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ATOMIC ENERGY OF CANADA LIMITED

L'ÉNERGIE ATOMIQUE DU CANADA LIMITÉE

SLIT-BURST TESTING OF COLD-WORKED Zr-2.5 Wt. % Nb PRESSURE TUBING FOR CANDU-PHW REACTORS

ESSAIS DE RUPTURE PAR FISSURE DE TUBES DE FORCE ECROUIS EN Zr-2.5% Nb EN POIDS DES REACTEURS CANDU-PHW

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RESUME

Ce rapport documente les données obtenues sur la longueur de fissure critique de tubes de force écrouis Zr-2.5% Nb en poids des réacteurs CANDU. Il comprend particulièrement des données sur les tubes retirés des réacteurs 3 et 4 de Pickering.

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PRESSURE TUBING FOR CANDU-PHW REACTORS

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ABSTRACT

This report documents the available data on critical crack length of cold-worked Zr-2.5 wt.% Nb pressure tubing in CANDU reactors. In particular, it includes data for tubing removed from the Pickering 3 and 4 reactors.

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CONTENTS

1. INTRODUCTION

In CANDU-PHW* reactors, fuel bundles are located in pressure tubes and cooled by heavy water. For the Pickering 3 and 4 and Bruce reactors, the pressure tubes are made of cold-worked Zr-2.5 wt.% Nb and operate at about 293°C and 9 MPa internal pressure. As the pressure tubes are the primary containment for the hot, pressurized coolant, their integrity is important. This has prompted studies of their fracture behaviour and flaw tolerance(1). The most damaging flaw in any pressurized tube is a sharp, through-wall axial crack. At any given internal pressure and temperature, there is a critical crack length (CCL) beyond which through-wall axial cracks will propagate rapidly in an unstable manner(2).

One of the safety criteria for the CANDU-PHW system is that 'pressure tubes will leak before they break', i.e., cracks will be smaller than the critical size and will leak(3). Work on pressure vessels with artificial flaws demonstrated that cracks initiated at a surface defect tend to grow into an elliptical shape and penetrate the vessel wall fully at lengths approximately two to three times the wall thickness(4). The wall thickness of the Pickering 3 and 4 and Bruce reactor pressure tubes is 4 mm. Hence, a growing crack may be expected to penetrate the wall of the pressure tube and leak when it is 8 to 12 mm in length. This length is between one tenth and one seventh of the CCL at the operating temperature and pressure for the Pickering 3 and 4 and Bruce pressure tubes(1). Also, leak-before-break has been demonstrated in cold-worked Zr-2.5 wt.% Nb pressure tubes in laboratory experiments(1).

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* CANada Deuterium Uranium - Pressurized Heavy Water

In late 1974 and early 1975, leakage of coolant led to the discovery of cracks adjacent to the rolled-joint assembly in some Pickering 3 and 4 pressure tubes. The cracks ranged in length from 2 to 20 mm. The leak-before-break criterion was proven by these cracks. Subsequently, it was established that the cracking mechanism was driven by large residual stresses which were the result of an incorrect procedure for fabrication of the rolled joints. The procedure has been rectified and the cracked pressure tubes have been replaced[5-7].

As a result, a supply of pressure tubing that had seen service in a power reactor* was available. This work was initiated to use that supply to confirm our understanding of the relationship between CCL and internal burst pressure in cold-worked Zr-2.5 wt.% Nb pressure tubes. Previous work had been conducted on tubing which had experienced less irradiation and was, in some instances, either over- or under-sized.

2. EXPERIMENTAL PROCEDURE

2.1 BURST-TESTING PROCEDURE

The burst test sections were 460-mm long sections of pressure tube sealed at each end by end caps as shown in Figure 1. A through-wall axial slit was cut at the mid-length of each test section. The slits were cut under oil using an electric discharge machine (EDM) and were typically 0.38 to 0.45 mm wide. This was preferred to mechanical machining because of the difficulty with the latter method of producing narrow slits of the required lengths. Metallographic examination of material at the ends of the spark-eroded slit showed no change in structure of the matrix or of the hydride. Hydraulic pressure (oil**) was

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* Irradiated to a fluence of $\sim 10^{25}$ n/m^2 > 1 MeV

** Monsanto Product OS-84

maintained in the test section by a thin aluminum alloy liner tube. Sandwiched between the liner tube and the pressure tube, underneath the slit, was a cold-rolled, stainless steel shim. In early tests, the shim thickness was 0.127 mm. In later tests, the thickness was increased to 0.254 mm. Bursting was achieved by increasing the oil pressure at 5.2 $MPa \cdot s^{-1}$. Tests were conducted at room and elevated temperatures.

