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REINFORCED PLASTICS FOR DEEP-SUBMERGENCE APPLICATION

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Abstract—This paper presents an overview of the present state of technology for reinforced plastic materials related to the ocean engineering field. Typical marine applications are described. Information and references are presented on fabrication and properties of high-strength, filament-wound plastic materials, pertinent to deep-depth pressure hull and buoyancy applications. Problem areas are discussed and future composite material improvements are projected. Much of the data presented has been developed through an extensive R & D programme sponsored by the Naval Ship Systems Command.

INTRODUCTION

GLASS reinforced plastics, often otherwise referred to as structural plastics, GRP, fibre glass, filament wound plastics or reinforced plastic laminates, are a composite of high-strength glass fibres bonded together by a resin matrix. The major strength and stiffness is derived from the reinforcement. The matrix provides the shear strength required to stabilize and support the fibres and protects them from damage. The glass fibres can be organized and oriented in a manner to best resist the imposed loads. The resin systems vary widely in characteristics and can be selected to impart particularly desired properties as, for example, heat resistance, resistance to a specific chemical or greater toughness.

It is emphasized that reinforced plastic refers to an almost infinite variety of composite systems, each of which has specific characteristics. These systems consist of:

(a) Fibrous reinforcements of different types and forms (e.g., woven cloth, random mat, woven roving, or strands which may be directionally oriented). Figure 1 shows the various steps in manufacture of multiple-end glass roving reinforcement.

(b) Matrices (resins) of different chemical natures (e.g. polyester, epoxy, phenolic), and

(c) The Matrix–Resin Interface—variously referred to as sizing, treatment, coupling agent or finish, which provides a "bridge" between the matrix and reinforcement.

It is necessary, therefore, to be precise in defining the specific composite system with which one is concerned.

Conventional glass reinforced plastic materials have demonstrated their versatility and usefulness in a wide variety of structural and semi-structural naval applications over the past 20yr. Some of these will be briefly reviewed in this paper.

It was as a result of such experience and the development of improved filament winding materials and techniques that the Navy became interested in exploring the potential of filament wound glass reinforced plastic (FWP) for pressure hull structure. As a result, a programme of broad scope varying from basic studies to model tests, Fig. 2, was initiated.

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†Formerly the Bureau of Ships.

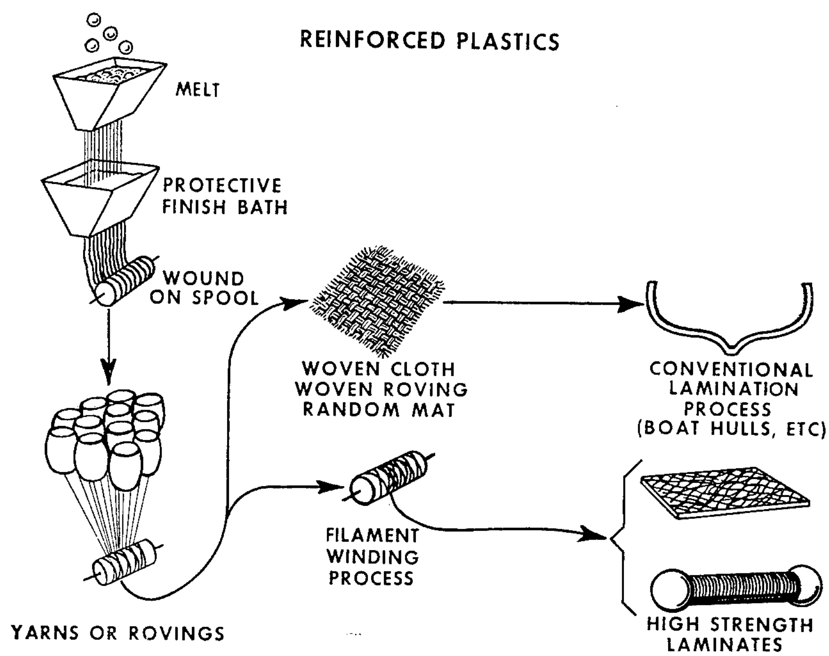


FIG. 1. Schematic showing fiberization, spooling and impregnating of glass roving.

I RESEARCH

Effect of Microvoids
Crack Propagation & Growth
Glass Finish Agents
Factors Influencing Fatigue
Mechanism of Water Absorption
Improved Resin Systems

II DEVELOPMENT

Material Studies (Properties, Long Term Static and Cyclic Fatigue, Effect of High Hydrostatic Pressure)
Inspection and Non-Destructive Tests

III PROCESS

Thick Walled Composites
Effect of Variables
Residual Stresses
Quality Control (Voids)

IV DESIGN

Design Concepts (Spheres, Spheroids, Hollow Filaments, Sandwich Construction Intersecting Spheres, Radial Fiber, Etc.)
Design Details (Enclosures, Penetrations, Attachments, Etc.)

FIG. 2. NAVSHIPS programme—filament-wound plastics for deep-submergence pressure hulls.

Hom (1967) has previously discussed in some detail, the results of design studies and model tests. This paper will present a brief review of the materials data which have been developed, related to deep ocean environment and service conditions, and will project future potential material improvements.

Let us first look at some long-term experience the Navy has had with GRP which, hopefully, may stimulate some new ideas on the use of these materials in ocean engineering.

CONVENTIONAL GLASS REINFORCED PLASTIC (GRP) LAMINATES

The term "Conventional laminates", for the purposes of this paper, is defined as com-

Type of Laminate	Style 181** Glass Cloth Polyester Resin	Random** Glass Mat Polyester Resin	Woven** Roving Glass Polyester Resin	Style*** 181 Glass Cloth Epoxy Resin
Property Direction of Test	0^0	Isotropic	0^0	0^0
Tensile-Dry (PSI)	37,000	9,000	35,000	47,000
Flexural-Dry (PSI)	50,000	18,000	32,000	70,000
Flexural-Wet*(PSI)	45,000	15,000	29,000	65,000
Flexural Modulus-Dry (PSI)	$2{\cdot}5\times10^6$	$0{\cdot}85\times10^6$	$1{\cdot}65\times10^6$	$3{\cdot}3\times10^6$
Flexural Modulus-Wet* (PSI)	$2{\cdot}3\times10^6$	$0{\cdot}77\times10^6$	$1{\cdot}5\times10^7$	$3{\cdot}2\times10^6$
Compressive Strength-Dry (PSI)	28,000	16,000	18,000	50,000
Resin Content (% By Weight)	35-43	65-75	45-56	25-30

*After 2 Hr. Boil
** Specification MIL-P-17549 (Minimums)
*** Specification MIL-P-25421 (Minimums)

FIG. 3. Typical properties of conventional GRP laminates.

prising laminates reinforced with random-oriented glass mat, woven cloth, woven rovings or combinations thereof bonded together by a resin matrix, usually polyester. The fabrication process used is designated as hand lay-up and may be accomplished using contact pressure, alone, or using pressure applied by vacuum bag or autoclave. These composite materials display a broad range of properties, Fig. 3, depending on such factors as the nature and type of reinforcement and resin, orientation of reinforcement, resin content, fabrication technique used, quality, etc. The materials, processes and properties are described in detail by Oleesky and Mohr (1964).

The durability and suitability of such materials for use in the ocean environment and the ability to withstand service abuse have been well demonstrated by years of experience in a wide variety of Navy applications, such as boats, submarine superstructures, masts, fairings, tanks, etc.

GRP construction has been used in Navy boats for 20yr. Spaulding and Della Roca (1965) indicate that fibreglass is firmly established as a hull material for naval craft up to 50ft in length. More than 2000 fibreglass craft from 9 to 57ft in length are presently in Navy service. Today, we are considering larger fibreglass craft, up to 200ft in length.

Glass-reinforced plastics are being used in several important submarine applications in which they have usually replaced aluminium, or have been used in place of other more expensive corrosion-resistant alloys. The advantages sought include: elimination of electrolytic corrosion, reduced maintenance, use of non-critical materials, ease of fabrication and repair, dielectric properties, cost and weight savings.

Submarine fairwaters have performed satisfactorily for over 11yr. These are large free-flooding structures which are designed to withstand 1000lb/sq. ft. wave slap, and weigh over 12,000lb. Fried and Graner (1966) report on the first installation on the U.S.S. *Halfbeak* (SS 352), Fig. 4. After 11yr of service, samples cut from the structure still met the original

(A) AVERAGE OF 3 PANELS
(B) SPECIFICATION MIL-P-17549 VALUES

PROPERTY	ORIGINAL VALUES (A)	AFTER 11-YEARS IN SERVICE PANEL-1	PANEL-2
FLEXURAL STRENGTH, PSI × 10^3			
DRY (AS REC'D)	52·4	51·9	51·9
WET (AFTER 2 HRS. BOIL)	54·3	46·4	47·3
(WET/DRY) × 100, %	104	89	91
FLEXURAL MODULUS, PSI × 10^6			
DRY	2·54	2·62	2·41
WET	2·49	2·45	2·28
(WET/DRY) × 100, %	98	94	95
COMPRESSIVE STRENGTH, PSI × 10^3			
DRY	33 (B)	40·2	38·0
WET	28 (B)	35·9	35·2
(WET/DRY) × 100, %		89	93
BARCOL HARDNESS	55	53	50
SPECIFIC GRAVITY	1·68	1·69	1·66
RESIN CONTENT, % (WEIGHT)	47·6	45·4	48·2

FIG. 5. Submarine fairwater material properties.

specification requirements, Fig. 5. Figure 6 shows the revised, high bridge type fairwater which is sectionalized in order to provide greater installation flexibility. Fairwaters of this type, together with sections of plastic decking and side plating, have been installed on over 50 Guppy class submarines.

An ECM mast section, which must resist external submergence pressure (Fig. 7), has performed satisfactorily on the U.S.S. *Atule* (SS 403) for over 10yr.

Mast fairings, Fig. 8, which are free flooding structures, have been installed to reduce the hydrodynamic resistance of pressure-resistant filament wound plastic masts, Fig. 9. Over 70 of these masts and fairings have been installed on Polaris and nuclear submarines since 1961. Such structures previously were fabricated of aluminium. GRP has been adopted to eliminate electrolytic corrosion problems and reduce maintenanec.

Several submarines have GRP sonar domes, such as the one on the bow of the U.S.S. *Nautilus* (SSN 571), Fig. 10, and deck domes which have performed satisfactorily for many years.

