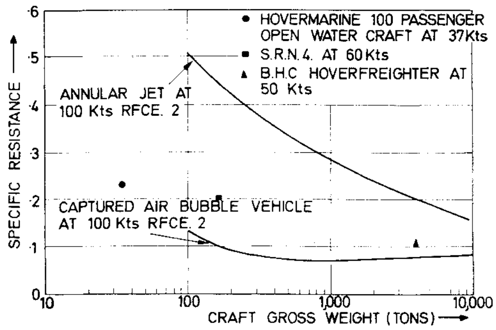

Fig. 2 Variation of specific resistance with craft design gross weight.

For existing hovercraft, values of A and B are approximately unity, and other constants may be taken to comprehend those anticipated, even for very large craft. Although the dependence of range is shown for values of (w/w_i) of 0.1 to 1.0, the lower of these values may be hypothetical, since it is very unlikely that, even for very large craft, values of less than 0.3 will be achieved.[2]

In Fig. 2, theoretical calculations of specific resistance of Fielding[2] are shown with those for other projected hovercraft. It can be seen that there is a beneficial size effect which favors the larger craft. This effect would be even more advantageous were it not that these large craft are designed to operate in the more adverse wind and wave conditions encountered on longer and more exposed routes.

The constant A is approximately proportional to the reciprocal of the cushion pressure. From structural and economic considerations[3] the larger craft will employ higher cushion pressures and thus will have lower values of A. From a comparison of Figs. 1a–1d it can be seen that these lower values of A will result in a slight increase in range capability. Thus there is again a beneficial size effect favoring the larger hovercraft.

The constant B is primarily a function of the reciprocal of the "daylight clearance." It is a matter of conjecture as to whether the present daylight clearances will be employed on very large craft, or, as seems more probable, the larger craft will employ greater clearances. Higher values of the daylight clearance result in lower values of B and increased range capability.

Also included on Figs. 1a–1d are results based on the assumption of 1) constant specific resistance, and 2) constant total power requirement. The former yields the expression

$$R = (375/\bar{s}\epsilon_1) \log_e(w_i/w) \text{ miles}$$

which is of the same form as the Breguet range formula for aircraft. However in the derivation of the Breguet formula, airspeed is not constant, whereas in the present instance it is. It can be seen that, for conventional hovercraft, in which the craft weight is almost completely supported by the air cushion, the Breguet formula overestimates range. Thus, although the formula draws attention to the importance of the "performance efficiency" $(1/\epsilon_i)$ and the "design efficiency" $\log_6(w/w_i)$ as per Mantle,[4] the formula should not be used to evaluate range.

Conclusions

The range of hovercraft operating at constant speed in an invariable environment is a function of the design efficiency, the way in which the total power is apportioned, and is directly proportional to the average specific fuel consumption and initial specific resistance. Larger hovercraft will have longer range primarily through achieving lower values of initial specific resistance and higher values of design efficiency. A secondary benefit for the larger craft is from the way in which the total power is apportioned.

References

[1] Burgess, A. J., "The Performance of Fans in Hovercraft. A Method of Reducing Experimental Results," R & M 3507, Nov. 1965, Aeronautical Research Council.

[2] Fielding, P. E., "Twentieth Century Yankee Clippers," *Hovering Craft and Hydrofoil*, Vol. 5, No. 2, Nov. 1965, pp. 6–17.

[3] Bingham, A. E., "The Hovercraft Ferry," *Hovering Craft and Hydrofoil*, Vol. 3, No. 7, April 1964, pp. 8–17.

[4] Mantle, P. J., "ACV Parametric Assessment," *Air Cushion Vehicles, Flight Supplement*, Vol. 8, No. 53, Nov. 1966, pp. 74–76; Vol. 8, No. 54, Dec. 1966, pp. 89–91.

Glass Submersibles

WILL FORMAN*

Naval Undersea Warfare Center, San Diego, Calif.