2.2 CRACK SHARPENING

Some tests used blunt slits, i.e., EDM slits "as-made". In others, the slit was fatigue-sharpened by pressure cycling. The cycle most often used was 7.58 ± 2.07 MPa at 0.833 Hz. This cycle was chosen to give a maximum pressure of 9.65 MPa, which is the Pickering 3 and 4 operating pressure. Some difficulties were experienced with crack sharpening because the progress of sharpening could not be observed directly. The practice followed initially was to subject the test section to a given number of pressure cycles at Hot Cell temperature (typically 27°C). Later the number of cycles chosen was based on experience. The final crack length prior to testing was determined fractographically after burst testing. Figure 2 shows a fracture surface with the typical fatigue-sharpened slit. Figure 3 charts fatigue crack extension versus pressure cycles in pressure tubing and illustrates the variability of the process from one pressure tube to another.

The test section identities used in this report are of two types. Those that contain only numerals refer to the pressure tube number. For example, 674-1 to 10 refer to pressure tube 674 sections 1 to 10. The remaining identities are prefixed by a letter. These indicate test sections cut from tubes removed from the Pickering 3 and 4 reactors. The letter gives the tube lattice position in the reactor core. For example, J4/3 refers to the tube from lattice position J4; the 3 refers to the test section cut from it. Tubes J4, J16 and R6 came from Pickering 3; the remaining lettered sections came from Pickering 4.

2.3 INTERPRETATION OF FAILURES IN THE CRACK-SHARPENING PHASE

Variability in the fatigue-sharpening process resulted in premature failures in some test sections during the crack-sharpening operation. The interpretation of these particular tests required examination of fracture replicas with a transmission electron microscope. As the frequency of pressure cycling was low (0.833 Hz), it was assumed that the test section had burst at the peak of the pressure cycle, 9.65 MPa, the operating pressure for Pickering 3 and 4. The fractures showed that there was no abrupt transition from slow crack growth via the fatigue mechanism to unstable fast fracture. This is illustrated in Figures 4 and 5 which show the fractures seen in specimens J4/5 and R6/3. In Figure 4, point A is the end of the original 25-mm EDM slit. Replicas of areas B, C and D were examined in the transmission electron microscope. Figure 6 shows the typical fatigue striations seen in the B areas. Figure 7 shows the fracture surface seen in areas C and D. It does not exhibit fatigue markings; rather it has the features expected from tensile rupture. The crack was considered to be critical at a point just beyond the last fatigue tide mark. Similar observations and judgements were made for tube sections J16/5, R6/6 and R6/3.

Two initial test sections, J16/4 and J16/10, fatigue sharpened at 240°C, failed in the sharpening phase and produced fractures that showed no obvious macroscopic fatigue tide marks. Estimation of their CCL was made exclusively from replicas. This was tedious and uncertain, especially with test section J16/4, for which the result was finally discarded.

It was concluded that tests were best rejected when failure occurred in the fatigue-sharpening phase. These tests underestimate CCL because fatigue cracks cannot always be identified unequivocally and because their absence does not guarantee that the crack at that point was propagating rapidly in an unstable manner.

2.4 LINER TUBE CORRECTIONS

The liner tube dimensions were 101.6 mm OD x 0.94 mm wall thickness. Hence, the liner initially fits loosely inside the pressure tube section whose ID is approximately 103.4 mm. As the liner is internally pressurized it yields and pressure is transmitted to the pressure tube test section. The yield stress of the liner (aluminum alloy 5052 temper 0) versus temperature is shown in Table 1. The pressure to just yield the liner is shown as a function of temperature in Figure 8. To estimate the pressure transmitted to the pressure tube test section, a correction is required to account for the pressure required to yield the liner. This pressure is subtracted from the measured burst pressure to give the effective burst pressure.

