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FATIGUE AND FRACTURE TESTS OF GAS BOTTLE MATERIAL

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A program of nondestructive inspection, mechanical tests, and fracture mechanics tests was performed on a high pressure air storage bottle. The tests were planned to provide the basis of fracture mechanics life analysis of gas bottles in their service environment. This report describes the procedures and results and gives a preliminary analysis of the results.

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We are pleased to acknowledge the work of R. S. McNeill, A. Rubin, H. R. Alford, and R. T. Abbott of Benet Weapons Laboratory, US Army ARRADCOM, in performing various tests and analyses described in this report, and P. E. Lewis of NASA Langley Research Center for overall direction and funding of the program.

INTRODUCTION

A program of nondestructive inspection, mechanical tests, and fracture mechanics tests was performed on material taken from a high pressure air storage vessel. The material is API N-80 steel, which is a low alloy quenched and tempered steel similar to ASTM A372, Grade 4, heat treated to a minimum yield strength of 80 Ksi. The tests were planned to provide the basis of fracture mechanics life analysis of gas bottles in their service environment. This report describes the test procedures and results and gives a preliminary analysis of the results.

SPECIMEN MATERIAL AND TESTS

One vessel was selected from a large high pressure air storage field by NASA Langley Research Center. Two sections about 760 mm (30 in.) long were flame-cut from the vessel and shipped to Benet Weapons Laboratory. The cylinder sections, identified as cylinder #1 and #2, were about 356 mm (14 in.) inner diameter, ID, and 406 mm (16 in.) outer diameter, OD. Visual examination showed that the ID surfaces of the cylinders were different in appearance. Cylinder #1 was a uniform dark grey in color, and cylinder #2 was mixed dark grey and tan in color and smoother to the touch. A magnetic particle inspection was performed, with the magnetic field applied so as to locate defects in planes normal to the circumferential direction. A continuous network of cracks was noted within 20 to 40 mm (1 to 2 in.) from each flame-cut end of each cylinder. No other cracks were observed. Based upon our experience with this inspection method it is estimated that a surface crack of 5 mm (0.2 in.) length along the ID in the longitudinal direction would have been detected if present.

Five types of mechanical and fracture mechanics test specimens were made from each of the cylinders. They are tension, Charpy impact, fracture toughness, K_{Ic}, fatigue crack growth rate, da/dN, and S-N fatigue life specimens. They were made from four rings of about 40 mm length (along the cylinder axis) and were located about 150 to 270 mm from one end of the cylinder section, as shown in Figure 1.

A determination of the residual stress present in the cylinder sections was made during the specimen fabrication process. After rings #1 and 2 were cut from the cylinder sections, two lines were scribed on the OD of each ring, and the change in spacing of the lines, Δd, was measured as a result of cutting through the ring wall between the lines; see Figure 2. A relation between Δd and the nominal circumferential residual stress, $\bar{\sigma}$, present at the ID of the ring before slitting can be obtained from curved beam theory[1]

$$\bar{\sigma} = \frac{-(r_2 - r_1)E\Delta d}{2\pi \, r_2(r_2 + r_1)}$$

Values of Δd measured and calculated $\bar{\sigma}$, using E = 207,000 MPa, r_1 = 178 mm, r_2 = 203 mm, are shown in Table I. The highest of these values of residual stress, although tensile, are not of great enough magnitude to have any significant effect on the service life of the cylinders.

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[1]Timoshenko, S., Strength of Materials, Part II, D. Van Nostrand, New York, 1941, p. 68.