There is little doubt that the inherent durability, high strength: weight efficiency, flexibility of design and ease of fabrication of glass-reinforced plastics will make them the material of choice for a variety of structural and semi-structural oceanographic applications such as housings and fairings, containers, pipe, tanks, decks, etc.

HIGH-STRENGTH, FILAMENT-WOUND PLASTIC (FWP)

The exploration of the depths of the seas introduces new, previously unknown demands on materials of construction for pressure hulls. As Fig. 11, demonstrates, an operating depth capability of 20,000ft would give man access to 95 per cent of the ocean areas. Krenzke, *et al.* (1965), in an analysis of deep-depth pressure hull structures, indicated that if a mobile vehicle capable of carrying a reasonable pay-load (say, for example, equal to the hull weight,

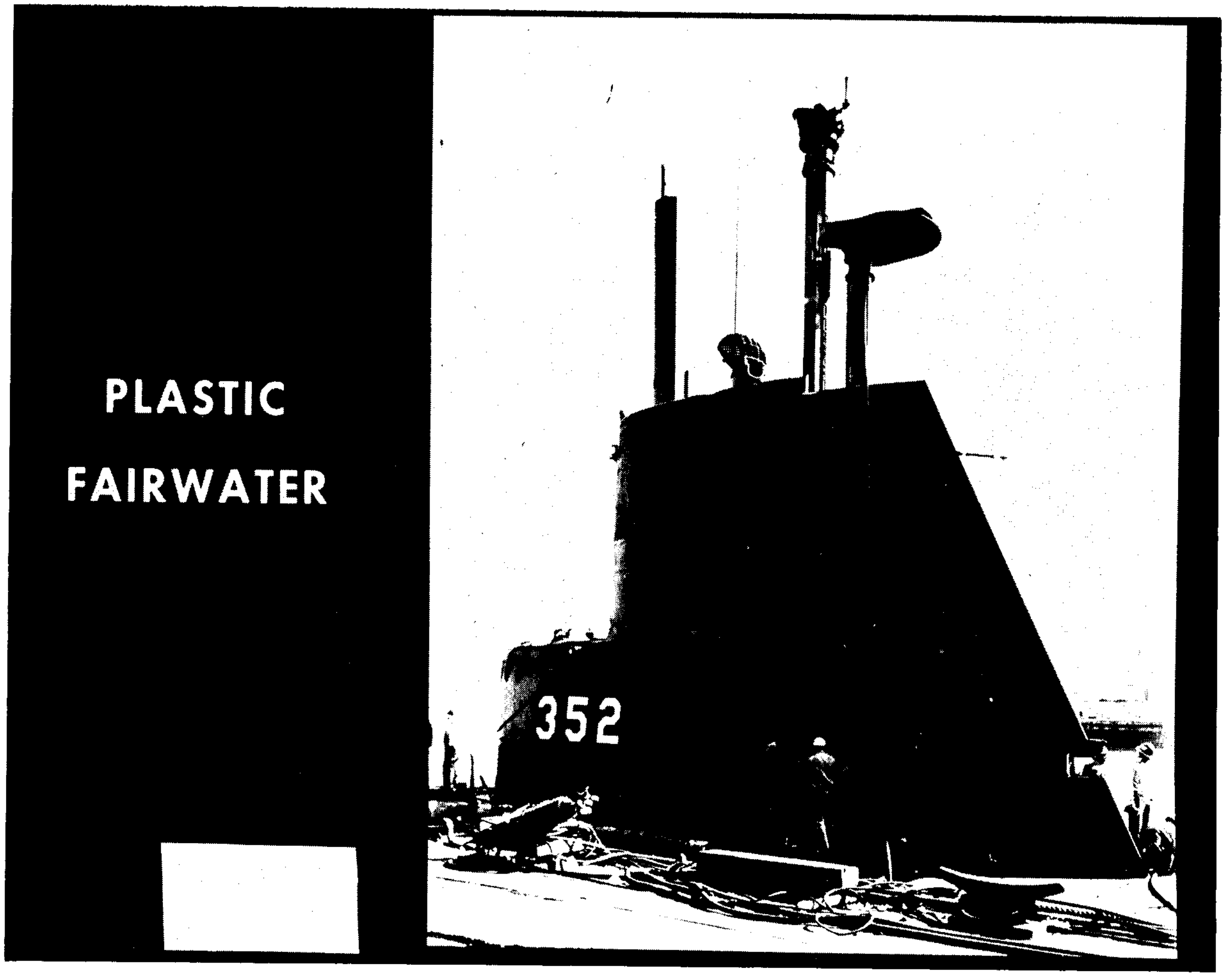


FIG. 4. Submarine fairwater—U.S.S. *Halfbeak*.

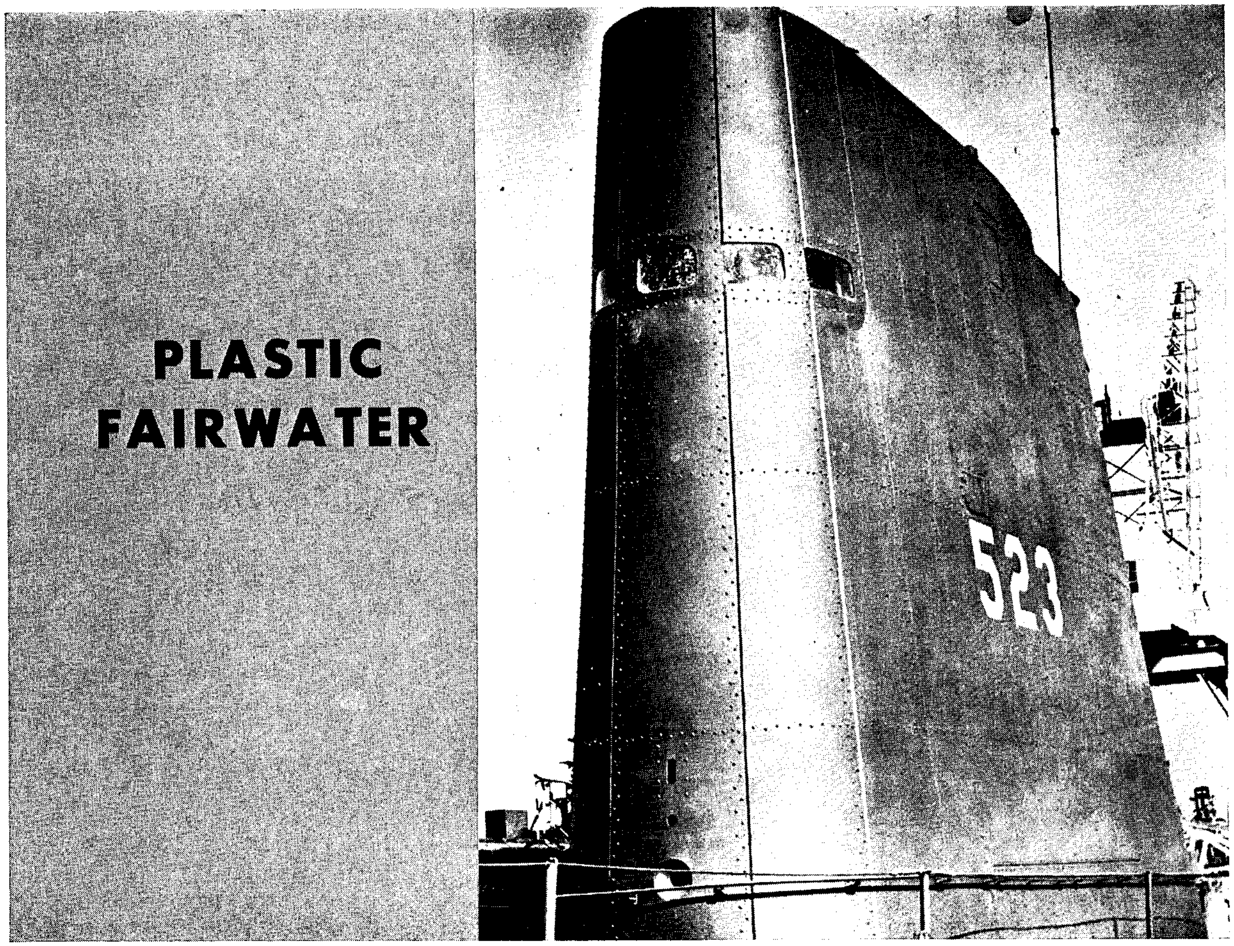


FIG. 6. Improved high-bridge submarine fairwater.

