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WOODS HOLE OCEANOGRAPHIC INSTITUTION

Reference No. 63-17

PRELIMINARY REPORT ON PRESSURE TEST OF ONE-SIXTEENTH SCALE "ALUMINAUT" MODEL

WOODS HOLE, MASSACHUSETTS

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Woods Hole, Massachusetts

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PRELIMINARY REPORT ON PRESSURE TEST OF ONE-SIXTEENTH SCALE "ALUMINAUT" MODEL

by

Joseph B. Walsh

Technical Report
Submitted to Undersea Warfare Branch, Office of Naval Research
Under Contract Nonr-3484(00) (

May 1963

APPROVED FOR DISTRIBUTION [signature]

Paul M. Fye
Director

Abstract

A pressure test of a one-sixteenth scale model of the ALUMINAUT was run to determine the collapse depth and to measure stresses at critical locations. The model test indicated that the collapse depth of the ALUMINAUT is about 23,000 ft. Strain gages on the forward hemisphere showed that plastic deformation would occur in the region around the central window at a depth between 15,000 ft. and 16,000 ft.

Table of Contents

1. Introduction

A pressure test of a one-sixteenth scale model of the ALUMINAUT hull was carried out at WHOI in order to determine the collapse depth of the hull and to measure stresses at critical points on the hull. Four previous tests carried out be General Dynamics, Electric Boat Div., were not considered definitive for several reasons:

(1) The possibility existed that the collapse pressure of their model was influenced by the fact that their model contained only one joint.

(2) The Electric Boat Div. models were not completely collapsed.

(3) The hemisphere containing the windows was not scaled in the Electric Boat Div. model. High stresses were predicted in the vicinity of the windows (Ref. 1).

Accordingly, each cylinder in the WHOI model was individually machined, and the forward hemisphere was scaled, including the window frames and the lucite windows. The machining was done at Oceanographic Research Equipment, Inc., Martha's Vineyard, and dimensionally checked at WHOI.

Stresses at various critical areas throughout the hull had been previously determined theoretically (Ref. 1). Strain gages, 101 in all, were applied in regions considered critical and at certain other points where comparison with theory was desired. The strain gages were applied by Lessells and Assoc., Boston. Some gages which had loosened were reapplied by Prof. H.A. Gaberson, Boston University, Boston.

The model was assembled and wired at WHOI, and tested in the WHOI 16 in. shell pressure tank. Two tests were run: The first test was run to 4,660 psi to obtain strains in the elastic region and check out the system; the second test was run to collapse.

2. Collapse Pressure

The model failed in the general instability mode at a pressure of 12,000 psi. Yielding which occurred at the inside of the stiffeners and at midbay of the cylinders precipitated the failure. A photograph of the collapsed model is shown in Figure 1.

The measured collapse pressure agrees well with that predicted in Ref. 1. The analysis in Ref. 1 (Eq. 27 and Eq. 29) shows that collpase would be expected to occur between 9,800 psi and 10,800 psi for a model with a yield strength of 60,000 psi (the specified minimum for the ALUMINAUT). The material from which the WHOI model was machined was found from compression tests on ten specimens (circumferentially oriented) to have a yield strength at 0.2% offset ranging between 67,000 psi and 73,000 psi with an average value of 70,500 psi. A typical stress-strain curve is shown in Figure 2. The collapse depth predicted for the WHOI model therefore lies between

$$9{,}800 \left(\frac{70{,}500}{60{,}000}\right) = 11{,}500 \text{ psi}$$

and

$$10{,}800 \left(\frac{70{,}500}{60{,}000}\right) = 12{,}700 \text{ psi.}$$

The measured collapse pressure of 12,000 psi lies nearly midway between these limits.

Conversely, the collapse depth for ALUMINAUT, as predicted from this model test, is $\frac{60{,}000}{70{,}500}$ (12,000) = 10,200 psi = 23,000 ft.

The collapse pressure measured with the WHOI model is in only minor disagreement with the results of the Electric Boat Div. tests (see Ref. 2). Their models collapsed at pressures ranging between 11,400 psi and 11,800 psi; however, the models were machined from material with circumferential yield strengths at 0.2% offset of 59,500 psi to 64,600 psi. Thus, their tests indicate a relative collapse strength 5 - 10% greater than that found in the WHOI test. The only difference between the WHOI test and the Electric Boat Div. test which would cause an increase in the relative collapse strength is in the number of joints. It appears from the small difference in the relative collapse depths as measured in the two series of tests that the number of joints does not have a large influence on the strength of the hull. Such a result would be expected theoretically.