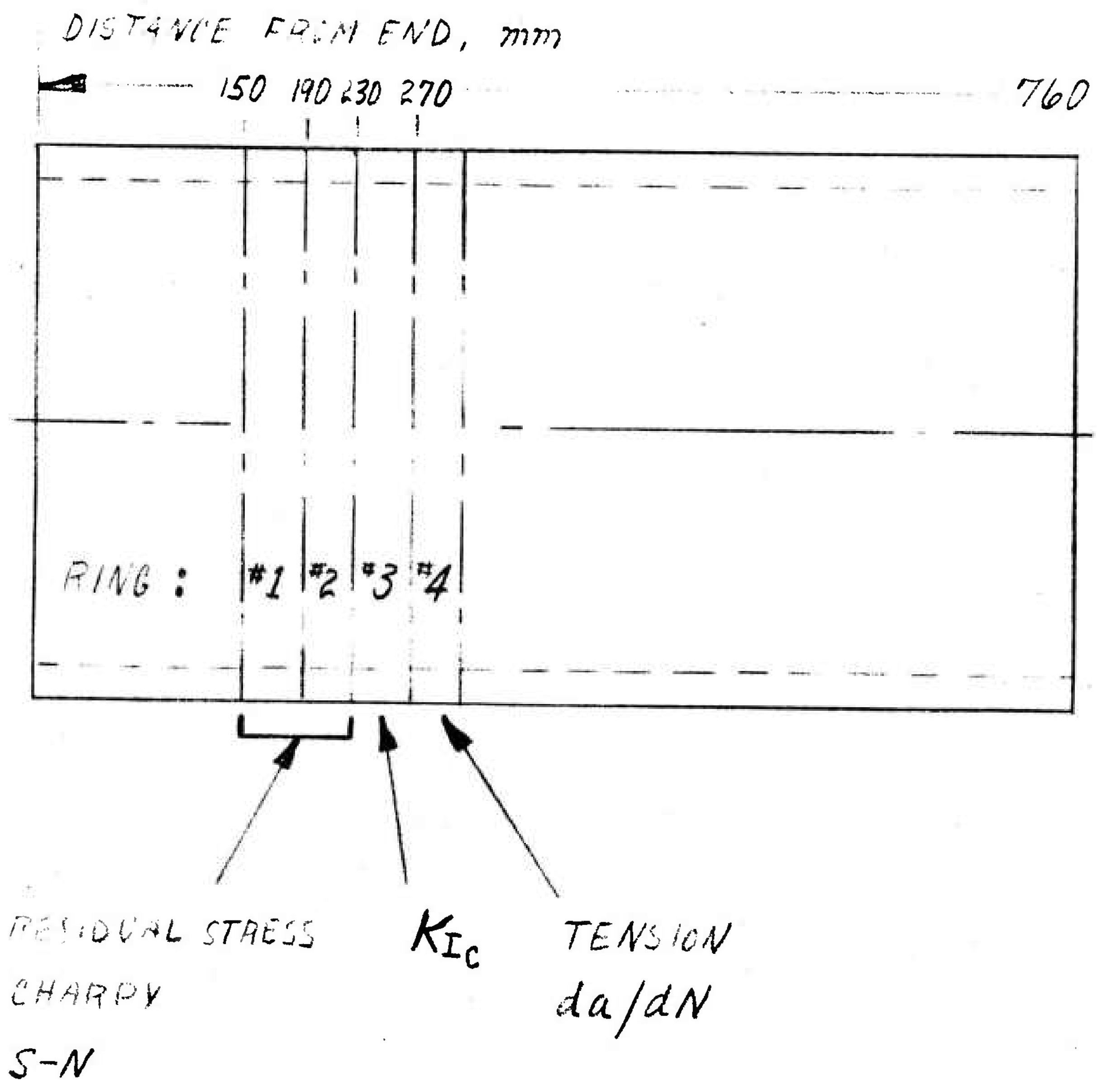

Figure 1. Test Specimen Location Along Cylinder Section.

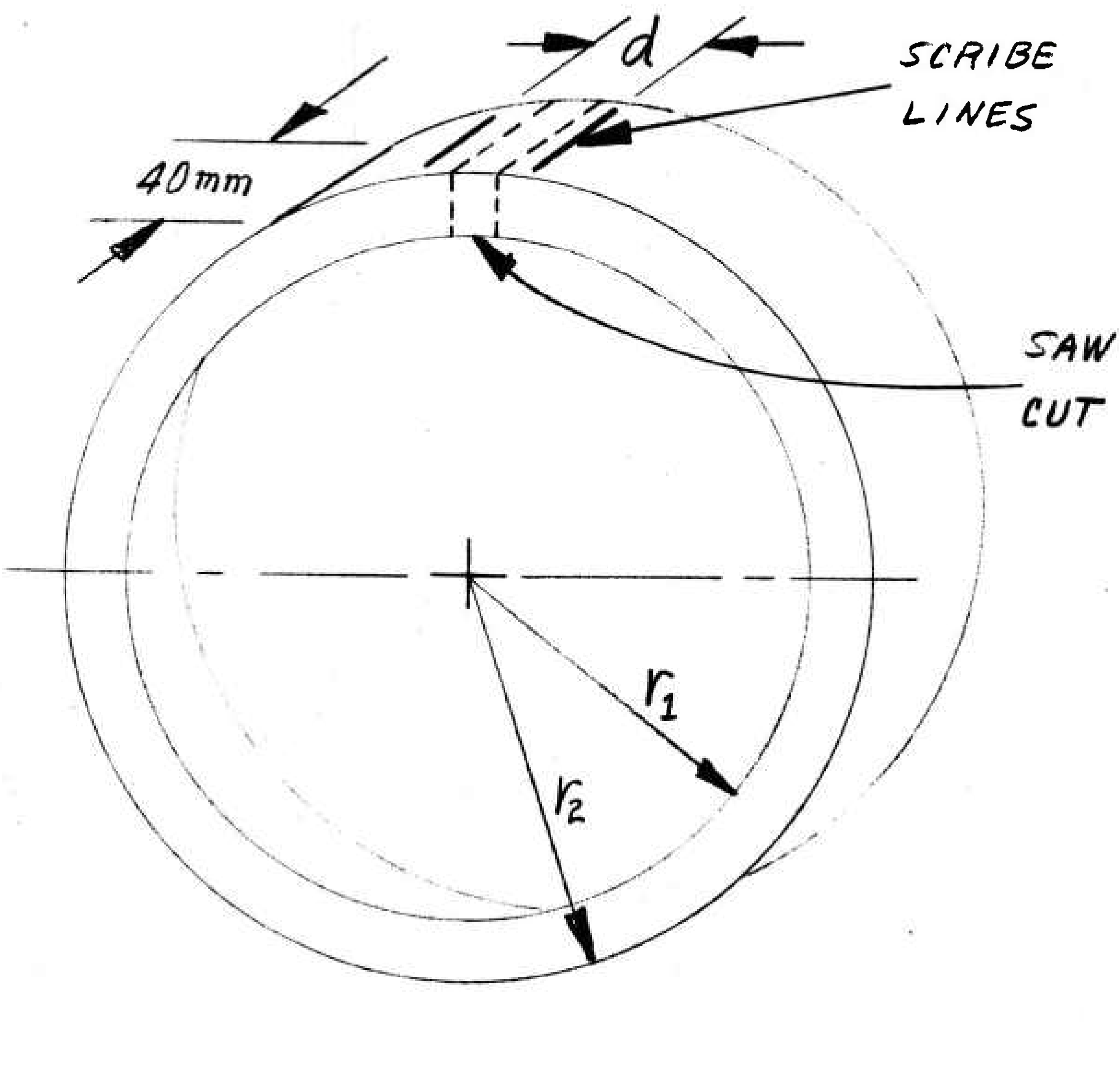

Figure 2. Slitting Method For Measuring Residual Stress.

TABLE I. CALCULATED RESIDUAL STRESS AT ID FROM SLITTING MEASUREMENTS

Specimen	Δd Due to Slitting mm	Residual Stress, $\bar{\sigma}$ MPa	(Ksi)
Cylinder #1			
Ring #1	+0.1	- 1	-0.1
Ring #2	+0.2	- 2	-0.3
Cylinder #2			
Ring #1	-1.7	+18	+2.6
Ring #2	-1.7	+18	+2.6

MECHANICAL PROPERTY TESTS

The mechanical tests performed from the cylinder material are tension tests using ASTM Method E8 and notched bar impact tests using the Charpy specimen of ASTM Method E23. The specimens for these tests were taken from mid-wall thickness of the cylinder and with the intended fracture plane normal to the circumferential direction.

