FINAL REPORT

on

PHASE I INVESTIGATION OF SCUBA CYLINDER CORROSION

to

U.S. NAVY SUPERVISOR OF DIVING
NAVAL SHIP SYSTEMS COMMAND

by

N. C. Henderson, W. E. Berry,
R. J. Eiber, and D. W. Frink

September, 1970

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BATTELLE MEMORIAL INSTITUTE – COLUMBUS LABORATORIES

FOREWORD

This report summarizes research conducted under Contract No. N00014-69-C-0352 from March to August 1970. The research was performed by the Columbus Laboratories of Battelle Memorial Institute under the auspices of the U. S. Navy Supervisor of Diving, Washington, D.C., with Mr. O. R. Hansen serving as project monitor. The principal investigators were W. E. Berry, Associate Chief; R. J. Eiber, Senior Project Leader; N. C. Henderson, Research Engineer; and D. W. Frink, Division Chief.

ABSTRACT

A program was conducted to determine the cause of the corrosion that was discovered in a number of aluminum scuba cylinders, and to determine whether the rupture strength of the cylinders had been degraded by the corrosion. An examination was made of 68 corroded cylinders received from Naval facilities. Rupture experiments were conducted on new cylinders and on the most severely corroded cylinders. Detailed analyses were made of corrosion products from selected aluminum cylinders, and of corroded and uncorroded material from the ruptured cylinders. It was concluded that the corrosion in the cylinders examined had not significantly reduced the rupture strength of the cylinders. Recommendations were formulated concerning changes in manufacturing specifications, cleaning procedures, and inspection procedures to provide increased assurance that corrosion will not progress to the point of significantly degrading the rupture strength of aluminum scuba cylinders.

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INTRODUCTION

During an inspection of aluminum scuba cylinders by Navy personnel at Indian Head, Maryland, quantities of a gelatinous corrosion product were discovered on the internal surfaces of a number of the cylinders. Because the air supply system at the facility had recently been cleaned using a caustic cleaning solution of trisodium phosphate, it was thought that this cleaning agent had not been adequately removed and that minute quantities of the cleaning solution had been introduced into the scuba cylinders during charging. However, a detailed analysis by Battelle-Columbus of the corrosion products from a selected cylinder indicated that fluorine was the corrodent instead of trisodium phosphate.

Because the corrosion of aluminum by fluorine can be a continuing process, the Supervisor of Diving requested the visual inspection of all aluminum scuba cylinders in use by the Navy. As summarized in an interim Navy report(1)*, 1336 cylinders had been inspected as of January 28, 1970. Of these, 16 percent showed evidence of corrosion, and 4 percent showed severe corrosion. Based on these results, and on a consideration of cylinder rupture pressures and cleaning procedures, it was recommended in the interim report that the possible degradation of cylinder strength by corrosion be determined, that acceptable cleaning procedures be formulated, and that modified field inspection techniques be developed.

Efforts related to cylinder corrosion were continued by the Navy through design analysis of the aluminum scuba cylinders, and through consideration of the implications on cylinder design of a neutral buoyancy requirement. The results of these efforts are described in a Navy status report(2) dated March 16,

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* Numbers in parentheses denote references, listed on page 74.

1970. Also described in this report are the results of the visual inspection survey as of March 16. Of 1623 cylinders inspected, 20.2 percent were judged to be moderately corroded, while 4.4 percent (72 cylinders) were judged to be severely corroded.

To assist with the problems of corrosion in aluminum scuba cylinders, the Navy initiated a Phase I effort at Battelle-Columbus to investigate the rupture strength of new and corroded cylinders, to analyze the severity and type of corrosion, and to formulate recommendations concerning manufacturing specifications, cleaning procedures, and field inspection techniques. This report summarizes the Phase I activities.

SUMMARY

The rupture strength of new aluminum scuba cylinders was investigated through the rupture and analysis of three new aluminum scuba cylinders, and through the review of developmental test data from the Pressed Steel Tank Company on the rupture strength of 29 aluminum scuba cylinders. Additional studies on new scuba cylinders were conducted in relation to the strength of aluminum cylinder threads, the buoyancy of aluminum cylinders, and the conformance of aluminum and steel scuba cylinders with the Department of Transportation (DOT) Specification 3AA requirements.

The rupture strength of corroded aluminum cylinders was investigated through the rupture and analysis of the three most corroded cylinders of the first 64 cylinders received and examined, and through the calculation and experimental verification of the critical flaw size that must be developed in aluminum scuba cylinders for rupture to occur at the maximum operating pressure (3000 psig).

The cause of corrosion in the aluminum scuba cylinders was investigated through the detailed analysis of corrosion products from selected aluminum cylinders, and through the detailed examination of typical pitted areas from the selected cylinders.

Based on these studies and on a review of the applicable manufacturing specifications and cleaning procedures, recommendations were formulated concerning changes in procedure that will provide increased assurance of manufacturing and maintaining satisfactory aluminum scuba cylinders.

CONCLUSIONS

The following conclusions were reached as a result of the Phase I activities:

(1) Although the rupture strength of aluminum scuba cylinders is not significantly affected by the type of corrosion observed in the cylinders received, periodic inspections are required to insure that an unusually severely corroded area does not progress to the point that a cylinder will be perforated or a critical flaw developed.

(2) The strength of the aluminum scuba cylinder threads is satisfactory.

(3) The buoyancy of aluminum scuba cylinders meets the intent of the manufacturing specification but consideration of the effect of the valve would be desirable.

(4) The aluminum and steel scuba cylinders that were ruptured and examined at Battelle-Columbus met the rupture requirements of the DOT Specification 3AA for pressure cylinders.

(5) Selected portions of the manufacturing specifications are not sufficiently detailed.

(6) The present field cleaning and inspection procedures may not always prevent the development of excessive corrosion in aluminum scuba cylinders.

RECOMMENDATIONS

The following recommendations are made concerning future activities in relation to the aluminum scuba cylinders.

(1) The manufacturing specifications should be revised in the areas indicated in this report.

(2) Field cleaning and inspection procedures should be revised to prevent the development of excessive corrosion in aluminum scuba cylinders.

RESEARCH ACTIVITIES

The specific objectives of the Phase I research were to:

(1) Determine the rupture strength of new aluminum scuba cylinders

(2) Determine whether the rupture strength of aluminum scuba cylinders is degraded by the internal corrosion observed in Navy cylinders

(3) Analyze the corrosion products to determine the cause of corrosion

(4) Formulate recommendations concerning the design of the cylinders, the materials, the manufacturing methods, and the field inspection and testing methods.

To assist in the conduct of the program, the Supervisor of Diving requested that several new cylinders and all of the severely corroded cylinders be forwarded to Battelle-Columbus. During the course of the work, 81 scuba cylinders were received. These included 10 new or noncorroded aluminum cylinders, 68 corroded aluminum cylinders, and 3 new DOT 3AA 2250 steel cylinders. As each cylinder was received it was assigned a number, and pertinent information about the cylinder was recorded. Table 1 shows this information, as well as comments denoting the use of each cylinder during the program.

In accordance with the program objectives, the results of the work are described in four report sections: (1) Determination of the Rupture Strength of New Aluminum Cylinders, (2) Investigation of Cylinder-Rupture-Strength Degradation by Corrosion, (3) Investigation of the Cause of Cylinder Corrosion, and (4) Consideration of Manufacturing and Field-Testing Procedures.

Experimental data, critical measurements, etc., are recorded in figures and tables distributed within these various report sections. Also, to provide additional clarity, selected information pertinent to the ten cylinder rupture tests conducted during this program are summarized in Appendix A.

Determination of the Rupture Strength of New Aluminum Cylinders

It was known that a comparison of the rupture pressures of new aluminum cylinders with the rupture pressures of corroded aluminum cylinders would provide a gross indication of whether corrosion had degraded the rupture strength of the corroded cylinders. However, differences in rupture pressures could also be caused by differences in material properties and differences in the cylinder

TABLE 1. GENERAL INFORMATION ON NEW AND CORRODED SCUBA CYLINDERS RECEIVED AT BATTELLE-COLUMBUS

Assigned Cylinder Number[(a)]	Ship or Facility	Corrosion Rating[(b)]	Manufacturer's Serial Number[(c)]	Date of Manufacture[(c)]	Cylinder Weight (Measured), lb	Internal Volume,[(c)] cu in.	Date(s) of Hydrostatic Tests[(c)]	Rockwell-E Hardness[(c)]	Comments Relative to the Use of the Cylinders During This Program
1	USS Krisnna	Moderate	1181B	6-63	32.75		7-66 12-69	94	
2	USS Krisnna	Moderate	1810B	6-63	33.06		7-66 12-69	94	
3	USS Krisnna	Slight/Moderate	80824C	12-64	34.06	700	12-69	92	
4	USS Krisnna	Slight/Moderate	1785B	6-63	32.12		7-66 12-69	92	
5	USS Tringa	Slight	2709	10-56	31.69		4-63 1-66 12-68	87	
6	USS Tringa	Slight	3770	11-56	32.19		4-63 1-66 12-68	92	
7	USS Tringa	Slight	3634	11-56	32.0		4-63 12-68	94	
8	USS Tringa	Slight	80301C	12-64	33.94	696	12-68	92	
9	USS Tringa	Slight	80369C	12-64	34.25		12-68	88	
10	USS Tringa	Slight	1649B	6-63	33.44		5-66 5-69	90	
11	–	(d)	8222J	9-67	34.56	699		94	Rupture tested, tensile tests
12	–	(d)	8414J	9-67	34.44	707		93	Rupture tested, tensile tests
13	–	(d)	8397J	9-67	34.44	700		94	Rupture tested, tensile tests
14	–	Slight	7076J	9-67	34.33	709		90	Buoyancy tests
15	–	None/Slight	8370J	9-67	34.80	700		92	Buoyancy tests
16	–	(d)	8545J	9-67	34.37	705		94	Buoyancy tests; thread strength tests
17	–	(d)	8178J	9-67	34.41	704		94	(Flawed) Pneumatic rupture tested
18	USS Holland	Slight/Moderate	2966B	7-63	33.78		1-69		
19	USS Sunbird	Moderate	1576	9-56	32.00		11-67	85	
20	Key West	Moderate	L21533	10-61	32.94		6-64 3-67	88	
21	Key West	Severe	78123C	10-64	34.25	707	9-67	90	Corrosion analysis, metallography, chemical analysis
22	Key West	Severe	L21659	10-61	32.81		6-64 4-67	90	
23	Key West	Moderate	L21831	10-61	32.56		3-67	87	
24	Key West	Moderate/Severe	L21745	10-61	32.75		3-67	87	
25	Key West	Moderate/Severe	L21780	10-61	33.00		6-64 4-67	93	
26	Key West	Severe	L21180	9-61	32.41		6-64 4-67	89	
27	Key West	Slight/Moderate	L21377	10-61	33.00		6-64 9-68	90	
28	Key West	Moderate/Severe	L21189	9-61	32.69		6-64 10-67	89	
29	Key West	Moderate/Severe	L21602	10-61	32.88		6-64 4-67	91	
30	Key West	Slight/Moderate	L21756	10-61	32.94		3-67	85	
31	Indian Head	Slight/Moderate	79959C	12-64	34.44	702		93	
32	Indian Head	Severe	79290C	10-64	34.31	711	2-68	93	Corrosion analysis, metallography, chemical analysis
33	Indian Head	Moderate	80210C	12-64	34.59	707		93	
34	Indian Head	Severe	78802C	10-64	34.38	707		91	Rupture tested, corrosion analysis, metallography, tensile tests
35	Indian Head	Slight	7442J	7-67	34.63	707		88	
36	Key West	Slight/Moderate	L21765	10-61	32.88		6-64 1-69 9-69	90	
37	Key West	Slight/Moderate	L21742	10-61	32.94		3-67	89	
38	Key West	Moderate	L21633	10-61	32.94		6-64 4-67	86	
39	Key West	Moderate/Severe	L21508	10-61	32.69		6-64 4-67	90	
40	Key West	Moderate	L21821	10-61	32.88		6-64 3-67	91	
41	Indian Head	Severe	78472C	12-64	34.12	704		91	Corrosion analysis, metallography, chemical analysis
42	Indian Head	Slight	2579B	6-63	32.28		9-66	93	
43	USS Shakori	None/Slight	50628C	3-65	33.75	699	6-68	88	
44	USS Shakori	None/Slight	8379J	9-67	34.69	704		94	

TABLE 1. (Continued)

Assigned Cylinder Number(a)	Ship or Facility	Corrosion Rating(b)	Manufacturer's Serial Number(c)	Date of Manufacture(c)	Cylinder Weight (Measured), lb	Internal Volume,(c) cu in.	Date(s) of Hydrostatic Tests(c)	Rockwell-E Hardness(c)	Comments Relative to the Use of the Cylinders During This Program
45	USS Shakori	Slight	50552D	3-65	33.94	698	6-68	91	
46	USS Shakori	Slight	L21376	10-61	33.00		6-68	95	
47	USS Shakori	None Slight	50643D	3-65	33.81	699	6-68	91	
48	USS Shakori	Slight	L21134	8-61	32.69		6-68	95	
49	USS Shakori	None Slight	80667C	12-64	34.50	700	6-68	94	
50	USS Shakori	None Slight	50485L	2-65	33.94	693	6-68	91	
51	USS Yosemite	Slight	L21684	10-61	32.88		1-68	91	
52	USS Yosemite	Slight	L21741	10-61	32.88		1-68	91	
53	USS Yosemite	Slight	2976B	7-63	32.28		1-68	94	
54	USS Yosemite	Slight	L21521	10-61	33.06		1-68	92	
55	USS Yosemite	Moderate	L21531	10-61	33.12		1-68	92	
56	USS Yosemite	Slight	L21271	10-61	32.63		1-68	92	
57	USS Dixie	Severe	1602B	6-63	32.50		4-68		Rupture tested, corrosion analysis, metallography, tensile tests
58	USS Dixie	Severe	2712B	6-63	33.31		4-68		Corrosion analysis, metallography, chemical analysis
59	USS Opportune	Slight	7092J	6-67	34.63	707		94	
60	USS Opportune	Slight	6298J	6-67	34.31	708		91	
61	USS Opportune	Slight	7168J	5-67	35.12	716		87	
62	USS Opportune	None	7220J	6-67	34.75	704		90	
63	USS Kittiwake	Severe	PST315	6-56	32.19		10 62		Corrosion analysis, metallography, chemical analysis
64	USS Kittiwake	Severe	PST2622	10-56	32.22		12-62		Rupture tests, corrosion analysis, metallography, chemical analysis, tensile tests
65	USS Holland	Slight	2816B	7-63	33.00		6-69	95	
66	USS Holland	None/Slight	78826C	10-64	34.16	700		90	
67	USS Holland	None	1459B	6-63	33.56		1-69		
68	USS Holland	None/Slight	1253B	6-63	33.81		1-69		
69	USS Holland	None/Slight	6135J	6-67	34.81	703		94	
70	USS Puget Sound	None	7722J	8-67	35.03	705		93	
71	USS Puget Sound	None	7976J	9-67	34.20	700		94	
72	USS Puget Sound	None	7939J	9-67	34.40	597		94	
73	USS Lipan	Slight	PST4356	8-58	36.82		6-68		
74	USS Greenlet	Moderate	PST3352	11-56	32.94		10-67	92.6	
75	USS Greenlet	Moderate	PST1108	8-56	31.92		10-67	87	
76	USS Greenlet	Moderate	2158B	6-63	32.86		10-67	94.6	
77	USS Greenlet	Moderate	2853B	7-63	32.87		10-67	93.6	
78	Pressed Steel Tank Co.	(e)	80377L	6-70	–				Rupture tests, tensile tests
79	Pressed Steel Tank Co.	(e)	80376L	6-70	–				Rupture tests, tensile tests
80	Pressed Steel Tank Co.	(e)	80375L	6-70	–				Rupture tests, tensile tests
81	USS Holland	(f)	2594B	6-63	–		1-69		

(a) A number was assigned to each cylinder for ease of identification in the order in which the cylinders were received.

(b) The corrosion rating was based on *naked-eye inspections* of the cylinder interiors by 3 different staff members; the interiors were in the received condition during these inspections and had not been cleaned of corrosion product.

(c) Denotes information stamped on the cylinder.

(d) New aluminum cylinders – utilized for experiments before inspection.

(e) New steel cylinders – not inspected.

(f) Extra cylinder sent by USS Holland; arrived following formal inspection; appeared to be severely corroded.

dimensions. Therefore, it was highly desirable that these parameters be included in the comparison of the rupture strength of new cylinders with the rupture strength of corroded cylinders.

The ultimate strength of the basic cylinder materials could be determined using tensile specimens made from new and corroded cylinders after rupture. The rupture strength of the materials in these cylinders could be calculated using the measured rupture pressures and selected cylinder dimensions. By comparing the ratios of the rupture stresses to the ultimate tensile stresses for the new cylinders with the ratios of the rupture and ultimate tensile stresses for the corroded cylinders, it was believed that a more accurate measure could be obtained of the effect of corrosion on cylinder rupture strength.

The ultimate stress in a given cylinder at the point of rupture is determined basically by the internal pressure and by certain dimensions at the time of rupture, i.e., the diameter of the cylinder and the wall thickness. The internal pressure can be accurately measured, but the elastic and plastic yielding of the cylinder material causes a continuing change in the cylinder diameter and wall thickness from the time of initial pressurization until the time of rupture. Furthermore, these dimensions change differently for each cylinder because of differences in material properties (such as the yield strength) and differences in cylinder dimensions (such as the concentricity of the inside diameter with the outside diameter).

Because of these variables, it is difficult to make an accurate calculation of the stress at the instant of rupture in a cylinder. One approach is the selection of an equation which will approximate the rupture stress when the rupture pressure and the initial dimensions of the cylinder are used. Another approach is the use of calculation procedures which provide for an estimate of the elastic or elastic-plastic deformation of the cylinder. The following steps were used for selecting the method for calculating the rupture stresses in aluminum cylinders: (1) select new cylinders representative of the design, (2) measure the critical dimensions of each cylinder, (3) conduct rupture tests of the selected cylinders, (4) determine the tensile strength of the cylinder materials, and (5) compare the rupture stresses calculated for the cylinders with the ultimate tensile stresses calculated from the tensile test results.

In addition to the work on rupture stresses, brief studies were also made on: (1) analysis of the ruptured aluminum cylinders for conformance with the requirements of DOT Specification 3AA cylinders, (2) determination of the strength of aluminum cylinder threads, (3) determination of the conformance of aluminum scuba cylinders with buoyancy requirements, and (4) analysis of 3 steel cylinders for conformance with the requirements of DOT Specification 3AA cylinders. These studies are described in a report section titled Additional Investigations.

Selection of Representative New Cylinders

After a brief examination of the new and noncorroded aluminum scuba cylinders submitted to Battelle-Columbus, Cylinders 11, 12, and 13 were selected for the rupture tests. To determine that these cylinders were representative of the design under consideration, selected values from the cylinders (see Table 2) were checked against the manufacturing specification, i.e., MIL-C-24316 (SHIPS). A copy of this specification is included as Appendix B. As is noted in Table 2, some of the cylinder values were obtained after the rupture tests. Table 2 also shows similar information for other aluminum cylinders tested during the program.

TABLE 2. SELECTED COMPARISON OF NEW AND CORRODED TEST CYLINDERS WITH THE REQUIREMENTS OF MIL-C-24316 (SHIPS)

Specification Requirement	Cylinder Number 11	12	13	17	34	57	64
Internal volume[(a)] 670 to 730 in.^{3}	699.0	707.0	700.0	704.0	707.0	not given	not given
Wall thickness[(b)] 0.540 in., min	0.587 av 0.544 min	0.580 av 0.548 min	0.548 av 0.545 min	0.594	0.567 av 0.555 min	0.547 av 0.515 min	0.549 av 0.528 min
Yield strength[(b)] 35.0 ksi, min	39.5	39.5	41.3	43.2	51.8	48.8	47.5
Ultimate Strength[(b)], 38.0 ksi, min	47.4	47.2	47.7	48.8	55.0	53.0	52.2
Vol. exp. at 5000[(a)] psi, 58 to 72 in.^{3}	62.4	62.2	63.0	62.0	63.2	not given	not given

(a) Determined from information stamped on the cylinders.
(b) Determined by measurement after the rupture test.

Measurement of Critical Cylinder Dimensions

The length of the cylindrical portion of the cylinder configuration was sufficiently great that rupture was not expected to be influenced by the end closures. For this type of rupture, the critical dimensions are the outside or inside diameter and the wall thickness. The outside circumferences of each cylinder were measured at the middles and at the ends of the cylindrical portions. The circumferences were found to be quite uniform. Table 3 shows the circumferences measured in the middle of each cylinder, and the outside diameters calculated from these circumferences. Also shown are the fracture-edge to fracture-edge measurements made at the middle of the rupture, and the percent of cylinder expansion at this location.

TABLE 3. MEASURED OUTSIDE CIRCUMFERENCES AND CALCULATED OUTSIDE DIAMETERS OF NEW ALUMINUM CYLINDERS

Cylinder No.	Circumference at Cylinder Center Before Rupture, inches	Outside Diameter at Cylinder Center Before Rupture, inches	Fracture-Edge to Fracture-Edge, inches	Percent Expansion
11	24-3/16	7.70	25-1/16	3.6
12	24-3/16	7.70	25-11/16	6.2
13	24-3/16	7.70	24-13/16	2.9

Accurate measurement of the wall thicknesses before rupture was difficult because of the small cylinder openings. It was decided that better values could be obtained if wall-thickness measurements were made after the rupture tests. To provide an estimate of the wall thicknesses of the cylinders before rupture, a series of wall-thickness measurements was made on each ruptured cylinder. Since the occurrence of rupture was known to cause thinning of the material near the rupture, measurements were started 2 inches from the fracture edge. Additional measurements were made 90 degrees and 180 degrees from the first measurement. As shown in Table 4, these types of measurements were made at 5 equidistant locations along the cylindrical portion of each cylinder. This was done to minimize the effect of possible thinning of the cylinder walls in the

TABLE 4. WALL-THICKNESS MEASUREMENTS FOR ALUMINUM CYLINDERS 11, 12, AND 13 AFTER RUPTURE

Cylinder	Wall-Thickness-Measurement Designation and Location			
	A	B	C	D
	2 In. From Fracture Edge, inch	90° From A, inch	180° From A, inch	At the Fracture Edge, inch
Cylinder 11				
Neck end				
1	0.578	0.609	0.607	0.560
2	0.555	0.598	0.600	0.503
3	0.554	0.595	0.597	0.487
4	0.554	0.595	0.598	0.520
5	0.564	0.606	0.601	0.553
Closed end		Average of A, B, C = 0.587		
Cylinder 12				
Neck end				
1	0.586	0.596	0.594	0.572
2	0.561	0.579	0.603	0.552
3	0.550	0.570	0.597	0.517
4	0.548	0.578	0.600	0.530
5	0.564	0.590	0.590	0.564
Closed end		Average of A, B, C = 0.580		
Cylinder 13				
Neck end				
1	0.572	0.600	0.600	0.547
2	0.553	0.595	0.596	0.541
3	0.545	0.593	0.595	0.526
4	0.552	0.594	0.601	0.530
5	0.566	0.599	0.602	0.561
Closed end		Average of A, B, C = 0.584		

Note: The measurements were made in the cylindrical portion of the cylinder at 5 equally spaced locations.

middle of the cylinder. The average of the 15 dimensions made for each cylinder was used to estimate the average wall thickness of each cylinder before rupture.

Because the degree of thinning at the fracture edge was of possible future interest, wall-thickness measurements were also made at the edge of each fracture. These are also shown in Table 4.

Rupture Tests of New Aluminum Cylinders

Cylinders 11, 12, and 13 were pressurized with water at approximately 80 F to rupture using the system shown schematically in Figure 1. The pressures were recorded to the nearest 5 psi using a dead-weight pressure gage. The volume of water pumped into the system for each cylinder was measured with a standpipe. The cylinders were pressurized at the approximate rate of 150 psi per minute in the elastic region. The time required to rupture each cylinder was approximately 75 minutes. Pressure volume plots for each of these cylinders are presented in Appendix C. The rupture pressures for Cylinders 11, 12, and 13 were 7255, 7025, and 7740 psig, respectively.

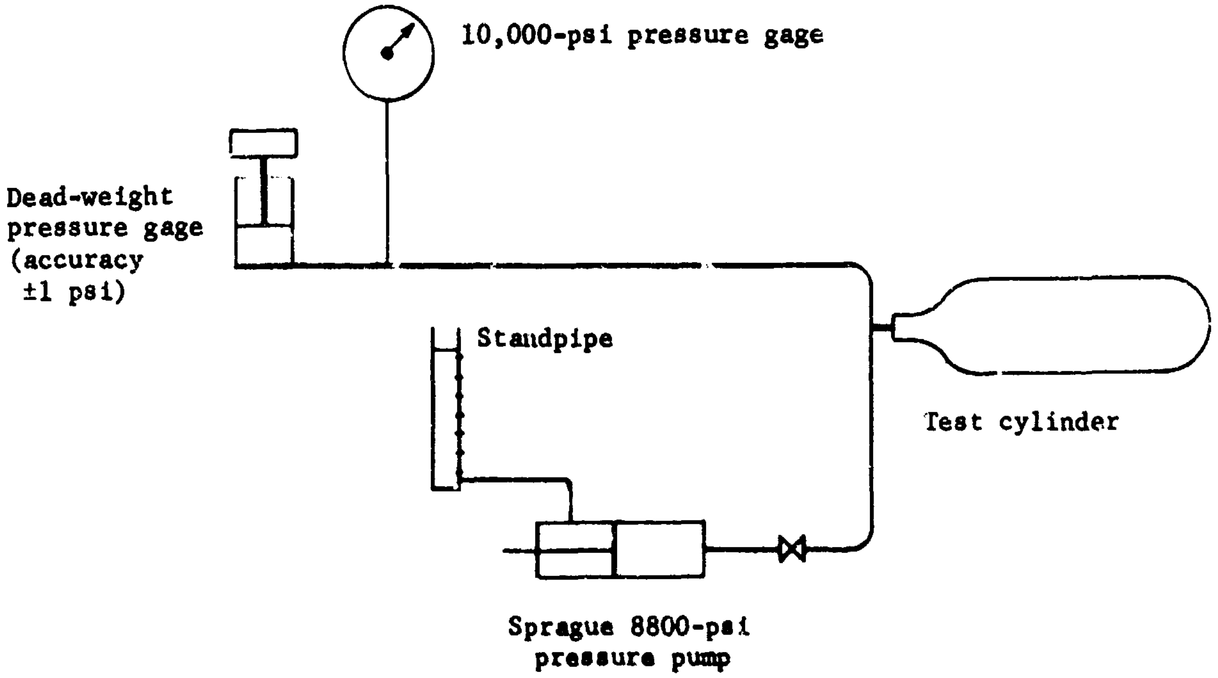

FIGURE 1. CYLINDER-PRESSURIZING SYSTEM

Figure 2 is a photograph of the cylinders after rupture. The numbers written on the cylinders are the circumferences measured before the test, and fracture-edge to fracture-edge dimensions measured after the test. In general, the fractures originated two inches from the midpoint of the straight cylindrical section in a direction toward the neck of the cylinder.

