DEPARTMENT OF THE NAVY
DAVID TAYLOR MODEL BASIN

HYDROMECHANICS

○

AERODYNAMICS

○

STRUCTURAL MECHANICS

○

APPLIED MATHEMATICS

EXPLORATORY TESTS OF LONG GLASS CYLINDERS UNDER EXTERNAL HYDROSTATIC PRESSURE

by

Martin A. Krenzke

STRUCTURAL MECHANICS LABORATORY

RESEARCH AND DEVELOPMENT REPORT

August 1962

Report 1641

PRNC-TMB-648 (Rev. 3-58)

DEPARTMENT OF THE NAVY
DAVID TAYLOR MODEL BASIN
WASHINGTON 7, D.C.

IN REPLY REFER TO
9110/Subs
5605
(726:MAK:lkg)
Ser 7-376
26 October 1962

From: Commanding Officer and Director, David Taylor Model Basin
To: Chief, Bureau of Ships (442) (in duplicate)

Subj: Exploratory tests of long glass cylinders; forwarding of report on

Encl: (1) David Taylor Model Basin Report 1641 entitled, "Exploratory Tests of Long Glass Cylinders under External Hydrostatic Pressure" 2 copies

1. High strength-weight characteristics will be of prime importance for the hulls of vehicles and buoys designed for extremely large operating depths, but transparency of hull materials may also be highly desirable. Glass is a material well known for its transparency, but little is known of its compressive strength. To explore the potential of glass hulls, 20 long cylinders were picked at random from open stock and tested under hydrostatic pressure. Enclosure (1) reports the test results of these cylinders. This study was conducted under the Structural Mechanics Laboratory Fundamental Research Program (SR-011-0101, Task 0401).

2. The experimental collapse pressures, which ranged between 2000 and 15,000 psi, were in excellent agreement with classical theory for the elastic buckling of long cylinders. Although all failures appeared to initiate in the elastic range, maximum circumferential stresses of about 100,000 psi were reached. This high working stress together with a rather low density indicates that glass offers very high strength-weight ratios and thus may be of use in deep hull applications.

E. E. Johnson

E. E. JOHNSON
By direction

9110/Subs
5605
(726:MAK:lkg)
Ser 7-376
26 October 1962

Copy to:
BUSHIPS (320) with 1 copy of encl (1)
(335) with 3 copies of encl (1)
(341A) with 1 copy of encl (1)
(420) with 1 copy of encl (1)
CHONR (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)
CDR, ASTIA, with 10 copies of encl (1)
DIR, USNEES, with 10 copies of encl (1)
CDR, USNOL (R B) with 1 copy of encl (1)
DIR, USNRL (2027) 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)
CDR, USNOTS, China Lake with 1 copy of encl (1)
CO, USNUOS, with 1 copy of encl (1)
DIR, DEF R and E, Attn: Tech Library with 1 copy of encl (1)
CO, USNROTC and NAVADMINU, MIT with 1 copy of encl (1)
O in C, PGSCOL, Webb, with 1 copy of encl (1)
DIR, APL, Univ of Washington, Seattle with 1 copy of encl (1)
NAS, Attn: Comm on Undersea Warfare with 1 copy of encl (1)
WHOI with 1 copy of encl (1)
Dr. E. Wenk, Jr., Tech Asst, The White House with 1 copy of encl (1)
CO and DIR, NAVENGRXSTA with 1 copy of encl (1)

Open Files

EXPLORATORY TESTS OF LONG GLASS CYLINDERS UNDER EXTERNAL HYDROSTATIC PRESSURE

by

Martin A. Krenzke

August 1962

Report 1641
S-R011 01 01

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

The potential of glass as a hull material for hydrospace vehicles was investigated by determining the hydrostatic strength of 20 long cylinders of No. 7740 glass. The experimental collapse pressures, which ranged between 2000 and 15,000 psi, were in excellent agreement with classical theory for elastic buckling of long cylinders. Calculations were based on minimum measured thicknesses. Although all failures appeared to initiate in the elastic buckling range, maximum circumferential stresses of about 100,000 psi were reached. This high strength coupled with a relatively low weight makes glass appear very attractive for some deep-depth applications. Although these tests were conducted on long unstiffened cylinders, calculations indicate that glass spheres have a potential of demonstrating higher strength-to-weight ratios than is attainable by any other type hull using currently available materials.