The collapse depth predicted by Electric Boat Div. (see Ref. 2) is also slightly higher than predicted by WHOI (Ref. 1). The analysis leading to the Electric Boat Div. prediction has not been published, so no comparison of methods is possible.

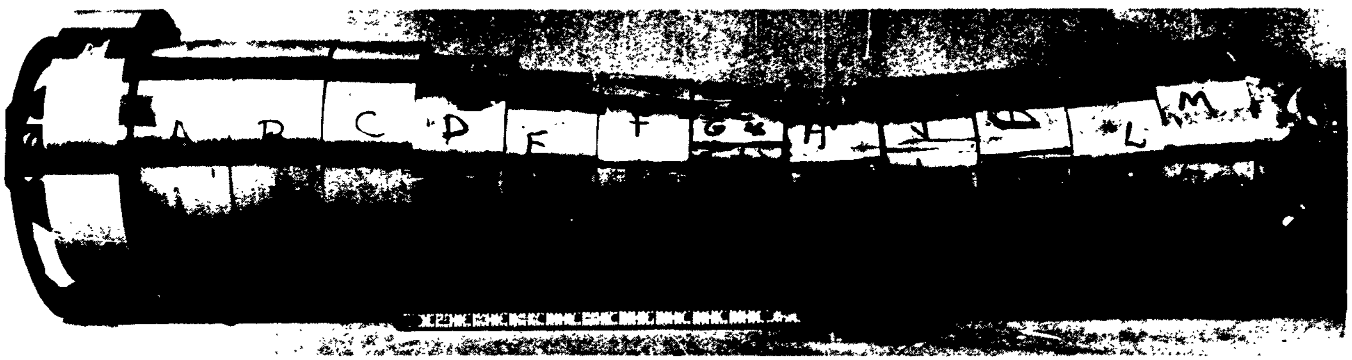


FIGURE 1. COLLAPSED MODEL

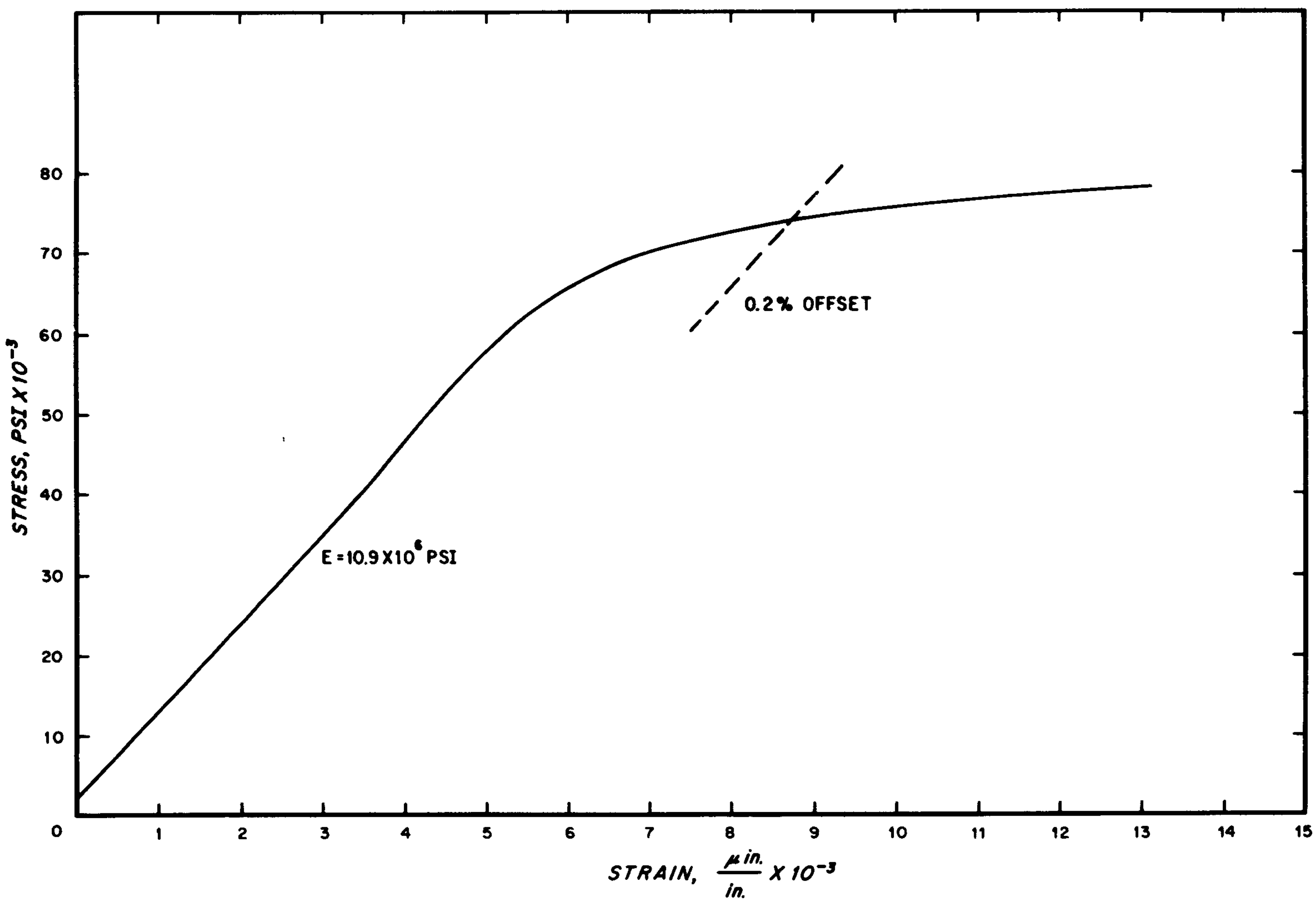


FIGURE 2. TYPICAL UNIAXIAL COMPRESSIVE STRESS-STRAIN CURVE — CIRCUMFERENTIALLY ORIENTED SPECIMEN

3. Strain Gage Results

Schematic drawings showing the positions of the strain gages are presented in Figure 3 and Figure 4. The first test was run to 4,660 psi in increments of approximately 1,000 psi. Measurements of strain were made on the depressurizing cycle at 2,650 psi and at 0 psi. The rather low maximum pressure in the first test was chosen to insure that all strains would be in the elastic region. The second test was run to collapse, with strain measurements taken at 0, 4,700, 6,700, 7,700, 8,700, 9,650, 10,150, 10,600, and 11,000 psi.