The rupture pressures for these cylinders were compared to the rupture pressures of 29 cylinders tested during the initial cylinder development to evaluate the range of rupture pressures to be expected. According to data supplied by the Pressed Steel Tank Company, 51 cylinders had been included in the initial development of the aluminum scuba cylinders. Twenty-nine of those had met the requirements of MIL-C-24316 (SHIPS) and did not appear to have received any damage as a result of cyclic pressure tests to which they had been subjected. A histogram of the rupture pressures for the 29 cylinders was developed as shown in Figure 3. The locations of Cylinders 11, 12, and 13 are also shown in Figure 3. It was judged from these comparisons that the rupture pressures of Cylinders 11, 12, and 13 were representative of the rupture pressures obtained by the Pressed Steel Tank Company for the cylinder design.

Tensile Strength of Cylinder Material

The yield and ultimate tensile strengths of the materials in the new aluminum cylinders were obtained from uniaxial tensile tests conducted with 0.312-inch-diameter tensile specimens prepared from the ruptured cylinder walls. The specimens, which were 180° from the points of rupture, were taken in the longitudinal direction because this was the only direction in which relatively large cross-section specimens could be obtained. The yield and ultimate tensile-strength results for Cylinders 11, 12, and 13 are shown in Table 5.

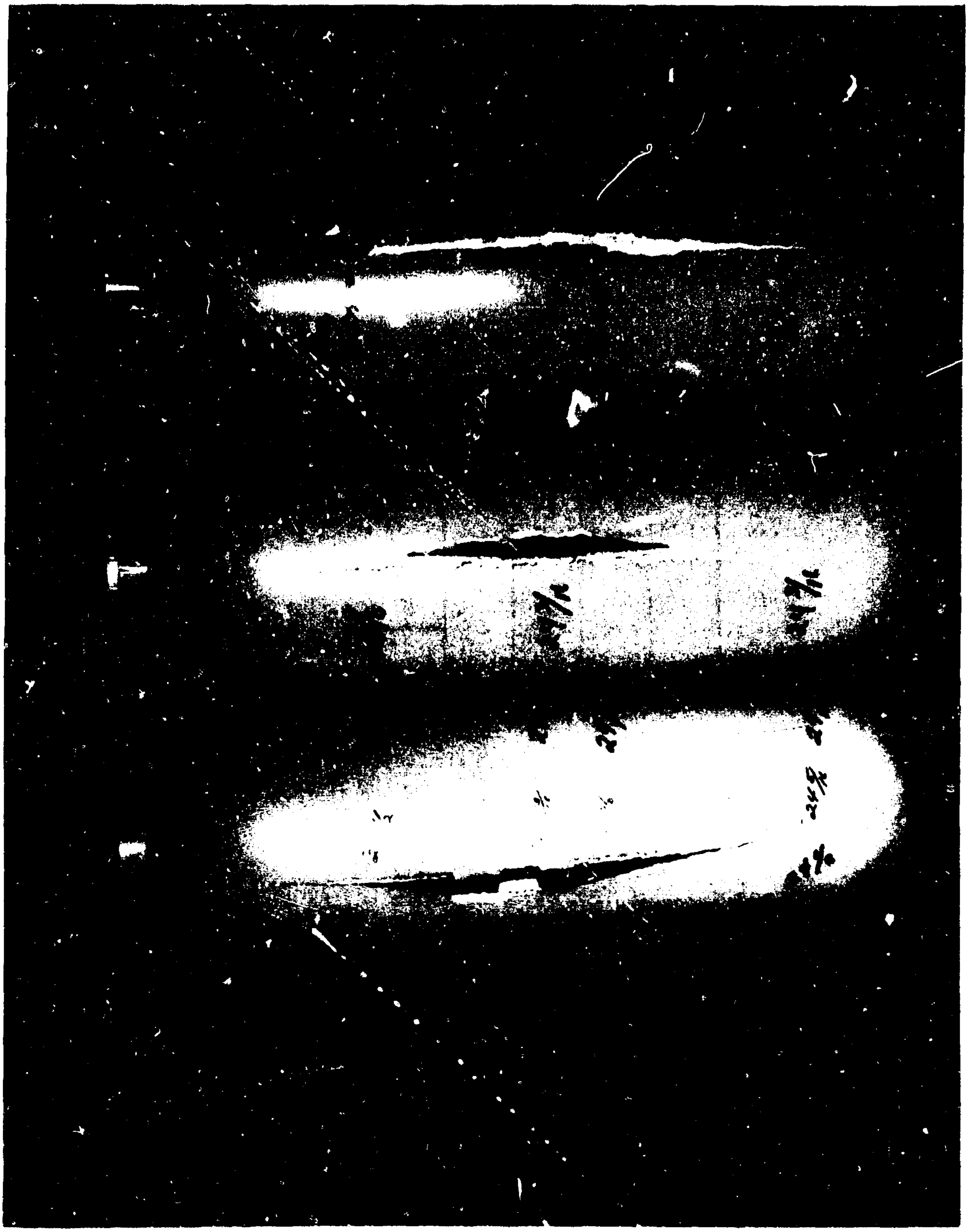

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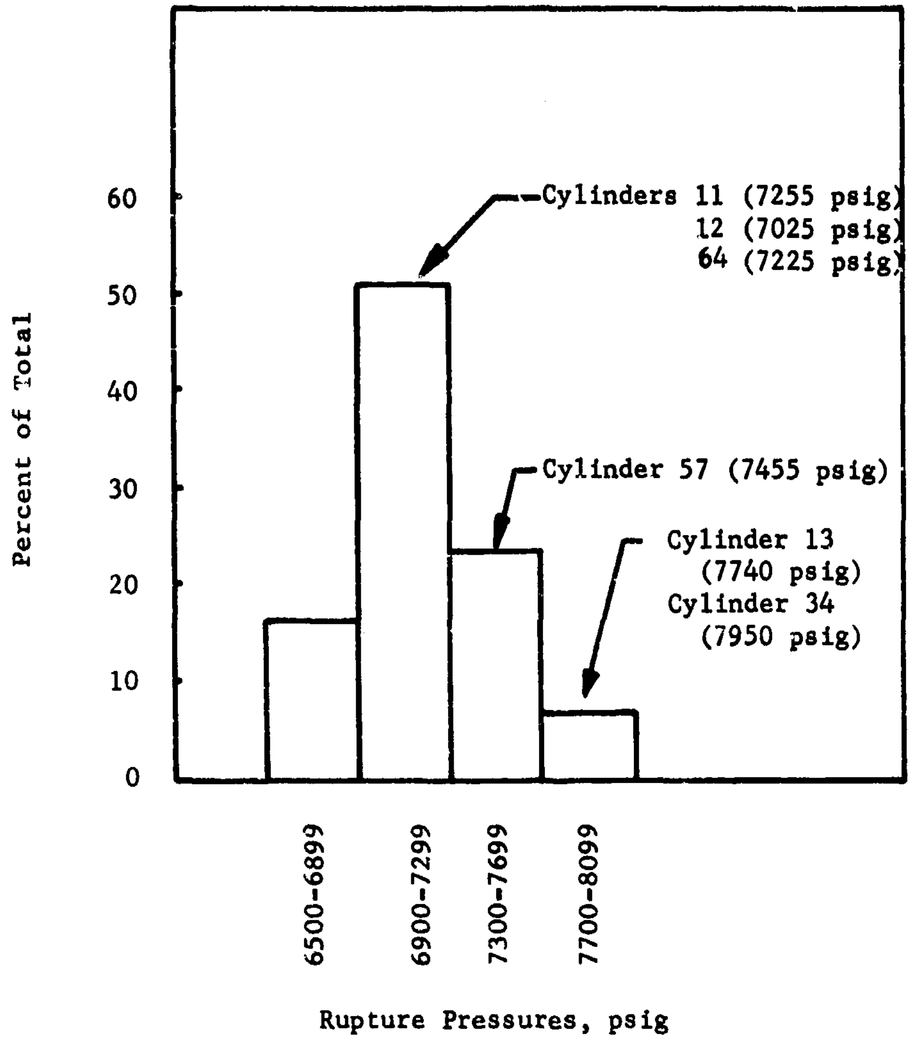
FIGURE 2. RUPTURED NEW ALUMINUM CYLINDERS



Data from Pressed Steel Tank Report Test Summary Sheet,
Report Index No. S-F011-06-03, dated February 15, 1963

FIGURE 3. FREQUENCY HISTOGRAM OF 29 ALUMINUM SCUBA CYLINDER RUPTURE TESTS

TABLE 5. LONGITUDINAL TENSILE TEST DATA FROM RUPTURED NEW ALUMINUM CYLINDERS

Cylinder No.	Yield Stress, S_y, 0.2 Percent Offset, psi	Ultimate Stress S_u, psi	Elongation in 2 Inches, percent
11	39,500	47,400	18.0
12	39,500	47,200	17.5
13	41,300	47,700	16.5

Comparison of Cylinder Rupture Strength to Ultimate Tensile Strength

The wall thicknesses of the selected new cylinders averaged about 15 percent of the outside radius. Although this was too thick to be considered a thin-wall cylinder, it was also much thinner than many thick-wall cylinders. Fortunately considerable work has recently been done by Battelle-Columbus for the AEC on the problem of calculating the maximum pressure stress attained in a pressure cylinder. To quote from a section of the "Survey Report on Structural Design of Piping Systems and Components" that will be published in the near future:

"The maximum pressure capacity of cylindrical shells has been a matter of practical significance for many years; considerable experimental data exist in the literature. The earliest known tests were published by Cook and Robertson(3)* in 1911. Additional data are given in References (4) through (16). These tests cover a wide range of OD/ID ratios from 1.07 to 12. These tests were used, in part, to evaluate the accuracy of theoretical methods of calculating the 'instability pressure' of thick-wall cylinders. A practical observation, noted by several of the authors and discussors, is that the test data** correspond about as well with the mean diameter formula as with any of the theoretical equations.

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* The references from the quotation have been renumbered for inclusion in this report.

** While the test data cover a wide variety of materials, they do not cover "brittle" materials. For such materials, particularly in thick-wall cylinders, Equation (1) may be unconservative. (Note: 6061-T6 aluminum is not generally considered to be a brittle material.)

The mean diameter formula is simply:

$$P_u = 2\ S_u\ t/D_m, \tag{1}$$

where P_u = ultimate pressure capacity, psi

S_u = nominal tensile strength of the material, psi

t = wall thickness, in.

D_m = mean (average of inside and outside) diameter.

"With one exception, all of the data in References (4) through (16) are on seamless cylindrical shells. . . . No quantitative data on the effect of out-of-roundness on maximum pressure capacity of pipe is available. . . ."

Because of the broad applicability of Equation (1), it was used with the measured rupture pressures and the dimensions from Tables 3 and 4 to calculate the rupture stresses of the materials in the ruptured cylinders. Table 6 shows a comparison of these values with the ultimate tensile stresses of the cylinder materials as determined by the tensile-specimen tests.

TABLE 6. COMPARISON OF RUPTURE STRESSES AND TENSILE STRESSES FOR RUPTURED NEW ALUMINUM CYLINDER MATERIALS

Cylinder No.	Ultimate Tensile Stress From Tensile Test, S_u, ksi	Cylinder Rupture* Stress, s_u ksi	Difference, ksi	Ratio of Rupture to Tensile Stress
11	47.4	43.9	-3.5	0.927
12	47.2	43.1	-4.1	0.913
13	47.7	47.2	-0.5	0.980

* Using Equation (1).

The comparison of the cylinder rupture stresses with the ultimate tensile stresses from tensile tests indicates that the cylinder rupture stress ranges from 91.3 to 98.9 percent of the ultimate tensile stress. This is a reasonable agreement for this type of comparison with the formula. Published information(17) indicates that this formula can be expected to calculate rupture stresses that are between 92 and 110 percent of the tensile stress.

Additional Investigations

As explained previously, 4 brief studies were conducted in addition to those needed for comparing the rupture strengths of new and corroded cylinders. Since these studies were related to the design of new cylinders, they are described in the following parts.

Analysis for DOT 3AA Specification Requirements. Cylinders 11, 12, and 13 were analyzed to determine if they met the general requirements of DOT Specification 3AA cylinders. The requirement for steel cylinders is that the wall stress calculated by Equation (2) shall not exceed 67 percent of the minimum tensile strength as determined from physical tests of the material.

$$S = \frac{P(1.3D^2 + 0.4d^2)}{D^2 - d^2} , \tag{2}$$

where S = wall stress, psi

P = minimum test pressure = 5/3 maximum operating pressure, psi

D = outside diameter, in.

d = inside diameter, in.

Because Equation (2) was developed for steel materials, the equation was modified for aluminum materials by changing Poisson's ratio to 0.333(2). This resulted in Equation (3).

$$S = \frac{P(1.333D^2 + 0.333d^2)}{D^2 - d^2} . \tag{3}$$

The S values calculated from Equation (3) for Cylinders 11, 12, and 13 at a 5000-psi test pressure were 28,000 psi, 28,200 psi, and 28,000 psi, respectively. A comparison of the S values to 67 percent of the measured tensile strengths of the cylinder materials (31,800 psi, 31,600 psi, and 32,000 psi, respectively for Cylinders 11, 12, and 13) showed that the three cylinders met the intent of the DOT 3AA requirements.

Strength of Aluminum Cylinder Threads. Scuba Cylinder 16, an unused cylinder, was used to check the shear strength of the 3/4-14 straight pipe threads used to fasten the valve to the cylinder. Since standard scuba cylinder valves were used for the aluminum scuba cylinders, the thread configuration was the same as originally designed for steel cylinders. With the strength of 6061-T6 aluminum being lower than that of 4130 steel, it was deemed advisable to check the strength of these threads to determine if a potential personnel hazard existed.

The head (valve end) of the cylinder was cut from the main cylinder body, and was supported by a tapered fixture in a Universal Testing Machine. A steel tension bar, shown to the left in Figure 4, was mated with the scuba cylinder threads. With 0.85 inch of threaded engagement, 54,200 lb of tension were required to fail the threads.

Since the surface area of the standard scuba cylinder valve is approximately 0.785 sq in., the failure load was equivalent to an internal pressure of approximately 69,000 psi. However, a scuba cylinder valve may engage the cylinder threads only to a depth of 0.75 in. For this condition, the corresponding draw-bar pull and equivalent pressure to fail the threads would be approximately 47,800 lb of tension and 61,000 psi. With a margin of safety (relative to test pressure) of approximately 12, it was concluded that the standard valve thread design was adequate.

Buoyancy Determination for New Aluminum Cylinders. Three of the new aluminum scuba cylinders were utilized to investigate the degree of their conformity to the buoyancy criteria defined in MIL-C-24316 (SHIPS) as follows: "The cylinders shall be neutrally buoyant when charged to 1500 psi". Unfortunately, the specification does not define whether the cylinders are to be neutrally buoyant in fresh water or seawater, nor does it say whether the valve should be considered as part of the cylinder weight. Therefore, both fresh- and salt-water buoyancies were calculated for the cylinders, with and without a standard scuba cylinder valve.

It was originally proposed that the displacement would be measured by weighing the overflow of water from the tank into which 3 scuba cylinders were successively submerged. The resulting displacement measurements combined with

FIGURE 4. TENSION BAR AND CYLINDER HEAD AFTER THREAD STRENGTH TEST

the respective dry weights of the cylinders as measured plus the theoretical weight of the air in each cylinder when charged to 1500 psig would indicate if the buoyancy criteria had been met. A 55-gal drum was fitted with a spout and filled with water. New Cylinders 14, 15, and 16 were successively placed in the 55-gal drum. The amount of water displaced out of the spout for each cylinder was weighed and its volume measured. The resulting data, however, were found to be in error greater than could be tolerated.

A more direct approach was selected which consisted of fitting each of the three cylinders with a valve and charging them with air to 1500 psig. Each cylinder was then suspended from a hand-held springscale, with the cylinder completely submerged in fresh water. The fresh-water buoyancy for each cylinder (with 1500-psig air and a valve) was then measured directly. The buoyancy of the valve alone was also measured directly using the same springscale experiment. The arithmetic difference between these two buoyancy measurements resulted in a fresh-water buoyancy of the cylinder and air only. This fresh-water direct buoyancy measurement combined with the measured cylinder and valve weight permitted calculation of the salt-water buoyancy of the cylinder and air only. Both the measured and calculated buoyancy data relative to this experiment are summarized in Table 7.

<u>Rupture Experiments With DOT 3AA 2250 Cylinders.</u> Rupture experiments were conducted with 3 steel cylinders fabricated by the Pressed Steel Tank Company to meet DOT 3AA 2250 requirements. Appendix D contains the manufacturer's certification of the cylinders. The cylinders had a measured outside diameter of 6.88 inches.

The cylinders (assigned Numbers 78, 79, and 80) were pressurized to rupture using the same procedures described previously for the new aluminum cylinders. As shown by the pressure-volume plots in Appendix C, the rupture pressures were 5435 psig, 5280 psig, and 5330 psig for Cylinders 78, 79, and 80, respectively. Figure 5 shows the three ruptured cylinders. The origin of the fracture in all three cylinders was approximately 3 in. from the transition to the head. Wall-thickness measurements were made on the ruptured cylinders as listed in Table 8. It is apparent from the thickness measurements that there was a

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FIGURE 5. RUPTURED STEEL DOT 3AA 2250 CYLINDERS

TABLE 7. BUOYANCY DATA AND CALCULATIONS

	Cylinder No.		
	14	15	16
Measured cylinder and valve weight (without 1500-psig air), lb	36.10	36.56	36.13
Measured internal volume, cu in.	709	714	713
Calculated weight of air at 1500 psig, 70 F, lb	3.21	3.23	3.23
Calculated weight of cylinder, valve, and 1500-psig air, lb	39.31	39.79	39.36
Measured fresh-water buoyancy of cylinder, valve, and air, lb	0.4 (neg)	0.7 (neg)	9.6 (neg)
Measured fresh-water buoyancy of valve only, lb	1.25 (neg)	1.25 (neg)	1.25 (neg)
Calculated fresh-water buoyancy of cylinder and 1500-psi air only (without valve), lb	0.9 (pos)	0.6 (pos)	0.7 (pos)
Calculated weight of fresh water displaced by cylinder and valve, lb	38.91	39.09	38.76
Calculated volume of cylinder and valve, cu in.	1076	1082	1072
Calculated weight of salt water displaced by cylinder and valve, lb	39.90	40.20	39.70
Calculated salt-water buoyancy of cylinder, valve, and 1500-psi air, lb	0.6 (pos)	0.4 (pos)	0.3 (pos)
Measured cylinder weight, lb	34.33	34.80	34.37
Calculated weight of cylinder and 1500-psi air only (without valve), lb	37.54	38.03	37.60
Calculated weight of fresh water displaced by valve only, lb	0.52	0.52	0.52
Calculated volume of valve only, cu in.	14	14	14
Calculated volume of cylinder only, cu in.	1062	1068	1058
Calculated weight of salt water displaced by cylinder only, lb	39.35	39.60	39.20
Calculated salt-water buoyancy of cylinder and air only (without valve), lb.	1.8 (pos)	1.6 (pos)	1.6 (pos)

TABLE 8. WALL-THICKNESS MEASUREMENTS FOR DOT 3AA 2250 STEEL CYLINDERS

	Wall-Thickness-Measurement Designation and Location	
	A	B
Cylinder	90° From Fracture, inch	180° From A, inch
Cylinder 78		
Neck end		
1	0.173	0.160
2	0.170	0.162
3	0.167	0.168
4	0.169	0.173
Closed end	Average, A and B = 0.168	
Cylinder 79		
Neck end		
1	0.158	0.161
2	0.161	0.162
3	0.164	0.165
4	0.164	0.171
Closed end	Average, A and B = 0.163	
Cylinder 80		
Neck end		
1	0.163	0.157
2	0.166	0.164
3	0.170	0.165
4	0.169	0.167
Closed end	Average, A and B = 0.165	

slight taper in the cylinders, with the thinnest region generally occurring near the top. It appeared that this variation in wall thickness caused the fractures to occur near the top of the cylinders.

The cylinders were checked for compliance with the DOT 3AA 2250 requirements using Equation (2). The calculated stress values were 64,700 psi, 66,600 psi, and 66,600 psi respectively, for Cylinders 78, 79, and 80. The maximum permissible stresses, which are 67 percent of ultimate, were 68,400 psi, 69,300 psi, and 69,000 psi, respectively, for Cylinders 78, 79, and 80. Thus the three cylinders met the DOC 3AA 2250 strength requirements.

An interesting comparison was the ratio of the rupture pressures to the operating pressures for the steel and the aluminum cylinders. For the steel cylinders, the ratios were 2.41, 2.35, and 2.37. For the new aluminum cylinders the ratios were 2.42, 2.34, and 2.56, while for the corroded aluminum cylinders the ratios were 2.65, 2.48, and 2.41. From this it appeared that there was not a significant difference between the steel cylinders and the aluminum scuba cylinders from the viewpoint of the margin of safety.

Investigation of Cylinder-Rupture-Strength Degradation by Corrosion

This report section describes the investigation to determine whether corrosion had degraded the rupture strength of the aluminum scuba cylinders.

Comparison of New-Cylinder Rupture Strength with Corroded-Cylinder Rupture Strength

The previous report section describes the investigation of the rupture strength of new aluminum cylinders. This report section describes the investigation of the rupture strength of corroded cylinders and the determination of the degradation of cylinder rupture strength by corrosion. This was undertaken in the following steps: (1) select cylinders to represent the worst corrosion conditions; (2) measure the critical dimensions of the selected corroded cylinders; (3) conduct rupture tests of the selected cylinders; (4) determine the basic strengths of the cylinder materials using tensile specimens from the ruptured corroded cylinders; (5) using the initial cylinder dimensions and the measured rupture pressures, calculate the rupture stresses in the corroded cylinders; and (6) compare the ratios of the calculated rupture stresses to the tensile test ultimate stresses for the corroded cylinders with the ratios of the calculated rupture stresses to the tensile test ultimate stresses for the new cylinders to determine whether the rupture strengths of the corroded cylinders had been measurably reduced by the corrosion.

Selection of Corroded Cylinders. The corroded aluminum cylinders shipped to Battelle were judged by the respective Navy facilities to be representative of the most severely corroded cylinders in their possession. A brief survey of the 64 cylinders received at the time that tests were begun, however, showed that they varied significantly in the severity of corrosion. Since it was important to select the most severely corroded cylinders of those received for the rupture tests, it was considered advantageous to provide a photographic record of each cylinder's interior. Utilizing a "fisheye" lens placed in the neck of a cylinder with interior illumination, photographs were made of the interior surfaces. Unfortunately, the photographs were in focus only for a depth of about 1 to 2 inches and, therefore, were considered inadequate for selection purposes.

In another inspection technique, attempts were made to use a borescope which was designed and fabricated specifically for these cylinders. This borescope was found to be useful for the inspection of relatively small areas, but it was not applicable to a general survey of the interior of the cylinders.

The most successful inspection procedure consisted of placing a small automobile lightbulb inside each cylinder, and conducting a systematic naked-eye inspection of the cylinder interior. Using this procedure, Cylinders 34, 57, and 64 were judged to be the most severely corroded and they were selected for the rupture tests.

Measurement of Critical Cylinder Dimensions. The procedures described previously for measuring the new aluminum cylinders were also used for measuring the corroded aluminum cylinders. Table 9 gives the measured outside circumferences and the calculated outside diameters for the corroded cylinders. Table

10 gives the wall thickness measurements made after rupture to make possible an estimate of the wall thicknesses of the cylinders before rupture.

TABLE 9. MEASURED OUTSIDE CIRCUMFERENCES AND CALCULATED OUTSIDE DIAMETERS OF CORRODED ALUMINUM CYLINDERS

Cylinder No.	Circumference at Cylinder Center Before Rupture, inches	Outside Diameter at Cylinder Center Before Rupture, inches	Fracture Edge to Fracture Edge, inches	Percent Expansion
34	24-1/8	7.68	24-7/8	3.1
57	24	7.64	24-5/8	2.6
64	24-3/16	7.70	25-1/4	4.4

Rupture Tests of Corroded Aluminum Cylinders. Cylinders 34, 57, and 64 were pressurized to rupture using the same procedure as that described previously for the new aluminum cylinders. Pressure-volume plots for each cylinder are contained in Appendix C. The rupture pressures for Cylinders 34, 57, and 64 were 7950 psig, 7455 psig, and 7225 psig, respectively. As shown in Figure 3, these values were well within the frequency histogram for the rupture pressures of new cylinders.