Introduction

GLASS, which contains melted silica sand, one of the earth's more abundant materials, has been in use by man for as long as or longer than most common metals and far longer than such new metals as aluminum and titanium. Its use is confirmed by the discovery of glass artifacts in the ruins of nearly every ancient civilization. Yet, until recently, little or no structural use has been made of glass. Although according to legend Alexander the Great submerged in a glass barrel about 323 B.C., modern submersible applications of glass until very recently have been limited to its use for the viewing ports in the Japanese submersibles Kuroshio and Yomiuri.

Glass has significant advantages for underwater use. Its high intrinsic strength allows it to withstand pressures approaching 3,000,000 psi; glass fibers have supported as much as 1,000,000 psi in tension; and in tests made recently at the University of Vermont, uniaxial compressive loads of 500,000 psi were imposed.

This ability of glass to withstand compressive loads makes it an ideal material for submersibles, provided we can design configurations and joints in which practically no tension is allowed to exist in the glass hull. The fragility of glass is due primarily to its poor resistance to tensile stress. The strength of a glass hull under pressure is primarily limited by its ability to withstand compressive loads and is therefore enormous.

The purpose of this paper is to discuss the glass submersibles now under construction at the Naval Undersea Warfare Center. (Formerly NUWC was part of the Naval Ordnance Test Station, and the present NUWC submersible development groups began their work at NOTS China Lake as part of that Station's oceanographic research and development program.) Before speaking of present models, however, it will be helpful to review earlier submersibles in order to illustrate the need for current changes and modifications to design concepts.

Background

Deep Jeep, one of the first American-built deep-sea research vehicles, was designed, fabricated, and operated by my group when we were at NOTS. Deep Jeep was launched in Jan. 1964 and was operated to 2000-ft depths during part of its development test phase. Submarine rescue experiments and oceanographic research were conducted in several coastal areas off California with it. In Jan. 1966 it was the first submersible to reach the Mediterranean for use in the

Presented as Paper 68-478 at the AIAA 3rd Marine Systems and ASW Meeting, San Diego, Calif., April 29–May 1, 1968; submitted May 9, 1968.

*Submersible Project Manager.

search for the lost hydrogen bomb. In June 1967 it was transferred on indefinite loan to Scripps Institution of Oceanography near San Diego.

Another submersible built and operated at China Lake was called Moray. The project had the mission of investigating the feasibility of locating or identifying underwater objects by sonar techniques from a submerged vehicle. The submersible, when equipped with silver-cadmium batteries, attained speeds of 15 knots for brief periods of time. Its structural system was designed for depths of 2000 ft or less.

The third submersible used in the past for oceanographic research was Jacques Cousteau's Soucoupe. In it many of our vehicle designers and ocean scientists made dives as deep as 1000 ft in Southern California waters. It was during these dives that we collected our first in situ data and obtained our first selective deep-ocean photographs. Because of the California diving operations by the Soucoupe, many of the early ocean research programs received more interest and attention.

NUWC's experience with Deep Jeep, Moray, Soucoupe, CURV (cable controlled underwater research vehicle), Trieste, and Deep Star has been used to tailor the design characteristics of our new generation of submersibles. We have recognized the need for improvement in the following characteristics: 1) omnidirectional visibility for complete comprehension of the underwater environment, visibility we had not experienced in the tunnel vision provided by view ports; 2) complete control of all directions of motion, including the ability to turn about all three axes; 3) the elimination of all fouling hazards; 4) the elimination of the need for large surface-support ships; 5) greater reliability; 6) very low maintenance requirements; 7) larger deep-water cargo capacity; and 8) transportability.

Improvement in maneuverability in deep water, especially near subsurface crags, canyons, and rugged ocean bottom, can be obtained by reducing the hull size. The requirement for minimized size, self-buoyant hulls, and optimum visibility has led to the research on the use of glass for submersible pressure hulls that is the chief subject of this paper.

Glass Submersible Designs

Twenty-three hundred years after Alexander's glass barrel we have under construction the first practical research submersibles to be made of glass. The new generation of manned research submersibles is unusual because of at least one distinctive feature which they have in common: their pressure hulls are constructed of glass hemispheres or spheres.

The first of the three submersibles under construction at NUWC has been named Hikino, which in Hawaiian means "can do." The designers and operators of the project expect to demonstrate the advantages of a spherical-glass-hull construction as a potential solution to some of the Navy's problems in deep submergence research and development programs.