3.1 Stresses in Cylinders

A facsimile of Figure 3 showing the stresses at 1,000 psi as calculated from measurements at the corresponding gage location is given in Figure 5. The measured values of the nominal stresses are compared where possible in Table 1 with the values predicted in Ref. 1. The predicted values agree quite closely with the measured values except for the "Stiffener, inside, circum." value. The predicted value in this location was based on an approximate method of correcting the thin shell theory for the thick section in way of the stiffeners; evidently, the approximate method is not satisfactory.

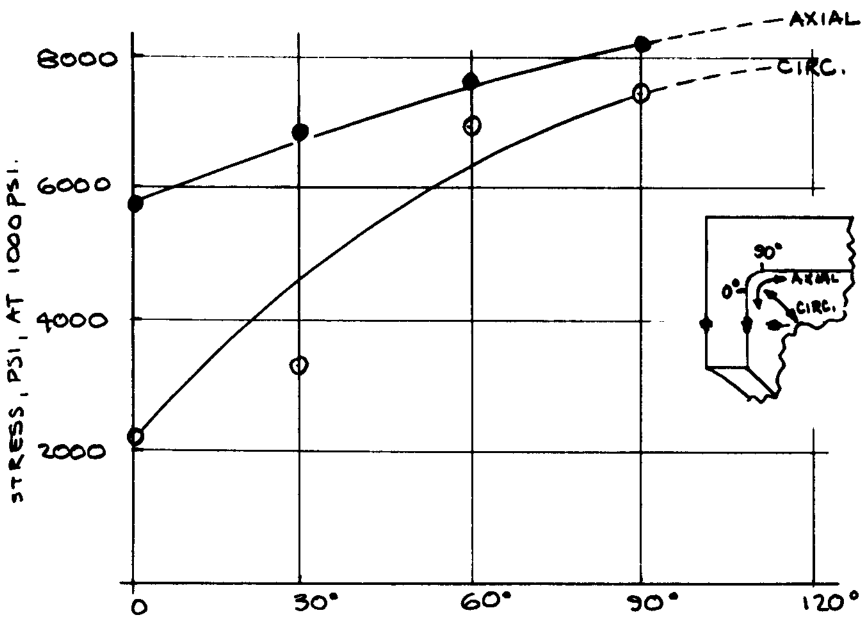
Typical Cylinder	Avg. Measured	Predicted
Mid-bay inside, circum.	7080	7140
" " , axial	3090	3450
" outside, circum.	6620	6560*
" " , axial	4610	4500
Stiffener, inside, circum.	6620	7580
" " , axial	260	0
" outside, axial	1720	1610