Figure 6 is a photograph of the corroded cylinders after rupture. The ruptures were similar to those experienced in Cylinders 11, 12, and 13.

Tensile Strengths of Corroded Cylinder Material. The yield and ultimate tensile strengths of the materials in the corroded aluminum cylinders were attained in the same manner as were the yield and ultimate tensile strengths for the new aluminum cylinders, described previously. Table 11 shows the longitudinal tensile test data for the corroded cylinders.

Calculation of Cylinder Rupture Stress. Equation (1) was used to calculate the rupture stresses in corroded Cylinders 34, 57, and 64. These values were 49,800 psi, 48,300 psi, and 47,000 psi, respectively, for these cylinders.

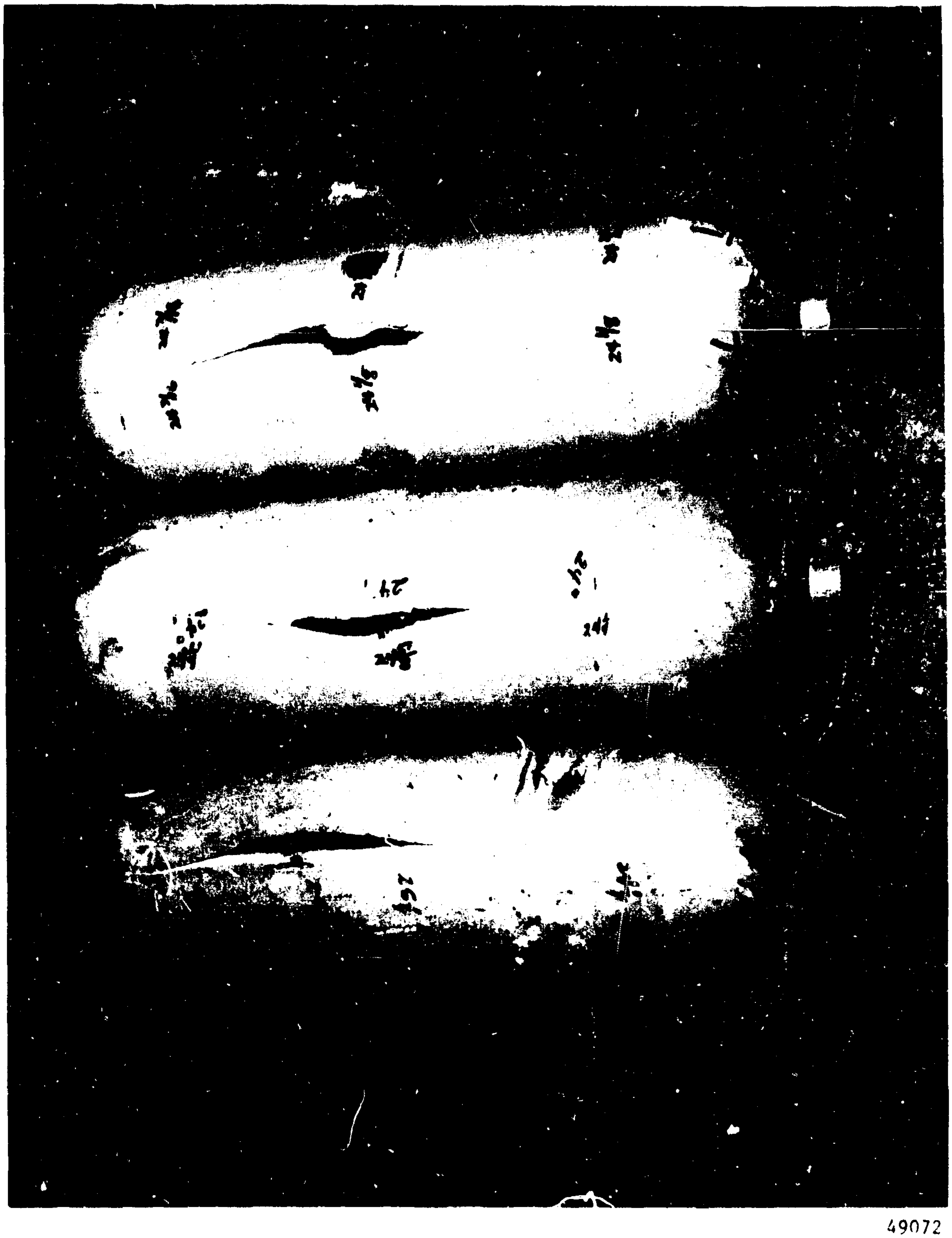

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FIGURE 6. RUPTURED CORRODED ALUMINUM CYLINDERS

TABLE 10. WALL-THICKNESS MEASUREMENTS FOR CORRODED ALUMINUM CYLINDERS 34, 57, AND 64

	Wall-Thickness-Measurement Designation and Location			
	A	B	C	D
Cylinder	Approximately 60° to the Fracture, inch	90° From A, inch	180° From A, inch	At the Fracture Edge, inch
Cylinder 34				
Neck end				
1	0.581	0.580	0.580	0.570
2	0.568	0.565	0.563	0.539
3	0.555	0.563	0.561	0.511
4	0.559	0.562	0.561	0.547
5	0.571	0.570	0.571	0.550
Closed end	Average of A, B, C, = 0.567 inch			
Cylinder 57				
Neck end				
1	0.539	0.558	0.561	0.525
2	0.529	0.556	0.562	0.503
3	0.515	0.553	0.560	0.480
4	0.520	0.551	0.561	0.495
5	0.527	0.555	0.561	0.511
Closed end	Average of A, B, C = 0.547 inch			
Cylinder 64				
Open end				
1	0.570	0.554	0.561	0.550
2	0.558	0.542	0.548	0.514
3	0.550	0.528	0.541	0.473
4	0.540	0.529	0.541	0.507
5	0.557	0.555	0.559	0.520
Closed end	Average of A, B, C = 0.549 inch			

Note: The measurements were made in the cylindrical portion of the cylinder at 5 equally spaced locations.

TABLE 11. LONGITUDINAL TENSILE TEST DATA FROM CORRODED RUPTURED ALUMINUM CYLINDERS

Cylinder No.	Yield Stress, S_y, psi	Ultimate Stress, S_u, psi	Elongation in 2 inches, Percent
34	51,800	55,000	15.0
57	48,800	53,000	16.0
64	47,500	52,200	14.0

Determination of Cylinder Degradation. Columns C and D of Table 12 contain the tensile and rupture stresses for the new and corroded aluminum cylinders that have been described previously. Table 12 also contains the yield stresses of the test cylinder materials as determined from the tensile test data (Column A), and yield stresses of the test cylinders as calculated using the measured internal pressure at cylinder yielding (Column B). An examination of Columns A, B, C, and D shows that good agreement was obtained between the tensile and cylinder test values for the yield stresses, while only fair agreement was obtained between the measured ultimate tensile stresses and the calculated cylinder rupture stresses.

Comparing the ratio of the cylinder test rupture stress (Column D) to the tensile test ultimate stress (Column C) it can be noted that the average value for the three new cylinders is 0.943 and for the corroded cylinders is 0.905. Thus these results indicate that corrosion of the type found in Cylinders 34, 57, and 64 reduced the rupture stress of the aluminum cylinders 4.0 percent on the average from the tensile ultimate stress. It should be pointed out that limited data were available in this investigation, and that experimental results under closely controlled conditions will generally exhibit scatter in the range of about 5 percent. Furthermore, even if the 4.0 percent is approximately correct, this amount of strength reduction is not believed to be significant because of the margin of safety that must be provided in the cylinder design for other, larger variables.

TABLE 12. RUPTURE-STRENGTH COMPARISON OF NEW AND CORRODED CYLINDERS

Cylinder No.	A Tensile Test, S_y, ksi	B(a) Cylinder Test, S_y, ksi	C Tensile Test, S_u, ksi	D(b) Cylinder Test, S_u, ksi	E Ratio Col D/Col C
11 (new)	39.5	40.0	47.4	43.9	0.926
12 (new)	39.5	37.7	47.2	43.1	0.913
13 (new)	41.3	44.3	47.7	47.2	0.990
34 (corroded)	51.8	Yield pressure not available	55.0	49.8	0.905
57 (corroded)	48.8	46.0	53.0	48.3	0.911
64 (corroded)	47.5	45.1	52.2	47.0	0.900

(a) Calculated using Equation (1) and measured internal pressure at yield.
(b) Calculated using Equation (1) and measured rupture pressure.

Analysis for DOT Requirements. Wall thickness measurements from the ruptured corroded cylinders were used with Equation (3) to determine whether the corroded cylinders met (before rupture) the intent of the DOT 3AA requirements. The calculated stresses for Cylinders 34, 57, and 64 with an internal pressure of 5000 psig were 28,800 psi, 30,000 psi, and 29,800 psi, respectively. Sixty-seven percent of the measured tensile strengths for these cylinders were 36,900 psi, 35,500 psi, and 35,000 psi, respectively. Thus, the corroded cylinders met the intent of the DOT 3AA specification.

Degradation of Cylinder Rupture Strength by the Development of a Critical Flaw

During the initial examination of the corroded aluminum cylinders, a few instances were found in which the majority of the corrosion had occurred in a narrow strip parallel with the cylinder axis. It appeared that these few cylinders had been placed horizontally in storage and that moisture had accumulated at the corroded area. A study was made to determine whether this or a similar corrosion mechanism might produce a sufficiently weakened strip of material that a critical flaw would be developed, resulting in cylinder rupture.

The potential hazard of a critical flaw was investigated in two ways. First, calculations were made to estimate the length of a critical flaw for the aluminum scuba cylinders and a test was conducted with an artificially flawed new cylinder to check the calculation. Second, the corrosion and ruptures in Cylinders 34, 57, and 64 were examined to determine the character of the cylinder corrosion.

Rupture Test of Flawed Cylinder. Consideration of the critical flaw test led to the decision to use pneumatic pressure to rupture the cylinder. By doing this, it was possible to accomplish the following objectives: (1) determine the flaw size required to produce rupture at the operating pressure, (2) determine the nature of the rupture when the cylinder is filled with air, and (3) calculate the maximum flaw size that will leak without causing cylinder rupture.

Cylinder 17, a new cylinder, was selected for this experiment. An estimate of the flaw size for failure at 3000 psig was calculated, based on surface flaw equations developed on other programs(18) and ultrasonic wall-thickness measurements made on this cylinder. Equation (4), below, was the mathematical relationship used:

$$\sigma_h = \sigma^* \frac{t/d - 1}{t/d - 1/M} , \qquad (4)$$

where σ_h = nominal hoop stress at failure, psi

σ^* = flow stress of the material, psi - taken as the estimated yield stress for the calculation of the flaw size

t = wall thickness at the flaw, in.

d = depth of flaw, in.

M = stress magnification factor(18) which is a function of flaw length, vessel radius, and thickness.

A flaw size of the shape and dimensions shown in Figure 7 was placed in the cylinder in an axial direction. The width of the flaw was uniform at 1/16 inch, and the bottom of the flaw contained a 60° included angle which had a root radius of 0.0015 inch.

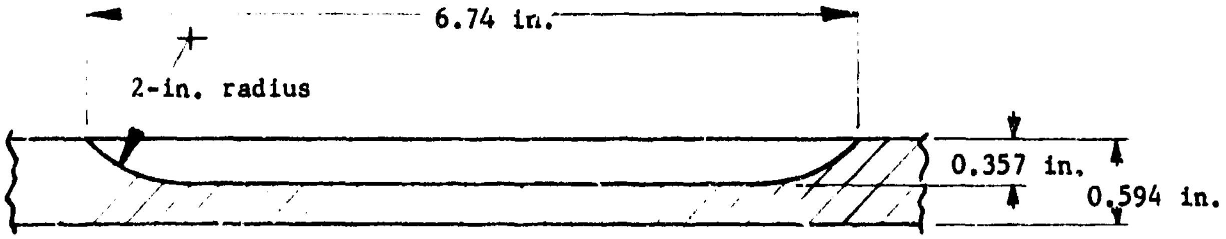


FIGURE 7. ARTIFICIAL FLAW DIMENSIONS FOR CYLINDER 17

Cylinder 17 was pressurized internally with nitrogen until rupture. The rupture pressure was 3430 psig. The difference noted between the estimated and actual failure pressure was partially due to the inaccuracy of the ultrasonic wall-thickness measurement. This measurement, which in part determined the dimensions of the flaw to be created, showed a wall thickness of 0.582 inch, while the actual wall thickness measured after the experiment was found to be 0.594 inch.

Figure 8 is a photograph of Cylinder 17 after rupture. It can be observed that the energy stored in the pneumatically pressurized cylinder caused the cylinder to split in half and almost fracture into three pieces. Longitudinal tensile tests utilizing specimens from the ruptured cylinder showed that the yield stress of the material was 43,200 psi. The calculated flow stress after the experiment was 36,300 psi, or 84 percent of the yield stress.

This experiment confirmed that a ruptured, pneumatically pressurized scuba cylinder represents a serious potential personnel hazard. However, the experiment also showed that it would take a large flaw to produce rupture at the 3000-psig operating pressure of the cylinder. Based on this experiment, it was calculated that flaw lengths less than 3.0 in. would leak at 3000 psig but would not be expected to cause rupture of the cylinder. This estimate was based on the minimum yield strength of material specified in MIL-C-24316(SHIPS), and on a minimum wall thickness of 0.540 in.

Characterization of Corrosion in Ruptured Cylinders. Figures 9, 10, and 11 show the corrosion on the inside of Cylinders 34, 57, and 64 following

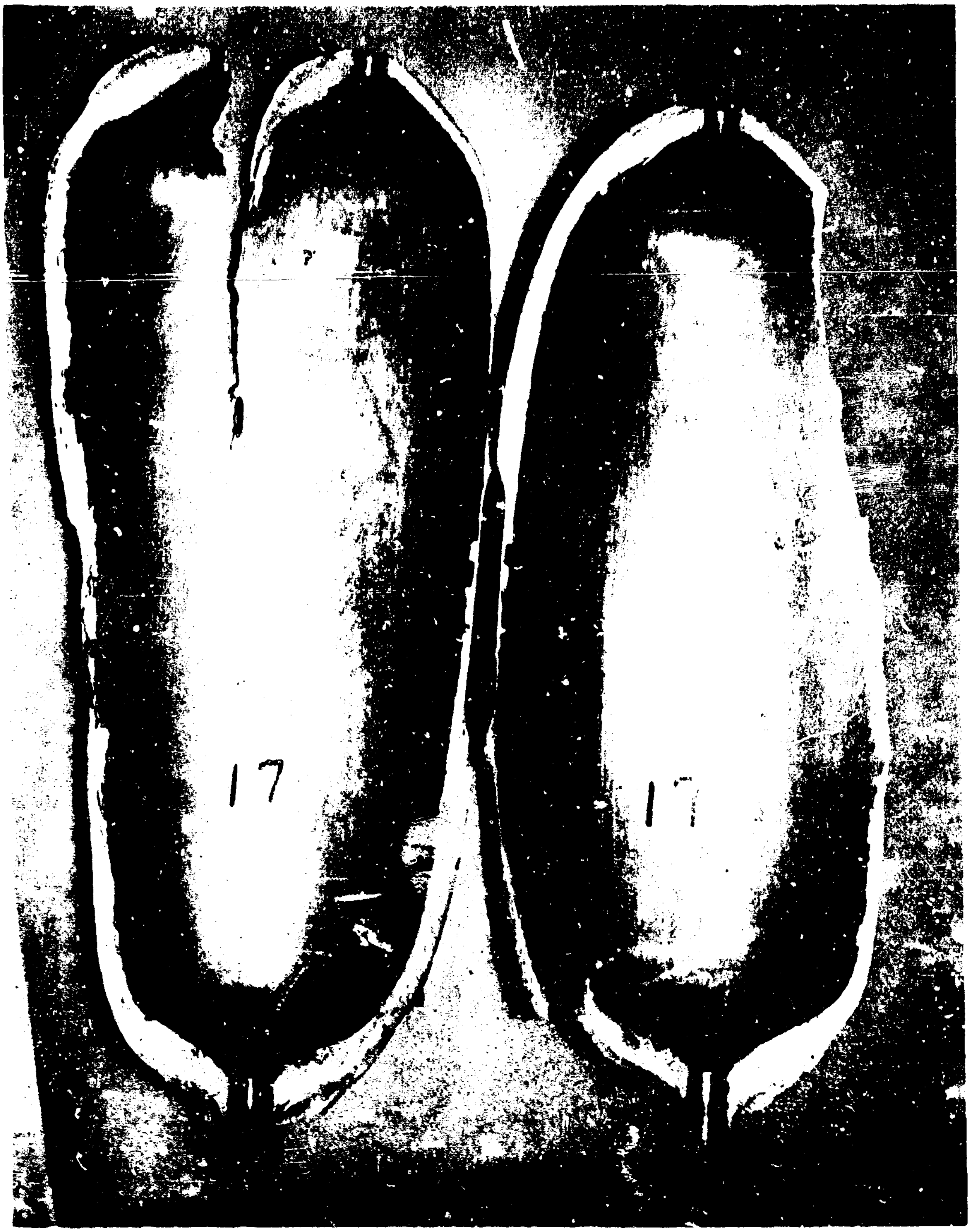


FIGURE 8. PNEUMATICALLY RUPTURED CYLINDER 17

FIGURE 9. CORROSION IN CYLINDER 34

FIGURE 10. CORROSION IN CYLINDER 57

FIGURE 11. CORROSION IN CYLINDER 64

the rupture tests. In Cylinder 34, the most severely corroded area was roughly 90 degrees from the fracture. In Cylinder 57, the corrosion was generally all over the inside surface. In Cylinder 64, the inside was generally corroded, and a line of corrosion existed approximately 180 degrees from the fracture.

Figures 12 and 13 show closeups of the inside surfaces of Cylinders 57 and 64, respectively, in the origin region of the fracture. In Cylinder 57, the inside edge of the fracture was jagged and appeared to have progressed from one corrosion pit to another. In Cylinder 64, there was no indication that the fracture followed or was affected by the corrosion pits because the inside edge of the fracture was a smooth, essentially straight line. Thus it appeared that the corrosion pits may have guided the fracture in the origin area of Cylinder 57, but not in the other two cylinders.

Metallographic sections were prepared of the fracture origin regions in the three corroded cylinders. Figures 14, 15, and 16 show micrographs of matching sections at the origins of the fracture in Cylinders 34, 57, and 64, respectively. In none of these sections were the corrosion pits believed to be deep enough to have had a significant effect on the fracture.

In addition to the fracture origin sections, 13 additional sections were taken through corrosion pits remote from the origin to characterize the pits. Table 13 summarizes the length and depth of the selected pits. Also presented in Table 13 are thickness measurements and Rockwell E hardness values measured on the sections. Micrographs of three of the sections through the deepest pits are shown in Figures 17, 18, and 19. In Figures 17 and 19 (from Cylinders 34 and 64, respectively) the corrosion appeared to have progressed into the wall thickness and also parallel to the surface, producing a flat bottom in the corrosion pit. This type of pit appeared to be representative of most of the pits sectioned. Figure 18 shows the only corrosion pit sectioned which appeared to contain a relatively sharp tip at the bottom. This pit was also the largest pit sectioned and yet it existed approximately 90° from the fracture origin.

<u>Conclusions</u>. Based on the examination of the 68 corroded aluminum scuba cylinders that were received at Battelle-Columbus, on the rupture test of an intentionally flawed aluminum cylinder, and on a detailed examination of the three most corroded cylinders, it was concluded that corrosion apparently did not constitute an immediate personnel hazard. Because the exact nature of the