INTRODUCTION

Anticipating a future requirement of deep-depth capability for underwater vehicles, the David Taylor Model Basin, in 1957, initiated a limited fundamental research program to investigate structures to operate at great depths. The program was divided into two phases, one in which new hull shapes were considered and one in which new hull materials were investigated. Although the limited program was initially sponsored under Project S-R011 01 01, considerable exploratory work has also been accomplished under direct sponsorships of the Bureau of Ships and the Office of Naval Research.

Research in the area of hull shapes has been conducted both analytically and experimentally. The material studies have normally involved tests of small models as new materials become available. The analytical and experimental studies of new structural shapes and configurations have dealt with sandwich, composite, multilayer, and membrane cylinders, and oval, spherical, and spheroidal shells. Model studies have been conducted on cylindrical hulls of HY-150 to HY-220 steel, HY-120 to HY-200 titanium alloys, HY-60 to HY-80 aluminum alloys, and Fiberglas-reinforced plastics with yield strengths of 75,000 psi and greater. In addition, cylinders of plastics with reinforcement other than Fiberglas are currently being considered.

The chief advantage of each of the materials used thus far has been their relatively high strength-weight characteristics. However, another desirable characteristic for hull materials to be used in many underwater vehciles at deep depth is transparency. For example, a high transparency of hull material to gamma rays would be helpful in the detection of underwater radiation, and transparency to visible rays would be advantageous in such applications as hull material for oceanographic research vehicles and instrument casings.

Glass is a material well known for its transparency. However, very little data are available on the compressive strength-weight characteristics of glass. The rather poor reputation of glass as a structural material has been based on experience under tensile loads, where serious effects of scratches and other flaws and imperfections on ultimate strength have been observed.

The lack of any test data on the strength of glass under biaxial compression led to the exploratory tests described herein on 20 unstiffened long glass cylinders. These tests were conducted under hydrostatic pressure to determine whether glass deserves consideration as a hull material for deep-depth application. This report summarizes the tests, compares the results with existing theory, discusses the strength-weight merits of glass, and outlines the areas of research required before glass can be considered as a hull material.

DESCRIPTION OF CYLINDERS

Twenty cylinders of Pyrex brand "double-tough" pipe were selected at random from open stock.[1] "Double-tough" pipe is composed of No. 7740 barosilicate glass in a semitempered condition. In a semitempered condition No. 7740 glass has a Young's modulus E of 8.96×10^6 psi, a

---

[1] References are listed on page 14.

Poisson's ratio of 0.19, and a specific gravity of 2.23[2]. A sketch of the cylinders is given in Table 1, together with nominal dimensions and a limited number of measured dimensions. The thickness and diameter measurements listed in Table 1 were obtained at a single location along the length of each cylinder away from the tapered ends. However, spot checks made along the length of the cylinders indicated that the thickness was quite consistent. Cylinders 1 through 6 were about 6 diameters long, and the other cylinders were 10 diameters long or greater.

Local imperfections were observed in the cylinder walls in addition to the variations in thickness and diameter indicated in Table 1. Small "bubbles" and surface scratches were observed in many of the models although no record of these observations was made. Numerous irregularities were also present in the buildup area where the tapered flange was welded to the cylinderical portion.

TEST PROCEDURE AND RESULTS

Each cylinder was sealed by a lead disk placed between the glass and heavy steel end plates and was subjected to external hydrostatic pressure. Cylinders 1 through 6 were tested in the Model Basin's 13-in., 9000-psi pressure tank, and Cylinders 7 through 20 were tested in the Model Basin's new 17 1/2-in., 25,000-psi tank. Cylinders 1 and 6 were subjected to a maximum pressure of 9000 psi without collapsing. All other cylinders were tested to collapse.

Pressure was applied in increments during each test. Each new pressure level was held at least 1 min, and the final pressure increment was normally less than 2 percent of the maximum pressure applied.

The collapse of the cylinders caused complete crystalization of the glass walls and was accompanied by a loud, sharp noise. Most of the cylinders collapsed while the pressure load was being increased. In no case was a "fall off" in pressure observed prior to collapse. The collapse pressure of all cylinders except 1 and 6 are presented in Table 2.

