[redacted]

YLOR MODEL BASIN
WASHINGTON D.C.

DEPARTMENT OF THE NAVY

HYDROMECHANICS

○

AERODYNAMICS

○

STRUCTURAL MECHANICS

○

APPLIED MATHEMATICS

HYDROSTATIC PRESSURE TESTS OF UNSTIFFENED AND RING-STIFFENED CYLINDRICAL SHELLS FABRICATED OF GLASS-FILAMENT REINFORCED PLASTICS

by

Kenneth Hom, John E. Buhl, Jr.
and William P. Couch

[redacted]

STRUCTURAL MECHANICS LABORATORY

RESEARCH AND DEVELOPMENT REPORT

September 1963

Report 1745

DEPARTMENT OF THE NAVY
DAVID TAYLOR MODEL BASIN
WASHINGTON D.C. 20007

IN REPLY REFER TO

5605
(732:KH:mab)
Ser 7-456
30 October 1963

From: Commanding Officer and Director, David Taylor Model Basin
To: Chief, Bureau of Ships (634C) (in duplicate)

Subj: S-F013 0503: Hydrostatic tests of unstiffened and ring-stiffened cylinders fabricated of glass-reinforced plastics; forwarding of report on

Ref: (a) BuSHIPS ltr R007-03-4 Ser 634C-1108 of 20 Jul 1960 to DTMB

Encl: (1) DTMB Report 1745 entitled "Hydrostatic Pressure Tests of Unstiffened and Ring-Stiffened Cylindrical Shells Fabricated of Glass-Filament Reinforced Plastics" (9 copies)

1. In conjunction with structural research authorized under reference (a), the David Taylor Model Basin is investigating the use of glass-filament reinforced plastics as a material for pressure hulls of deep-submergence vehicles.

2. Enclosure (1) presents the test results of unstiffened and ring-stiffened cylinders fabricated of glass-reinforced plastics. Results indicated that considerable weight saving in hull structure can be realized with glass-reinforced plastics; this is based on studies with cylinders subjected to short-term hydrostatic loading. Potential shortcomings, such as the deleterious effects of cyclic fatigue and long-term exposure to a deep-submergence environment on the load-carrying capacity of filament-wound structures, have not been answered and can be established only after extensive investigations.

E. E. Johnson
E. E. JOHNSON
By direction

5605
(732:KH:mab)
Ser 7-456
30 October 1963

Copy to:
CHBUSHIPS (210L) with 3 copies of encl (1)
(320) with 1 copy of encl (1)
(341A) with 1 copy of encl (1)
(342A) with 1 copy of encl (1)
(420) with 1 copy of encl (1)
(421) with 1 copy of encl (1)
(423) with 1 copy of encl (1)
(440) with 1 copy of encl (1)
(442) with 1 copy of encl (1)
(443) with 1 copy of encl (1)
(525) with 2 copies of encl (1)
(633) with 1 copy of encl (1)
(651F) with 1 copy of encl (1)
CHBUDOCKS (Attn: C-423) with 1 copy of encl (1)
CHONR (104) with 1 copy of encl (1)
(419) with 1 copy of encl (1)
(439) with 1 copy of encl (1)
(466) with 1 copy of encl (1)
CNO (OP 07T) with 1 copy of encl (1)
(OP 311) with 1 copy of encl (1)
(OP 713) with 1 copy of encl (1)
(OP 725) with 1 copy of encl (1)
CO USNAVAPSCILAB (9350) with 2 copies of encl (1)
CHBUWEPS (RRMA) with 1 copy of encl (1)
(RMMP-23) with 1 copy of encl (1)
(SP S6-27012 Mr. Bernstein) with 1 copy of encl (1)
CDR, USNOL (W Dept) with 1 copy of encl (1)
(WM Div) with 1 copy of encl (1)
DIR, USNRL (2027) with 1 copy of encl (1)
(6120) with 1 copy of encl (1)
(6210) with 1 copy of encl (1)
DIR, Plastics Tech Evaluation Center, Picatinny
Arsenal, Dover, with 2 copies of encl (1)
CDR, USNOTS China Lake (5557) with 1 copy of encl (1)
US Naval Ordnance Test Station (Mr. J.L. Phillips P-8082)
Pasadena, California (with 1 copy of encl (1)
CDR, DDC - with 10 copies of encl (1)
CO and DIR, USNEES, with 1 copy of encl (1)
CO and DIR, USNUSL, with 1 copy of encl (1)
CO and DIR, USNEL, with 1 copy of encl (1)
CO USNROTC and NAVADMIN U, MIT, with 1 copy of encl (1) ←
CO, USNUOS, with 1 copy of encl (1)
DIR of Def R and E, Attn: Tech Lib, with 1 copy of encl (1)
NAVSHIPYD PTSMH, with 2 copies of encl (1)

5605
(732:KH:mab)
Ser 7-456
30 October 1963

Copy to: (continued)
O in C, PGSCOL, Webb Inst, with 1 copy of encl (1)
Dir, APL, Univ of Wash, Seattle, with 1 copy of encl (1)
NAS, Attn: Comm on Undersea Warfare, with 1 copy of encl (1)
CO and DIR, USMDL, with 1 copy of encl (1)
CG, Aero Syst Div (ASRCNC-1) Wright Patterson Air Force Base, Ohio, with 2 copies of encl (1)
Aerojet-General Corp, with 1 copy of encl (1)
NARMCO Res and Dev Div of Telecom, with 1 copy of encl (1)
Armour Research Foundation, with 1 copy of encl (1)
Gen Mot Corp, Def Systems Div, with 1 copy of encl (1)
Battelle Memorial Inst, with 1 copy of encl (1)
H I Thompson Fiberglas, with 1 copy of encl (1)
Owens-Corning Fiberglass Corp, with 1 copy of encl (1)
US Rubber Res Center, with 1 copy of encl (1)
Shell Chem Co, Plastics and Resin Div, with 1 copy of encl (1)
North Am Aviation Inc, with 1 copy of encl (1)
Hercules Powder Co, with 1 copy of encl (1)
Brunswick Corp, with 1 copy of encl (1)
Douglas Aircraft Corp, with 1 copy of encl (1)
Goodyear Aircraft Corp, with 1 copy of encl (1)
A.O.Smith Corp, with 1 copy of encl (1)
Univsity of Ill, with 1 copy of encl (1)
AVCO Corp, Undersea Proj Dir, with 1 copy of encl (1)
Union Carbide Plastics Corp, with 1 copy of encl (1)

HYDROSTATIC PRESSURE TESTS OF UNSTIFFENED AND RING-STIFFENED CYLINDRICAL SHELLS FABRICATED OF GLASS-FILAMENT REINFORCED PLASTICS

by

Kenneth Hom, John E. Buhl, Jr.
and William P. Couch

September 1963

Report 1745
S-F013 05 03

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

The results of a structural research program to investigate lightweight, glass-reinforced plastic laminates or composite materials for pressure hulls of deep-submergence vehicles are summarized. Unstiffened and ring-stiffened cylinders fabricated of commercially available reinforced plastics are described. Extensive studies of hydrostatic strength and limited studies of creep were conducted. The results of the hydrostatic tests agree well with pressures computed from formulas developed for isotropic materials. An effective modulus of elasticity of 5.5×10^6 psi and compressive stresses over 120,000 psi were measured from tests of the unstiffened cylinders. Results indicated that considerable weight saving in hull structure can be realized with glass-reinforced plastics.

INTRODUCTION

Under the initial sponsorship of the Office of Naval Research[1] and the continuing sponsorship of the Bureau of Ships,[2] the David Taylor Model Basin has a program of structural research to investigate lightweight, glass-reinforced plastic laminates or composite materials for pressure hulls of deep-submergence vehicles.

Theoretical strength-weight curves for unstiffened and ring-stiffened cylinders of glass-reinforced plastics with various combinations of density, strength, and modulus of elasticity were compared with those for cylinders of the better known metals.[3] This comparison indicated that by virtue of their high strength-weight characteristics, glass-reinforced plastics appeared to have great promise as a structural material for deep-diving submersibles.

---

[1] References are listed on page 24.

A survey of the literature, conducted in the early phase of this program, showed that design data were extremely limited for shell structures of composite materials, such as glass-fiber reinforced plastics, to withstand external pressures on the order of 3000 to 15,000 psi. Such information was virtually nonexistent in the areas of interest to the designer of submarine pressure hulls. Accordingly, a series of tests with small-scale models manufactured by various commercial firms was conducted to obtain much of this necessary information.

This report presents test results obtained by the Model Basin on the structural response of glass-reinforced plastic cylindrical pressure hulls subjected to hydrostatic pressure. In addition, the results of two unstiffened cylinders subjected to long-duration loading are given. Previously published results[3,4] have been included for completeness. The test results are assessed in terms of suitability of these materials for pressure-hull application.