*Corrected for thick cylinder effect, c.f. Ref.1, App. C.

Cylinder near a Hemisphere		
Mid-bay, inside, circ.	7120	7140
" " , axial	2760	2940

NOMINAL STRESSES in CYLINDERS
Table 1

Narrow width gages (0.031 in.) were applied to the fillet region in an attempt to measure the fillet stress. A maximum axial fillet stress of 9,930 psi at 1,000 psi pressure was predicted in Ref. 1. The measured values, plotted in Figure 6, show that the gages were not located sufficiently far away from the flange to show the maximum stress. The maximum extrapolated value appears to be closer to 9,000 psi than the 9,900 psi value predicted.



FILLET STRESSES
Figure 6

Prediction from a uniaxial stress-strain curve of the "yield stress" for a triaxial stress state is usually carried out by calculating the uniaxial stress equivalent to the triaxial stresses from the Mises-Henky theory. Figure 2 shows that the uniaxial stress strain curve departs from linearity at about 60,000 - 65,000 psi. The equivalent uniaxial stress for "mid-bay, inside" was predicted in Ref. 1, Table 7 to be 6,190 psi at 1,000 psi pressure. The pressure at which the stress-pressure curve for the mid-bay, inside location should depart from linearity is thus between

$$\frac{60,000}{6,190} = 9,700 \text{ psi and } \frac{65,000}{6,190} = 10,500 \text{ psi.}$$

A typical stress-pressure plot for the "mid-bay, inside" region

(Figure 7) shows departure from linearity at about 10,000 psi. Thus, use of the Mises-Henky theory for predicting yielding in this structure is validated.

Typical strain-pressure plots from the WHOI model are compared with available curves from the Electric Boat Div. tests in Figure 8. Good correlation is obtained at all three gage locations. Non-linearity in the EB plots occurs at a lower pressure than in the WHOI plots as would be expected from a lower yield strength material.

3.2 Stresses in the Hemisphere

The highest stresses recorded in the WHOI test are found around the ports in the hemispheres. The stresses measured at various locations in the hemisphere are displayed in Figure 9 for a pressure of 1,000 psi. Some of the gages located normal to the port axes had some non-linearity in the stress-pressure plots, at low pressures, probably due to poor seating of the frames in the seats. These stresses are small and do not influence the results significantly.

Uniaxial stresses equivalent to the biaxial and triaxial stress states displayed in Figure 9 can be computed using the Mises-Henky theory. Values so obtained for gage locations near the ports are tabulated in Table 2 for a confining pressure of 1,000 psi. The highest values are found at the center port. The highest value, 8,300 psi at 1,000 psi pressure, predicts that yielding in the full scale hull (having a yield strength of 60,000 psi) will occur in the vicinity of gages 89-90 at a pressure of $\frac{60,000}{8,300}$ = 7,230 psi = 16,300 ft.

Gage Nos.	Location	Stress
75-76	Center port, inside	7,900
89-90	" " "	8,000
89-90	" " outside	8,300
77-78	" " inside	8,200
76-77	" " outside	6,800
81-82	0° Port, inside	7,500
87-88	" inside	7,800
87-88	" outside	7,000
83-84	" inside	7,100
83-84	" outside	6,600
91-92	270° port, inside	6,200
91-92	" " , outside	7,500
93-94	" " , inside	7,200
95-96	" " , inside	8,200

EQUIVALENT UNIAXIAL STRESS at 1,000 PSI NEAR PORTS
Table 2

The stress right at the port edge is somewhat higher than that measured at gage 89. Gage 89 could not be located closer than about 3/32" from the edge of the port. Figure 8 shows that stresses increase with decreasing distance from the port. Therefore, yielding at the port edge would be expected at a proportionally lower depth. Comparison of stresses for gages 77 and 79 shown in Figure 8 shows that the stress increases by about 30% as one proceeds 1/2 in. closer to the port edge on the inside of the hemisphere. If we assume that approximately the same gradient exists on the outside of the hemisphere, the stress at the port would be expected to be about 6% greater than that measured at gages 77 - 78. The stress at which yielding starts is thus roughly 6% lower than that calculated above, or

depth for yielding at port = 0.94 (16,300) = 15,300 ft.