The tension test specimens were 8.9 mm (0.35 in.) diameter with a 64 mm (2.5 in.) reduced section length, which is above the minimum required length (see Figure 8 of E23). Four specimens were tested at 25°C from each cylinder; results are in Table II. The specimen designation used here and for all test specimens is cylinder number, followed by ring number, followed by specimen number, so that 1-4-2, for example, refers to cylinder #1, ring #4, and specimen #2 from that ring.

TABLE II. TENSILE TEST RESULTS

Specimen Designation	Yield Strength 0.2% Offset MPa	(Ksi)	Tensile Strength MPa	(Ksi)	Elongation %	Reduction in Area %
<u>Cylinder #1</u>						
1-4-1a	643	(93.3)	869	(126)	19	45
b	643	(93.3)	869	(126)	19	44
1-4-2a	647	(93.9)	889	(129)	19	43
b	665	(96.4)	883	(128)	19	46
<u>Cylinder #2</u>						
2-4-1a	673	(97.6)	889	(129)	19	45
b	665	(96.4)	889	(129)	19	43
2-4-2a	665	(96.4)	876	(127)	19	46
b	643	(93.3)	883	(128)	19	45

The notched bar impact specimens were Charpy, Type A, (shown in Figure 4 of ASTM E23), that is with the commonly used 2 mm deep, 45°, 0.25 mm radius notch. Three specimens were tested at four temperatures from each cylinder, 24 tests total. The absorbed energy, percent shear on the fracture surface, and the lateral expansion were measured and are listed in Table III. A plot of absorbed energy versus test temperature is shown as Figure 3, which gives a measure of the ductile-to-brittle transition of Charpy energy with decreasing temperature for each cylinder. The smooth curves drawn through the mean of the three data points of each set (except excluding specimen 1-2-3) show a significant transition in Charpy energy over the temperature range of the tests.

FRACTURE MECHANICS TESTS

Three types of tests were performed: plane strain fracture toughness, K_{Ic}, using ASTM Method E399, fatigue crack growth rate, da/dN, generally following ASTM Method E647, and fatigue life tests using S-N type, full-wall-thickness, bend specimens and where possible the procedures of ASTM Method E606. The specimens for all fracture tests had the same basic contour. It was a 165 mm (6.5 in.) long segment from the cylinder wall, with the ID and OD surfaces left unmachined, see Figure 4. The K_{Ic} and da/dN specimens were notched and were loaded by 13 mm (0.5 in.) pin holes; the S-N specimens were unnotched and were loaded in three-point bending, using a 143 mm span, ℓ, between the outer load points.

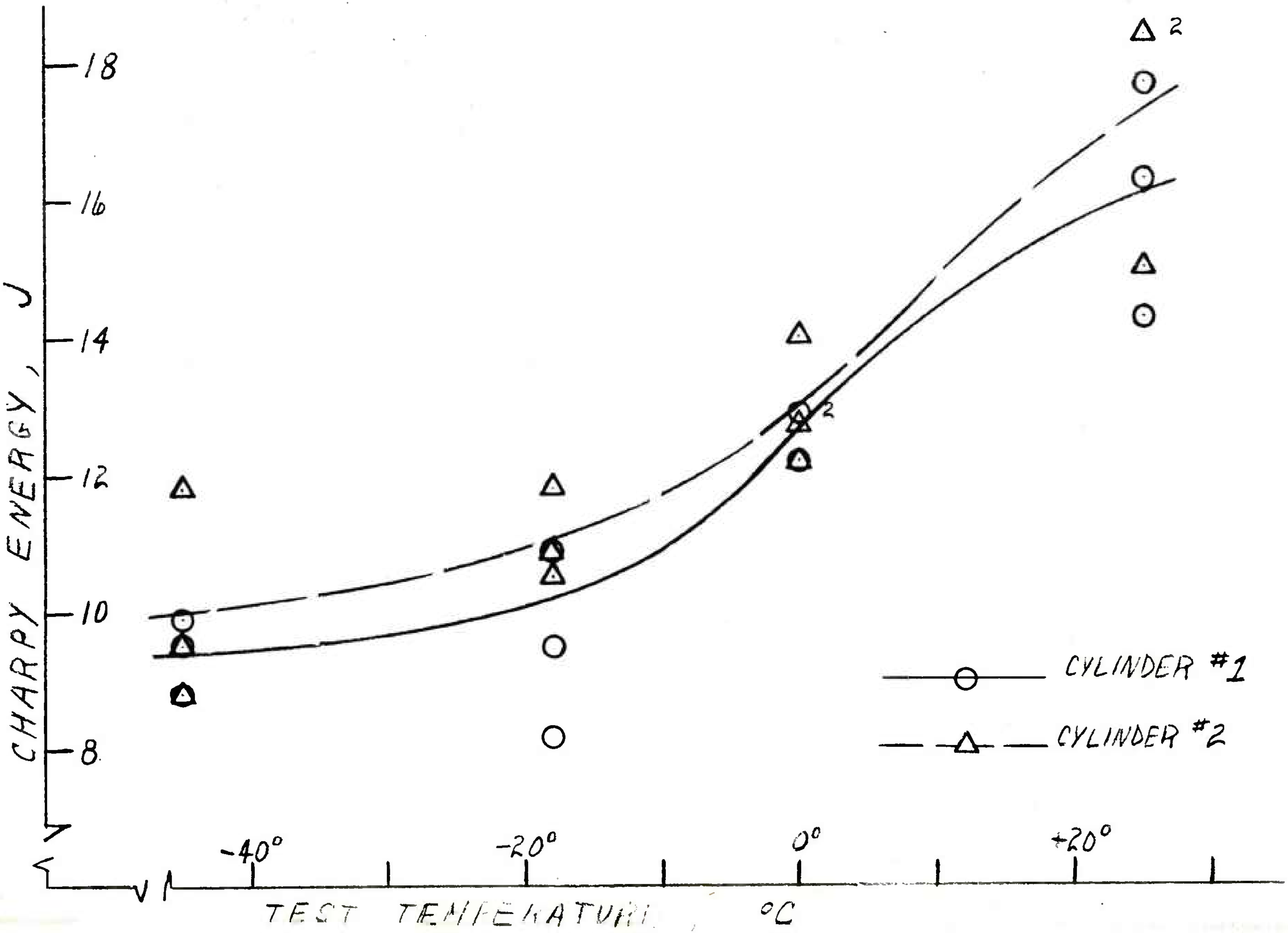

Figure 3. Charpy Energy Versus Test Temperature.