UNSTIFFENED CYLINDERS

DESCRIPTION OF THE CYLINDERS

Tests were conducted with unstiffened cylinders of approximately 6-in. inside diameter and 11.4-in. length. The shell thickness of these cylinders ranged from 0.172 to 0.751 in. The actual dimensions are shown in Table 1 and represent the average of measured values. These cylinders were fabricated by various manufacturers using different winding sequences and patterns, resin systems, and fabricating techniques. The A-cylinders were filament-wound in five discrete layers, producing a 2C:1L fiber distribution through the shell thickness. The B-cylinders were also filament-wound in five discrete layers but produced a 3C:2L fiber distribution. The G-cylinders were wound using about 12 layers of fibers in a 2C:1L buildup. The H-cylinders had a buildup of one circumferential layer to two layers helically wound at 45 deg. The HT-cylinders and Z-cylinders were wound with glass-fiber-reinforced epoxy-resin tapes in a sequence of two circumferential plies and one longitudinal ply, repeated to produce a 2C:1L distribution of fibers completely dispersed through the thickness. Information

TABLE 1

Dimensions and Test Results for Unstiffened Cylinders

Cylinder No.	Shell Thickness in	Overall Length in.	Inside Diameter in	Material Density lb/cu in.	Weight/Displacement x 100	Collapse Pressure psi	Maximum Computed Stress at Collapse psi	Strain-Sensitivity Factor, μ in./in./psi				Modulus of Elasticity, 10^6 psi		
								Circumferential		Longitudinal		Circumferential	Longitudinal	Effective
								Outside	Inside	Outside	Inside			
A-1	0.373	11.40	6.002	0.0809	46	5000	47,900	-1.08	-1.50	-0.51	-0.64	6.13	5.46	5.91
2	0.373	11.41	6.001	0.0791	45	6850	65,600	-1.04	-1.29	-0.42	-0.68	6.72	5.89	6.44
B-1	0.319	11.47	5.987	0.0780	39	5000	54,500	-1.53	-1.75	-0.64	-0.67	5.56	5.36	5.48
2	0.320	11.40	5.986	0.0780	39	5350	58,200	-1.38	-1.66	-0.63	-0.70	5.96	5.39	5.73
3	0.178	11.43	5.984	0.0752	22	1225	22,400	-2.81	-3.16	-0.95	-0.92	5.42	6.12	5.70
4	0.309	11.46	5.983	0.0779	38	5150	57,700	-1.43	-1.67	-0.58	-0.66	6.06	5.84	5.97
5	0.384	11.46	5.977	0.0787	46	8850	82,400	-1.19	-1.43	-0.61	-0.57	5.79	5.17	5.54
6	0.457	11.28	5.982	0.0780	52	8500	68,700	-1.01	-1.27	-0.49	-0.51	5.67	5.13	5.45
7	0.457	11.47	5.975	0.0789	53	8950**	72,300	-1.03	-1.28	-0.50	-0.49	5.60	5.16	5.42
8	0.551	11.42	5.990	0.0780	60	12,950	90,400	-0.89	-1.16	-0.41	-0.46	5.33	4.93	5.17
9	0.552	11.43	5.980	0.0761	59	8200	57,100	-0.91	-1.18	-0.48	-0.48	5.18	4.55	4.93
10	0.650	11.43	5.992	0.0771	68	14,150	87,100	-0.75	-1.00	-0.44	-0.45	5.31	4.35	4.93
11	0.650	11.39	5.993	0.0759	67	17,500**	107,800	-0.73	-0.99	-0.38	-0.43	5.44	4.68	5.13
12	0.751	11.43	5.991	0.0773	75	18,590	103,100	-0.60	-0.86	-0.35	-0.37	5.62	4.68	5.25
13	0.750	11.43	5.981	0.0766	75	22,900	126,900	-0.66	-0.91	-0.33	-0.33	5.26	4.92	5.12
G-1	0.198	11.37	5.998	0.0745	24	1470	24,500	-2.26	-2.53	-1.37	-1.45	5.87	4.32	5.35
2	0.315	11.47	5.998	0.0745	36	4750	52,500	-1.50	-1.75	-0.93	-1.00	5.54	4.05	5.04
3	0.382	11.33	5.998	0.0747	43	7300	68,500	-1.03	-1.35	-0.70	-0.70	6.33	4.65	5.77
4	0.455	11.42	5.998	0.0738	49	10,000	81,300	-1.03	-1.31	-0.62	-0.67	5.48	4.22	5.06
H-1	0.197	11.40	5.942	0.0751	24	910	15,100	-3.12	-3.31	-1.24	-1.29	4.47	4.36	4.43
2	0.172	11.41	5.943	0.0755	22	1050	19,700	-2.99	-3.27	-1.07	-0.90	5.30	6.00	5.53
3	0.308	11.41	5.938	0.0753	36	4100	45,800	-1.80	-2.08	-0.45	-0.47	4.94	6.60	5.49
4	0.305	11.40	5.936	0.0763	37	4050	45,600	-1.99	-2.12	-0.64	-0.55	4.67	5.58	4.97
5	0.378	11.40	5.938	0.0763	44	6600	61,900	-1.40	-1.62	-0.56	-0.54	5.13	5.27	5.18
7	0.452	11.40	5.937	0.0751	50	8200	66,400	-0.99	-1.37	-0.42	-0.51	5.57	5.39	5.51
8	0.451	11.40	5.938	0.0750	50	9000	73,100	-1.05	-1.49	-0.35	-0.46	5.26	5.85	5.46
9	0.465	11.38	5.934	0.0761	52	8000	63,300	-1.17	-1.42	-0.36	-0.39	4.98	5.91	5.29
HT-1	0.457	11.40	5.997	0.0767	51	12,200	98,800	-0.97	-1.21	-0.64	-0.63	5.83	4.33	5.33
2	0.554	11.40	5.992	0.0764	59	16,500	114,700	-0.81	-1.05	-0.56	-0.56	5.70	4.14	5.18
3	0.555	11.40	5.992	0.0762	59	16,400	113,800	-0.82	-1.05	-0.55	-0.57	5.66	4.13	5.15
4	0.651	11.40	6.001	0.0757	66	19,500	120,100	-0.72	-0.96	-0.45	-0.49	5.49	4.19	5.05
5	0.651	11.39	6.000	0.0764	67	20,000	123,100	-0.72	-0.97	-0.47	-0.48	5.46	4.16	5.02
6	0.750	11.40	6.000	0.0758	74	19,000	105,600	-0.61	-0.85	-0.43	-0.45	5.54	4.02	5.03
7	0.750	11.40	6.000	0.0761	74	20,375	113,200	-0.61	-0.85	-0.42	-0.44	5.55	4.09	5.06
Z-1	0.313	11.39	6.012	0.0680	33	3550	39,500	-2.07	-2.40	-1.12	-1.18	4.10	3.33	3.84
2*	0.313	11.39	6.012	0.0680	33	3400	37,800	-1.78	-1.96	-0.87	-0.84	4.94	4.36	4.75
3	0.373	11.40	5.994	0.0781	44	7900	75,600	-1.15	-1.35	-0.66	-0.67	6.18	4.90	5.75
4	0.380	11.40	5.997	0.0773	44	7400	69,700	-1.15	-1.36	-0.60	-0.60	6.10	5.21	5.80
5*	0.450	11.40	6.001	0.0754	50	9025	74,000	-1.03	-1.27	-0.59	-0.61	5.65	4.54	5.28
6	0.449	11.40	5.997	0.0749	49	8975	73,700	-1.04	-1.28	-0.58	-0.60	5.62	4.60	5.28
7	0.180	11.40	5.995	0.0752	22	1325	24,100	-2.61	-2.79	-1.01	-1.03	5.88	5.88	5.88

* Creep tests

** Maximum sustained pressure

furnished by the manufacturers indicated that the average resin content of the finished laminates was 14 percent for the A-cylinders, 22 percent for both the B- and G-cylinders, 34 percent for Z-1 and Z-2, and 16 percent for the other Z-cylinders. HTS E-787 prepreg material with a 19-percent resin content was used to construct the HT-cylinders.

Visual inspection of the cylinders, upon arrival from the manufacturers, showed crazed cracks running in the circumferential direction on the inside surface of Cylinders B-9, B-10, B-11, B-12, and B-13. It was decided to test these cylinders to determine the influence of this type of imperfection on the overall short-term strength of the structure.

The density of the material for each cylinder was measured and their respective values along with their weight-displacement ratios* are listed in Table 1. It can be seen that a material density of 0.077 lb/cu in. is a representative value for the cylinders tested.

All of the cylinders except Z-2 and Z-5 were subjected to short-term hydrostatic pressure loading. Z-2 and Z-5 were subjected to long-duration loading in order to study the creep behavior of cylindrical-shell laminates under external pressure.

TEST PROCEDURE

The unstiffened cylinders were instrumented with strain gages on both the inside and outside surfaces of the cylinder at midlength. Strain gages were placed in four locations evenly spaced in the circumferential direction on Cylinders B-1, B-2, Z-1, and Z-2 and in eight locations on the other cylinders. The ends of each cylinder were closed with steel plates having a shoulder extending into the cylinder and made pressure tight by using a sealing compound.

The thin-walled cylinders were tested to collapse in a 9000-psi capacity tank under oil pressure; these cylinders were filled with oil and vented to the atmosphere to restrict the extent of damage. The thick-walled

---

*This ratio is the weight of the pressure hull or cylinder divided by the weight of water (64 lb/cu ft) displaced by the structure.

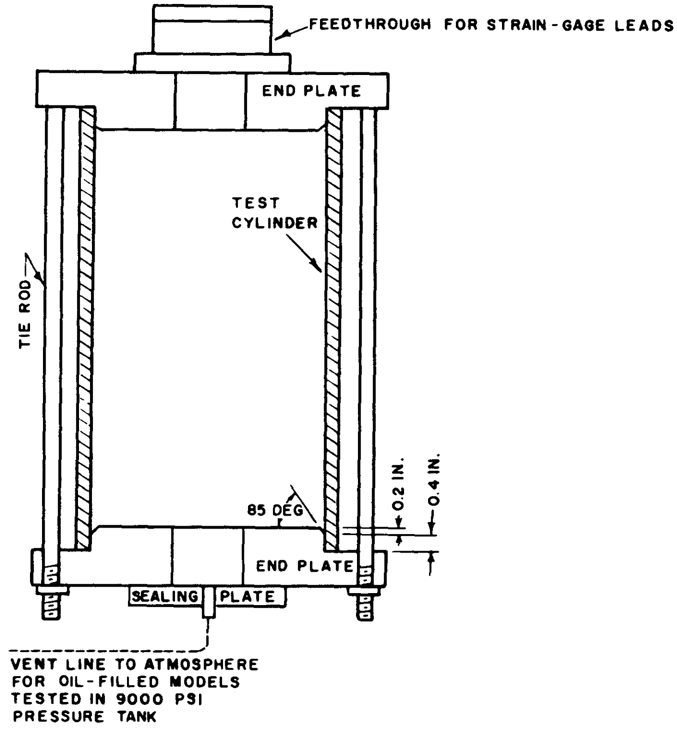


Figure 1 - Unstiffened Cylinder with End Closure Plates

cylinders were initially tested in this tank to obtain elastic strain data after which they were transferred to other tanks having greater pressure capacities and tested to failure in a water or oil pressure medium. No attempt was made to contain the degree of damage of these cylinders. The test setup is shown schematically in Figure 1.