Plots of stress vs. pressure for gages located near the ports show that non-linearity in the curves occurs at approximately the pressure predicted from the equivalent uniaxial stresses in Table 2 and the stress-strain curve in Figure 2. In spite of yielding at the ports, it was found in the WHOI test that leaking past the window frames was very slight or non-existent.

Figure 8 shows that the stresses around the ports at the test depth of 17,500 ft. vary from about 55,000 psi to 75,000 psi. Ref. 1 predicts by an approximate analysis a stress of 57,000 psi around an outside window and a stress of 67,000 psi around the central window. Such agreement between analysis and experiment is quite good, considering the approximate nature of the analysis.

4. Conclusion

The one-sixteenth scale structural model test carried out at WHOI has provided extremely valuable information pertinent to safe operation of the ALUMINAUT:

(1) High stresses, found near the ports in the forward hemisphere, indicate that yielding should be expected near the central window in the ALUMINAUT at a depth between 15,000 ft. and 16,000 ft. The ports in the model did not leak in spite of the plastic deformation; however, this result is not necessarily true for ports of the full scale hull.

(2) Collapse of the ALUMINAUT should occur at a depth of about 23,000 ft. This depth is in agreement with theoretical predictions and with previous tests made by Electric Boat Div., General Dynamics Corp.

(3) Good agreement between experimentally obtained values of stress and theoretically predicted values was obtained. Approximate analyses used in Ref. 1 to determine stress concentration factors at

fillets, ports, etc. were shown to be adequate.

(4) The test showed that the Mises-Hènky theory can be used to determine from the uniaxial stress-strain curve and the elastic stresses the pressure at which yielding will start.

(5) Collapse occurs in the general instability mode preceded by yielding at the inside of the stiffener and at mid-bay in the cylinders. Collapse of the ALUMINAUT by general instability could be detected by mounting circumferentially oriented strain gages on the stiffeners and at mid-bay near the midship section of the ALUMINAUT Measurement of a departure from linearity would give an indication of impending collapse at a depth 10 - 15% less than the collapse depth.

(6) The final collapse of the model was catastrophic, with the midship cylinders fracturing into many pieces. Many of the surfaces displayed characteristics of brittle fracture; i.e., no shear lip, little reduction of area, and a rough surface. Thus, a small fracture in a region of high stress concentration or a fatigue crack would tend to "run". This problem is even more serious than indicated by the model tests since the ductility of the full scale cylinders is much less than that of the model. Rapid growth of a crack in a critical region such as a stiffener or a port could result in collapse or large scale leakage without prior warning.

The relatively small scale of the WHOI model did not allow scaling down of all details. One such detail that was not scaled was the bolt holes in the stiffeners. These bolt holes are located in a region of high stress and have a high stress concentration factor associated with them (estimated in Ref. 1 to be 2.75). Since failure of the stiffeners precipitates collapse of the hull, the collapse depth would be affected by large deformation or cracking at the bolt holes.

Another region that was not thoroughly was the fillet between the stiffener and the cylinder. The measurements that were made showed high stresses in the fillet region. Extensive cracking along the fillet was present in the collapsed model. Accurate measurement of the stresses in this region is very desirable.

There is some question as to whether the highest stress existing in the forward hemisphere was measured in the WHOI test. The gages could not be located close enough to the highly stressed regions because of the small scale of the model. Also, some details of the window frames could not be included. No attempt was made to scale the hatch because the clearance between the hatch and seat, which appeared to be an important consideration in the stress concentration factor, could not be scaled accurately. Therefore, the stresses measured in the hemisphere, while certainly indicative of the general level of stress, do not show local highly stressed regions which would be important from the standpoint of leakage and fatigue. The stern hemisphere, which contains penetrations for electrical leads was not scaled at all.