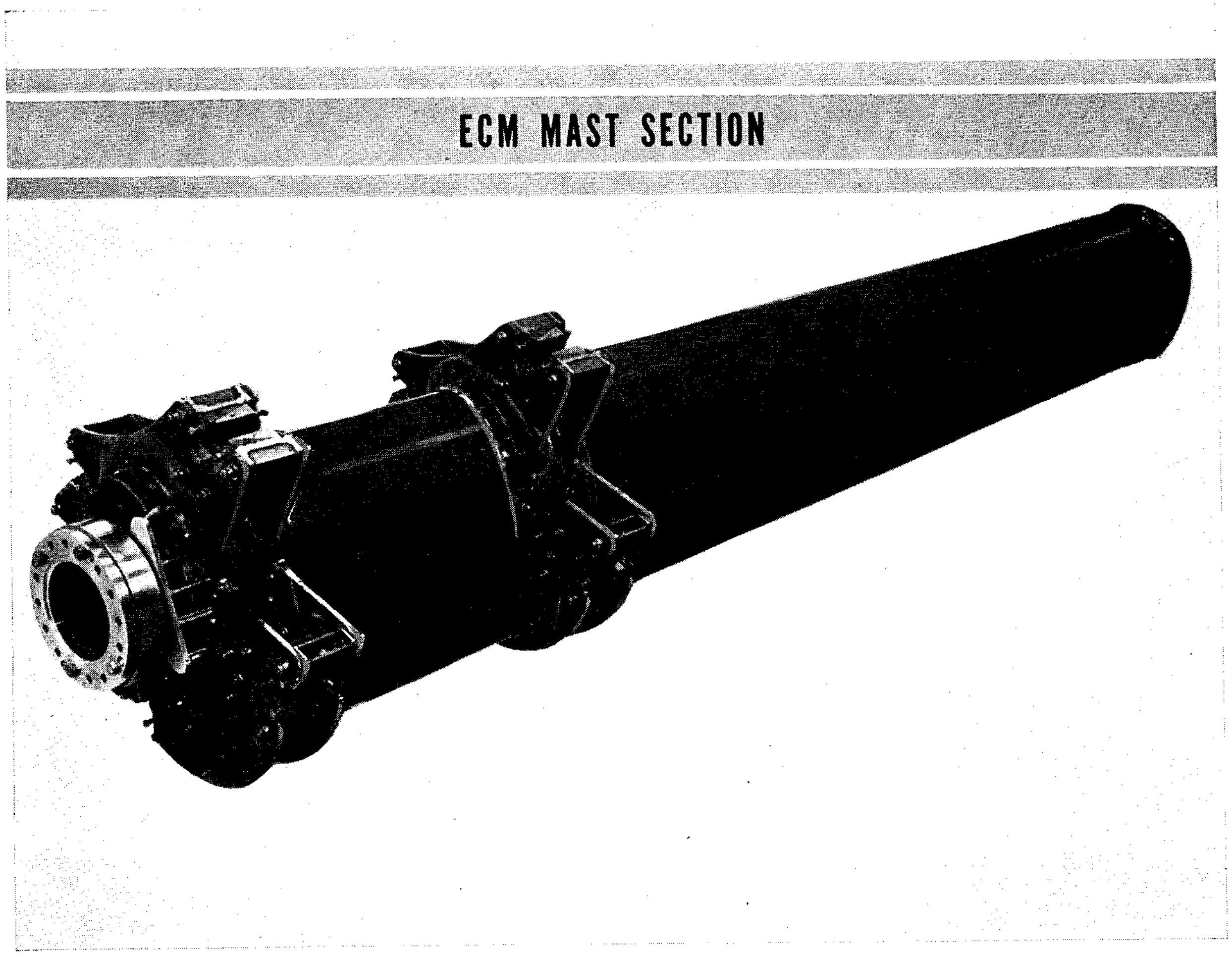


FIG. 7. ECM mast.

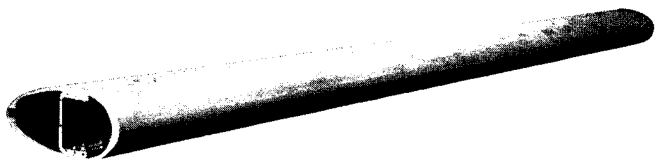


FIG. 8. Mast fairing.

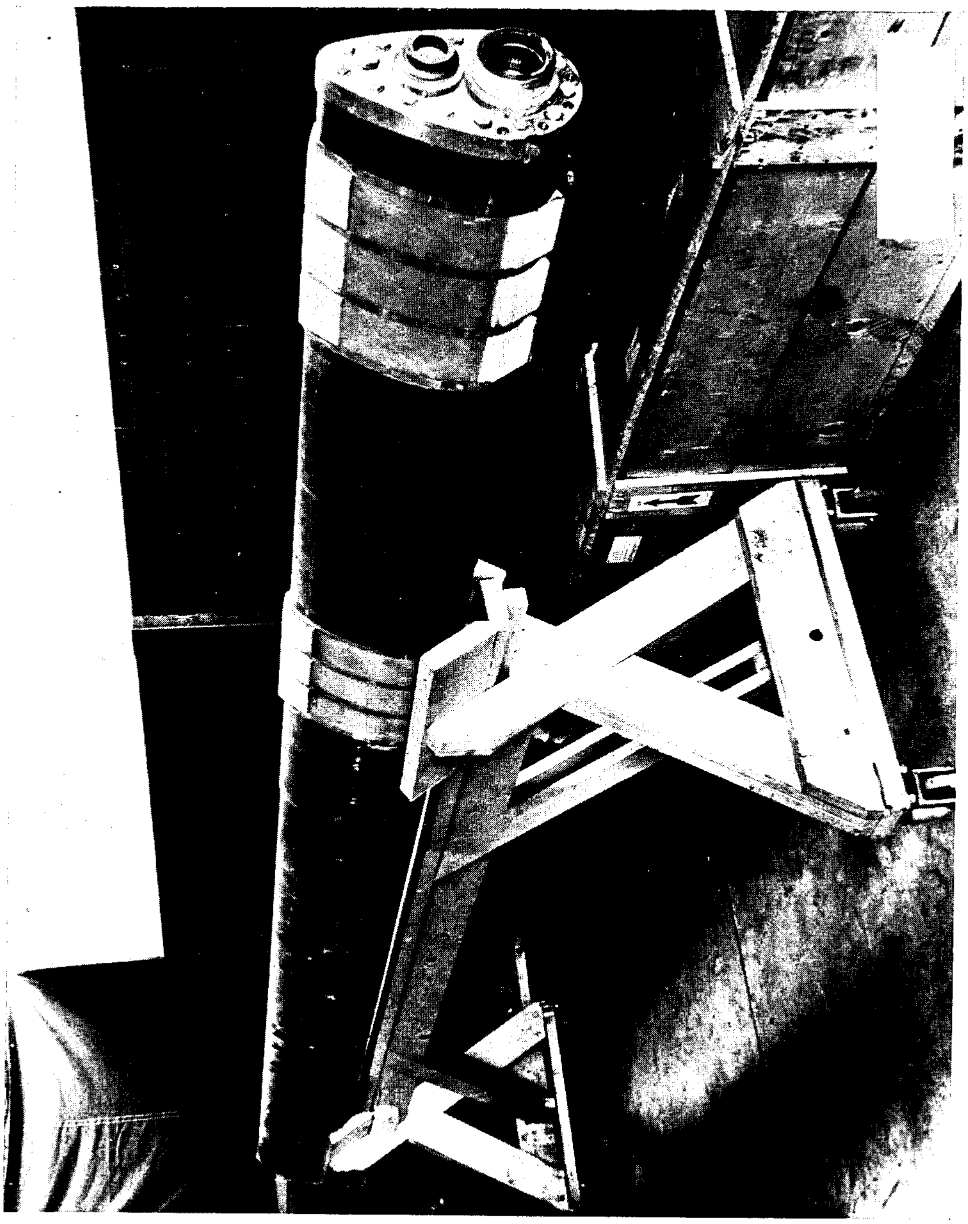


FIG. 9. Pressure-resistant FWP mast.

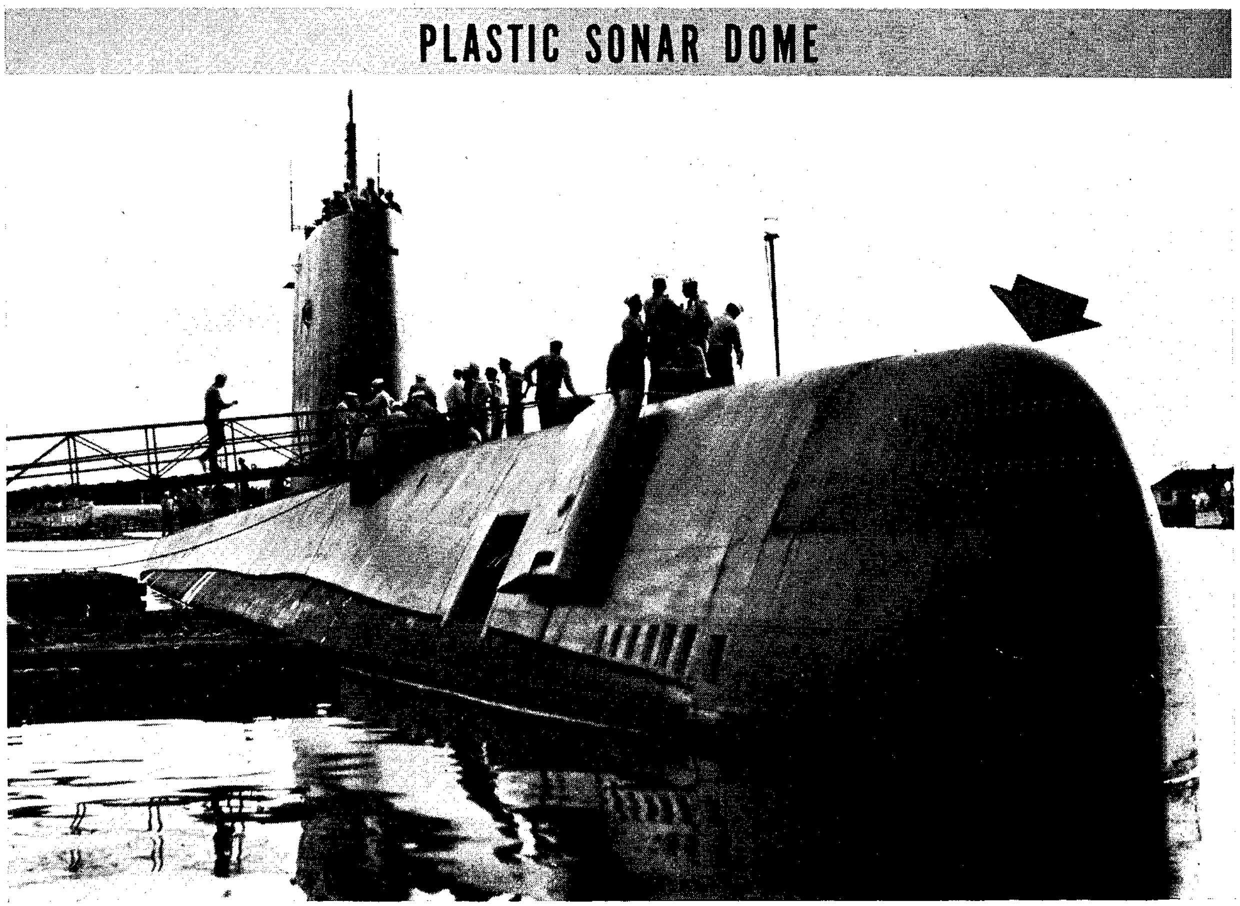


FIG. 10. Submarine bow dome.