FIGURE 12. CLOSE-UP OF CORRODED CYLINDER 57

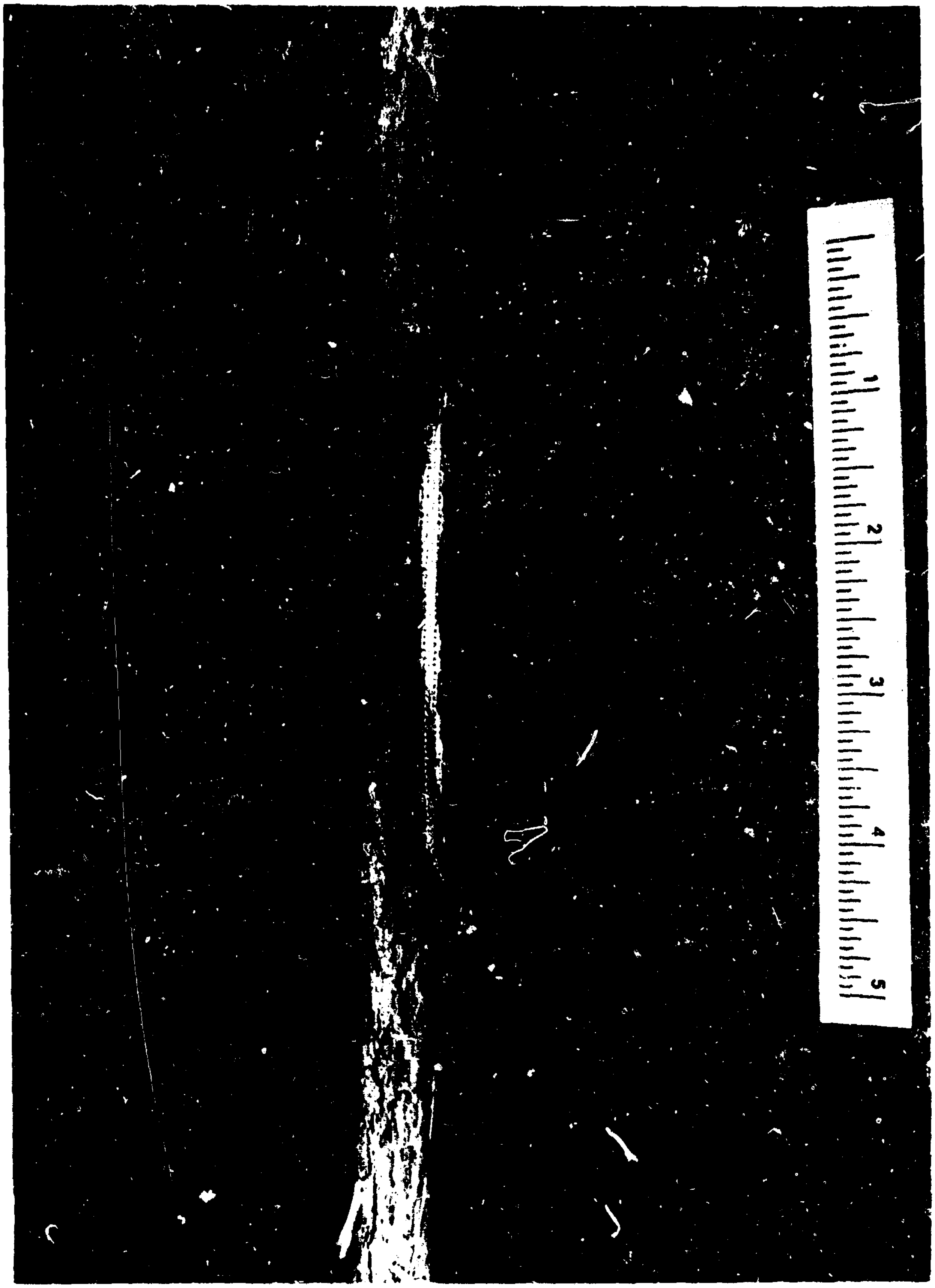


FIGURE 13. CLOSE-UP OF CORRODED CYLINDER 64

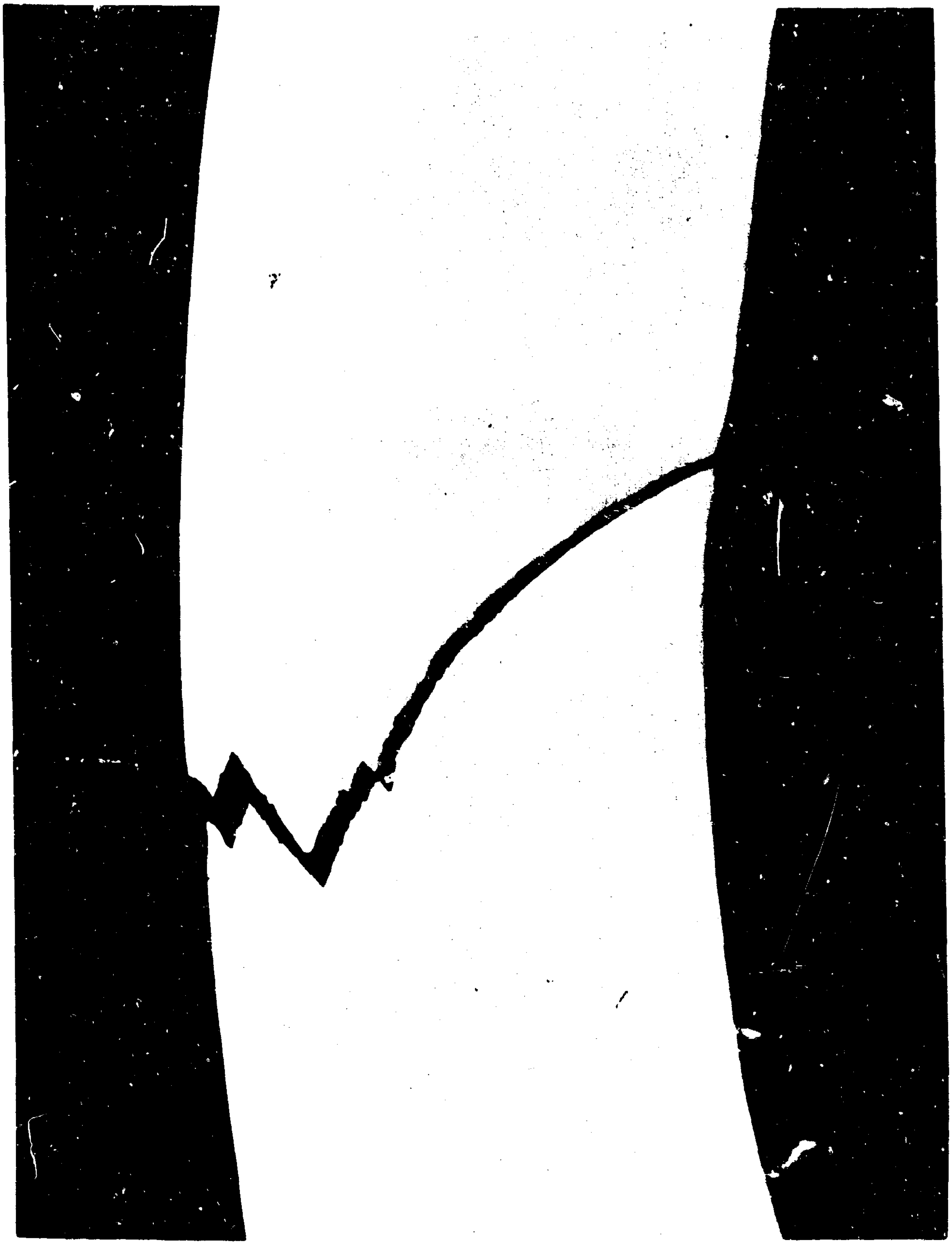


FIGURE 14. SECTION THROUGH FRACTURE ORIGIN IN CYLINDER 34

FIGURE 15. SECTION THROUGH FRACTURE ORIGIN IN CYLINDER 57

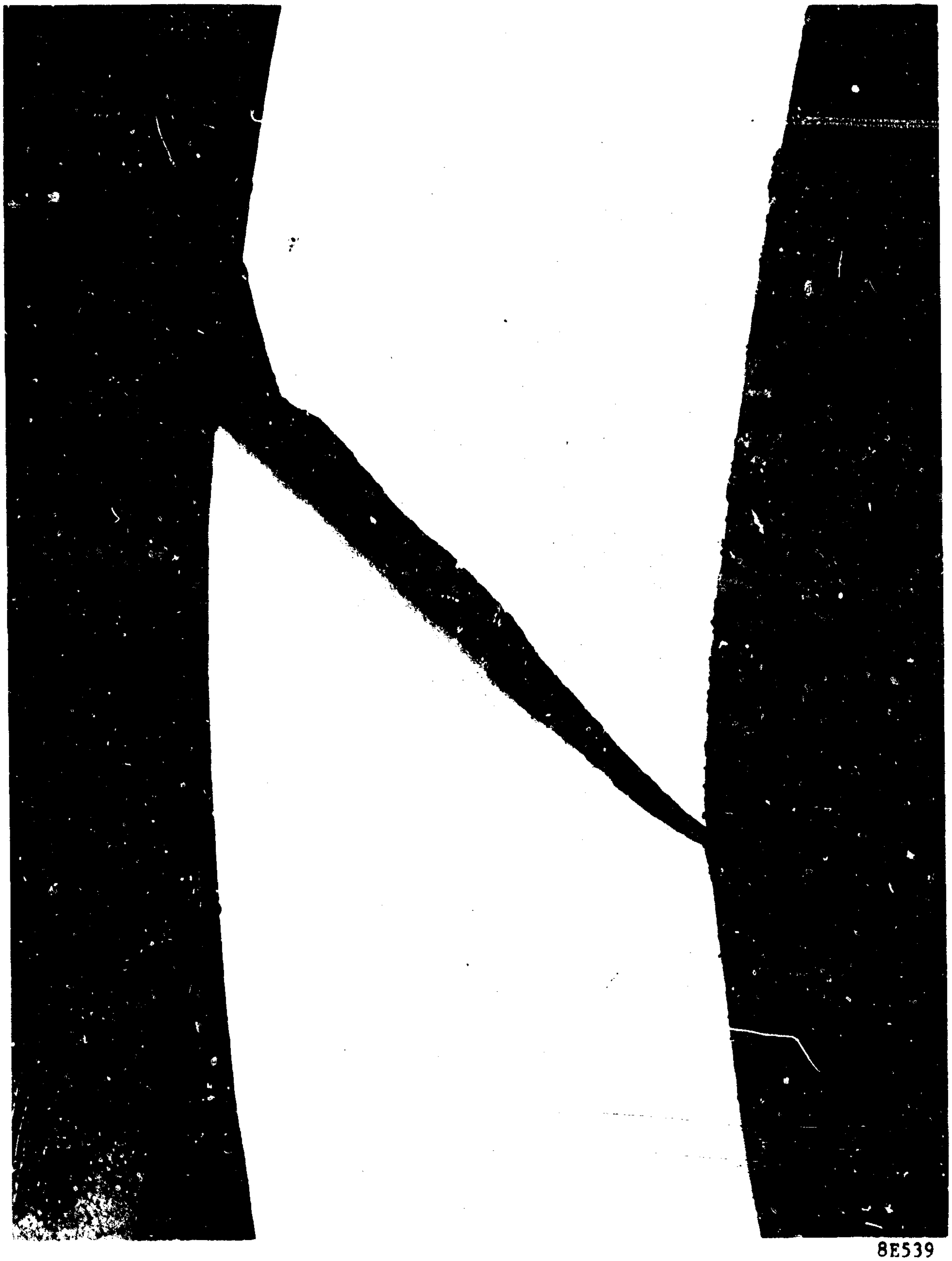
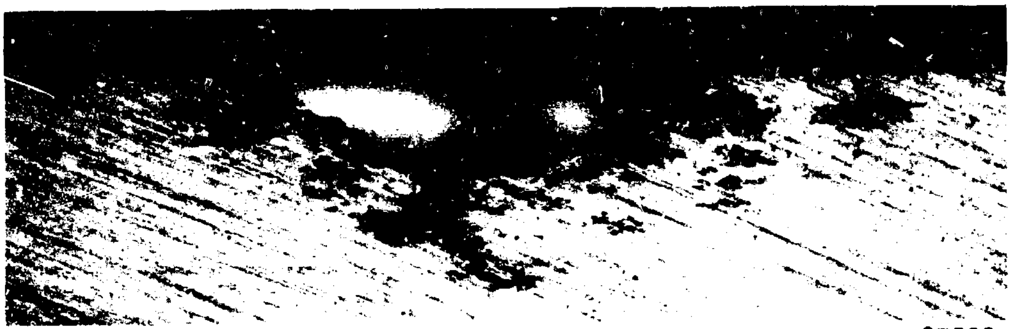

8E539

FIGURE 16. SECTION THROUGH FRACTURE ORIGIN IN CYLINDER 64

25X As Ground 8E537

Pit Depth 0.040"
Pit Length 0.125"

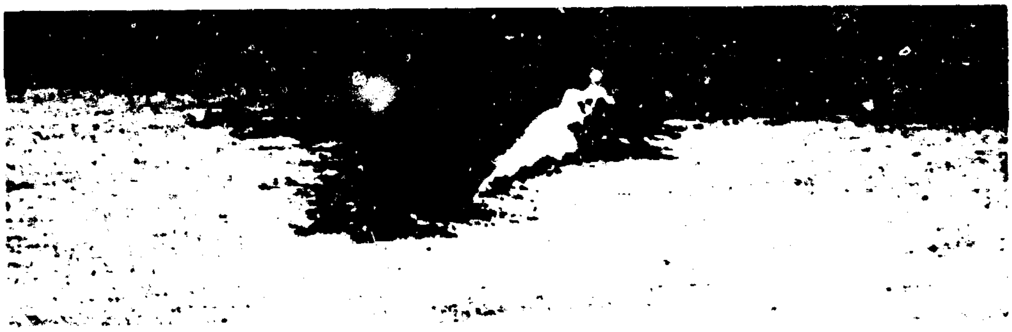
FIGURE 17. DEEPEST PIT IN CYLINDER 34 (SECTION 34-1)



25X As Ground 8E538

Pit Depth 0.047"
Pit Length 0.39"

FIGURE 18. DEEPEST PIT IN CYLINDER 57 (SECTION 57-5)



25X As Ground 8E535

Pit Depth 0.032"
Pit Length 0.250"

FIGURE 19. DEEPEST PIT IN CYLINDER 64 (SECTION 64-4)

TABLE 13. RESULT OF METALLOGRAPHIC SECTIONS OF SELECTED CORROSION PITS

Cylinder	Maximum Pit Depth, inch	Pit Length, inch	Wall Thickness, inch	Rockwell E Hardness Value
Cylinder 34				
Section 34-1	0.040	0.125	0.580	97.
34-2	0.036	0.312	0.584	96.
34-3	0.031	0.282	0.585	96.3
34-4	0.030	0.312	0.593	95.
Cylinder 57				
Section 57-1	0.026	0.266	0.520	98.6
57-2	0.022	0.312	0.532	94.
57-3	0.012	0.360	0.518	96.
57-4	0.020	0.297	0.520	93.7
57-5	0.047	0.390	0.525	97.0
Cylinder 64				
Section 64-1	0.025	0.125	0.489	96.3
Section 64-2	0.024	0.125	0.520	97.3
64-3	0.032	0.219	0.571	96.6
64-4	0.032	0.250	0.561	95.3

corrosion remains in doubt, however (see below), it is possible that an active pit could penetrate the cylinder wall. With an internal cylinder pressure of 3000 psi, the gas issuing from such a pit could constitute a personnel hazard. Although less likely, it is also possible that a number of pits, oriented in a line nearly parallel to the cylinder axis, could approach the critical flaw size, resulting in a potentially hazardous situation. Thus some schedule of cylinder examination is mandatory.

Investigation of the Cause of Cylinder Corrosion

Prior to the initiation of this program, an aluminum scuba cylinder was received and examined at Battelle-Columbus to determine whether a caustic cleaning solution, trisodium phosphate, had caused corrosion of the cylinder. As received, the cylinder contained a gelatinous residue (both solid and liquid). This was removed and dried. The dried residue was found to consist of white and black particles corresponding to the physical description found in the Naval Ordnance Station report, "Residue in Divers' Air Tanks", September 1969.

The cylinder was then slit lengthwise, as shown in Figure 20. The white areas are the corrosion products. A number of pits were found under these white corroded areas. Several of the pits were probed and found to have a depth of about 0.15 inch. A metallographic cross section was made through one of the pits. Figure 21 shows an enlarged photograph of the base of the pit--intergranular attack can be clearly seen. This type of intergranular pitting attack is often associated with chlorides and fluorides.

Chemical analyses were then made of the dried corrosion product. Initially, an overall survey of the corrosion product was made using optical-emission spectrography. The results of this analysis are shown in Table 14.

TABLE 14. QUALITATIVE OPTICAL EMISSION SPECTROGRAPHIC ANALYSIS OF CORROSION DEPOSIT IN PREPROGRAM CYLINDER

Element	Relative Amount Found
B	Low
Na	Low
Mg	Low
Al	Major
Si	Low
Ca	Low
Ti	Trace
Cr	Trace
Mn	Trace
Fe	Low
Ni	Trace
Cu	Low
Zn	Trace
Ga	Trace
Sr	Trace
Sn	Trace

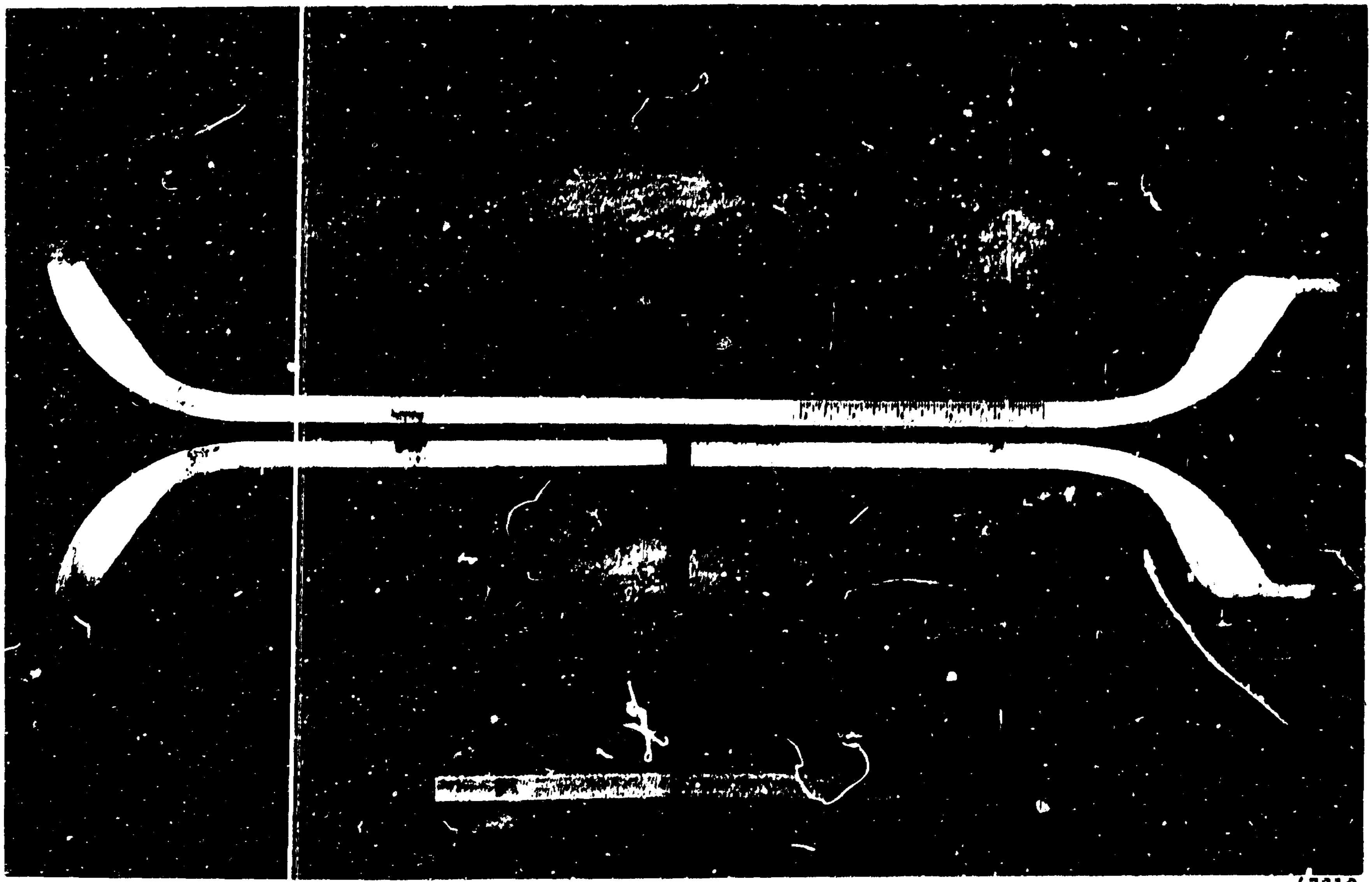
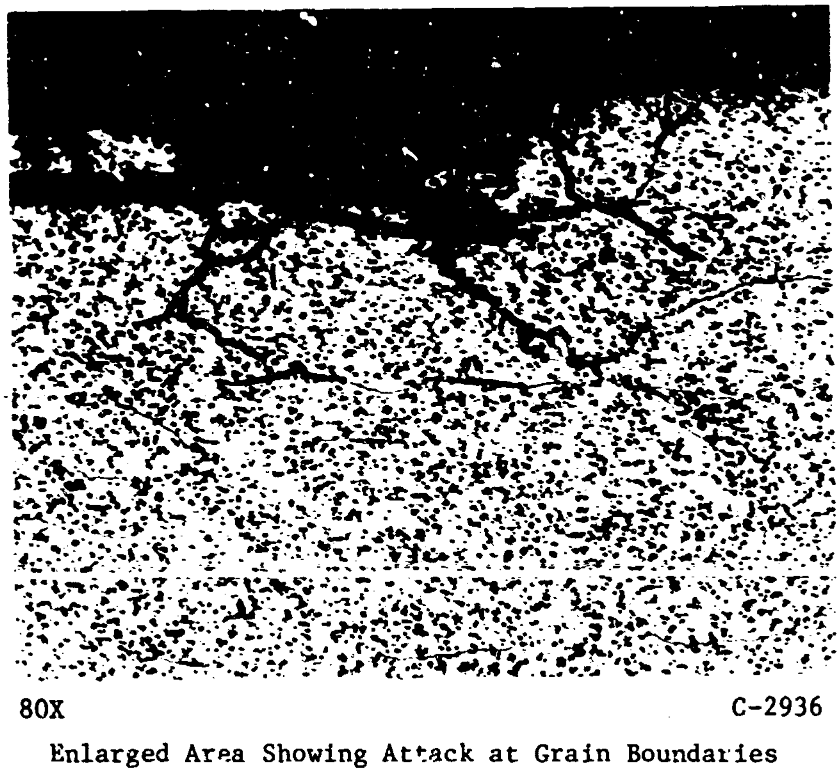


FIGURE 20. CORROSION OF CYLINDER EXAMINED PRIOR TO THE PROGRAM

9X C-2935

Entire Cross Section of Pit



80X C-2936

Enlarged Area Showing Attack at Grain Boundaries

FIGURE 21. PHOTOMICROGRAPHS OF A CROSS SECTION THROUGH ONE PIT IN THE PREPROGRAM CYLINDER

Etchant: 3.5 parts HNO_3 - 1.5 parts HF - balance water.

No significant amount of the corrosive agent originally suspected, i.e., phosphorus, was discovered. A more detailed and quantitative analysis was conducted on the corrosion product and the cylinder alloy using optical-emission spectrography, X-ray fluorescence spectrography, and spark-source mass spectrography. The results of these analyses are summarized in Table 15. Again, it was noted that a very low concentration of phosphorus (0.003 percent) was present in the corrosion product. Fluorine, however, was indicated by spark-source mass spectrography at 0.7 percent in the corrosion product, which was considered abnormally high. The fluorine content was then measured more accurately utilizing wet-chemical analytical procedures, and its concentration was determined to be 0.3 percent--an amount still considered abnormally high.

It was concluded that 0.3 percent fluorine was sufficient to account for the pitting observed and was the probable corrodent. Although the source of the fluorine was unknown, fluorine is contained in hydrofluoric cleaning acids which are sometimes used to clean aluminum. Based on this initial examination, it was expected that the corrosion products in the cylinders to be examined during the Phase I program would contain a high fluorine content. The examination of the cylinders is discussed in three parts: corrosion examination, chemical analysis, and conclusions.

Corrosion Examination

Based on the optical survey of the corroded cylinders described previously, the following five cylinders were selected as being the most severely corroded of those remaining after the rupture tests - Cylinders 21, 32, 41, 58, and 63. These cylinders were slit lengthwise on a large bandsaw with no lubricant. One-inch-square pieces covered with heavy corrosion product were cut from the most corroded half of each tank to be used for microprobe analyses. The remainder of the sampled half of each cylinder was then descaled in 5 weight percent phosphoric acid (H_3PO_4) at room temperature. The pit depths in the descaled halves were measured, and a maximum and average depth were recorded. Metallographic examinations were made of at least one pit (usually the deepest one) found in each cylinder.

The internal surfaces of each cylinder after the slitting operation are shown in Figure 22. The amount of corrosion product, which was not the same on each half, appeared to be greatest on Cylinders 21, 32, and 58. The corrosion

TABLE 15. ANALYSIS OF CORROSION PRODUCTS IN PREPROGRAM CYLINDER

	Measured Weight Percent of Corrosion Products					
	Whitish Residue			Cylinder Alloy		
Element	OES$^{(a)}$	OES$^{(b)}$	SSMS$^{(c)}$	OES$^{(b)}$	XRF$^{(d)}$	SSMS$^{(c)}$
Li	--	--	0.0001*	--	--	0.0001*
B	0.1*	--	0.006	--	--	0.0002*
F	--	--	0.7(e)	--	--	0.01*
Na	--	--	0.03	--	--	0.03*
Mg	0.3	0.6*	≤1.0	0.9	0.93*	≤1.0
Al	Major	Major	Major	Major	Major	Major
Si	0.3*	--	≤1.0	--	0.43*	≤1.0
P	--	--	0.003*	--	--	≤0.003*
S	--	--	0.02*	--	0.05*(f)	0.6(f)
Cl	--	--	0.005*	--	--	0.02*
K	0.3*	--	≤1.0	--	--	0.01*
Ca	0.5*	--	≤1.0	--	--	0.2*-0.5*
Ti	0.01*	--	0.07	--	0.04*	≤0.5
V	<0.01	--	0.01*	--	--	0.01*
Cr	0.03	0.035*	0.06	0.085*	0.04	0.06
Mn	<0.01	--	0.01*	--	0.016*	0.01
Fe	0.3	0.2*	0.3	0.4*	0.26	0.6
Co	--	--	<0.002*	--	--	<0.0003*
Ni	0.02	0.024*	0.03	0.01*	0.05	0.008
Cu	0.1*	--	0.3	--	0.26*	≤1.0
Zn	--	--	0.03*	--	0.14*	0.3
Ga	<0.01	--	0.03*	--	--	0.003*
As	<0.01	--	≤0.0002*	--	--	≤0.0002*
Sr	--	--	0.03*	--	--	0.001*
Zr	--	--	0.002*	--	--	0.004*
Ag	<0.01	--	≤0.0004*	--	--	≤0.0004*
Cd	--	--	≤0.002*	--	--	≤0.002*
Sn	0.01	--	0.01*	--	0.035*	≤0.0007
Sb	--	--	≤0.0001*	--	--	0.0004*
Ba	--	--	0.005*	--	--	0.001*
Hg	--	--	<0.0002*	--	--	<0.0002*
Pb	<0.01	--	0.01*	--	0.04*	0.005

Note: Preferred value marked with asterisk.

(a) Optical emission spectrography, approx. accuracy - x factor of 3.0
(b) Optical emission spectrography, ditto x factor of 0.5
(c) Spark source mass spectrography, " x factor of 3.0
(d) X-ray fluorescence spectrography, " ± 5 percent
(e) Wet chemical result = 0.30* percent, " ± 5 percent
(f) Apparent SSMS error, rechecked with XRF.

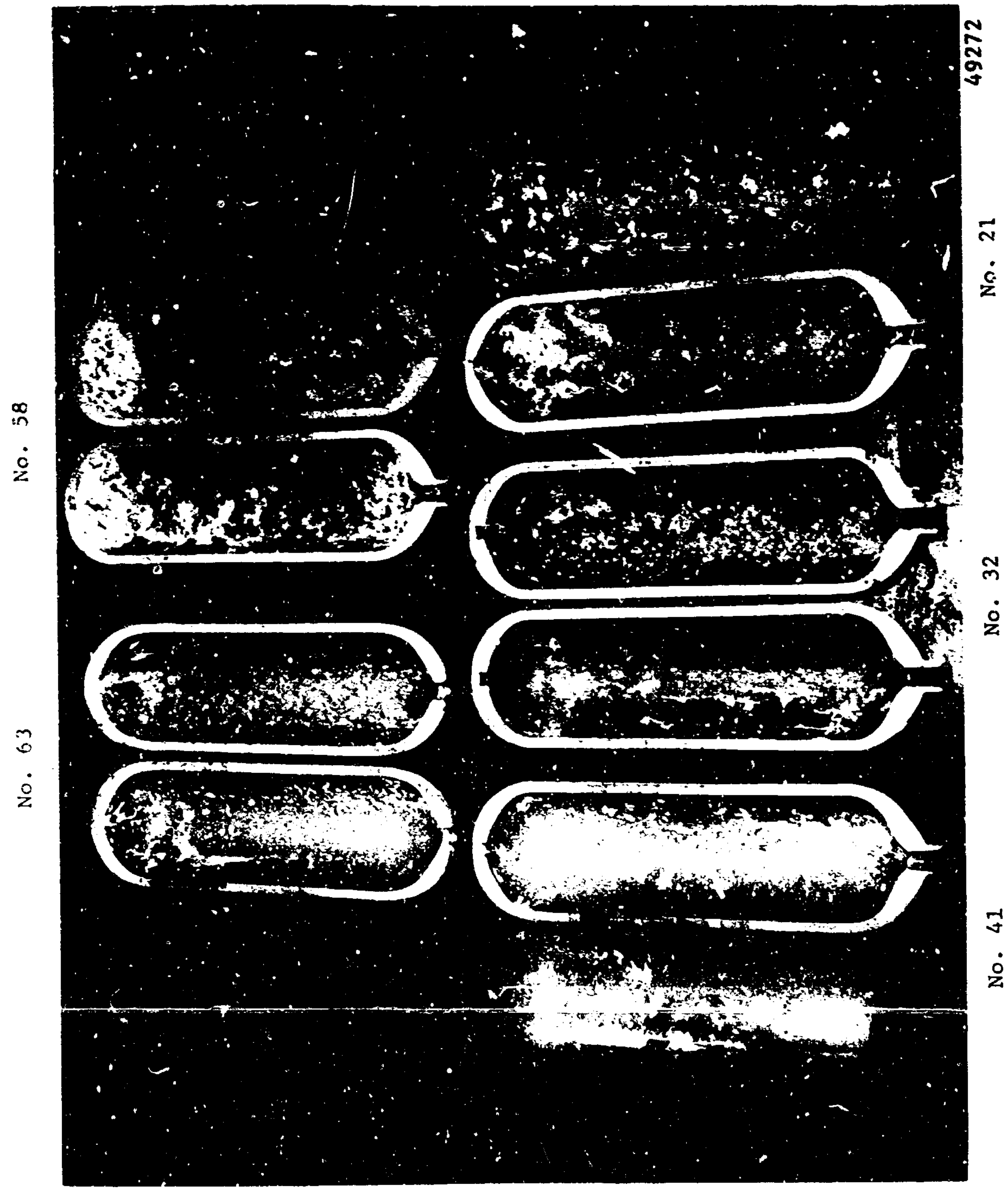


FIGURE 22. CORRODED INTERIORS OF SELECTED ALUMINUM CYLINDERS

product was white in all cylinders except for three areas in Cylinder 63 which were a pale yellow. The yellow product in this cylinder (see Figure 22) was located on the threads at the plugged end, and in the two almost vertical light areas at the bottom left on the left half.