Hikino will consist of a twin-hulled catamaran with a glass sphere for a cabin. A prototype is currently under construction; it will employ battery-driven motors that turn cycloidal propellers. The catamaran hull was selected for the stability that it will provide during surface travel, such as from the shore to the dividing site. For submerged operations, the catamaran hull will be flooded.

Hikino provides a large surface freeboard and operating platform while surfaced. The surface buoyancy facilitates entering and leaving the submersible at the surface without outside assistance. This characteristic will be especially useful in independent operations that will be conducted near the shore. The cycloidal propellers are π pitch in operational characteristic, and the entire submersible is trailer-mounted. The trailer is used for transportation and for launch or recovery of the vehicle. Since the spherical glass cabin is buoyant, it will float to the surface if released from the rest of the boat during an emergency.

Another submersible which is presently under construction is being built with private funds by W. B. McLean, Technical Director of NUWC. He was a recent recipient of his sixth American high honor in less than 10 years. His latest award, $10,000 from the Rockefeller Foundation, is being used by him to build a glass submersible. His research vehicle is intended for civilian use. Its purpose is to make it possible for small institutions and private individuals to take part in opening up the new ocean frontier. In production, his submersible will cost about $10,000. The completely transparent hull will provide its occupants with a spectacular omnidirectional view of the ocean. No electrical leads will penetrate the $1\frac{1}{2}$-in.-thick glass hull. Instead, the vehicle will be remotely controlled by radio waves transmitted through the sea water from within the glass cabin to the motor and other external equipment. Reversible, axial-flow motor pumps will provide the propulsion for the vehicle. The motor pump under development will have vanes mounted inside its hollow armature, which will provide the thrust for the system. Oil-encased lead-acid batteries will be located in the pontoons of the catamaran.

A CURV vehicle with a spherical glass hull designed for 20,000-ft depths is currently under consideration. The strong, lightweight transparent hull could provide extensive experience and data from an unmanned deep vehicle.

Sea See is a surface running boat that employs the catamaran hulls from the old Moray program to support a submerged plastic sphere that is connected to the surface by a steel cylinder. It developed from some early experiments by K. Norris using a wing tip gas tank and vertical cylinder. His "sea-sick machine" as many called it, although not sea-kindly, successfully showed the advantages of near surface submerged observations of marine animals.

Glass and Steel Hull Submersible

The last submersible under fabrication, called Deep View, is the project which I manage. It is intended for oceanographic research and consists of a single hemisphere of glass located on the forward end of a ring-stiffened steel cylinder that forms the hull. It was designed for a maximum volume of cabin space at a minimum of drag and size. It will operate to depths of 5000 ft. The skids of the vehicle will be the battery pods, which are droppable in an emergency. The occupants will normally be in a prone position, but the hull is big enough to allow sitting upright for note taking, etc. The streamlined hull will permit rapid transit when surfaced and when diving. A large sliding tray located between the skids will hold the oceanographers' instruments and tools, which will be used with a manipulator. There will be a raisable tube on the entrance hatch to permit changing of personnel in calm or sheltered water, eliminating the need to recover the vehicle or send it ashore for such changes.

A manipulator, coring tools, biological samplers, and transponders for marine geological surveying will be standard equipment. Four motors and propellers make up the propulsion systems which will provide complete maneuverability and the ability to hover. The vehicle on its trailer will be transportable by aircraft, train, or truck, and will be towable by automobile. The transportation trailer will serve as the launch and recovery platform at the water's edge; the operation will be similar to the launch and recovery of pleasure craft.

The selection of a hemispherical glass and steel cylinder hull design presents almost the same major problem as a spherical glass design. The need for an access hatch or opening in either design dictates some form of protective rim for the very brittle glass edge. Glass in contact with glass, as in the case of two glass hemispheres, appears to behave as if no joint existed. This is not the case if glass is mated to material such as metal having a modulus and Poisson ratio different from the glass. As a result of this dissimilarity in mechanical properties, tensile stresses occur in the glass. If the radial deformation of the glass and metal are closely matched, the tensile stresses are lowered but are not necessarily eliminated. Failure at the joint is usually induced by cycling, presumably due to crack propagation of surface blemishes, since hemisphere surfaces polished mechanically or by fire give better results when proof-tested or cycled than hemispheres with rough-surfaced edges. Some marked success has been made with ion-exchanged or fortified shell surfaces, but we are not ready as yet to rely on this technique alone for manned submersible pressure hulls.