This was confirmed experimentally by measuring circumferential and longitudinal strains on the OD of the pressure tube test section during internal pressurization with and without the liner. The strain measurements are summarized in Figure 9. The tests in order were:

(i) pressure tube without liner up to 17.24 MPa - plot A

(ii) pressure tube with liner to 17.24 MPa - plot B

(iii) pressure tube with liner, repeat of (ii) up to 20.68 MPa - plot C

(iv) pressure tube with liner, repeat of (ii) up to 41.37 MPa - plot D

These tests were conducted at the Hot Cell temperature of approximately 27°C. The pressure was raised in 1.724 MPa steps and allowed to equilibrate for 60 s. For clarity, and because the experimental points exhibited negligible scatter about the lines shown, the experimental points were omitted from Figure 9. The results show the correction required is essentially constant up to at least an internal pressure of 41.37 MPa. The difference between the first and second pressurizations, i.e., plots B and C, is due to the expansion of the liner onto the inside of the pressure tube test section during the first pressurization. When the internal pressure exceeds that of the previous pressurization, the plot runs parallel to that for the case without a liner, i.e., plot A. Hence, it is reasonable to infer that, in tests where dynamic loading (pressure cycling) is used for slit sharpening, the plot of interest will be from the origin to the point P (Figure 9) at 9.65 MPa and parallel to plot A. Therefore, the correction due to the liner is the same whether the slit in the test section is left blunt or is sharpened by pressure cycling prior to bursting.

The correction measured in these tests at approximately 27°C exceeded that required to just yield the liner as shown in Figure 8. The extra pressure was that required to strain the liner beyond its yield to accommodate the small clearance between the liner OD and the pressure tube section ID. It varies according to the initial fit between the two tubes. As the rate of strain hardening of the liner decreases with increasing temperature, the pressure correction is expected to approach that required to just yield the liner in the 240-300°C tests.

3. RESULTS AND DISCUSSION

Examination of tube test sections after burst testing usually showed a slight bulging of the tube at the site of the original crack (see Figure 10). The crack often had propagated from end to end of the test section, however, at 240-300°C tube bulging was accentuated and crack openings after testing were often large (5-8 mm). Frequently in these tests, stable crack tearing and excessive crack open-mouthing caused premature failure of the pressure-sealing aluminum liner. These tests under-estimated burst pressures; however, the results were included in the overall data to ensure that any bias would be towards a low estimated pressure. Tube outward bulging and crack open-mouthing are shown in Figures 10 and 11.

Tables 2 to 5 list the data* on the cold-worked Zr-2.5 wt.% Nb pressure tubing. Figures 12 to 15 show these data graphically. Some of the data shown in the tables are not included in the figures or in the statistical analysis because they were obtained from undersized tubing, i.e., either thin wall or reduced diameter. The data obtained from the Pickering tubing have been analyzed in the following categories:

Blunt crack at 23-27°C, Figure 12
Sharp crack at 23-32°C, Figure 13
Blunt crack at 240-300°C, Figure 14
Sharp crack at 237-300°C, Figure 15

In all data groups, the mean line was obtained by regressing hoop stress at burst (σ) upon crack length (L) according to the expression:

$$\ln \sigma = ML + C,$$

where M and C are constants. The equations of the mean lines and the coefficients of correlation are found in Table 6. The expression was chosen because it has the correct form and is simple. The confidence limits shown in Figures 12 to 15 were estimated assuming that the distribution of $\ln \sigma$ for any given value of crack length is normal.

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* Includes for completeness, results obtained at Chalk River Nuclear Laboratories (CRNL) by Langford and Mooder (1)

Examination of the correlation coefficients, r, and the graphs of hoop stress at burst versus CCL, show that the expression used to fit the data is reasonable. For sharp cracks at elevated temperatures, i.e., operating temperatures, the data fit is excellent. In Pickering 3 and 4 pressure tubes, the hoop stresses at the operating and emergency over-pressure are 124 and 205 MPa, respectively. The mean CCL at these hoop stresses are 86 mm (80 mm at minus one standard deviation) and 61 mm (55 mm at minus one standard deviation), respectively. The mean CCL for sharp cracks at 23 to 32°C is 58 mm. It should be noted that, at these low temperatures, the reactor is not at power.

4. CONCLUSIONS

1. At the emergency over-pressure at elevated temperatures, the CCL is at least three times longer than the longest cracks (20 mm) seen in the Pickering 3 and 4 reactors. For operating pressure, the CCL is greater than four times the longest cracks seen.