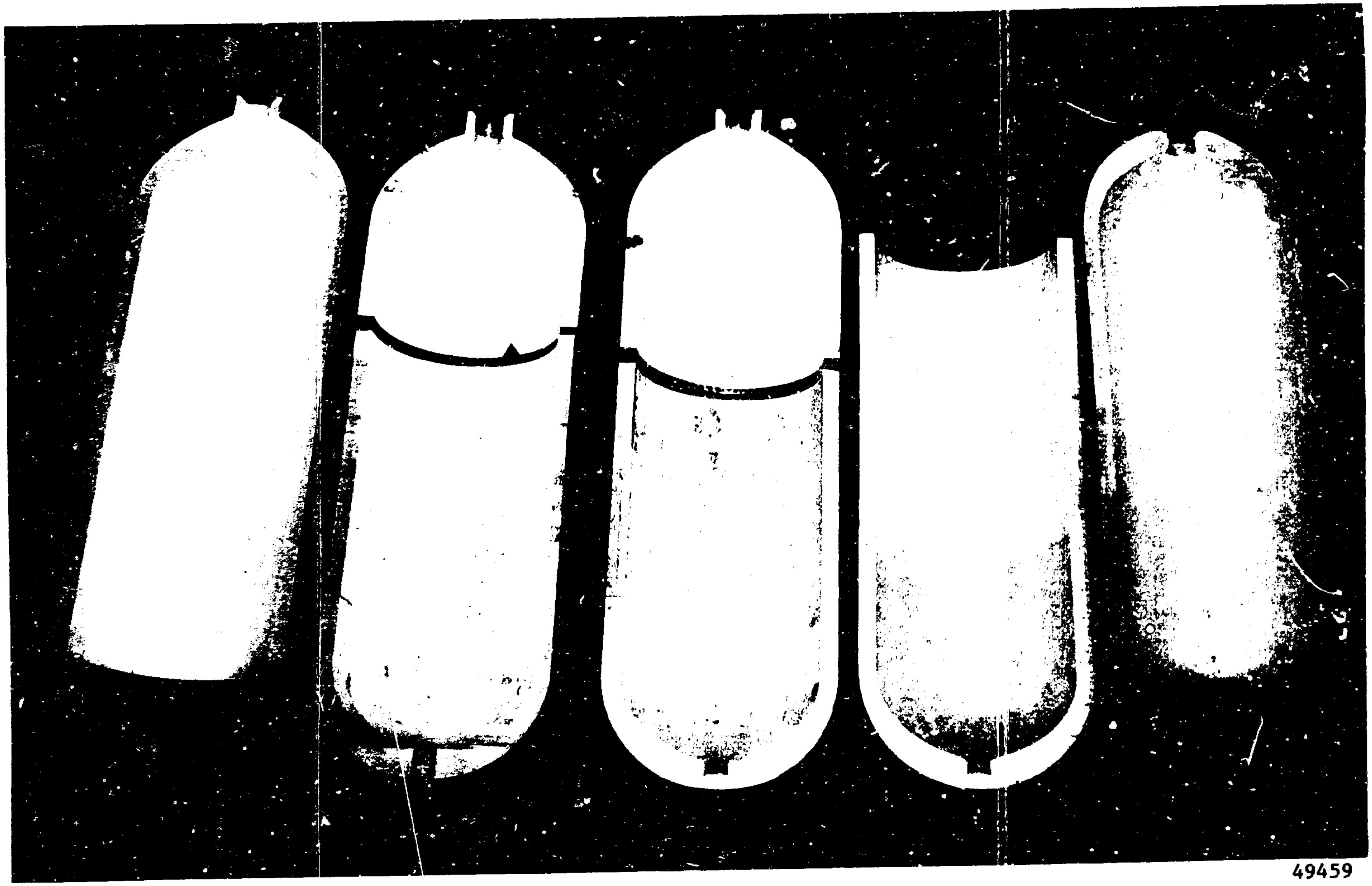
The left half of Cylinders 21, 32, 41, and 63 and the right half of Cylinder 58 as shown in Figure 22 were judged to be the most heavily corroded halves for each cylinder. The appearance of these halves after removal of the specimens for microprobe examination and after descaling are shown in Figures 23 through 26. The most extensive attack occurred in Cylinders 32 and 41 as a row of pits along the length of the cylinders. This suggested that these cylinders were stored on their sides for a long period of time, and that the moisture in the cylinders drained to the lowest areas, causing accelerated attack. The pitting attack was random in Cylinders 21, 58, and 63, and the attack tended to be filamentary. Photomacrographs of the deeper pits in Cylinders 32, 41, and 58 are shown in Figures 27 and 28.

The pit depths were measured with a micrometer depth gage in which the "feeler" had been machined to 1/64-inch diameter to permit penetration into the pits. The pit depths as measured by this technique ranged from <0.001 to 0.056 inch. The maximum and average pit depths for each of the cylinders are listed in Table 16. Two cylinders exhibited light pitting, two cylinders exhibited severe pitting, and the pitting in the fifth cylinder was intermediate.

TABLE 16. MAXIMUM AND AVERAGE PIT DEPTHS FOR SAMPLE CORRODED CYLINDERS

Cylinder No.	Maximum Pit Depth Discovered, inch	Average Pit Depth, inch
41	0.053	0.031
32	0.056	0.030
63	0.015	0.010
58	0.001	< 0.001
21	0.002	< 0.002

One of the deeper pits from each cylinder was examined in cross section perpendicular to the long axis of the cylinder. Photomicrographs of these pits are shown in Figures 29 to 33. The photomicrographs show that the



No. 21　No. 32　No. 41　No. 58　No. 63

FIGURE 23. ALUMINUM CYLINDERS AFTER DESCALING IN 5 PERCENT H_3PO_4

FIGURE 24. TYPICAL CORRODED AREAS ON CYLINDERS 21 AND 32 AFTER DESCALING

1X No. 41 C-3078

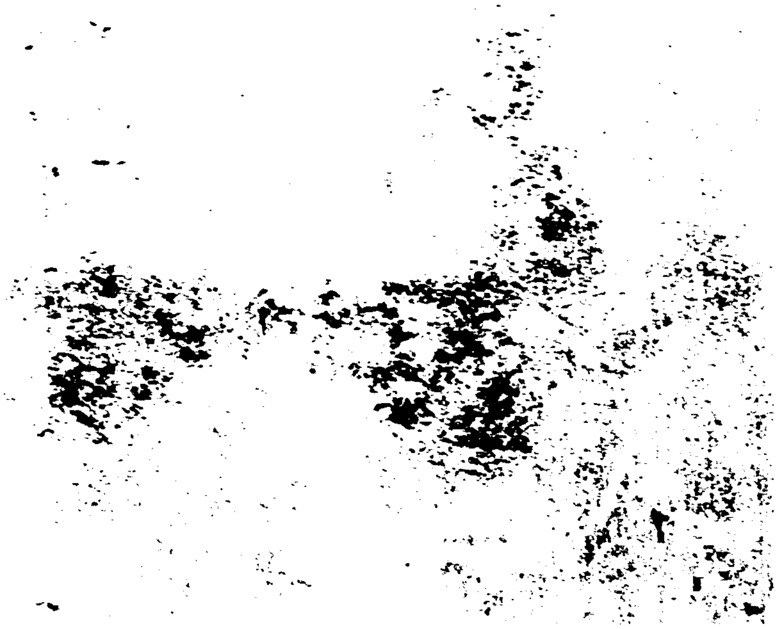
1X No. 58 C-3079

FIGURE 25. TYPICAL CORRODED AREAS ON CYLINDERS 41 AND 58 AFTER DESCALING

FIGURE 26. TYPICAL CORRODED AREA ON CYLINDER 63 AFTER DESCALING

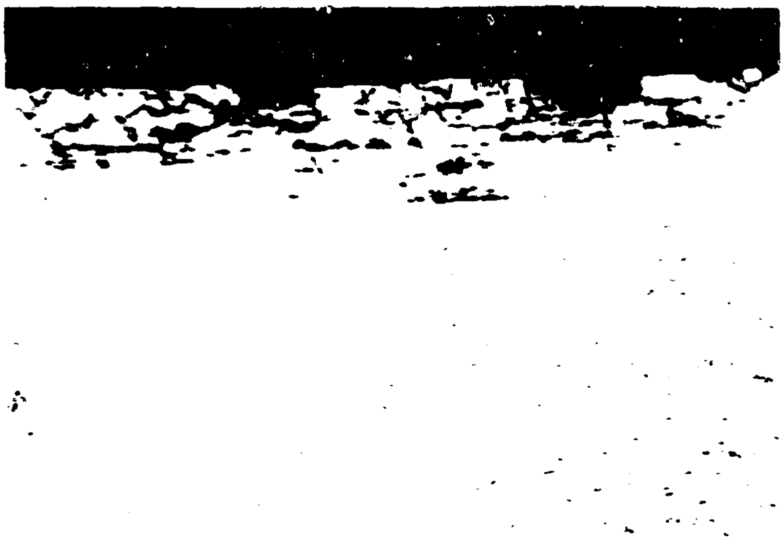
FIGURE 27. DEEPEST PITTED AREA IN CYLINDER 41

10X No. 32 C-3082

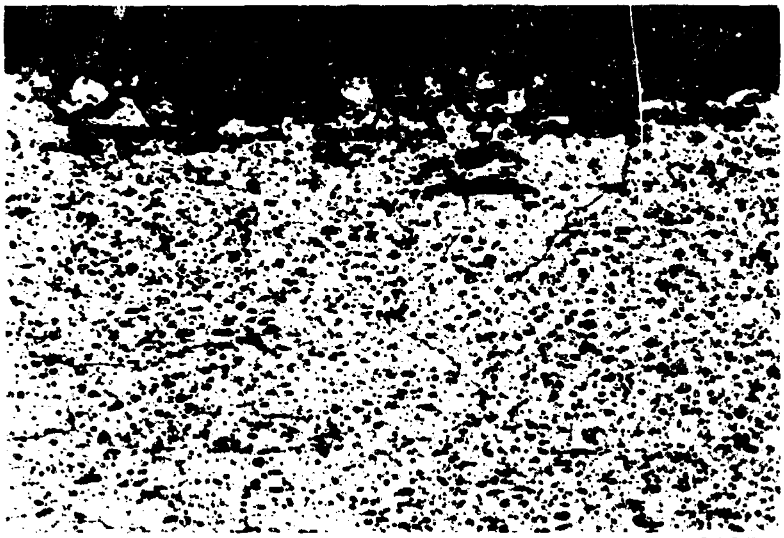


10X No. 58 C-3083

FIGURE 28. DEEPEST PITS IN CYLINDERS 32 AND 58



90X As Polished C-3084



90X Etched C-3085

FIGURE 29. CROSS SECTION OF A DEEP PIT IN CYLINDER 21

Note laminar attack.

Etchant: 3.5 parts HNO_3 - 1.5 parts HF - balance water.

20X As Polished C-3086

90X Etched C-3087

FIGURE 30. CROSS SECTION OF A DEEP PIT IN CYLINDER 32

Note laminar attack.

Etchant: 3.5 parts HNO_3 - 1.5 parts HF - balance water

20X As Polished C-3088

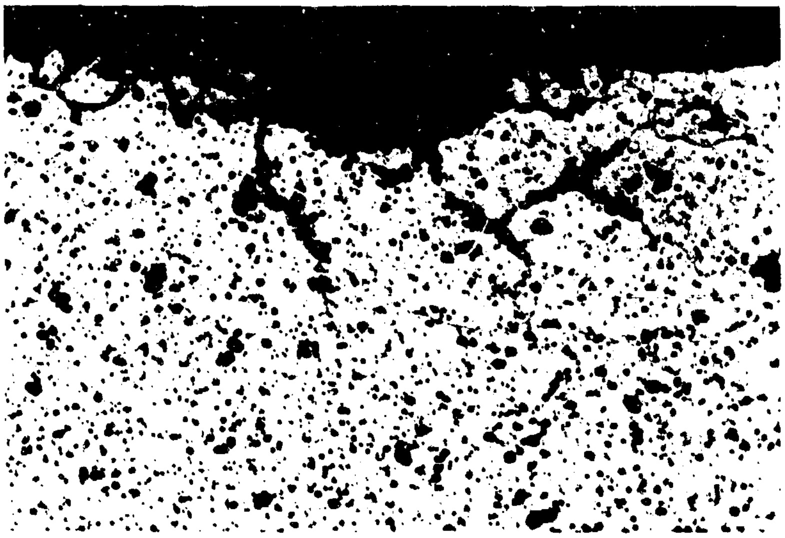
90X Etched C-3089

FIGURE 31. CROSS SECTION THROUGH A PIT IN CYLINDER 41

Note the laminar attack and upward movement of metal layers by oxide expansion.

Etchant: 3.5 parts HNO_3 - 1.5 parts HF - balance water.

90X As Polished C-3090



90X Etched C-3091

FIGURE 32. CROSS SECTION OF A DEEP PIT IN CYLINDER 58

Note that this attack is intergranular in contrast to the laminar attack observed in the pits in other cylinders.

Etchant: 3.5 parts HNO_3 - 1.5 parts HF - balance water.

90X As Polished C-3092

90X As Polished C-3093

FIGURE 33. CROSS SECTION THROUGH DEEPEST PITS (TOP) AND LEAD PRODUCT ON SURFACE (BOTTOM) IN CYLINDER 63

Note that the pit depth beneath the lead deposit is less than the maximum pit depth.

attack in the pits generally occurred along stringer paths oriented in the direction of fabrication of the original heavy tubing. This is not uncommon in aluminum alloys, being somewhat analogous to end-grain attack observed in high-strength aluminum alloy forgings. Figure 31 shows the wedging action of the corrosion product in the pit in Cylinder 41 which forced up layers of metal previously isolated by the stringer-like attack.

A metallographic examination was also made beneath the yellow corrosion product found in Cylinder 63. The photomicrograph of this area is also shown in Figure 33. No accelerating effect was observed from a comparison of the depth of pitting in this area with the maximum depth of attack observed elsewhere in Cylinder 63.

Chemical Analysis

Corrosion products were obtained from Cylinders 21, 58, and 63 before they were cut open as described above, and from Cylinders 34, 57, and 64. The six samples were analyzed with a spark-source mass spectrometer. Particular attention was given to chlorine, fluorine, sulfur, and phosphorus because the first two are known pitting agents and the latter two are often found in alkaline cleaners. The results are summarized in Table 17. The fluorine content was ≥200 ppm in all samples but one, and the chlorine content ranged from 50 to 200 ppm. Lead was extremely high in the samples from Cylinders 63 and 64.

The lead in the six samples was checked by atomic absorption, while the fluorine was checked by a fusion-distillation-titration technique. These results are summarized in Table 18. Reasonably good duplication with the mass-spectrographic analysis was obtained for all results except the fluorine in Cylinder 64, which was lower by an order of magnitude in the wet analysis. However, there was sufficient sample to permit duplicate analyses for fluorine in Cylinder 63 and lead in Cylinder 64. The duplication was not good, particularly with respect to lead, thus suggesting that the corrosion product was nonhomogeneous.

Microprobe examination and analyses were conducted on the surface deposits located on the 1-inch-square specimens removed from Cylinders 21, 41, 58, and 63. A large part of the area of the surface deposit on the sample

TABLE 17. MASS SPECTROGRAPHIC ANALYSIS OF RESIDUE IN CORRODED CYLINDERS (Ppm or percent by weight)

Element	Cylinder					
	21	34	57	58	63	64(a)
F	200	600	60	600	300	4000
P	10	100	6	50	20	50
S	300	80	200	600	500	100
Cl	100	50	100	200	150	70
Pb	200	10	1	80	~4%	~10%

(a) Cylinder 64 had a high hydrocarbon content.

TABLE 18. CHEMICAL ANALYSIS OF CORROSION PRODUCTS FOR SELECTED ELEMENTS (Ppm or percent by weight)

Cylinder	Lead	Fluorine
21	100	330
34	(Not enough sample for analysis)	
57	23	175
58	150	430
63	8.7%	220(a) 160(a)
64	12.5%(a) 5.9%(a)	230

(a) Sufficient sample permitted duplicate analyses.

from Cylinder 21 was checked for fluorine, but none was detected. One part of the deposit showed a small concentrated spot of lead and a relatively low concentration of chlorine. Some low-intensity areas of sulfur were also seen on the sample. A large portion of the surface area of the sample from Cylinder 58 was checked for fluorine and lead, but neither was detected. Some low-intensity areas of chlorine and sulfur were detected. The sample from Cylinder 63 had a relatively thick deposit that was creamy or yellow in appearance. Microprobe analysis of this deposit showed a high concentration of lead. Low-intensity spots of chlorine were also detected, but no fluorine was detected. For the sample from Cylinder 41, no lead or fluorine were detected, but some small spots of low-intensity chlorine and sulfur were found.

The creamy, yellowish deposit noted in Cylinder 63 was analyzed using optical-emission spectrography and X-ray diffraction techniques. Optical-emission spectrography indicated extremely high concentrations of lead and aluminum, low concentrations of sodium, iron, copper, bismuth, and phosphorus, and trace amounts of chromium, nickel, magnesium, silicon, and calcium. Utilizing X-ray diffraction techniques, lead carbonate ($PbCO_3$) was identified as the major compound present, with a possible trace of pure lead.

Conclusions

The variation in the degree of corrosion attack in the cylinders, and the variation in the chemical-analysis results for the corrosion products obtained from intact cylinders as compared with corrosion products occurring on 1-inch-square metal specimens indicate that the corrosion attack and the corrosion products were not homogeneous. On the basis that the corrosion products from the intact cylinders were more indicative of the corrodents than the small samples, it was concluded that the fluorides found in the corrosion product together with moisture from the air were the probable corrosive agents. The concentrations of fluorides in the present study were of the order of hundreds of ppm while those in the previous study were in the thousand-ppm range. However, the lower level was still considered to be sufficiently high to cause pitting attack of the type noted. The lead, which was probably present as the result of using pipe "dope" on the threaded bottom plug, did not appear to influence the corrosion of the cylinder. However, lead could be a harmful constituent in the breathing air.

Consideration of Manufacturing and Field-Testing Procedures

A further objective of the program was the consideration of the existing manufacturing specifications and field-testing procedures to determine whether aluminum scuba cylinders can be produced and used with a high degree of confidence. This work is described in the following sections.

Manufacturing Specifications

The aluminum scuba cylinders are manufactured in accordance with MIL-C-24316(SHIPS), Cylinder, Compressed Gas, Diver's, Nonmagnetic, Aluminum (see Appendix B). This specification was prepared in accordance with the format and standard requirements of similar military specifications.

Military specifications of this type consist of six sections. The first section--Scope--describes the item covered by the specification. The second section--Applicable Documents--lists all applicable documents which have been selected to be included in the specification under preparation. The use of such past documents greatly simplifies the writing of the new document. The third section--Requirements--describes the physical and performance characteristics which are required by any item covered by the specification. The fourth section--Quality Assurance Provisions--describes the manufacturing procedures that are required in order to assure the manufacture of acceptable components. Section five--Preparation for Delivery--describes different packaging and packing procedures that must be followed, while the sixth section--Notes--describes any general comments that are desirable in the interpretation and use of the specifications.

Detailed consideration was given to the sections of the specification covering Requirements and Quality Assurance Provisions. The other sections of the specification were reviewed briefly. In general it was concluded that the specification is well written and represents detailed consideration of the areas covered. No problems were envisioned for the sections on Scope, Applicable Documents, Preparation for Delivery, or Notes.

However, several possible problem areas were found to exist with different parts of the sections on Requirements and Quality Assurance Provisions. The correction of the specification to solve these problems would require effort beyond the scope of this program. However, a brief description of the possible problems is given below. For completeness, comments are included for each part of the sections on Requirements and Quality Assurance Provisions. The numbers of the comments correspond to the associated numbers in the specification.

3.1 Description. No change is recommended.

3.2 Physical Parameters. A change is recommended because it is believed that additional dimensions are needed in Figure 1 of the specification to prevent the fabrication of an unusual shape which might have a section with insufficient strength. The three areas of most concern are the curvature of the base end, the curvature of the neck end, and the length and uniformity of the cylindrical section.

After conducting the rupture tests on these aluminum scuba cylinders and comparing the results to those for the DOT 3AA 2250 steel cylinders, it is believed that the DOT strength requirement [Equation (3), herein] could be included in this specification as a strength requirement. This would provide greater assurance of the strength characteristics of the cylinders produced to this specification. At present, the strength requirements are hidden in other requirements such as the elastic expansion and permanent expansion characteristics of the cylinders.

3.2.1 Material. No change is recommended.

3.2.2 Necked End. A change is recommended because the length of the neck is not adequately defined. The correction of this would include a better dimensioning approach than that shown on Figure 1 for the neck length.

3.2.3 Threading. No change is recommended.

3.2.3.1 Protection of Threads. A change is recommended to require the exclusion of moisture and foreign matter.

3.2.4 Base End. A change is recommended because the required weld is inadequately described, and because the second sentence of 3.2.4 conflicts with the use of a weld. The correction could include the elimination of the second sentence, and the inclusion in Figure 1 of a blow-up section showing the type and depth of the weld required.

3.2.5 Interior Surfaces. No change is recommended.

3.2.6 Pressure. No change is recommended.

3.2.7 Expansion Characteristics. A change is recommended because the permanent expansion value is based on the consideration that the cylinder expands relatively uniformly. If the cylinder has a relatively small, weak section, such as might be provided by a tapered cylindrical section, the weak section could yield excessively while the overall permanent expansion value would not be excessive. It is believed that the overall permanent expansion value should be combined with specific measurements on selected parts of the cylinder.

3.2.8 Hardness. A change is recommended because of the maximum hardness value. Either no maximum hardness should be used, or the value should be higher. The better approach has not yet been selected.

3.2.9 Magnetic Effects. No change is recommended.

3.2.10 Buoyancy and Trim. A change is recommended because the conditions and tolerances of buoyancy and trim are not specified. The change should include a description in the Quality Assurance Provisions section of adequate test procedures.

3.3 Serial Number. No change is recommended.

3.4 Marking. A change is recommended because there is no provision against marking on the cylindrical portion of the cylinder.

3.5 Coating. No change is recommended.

3.6 Cleaning. A change is recommended because there is no provision for preventing the use of cleaning agents which could be corrosive to the cylinder.

3.7 Workmanship. No change is recommended.

4.1 Responsibility for Inspection. No change is recommended.

4.2.1 Inspection Lot. A change is recommended because the maximum lot size is not specified.

4.2.2 Sampling for Tensile Test of Cylinder Material. A change is recommended because the sampling should include a material certification requirement.

4.2.3 Sampling for Visual and Dimensional Inspection. No change is recommended.

Record Maintenance. The 4.2 series should include a requirement for record maintenance. A possible wording is "The supplier shall maintain a record of the inspection applied to each lot".

4.3 Visual and Dimensional Inspection. No change is recommended.

4.4.1 Tensile Test. A change is recommended because the location is not specified for the tensile test specimens. They probably should be obtained from equally spaced portions of the cylindrical wall.

4.4.2 Magnetic Test. No change is recommended.

4.4.3 Hydrostatic Test. No change is recommended.

4.4.4 Wall Thickness Test. A change is recommended because the accuracy of the measurement is in doubt. It is probable that either the testing equipment should be more accurately specified or the accuracy should be changed. The number and location of the measurements should also be specified.

4.4.5 Water Volume Test. No change is recommended.

4.4.6 Hardness Test. A change is recommended because the locations of the hardness impressions are insufficiently specified. They should probably be equally spaced around the middle of the cylindrical section of the cylinder.

4.4.7 Inspection of Preparation for Delivery. No change is recommended.

Buoyancy and Trim Test. A change is recommended to include a test procedure for a buoyancy and trim test.

Yield Measurement Test. A change is recommended to include the description of a measurement procedure other than the volume change for determining whether any measurement of the cylinder has permanently increased a certain percent as a result of the hydrostatic test.

Field Inspection and Cleaning of Aluminum Scuba Cylinders

During the course of this research program, systematic naked-eye inspections of 72 aluminum scuba cylinders were conducted. As discussed in a preceding section, the inspection technique found most effective utilized a small lightbulb which was inserted into the cylinder through the threaded valve hole following valve removal. This light provided adequate illumination of the cylinder interior permitting an overall visual survey of the interior wall surfaces. Figure 34 shows the insertion of the lightbulb into one of the cylinders.

Basically, the inspection equipment consisted of a 12-volt stepdown transformer, an automobile lightbulb and socket of the type used for either interior or backup lights, and three or four feet of extension-cord wire connecting the lightbulb to the transformer. These items are shown in Figure 35.

The transformer used was a Triad F-26X filament transformer and the lightbulb was a No. 1004. Any 12-volt stepdown transformer, however, may be used and the lightbulbs and sockets are available at any automotive supply house. The schematic diagram for this equipment is shown in Figure 36. If the lightbulb socket purchased is found to have a mounting flange greater than 7/8 inch in diameter, it must be reduced by grinding to allow passage through the valve hole.

Protection of the lightbulb is not normally necessary since it is relatively sturdy and quite inexpensive. If, however, for safety or other reasons, shielding of the lightbulb is desired, window-screen material can be soldered or brazed to the socket, allowing it to extend cylindrically about the lightbulb. Since the inspection light must be able to pass through the valve hole of the scuba cylinder, any shielding added should not be greater than 7/8 inch in diameter.

Utilizing the above inspection technique and equipment, the results of three independent inspections by three different staff members were in very good agreement. Because of the success of this technique during the program, it is recommended that the procedure be used during periodic field inspections of scuba cylinders.