Large cracks, apparently originating at the ends of the cylinder, were observed in Cylinders 1 and 6 after they were subjected to 9000 psi. Although the cracks extended throughout the thickness of the glass, no leakage of water into the cylinders occurred during the test. It may be worth

TABLE 1

Measured Dimensions of Cylinders

Cylinder	Maximum Outside Diameter in.	Minimum Outside Diameter in.	Maximum Wall Thickness in.	Minimum Wall Thickness in.	Overall Length in.
1	2.365	2.345	0.179	0.172	12
2	4.562	4.538	0.286	0.261	24
3	4.568	4.542	0.275	0.255	24
4	4.555	4.534	0.278	0.255	24
5	4.551	4.526	0.290	0.250	24
6	2.361	2.352	0.183	0.175	12
7	6.661	6.604	0.330	0.313	60
8	6.689	6.636	0.328	0.311	60
9	6.654	6.608	0.332	0.314	60
10	6.754	6.688	0.376	0.352	60
11	4.518	4.502	0.297	0.278	48
12	4.513	4.508	0.294	0.272	48
13	2.318	2.310	0.180	0.174	24
14	2.334	2.326	0.180	0.171	24
15	2.337	2.324	0.185	0.172	24
16	2.328	2.317	0.185	0.170	24
17	1.866	1.845	0.176	0.164	18
18	1.859	1.837	0.174	0.163	18
19	1.859	1.838	0.175	0.161	18
20	1.855	1.837	0.173	0.161	18

TABLE 2

Experimental Collapse Pressures

Cylinder	Exp. Collapse Pressure, psi
1	*
2	4,400
3	4,350
4	4,475
5	4,425
6	*
7	1,970
8	2,020
9	1,970
10	2,700
11	5,040
12	5,130
13	9,250
14	9,115
15	9,760
16	8,970
17	14,750
18	12,500
19	14,500
20	15,450

* Were not collapsed.

noting that cracking noises were heard during the tests of Cylinders 1 and 6 as well as during the tests of several other cylinders. In each instance, the pressure at which these noises occurred was well below the maximum pressure applied. It was observed after tests that, in many cases, the cylinder ends had punched through the lead gaskets and were in direct contact with the steel and plates.

DISCUSSION AND CONCLUSIONS

Cylinders 7 through 20 were of sufficient length to behave as semi-infinite tubes.[3] Figure 1 compares the collapse pressure of these cylinders with the classical theory of Bresse[4] and Bryan[5] for the elastic buckling strength of long, unstiffened cylinders under external hydrostatic pressure.* The agreement between experiment and theory was extremely good for all cylinders except Cylinder 18 when based on minimum measured thicknesses; see Figure 1a. When the mean measured thickness was used in theoretical calculations the experimental values were on an average about 15 percent below the calculated values; see Figure 1b.

There is no apparent explanation of the relatively low collapse pressure of Cylinder 18. After collapse, it was observed that the ends of the cylinder had punched through the lead gasket during the pressure test. However, each of the 1 1/2-in.-diameter cylinders punched through the lead gaskets, and yet Cylinder 18 was the only one of the group which collapsed at a pressure appreciably below that pressure predicted by theory.

---

* The theory of Bresse and Bryan was modified for the pressures presented in Figure 1 to account for the difference in the radius to the neutral axis of the tube and the outside radius where the pressure load is acting.

The collapse strengths of Cylinders 2, 3, 4, and 5 were affected by the closure plates. Their average collapse strength was about 15 percent higher than would be expected for a semi-infinite cylinder. This is in good agreement with the theory of Sturm[3] for simply supported cylinders of critical length under external hydrostatic pressure.

There is no concrete explanation for the cracks which were observed in Cylinders 1 and 6 although several possibilities exist. The most probable explanation is that the cracks were caused by high local stresses occuring at the ends of the cylinders as they punched through the lead and came in direct contact with the steel end plate. This assumption is supported by the fact that each time a cracking noise occurred, it was heard while pressure was being applied to the cylinders. It is also possible that the glass cracked while unloading although no noise from the pressure chamber was heard while pressure was being released.

If the cracks were caused by high local bearing stresses, it appears possible that this drawback may be overcome. By proper design of the end closures, the bearing stresses can be minimized and the cracks may possibly be eliminated. Although the cracks had no apparent influence on collapse strength, they must be eliminated before glass can be seriously considered as a hull material for deep-depth vehicles. This is true since water would very likely flow through the cracks when on or near the surface and would prohibit recovery of the vehicle.