5. Recommendations

The model test provides the only way in which the collapse depth of the ALUMINAUT can be determined. It is important that the collapse depth be predicted with as much accuracy as possible.

Two regions in the hull with high stresses could not be investigated accurately because of the small scale of the WHOI model: the region around a stiffener and the hemispheres. The stiffener region is considered very important because of the important role the stiffeners play in the collapse depth. It is recommended, therefore, that a scale model of the stiffener region, large enough that bolt holes and fillets can be accurately scaled, be gaged and tested.

The hemispheres, while very important from a leakage and fatigue standpoint, do not play an important part in the overall collapse. In addition, the most important dimensions such as clearances cannot be accurately scaled. It is recommended that measurements of the stresses around penetrations in the hemispheres be done on the full scale submarine on a preliminary test dive to some relatively shallow depth. The elastic stresses measured on this dive can be used to predict the depth at which yielding will take place.

One variable which affects the operating depth and the factor of safety of the ALUMINAUT is time. The effect of time-dependent factors, such as corrosion and fatigue, on the collapse depth and the factor of safety has not been investigated adequately.

6. References

1) Walsh, Joseph B., "Strength of the ALUMINAUT Hull", Woods Hole Oceanographic Institution Ref. No. 62-32, Apr., 1962.

2) Duffy, D.J., and McGrattan, R.J., "ALUMINAUT Model Tests", General Dynamics, Electric Boat Div. Report V411-62-040, Aug. 21, 1962.