TABLE III. CHARPY IMPACT TEST RESULTS

Specimen	Temperature °C	Absorbed Energy J	(ft-lb)	Percent Shear %	Lateral Expansion mm	(in.)
1-1-1	25°	14.3	(10.5)	5	0.2	(0.007)
1-1-2	25°	17.7	(13.0)	6	0.3	(0.010)
1-1-3	25°	16.3	(12.0)	5	0.2	(0.008)
2-1-1	25°	15.0	(11.0)	5	0.2	(0.008)
2-1-2	25°	18.4	(13.5)	6	0.3	(0.012)
2-1-3	25°	18.4	(13.5)	6	0.3	(0.010)
1-1-4	0°	12.9	(9.5)	< 5	0.2	(0.006)
1-1-5	0°	12.9	(9.5)	< 5	0.2	(0.006)
1-1-6	0°	12.2	(9.0)	< 5	0.1	(0.005)
2-1-4	0°	12.2	(9.0)	< 5	0.1	(0.005)
2-1-5	0°	14.0	(10.3)	< 5	0.2	(0.006)
2-1-6	0°	12.7	(9.3)	< 5	0.2	(0.006)
1-2-1	-18°	9.5	(7.0)	< 5	0.1	(0.004)
1-2-2	-18°	10.9	(8.0)	< 5	0.1	(0.004)
1-2-3	-18°	8.2	(6.0)	< 5	0.1	(0.003)
2-2-1	-18°	10.9	(8.0)	< 5	0.1	(0.005)
2-2-2	-18°	10.5	(7.7)	< 5	0.2	(0.006)
2-2-3	-18°	11.8	(8.7)	< 5	0.1	(0.005)
1-2-4	-40°	8.8	(6.5)	< 5	0.1	(0.004)
1-2-5	-40°	9.5	(7.0)	< 5	0.1	(0.004)
1-2-6	-40°	9.9	(7.3)	< 5	0.1	(0.003)
2-2-4	-40°	8.8	(6.5)	< 5	0.1	(0.004)
2-2-5	-40°	9.5	(7.0)	< 5	0.1	(0.004)
2-2-6	-40°	11.8	(8.7)	< 5	0.1	(0.005)

The K_{Ic} test results are shown in Table IV. The only significant trend in the results was the decrease in K_{Ic} with decrease in test temperature from -1°C to -18°C. This is consistent with the transition in Charpy energy with temperature, Figure 3. Also, the larger standard deviation of K_{Ic} at the lower temperature would be expected if the lower temperature was in the range of K_{Ic} transition. All specimens were similar in fracture surface appearance and load-deflection behavior. The fracture surfaces were generally flat with 0.2 to 0.5 mm shear lips. The load-deflection plots were almost ideally elastic, that is, no plastic deformation before abrupt fracture; all failure points fell within a 1% secant offset, compared with the 5% secant offset of E399. The only significant variation from a valid K_{Ic} test was the specimen size requirement of E399, that is that crack length, a, be at least 2.5 $(K_{Ic}/\sigma_{ys})^2$. The crack length was nominally 13 mm, where as 2.5 $(100\ MPm^{1/2}/650\ MPa)^2$ equals 59 mm, using nominal K_{Ic} and σ_{ys}. Thus, the largest available specimen from the cylinder was about one quarter required size. However, because of the indications of brittle failure mentioned above, we believe that the K_{Ic} results are a good indication of the fracture toughness of the cylinder material.

TABLE IV. FRACTURE TOUGHNESS TEST RESULTS

Tested at -1°C (30°F)			Tested at -18°C (0°F)		
Specimen	K_{Ic}* MPa(m)$^{1/2}$	K_{Ic}* Ksi(in)$^{1/2}$	Specimen	K_{Ic}* MPa(m)$^{1/2}$	K_{Ic}* Ksi(in)$^{1/2}$
1-3-2	109.7	(100.1)	1-3-1	109.5	(99.9)
1-3-4	107.5	(98.1)	1-3-3	89.1	(81.3)
1-3-6	107.1	(97.7)	1-3-5	89.5	(81.7)
	Mean 108.1			Mean 96.0	
2-3-2	108.8	(99.3)	2-3-1	98.0	(89.4)
2-3-4	113.2	(103.3)	2-3-3	96.7	(88.2)
2-3-6	108.9	(99.4)	2-3-5	103.9	(94.8)
	Mean 110.3			Mean 99.5	
	Grand Mean 109.2			Grand Mean 97.8	
	St. Deviation 2.2			St. Deviation 8.0	

*Data met all requirements of E399 except for the specimen size requirement of paragraph 7.1.1.

The da/dN test results are shown in Figure 5. Three specimens were tested at 25°C with maximum loads of 5.83 KN and 8.08 KN for each cylinder; 12 specimens in all. The minimum load was always 10% of maximum load. The specimen, shown in Figure 4, is the C-shaped specimen, one of the standard specimens for K_{Ic} tests. This specimen is not standard in the da/dN test method, E647; however, the geometry and the stress and K analysis of the C-shaped specimen have been shown[2] to be similar to the compact specimen, which is standard in E647.

The average crack length, nominally 5 to 15 mm, averaged from the two sides of the specimen was plotted versus number of cycles, and slopes were taken at five or six points, converted to da/dN and plotted on log-log axes versus the range of K, ΔK, as shown in Figure 5. An "eyeball fit" straight line with a prescribed slope of three is shown, to serve as a representation of the da/dN data in a form which can be easily integrated. It is emphasized that the expressions shown are known to represent the da/dN behavior of the cylinders only within the range of data presented.