No definite conclusions can be made concerning any systematic effect of initial imperfections on collapse strength. Obviously, more elaborate measurements than those taken during these rather exploratory tests are required before any definite conclusions can be drawn. However, several general observations can be made concerning the effect of initial imperfections from the tests described herein. As shown in Figure 1a, the observed collapse strength agrees very well with classical theory when based on minimum measured thickness. This is not surprising since the eccentricity of the bore relative to the exterior surface caused the minimum thickness to occur at a particular angular orientation along the entire length of the cylinder. Although the limited measurements indicate that varying degrees of out-of-roundness were present in the cylinder, there was no significant effect on collapse pressures. One possible explanation is that the out-of-roundness is small in each instance relative to radius and shell thickness and, therefore, has a negligible effect on collapse strength. Many of the cylinders had initial flaws in the walls. In addition, the surfaces had varying degrees of imperfections, as is to be expected from shelf stock. Although these flaws and surface imperfections would be expected to have considerable detrimental effect on cylinders under tension or internal pressure, no effect on collapse under external pressure was observed.

The tests do not demonstrate the maximum compressive strength of glass since the cylinders collapsed by elastic instability. The tests do show, however, that compressive stresses of about 100,000 psi may be developed in No. 7740 glass cylinders. Specifically, the maximum calculated circumferential stress in Cylinder 20 prior to collapse was 97,000 psi.[6] Tests of thicker long cylinders, short or stiffened cylinders, or spheres would provide the maximum compressive strength of glass as a hull material.

Glass shows promise of providing higher strength-to-buoyancy ratios for pressure hulls than can be realized by hulls of presently available metals such as high-strength steels, aluminum alloys, and titanium alloys. Although Cylinder 20 collapsed by elastic instability, a hull of steel with a yield strength in excess of 300,000 psi, a hull of aluminum with a yield strength in excess of 100,000 psi, or a hull of titanium with a yield strength of about 200,000 psi would be required to equal its performance on a strength-weight basis.

Glass spheres should provide even higher strength-to-buoyancy ratios than are attainable from cylinders. Figure 2 shows the relative strength-buoyancy ratios for long glass cylinders, stiffened glass cylinders, and glass spheres. The collapse strength of the long glass cylinders are based on the elastic theory of Bresse and Bryan. The predicted collapse strength of the stiffened cylinders is based on the assumption that stiffeners are placed in such a manner that the yield strength of all of the material may be utilized. The solid curves for the elastic buckling of spheres are based on experimental tests of machined aluminum deep spherical shells,[7] and the broken curves are based on tests of fabricated steel ellipsoidal shells.[8] The solid line, therefore, represents the upper bound of experimental results, and the broken line represents the lower bound for tests of shells with various initial imperfections. It can be seen from Figure 2 that spherical glass shells should always be considerably more efficient than long cylindrical shells and should also be more efficient than stiffened cylindrical shells for a considerable portion of the ocean depth. Tests of spherical glass shells are required to verify these calculations.

Many unknowns must be determined before glass may seriously be considered as a hull or float material. Specifically, tests must be conducted to study cyclic strength, creep strength, impact strength, and the combined effects of marine atmosphere, interior flaws in the glass, and surface imperfections. The present study demonstrates, however, that in addition to its excellent transparency properties, glass has a very high strength-weight ratio when under favorable compressive static loads, as created in a cylinder under external hydrostatic pressure.

RECOMMENDATIONS

The utilization of glass spheres imbedded in a plastic matrix as float material and appendages should be studied.

ACKNOWLEDGMENTS

The author wishes to express his appreciation to Mr. E. E. Johnson, Head, Ship Structures Division, for his initial and continued interest in this project and to Mr. L. J. Ginffreda for conducting the hydrostatic tests.