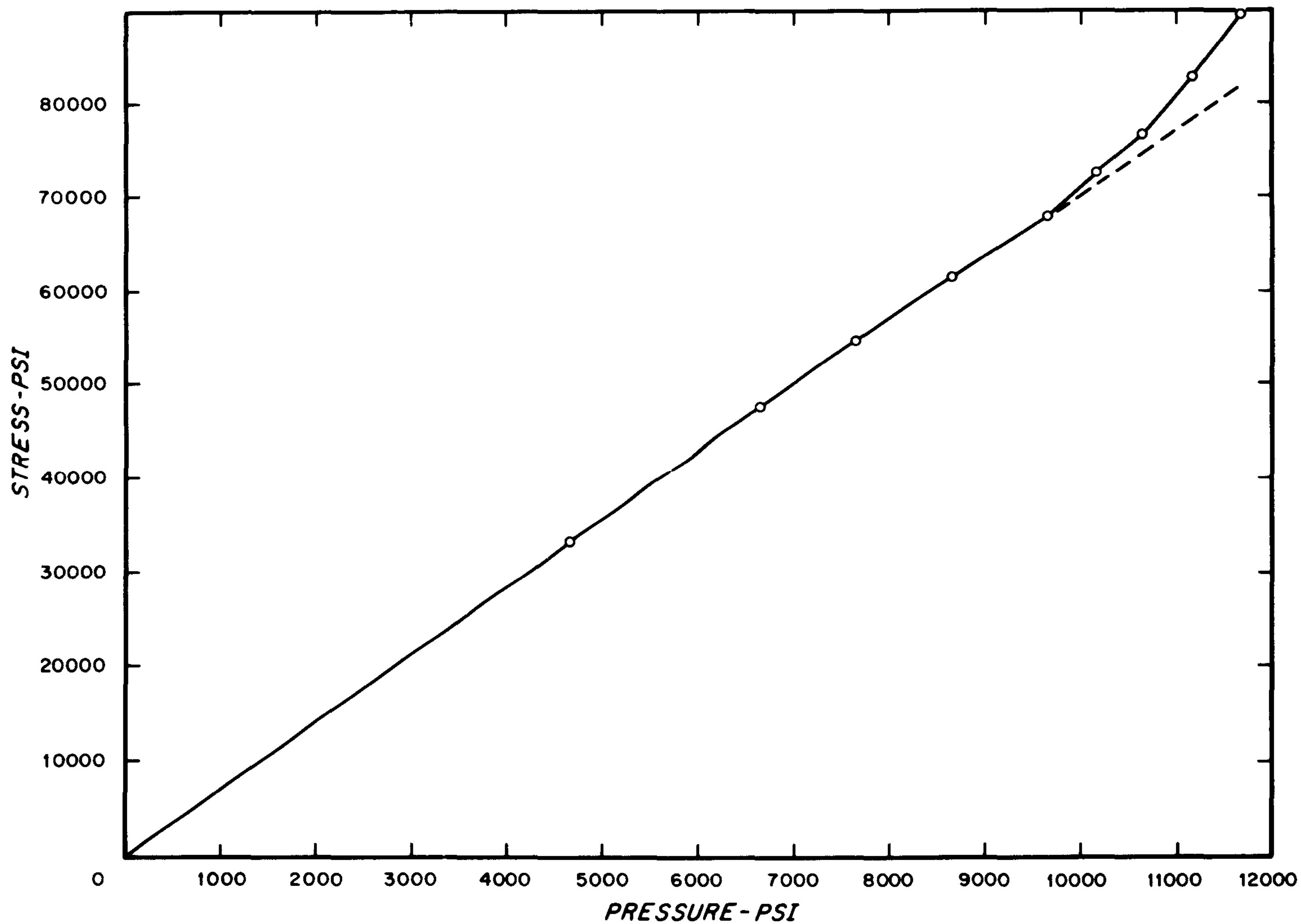


FIGURE 7. RESULTS FOR TYPICAL MIDBAY-INSIDE CIRCUMFERENTIAL GAGE

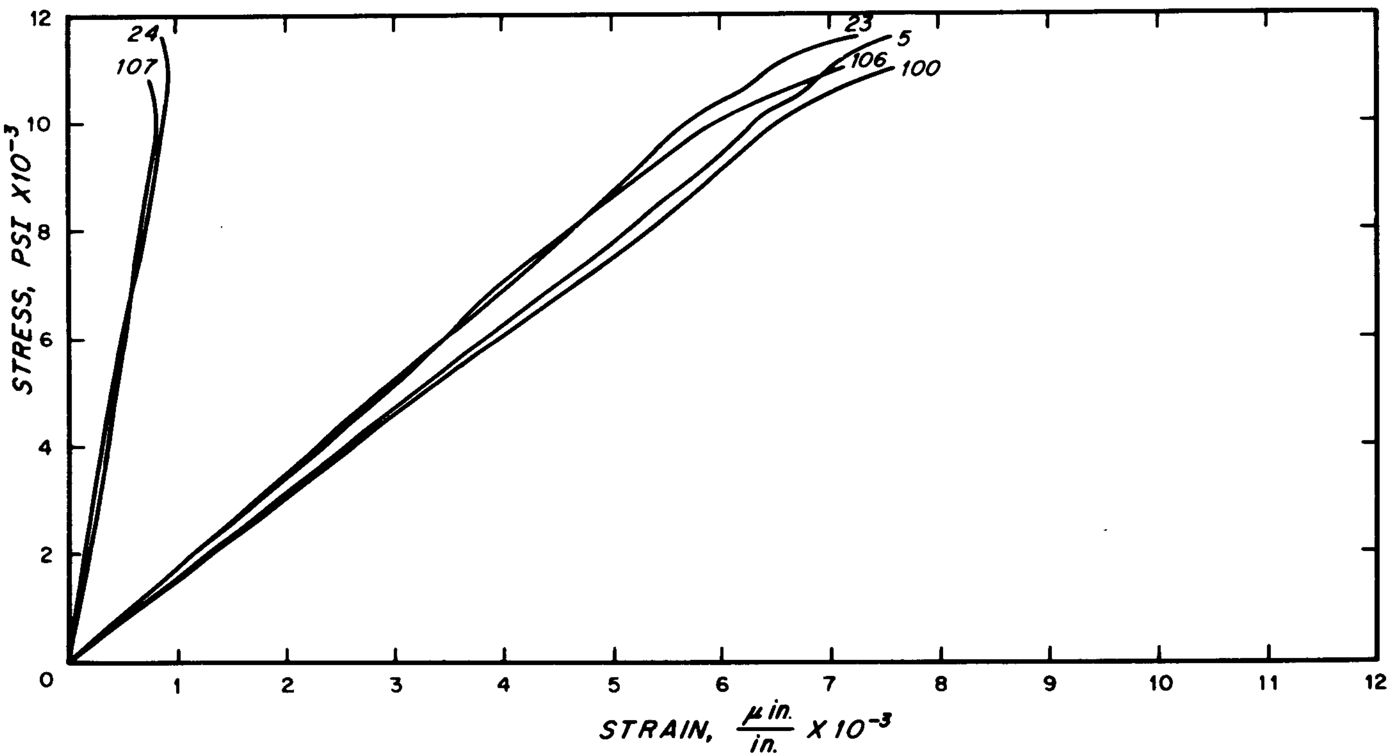


FIGURE 8. COMPARISON OF