The S-N test data are shown in Table V. Two or three specimens from each cylinder were tested at 25°C with four maximum loads. The minimum fatigue load was always 10% of maximum load. The wall thickness, W, of each specimen was recorded. Shallow grooves were noted on the ID surface of most specimens, running in the longitudinal direction of the cylinder. The depth of the grooves was estimated by measuring some grooves on an optical comparitor.

---

[2]Underwood, J. H. and Kendall, D. P., "Fracture Toughness Testing Using the C-Shaped Specimen," Developments in Fracture Mechanics Test Methods Standardization, ASTM STP 632, W. F. Brown, Jr., and J. G. Kaufman, Eds., American Society for Testing and Materials, 1977, pp. 25-38.

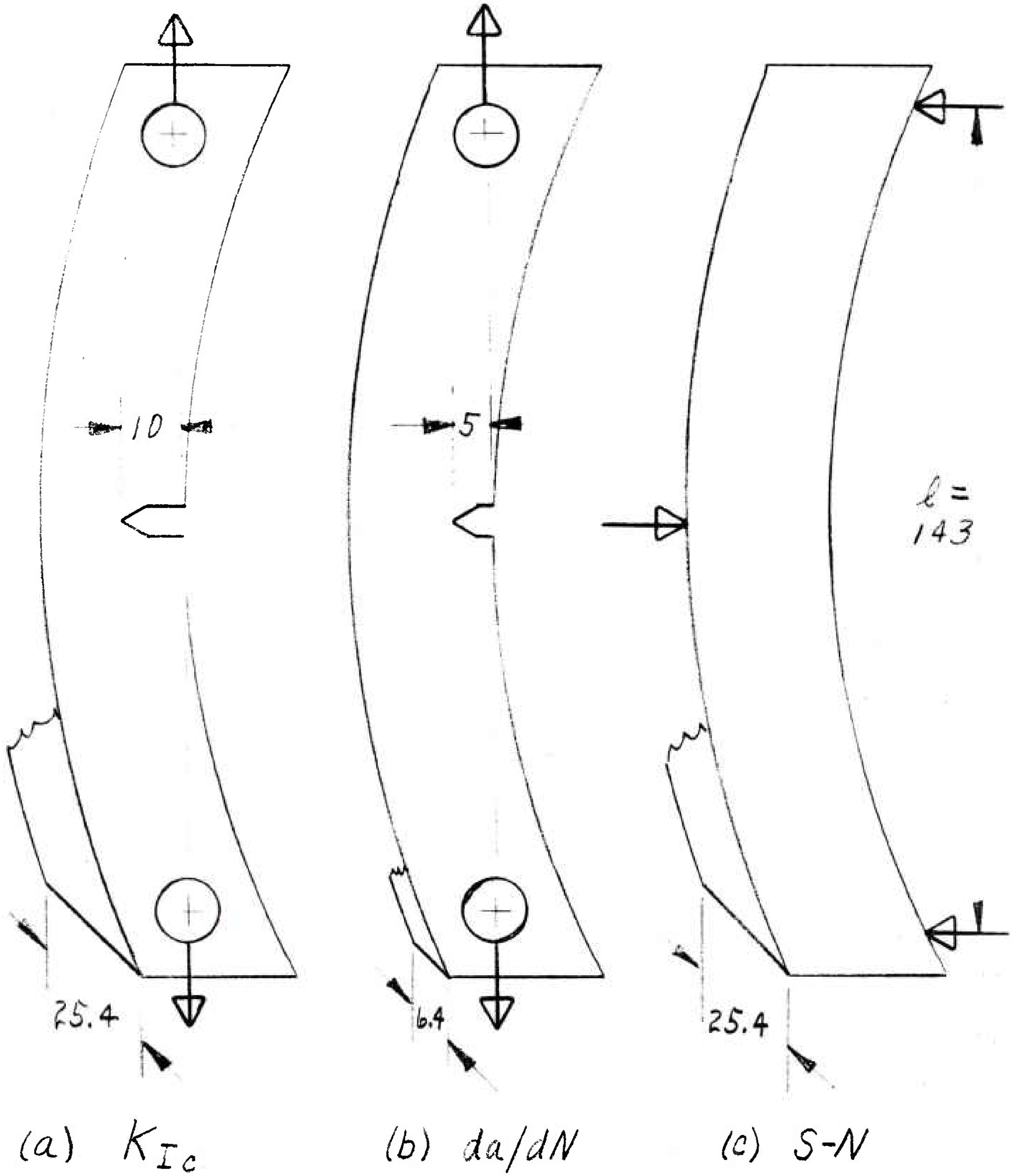

Figure 4. Fracture Mechanics Test Specimens.