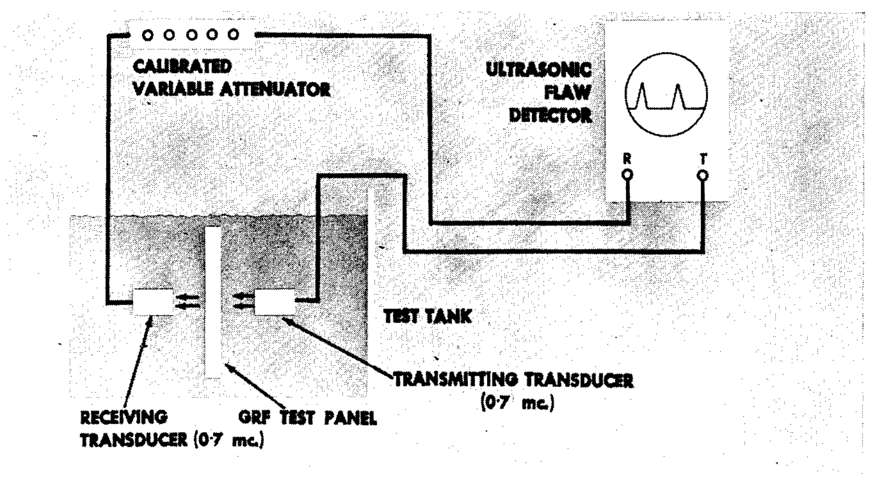


FIG. 21. Ultrasonic tester-schematic.

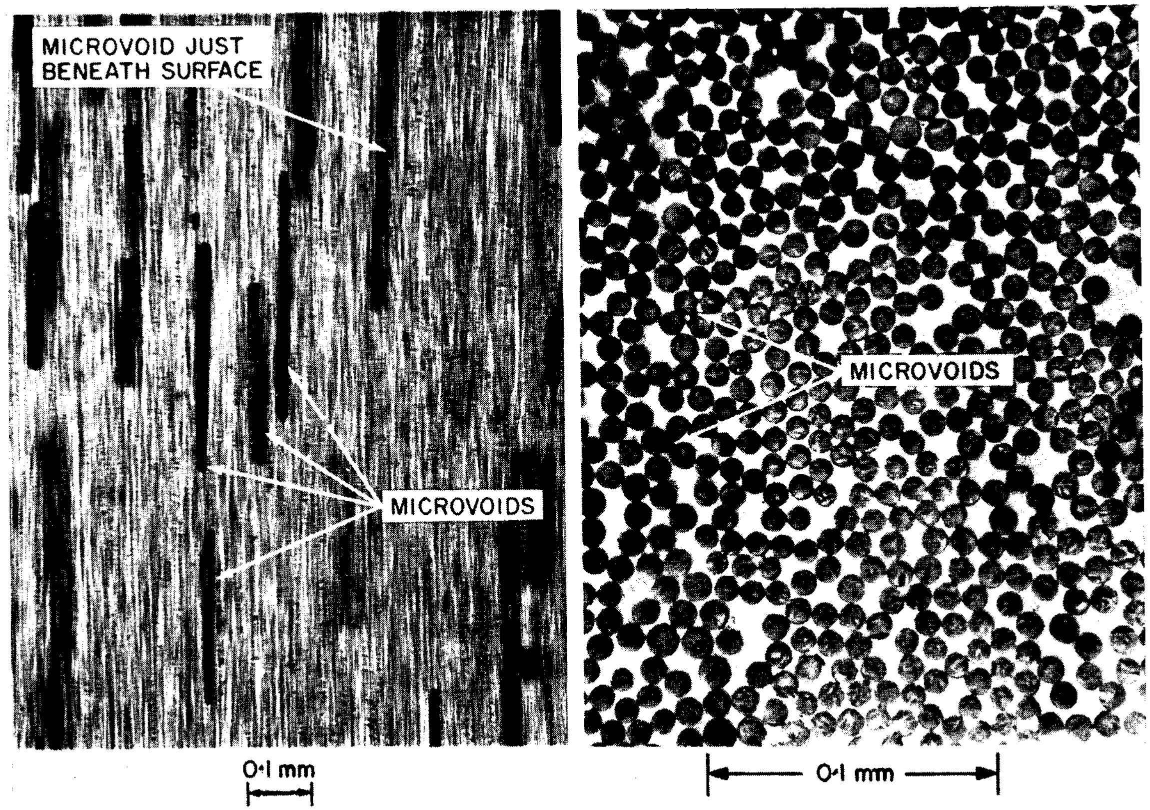


FIG. 23. Photomicrographs of microvoids—transverse and cross-sections.

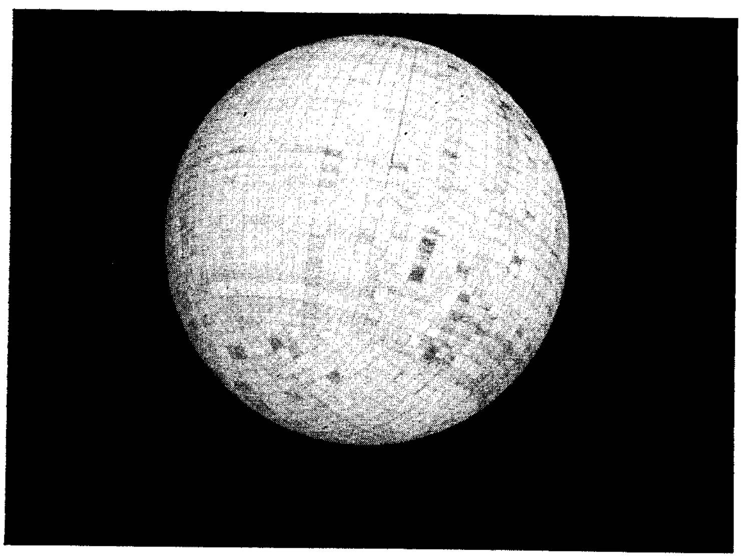
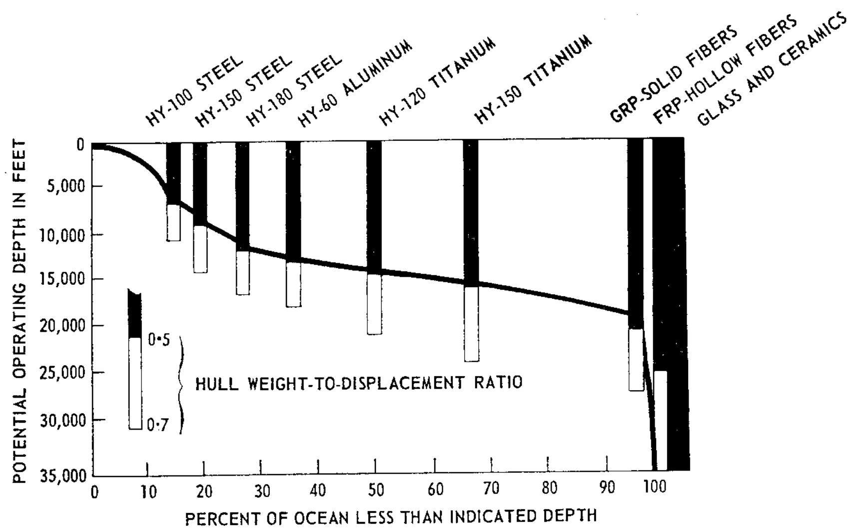


FIG. 27. Radial fibre reinforced sphere.



NOTE: "HY" DENOTES YIELD STRENGTH ASSUMED IN CALCULATIONS.

OPERATING DEPTH POTENTIAL OF SPHERICAL PRESSURE HULLS

FIG. 11. Materials vs. ocean depth.

	Compressive Strength (Ksi) "F_C"	Compressive Modulus (10^6psi) "E"	Density ($lb/in.^3$) "D"	Specific Strength (10^6in.) "$F/_{C/D}$"	Specific Stiffness (10^9) "$E/_D 2{\cdot}5$"
Steel	150	30	0·28	0·5	0·7
Aluminium	50	10	0·099	0·5	3·2
Titanium	100	15·5	0·17	0·6	1·3
	150			0·9	
FWP	100	5·6	0·075	1·3	3·7
(2:1 Orientation)	200			2·7	

FIG. 12. Specific strength characteristics. NRL Rpt 6167.

which would be equivalent to a weight : displacement of 0·5) at operational depths down to 20,000ft is to be achieved, new materials having high strength:weight efficiency must be used for either the pressure-hull or for supplementary buoyancy chambers. They indicate the most promising materials to be titanium with a compressive yield strength of about 150,000psi, glass-reinforced plastics, and glass. All of these materials are in a developmental state. Figure 12 indicates the specific strength characteristics for various structural materials.

The glass-reinforced plastics referred to by Krenzke are a highly sophisticated composite of glass fibres, which are oriented in a manner to best resist the particular loads imposed and are bonded together by epoxy resin.

The filament-wound plastics with which we will be primarily concerned in this paper are produced by an automated process capable of high-speed production and subject to close control. Figure 13 shows a schematic arrangement for one type of filament winding machine

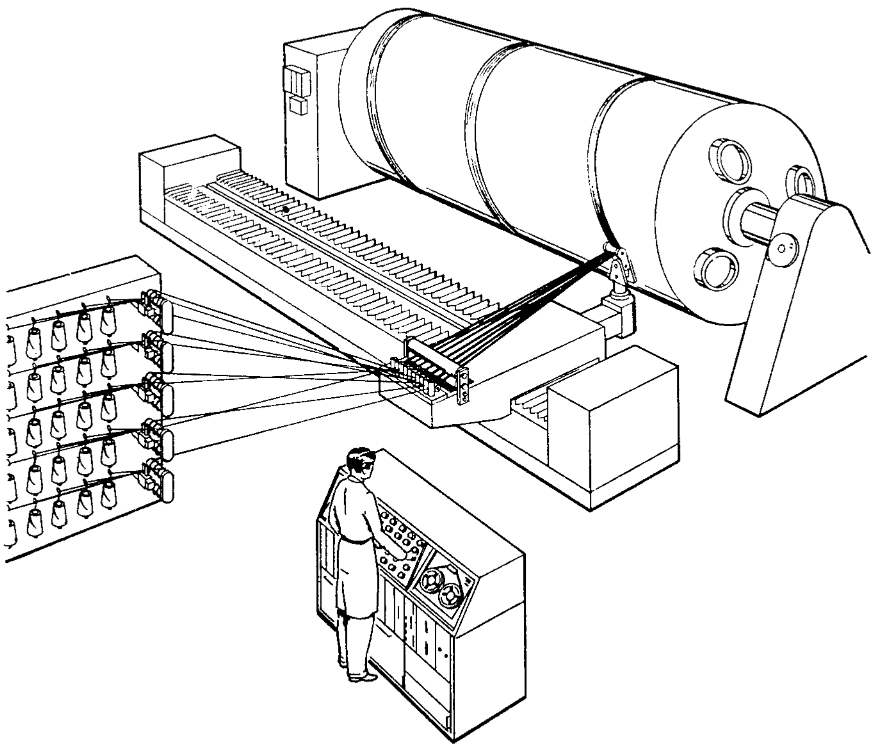
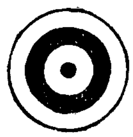


FIG. 13. Typical filament-winding machine.