Each cylinder was loaded in a series of pressure runs. Table 2 lists the maximum pressures during each run for the cylinders tested under short-term loading. The loading schedule for the creep test of Cylinders Z-2 and Z-5 is given in Table 3.

During the third pressure runs of Cylinders B-7 and B-11, in what was expected to have been the pressure runs to failure, leaks developed in the tank seal at pressures of 8950 and 17,500 psi, respectively. The cylinders were removed from the tank and inspected. No visible damage was noticed on the outside surfaces of these two cylinders; however, the cylinders failed at lower pressures (7600 and 12,800 psi, respectively) during the next pressure run.

TABLE 2

Maximum Pressures Obtained during Each Pressure Run

Cylinder No.	Maximum Pressure, psi				
	Run 1	Run 2	Run 3	Run 4	Run 5
A - 1	2500	4000	5000		
2	2500	4000	6850		
B - 1	1500	3000	4150	5000	5000
2	1000	2000	5350		
3	600	775	1225		
4	1500	3000	5150		
5	3000	5000	4000	8850	
6	4000	8000	8500		
7	4000	8000	8950	7600	
8	4000	8000	12,950		
9	4000	8000	8200		
10	4000	8000	12,800	14,150	
11	2000	2000	17,500	12,800	
12	2000	2000	18,590		
13	2000	2000	22,900		
G - 1	500	750	1470		
2	1000	2300	4750		
3	2500	4000	6000	7300	
4	4000	8000	10,000		
H - 1	600	775	910		
2	600	775	1050		
3	1500	3000	4100		
4	1500	3000	4050		
5	3200	6000	6600		
7	2000	4000	8200		
8	5500	5000	8000	9000	
9	4000	8000			
HT - 1	4000	4000	12,200		
2	4000	4000	16,500		
3	4000	4000	16,400		
4	6400	8000	11,300	14,600	19,500
5	8000	8000	20,000		
6	8000	8000	19,000		
7	8000	8000	20,000	20,375	
Z - 1	1500	3000	3550		
3	2500	4000	6500	7900	
4	4000	7400			
6	4000	8000	8975		
7	600	775	1325		

TABLE 3

Long-Term Loading Schedules for Cylinders Z-2 and Z-5

Cylinder No.	Run 1		Run 2		Run 3		Run 4		Run 5	
	Duration	Pressure psi	Duration	Pressure psi	Duration	Pressure psi	Duration	Pressure psi	Duration	Pressure psi
Z-2	≈ 0	1000	1 week	2000	19 days	3200	26 days	3300	27 hours	3400*
			1 week	2500			8 days	3350		
			19 days	3000			26 days	3400		
Z-5	≈ 0	4000	50 days	7315	≈ 0	9025**				

* Cylinder Z-2 failed after sustaining 3400 psi for 27 hours during Run 5.

** Cylinder Z-5 failed under short-term loading at a pressure of 9025 psi after sustaining a pressure of 7315 psi for 50 days.

A similar problem with the seal in the test tank also occurred at a pressure of 18,590 psi during the test of Cylinder B-12. An inspection of this cylinder after removal from the tank revealed gross cracking and separation of the fibers on both the inside and outside surfaces. The test was discontinued since it was felt that failure of this cylinder was imminent and that the cylinder would probably not sustain a higher pressure during a succeeding pressure run.

TEST RESULTS

The results of tests conducted with the unstiffened cylinders are summarized in Table 1 which shows the collapse pressure of each cylinder and the stress at collapse computed from Lamé's solution for a thick-walled cylinder for which the maximum stress occurs on the inside surface and in the circumferential direction of the cylinder. Also listed in Table 1 are the strain sensitivity factors obtained as the slopes of the linear portions of the pressure-strain plots and measured in microinches per inch per psi of pressure. Each factor given in the table is the average of the measured values.

From the measured strains, an effective modulus of elasticity was computed to assist in determining the theoretical buckling pressures of the cylinders. The measured strains were used in conjunction with the computed stresses for a thick-walled cylinder and an assumed* Poisson's ratio of 0.15 to compute the modulus of elasticity in the circumferential and longitudinal directions. An effective modulus was computed by weighting the circumferential and longitudinal moduli in the same proportions as the fiber distribution. It can be seen from Table 1 that an effective modulus on the order of 5.5×10^6 psi is representative of the cylinders tested.

In general, the A- and H-cylinders failed at lower collapse pressures than those observed for corresponding cylinders made by the other manufacturers. Since the resin content of the A-cylinders was only 14 percent, it is suspected that the low collapse pressures of these cylinders can probably be attributed to fiber damage and resin-starved regions in the laminates. It should also be noted that although Cylinder A-2 was of the same wall thickness as A-1, it failed at a 37-percent higher pressure. The H-cylinders appear to have collapsed prematurely either by virtue of their helical construction or from a lack of longitudinally oriented fibers which would directly resist the longitudinal bending stress induced by the rigid end plates inserted into the end of the cylinders.

It was mentioned previously in this report that the inside surfaces of Cylinders B-9, B-10, B-11, B-12, and B-13 were crazed during fabrication. A comparison of the collapse strengths of B-8 and B-9, two cylinders of nearly equal thickness, affords an opportunity to assess the effects of this type of imperfection. Cylinder B-8, one without any visible defects, failed at a pressure of 12,950 psi; B-9, the crazed cylinder, had a collapse pressure of 8200 psi. Thus, the overall strength of Cylinder B-9 appeared to be seriously reduced by crazing of the laminate. It is interesting also to note that prior to failure, stresses over 100,000 psi were developed in a few of the crazed cylinders. In fact, the highest stress level obtained for any of the cylinders tested was that achieved by a crazed cylinder (B-13).

---

*The assumption that Poisson's ratios ν_ϕ and ν_x are equal violates Maxwell's reciprocal theorem, but it may be of no great importance as far as determining the buckling pressure is concerned because ν always appears in the form $(1-\nu^2)$ in the more important terms of the stability determinant.