49697

FIGURE 34. INSERTION OF INSPECTION LIGHT INTO VALVE HOLE OF ALUMINUM SCUBA CYLINDER

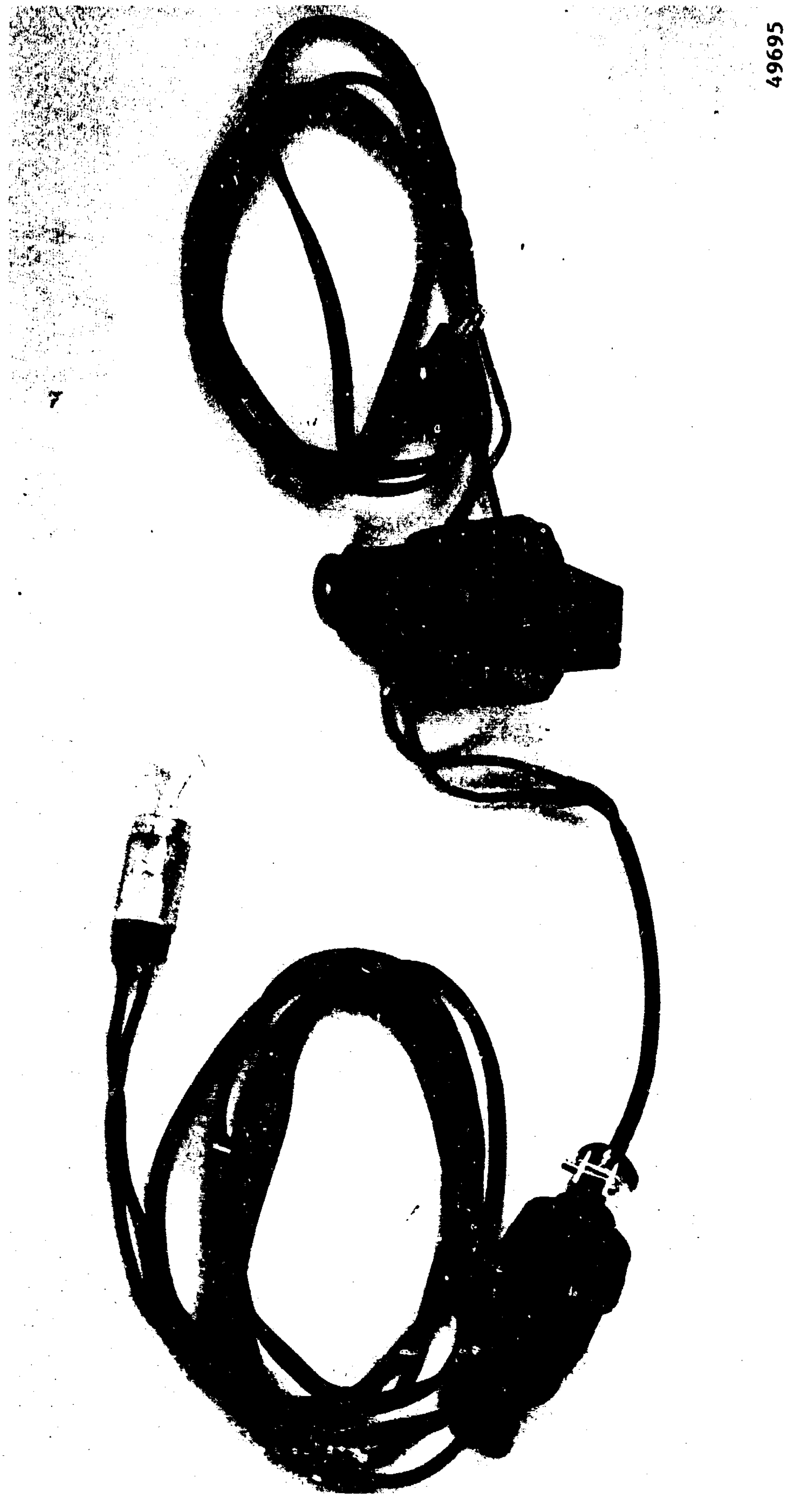


FIGURE 35. INSPECTION-LIGHT COMPONENTS

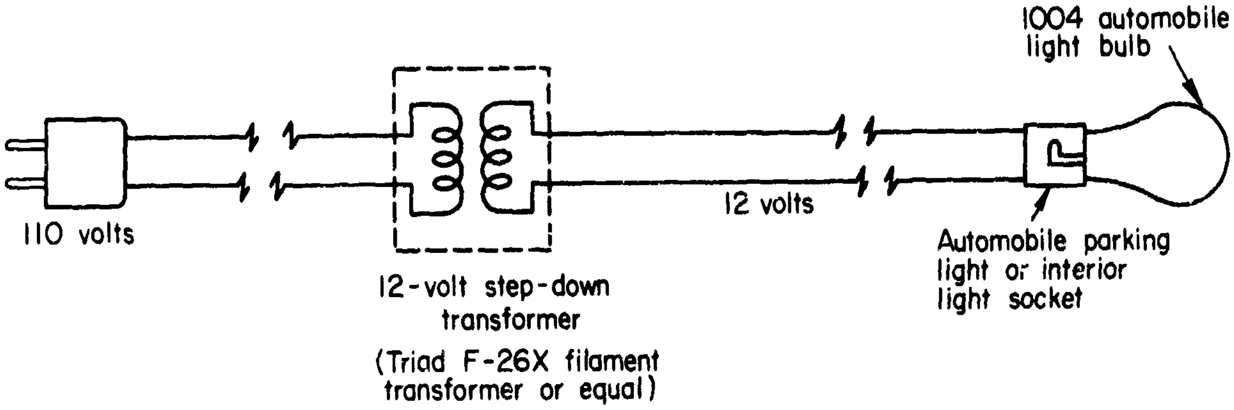


FIGURE 36. SCHEMATIC OF SCUBA CYLINDER INSPECTION-LIGHT EQUIPMENT

Three of the cylinders which were rated as "severely corroded" during this inspection were used in rupture experiments and for corrosion examination, while five additional cylinders, also rated "severely corroded", were selected for an independent corrosion examination. It was interesting to note that although the corrosion in each of these cylinders had been rated "severe", the maximum and average pit depths measured following a thorough cleaning of the interior surfaces varied significantly (see Table 16). It therefore became apparent that the quantity and deposition of the corrosion product on the cylinder interior was somewhat misleading and that a reasonably accurate visual cylinder inspection required a precleaned interior exposing the actual pits to view.

A simple phosphoric acid cleaning process was used during this program. The effectiveness of this process can be visualized by referring to Figures 22 and 23 for comparison of the as-received condition and cleaned condition of the cylinders.

If the initial field inspection shows that corrosion product similar to that shown in Figure 22 is present, it is recommended that the corrosion product be removed by filling the cylinder with a 5 weight percent solution of phosphoric acid and water and letting it stand for approximately 30 minutes. This should be followed by a thorough rinsing with fresh water and drying. The cylinder can then be reinspected.

Phosphoric acid (H_3PO_4) is supposed to form a stable compound with aluminum. [This is opposed to hydrofluoric acid (HF), for example, which acts somewhat like a catalyst, continually reacting with aluminum for an indefinite period.] However, detrimental corrosive side effects due to the use of phosphoric acid are a slight possibility, considering the moist, high-pressure environment to which the internal surfaces of these cylinders are subjected. Therefore, some tests should be conducted utilizing phosphoric acid on 6061-T6 aluminum under hyperbaric conditions to verify the apparent nondetrimental character of the phosphoric acid recommended for this cleaning procedure.

If the extent of the corrosion discovered following the second inspection is similar to that discovered during the research program, it appears that the cylinder is not an immediate hazard. However, due to the potential hazard that exists with these cylinders (as well as any pressure vessel) a conservative approach following the cylinder cleaning and inspection procedures is recommended. Large pits, 1/4 inch in diameter or larger, or a number of pits clustered together in one spot may suggest that a 5000-psi hydrostatic pressure test should be conducted to reinstate confidence in the immediate safety of the cylinder. Any widespread thinning of the wall is, of course, also cause for concern, indicating that a 5000-psi hydrostatic test should be conducted.

Frequent reinspections of previously corroded cylinders are also recommended since the type of corrosion investigated during this program will probably continue throughout the life of the cylinder even if the cylinder is cleaned as outlined above.

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APPENDIX A

SUMMARY OF INFORMATION PERTINENT TO RUPTURE TESTS OF TEN CYLINDERS

TABLE A-1. SUMMARY OF INFORMATION PERTINENT TO RUPTURE TESTS OF TEN CYLINDERS

Assigned Cylinder Number	Manufacturer's Serial No.	Date of Manufacture	Outside Diameter, inches	Average Wall Thickness, inch	Yield Pres., 0.4 Percent Volumetric Offset, psig	Failure Pressure, psig	Calculated Yield Stress Using Equation (1), ksi	Calculated Ultimate Stress Using Equation (1), ksi	Tensile Test Yield Stress, 0.2% Offset, ksi	Tensile Test Ultimate Stress, ksi	Comments
11(a)	8222J	9-68	7.70	0.587	6600	7255	40.0	43.9	39.5	47.4	
12(a)	8414J	9-67	7.70	0.580	6150	7025	37.7	43.1	39.5	47.2	
13(a)	8397J	9-67	7.70	0.584	7260	7740	44.3	47.2	41.3	47.7	
17(b)	8176J	9-67	-	0.594	-	3430	-	-	43.2	48.8	
34(c)	78802C	10-64	7.68	0.567	-	7950	-	49.8	51.8	55.0	Yield pr. not avail.
57(c)	1602 B	6/63	7.64	0.547	7100	7455	46.0	48.3	48.8	53.0	
64(c)	2622	10-56	7.70	0.549	6920	7225	45.1	47.0	47.5	52.2	
78(d)	80377L	6-70	6.88	0.168	4480	5435	-	-	89.5	102.0	
79(d)	80376L	6-70	6.88	0.163	4470	5280	-	-	82.5	103.6	
80(d)	80375L	6-70	6.88	0.165	4320	5330	-	-	91.0	103.0	

(a) New aluminum cylinders.

(b) Artificially flawed new aluminum cylinder.

(c) Corroded aluminum cylinders.

(d) New steel cylinders.

APPENDIX B

MIL-C-24316 (SHIPS),
MILITARY SPECIFICATION,
CYLINDER, COMPRESSED GAS, DIVER'S
NONMAGNETIC, ALUMINUM

This document is subject to special export controls and each transmittal to Foreign governments or foreign nations may be made only with prior approval of the Naval Ship Systems Command.

MIL-C-24316(SHIPS)

AMENDMENT - 1
15 November 1968

MILITARY SPECIFICATION

CYLINDER, COMPRESSED GAS, DIVER'S,

NONMAGNETIC, ALUMINUM

This amendment forms a part of Military Specification MIL-C-24316(SHIPS) dated 21 June 1968.

Page 2

3.2.7, line 2: Delete "68±4" and substitute "6_±7".

Preparing activity:
Navy - SH
(Project 4220-N152)

MIL-C-24
21 June 1968

MILITARY SPECIFICATION

CYLINDER, COMPRESSED GAS, DIVER'S,

NONMAGNETIC, ALUMINUM

1. SCOPE

1.1 This specification covers a compressed gas cylinder for stowage of high pressure air for use in demand type, self-contained underwater breathing apparatus.

2. APPLICABLE DOCUMENTS

2.1 The following documents of the issue in effect on date of invitation for bids or request for proposal, form a part of the specification to the extent specified herein.

SPECIFICATIONS

FEDERAL

QQ-A-200/3 - Aluminum Alloy Bar, Rod, Shapes, Tube and Wire, Extruded, and Structural Shapes, 6061.
PPP-B-636 - Box, Fiberboard.
PPP-B-640 - Boxes, Fiberboard, Corrugated, Triple Wall.

MILITARY

MIL-P-116 - Preservation, Methods of.
MIL-E-15090 - Enamel, Equipment, Light Gray (Formula No. 111)
MIL-P-15328 - Primer, Pretreatment, (Formula No. 117 for Metals).
MIL-P-15930 - Primer Coating, Shipboard Vinyl - Zinc Chromate (Formula No. 120-for Hot Spray).

MIL-M-19595 - Magnetic Effects Limits for Nonmagnetic Equipment Used in Proximity of Magnetic Influence Ordnance.

STANDARDS

FEDERAL

FED-STD-151 - Metals, Test Methods.

MILITARY

MIL-STD-105 - Sampling Procedures and Tables for Inspection by Attributes.
MIL-STD-129 - Marking for Shipment and Storage.
MIL-STD-147 - Palletized Unit Loads (40" X 48" 4-way Partial and 4-way Pallets).
MIL-STD-1186 - Cushioning, Anchoring, Bracing, Blocking and Waterproofing, with Appropriate Test Methods.

Copies of specifications, standards, drawings, and publications required by suppliers in connection with specific procurement functions should be obtained from the procuring activity or as directed by the contracting officer.)

2.2 Other publications.- The following documents form a part of this specification to the extent specified herein. Unless otherwise indicated, the issue in effect on date of invitation for bids or request for proposal shall apply.

NATIONAL BUREAU OF STANDARDS

Handbook H-28 - Screw-Thread-Standards for Federal Services.

(Applications for copies should be addressed to the Superintendent of Documents, Government Printing Office, Washington, D. C. 20402.)

UNIFORM CLASSIFICATION COMMITTEE

Uniform Freight Classification Rules.

Application for copies should be addressed to the Uniform Classification Committee, 202 Union Station, 516 West Jackson Boulevard, Chicago, Illinois 60606.)

FSC 4220

COMPRESSED GAS ASSOCIATION (CGA)

Pamphlet C-1 - Methods for Hydrostatic Testing of Compressed Gas Cylinders.

(Application for copies should be addressed to the Compressed Gas Association, Suite 2400-6, 500-5th Avenue, New York City, New York 10036.)

(Technical society and technical assocation specifications and standards are generally available for reference from libraries. They are also distributed among technical groups and using Federal agencies.)

3. REQUIREMENTS

3.1 Description. The cylinder is for use as the compressed air supply in nonmagnetic demand type self-contained underwater breathing apparatus.

3.2 Physical parameters. The cylinder shall be in accordance with figure 1 and have a nominal overall length of 26-3/8 inches. It shall have an internal volume of 700 ± 30 cubic inches. The cylinder wall thickness shall be such as to attain the required buoyancy and trim (see 3.2.10), but shall be not less than 0.540 inch thick.

3.2.1 Material. The cylinder shall be spun from aluminum alloy 5061-0 tubing and then treated to temper T-6 of QQ-A-200/8.

3.2.2 Necked end. In forming, sufficient material shall be provided in the neck of the cylinder to face off a flat of minimum diameter of 1-5/8 inches (see figure 1).

3.2.3 Threading. The cylinder neck shall be configured with the "O" ring type arrangement of figure 1. The thread shall be 3/4-14 NPSM (modified). After machining, there shall be no evidence of folds, cracks, or other imperfections in the threaded area.

3.2.3.1 Protection of threads. The neck of the finished cylinder shall be provided with a plastic cap to protect the threads, "O" ring groove and finished flat surface.

3.2.4 Base end. The base end closure of the cylinder shall be made by means of an aluminum plug as shown in figure 1. If required to effect a seal, a non-leaded, non-toxic sealing compound shall be utilized.

3.2.5 Interior surfaces. There shall be no visible evidence of folds, cracks, pits, or extreme waviness on the internal surfaces (including the ends) of the cylinder.

3.2.6 Pressure. The cylinder is for 3000 pounds per square inch gage (psig) working pressure and shall be hydrostatically tested to withstand 5000 psig.

3.2.7 Expansion characteristics. When hydrostatically tested to 5000 psi, the cylinder shall exhibit a total volumetric expansion of 68 ± 4 cubic centimeters. The permanent expansion (PE) shall not exceed 5 percent of the total volumetric expansion, the remainder to be elastic expansion (EE).

3.2.8 Hardness. The cylinder shall have an average hardness on the Rockwell "E" scale (RE) of 90 ± 4.

3.2.9 Magnetic effects. The magnetic effect of the finished cylinder shall be no greater than 0.05 millioersteds when measured in accordance with 4.4.2.

3.2.10 Buoyancy and trim. The cylinder shall be neutrally buoyant when charged to 1500 psi. The cylinder's trim shall also be neutral.

3.3 Serial number. The cylinder shall be marked with a serial number (see 3.4). This serial number shall be assigned by the manufacturer so that no two cylinders manufactured by him, either in the same lot or offered for delivery in the same calendar year, shall bear the same serial number.

3.4 Marking. The cylinder shall be marked (indented) with the following information in letters not less than 1/4 inch high, as near to the neck of the cylinder as practicable:

On one side: Serial number
"N-MAG"
"3000 psig (SPUN)"
"RE XX"
Government inspector's stamp

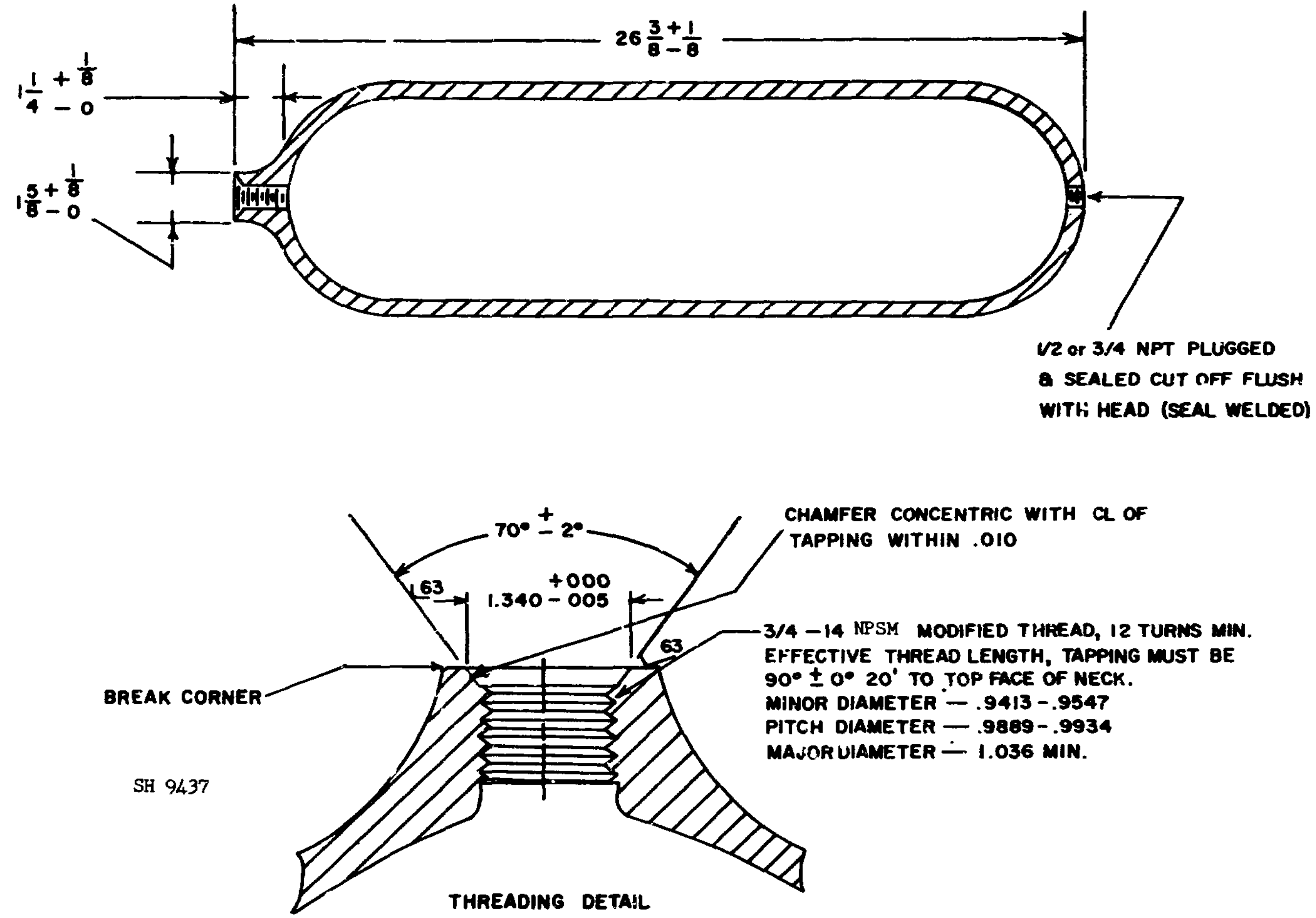

FIGURE B-1. CYLINDER

On opposite side: "Test 5000 psig"
Month, year of test
"EE XX.X cc"
"PE X.X cc"
"Volume XXX cu in"

3.5 Coating. The cylinder shall be coated as follows:

(a) The cylinder shall be degreased inside and out.
(b) The exterior surface (except the flat at the cylinder neck) shall be anodized.
(c) The outside surface (except the flat at the cylinder neck) shall be coated with:
  (1) One coat of pretreatment primer in accordance with MIL-P-15328, followed by:
  (2) One coat of vinyl-zinc chromate primer in accordance with MIL-P-15930, followed by:
  (3) Two coats of enamel in accordance with MIL-P-15090, class 2.

3.6 Cleaning. The finished cylinder shall be cleaned of any impurities which would be detrimental to use with high partial pressures of oxygen.

3.7 Workmanship. Only first class workmanship will be acceptable. Except where specified all surfaces shall be smooth and continuous and there shall be no evidence of gross tool marks; neither shall there be evidence of puddling of the coating. All indentations shall be clear and legible.

4. QUALITY ASSURANCE PROVISIONS

4.1 Responsibility for inspection. Unless otherwise specified in the contract or purchase order, the supplier is responsible for the performance of all inspection requirements as specified herein. Except as otherwise specified in the contract or order, the supplier may use his own or any other facilities suitable for the performance of the inspection requirments specified herein, unless disapproved by the Government. The Government reserves the right to perform any of the inspections set forth in the specification where such inspections are deemed necessary to assure supplies and services conform to prescribed requirements.

4.2 Sampling.

4.2.1 Inspection lot. A lot shall consist of all cylinders made from the same run of tubing, fabricated and treated at the same time.

4.2.2 Sampling for tensile test of cylinder material. One finished cylinder shall be selected at random from each lot for tensile test bar specimens (see 4.4.1).

4.2.3 Sampling for visual and dimensional inspection. Cylinders shall be selected in accordance with MIL-STD-105, General Inspection Level II, for the inspection of 4.3. The Acceptable Quality Level (AQL) shall be 1.5 percent.

4.3 Visual and dimensional inspection. Cylinders selected in accordance with 4.2.3 shall be examined and measured to verify conformance to all of the requirements of this specification which do not involve tests. Threads shall be checked by means of "GO" and "NO-GO" gages as specified in H-28.

4.4 Test procedures.

4.4.1 Tensile test. Test bars shall be tested according to FED-STD-151 to comply with the properties of 6061 T-6 aluminum set out in QQ-A-200/8. A lot failing to pass this test shall not be offered for delivery.

4.4.2 Magnetic test. Each cylinder in the lot shall be tested to meet the requirements of 3.2.9. This test shall be in accordance with MIL-M-19595 except that readings of magnetic effects that are taken while the cylinder is in motion shall not be considered. Cylinders that fail to pass this test shall be rejected.

4.4.3 Hydrostatic test. Each cylinder in the lot shall be hydrostatically tested to 5000 psi by the water jacket method of CGA Pamphlet C-1. The total volumetric, elastic and permanent expansions shall be determined in accordance with 3.2.7. Cylinders that leak or fail to meet these requirements shall be rejected.

4.4.4 Wall thickness test. The wall thickness of each cylinder in the lot shall be determined by ultra-sonic (with the pulse-echo type) equipment calibrated to an accuracy of 3 percent. Cylinders that fail to meet the wall thickness requirements of 3.2 shall be rejected.

4.4.5 Water volume test. The water volume of each cylinder in the lot shall be determined to the nearest cubic inch. Cylinders that fail to meet the requirements of 3.2 shall be rejected.

4.4.6 Hardness test. The average hardness of each cylinder in the lot shall be determined in accordance with the requirements of 3.2.8 by averaging at least three values taken by impressions around its girth. No impression shall indicate hardness less than 86 Rockwell "E". Cylinders that fail to pass the hardness test shall be rejected.

4.4.7 Inspection of preparation for delivery. The packaging, packing, and marking of the cylinder shall be inspected to determine compliance with the requirements of section 5.

5. PREPARATION FOR DELIVERY

(The preparation for delivery requirements specified herein apply only for direct Government procurements. Preparation for delivery requirements of referenced documents listed in Section 2 do not apply unless specifically stated in the contract or order. Preparation for delivery requirements for products procured by contractors shall be specified in the individual order.)

5.1 Packaging. Cylinders, cleaned and capped in accordance with 3.2.3.1 and 3.6, shall be packaged in accordance with Level A or C as specified (see 6.2).

5.1.1 Level A. Cylinders shall be cushioned, blocked or braced in accordance with MIL-STD-1186 and individually packaged in accordance with the requirements of MIL-P-116.

5.1.2 Level C. Packaging shall be sufficient to afford adequate protection against corrosion, deterioration, contamination (both magnetic and chemical), and physical damage from the supply source to the using activity for immediate use. When it meets these requirements, the supplier's commercial practice may be utilized.

5.2 Packing. Packing shall be in accordance with Level A, B, or C, as specified (see 6.2).

5.2.1 Level A. Cylinders, packaged in accordance with 5.1, shall be individually packed in boxes conforming to any one of the following specifications at the option of the contractor:

Specifications	Class or type
PPP-B-636	Class weather-resistant
PPP-B-640	Class 2

Cushioning, blocking, and bracing in accordance with MIL-STD-1186 shall be required. All center and edge seams and the manufacturer's joint shall be sealed and waterproofed with pressure-sensitive tape in accordance with the applicable box specification or appendix thereto. Shipping containers shall be closed and reinforced in accordance with the applicable box specification or appendix thereto, except that reinforcement shall be accomplished using filament-reinforced, pressure-sensitive tape in accordance with the appendix to the box specification.