There are a number of machines in being which are capable of winding structures up to 13ft dia. Filament winding has generally been limited to generatable shapes such as cylinders or spheres and has been used to produce such internally loaded structures as piping, tubes, high-pressure gas storage containers and Polaris motor cases.

In undertaking an evaluation of FWP for deep-submergence pressure hulls, a target objective was adopted for a small research vehicle, Fig. 14. A specific glass-reinforced composite system was then selected for all development, test and evaluation programmes. This consisted of "S" glass fibres (which identifies the chemical composition of the glass) with HTS finish (a proprietary designation), in the form of multiple-end rovings, pre-impregnated with 18–20% by weight of a resin system consisting of EPON 828 (50 parts by weight), EPON 1031 (50pbw), Methyl Nadic Anhydride (MNA) (90pbw), and Benzyl Dimethyl Amine (BDMA) (0·5pbw). This material was chosen because it was commercially available to a stringent Polaris specification. An extensive evaluation of all types of resin systems by Petker and Eilfort (1963) indicated the resin system to be among the better formulations available, on the basis of compressive and shear strengths.

Tests were conducted, using simple filament-wound specimens and unstiffened, thick-walled cylinders having a fibre orientation of 2:1. The 2:1 directionality is best suited for resisting hydrostatic pressure on a cylinder, in which the resulting stresses in the circumferential direction are twice those in the longitudinal direction. Objectives of the tests were to determine: (a) Short-term properties; (b) Effects of exposure to hydrostatic pressure; (c) Effects of long-term cyclic and static fatigue stresses under hydrostatic pressure.



OPERATING DEPTH	15,000 FT (6,670 PSI)
COLLAPSE DEPTH	30,000 FT (13,300 PSI)
NO. OF EXCURSIONS TO MAX DEPTH	1,000 TO 2,000
LENGTH/DIAMETER	4/1 TO 5/1

WEIGHT DISPLACEMENT 0·64
(INCLUDING END-CLOSURES AND PENETRATIONS)

FIG. 14. Target requirements for research vehicle.

In order to determine the true compressive strength of simple FWP specimens, new test methods had to be devised such as the NASL Notched Flat Method, Winans and Fried (1963), and the NOL Ring Test, Prosen (1964), to preclude failure by buckling or shear.

Typical short-term properties of a 2:1 oriented filament-wound plastic material are listed in Fig. 15. The outstanding characteristics of such a laminate are high compressive strength in combination with low density. As indicated by Hom (1967), the comparatively low modulus and the high ratio of compressive to interlaminar shear strengths have a significant bearing on the ability to design an efficient structure. Schneider and Miller (1966) have conducted an analytical optimization study of filament-wound pressure hull shapes, taking into account filament orientation and fabrication techniques. In their investigation, they have paid particular attention to buckling (general instability) and interlaminar shear. The types of shapes considered were spheres, segmented spheres, cassinians, prolate spheroids and ogives. Allowable biaxial and shear strengths were appropriately reduced to meet a cyclic fatigue life requirement of 10,000 cycles. Intersecting spheres with boron rings at the intersections were found to have the lowest weight : displacement ratio. Intersecting spheres with fibreglass rings ranked next. Because it more closely reflects current state of the art, models of the latter construction were selected for further evaluation and are being fabricated for test. A weight : displacement of 0·38 may be possible for 30,000ft collapse depth.

Figures 16 and 17 from Fried *et al.* (1966), show the effects of exposure to water at various pressures and time durations on compressive strength, compressive modulus and interlaminar shear strength of simple test specimens. It should be pointed out that the conditioning was most severe, since the test specimens were immersed at pressures up to 13,300psi (30,000ft) with all cut edges exposed. Despite this, even after a year of exposure, strengths did not fall below 90 per cent of the initial values.

Myers and Fink (1965) compare results of cyclic fatigue tests on unstiffened cylinders under hydrostatic pressure for two cycling rates and relate them to test data by Cornish *et al.* (1964), and Abbot *et al.* (1965), Fig. 18. Ten thousand cycles were arbitrarily chosen as the cut-off point. The differences in stress levels between the two sources can be attributed to

(2:1 FIBER ORIENTATION-POLARIS MATERIAL-TESTED IN "2" DIRECTION)

● COMPRESSIVE STRENGTH	170,000 PSI
● COMPRESSIVE MODULUS	$5{\cdot}8 \times 10^6$ PSI
● TENSILE STRENGTH	214,000 PSI
● TENSILE MODULUS	7×10^6 PSI
● FLEXURAL STRENGTH	190,000 PSI
● POISSON'S RATIO	0·15
● ULTIMATE ELONGATION	2·5 - 3·0%
● SHEAR STRENGTH	8-10,000 PSI
● SPECIFIC GRAVITY	2·0-2·1

FIG. 15. Typical properties for State-of-the-Art filament-wound plastics.

EFFECT OF TIME OF EXPOSURE AT 13,300 PSIG
ON STANDARD FILAMENT WOUND PLASTIC MATERIAL

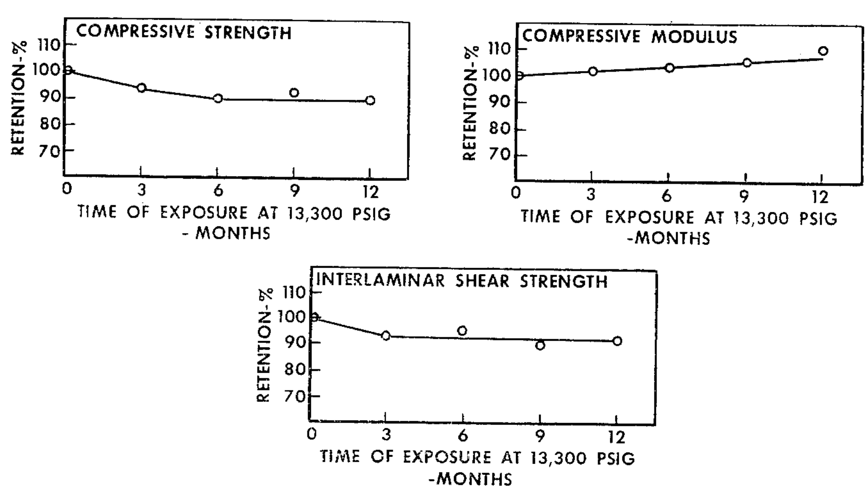


FIG. 16. Effect of extended exposure to high hydrostatic pressure on properties of FWP.

geometry of specimens and end-conditions. From these data, it appears that there is a wide amount of scatter. However, Freund and Silvergleit (1966) have analysed available data from several sources on the results of uniaxial, biaxial compressive and interlaminar shear cyclic fatigue tests numbering in the hundreds. They conclude "that a 'percentage of ultimate' concept exists wherein the applied fatigue stress, as a percentage of true ultimate static stress can be used in reliably predicting the fatigue life of FWP material. This percentile of

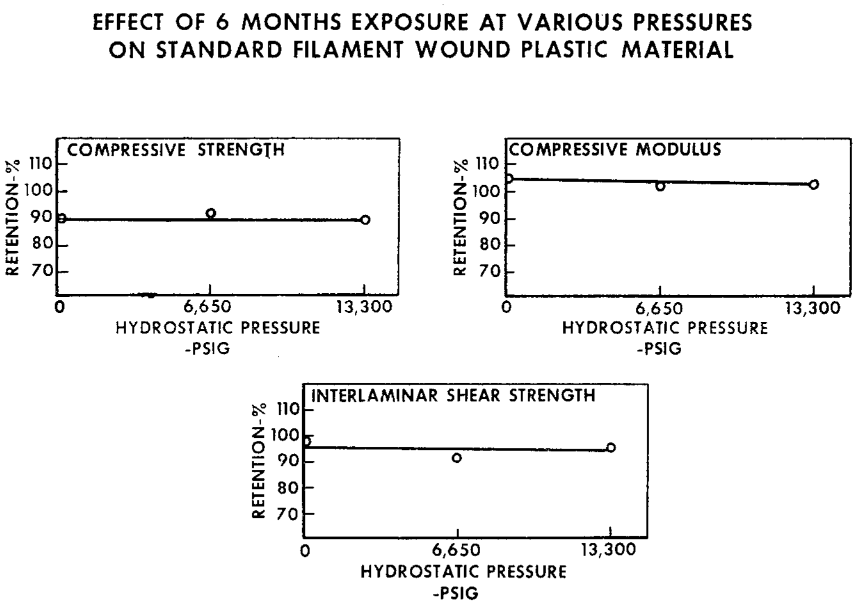


FIG. 17. Effect of various hydrostatic pressures on properties of FWP.

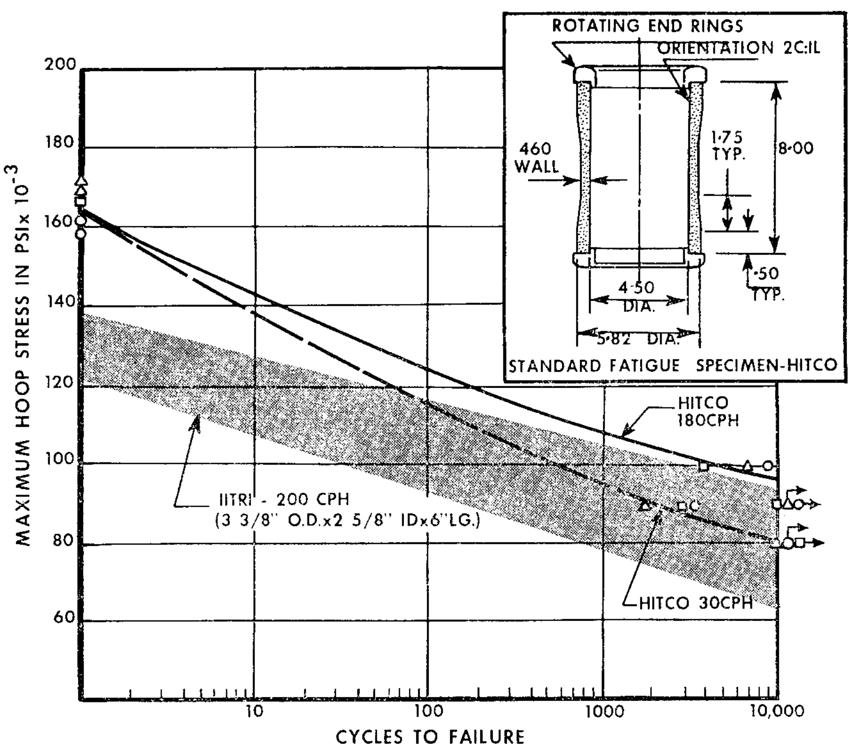


FIG. 18. Fatigue test-hoop stress vs. number of cycles.