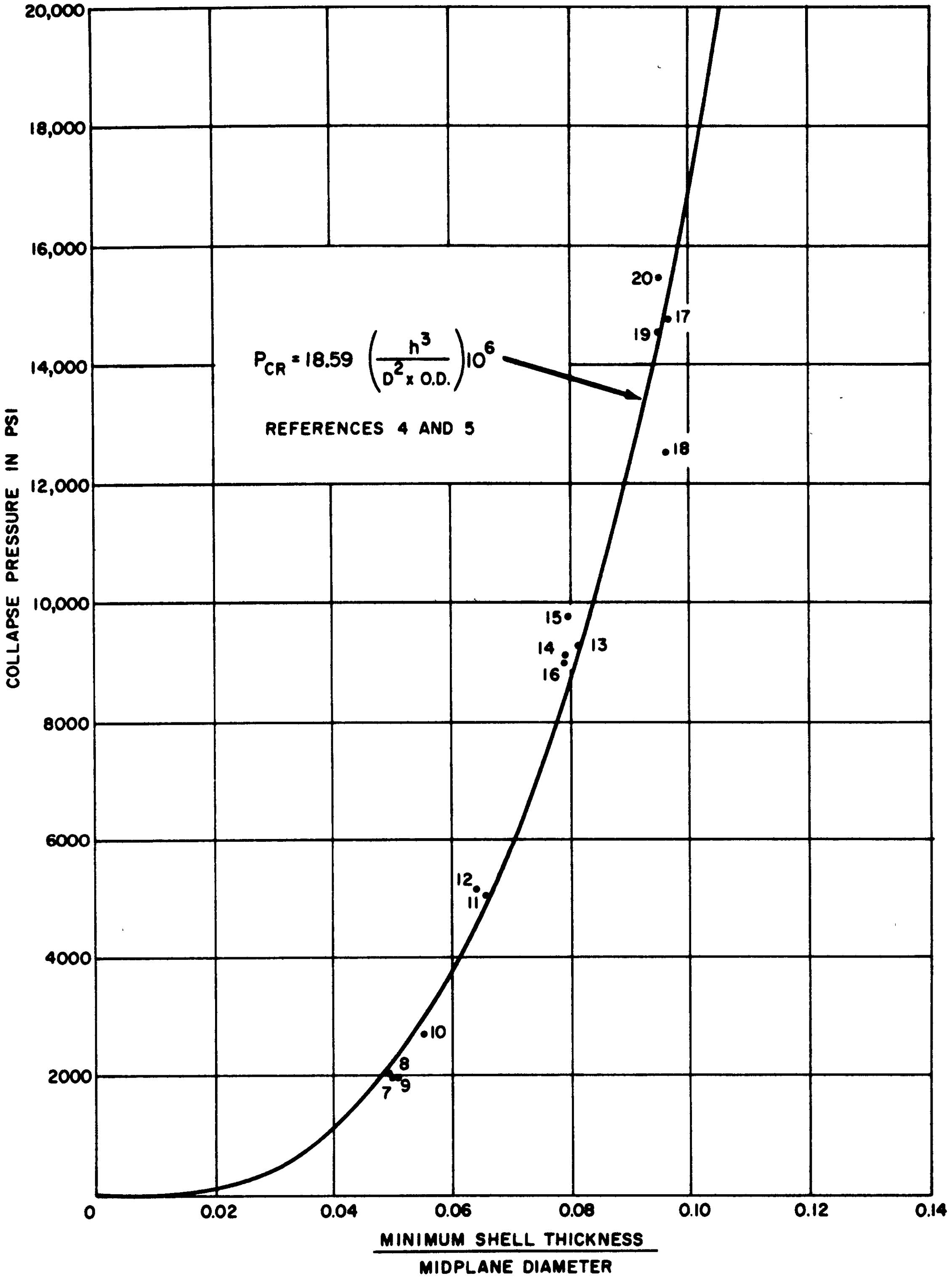

Figure 1a - Based on Minimum Measured Wall Thickness

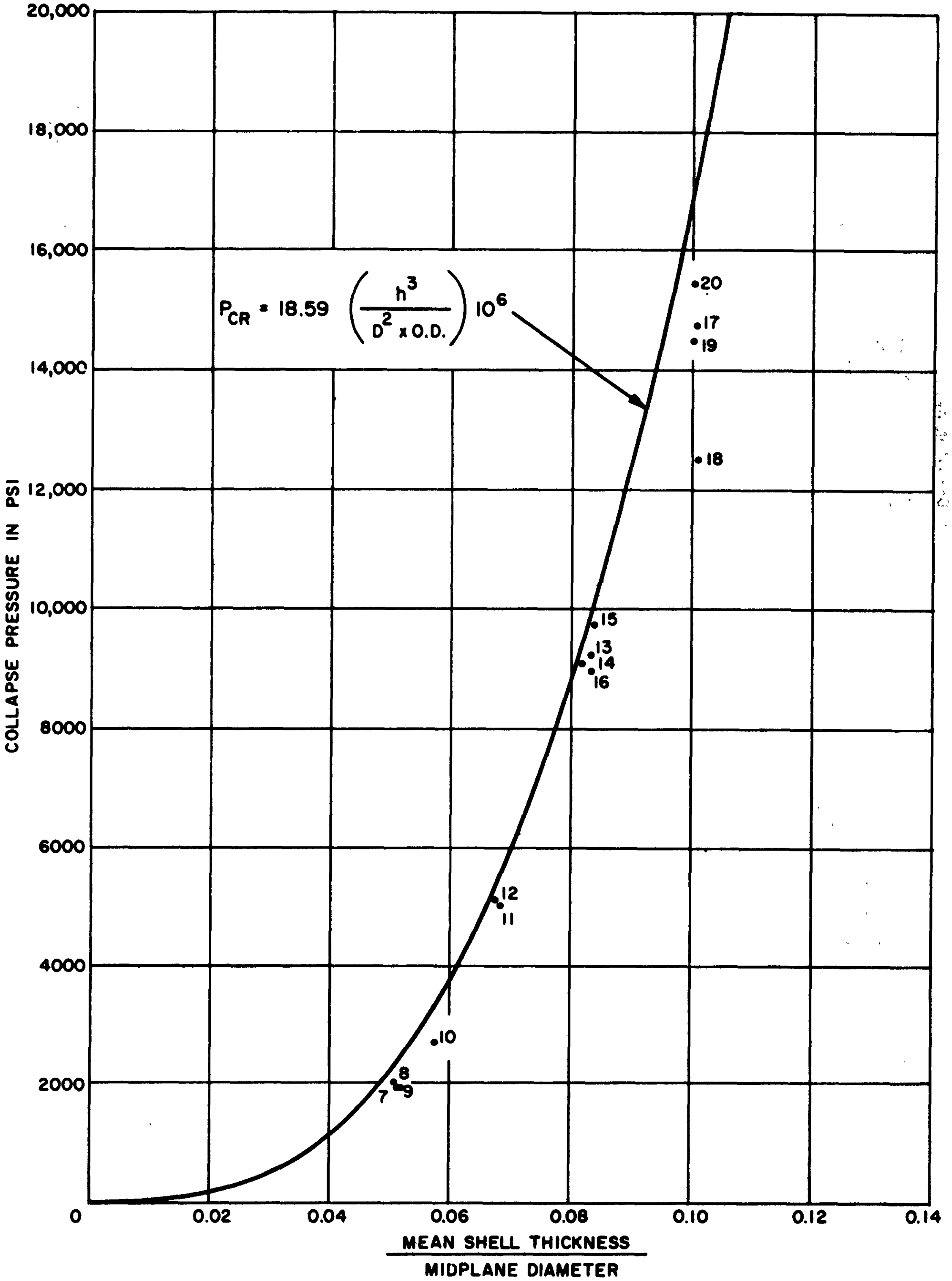

Figure 1b - Based on Mean Measured Wall Thickness

Figure 1 – Comparison of Experimental Collapse Pressure with Theory of Bresse and Bryan