Although extensive glass hemisphere tests indicated that well over 100,000-psi strengths were predictably attainable, the basic design depth of the Deep View was set for 5000 ft, which would subject the glass to only about 20,000-psi compressive loads, leaving an adequate margin of strength for proof testing, safety factors, etc., and providing an economical steel hull design with greater payload capacity.

Seven 44-in.-diam hemispheres of suitable quality, the largest available at the time, were delivered to NWC by Corning in December 1966. Development still continues for larger size domes.

Selection of the 44-in.-diam hemispheres was followed by a year and a half of testing 10-in.-diam models of the Deep View pressure hull. These tests preceded the full-scale tests of the steel and glass pressure hull which are now in process.

Glass hemisphere model tests

In the first model test series acid-etched flat-surfaced Pyrex hemispheres, all inspected with polarized light to insure the absence of residual grinding stresses, were used. Various interface materials and holding fixtures included Teflon and neoprene gaskets and single, double, and multiple "O" rings. Some of the fixtures provided for radial rotation of the glass. Strain-gaged models showed the strains to increase linearly with pressure, and no prediction of impending failure was indicated from the recorded strain data. In all these model tests single and multiple incipient cracks perpendicular to the gasketed or O-ringed metal surface resulted. They occurred usually in the middle one-third of the thickness of the glass and extended up the glass wall about the length of the hemisphere's radius.

The models failed at pressures between 3000 and 4000 psi, which is less than one-half that usually attainable with a glass-to-glass joint. The joint was considered a possible source of the fractures because of nonuniform radial deformation.

Glass and steel hull model tests

To test the complete hull design, a 1:44-scale HY100 steel and glass model was made incorporating an accurately scaled steel-to-glass joint designed to have the same radial deformation as the glass. These tests indicated that the metal hull design was adequate, but that the glass-to-steel joint and the model testing program required major alterations.

The flat-edge glass tests indicated the possibilities that tension was developing in the joints. To confirm this, and to understand better how to avoid it, a number of glass-to-metal joints were made of block glass. Until this point in the testing program, flat-edge glass domes had been used. The joints were then studied under polarized light, and it was confirmed that tensile stresses were present. Much of the literature on glass indicates that failure of glass at low stress levels results from the presence of tension. It therefore became obvious that the joint must be configured to eliminate all tensile stresses.

As a part of a program devoted to the development of a tension-free joint, a series of 10-in.-diam models was prepared. Three were considered as fulfilling all the compressive qualifications. A long radius edge having a radius several times greater than one-half the wall thickness of the glass; a wedge edge or "V" edge; and a full radius edge having a radius about equal to one-half the wall thickness. Sloped edges (inward or outward) were considered but not tested as the friction in the joint might unpredictably alter the edge effect. Two different surface finishes were tried: mechanical polishing and fire polishing. One set of the glass domes that were to be fire polished was first ground round, etched, and then fire polished. Another set was configured into a round edge from a flat acid-etched surface by extensive fire-polish heating until the surface tension of the "molten" glass edge caused it to be round. Warpage and lack of consistent geometric cross section throughout the glass periphery have so far limited the use of fire-polished edges. Fire polishing does not appear to be necessary if the glass surface is effectively in compression.

The "V" edge was found to be very difficult to align properly with the metal groove, and misalignment such as might occur under pressure set up higher moments than with the round edge.