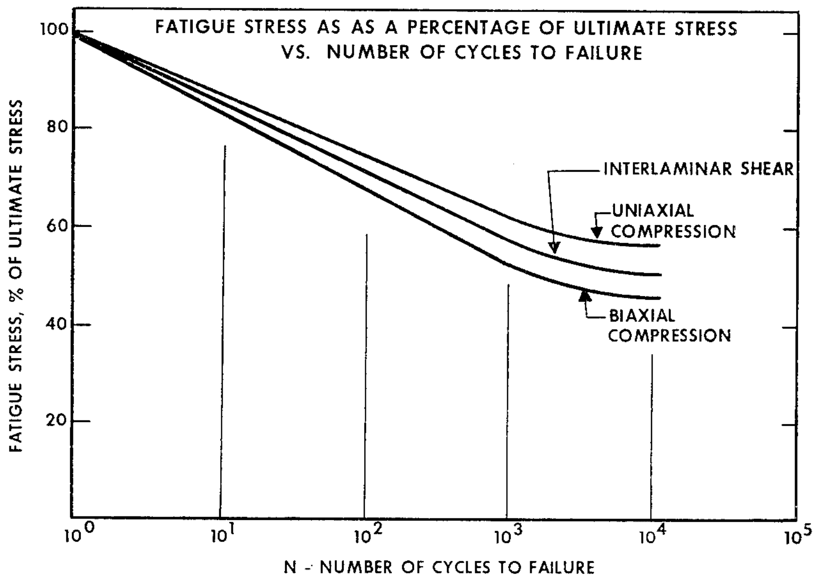


FIG. 19. Summary of uniaxial and biaxial compressive and interlaminar shear fatigue data.

MAXIMUM HOOP STRESS (PSI)	DURATION UNDER PRESSURE TO DATE (5/15/67) WITHOUT FAILURE (HOURS)
42,500	36,000
60,800	28,400
70,900	23,600
81,000	26,900
101,000	23,300

FIG. 20. Long-term exposure to hydrostatic pressure under biaxial stress.

true static stress appears to be constant for any given number of cycles, irrespective of test method, specimen fabrication, or specimen geometry." The data are summarized in Fig. 19. No specimen failed below the curves indicated for uniaxial, biaxial or shear fatigue, respectively. This conclusion is in agreement with the large amount of fatigue data obtained over the years for conventional laminates of all types.

Cole (1966) reports on biaxial creep performance of filament-wound laminates. Figure

20 indicates elapsed times under various stress levels to which unstiffened FWP cylinders have been subjected without failure, This test is continuing. The biaxial compressive stress rupture lives of the composite studied are quite long, even at high stress levels. It seems fair to say that a stress rupture life of at least 2yr at a stress level of 100,000psi can be expected and that much longer lives are to be expected at lower stress levels. The strain data observed does not show the material exhibiting any significant creep for stress levels up to 80,000psi; specimens tested at higher stress levels were not instrumented.

Undoubtedly, the three most significant discoveries resulting from work to date have been:

(1) the relationship of FWP laminate void content to acoustic attenuation;
(2) the relationship of FWP laminate void content to strength and % water absorption;
(3) the ability to predict residual cyclic life by through-transmission ultrasonics.

Hand (1965) describes the technique used for non-destructive evaluation of FWP using ultrasonic techniques, shown schematically in Fig. 21. The relationships of compressive strength, interlaminar shear strength, void content and ultrasonic attenuation as determined by Hand are summarized in Fig. 22.

Other investigators have confirmed the correlation of voids with strength. Sands *et al.* (1967) have made micrographs of microvoids in FWP (i.e., voids less than 0·05mm. dia.), Fig. 23, and have determined void content by a statistical point-count method adapted from petrographic modal analysis, which appears to be more precise at low void content level (below 1% by volume) than the ignition test method. They conclude that "a linear inverse relationship exists between interlaminar shear strength and void content", Fig. 24. Stone (1965), after studying fabrication variables and their effect on residual stresses in thick-walled, filament-wound cylinders concludes that residual stresses are small both in magnitude and effect on collapse pressure, but that void content affects laminate stiffness and has a

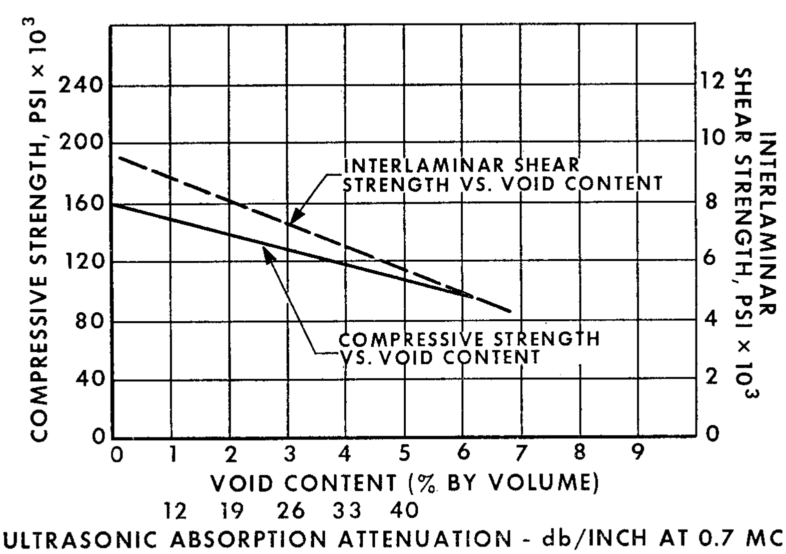


FIG. 22. Ultrasonic absorption attenuation and void content vs. compressive and interlaminar shear strengths.

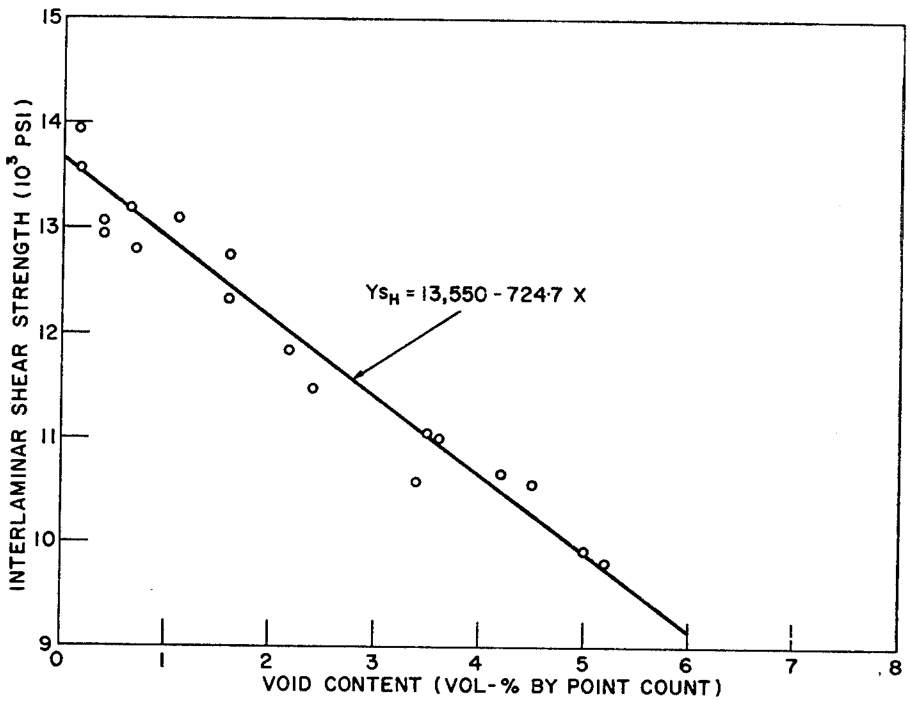


FIG. 24. Interlaminar shear strength vs. void content of NOL rings.

pronounced effect on interlaminar shear strength, particularly on shear fatigue; fabrication techniques are recommended to minimize residual stresses and voids.

The relationship of interlaminar shear to compressive strength has been confirmed by several investigators: Petker and Elfort (1963), Freund and Silvergleit (1966), Fried *et al.* (1966) and Cole and Mulvaney (1967).

Cole (1966) has studied the effect of cumulative damage on compressive fatigue performance of filament-wound laminates. He has determined "that ultrasonic through-transmission techniques can be used to trace the propagation of biaxial compressive fatigue induced damage in fibreglass reinforced plastic cylinders. Beam tests on cylinder longitudinal segments have shown that damage propagates from the inner surface of the cylinder outward and becomes critical when the neutral surface of the beam is damaged. The same phenomenon is shown to be governing in the compressive failure of the whole cylinder during biaxial fatigue.

"Because the damage propagates reasonably uniformly from the inner surface outward, as shown by Fig. 25, it has been possible to establish a level of critical damage, as measured by ultrasonic attenuation, which corresponds to imminent failure of the cylinder. Figure 26 shows the close correlation between prediction and actual failure obtained by this method. The fatigue cycle difference between prediction and failure is seen to be much less than the total scatter possible at a given stress level as shown by the S–N curve failure envelope. Thus, by the ultrasonic inspection method, better failure predictions can be made than by S–N curve methods. A significant advantage is obtained by the ultrasonic method for structures subjected to varying stress states since ultrasonic failure predictions depend

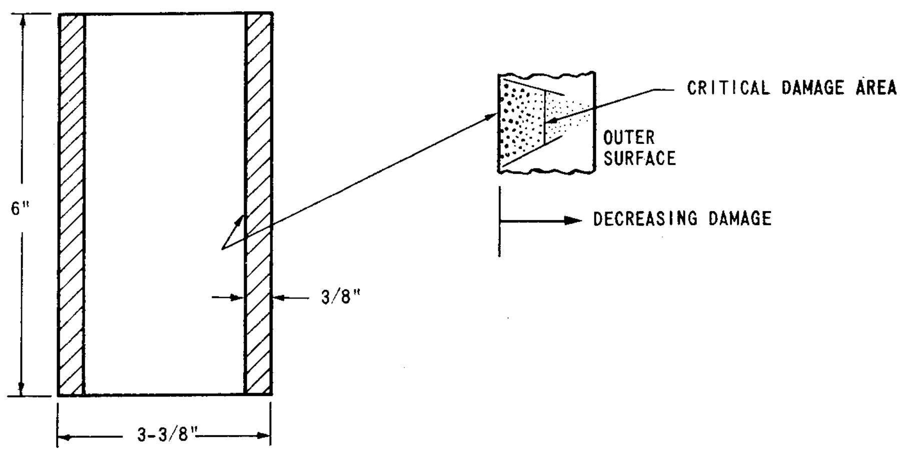


FIG. 25. Cumulative damage under cyclic fatigue.