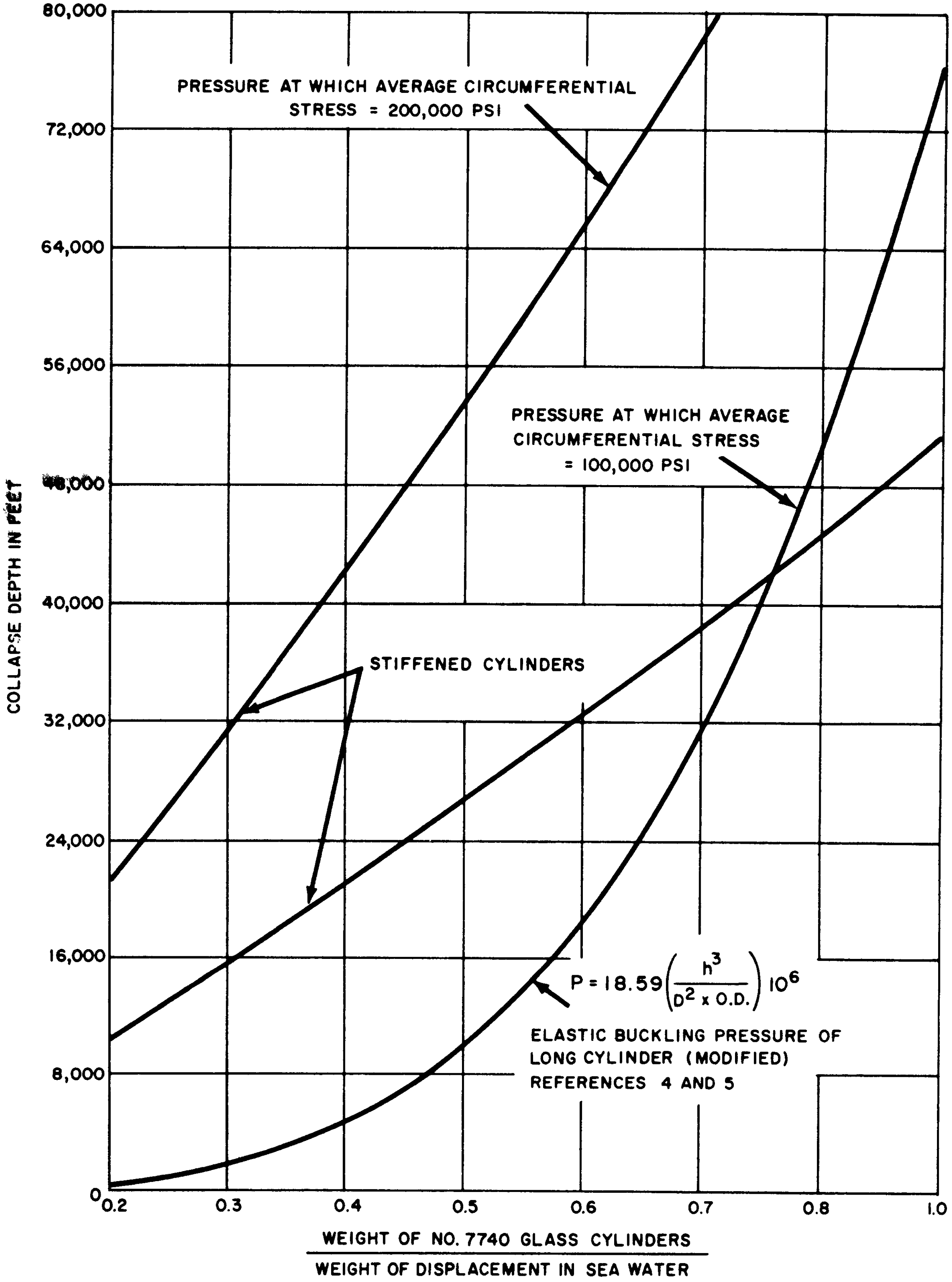

Figure 2a - Cylinders

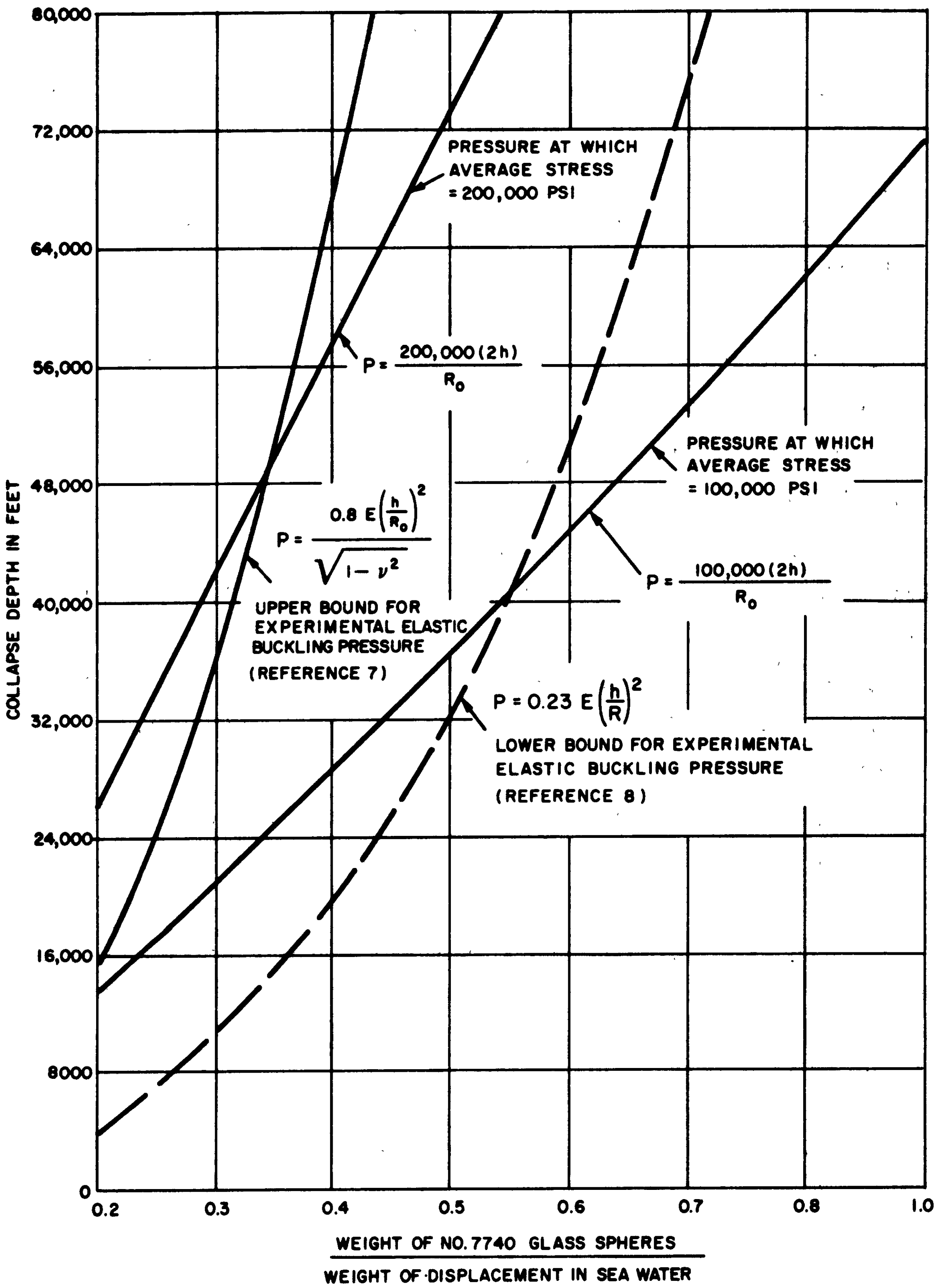

Figure 2b - Spheres

Figure 2 – Theoretical Collapse Depth versus Ratio of Weight to Displacement for No. 7740 Glass Cylinders and Spheres

REFERENCES

1. "Pyrex Brand "Double-Tough" Glass Pipe and Fittings" in "Manual for Design Engineering Installation," Corning Glass Works (1959).

2. Kerper, M. J., Diller, C. C. and Eimer, E. H., "Properties of Glass at Elevated Temperatures," Wright Air Development Center Report 56-645, Part III (Dec 1958).

3. Sturm, R. G., "A Study of Collapsing Pressure of Thin-Walled Cylinders," University of Illinois Engineering Experimental Station Bulletin No. 329 (1941).

4. Bresse, M., "Cours de Mécanique Appliqué," Paris, pp. 323-338 (1859).

5. Bryan, G. H., "Application of the Energy Test to the Collapse of a Long Thin Pipe under External Pressure," Cambridge Phil. Soc, Proc., Vol. 6, pp. 287-292. (1888).

6. Jeffery, G. B., "The Stresses in Cylinders and Pipes With Eccentric Bore," British Association for the Advancement of Science, pp. 356-358 (1921).