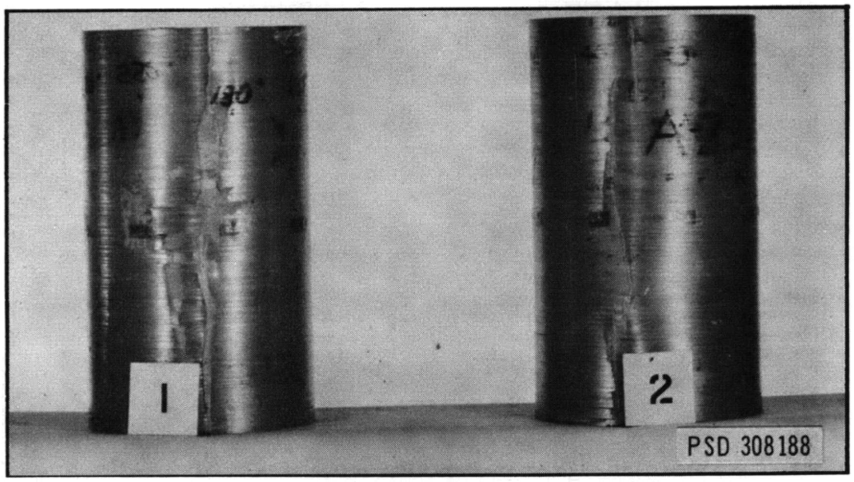


Figure 2 - A-Cylinders after Failure

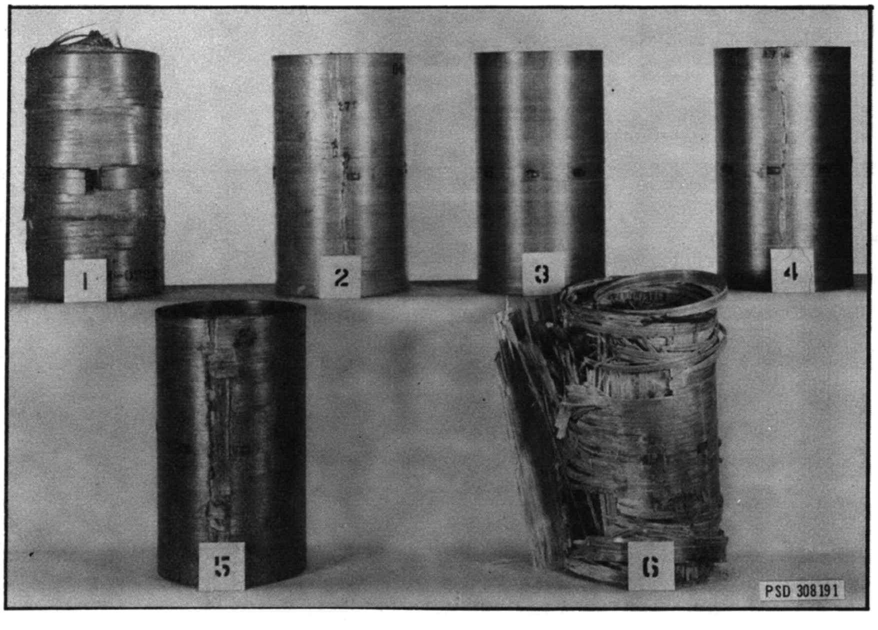


Figure 3 - Cylinders B-1 to B-6 after Failure

Figure 4 - Cylinders B-7 to B-13 after Failure

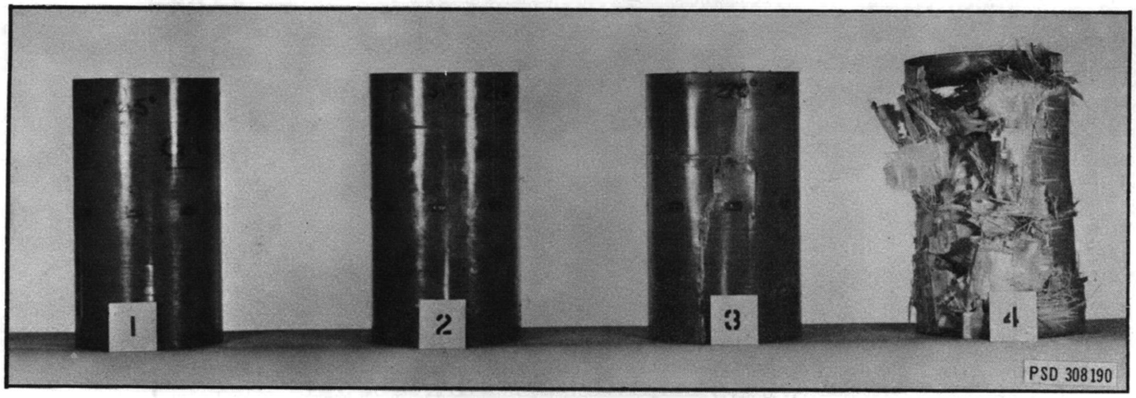


Figure 5 - G-Cylinders after Failure

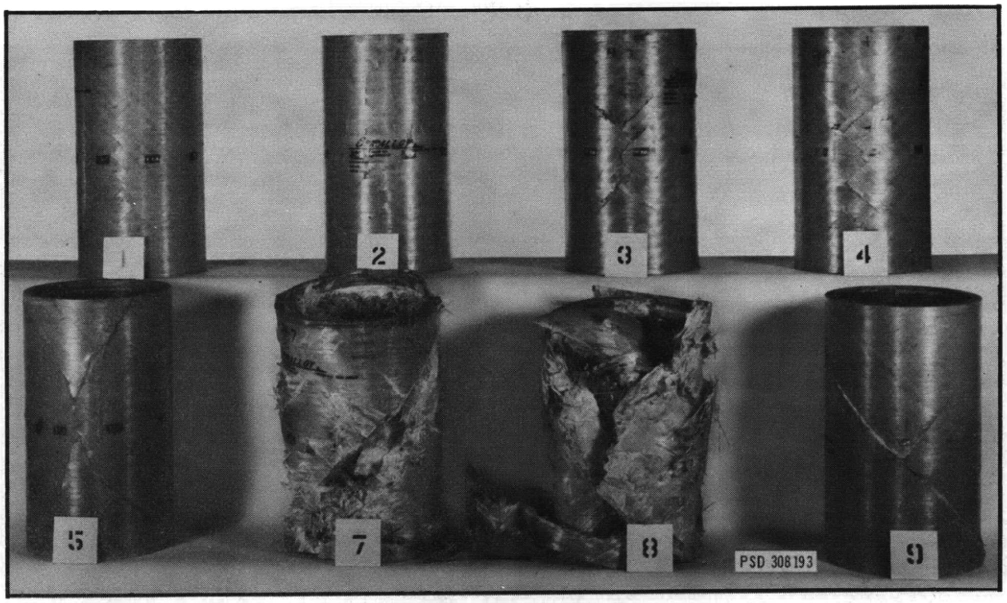


Figure 6 - H-Cylinders after Failure

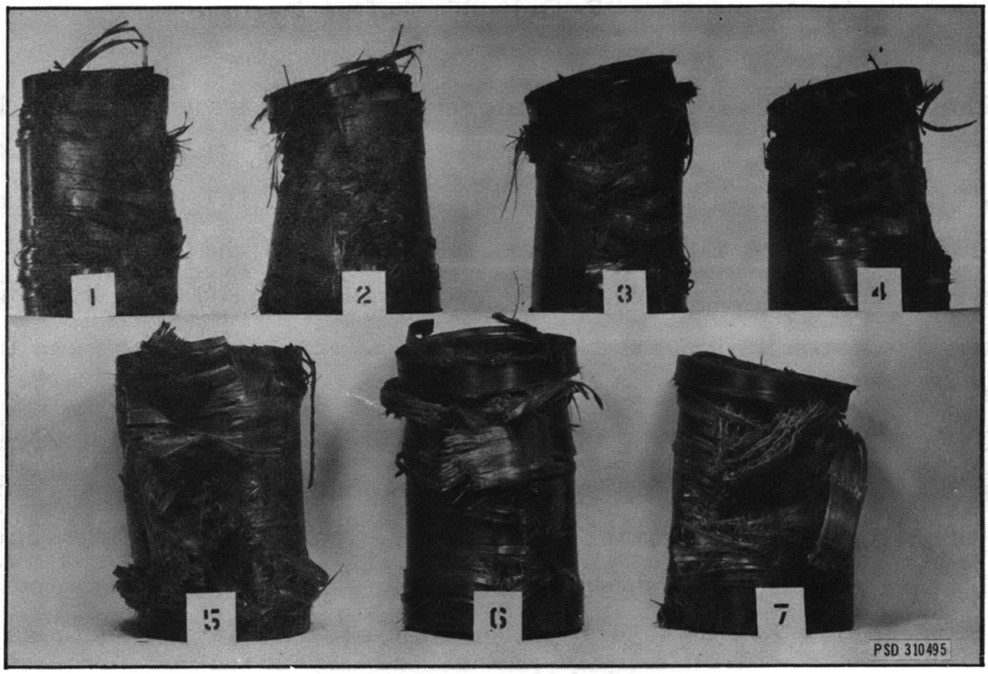


Figure 7 - HT-Cylinders after Failure

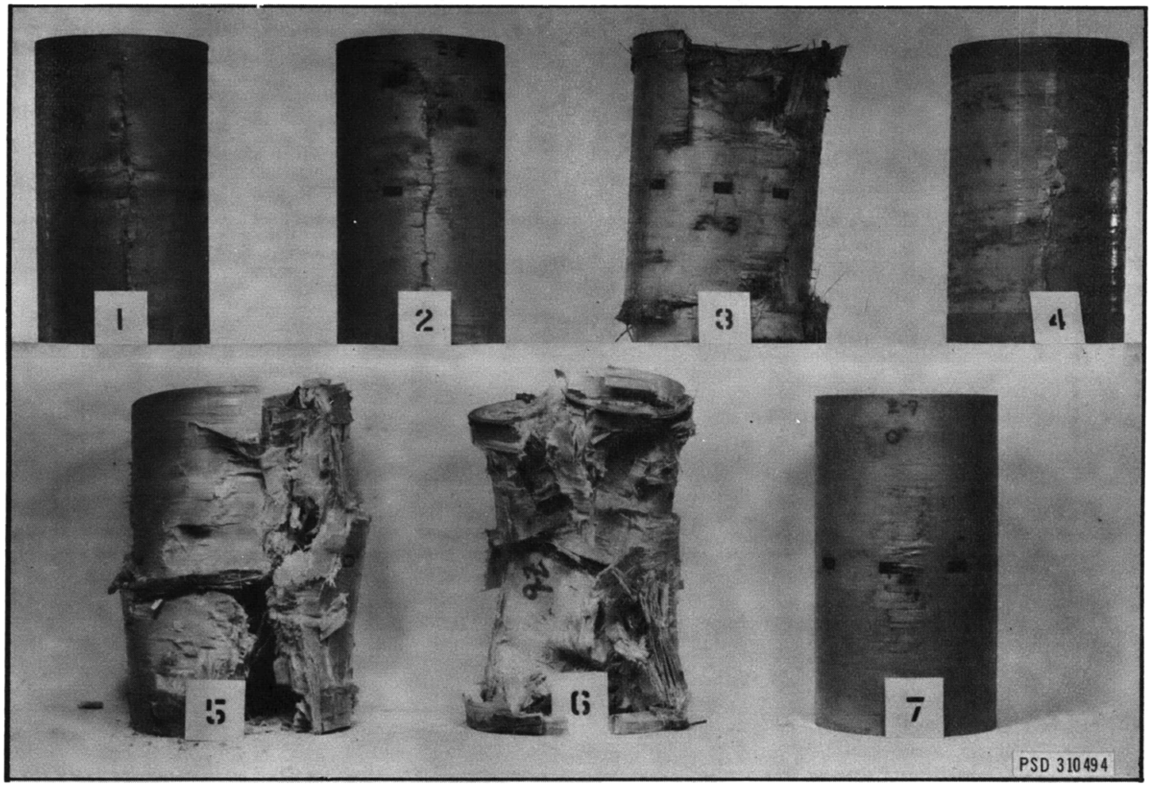


Figure 8 - Z-Cylinders after Failure

Photographs of all of the cylinders after failure are shown in Figures 2 through 8. Cylinders B-6 to B-13, G-4, H-7, H-8, Z-5, Z-6, and HT-1 to HT-7 were tested to collapse in large volume, high pressure tanks; the cylinders were not filled with oil and vented to the atmosphere. Thus, the energy released at failure by the pressurizing medium was unrestrained and extensive damage occurred in these cylinders, as can be seen in the photographs.