5.2.2 Level B. Cylinders, packaged in accordance with 5.1 shall be individually packed in boxes conforming to any one of the following specifications at the option of the contractor:

Specifications	Class or type
PPP-B-636	Class domestic
PPP-B-640	Class 1

Cushioning, blocking, and bracing in accordance with MIL-STD-1186 shall be required. Shipping containers shall be closed in accordance with the applicable box specification.

5.2.3 Level C. Packing shall be accomplished in a manner which will insure acceptance by common carrier, at lowest rate, and will afford protection against physical or mechanical damage during direct shipment from the supply source to the using activity for early installation. The shipping containers or method of packing shall conform to the Uniform Freight Classification Rules and Regulations or other carrier regulations applicable to the mode of transportation. When it meets these requirements, the manufacturer's commercial practice may be utilized.

5.3 Use of polystyrene (loose-fill) material.

5.3.1 For domestic shipment and early equipment installation and level C packaging and packing. Unless otherwise approved by the procuring activity (see 6.2), use of polystyrene (loose-fill) material for domestic shipment and early equipment installation and level C packaging and packing applications such as cushioning, filler and dunnage is prohibited. When approved, unit packages and containers (interior and exterior) shall be marked and labelled as follows:

"CAUTION

Contents cushioned etc with polystyrene (loose-fill) material.
Not to be taken aboard ship.
Remove and discard loose-fill material before shipboard storage.
If required, recushion with cellulosic material bound fiber, fiberboard or transparent flexible cellular material."

5.3.2 For level A packaging and level A and B packing. Use of polystyrene (loose-fill) material is prohibited for level A packaging and level A and B packing applications such as cushioning, filler and dunnage.

5.4 Palletization. When specified (see 6.2), shipping containers shall be palletized for shipment in accordance with MIL-STD-147.

5.5 Marking. In addition to any special marking required by the contract or order (see 6.2), unit packages, intermediate packages, shipping containers and palletized loads shall be marked in accordance with MIL-STD-129.

6. NOTES

6.1 Intended use. The cylinders covered by this specification are intended for use in demand type, self-contained underwater breathing apparatus.

6.2 Ordering data. Procurement documents should specify the following:

(a) Title, number and date of this specification.
(b) Level of packaging (see 5.1).
(c) Level of packing (see 5.2).
(d) If use of polystyrene is permitted (see 5.3.1).
(e) Palletization for shipment, when required (see 5.4).
(f) Special markings, when required (see 5.5).

Preparing activity:
Navy - SH
(Project 4220-N126)

SPECIFICATION ANALYSIS SHEET

Form Approved
Budget Bureau No. 119-R004

INSTRUCTIONS

This sheet is to be filled out by personnel either Government or contractor, involved in the use of the specification in procurement of products for ultimate use by the Department of Defense. This sheet is provided for obtaining information on the use of this specification which will insure that suitable products can be procured with a minimum amount of delay and at the least cost. Comments and the return of this form will be appreciated. Fold on lines on reverse side, staple in corner, and send to preparing activity *(as indicated on reverse hereof)*.

SPECIFICATION

ORGANIZATION *(Of submitter)*

CITY AND STATE

CONTRACT NO.

QUANTITY OF ITEMS PROCURED

DOLLAR AMOUNT
$

MATERIAL PROCURED UNDER A

☐ DIRECT GOVERNMENT CONTRACT ☐ SUBCONTRACT

1. HAS ANY PART OF THE SPECIFICATION CREATED PROBLEMS OR REQUIRED INTERPRETATION IN PROCUREMENT USE?

A. GIVE PARAGRAPH NUMBER AND WORDING.

B. RECOMMENDATIONS FOR CORRECTING THE DEFICIENCIES.

2. COMMENTS ON ANY SPECIFICATION REQUIREMENT CONSIDERED TOO RIGID

3. IS THE SPECIFICATION RESTRICTIVE?

☐ YES ☐ NO IF "YES", IN WHAT WAY?

4. REMARKS *(Attach any pertinent data which may be of use in improving this specification. If there are additional papers, attach to form and place both in an envelope addressed to preparing activity)*

SUBMITTED BY *(Printed or typed name and activity)*

DATE

DD FORM 1 APR 63 1426 REPLACES NAVSHIPS FORM 4863, WHICH IS OBSOLETE 610555
(NAVSHIPS OVPRT 12-66)

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APPENDIX C

PRESSURE-VOLUME PLOTS FOR RUPTURED TEST CYLINDERS

APPENDIX C

PRESSURE-VOLUME PLOTS FOR RUPTURED TEST CYLINDERS

Figures C-1 through C-9 show the plots of pressure versus the amount of water added to the pressurizing water for the ruptured test cylinders. The rupture pressures for each cylinder are shown on the plots.

To provide instrumentation and adequate safety for the test personnel, it was necessary to have a considerable length of piping in the system. Because of the piping and because of the compressibility of water, the volume of water added was not a measure of the expansion of each cylinder. However, the units of water added were carefully measured, and the plots are believed to show the yield and rupture pressures of the cylinders with good accuracy. The yield pressures, also shown, were found by determining the 0.4 percent volumetric offset for each plot*. These yield pressures were used to calculate the apparent yield stress for each cylinder using Equation (1) (see Table 12). The 0.4 percent volumetric offset yield stress was used because this corresponds roughly to a 0.2 percent yield stress in a uniaxial tensile test as shown in pages C-11 to C-13.

The total amount of water added to each cylinder was useful for indicating the relative amounts of total expansion experienced by the cylinders. Thus, an intermediate amount of water was added to Cylinder 11, the most water was added to Cylinder 12, and the least water was added to Cylinder 13. These values were in general agreement with the circumferential expansion of the cylinders at rupture as determined by the fracture-edge to fracture-edge measurements. For Cylinders 11, 12, and 13, these expansions were 3.6 percent, 6.2 percent, and 2.8 percent, respectively.

---

* Note: a leak in the pressurizing system prevented determination of the yield pressure for Cylinder 34.