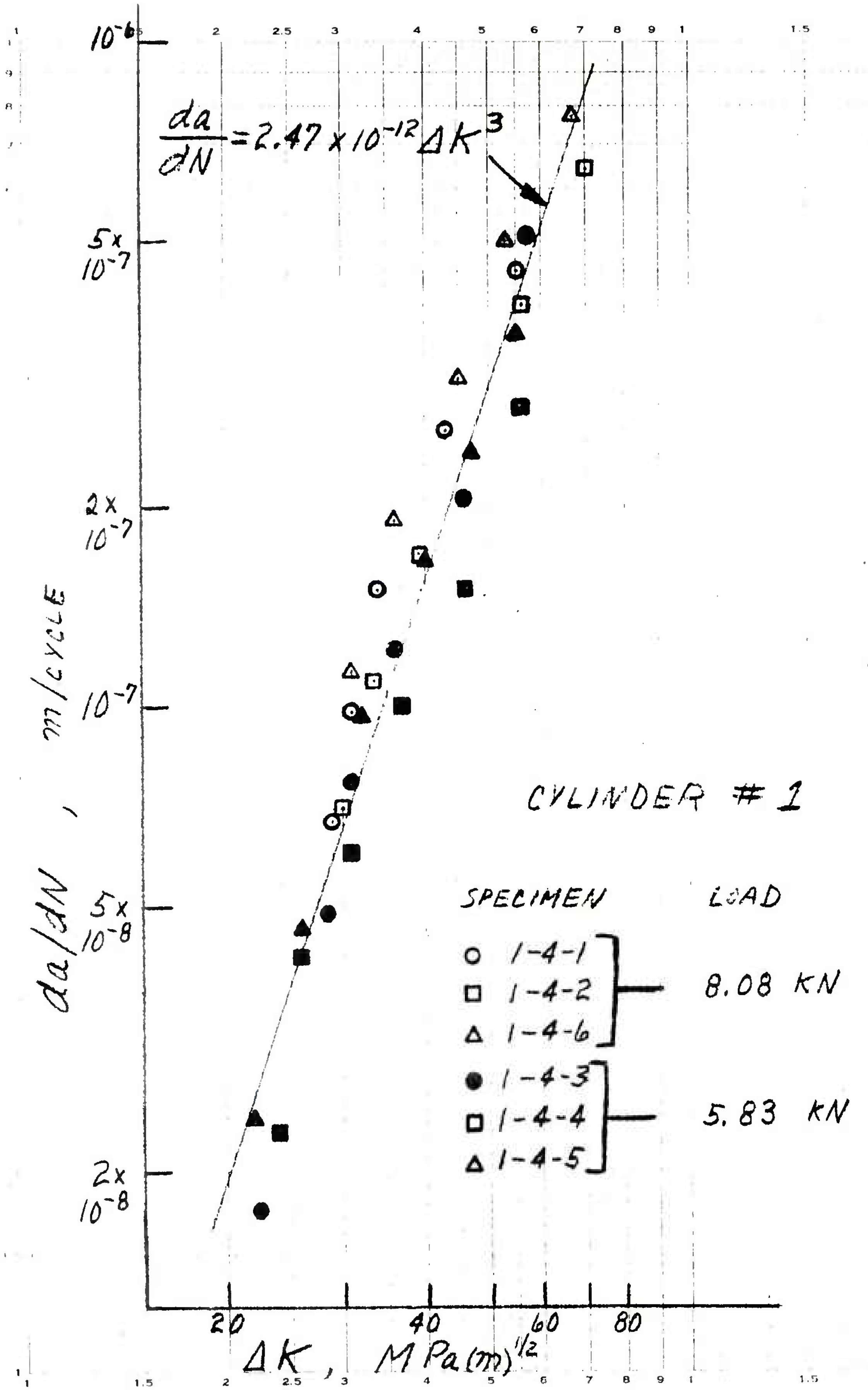

Figure 5a. Fatigue Crack Propagation Rate da/dN vs. Stress Intensity Factor Range, ΔK, For Cylinder #1.

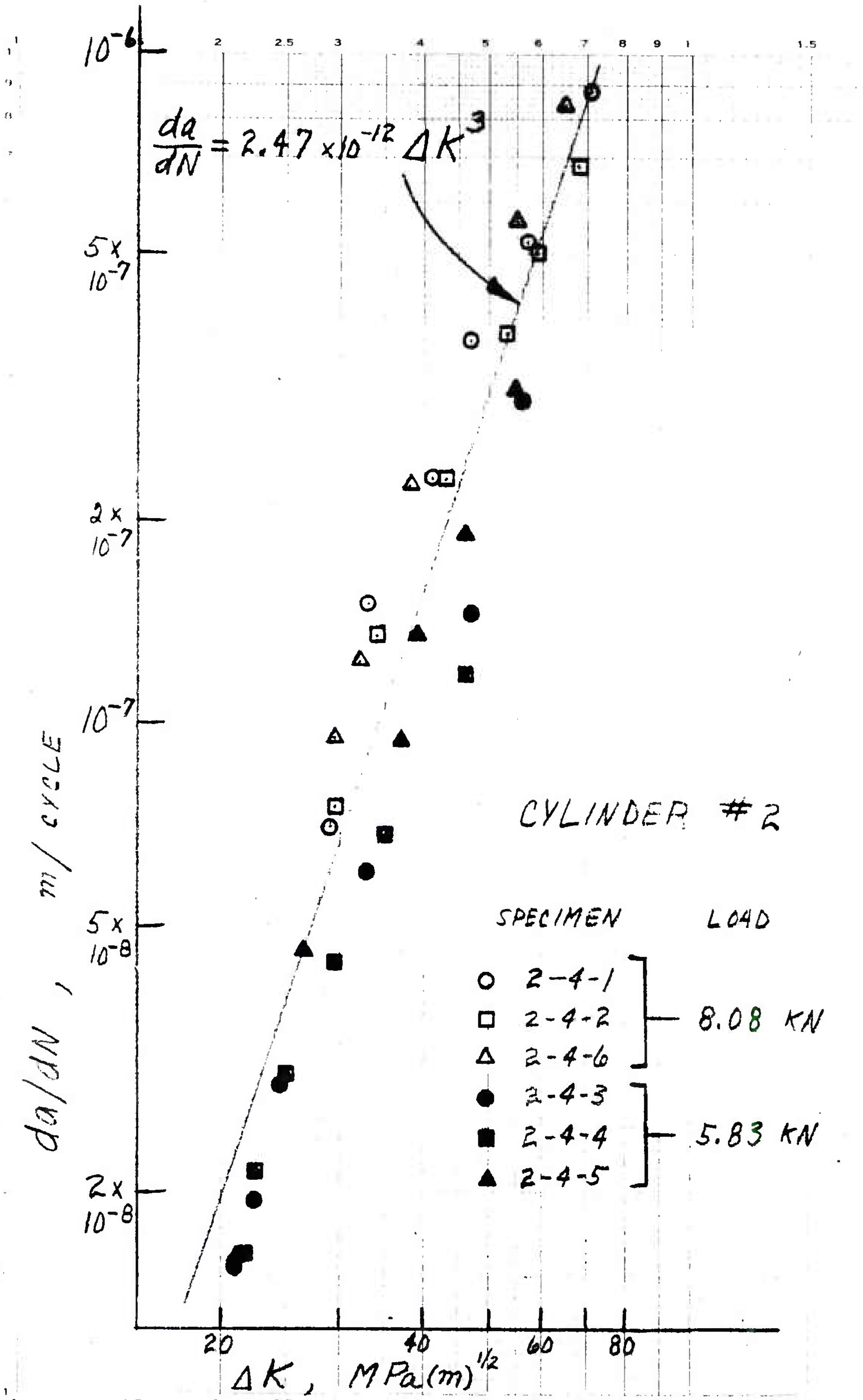

Figure 5b. Fatigue Crack Propagation Rate da/dN vs. Stress Intensity Factor Range, ΔK, For Cylinder #2.

