difficulties encountered in the static strength of compression joints in shell structures, no dynamic tests of joints were conducted. Tests were conducted to explore the dynamic response of simple glass shells. Approximately 100 small annealed glass cylinders were subjected to impact and underwater explosion loading. The strain distribution in the cylinders due to both static (point) and impact loading was established. Dynamic strains were found to vary directly with impact velocity. For nominally identical cylinders and test setups, fracture velocities and therefore critical tensile strains fluctuated by a factor of about 2. This may be attributed to the normal scatter associated with the tensile strength of annealed glass. Similar scatter was observed in the tests of the cylinders under explosion loading. Additional dynamic tests of glass are being conducted under the Model Basin Hull Toughness Program. Preliminary results of dynamic tests conducted on glass plates 2 ft X 2 ft X 2 in. in size indicate that the use of protective coatings can be very effective in reducing peak tensile strain.

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*One of the models may have been damaged during cyclic loading. This possibility is being investigated by additional tests with more systematic inspection prior to and during cycling.

TECHNICAL FEASIBILITY

Evaluating the technical feasibility of glass and ceramic pressure hulls is extremely difficult at this time. The broad technical background of research and experience upon which feasibility studies of metallic materials can be based is not present in the case of glass and ceramics. Therefore, comparable data for glass and ceramics must be generated and disseminated so that the factors influencing their behavior under high-compressive loading can be determined and evaluated. The need for basic materials research and exploratory structural research is clear if the full potential of these materials is to be achieved.

Glass and ceramic structures are being investigated under various Navy programs. The DSSP is sponsoring studies of a particular near-future application, namely reliable structural floats for the Operational Search Vehicle. Various aspects of this problem are being studied at the Naval Ordnance Laboratory, the Naval Research Laboratory, the Bureau of Standards, and the Model Basin. Under the sponsorship of Naval Ship Systems Command, the Model Basin is conducting studies to develop concepts which will permit the reliable use of low ductility and brittle materials in deep-submergence vehicles. Tests of glass (in addition to other materials) are also being conducted at the Model Basin under the Hull Toughness Program. Although these programs are aimed at investigating either a particular application of glass and ceramic structures or the use of nonductile materials in deep-depth pressure hulls, they will provide some information on the behavior of these materials under realistic loading conditions. Thus the data presented and the conclusions reached in this report are the results of exploratory study and must be continuously reviewed as additonnal data from other programs become available.

At the present time, the most attractive application of glass and ceramics is their use in structures to support a payload at any depth in the ocean. Glass and alumina spheres are being used for such applications today and are commercially available. Their use involves a tradeoff between cost and reliability. Industry is already producing alumina and glass hemispheres and spheres in diameters of 30 to 44-in. in anticipation of the need for large structural floats. The fabrication and operational experience with such floats will furnish useful information for a continuing evaluation of feasibility for other hull applications. In addition, they will provide a useful modeling tool to evaluate larger size structures.

The first application of glass and ceramics to deep-submergence vehicles will probably be in structural flotation spheres. These spheres would be used together with a metallic pressure hull to reduce the overall ratio of structural weight to displacement. This application is particularly attractive in that the spherical configuration is simple and penetrations are not required. In addition, the spheres could be encapsulated with a protective jacket and be supported inside an outer hull to minimize danger of damage due to impact or other dynamic loading. In such an application, however, reliability is essential and remains to be demonstrated. The chances of solving the problems involved in the use of such floats for the Search Vehicle by 1968, for example, are considered fair at best.[8] Since data are not available, a brute force approach is being followed which, hopefully, will demonstrate the reliability of a proof-test technique. The information generated by this program will furnish some of the basic data which are vitally needed to establish the feasibility of other glass and ceramic hulls.

The effect of spherical floats on the weight and displacement of deep-sea vehicles is illustrated in Figure 6. The abscissa is the displacement of the metallic pressure hull and floats, and the ordinate is the weight-to-displacement ratio of the hull and floats.* Two near-perfect metallic spheres 7 ft in diameter have been chosen for the illustration. Both are designed for an operating depth of 20,000 ft, displace approximately 5 tons, and are potential hulls for the Search Vehicle in the DSSP. The HY-150 steel pressure hull weighs 95 percent of its displacement, and the HY-110 titanium pressure hull weighs 72 percent of its displacement. The curves show the effects of adding structural floats weighing 30 and 40 percent of their displacement on the weight-to-displacement ratio and the displacement of the pressure hull and floats.