Cylinders Z-2 and Z-5, duplicates of Z-1 and Z-6, respectively, were used to investigate the creep properties of unstiffened glass-reinforced plastic structures under biaxial compressive load. The loading schedules of these two cylinders are shown in Table 3. The highest pressure sustained by Cylinder Z-2 was 3400 psi on Run 4 for 26 days. At that time, the O-ring seal in the test tank failed, causing the pressure to drop to zero. After the O-ring was replaced, the pressure was again raised to

3400 psi. The cylinder sustained 3400 psi for 27 hours before collapse occurred. An effective modulus of 4.75×10^6 psi was calculated from strain readings taken during the first and second pressure runs. For Run 3, an effective modulus of 4.24×10^6 psi was computed. Elastic-buckling pressures of 4046 and 3621 psi were computed from Equation (9) of Reference 5 for the respective moduli. Both of these pressures are higher than the collapse pressure of 3400 psi. In contrast, an elastic-buckling pressure of 3271 psi was computed for Cylinder Z-1, tested under short-term loading; this is lower than the collapse pressure of 3550 psi.

Unlike Z-2, changes in material properties were not detected from the creep test of Cylinder Z-5. This cylinder was loaded to a stress level of 60,000 psi and held there for 50 days in an oil pressure medium. Upon completion of the long-duration loading, Cylinder Z-5 was unloaded and then tested to collapse. The collapse pressure was slightly above that observed for the duplicate cylinder (Z-6); see Table 1. The initial modulus of Cylinder Z-5 was identical with Cylinder Z-6 and did not change after the long-duration loading.

The strain-time histories shown in Figure 9 represent the average measurements of gages located at midlength of Cylinder Z-5. An examination of these curves reveals that creep strain on the order of 200 to 400 μin./in. occurred mostly in the first 10 days of constant load and that insignificant changes in strains occurred thereafter.

DISCUSSION OF RESULTS

Figure 10 is a plot of collapse stress versus thickness-diameter ratio for the B-, G-, HT-, and Z-cylinders. The stresses were computed from Lamé's solution for a thick-walled cylinder for which the maximum stress occurs on the inside surface in the circumferential direction. It should be noted that Lamé's solution is for an isotropic material and when used in the present study, it applies only to regions away from the rigid closure plate of the cylinder. The curve drawn through the experimental points shows in Figure 10 that the variation of collapse stress with changing t/D ratios first increases to a maximum, remains constant, and then begins to decrease. A logical extension of this curve would show that

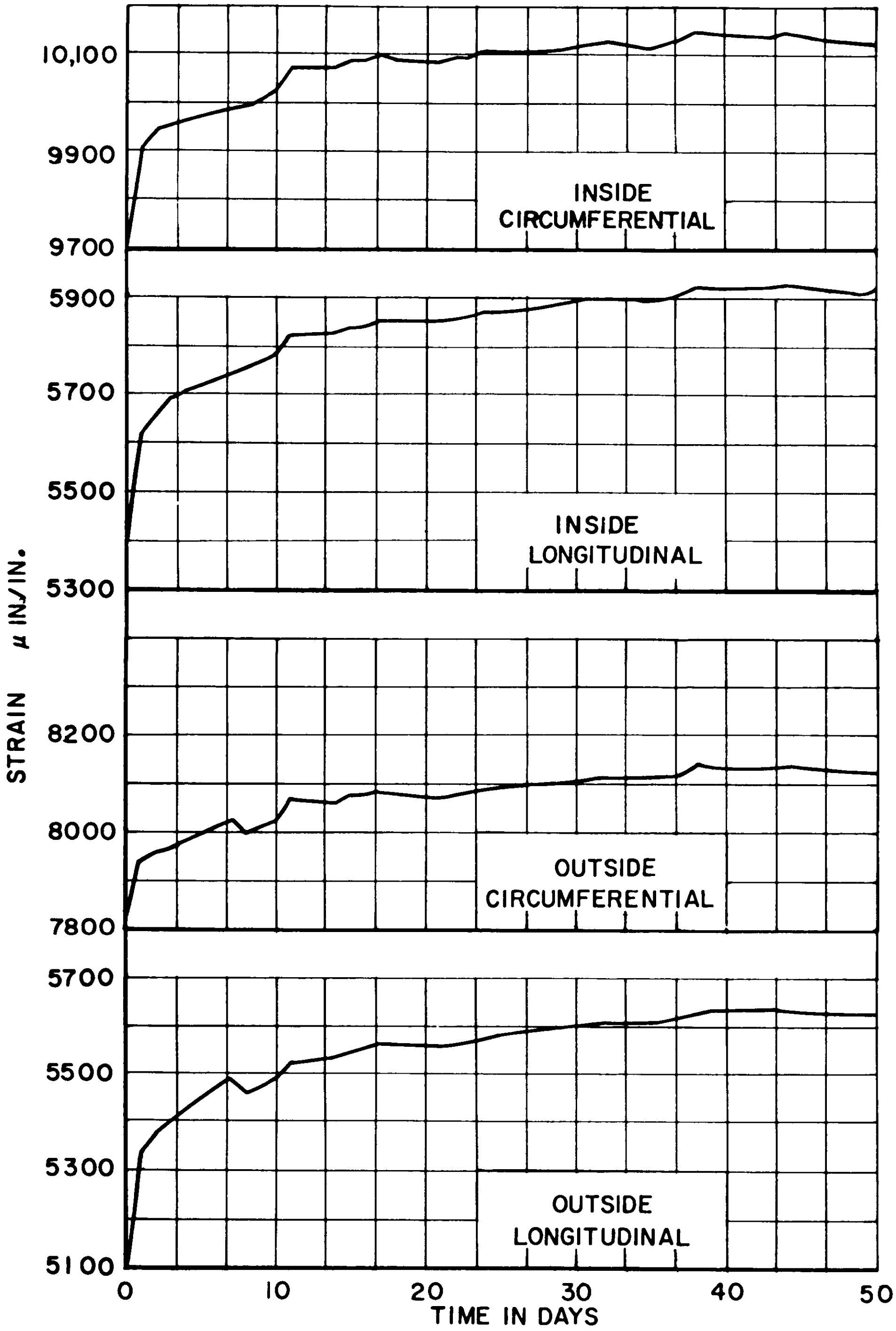


Figure 9 - Strain History of Cylinder Z-5 at Stress Level of 60,000 psi

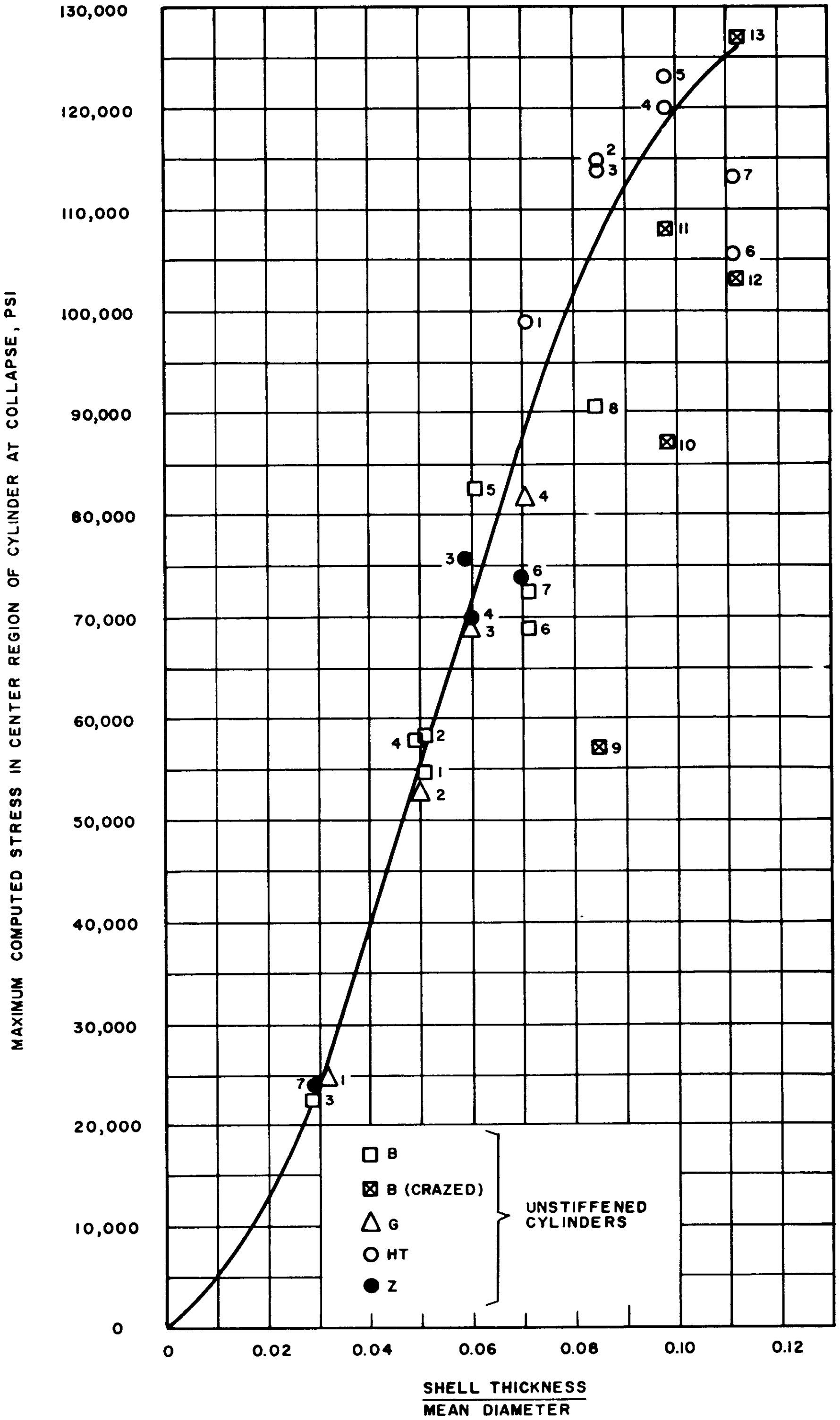


Figure 10 – Critical Stress in Center Region of B-, G-, HT-, and Z-Cylinders

collapse stress becomes independent of t/D at a stress value which is characteristic of pure fracture failures. This value appears to be on the order of 130,000 psi. However, this need not be indicative of the ultimate strength of the material since higher stresses may be developed in the region of the rigid closure plate.