Two categories of groove depth are indicated in Table V; the specimens from cylinder #2 were the only ones on which deep grooves were noted, with depth of about 0.05 to 0.1 mm. The grooves affected the S-N results because in all cases with a groove near the center of the specimen, that is, approximately in line with the center load point, the fatigue failure initiated at a groove. The number of cycles required to grow a crack of 5 mm length along the ID in the longitudinal direction is noted in Table V. In most cases, cracks as small as 2 mm could be detected using a magnetic particle inspection. The cylinder material did not retain a magnetic field as well as other steels we have tested. This, in part, explains the lack of 5 mm data for two specimens. The number of cycles to final failure, with failure defined as two pieces, was recorded. Finally, the stress at the ID surface of the specimen was calculated as:

$$S = \frac{6M}{BW^2} = \frac{3/2\ P\ell}{BW^2} \qquad (1)$$

where the maximum fatigue load, P and specimen wall thickness, W are from Table V, specimen thickness, B = 25.4 mm, and the span between outer load points, ℓ = 143 mm. This calculation uses standard beam analysis, with no consideration of the curvature of the specimen; this approach was found to be entirely adequate for specimens of this type in prior stress and K analysis.[2]

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[2]Underwood, J. H. and Kendall, D. P., "Fracture Toughness Testing Using the C-Shaped Specimens," Developments in Fracture Mechanics Test Methods Standardization, ASTM STP 632, W. F. Brown, Jr., and J. G. Kaufman, Eds., American Society for Testing and Materials, 1977, pp. 25-38.

TABLE V. FATIGUE LIFE TEST RESULTS

Specimen	Maximum Load KN	Wall Thickness, W mm	Depth of Grooves mm	Cycles to 5 mm Surface Crack	Cycles to Failure	Maximum Stress at ID MPa
1-1-1	53.4	26.7	< 0.05	44,000	50,900	633
1-1-2	53.4	27.1	< 0.05	55,000	59,400	614
1-1-5	53.4	25.8	< 0.05	34,000	40,400	678
2-1-1	53.4	25.7	> 0.05	-	19,650	683
2-1-2	53.4	27.2	> 0.05	31,000	45,900	610
2-1-5	53.4	25.9	< 0.05	19,000	27,800	672
1-1-4	66.7	25.9	< 0.05	9,400	10,000	839
1-2-8	66.7	26.5	< 0.05	9,600	11,700	802
2-1-4	66.7	27.7	> 0.05	11,300	13,600	734
2-2-8	66.7	28.6	< 0.05	18,000	23,500	688
1-2-6	80.1	26.9	< 0.05	8,900	9,750	934
1-2-7	80.1	27.1	< 0.05	9,300	10,100	920
1-2-10	80.1	25.5	< 0.05	4,700	5,150	1040
2-2-6	80.1	25.8	< 0.05	5,400	5,700	1016
2-2-7	80.1	26.8	< 0.05	6,300	7,800	941
2-2-10	80.1	26.4	> 0.05	-	3,360	970
1-1-3	90.7	25.5	< 0.05	2,200	2,720	1178
1-2-9	90.7	26.0	< 0.05	1,900	2,335	1133
2-1-3	90.7	28.7	< 0.05	2,500	4,820	930
2-2-9	90.7	28.1	> 0.05	2,600	2,815	970

The S-N plots of the data for each cylinder are shown in Figure 6. In general the ID stress required for lives in the range tested, 2,000 to 50,000 cycles, is at or above the yield strength. The lives from cylinder #2 tests are generally below those of cylinder #1 at similar stress levels. This is due, at least in part, to the fact that five of the ten specimens from cylinder #2 had relatively deep grooves present which lowered the fatigue life.

PRELIMINARY ANALYSIS OF RESULTS

Some indication of the type of analysis which could be performed is given here. An estimate of the critical crack size in the cylinder which would cause a brittle, K_{Ic} type failure is the following: Combining the K expression for a center crack of length 2a in a tension panel, $K = \sigma(\pi a)^{1/2}$, with the expression for the average circumferential stress in the wall of a pressurized thin-wall cylinder, $\sigma = pr/W$, gives the expression