The round-edged hemisphere design was selected to: 1) permit rotation in the joint as necessary to reduce or eliminate moment due to any end loading; 2) eliminate tension at the glass-metal interface; 3) provide a large area of pressure distribution free of point loading and not subject to sharp edge weakness; 4) provide a soft material buffer to minimize any adverse effects due to the soft and brittle glass being in contact with the hard and ductile steel, to distribute as evenly as possible the load from glass to steel by the gasket medium which is virtually liquid at high pressures but cannot extrude, and to a limited extent provide a shock buffer; 5) provide for balanced radial deformation between the steel (E = 30,000,000 psi) and glass (E = 9,000,000 psi); 6) minimize discontinuities and stress rise areas due to geometric discrepancies (out of roundness, etc.) since both the male and female parts are machined (or ground) surfaces; 7) insure that friction between the glass and steel cannot cause sudden shifts between the parts and introduce shock and uneven joint loadings as may occur in flat joints.

Tests of 10-in.-diam models have been conducted to 7000 psi or three times the design depth of the submersible. No adverse effect due to cycling can be observed in the glass. Glass-reinforced epoxy rings have been substituted for the metal (steel) female joints, but a maximum of 6500 psi was obtained because of the weakness of the epoxy ring. After 200 cycles at 5000 psi, or two times the operational pressure, the best gasket material used so far (a neoprene coated nylon fabric) indicates only minor gasket wear but no damage to the glass.

Full-scale tests

Full-scale testing of 44 $\frac{1}{2}$-in.-diam glass hemispheres has been conducted by NUWC for over eight months. Pressures of up to 3300 psi or $1\frac{1}{2}$ times the submersible's operating depth have been obtained. If we are careful to inspect and record the sphericity and shell thickness, and monitor by strain gages in the areas of highest strain, we can predict fairly accurately the test results.

One of the problems to date has been to get glass shells of high enough quality and uniform geometry. Recently we have developed a method of contour machining 10-in.-diam glass hemispheres with a diamond tip tool bit. If necessary, we will apply this procedure to larger hemispheres to obtain sphericity.

Transparent glass ceramics have just recently become available. We have used the diamond bit machining tool on several glass ceramic hemispheres and are presently testing these shells under pressure.

Models have been constructed and successfully tested using the round-edge glass mounted inside a metal hatch ring. The stress distribution is similar to that found in the equatorial joint, but the technique permits larger glass hulls made of hemispheres to be joined at the equator by a bonded glass-to-glass joint. With this design, a small metal hatch ring is inserted at the top of the pressure hull. A metal or glass hatch can be used. The smaller hatch may be an important feature as the hulls become larger and especially if metals like titanium are used for the glass-to-metal joint.

The combined techniques of 1) grinding the edges exposed to pressure, whether at the equator or at the hatch, 2) contour machining the shells, and 3) polishing afterward have made possible successfully repeatable and predictable tests of these glass structures. These tests indicate the feasibility of operational use of glass for submersible construction. The high strength-to-weight ratio and the transparency of glass and glass ceramics can provide the much needed visibility and cargo capacity in submersibles small enough to maneuver and operate effectively in deep water.

Fracture-Toughness Measurements on 12% Ni Maraging Steel Weldment

F. R. STONESIFER* AND H. L. SMITH*
Naval Research Laboratory, Washington, D.C.

A PROMISING alloy for use in ocean and space where materials of higher fracture toughness and strength-to-weight ratio are needed is 12Ni-5Cr-3Mo maraging steel. "Apparent" K_{Ic} (plane strain fracture-toughness values) for the 170–190 ksi yield strength range are reported for parent material and various welds. Three-point bend test values range from 200 to 300 ksi (in.)$^{1/2}$, corrected for plastic flowing. Parent metal size-effect studies, using up to 4-in. deep bend bars, were conducted to arrive at valid K_{Ic} values. Values are listed as apparent, since specimens are below minimum sizes proposed by ASTM (American Society for Testing Materials) Committee E-24. MIG (metal inert gas) welds gave apparent K_{Ic} values about 20% lower than TIG (tungsten inert gas) welds. When welded with no oxygen in the shielding gas, MIG welds showed 5–20% improvement.

Space and deep-ocean exploration requires optimization of pressure-vessel design. The desirable leak-before-failure situation for a pressure vessel can only be achieved with structural materials exhibiting high fracture toughness. Fracture mechanics is a valuable tool for analyzing, predicting, and helping to prevent catastrophic brittle failures, and specifications for structural materials often now include minimum fracture-toughness values. The fracture-toughness parameter K measures the ability to deform in the presence of a crack. Since all known materials contain flaws, the problem is to prevent such flaws from growing to critical size or to know the critical crack size for a given material and stress level. The critical crack size is proportional to K^2.