7. Krenzke, Martin A., "Tests of Machined Deep Spherical Shells under External Hydrostatic Pressure," David Taylor Model Basin Report 1601 (May 1962).

8. Bart, R., "An Experimental Study of the Strength of Standard Flanged and Disked and Ellipsoidal Heads Convex to Pressure," Pressure Vessel Research Committee Report for Subcommittee on Heads Convex to Pressure (Feb 1962).

INITIAL DISTRIBUTION

Copies	
8	CHBUSHIPS
	1 Lab Mgt (Code 320
	3 Tech Info Br (Code 335)
	1 Struc Mech, Hull Mat & Fab (Code 341A)
	1 Prelim Des Br (Code 420)
2	CHONR
	1 Struc Mech Br (Code 439)
	1 Undersea Programs (Code 466)
4	CNO
	1 Tech Anal & Adv Gr (Op 07T)
	1 Plans, Programs & Reg Br (Op 311)
	1 Sub Program Br (00 713)
	1 Tech Support Br (Op 725)
10	CDR, ASTIA
1	DIR, USNEES
1	CDR, USNOL (Code R B)
1	DIR, USNRL (Code 2027)
1	CO & DIR, USNUSL
1	CO & DIR, USNEL
1	CDR, USNOTS, China Lake
1	CO, USNUOS
1	DIR, DEF R & E, Attn: Tech Library
1	CO, USNROTC & NAVADMINU, MIT
1	O in C, PGSCOL, Webb
1	DIR, APL, Univ of Washington, Seattle
1	NAS, Attn: Comm on Undersea Warfare
1	WHOI
1	Dr. E. Wenk, Jr., Tech Asst, The White House