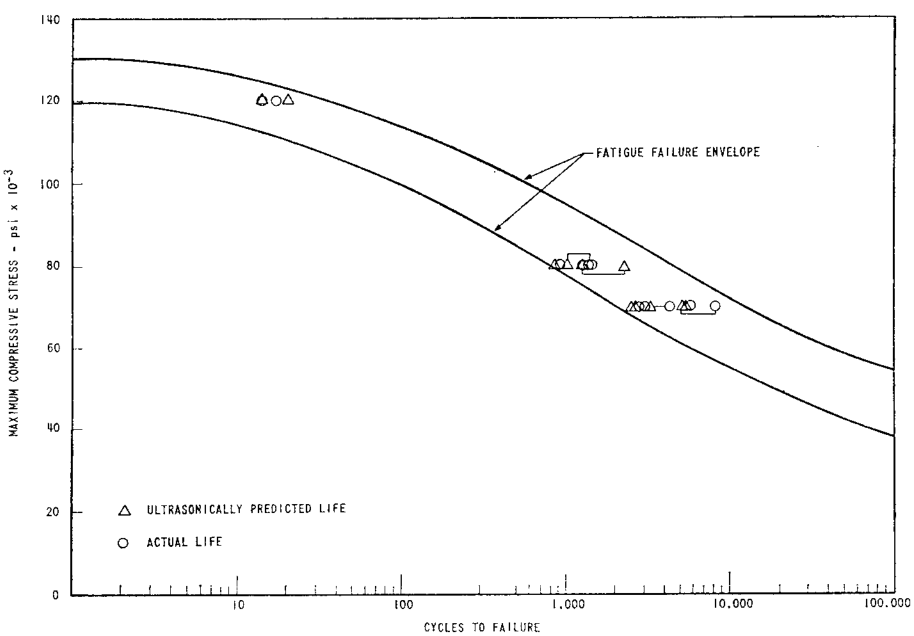


FIG. 26. Fatigue life prediction—S–N curves and ultrasonics.

entirely on a knowledge of the damage present in the structure and not on the fatigue history of the structure."

Finally, mention should be made of two unique variations of glass filament-wound plastic (i.e. filament-wound hollow glass fibres and radial fibre-reinforced spheres). Both of these constructions have been previously discussed in detail by Hom (1967).

Since hollow glass filament-wound laminates may be 20–30 % lower in density than solid filament laminates, the wall thickness may be proportionately thicker, on an equal weight basis, thus making it possible to design an unstiffened cylinder for collapse depths exceeding 35,000ft. Hom (1967) finds little or no static strength advantage but possible improvement in cyclic performance. Wright (1966) has conducted model tests using various fibre hollowness ratios and finds advantages in buckling, fatigue and stress rupture.

Hom (1967) also describes, in some detail, the radial fibre-reinforced sphere, Fig. 27. Static and fatigue tests have been performed on 3in. and 11in. dia. spheres and a 32in. dia. sphere is now being tested. Suffice it to say that at a weight : displacement of 0·39, radial fibre spheres, at present, are the leading contender for providing the necessary buoyancy for 20,000ft operating depth vehicles.

THE FUTURE

The glass filament-resin-finish systems available today have considerable potential for deep-submergence pressure hull or buoyancy chamber construction. However, based on present evidence and trends which are already apparent, it is easy to predict that in the next 20yr composite materials will become available which have several times the strength and stiffness to weight efficiency of those now available, along with improved durability. These materials may be fabricated using automated, high-speed, closely controlled filament-winding techniques, not too much different from those used today.

Figure 28 shows the potential strength of some fibres and whiskers now under development, and the strengths which are presently attainable. The potential strengths are based on theory which predicts that the upper strength limit for such fibres will be 1/10 of the modulus.

Boron filament, with a reported strength of about 350,000psi and a modulus of 60×10^6 psi at a density of 2·59, is the subject of an intensive multi-million dollar R & D programme by the Air Force. Considerable progress has been made in the application of boron composites to extremely weight-critical parts, where stiffness is an important consideration. Low fibre production rate and high cost are principal limitations today.

Continuous filaments of alumina (Al_2O_3) having a density of 3·97 are of interest because of their high modulus (76×10^6psi).

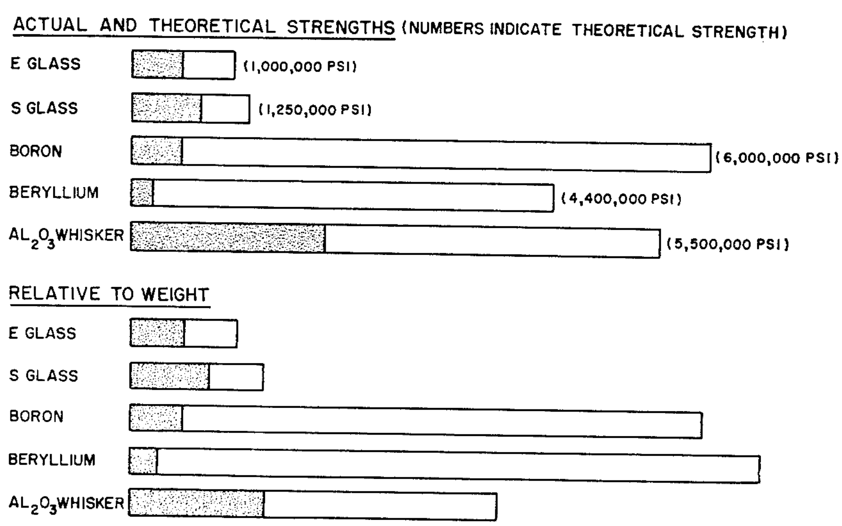


FIG. 28. Reinforcements for composites.

Whiskers, which are single-crystal filaments, have high potential strength and modulus (1,000,000psi and 100×10^6psi, respectively) and several times the elastic elongation of bulk materials. Techniques must be developed to produce composites with a significant proportion of strength of these short fibres.

Carbon fibres can be produced which have low specific gravity and a modulus as high as 68×10^6psi. The Naval Ordnance Laboratory (NOL), Prosen (1966), Barnet (1966), reports that "low modulus fibres, 6×10^6psi or lower, had tensile strengths of 50,000–190,000psi. Composites made from these fibres, when properly impregnated, gave shear, compressive and tensile strengths commensurate with fibre properties." Graphite fibres, which are more experimental than carbon fibres, exhibited low composite interlaminar shear strength, with the highest modulus fibre giving the lowest strength, Fig. 29. NOL is continuing its investigations to improve the shear properties of high modulus fibre-reinforced plastic. For example, composites made of graphite fibres on which beta silicon carbide whiskers have been grown exhibit interlaminar shear properties at least comparable to that for low modulus carbon composites.

The importance of the resin-glass interface, particularly with regard to long-term cyclic fatigue performance and the degrading effects of water, is universally accepted. Fried (1967) reviews the effect of water on the composite, describes possible mechanisms of water penetration and the role of the coupling agent. Levine and La Couse (1967) have studied surface properties of glasses as related to glass polymer interfacial bonding in GRP.

Many investigations, sponsored by the Office of Naval Research, Naval Ship Systems Command, the Air Force and various industrial concerns, are being conducted to obtain basic information on the surface chemistry of glass and the role of chemical finishes or treatments, as well as to develop improved bonding at the interface. The Naval Research Laboratory, Naval Ordnance Laboratory and Naval Applied Science Laboratory all have programmes in this technical area. The subject is an extremely complex one, technically, and too broad to attempt to treat adequately in this paper. Those who have an interest in this subject are referred to the Proceedings of the annual meetings of Society of Plastics Industry, Reinforced Plastics Division. For the last several years, these meetings have devoted

CARBON FIBER		GRAPHITE FIBER	
FIBER MODULUS	LESS THAN 6×10^6	20×10^6	68×10^6
TENSILE STRENGTH (SPLIT DISC)(psi)	88,700		
TENSILE MODULUS (psi)	$4{\cdot}6 \times 10^6$	16×10^6	
COMPRESSIVE STRENGTH (psi)	110,600		
COMPRESSIVE MODULUS (psi)	$4{\cdot}1 \times 10^6$	14×10^6	33×10^6
HORIZONTAL SHEAR (psi)	10,080	3,710	2,000
FLEXURAL STRENGTH (psi)	100,000	57,800	
FLEXURAL MODULUS (psi)		11×10^6	35×10^6
SPECIFIC GRAVITY	1·35	1·38	1·73
RESIN CONTENT (by weight)		25%	17%

NAVAL ORDNANCE LAB. (WHITE OAKS)

FIG. 29. Carbon and graphite fibres—composite properties.

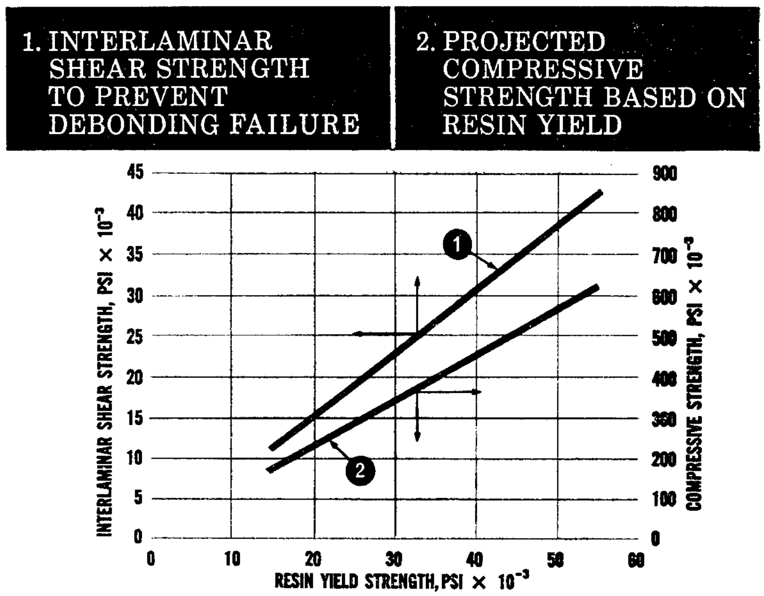


FIG. 30. Interlaminar shear and compressive strength of FWP vs. resin yield strength.