Table 1 Nominal composition limits for 12Ni-5Cr-3Mo maraging steel

Element	% by weight Minimum	Maximum
C	...	0.03
Ni	11.5	12.5
Cr	4.75	5.25
Mo	2.75	3.25
Ti	0.10	0.35
Al	0.20	0.50
Si	...	0.12
Mn	...	0.10
S	...	0.010
P	...	0.010
B and Zr	not intentionally added	

Presented as Paper 68-507 at the ICRPG/AIAA 3rd Solid Propulsion Conference, Atlantic City, N.J., June 4–6, 1968; submitted May 14, 1968; revision received August 28, 1968. Work supported by the Deep Submergence Systems Project and NASA with H. Bernstein and J. Misencik, respectively, as Project Engineers. H. E. Romine, E. O. Cook, and W. E. Anderson assisted in specimen preparation and testing.

* Ocean Materials Criteria Branch, Ocean Technology Division.

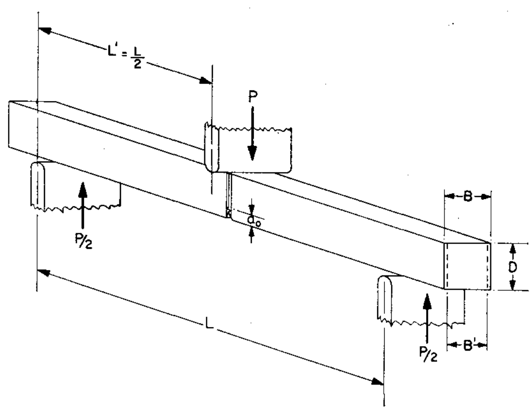

Fig. 1 Single-edge-cracked 3-point bend bar.

Space and ocean engineers strive to decrease weights by optimizing the structural strength-to-weight ratios. However, higher material strength is normally accompanied by lower toughness, small critical crack sizes, and danger of catastrophic brittle failures. Thus, one must choose a relatively strong material with sufficient toughness so that nondestructive testing will detect subcritical-sized flaws.

Fracture-Toughness Data for 12% Ni Maraging Steel

The 12% Ni maraging steel is emerging as such a material.[1] When properly aged, it obtains relatively high strength and maintains exceptionally high fracture toughness. The composition of commercially available 12% Ni maraging steel is shown in Table 1.

A number of heats and strengths of 12Ni-5Cr-3Mo maraging alloy were tested in 1- and 2-in. thick plates, and results are shown in Tables 2 and 3. [Plate numbers given are consistent with those used in NRL (Naval Research Lab) reports and chemical analysis and detailed properties of each individual plate are given in Ref. 2]. The precracked three-point bend-bar specimen (see Fig. 1) and testing method recommended in Ref. 3 were used in determining the apparent K_{Ic} values. The specimen orientation notations are those recommended by ASTM and are shown in Fig. 2. Since no pop-in was observed, the ultimate load was used to calculate values in Tables 2 and 3.

The net section stress was calculated from the standard bending-stress equation, considering the bar to be of depth D-a_0 and neglecting stress concentration due to the notch.

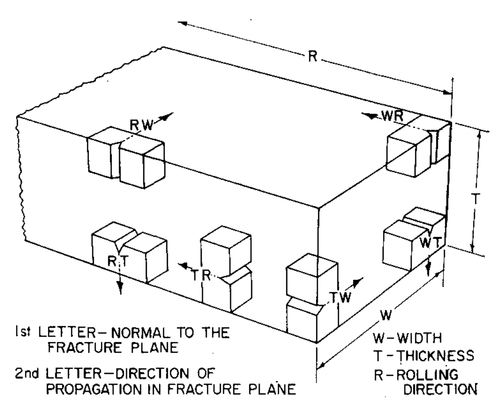

Fig. 2 Identification procedure for fractures in rolled material.