W.H.O.I. AND E.B. DIV. STRAIN GAGE RESULTS

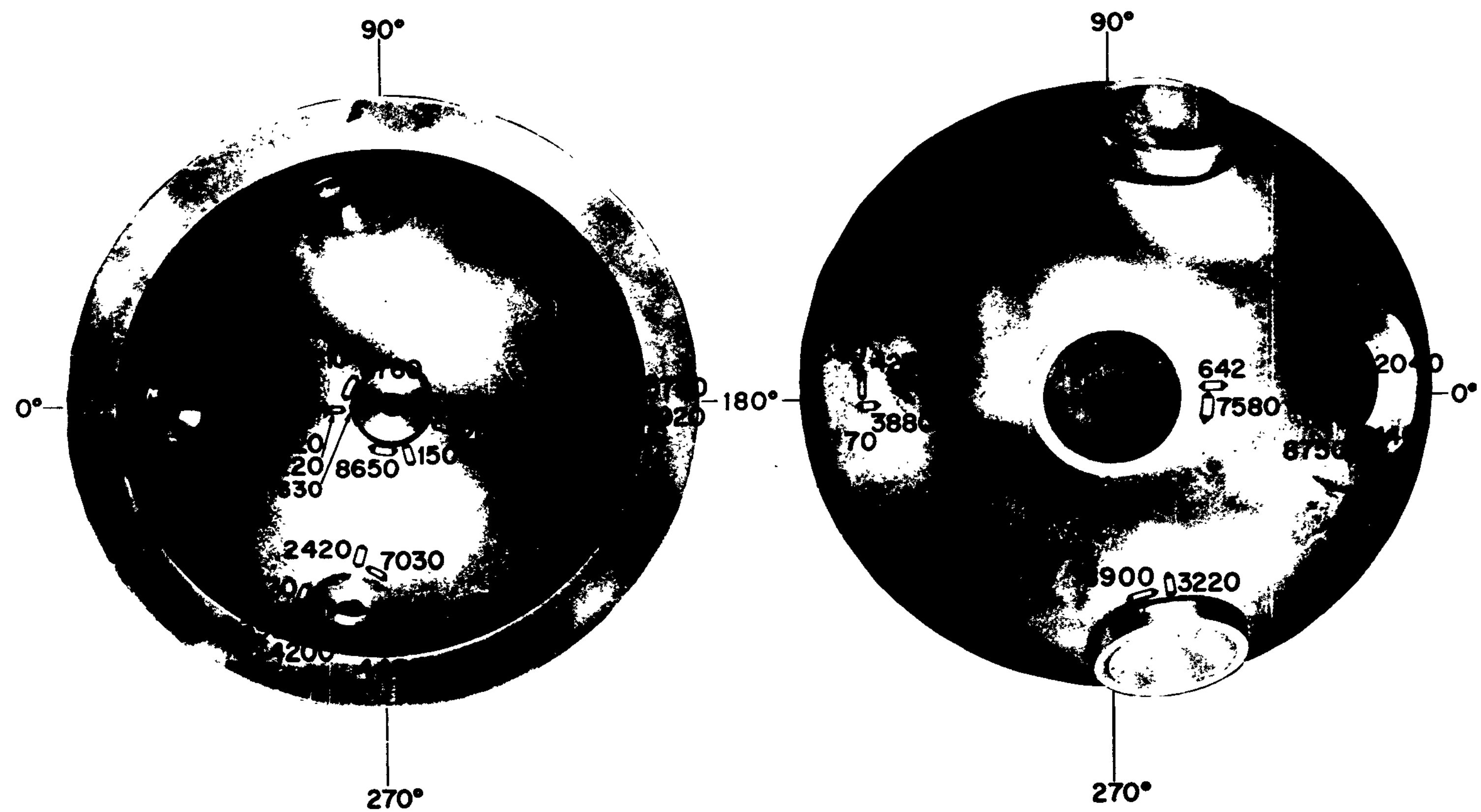


FIGURE 9 STRESSES IN HEMISPHERE AT 1000 PSI

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