Figure 11 compares theoretical and experimental collapse pressures of all of the unstiffened cylinders tested under short-term loading. Also included in this figure are five cylinders fabricated by Aerojet-General Corporation from E787 material which were evaluated[6] by the Model Basin at the request of the Bureau of Ships.[7] These cylinders, designated by the symbol "✱" in Figure 11, represent partial fulfillment of Aerojet's research contract (NObs 86406) with the Bureau of Ships to determine the effects and relationship of thickness on the physical and mechanical properties of filament-wound hull structures for deep submergence application.

A material density of 0.077 lb/in.^{3}, modulus of elasticity of 5.5×10^6 psi, material strength of 120,000 psi, and an assumed value of 0.15 for Poisson's ratio were used to obtain the theoretical curves in Figure 11. The nonlinear curve represents the elastic buckling mode of failure for unstiffened cylinders with a length of 1.7 diameters. The theoretical collapse pressures were computed from Equation (9) of Reference 5. This equation represents a simplification of Von Mises' solution for the elastic buckling of a thin-walled, isotropic cylinder with simple support boundary conditions. The straight lines represent the pressure at which the critical stress in a thick-walled cylinder reaches 120,000 psi. The experimental results show excellent agreement with the theoretical predictions when the low collapse pressures of cylinders designated by the symbols ◇, ◆, and ☒ are not taken into consideration. Probable explanations as to the poor test results of these cylinders were previously discussed in the report.

The theoretical curve in Figure 11 which has now been substantiated by experiment is redrawn in Figure 12 to show the apparent advantage of using glass-reinforced plastics as the material for cylindrical pressure hulls. The curves in Figure 12 show the predicted strength-weight characteristics of unstiffened cylinders made of various materials loaded by external hydrostatic pressure. The physical properties used in the

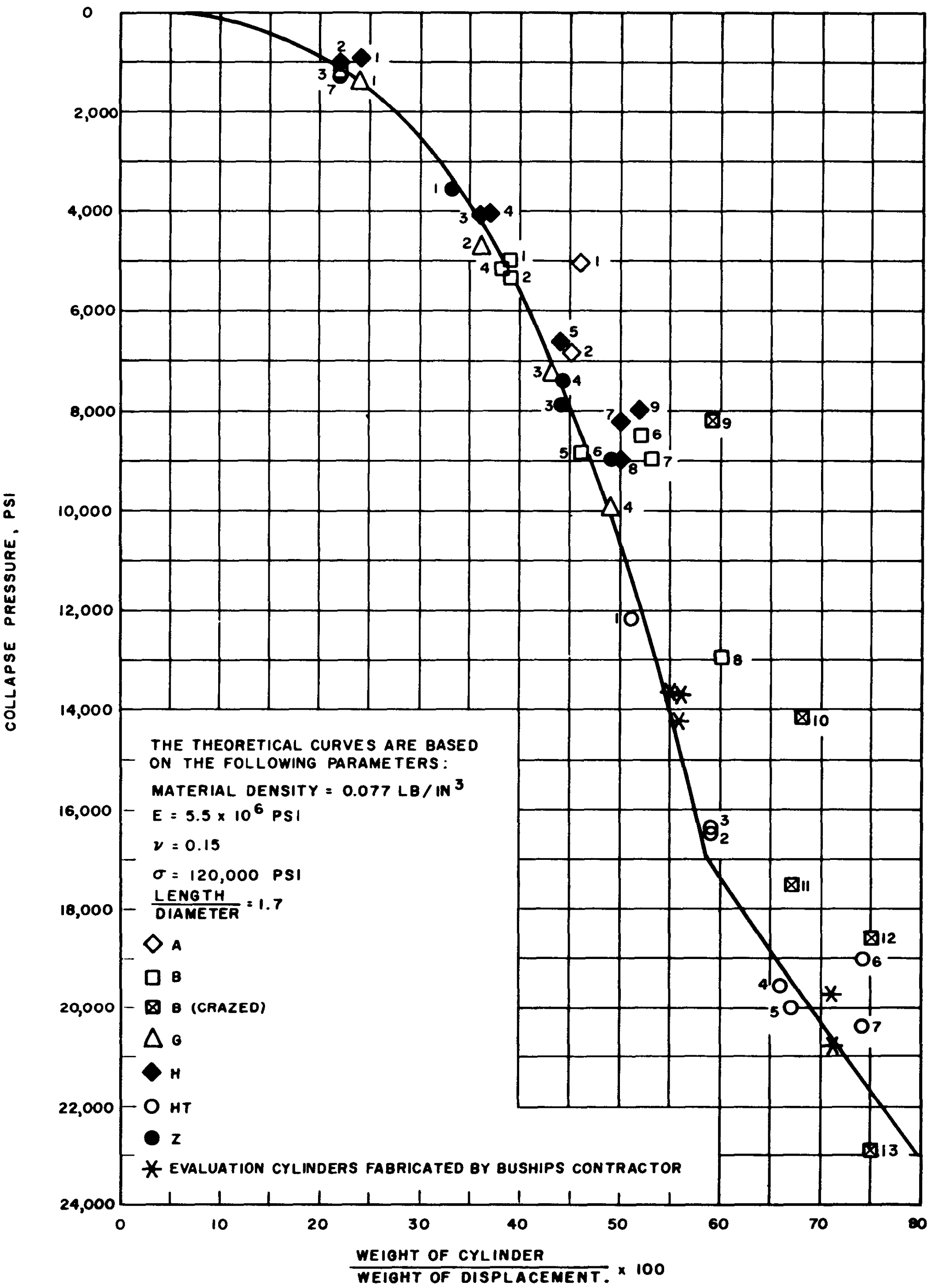
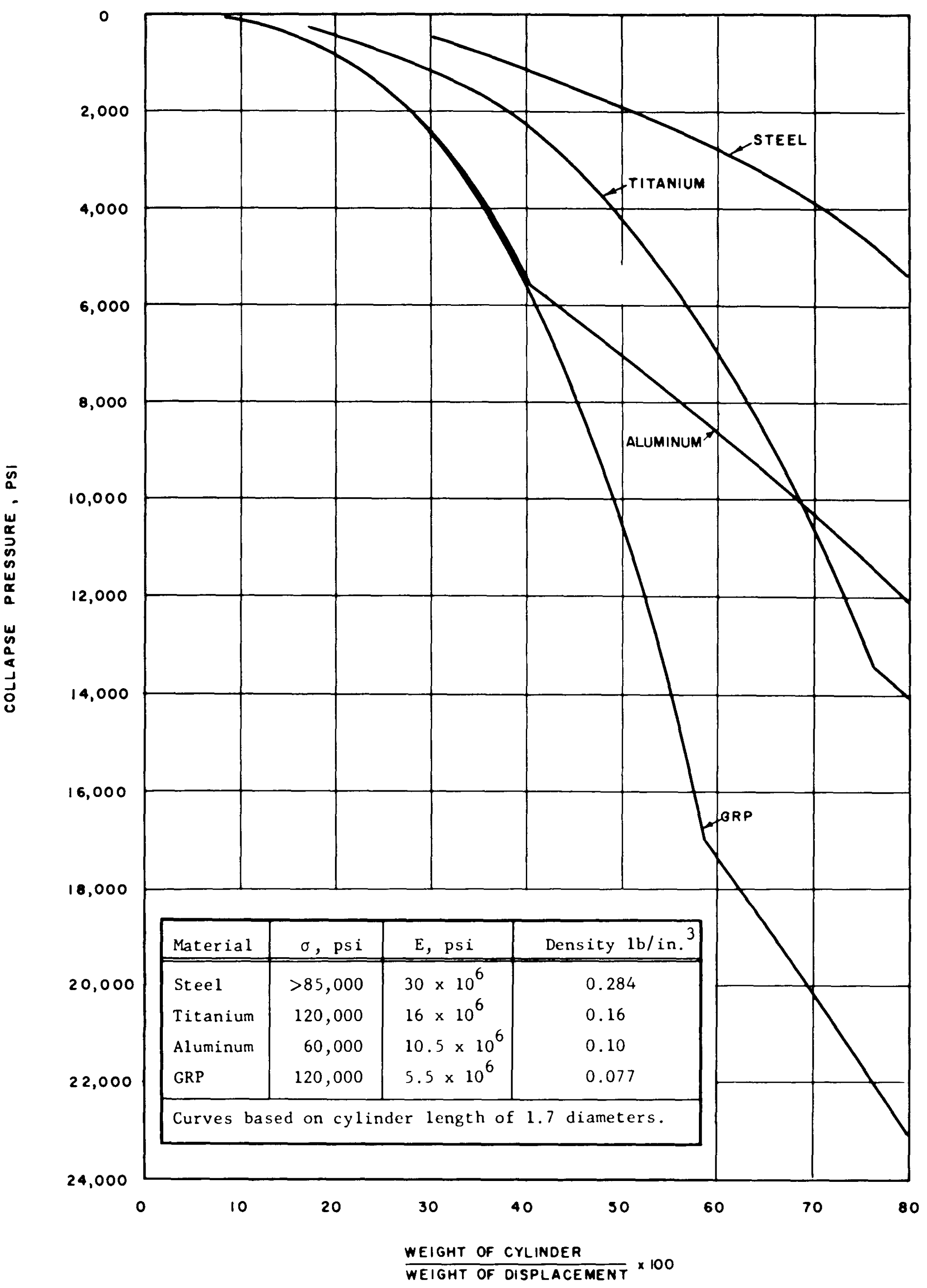


Figure 11 – Comparison of Theoretical and Experimental Collapse Pressure for Unstiffened Cylinders



Material	σ, psi	E, psi	Density lb/in.^{3}
Steel	>85,000	30×10^6	0.284
Titanium	120,000	16×10^6	0.16
Aluminum	60,000	10.5×10^6	0.10
GRP	120,000	5.5×10^6	0.077

Curves based on cylinder length of 1.7 diameters.