2. These data show that Pickering 3 and 4 and Bruce pressure tubes will leak before breaking. This confirms the original results of Langford and Mooder[1].

3. The critical crack length for cold-worked Zr-2.5 wt.% Nb pressure tubing is greater with blunt crack tips and elevated temperatures. However, the influence of crack tip acuity is less at elevated temperatures.

4. Zr-2.5 wt.% Nb Pickering pressure tubing is tolerant of sharp cracks.

5. ACKNOWLEDGEMENTS

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TABLE 1

VARIATION OF YIELD STRESS WITH TEMPERATURE FOR LINER MATERIAL*
(ALUMINUM ALLOY 5052 TEMPER 0)

Temperature °C	Yield Stress MPa
24	89.6
149	89.6
204	75.8
260	51.7
316	34.5
371	20.7

*Metals Handbook 8th Edit. Vol. 1 ASM

TABLE 2

SLIT-BURST DATA FOR COLD-WORKED Zr-2.5 WT.% Nb PRESSURE TUBING
BLUNT CRACKS IN TEMPERATURE RANGE 23-32°C

Identity	Temp. °C	Critical Crack Length mm	Irradiated x 10^{24} N/m^2 > 1 MeV	Corrected Hoop Stress MPa	Tested At
446-38(1)	23	51	0	195	CRNL
446-101(1)	23	51	0	338	CRNL
583-38(1)	23	51	4.5	244	CRNL
583-84(1)	23	51	4.3	230	CRNL
446-66(1)	23	64	0	233	CRNL
446-99(1)	23	76	0	190	CRNL
R6E3	27	25	10	334	WNRE
R6E2B(2)	27	50	10	258	WNRE
R6E2A(2)	27	50	10	369	WNRE
R6E7(2)	27	50	10	235	WNRE
J4/9(2)	27	70	10	115	WNRE

(1) Thin wall, 2.8 mm. Excluded from statistical analysis and from Figure 12

(2) Tube length, 305 mm

TABLE 3

SLIT-BURST DATA FOR COLD-WORKED Zr-2.5 WT.% Nb PRESSURE TUBING
SHARP CRACKS IN TEMPERATURE RANGE 23-32°C

Identity	Temp. °C	Critical Crack Length mm	Irradiated x 10^{24} N/m^2 > 1 MeV	Corrected Hoop Stress MPa	Tested At
J4/3	27	26	10	276	WNRE
J4/6	27	34	10	264	WNRE
J16/8	32	40	10	237	CRNL
J4/1	32	40	10	192	CRNL
R6/6	27	49	10	103	WNRE
R6/3	27	51	10	103	WNRE
J4/8	27	52	10	201	WNRE
J16/3	32	52	10	104	CRNL
J16/5	27	58	10	104	WNRE
445/130(1)	23	60	0	145	CRNL
437/25	23	60	0	120	CRNL
J16/1	32	60	10	124	CRNL
437/149(2)	22	75	0	145	CRNL
652/2	23	75	0	90	CRNL
J4/5	27	85	10	103	WNRE
M5E4/21	27	47	10	103	WNRE