$$a_c = \frac{K_{Ic}^2 W^2}{\pi p^2 r^2} \qquad (2)$$

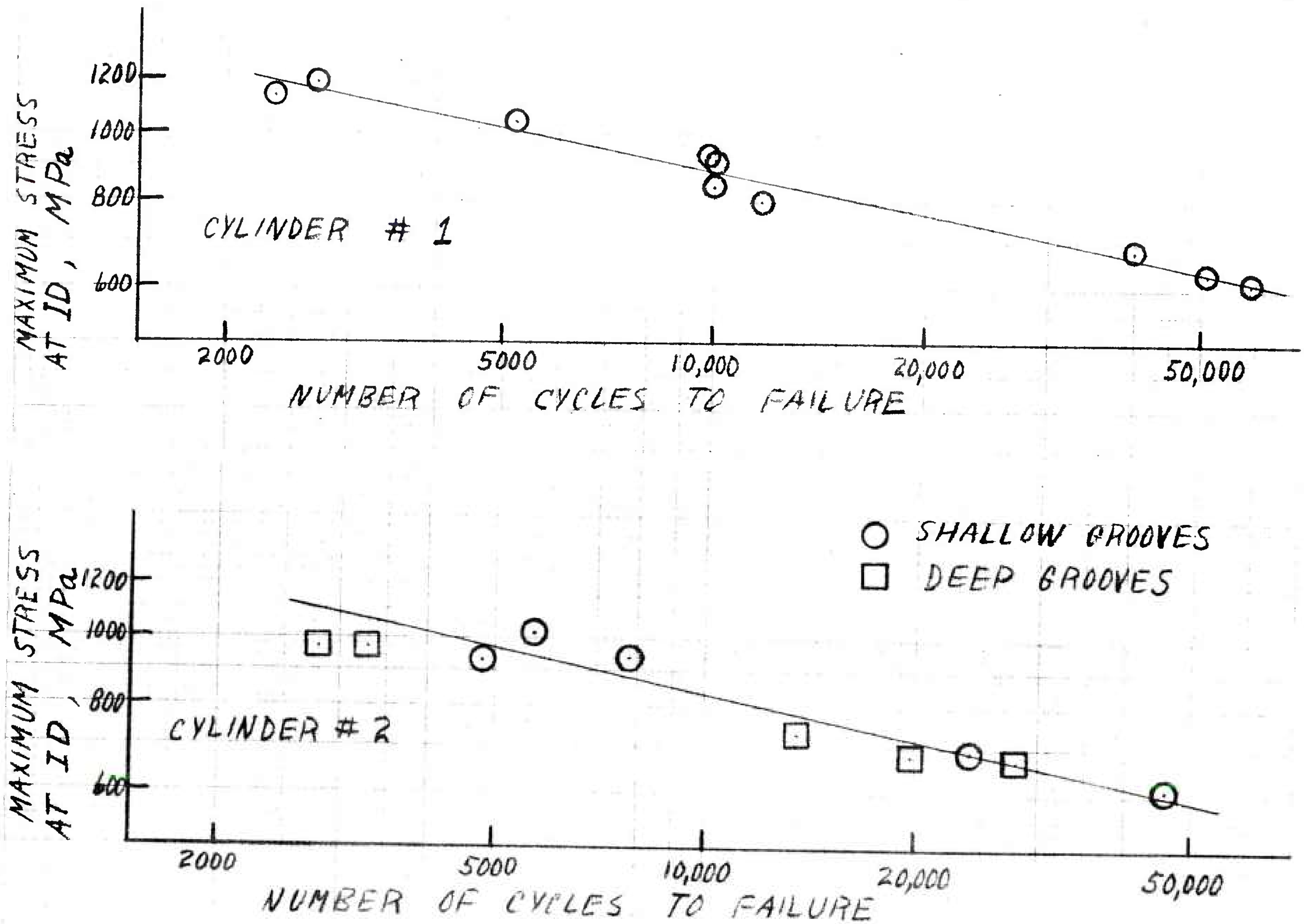

Figure 6. Fatigue Life, S-N Plots.

Using the lowest K_{Ic} value measured in the tests, 89.1 $MPa(m)^{1/2}$, the average radius r = 190 mm, W = 25 mm, p = 34.5 MPa (5.0 Ksi), then a_c = 37 mm, and the total critical length of a through crack growing down the axis of the cylinder is twice that, 74 mm.

An estimate of the number of fatigue cycles required to grow a crack from an initial size (which might be present at the cylinder ID) to a final size equal to the wall thickness, W, is as follows. Following the general procedure developed for cannon tubes,[3,4] the integrated form of a Paris type equation, $da/dN = C\Delta K^n$, is combined with a K expression for a shallow, semielliptical crack at the ID of a pressurized cylinder, $K = 1.12\ \alpha\sigma(\pi a)^{1/2} + 1.12\ \alpha p(\pi a)^{1/2}$, to give:

$$N_f = \frac{2\left[\frac{1}{\sqrt{a_i}} - \frac{1}{\sqrt{W}}\right]}{C\left[1.12\ \alpha p\left(\frac{2[r_2/r_1]^2}{[r_2/r_1]^2 - 1}\right)\right]^n} \qquad (3)$$

Using an initial crack depth, a_i, of 0.5 mm, (which is the depth of a crack with surface length, 2c along the ID of 5 mm, see page 1, and a/2c = 0.1), W = 25 mm, $C = 2.47 \times 10^{-12}$ and n = 3 to represent the da/dN behavior, $\alpha = 0.93$ which corresponds to a/2c = 0.1,[3] p = 34.5 MPa, and $r_2/r_1 = 1.14$, gives the result N_f = 1,020,000 cycles.

---

[3]Underwood, J. H., "Stress Intensity Factors for Internally Pressurized Thick-Wall Cylinders," Stress Analysis and Growth of Cracks, Proceedings of the 1971 National Symposium on Fracture Mechanics, Part I, ASTM STP 513, American Society for Testing and Materials, 1972, pp. 59-70.

[4]Underwood, J. H. and Throop, J. F., "Surface Crack K-Estimates and Fatigue Life Calculations in Cannon Tubes," Part-Through Crack Fatigue Life Prediction, ASTM STP 687, J. B. Chang, Ed., American Society for Testing and Materials, 1979, pp. 195-210.

These a_c and N_f estimates can be further refined, and more information on the service conditions of the vessels is required to more certainly determine the various parameters which appear in the analyses. Once the most appropriate service information is inserted into the analyses via the parameters in equations (2) and (3), quantitative determinations of the likelihood of brittle failure and fatigue failure of the vessels can be made.

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2. Underwood, J. H. and Kendall, D. P., "Fracture Toughness Testing Using the C-Shaped Specimen," Developments in Fracture Mechanics Test Methods Standardization, ASTM STP 632, W. F. Brown, Jr., and J. G. Kaufman, Eds., American Society for Testing and Materials, 1977, pp. 25-38.

3. Underwood, J. H., "Stress Intensity Factors for Internally Pressurized Thick-Wall Cylinders," Stress Analysis and Growth of Cracks, Proceedings of the 1971 National Symposium on Fracture Mechanics, Part I, ASTM STP 513, American Society for Testing and Materials, 1972, pp. 59-70.

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