Figure 12 - Strength-Weight Characteristics of Unstiffened Cylinders

calculations represent materials which are available today. The nonlinear portion of each curve represents the elastic buckling[5] mode of failure, and the straight line represents the pressure at which the stresses reach the strength of the material. For the metal cylinders, failure was assumed to occur when the biaxial "effective stress" determined from the Hencky-Huber-Von Mises theory of failure reached the yield strength of the material. The circumferential and longitudinal membrane stresses, $\sigma_\phi = \frac{pr}{t}$ and $\sigma_x = \frac{pr}{2t}$, respectively, were used in these calculations.

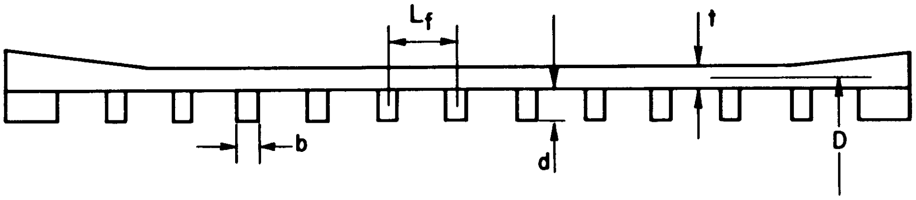
RING-STIFFENED CYLINDERS

In addition to the unstiffened cylinders, tests were carried out with seven ring-stiffened cylinders, all having approximately the same dimensions. Table 4 lists the actual dimensions in the typical region, the fiber distribution, the weight-displacement ratio (based on a material density of 0.077 lb/in.^{3}), and the collapse pressure of each model. Figure 13 shows the various end conditions of the models. Photographs of the models after failure are shown in Figures 14 to 16.

TABLE 4

Dimensions and Test Results for Ring-Stiffened Cylinders

Model	t	L_f	D	b	d	Shell Layup	Weight-Displacement Percent	Collapse Pressure psi
AR-1	0.209	0.921	6.209	0.216	0.425	70% Long	37	3500
AR-2	0.253	0.912	6.257	0.218	0.425	70% Long	42	4150
ZR-1	0.223	0.918	6.223	0.221	0.424	2C:1L	39	5400
ZR-2	0.223	0.918	6.223	0.221	0.424	1C:1L	39	6000
ZR-3	0.223	0.918	6.223	0.221	0.424	2C:1L	39	3750
ZR-4	0.223	0.918	6.223	0.221	0.424	2C:1L	39	3100
HTR-1	0.244	0.918	6.244	0.221	0.424	2C:1L	41	8100



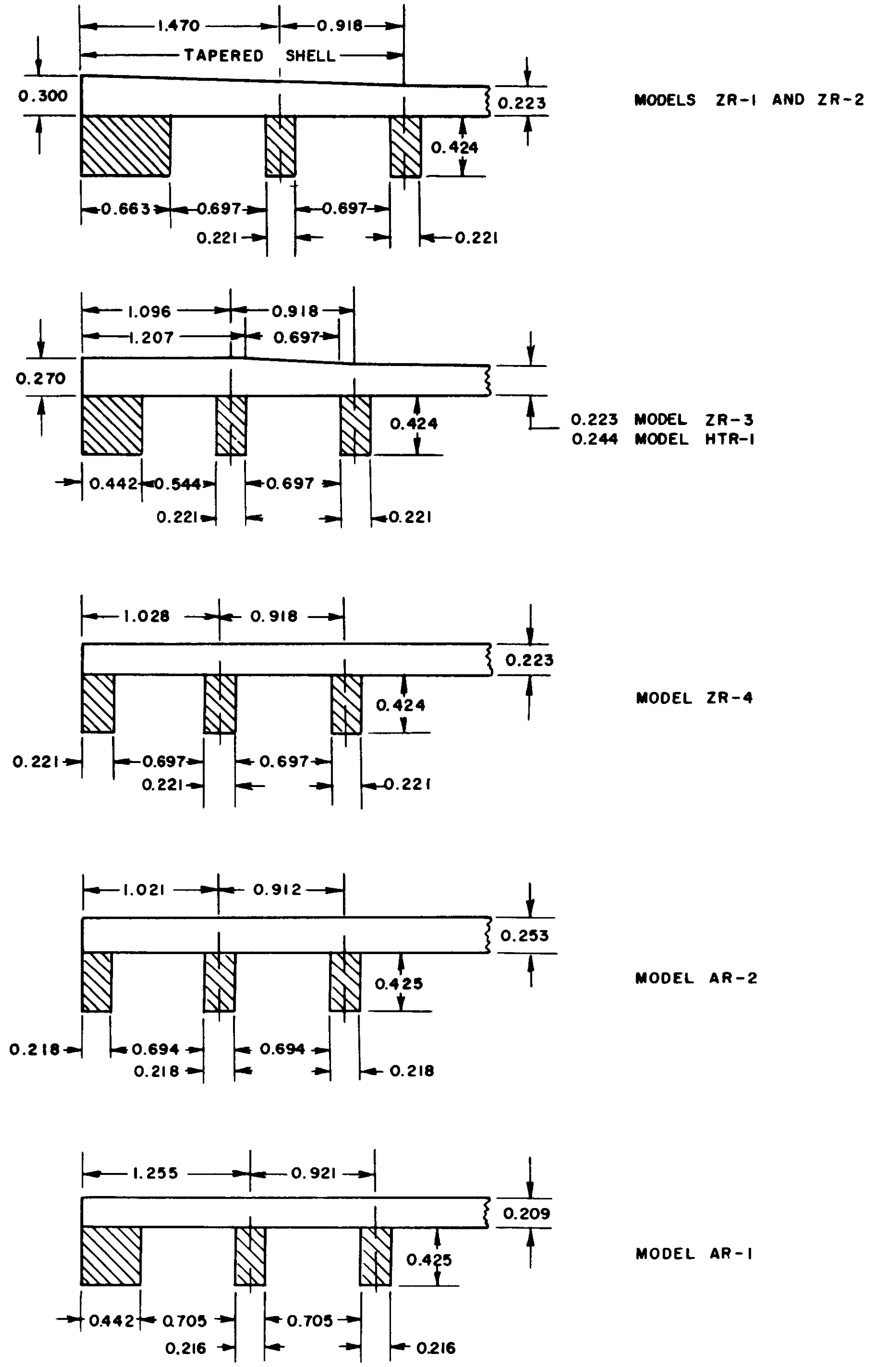


Figure 13 - End Details for Ring-Stiffened Cylinders

Figure 14a - Exterior View

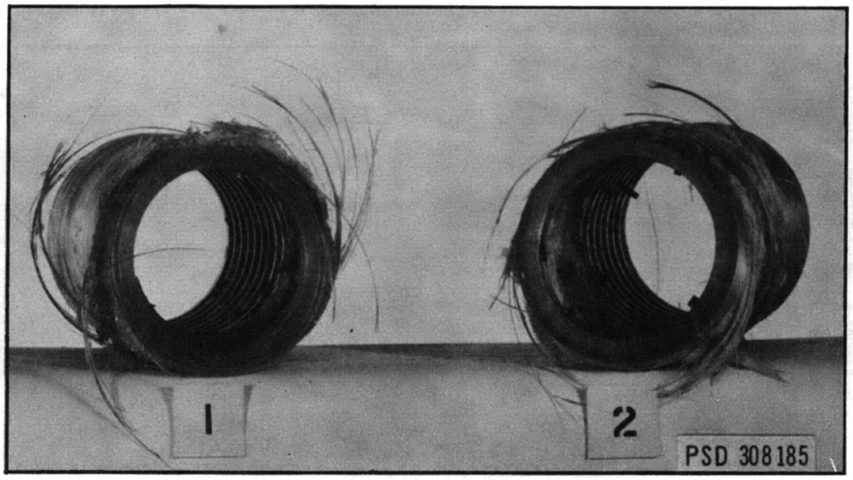


Figure 14b - Interior View

Figure 14 - Models AR-1 and AR-2 after Failure

The weight-displacement ratios for these models were in the order of 40 percent; for this weight and overall length, the collapse pressure of a ring-stiffened cylinder should exceed by an appreciable margin the elastic instability pressure for an unstiffened cylinder of the same weight and length. From Figure 11, an instability pressure of about 5600 psi is obtained for an unstiffened cylinder with a 40 percent weight-displacement ratio. It can be seen from Table 4 that the collapse pressure (8100 psi)