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*Past experience indicates that the total vehicle displacement may be considerably greater than the displacement shown.

Two spherical floats, approximately 5 1/2 ft in diameter and weighing 30 percent of their displacement would reduce the net weight-to-displacement ratio of the titanium hull from 0.72 to 0.50 and double the displacement. Two similar floats weighing 40 percent of their displacement would reduce the net weight-to-displacement ratio of the steel hull from 0.95 to 0.68. Three spherical floats approximately 7 ft in diameter and weighing 40 percent of their displacement and the 7-ft diameter HY-150 steel sphere would displace approximately 20 tons and have a net weight-to-displacement ratio of 0.54.

The second possible application of glass and ceramics to deep-submergence vehicles is their use as the material for simple spherical pressure hulls. Such a hull would probably contain a minimum number of penetrations, possibly only one, and might be connected with a smaller metallic hull which would provide for additional penetrations of the structure. One such design under study at the Model Basin is shown in Figure 7. The projected pressure hull is 7 ft in diameter and is composed of two glass hemispheres (possibly chemically strengthened) butted together. The thickness at the joint has been increased to reduce the bearing stresses to 50,000 psi at an operating depth of 20,000 ft. A 21-in.-diameter penetration provides access to the sphere. A factor of safety of 2 was assumed. The weight-to-displacement ratio of the 2-in.-thick sphere is approximately 0.32. By restricting bearing stresses, the weight-to-displacement ratio will increase to 0.37 to 0.40, depending on the detail of the joint.

In the absence of a real understanding of the behavior of glass and ceramic shells under compressive loading, the proof-test approach appears to be the only potentially acceptable method of demonstrating reliability for near-future applications. Therefore, there is a need for a pressure-testing facility capable of cycling and testing full-scale pressure hulls to destruction (or to 1.5 times the operating depth). Since the structures may not contain penetrations, standard techniques of using internal pressure for cycling and partially filling the models with liquid to reduce the dynamic loads may not apply.

Glass, glass ceramic, and ceramic structures are currently being used for unmanned structures to depths of 20,000 ft. These structures are

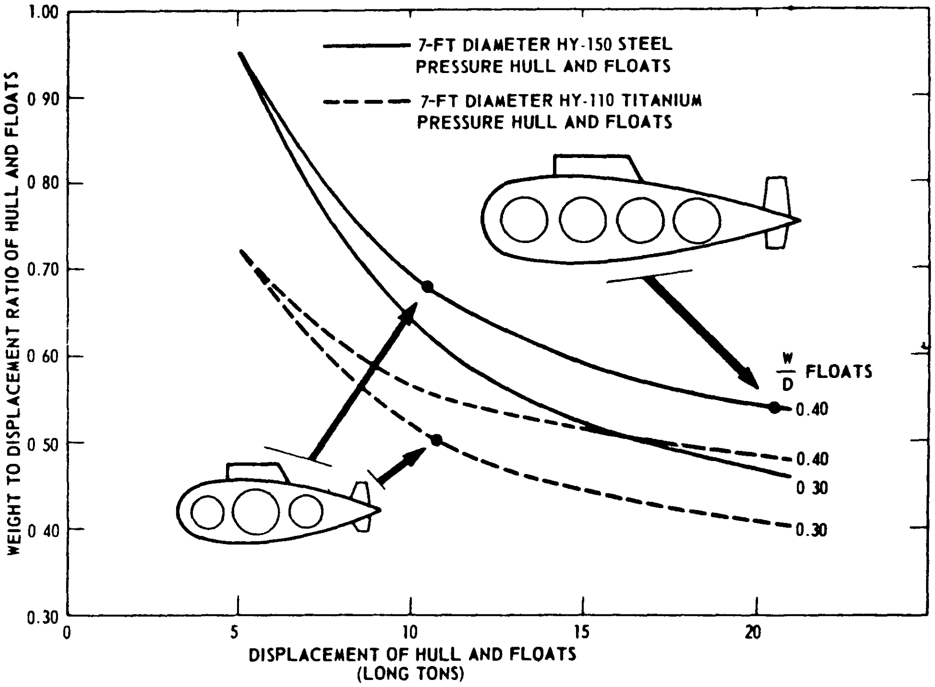
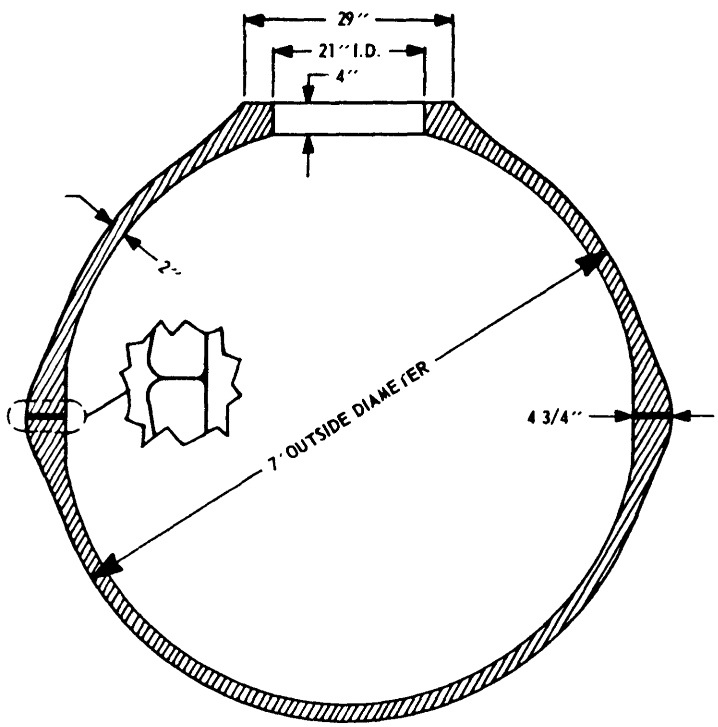