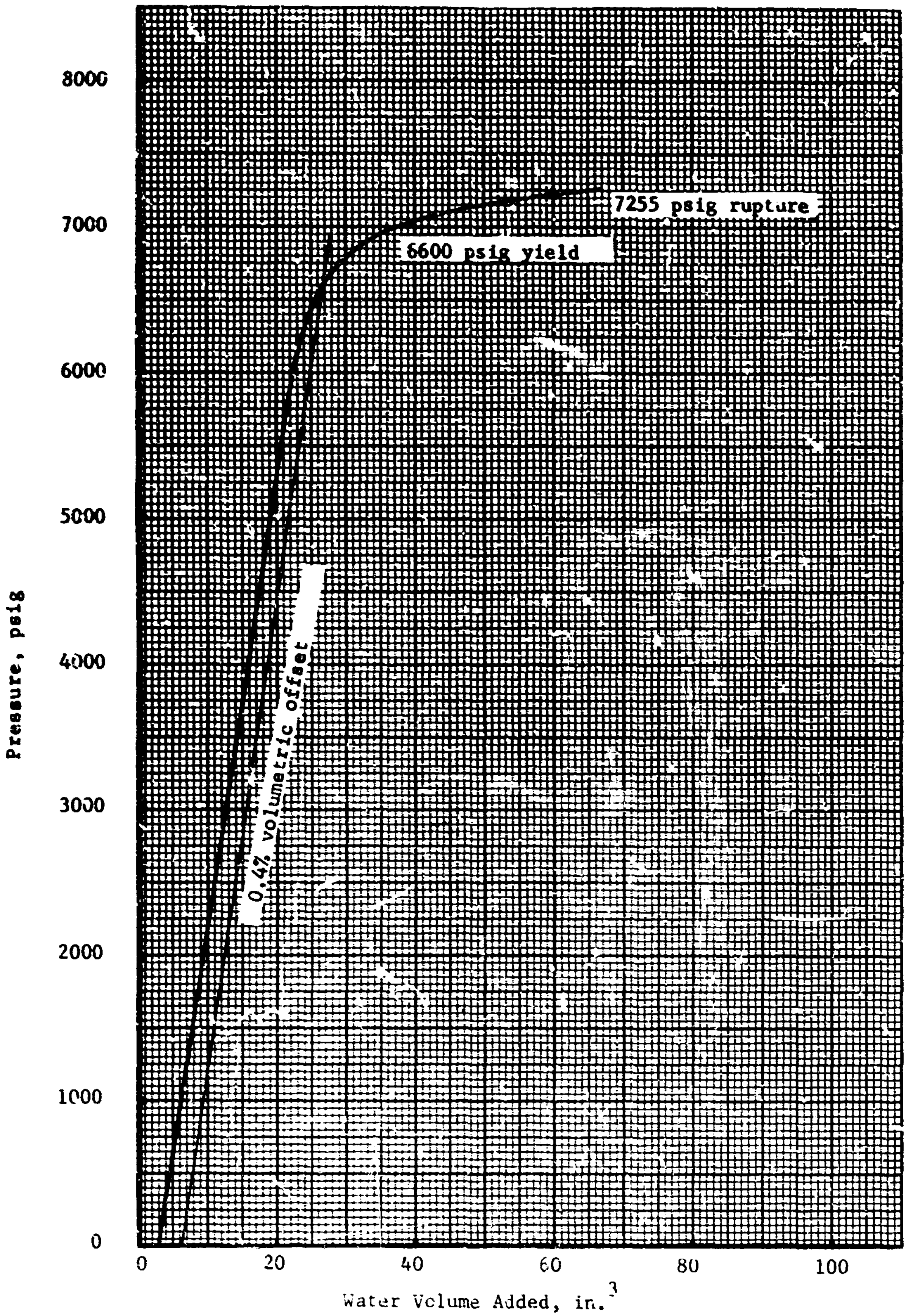

FIGURE C-1. PRESSURE-VOLUME PLOT FOR THE RUPTURE OF ALUMINUM CYLINDER 11

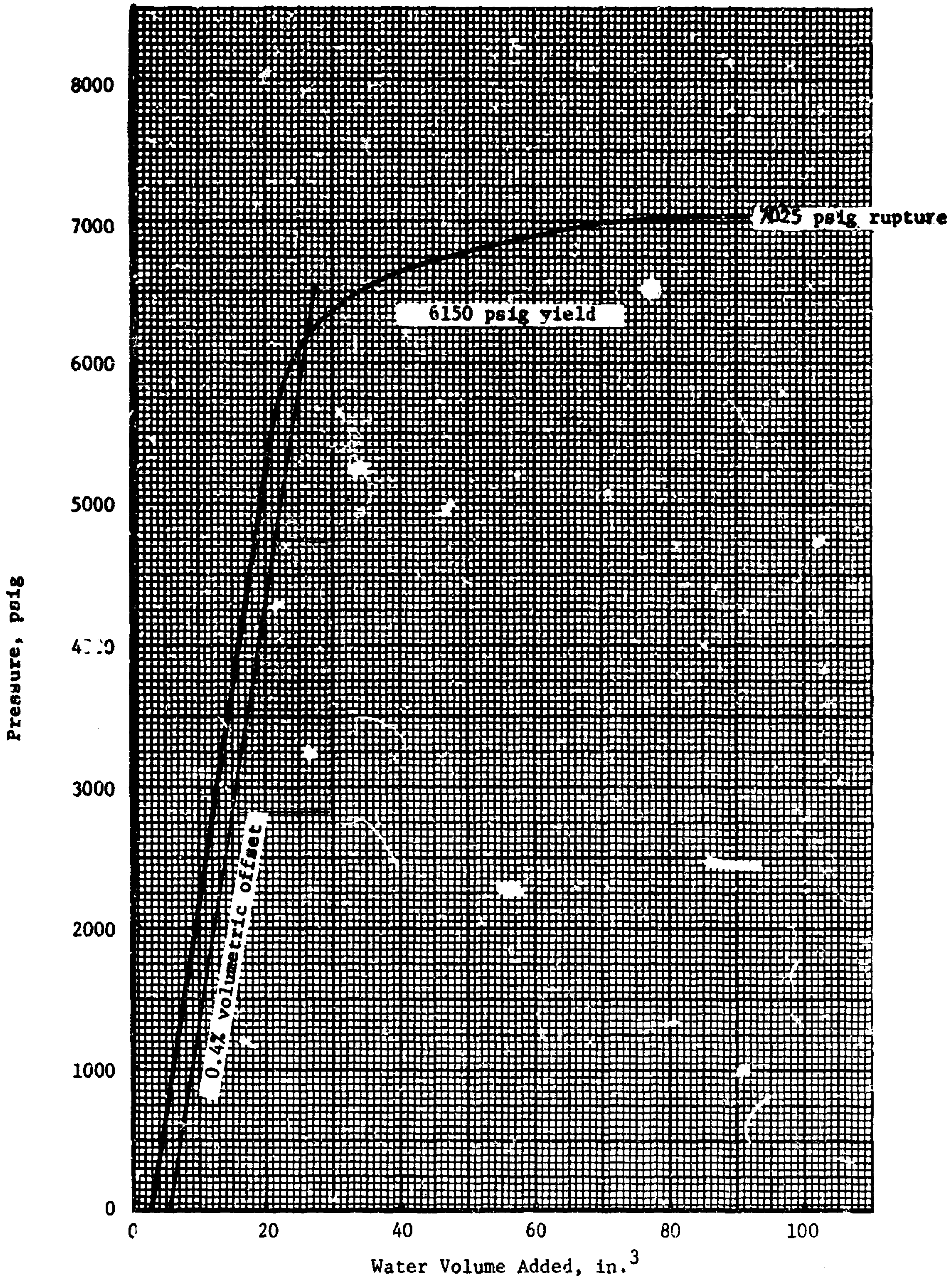

FIGURE C-2. PRESSURE-VOLUME PLOT FOR THE RUPTURE OF ALUMINUM CYLINDER 12

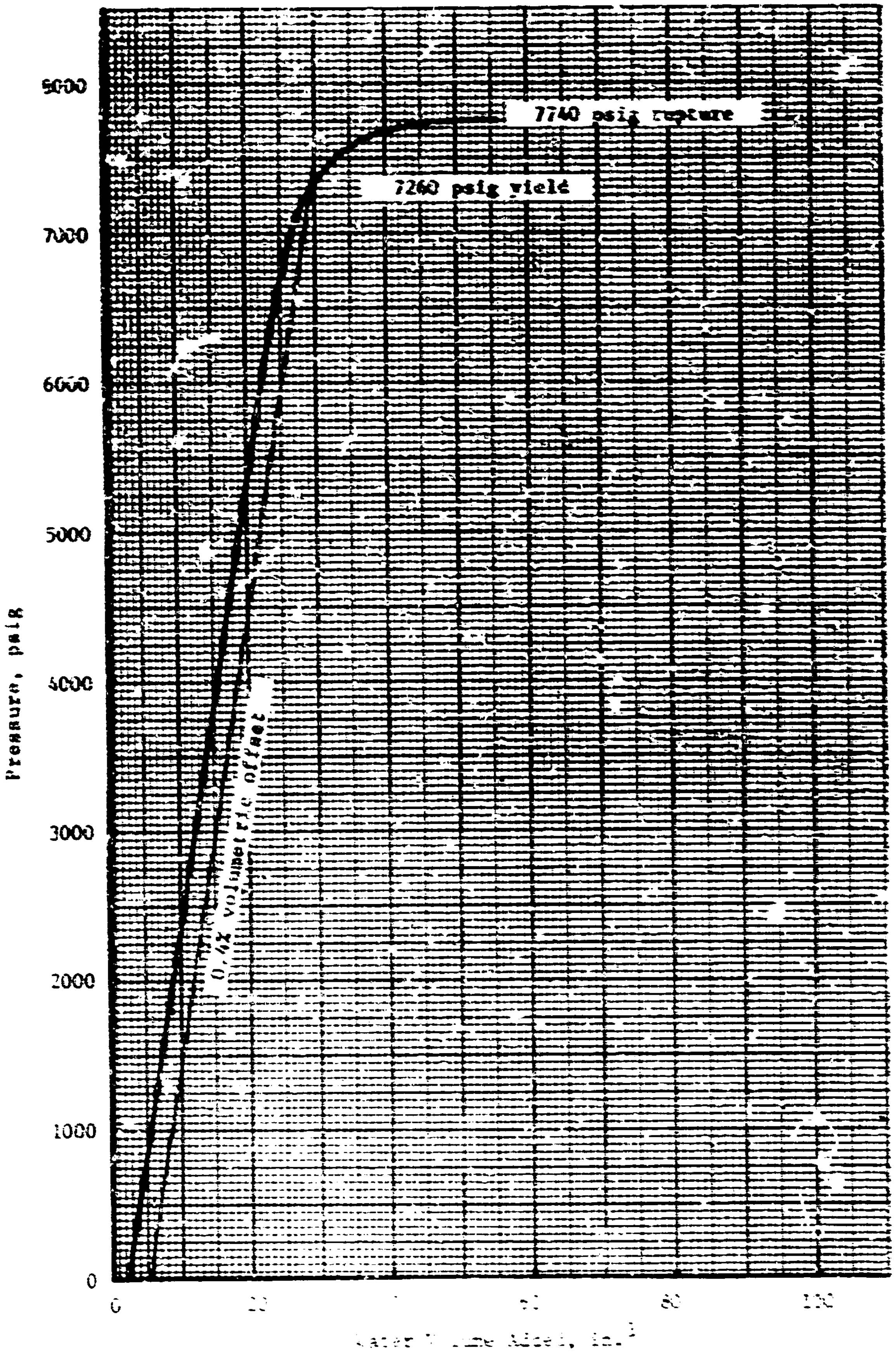

FIGURE C-3. PRESSURE-VOLUME PLOT FOR THE FAILURE OF ALUMINUM CYLINDER 13

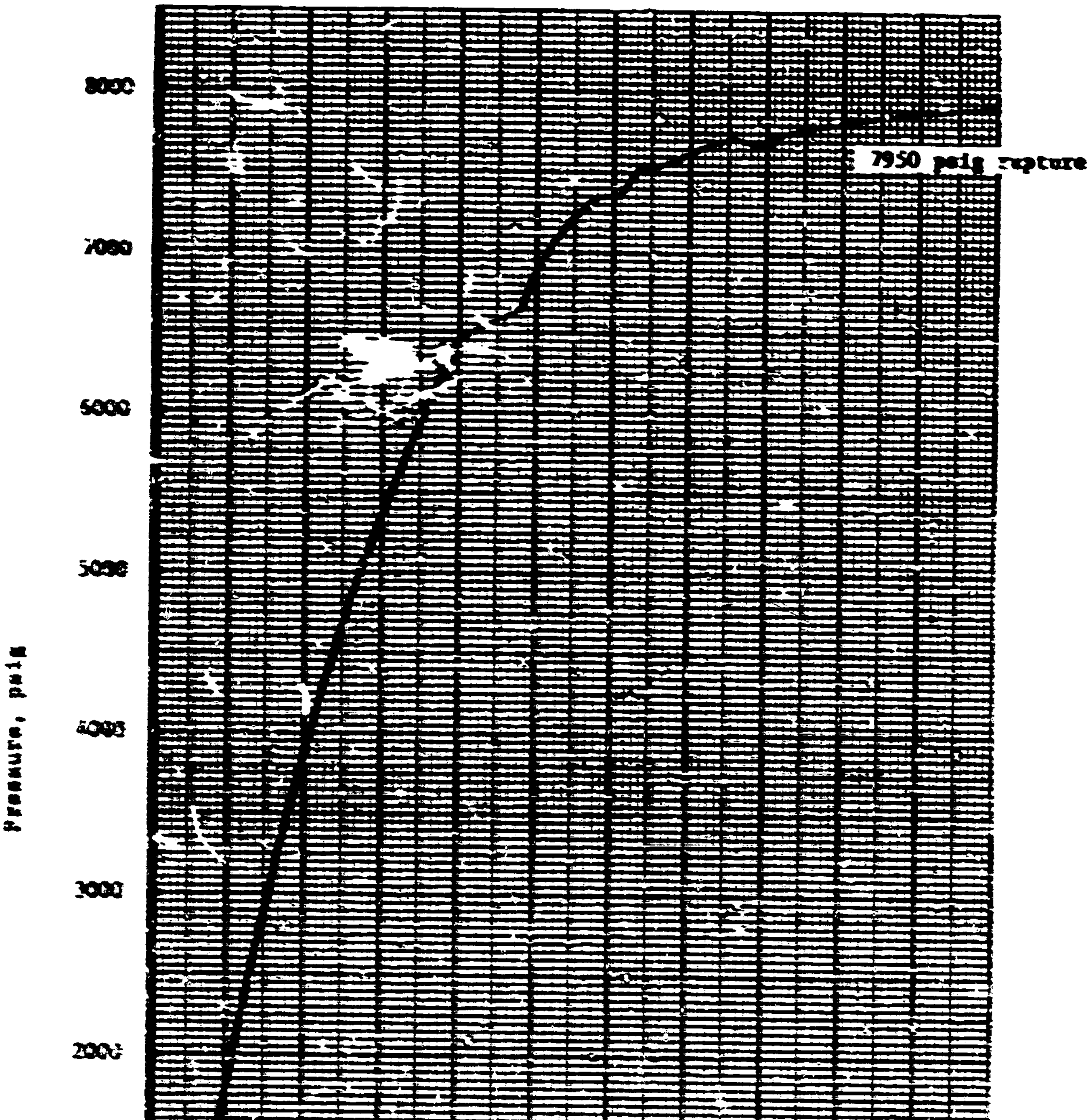

FIGURE C-4. PRESSURE-VOLUME PLOT FOR THE RUPTURE OF ALUMINUM CYLINDER 3L

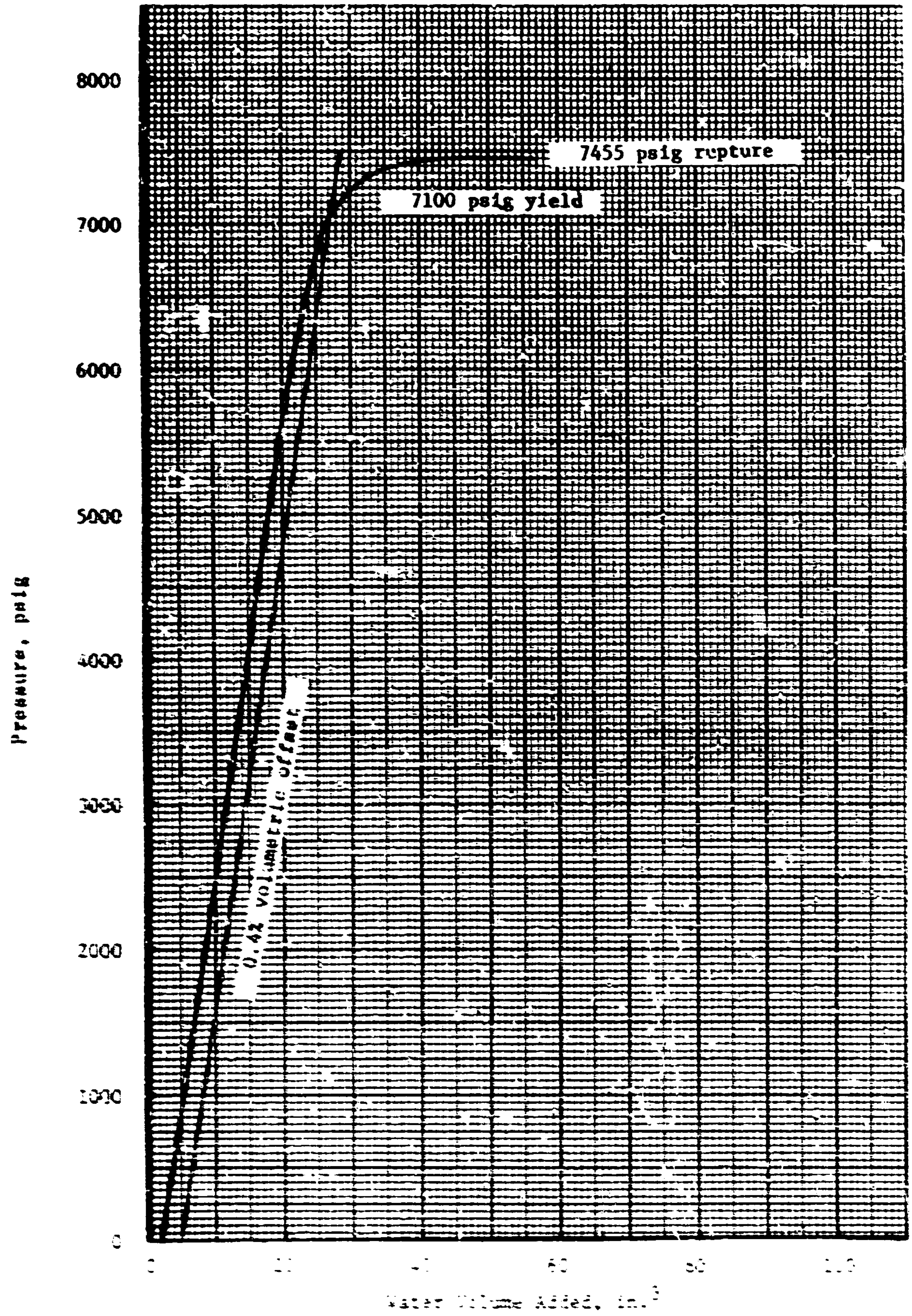

FIGURE C-5. PRESSURE-VOLUME PLOT FOR THE RUPTURE OF ALUMINUM CYLINDER

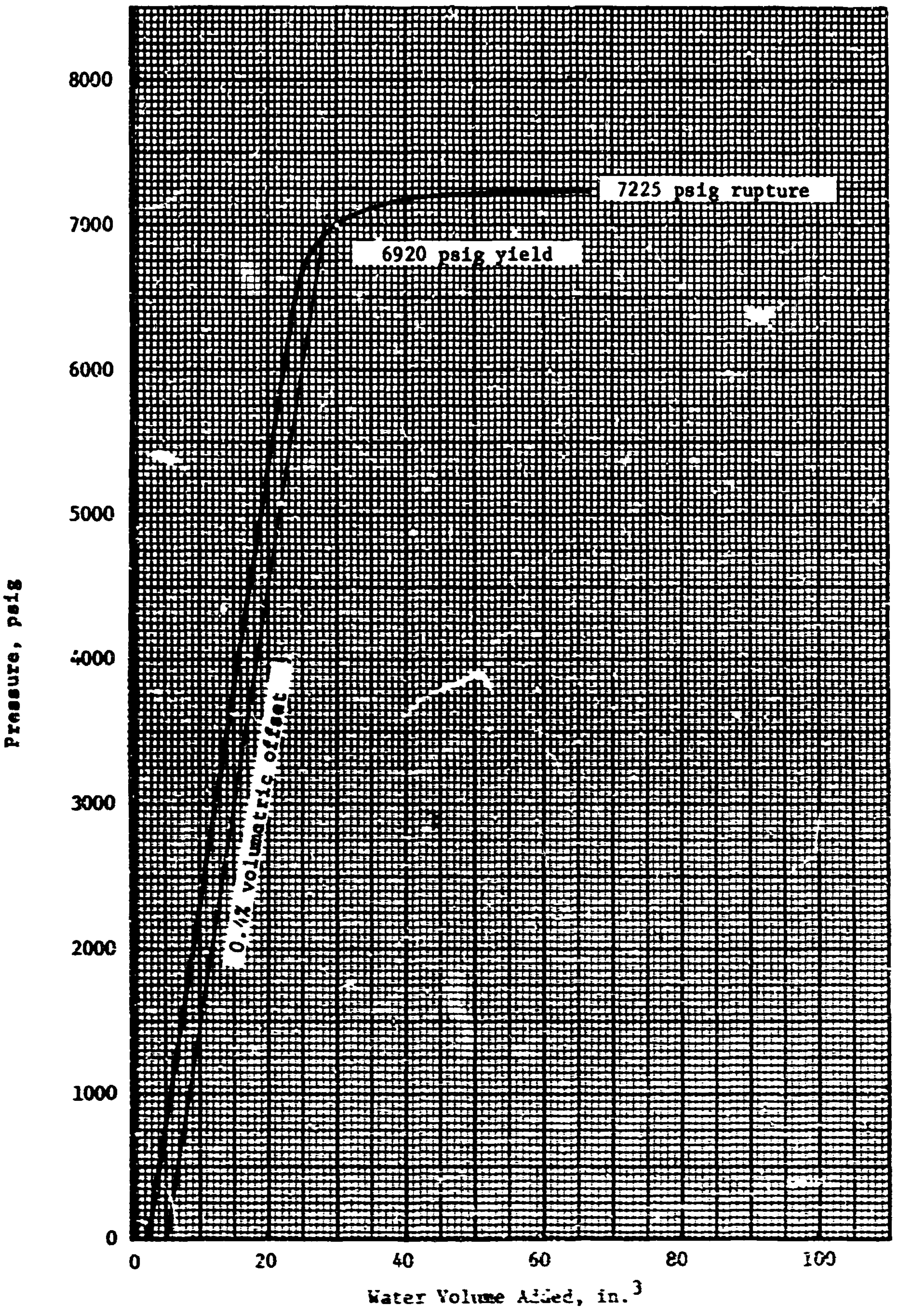

FIGURE C-6. PRESSURE-VOLUME PLOT FOR THE RUPTURE OF ALUMINUM CYLINDER 64

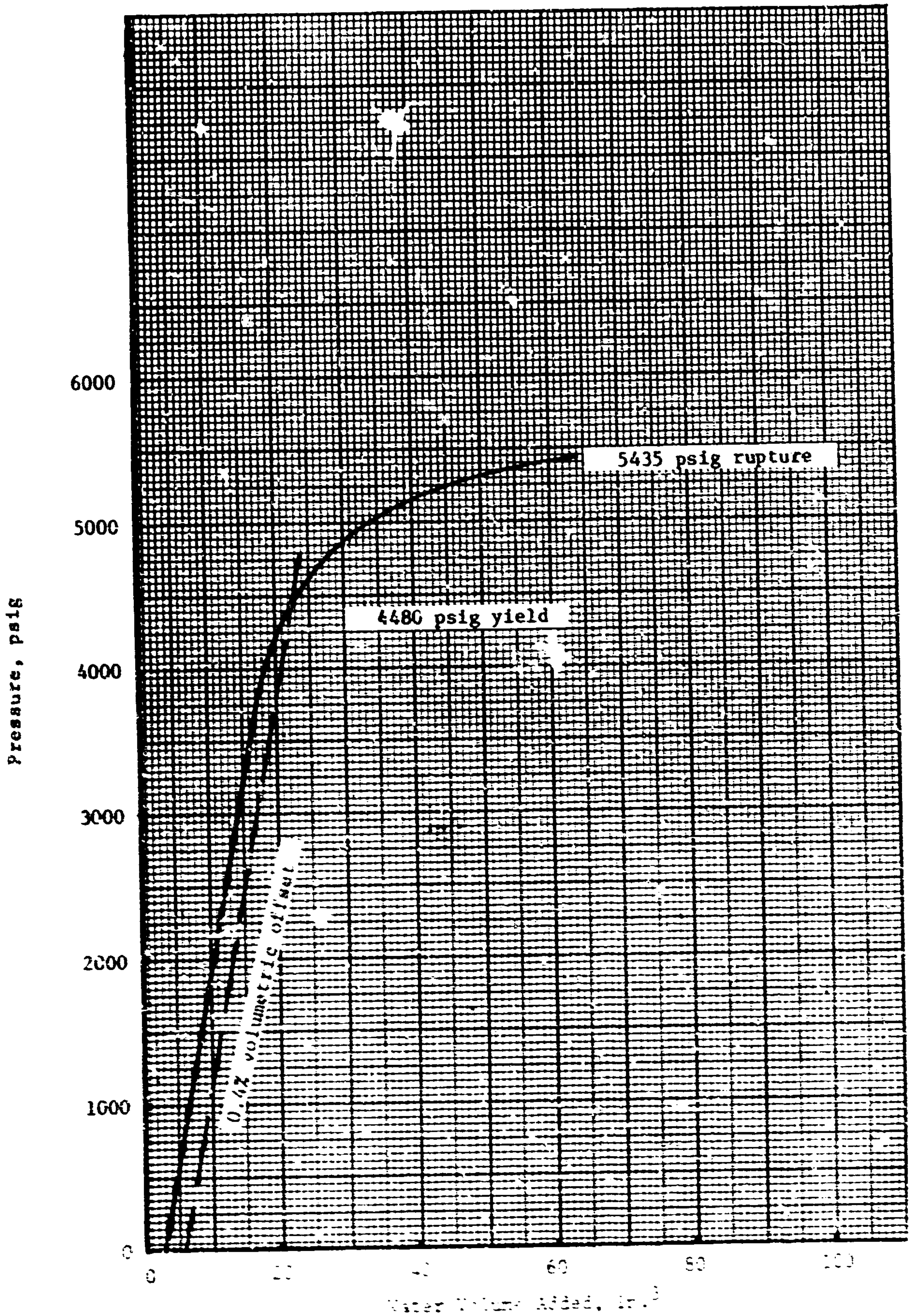

FIGURE C-7. PRESSURE-VOLUME PLOT FOR THE RUPTURE OF STEEL CYLINDER 7S

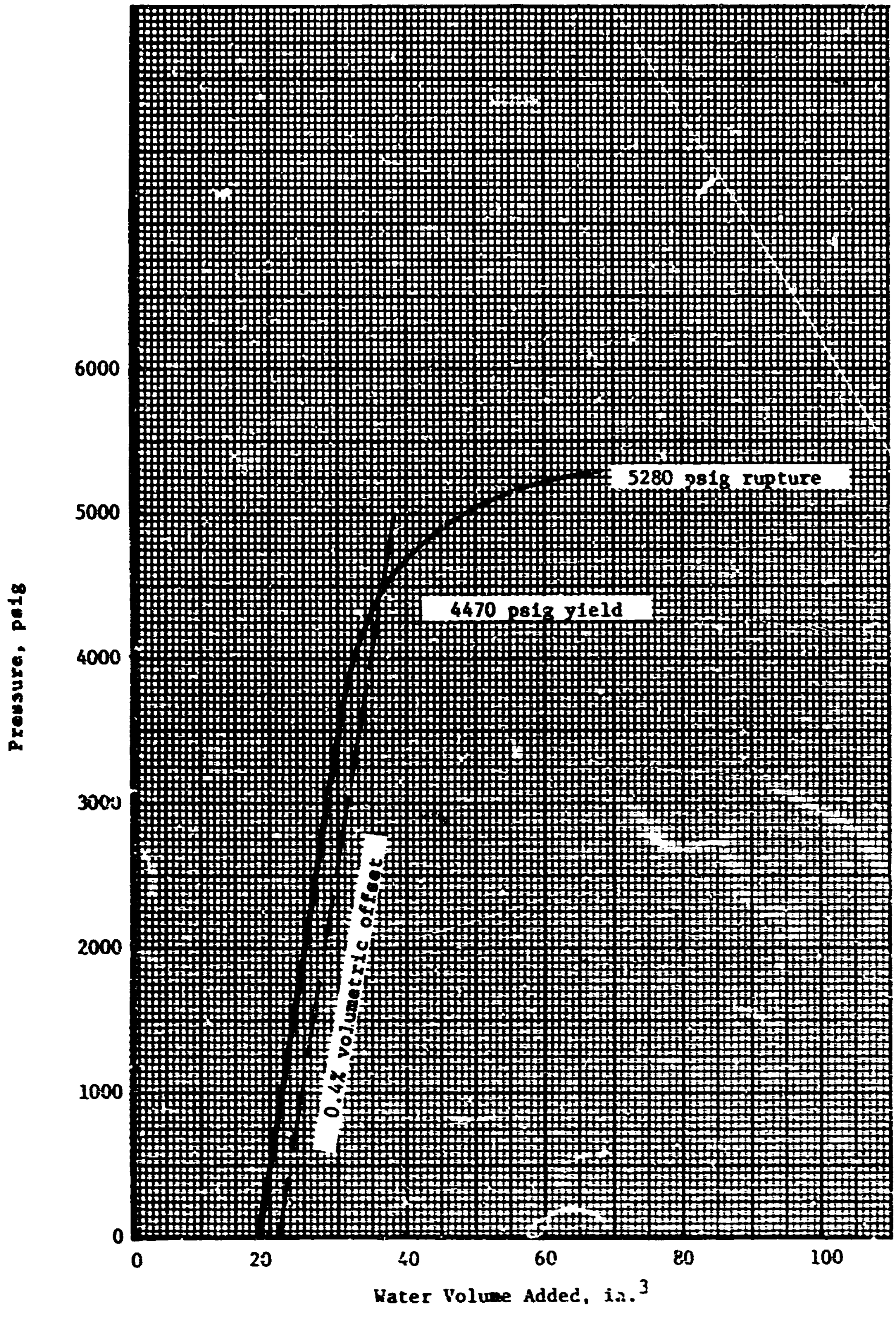

FIGURE C-8. PRESSURE-VOLUME PLOT FOR THE RUPTURE OF STEEL CYLINDER 79

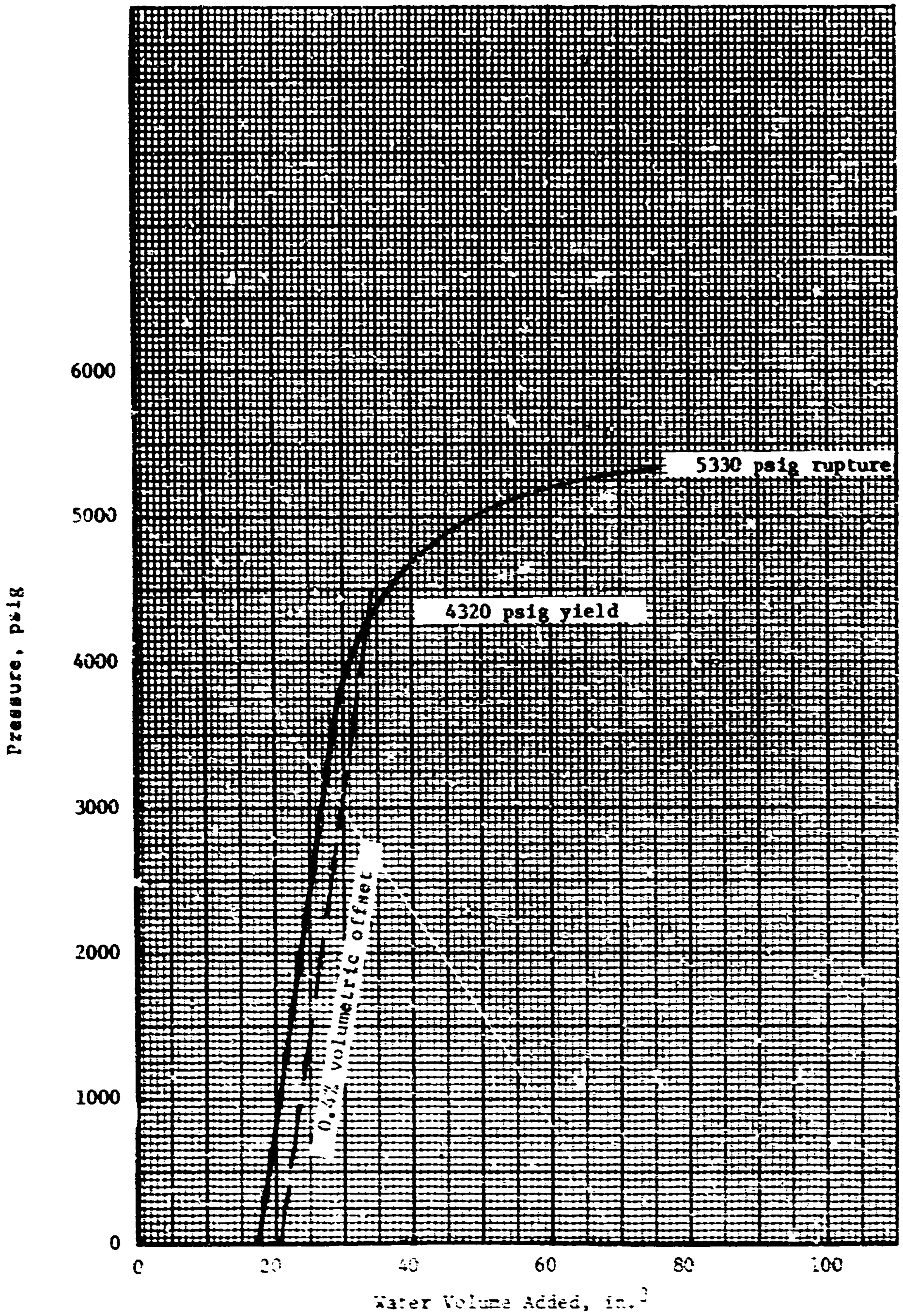

FIGURE C-9. PRESSURE-VOLUME PLOT FOR THE RUPTURE OF STEEL CYLINDER 80

Relationship Between Volume Change and Circumferential Strain for a Pressure Vessel

C_{io} = inside original circumference, in. = $2\pi r_{io}$

r_{io} = inside original radium

C_{if} = inside final circumference, in. = $2\pi r_{if} = C_{io}(1 + \epsilon_c)$

ϵ_c = circumferential strain = $\frac{1}{E}(\sigma_c - \nu\sigma_L)$

ϵ_L = longitudinal strain = $\frac{1}{E}(\sigma_L - \nu\sigma_c)$

σ_c = Circumferential stress, psi

σ_L = longitudinal stress, psi

V_o = original vol., in.^{3} ℓ_f = final length = $\ell_c(1 + \epsilon_L)$, in.

V_f = final vol., in.^{3} ℓ_o = original length, in.

The volume change is:

$$\Delta V = V_f - V_o$$

$$= \pi\left[(r_{if})^2\ell_f - (r_{io})^2\ell_o\right] \quad \text{(assuming the increase in volume due to decrease in wall thickness is negligible)} \qquad (1)$$

and

$$r_{if} = \frac{C_{if}}{2\pi} = \frac{C_{io}(1 + \epsilon_c)}{2\pi} = r_{io}(1 + \epsilon_c)$$

$$r_{if} = r_{io}(1 + \epsilon_c)\ . \qquad (2)$$

Also

$$\ell_f = \ell_o\,(1 + \epsilon_L) \quad ,$$

since

$$\sigma_L = \sigma_c/2 \text{ because } \sigma_c = \frac{Pr_i}{t}\ , \ \sigma_L = \frac{Pr_i}{2t}$$

$$\epsilon_c = \frac{1}{E}\,(\sigma_c - 1/3\ \frac{\sigma_c}{2}) = \frac{5/6\sigma_c}{E}$$

$$\epsilon_L = \frac{1}{E}\,(\frac{\sigma_c}{2} - 1/3\ \sigma_c\ ) = \frac{1/6\sigma_c}{E}$$

$$\frac{\epsilon_c}{\epsilon_L} = \frac{5/6}{1/6} \quad \text{or } \epsilon_L = 0.20\ \epsilon_c\ .$$

Thus $$\ell_f = \ell_o\ (1 + 0.20\ \epsilon_c)\ . \qquad (3)$$

Substituting (2) and (3) into (1)

$$\Delta V = \pi\left[r_{io}^{\ 2}\ (1 + \epsilon_c)^2\ \ell_o\ (1 + 0.20\ \epsilon_c) - r_{io}^{\ 2}\ \ell_o\right]\ .$$

Expanding terms

$$\Delta V = \pi\left[\ r_{io}^{\ 2}\ \ell_o\ \ (2.20\ \epsilon_c + 1.40\ \epsilon_c^{\ 2} + 0.20\ \epsilon_c^{\ 3})\right]\ .$$

Since

$$V_o = \pi r_{io}^{\ 2}\ell_o$$

and

$$\epsilon_c^{\ 3} << \epsilon_c^{\ 2} << \epsilon_c\ ,$$

the higher order terms can be neglected.

Therefore, $$\frac{\Delta V}{V} = 2.20\ \epsilon_c \ .$$

According to the above analysis, a circumferential strain of 0.2 percent is equal to a $\frac{\Delta V}{V}$ of (2.20)(0.20) = 0.44. Thus a 0.2 percent offset yield stress in a tensile test is roughly equivalent to 0.4 percent volumetric offset yield stress.

APPENDIX D

MANUFACTURING CERTIFICATION FOR THREE DOT 3AA 2250 STEEL SCUBA CYLINDERS

D-1

F-4HP
P.S.T. Order No. **87187** Milwaukee, Wis. 53214
STEEL GAS CYLINDERS **July 3, 19 70**

Manufactured for **Battelle Memorial Institute**
Columbus Laboratories
Location at **Columbus, Ohio 43201**

Manufactured by Pressed Steel Tank Co., Inc.

Location at Milwaukee, Wis. 53214

Consigned to **Battelle Memorial Institute**
Columbus Laboratories
Location at **Columbus, Ohio 43201**

Quantity **3** Size **6.81** inches outside diameter by **25** inches long.

Marks stamped into the shoulder of the cylinder are: (Rep. **723** cu. in.)

Specifications DOT **3AA2250**

OTHER MARKS

Serial Nos. **80375L** to **80377L** incl.

Inspectors mark **Ⓛ**

Identifying symbol (registered) **PST**

Test date **6-70+**

Tare weights (yes or no) **No**

Cylinders marked with a plus (+) sign signify compliance with paragraphs 173.302(c)(2), (3) & (4) of the Department of Transportation Regulations. (Title 49 of the Code of Federal Regulations.) Thus, they can be charged to a pressure 10 percent in excess of their marked service pressure. This excess charging is permissible only if the gas contained is not liquefied, dissolved, poisonous, or flammable. Cylinders having this excess charge must be equipped with frangible disc safety relief devices (without fusible metal backing) having a bursting pressure not exceeding the minimum prescribed test pressure.

These cylinders were made by process of hot and cold cupping and cold drawing to a seamless shell, the open end of which is necked by spinning.

The material used was identified by the following heat numbers **99D 30E 33E 40E 41E 42E**

The material used was verified as to chemical analysis and record thereof is attached hereto. The heat numbers were marked on the material.

All material, such as plates, billets and seamless tubing, was inspected and each cylinder was inspected both before and after closing in the ends: All that was accepted was found free from seam cracks, laminations, and other defects which might prove injurious to the strength of the cylinder. The processes of manufacture and heat treatment of cylinders were supervised and found to be efficient and satisfactory.

The cylinder walls were measured and the minimum thickness noted was **.156** inch. The outside diameter determined by a close approximation to be **6.812** inches. The wall stress was calculated to be **69725** pounds per square inch under an internal pressure of **3750** pounds per square inch.

Hydrostatic tests, flattening tests, tensile tests of material, and other tests as prescribed in specification No. **3AA** were made in the presence of the inspector and all material and cylinders accepted were found to be in compliance with the requirement of that specification. Records thereof are attached hereto.

I hereby certify that all of these cylinders proved satisfactory in every way and comply with the requirements of the DEPARTMENT OF TRANSPORTATION SPECIFICATIONS NO. **3AA** Except as noted.

EXCEPTIONS:

D. O. T. Inspection made by
T. H. Cochrane Laboratories
Milwaukee, Wis.

PRESSED STEEL TANK CO., INC.
Manufacturer
By R. F. Spangenberg

Sign by Peter A. Harris
Inspector

F-84R

Milwaukee, Wis. 53214 July 3, 1970

RECORD OF CHEMICAL ANALYSIS OF STEEL FOR CYLINDERS

Numbered 80375L To 80377L Inclusive.

Size 6.81 inches outside diameter by 25 inches long.

Made by Pressed Steel Tank Co., Inc., Milwaukee, Wis. 53214

For **Battelle Memorial Institute, Columbus Laboratories, Columbus, Ohio 43201**

HEAT NUMBER	CYLINDERS REPRESENTED (SERIAL NUMBERS)	CHEMICAL ANALYSIS											
		C	P	S	MN	SI	CR	MO	CB	CU	NI	AL	ZR
30E	80375L - 80377L	.30	.018	.019	.49	.29	.88	.18					
33E		.29	.017	.020	.52	.25	.87	.19					
40E		.30	.014	.025	.60	.29	.77	.20					
41E		.32	.015	.021	.55	.25	1.00	.18					
42E		.305	.004	.022	.51	.25	.81	.19					
99D		.31	.009	.022	.54	.29	.91	.17					

Certified by A. Marcontonio The originals of the certified MILL TEST REPORTS are in the files of the manufacturer. Chemical Analyses were made by the steel manufacturer.

RECORD OF PHYSICAL TESTS OF MATERIAL FOR CYLINDERS 4" 24T

TEST NO	CYLINDERS REPRESENTED BY TEST	YIELD POINT IN LBS. PER SQUARE INCH	TENSILE STGTH. IN LBS. PER SQUARE INCH	ELONGATION PER CENT IN INCHES	REDUCTION OF AREA PER CENT	WELD TEST		FLATTENING TEST
						TENSILE	BEND	
147660	80375L - 80377L	97,610 98,890	111,670 112,440	16.0 14.0	63.3 61.6			OK

Heat treated by a process of quenching and tempering.

D. O. T. Inspection made by
T. H. Cochrane Laboratories
Milwaukee, Wis.

Sign by A. Harris

D-3

RECORD OF HYDROSTATIC TESTS OF CYLINDERS

MILWAUKEE, WIS 53214 July 3, 19 70

NUMBER 80375L TO 80377L INCLUSIVE

SIZE 6.81 INCHES OUTSIDE DIAMETER 25 INCHES LONG

MADE BY PRESSED STEEL TANK CO., INC., MILWAUKEE, WIS. 53214

FOR **Battelle Memorial Institute, Columbus Laboratories, Columbus, Ohio 43201**

SERIAL NUMBERS OF CYLINDERS TESTED	ACTUAL TEST PRESSURE LBS PER SQ INCH	TOTAL EXPANSION C C	PERMANENT EXPANSION C C	PER CENT RATIO OF PERMANENT TO TOTAL EXPANSION	TAPE WEIGHT NOT WITH VALVE LBS	VOLUMETRIC CAPACITY CU. INCHES
80375L	3750	564	0 0	000	2712	716
80376L		558	0 0	000	279	723
80377L		558	0 0	000	2710	726

D. O. T. Inspection made by
T. H. Cochrane Laboratories
Milwaukee, Wis.

Sign by Peter A. Harris
INSPECTOR

Unclassified
Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

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Supervisor of Diving
Naval Ship Systems Command
Washington, D. C. 20360

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unclassified

2b. GROUP

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Final

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12. SPONSORING MILITARY ACTIVITY
Supervisor of Diving
Naval Ship Systems Command
U. S. Navy

13. ABSTRACT

A program was conducted to determine the cause of the corrosion that was discovered in a number of aluminum scuba cylinders, and to determine whether the rupture strength of the cylinders had been degraded by the corrosion. An examination was made of 68 corroded cylinders received from Naval facilities. Rupture experiments were conducted on new cylinders and on the most severely corroded cylinders. Detailed analyses were made of corrosion products from selected aluminum cylinders, and of corroded and uncorroded material from the ruptured cylinders. It was concluded that the corrosion in the cylinders examined had not significantly reduced the rupture strength of the cylinders. Recommendations were formulated concerning changes in manufacturing specifications, cleaning procedures, and inspection procedures to provide increased assurance that corrosion will not progress to the point of significantly degrading the rupture strength of aluminum scuba cylinders.

DD FORM 1 JAN 64 1473

Unclassified
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Scuba cylinders						
Aluminum cylinders						
Steel cylinders						
Rupture stress						
Rupture strength						
Aluminum corrosion						
Corrosion analysis						