Figure 15a - Exterior View

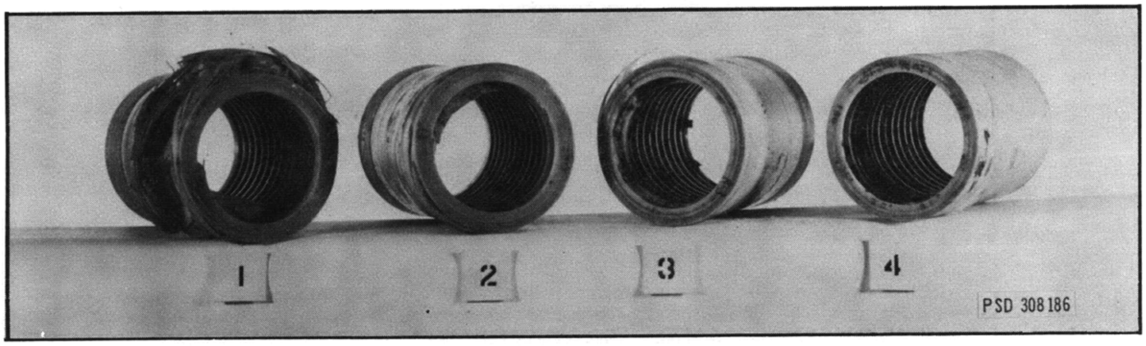


Figure 15b - Interior View

Figure 15 - ZR-Models after Failure

of Model HTR-1 was the only one that greatly exceeded this value. A duplicate model of HTR-1 was tested by H. I. Thompson Fiber Glass Company with a resultant collapse pressure of 8600 psi. These two models were made of E787 material. The extremely low collapse strengths of Models AR-1 and AR-2 were probably due to an overabundance of longitudinal fibers (70 percent) distributed in the shells. Information supplied by Zenith Plastics Company indicated that, unknown to them at the time, Models ZR-3 and ZR-4 were fabricated from defective material; poor results were also obtained with similar cylinders tested by them. Duplicates of Models ZR-1 and ZR-2 were tested by Zenith Plastics with resulting collapse pressures of 7300 and 6500 psi, respectively. It appears that there was a premature failure for Model ZR-1. When all of these facts are taken into consideration, a short-term collapse pressure on the order of 7500 psi at a weight-displacement ratio of 40 percent appears to be representative of GRP ring-stiffened cylinders fabricated under high quality control. This reflects the considerable weight saving in hull structures that can be realized with glass-reinforced plastics.

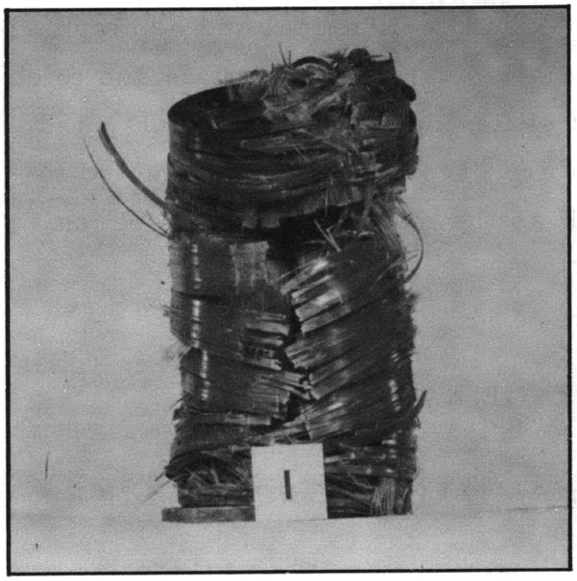


Figure 16 - Model HTR-1 after Failure

CONCLUSION

It should be emphasized that most of the experimental data given in this report were for glass-reinforced plastic cylinders subjected to short-term hydrostatic loading. Potential shortcomings, such as the deleterious effects of cyclic fatigue and long-term exposure to a deep-submergence environment on the load-carrying capacity of filament-wound structures, have not been answered and can be established only after extensive investigations. Much work must be done to determine the design limitation of filament-wound structures subjected to deep-submergence pressures. Confidence levels must be established to give the designer assurance that the materials in the hull structure will perform in accordance with established design criteria. Quality-control practices and inspection-test techniques must be devised to give this assurance.

Research programs to study resin-glass reinforcement systems under carefully controlled laboratory conditions are being sponsored by the Bureau of Ships to develop materials which have improved compressive strength and modulus. Investigations are being conducted by Bureau of Ships contractors and at the Model Basin to determine response to both static and dynamic loading of filament-wound cylindrical and hemispherical shell structures made of commercially available materials and to obtain design information on methods of stiffening, closures, joints, and openings. Small-scale model studies are presently being conducted to determine the feasibility of using GRP as the material for a research vehicle operating at deep depths.

REFERENCES

1. Office of Naval Research letter A/11/4 ONR:438:PE:el of 20 Feb 1959 to Bureau of Ships (Code 440).

2. Bureau of Ships letter R007-03-4 Ser 634C3-1108 of 20 Jul 1960 to David Taylor Model Basin.

3. Buhl, J.E., Jr. and Pulos, J.G., "Strength-Weight Characteristics of Laminated Cylindrical Pressure Hulls Fabricated of Glass-Filament Reinforced Plastics, Progress Report 1," David Taylor Model Basin Report C-1285 (Oct 1961) CONFIDENTIAL.

4. Buhl, J.E., Jr., Pulos, John G., and Graner, W.R., "Reinforced Plastics for Hydrospace Vehicles," David Taylor Model Basin Report 1524 (Aug 1961).

5. Windenburg, D.F. and Trilling, C., "Collapse by Instability of Thin Cylindrical Shells under External Pressure," Experimental Model Basin Report 385 (Jul 1934).

6. David Taylor Model Basin letter 9110.1 Ser 7-128 of 11 Apr 1963 to Bureau of Ships.

7. Bureau of Ships letter F-013-05-03 Ser 634C3-438 of 9 May 1962 to David Taylor Model Basin.

INITIAL DISTRIBUTION

Copies	
25	CHBUSHIPS 9 Polymer, Fiber and Pack Sec (Code 634C) 1 Lab Mgt (Code 320) 3 Tech Lib (Code 210L) 1 Struc Mech, Hull Mat & Fab (Code 341A) 1 Matls. Fuels & Cold Weather (Code 342A) 1 Prelim Des Br (Code 420) 1 Prelim Des Sec (Code 421) 1 Ship Protec (Code 423) 1 Hull Des Br (Code 440) 1 Sci & Res Sec (Code 442) 1 Struc Sec (Code 443) 2 Sub Br (Code 525) 1 Hull Arrgt, Fittings & Preserv (Code 633) 1 Pres Ves Sec (Code 651F)
1	CHBUDOCKS, Attn: C-423
4	CHONR 1 Res Coordinator (Code 104) 1 Matl Sci Div (Code 419) 1 Struc Mech Br (Code 439) 1 Undersea Prog (Code 466)
4	CNO 1 Tech Anal and Adv Gr (OP 07T) 1 Plans, Prog & Reg Br (OP 311) 1 Sub Program Br (OP 713) 1 Tech Support Br (OP 725)
2	CO U.S. Naval Applied Sci Lab (Code 9350)
3	CHBUWEPS 1 (Code RRMA) 1 (Code RMMP-23) 1 Special Projects Office S6-27012 (Mr. H. Bernstein)
2	CDR, USNOL 1 W Dept 1 WM Div

Copies	
3	DIR, USNRL 1 (Code 2027) 1 (Code 6120) 1 (Code 6210)
2	DIR, Plastics Tech Evaluation Center, Picatinny Arsenal, Dover
1	CDR, USNOTS (Code 5557), China Lake
1	US Naval Ordnance Test Station (Mr. J. L. Phillips P-8082) Pasadena, California
10	CDR, DDC
1	CO & DIR, USNEES
1	CO & DIR, USNUSL
1	CO & DIR, USNEL
1	CO USNROTC & NAVADMIN U, MIT
1	CO, USNUOS
1	DIR of Def R & E, Attn: Tech Lib
2	NAVSHIPYD PTSMH
1	O in C, PGSCOL, Webb Inst
1	Dir, APL, Univ of Wash, Seattle
1	NAS, Attn: Comm on Undersea Warfare
1	CO & DIR, USMDL
2	Commanding General Aeronautical Systems Div (ASRCNC-1) Wright Patterson Air Force Base, Ohio
1	Aerojet-General Corp, (Mr. S. Stokes) Azusa, California
1	NARMCO Research & Dev Div of Telecomputing Corp., San Diego, Calif (Mr. B. Duft)

Copies	
1	Armour Research Foundation (Dr. J. W. Dally) Illinois Inst of Tech Chicago, Ill
1	(Gen Motors Corp.) (Dr. R. B. Costello) Def Systems Div, Santa Barbara Lab Santa Barbara, Calif.
1	Battelle Memorial Inst (Dr. R. Leininger) Columbus, Ohio
1	H. I. Thompson Fiberglas (Mr. N. Meyers) Gardena, Calif.
1	Owens-Corning Fiberglass Corp. (Mr. R. J. Weaver) Washington, D. C.
1	U. S. Rubber Research Center (Mr. E. Francois, Jr.) Wayne, N. J.
1	Shell Chemical Co. (Mr. R. E. Bayes), Plastics & Resin Div, New York, N. Y.
1	North American Aviation Inc. (Mr. R. Gorcey) Rocketdyne Div Canoga Park, Calif.
1	Hercules Powder Co (Mr. J. A. Scherer) Wilmington, Del.
1	Brunswick Corp. (Mr. W. McKay) Marion, Va.
1	Douglas Aircraft Corp. (Mr. J. H. Cunningham) Missile & Space Systems Div. Santa Monica, Calif.
1	Goodyear Aircraft Corp. 1210 Massillon Rd Akron, Ohio
1	A. O. Smith Corporation (Mr. W. A. Deringer) Milwaukee, Wisconsin

Copies	
1	University of Ill. (Prof H. R. Corten) Dept of T & AM Urbana, Ill
1	AVCO Corp. Undersea Projects Directorate Wilmington, Mass
1	Union Carbide Plastics Corp. (Mr. Charles Platt) Brunswick, N. J.