Figure 6 - Effects of Floats on Vehicle Weight and Displacement



COLLAPSE DEPTH	40,000 FT
OPERATING DEPTH	20,000 FT
WEIGHT TO DISPLACEMENT RATIO	0.37–0.40
DISPLACEMENT	11,700 LBS
BEARING STRESS ACROSS JOINT AT OPERATING DEPTH	50,000 PSI
STRESS IN SHELL AT OPERATING DEPTH	100,000 PSI

Figure 7 - Glass Pressure Hull

commercially available in sizes up to 16 in. in diameter. The industry has tooled up for the production of spherical floats to 4 1/2 ft in diameter. As far as manned vehicles are concerned, glass microballoons embedded in various matrix materials have been developed for reliable flotation systems. Glass, ceramic, and glass ceramic spheres up to 7 ft in diameter are being considered for possible use as structural floats or even as the main pressure hulls for small manned oceanographic vehicles. Thus, glass, glass ceramic, and ceramic structures of relatively small displacement are being and will be used for manned and unmanned structures to the deepest parts of the ocean Potentially, these materials can provide light hulls of much larger displacements if the proper attention is given now to basic materials research and exploratory structural research.

SUMMARY

Very little information is available on the behavior of glass and ceramic structures under high compressive loads. The exploratory tests described in this report have provided some guidelines and have shown some trends. The lack of available data on factors that influence strength emphasize the need for basic materials research on glass and ceramics. An exploratory structural research program conducted concurrently with the materials research would orient the designer towards particular hull configurations and fabrication techniques which take advantage of the potential and would correlate the behavior of material in the structure with the behavior of the material in laboratory tests. At the present time, the most attractive potential applications of these materials are simple structural floats or possibly simple spherical pressure hulls for oceanographic vehicles. For near-future applications, a proof-test approach appears to be the only potentially acceptable method of demonstrating reliability.

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An exploratory study was conducted to determine the feasibility of using glass and ceramic materials for deep-submergence pressure hulls. In general, the study confirmed the potential use of these materials in pressure hulls capable of withstanding pressures at the deepest part of the ocean with very little structural weight. However, the study also showed that very little is known about the behavior of glass and ceramic structures under high-compressive loading and that a great deal of basic data must be generated before this potential can be achieved. The use of simple spheres of glass and ceramic materials for providing buoyancy is considered to be the most promising near-future application.

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