(1) Thin wall, 2.8 mm. Excluded from statistical analysis and from Figure 13

(2) Thick wall, 5 mm. Excluded from statistical analysis and from Figure 13

TABLE 4

SLIT-BURST DATA FOR COLD-WORKED Zr-2.5 WT.% Nb PRESSURE TUBING.
BLUNT CRACKS IN TEMPERATURE RANGE 240-300°C

Identity	Temp. °C	Critical Crack Length mm	Irradiated $\times 10^{24}$ N/m^2 > 1 MeV	Corrected Hoop Stress MPa	Tested At
R62W	240	27	10	542	WNRE
34/10	240	70	10	202	WNRE
R6/7W	240	70	10	241	WNRE
M13W4A	240	70	10	270	WNRE
M13W4B	240	70	10	203	WNRE
D17E4E	240	70	10	242	WNRE
D17E4B	240	70	10	290	WNRE
D17E4A	240	70	10	250	WNRE
D17E4F	240	70	10	245	WNRE
447 (2)	300	51	0	212	CRNL
437-108 (2)	300	51	2.1	284	CRNL
446-10 (2)	300	64	0	171	CRNL
437-97 (2)	300	64	2.1	164	CRNL
437-131 (3)	300	64	1.9	174	CRNL
446-9 (3)	300	76	0	145	CRNL
583-71 (1)	300	76	4.8	142	CRNL
445-10 (1)	300	76	5.1	160	CRNL
553-52 (1)	300	76	2.7	155	CRNL
437-86 (2)	300	76	2.1	136	CRNL
583-13 (2)	300	76	0	147	CRNL
445-56 (2)	300	76	1.1	138	CRNL
445-85 (2)	300	76	3.1	140	CRNL
445-74 (2)	300	76	3.8	140	CRNL
411-12 (1)(2)	300	76	0	123	CRNL
411-42 (1)(2)	300	76	1.3	120	CRNL
411-88 (1)(2)	300	76	8.4	120	CRNL
445-147 (2)	300	102	2.8	109	CRNL

(1) 82.6 mm I.D.
(2) Thin wall, 2.8 mm
(3) Thick wall, 5 mm

TABLE 5

SLIT-BURST DATA FOR COLD-WORKED Zr-2.5 WT.% Nb PRESSURE TUBING.

SHARP CRACKS IN TEMPERATURE RANGE 170 - 300°C

Identity	Temp. °C	Critical Crack Length mm	Irradiated $\times 10^{24}$ N/m^2 > 1 MeV	Corrected Hoop Stress MPa	Tested At
543-2 [1]	215	42	0	303	CRNL
J16/6	237	40	10	332	CRNL
J16/7	237	40	10	327	CRNL
674-9	237	44	0	257	CRNL
674-6	237	45	0	284	CRNL
674-8	237	45	0	248	CRNL
674-7	237	47	0	265	CRNL
J16/2	237	79	10	139	CRNL
674-8 [1,2]	237	80	0	190	CRNL
J16/10	240	100	10	110	WNRE
J4/4	240	29.5	10	438	WNRE
D17/W4/2	240	39	10	341	WNRE
D17/W4/4	240	40	10	369	WNRE
J4/7	240	41	10	340	WNRE
M5E4	300	22	10	464	WNRE
M5W4	300	22	10	439	WNRE
M15E4	300	23	10	480	WNRE
674-3	300	45	0	252	CRNL
674-4	300	45	0	252	CRNL
543-1	300	45	0	252	CRNL
674-2	300	48	0	257	CRNL
674-5	300	49	0	234	CRNL
674-1 [1,2]	300	63	0	208	CRNL
674-2 [1,2]	300	81	0	177	CRNL
M13E4A [1]	170	40.5	10	295	WNRE
M13E4B [1]	170	41	10	301	WNRE

(1) Excluded from statistical analysis and from Figure 15

(2) Retested with new shim

TABLE 6

EQUATIONS OF MEAN LINES THROUGH BURST TEST DATA AND COEFFICIENTS OF CORRELATION (r)

Crack	Temp. °C	ln stress =	r
Blunt	23-27	-0.022 451L + 6.596 003	0.782
Sharp	23-32	-0.019 545L + 5.957 783	0.741
Blunt	240-300	-0.022 539L + 6.783 026	0.782
Sharp	237-300	-0.019 910L + 6.536 041	0.961