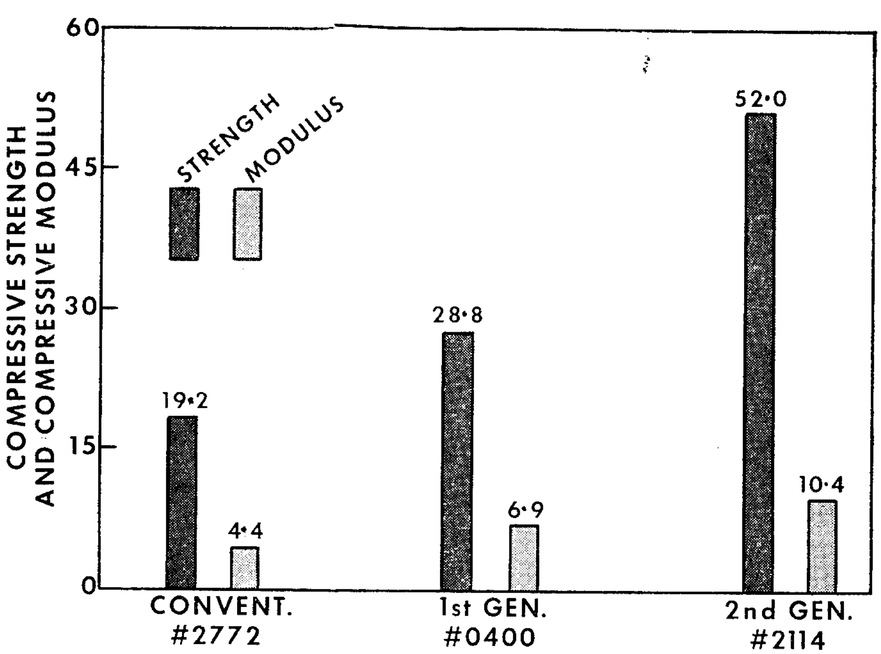


FIG. 31. Trend of resin properties.

at least two sessions to this important subject. Suffice it to say that progress is being made and we may look forward to the day when water effects will be eliminated and the matrix and reinforcement will work together in a more compatible fashion.

The relationship of shear strength to composite properties has previously been described. The compressive yield strength and modulus of the resin matrix has also been shown to be significant. Fried (1966) has postulated that composite compressive strength is related to the compressive yield strength of the resin, Fig. 30. This assumes that there will be similar improvements in the adhesive bond between resin and reinforcement. For several years, NAVSHIPS has sponsored a programme on resins at Union Carbide Plastics, in conjunction with supporting programmes at the Naval Research Laboratory and the Naval Applied Science Laboratory. Berhans (1966) has reported on some of the new resins evaluated. Figure 31 compares the properties of two of these resins with a conventional epoxy resin. It is apparent that significant improvements in matrix are possible. Not only is it desirable to improve the mechanical properties, however, but the resin system must also have practical handling capabilities. At the present time, this is the major obstacle to general use of these improved resins. The Applied Science Laboratory, however, has made and tested laminates using such a resin, Fig. 32, which show promising results.

In 1964, the Undersea Technology Panel of the Project Seabed summer study group reviewed hull structural materials for deep-ocean vehicles. A report, edited by Pellini (1964) of the Naval Research Laboratory, was prepared. Present status and future potential of various candidate materials were considered. Figure 33 summarizes the potential for non-metallic and metallic materials. The lower curve for each is based on information submitted by various sources to the Panel. Examining the predictions, we find that compressive strengths of 200,000psi have already been obtained for simple filament-wound plastic specimens. The challenge that still remains, however, is to develop this strength in usable complex structures. As indicated by Hom (1967), "since the dominant mechanism of failure of laminated GRP structures can be attributed to shear, there is a continuing need to develop (structural design) concepts and structural details which would lend themselves to these materials".

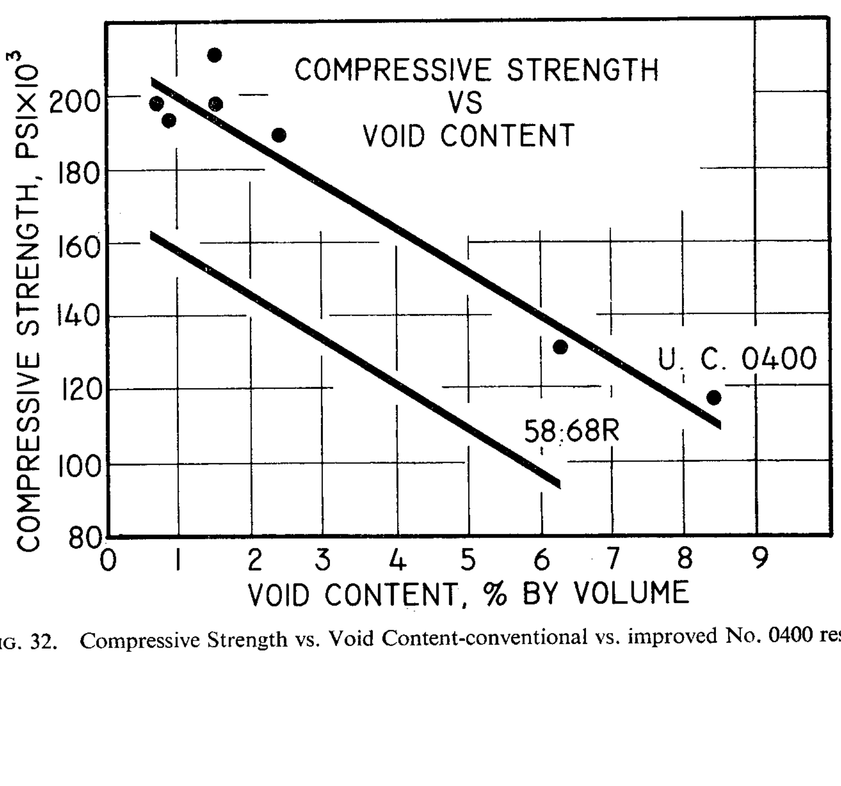


FIG. 32. Compressive Strength vs. Void Content-conventional vs. improved No. 0400 resin.

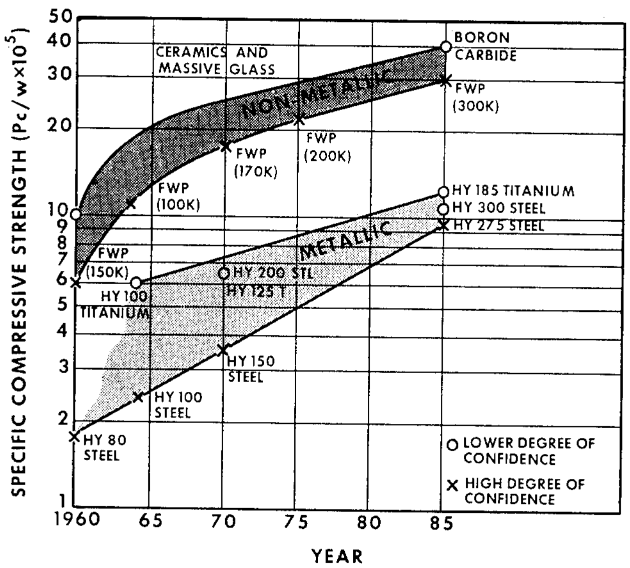


FIG. 33. Predicted specific compressive strength trends to year 1985.

CONCLUSIONS

Experience gained over the past 20yr has indicated the suitability of glass-reinforced plastics for a wide variety of marine applications.

A review of the current State-of-the-Art for high strength, glass filament-wound reinforced plastics (FWP) indicates that significant progress has been made toward defining the capabilities of this material for deep-ocean structural applications.

Considerable information has been obtained on the effects of deep submergence pressure and the resistance of FWP to sustained and cyclic, long-term biaxial stresses applied under high hydrostatic pressure.

The importance of quality, in terms of void content, has been demonstrated. Fabrication techniques for minimizing voids, residual stresses and other defects have been defined and further studies are underway.

Cyclic fatigue, rather than long-term creep or stress rupture, has been shown to be the controlling design factor. The ability which has been indicated, to predict fatigue life under various compressive stress levels, as a percentage of the short-term strength, coupled with the ability to determine strength characteristics by non-destructive ultrasonic techniques, should provide a high degree of design confidence.This will be further enhanced by the recent report of Cole (1966) that ultrasonic inspection can measure cumulative damage and predict residual life after previous hydrostatic, biaxial cycling history.

A related reinforced plastic material, in the form of a radially oriented, glass filament reinforced sphere, is a leading contender for use as supplementary buoyancy on submersibles capable of 20,000ft operating depth.

Composite materials will assume increasing importance in the future, as improved matrices, interfaces and reinforcements are developed which make possible even greater structural efficiency and improved resistance to ocean environment.

The Navy's total programme is supporting Research and Development in these areas.

Efforts are going forward to develop new resin systems and advance them to the stage of commercial practice. It is anticipated that greater emphasis will be given to development of graphite fibre composites, which appear to have such great potential. Programmes are also under way to improve the quality and reliability of presently available reinforced plastic materials. Investigation of processing techniques to minimize void content will be continued and attention will be given to development of practical non-destructive test procedures which may be applied to large structures.

The challenge, today, is to take the knowledge which has already been developed on available filament-wound plastics and to apply it to new design concepts which will emphasize the materials virtues and minimize its short-comings, in order to advance the state of the art to large-scale structures for service evaluation. The experience thus gained will be prologue to the greatly improved composite of tomorrow.

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(NOTE: Reports on Navy Contracts may be obtained by qualified requestors from the Defense Documentation Center, Cameron Station, Alexandria, Virginia, 22314.)