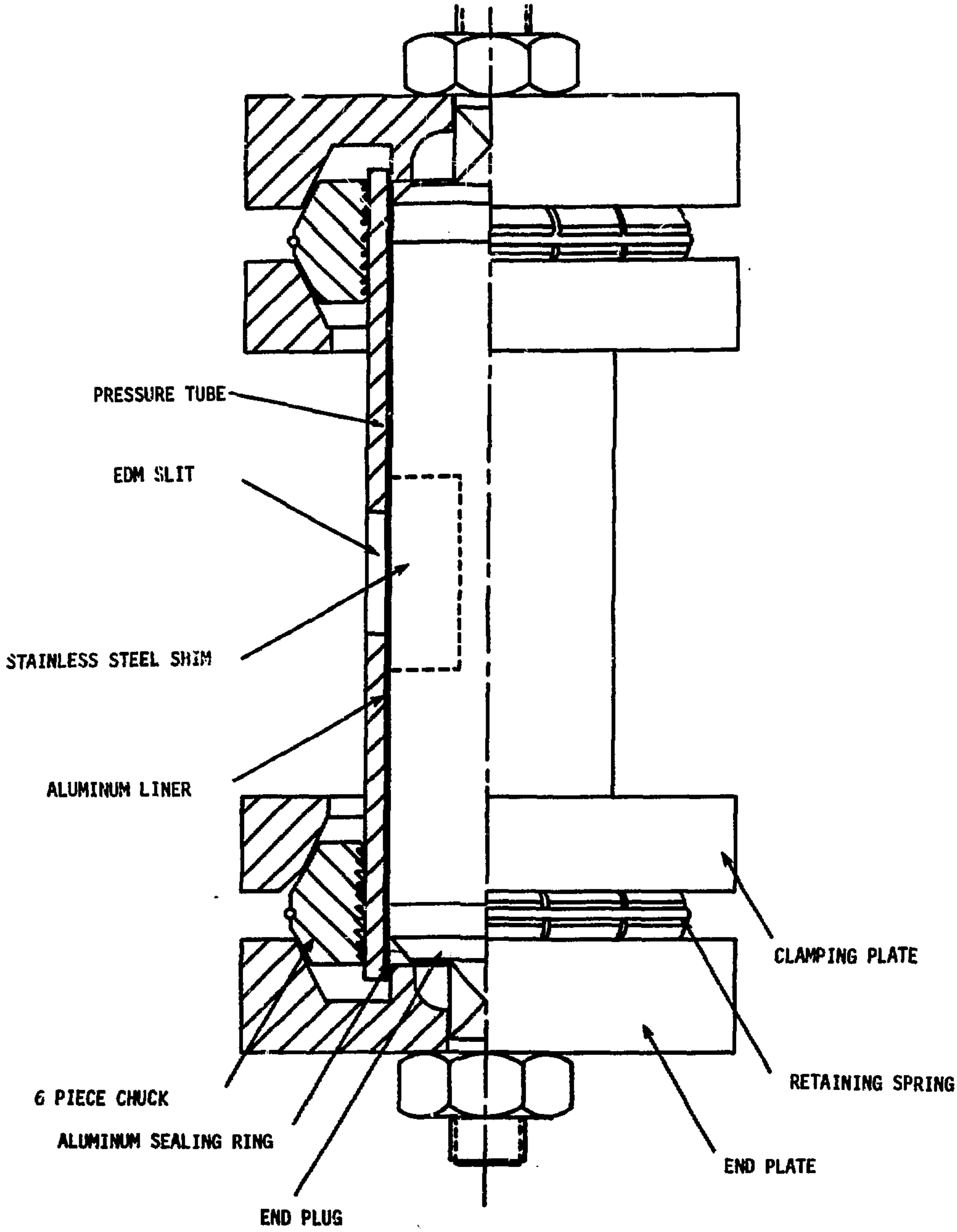

FIGURE 1: BURST TEST ASSEMBLY. CLAMPING AND END PLATES ARE BOLTED TOGETHER

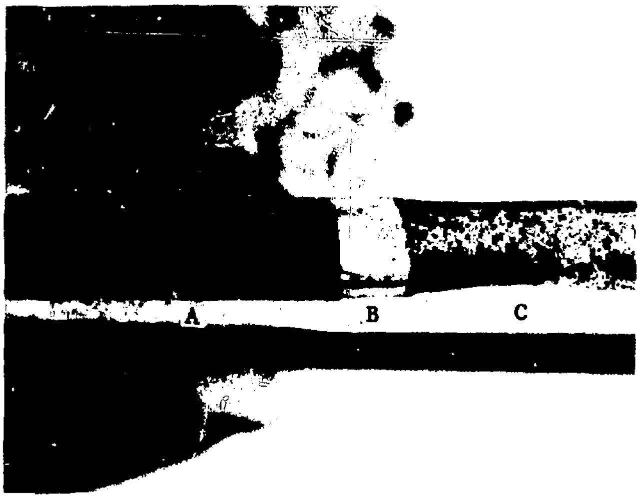

FIGURE 2: BURST TEST FRACTURE SHOWING AT A, THE EDM SLIT, AT B, THE FATIGUE CRACK EXTENSION AND AT C, THE FAST FRACTURE

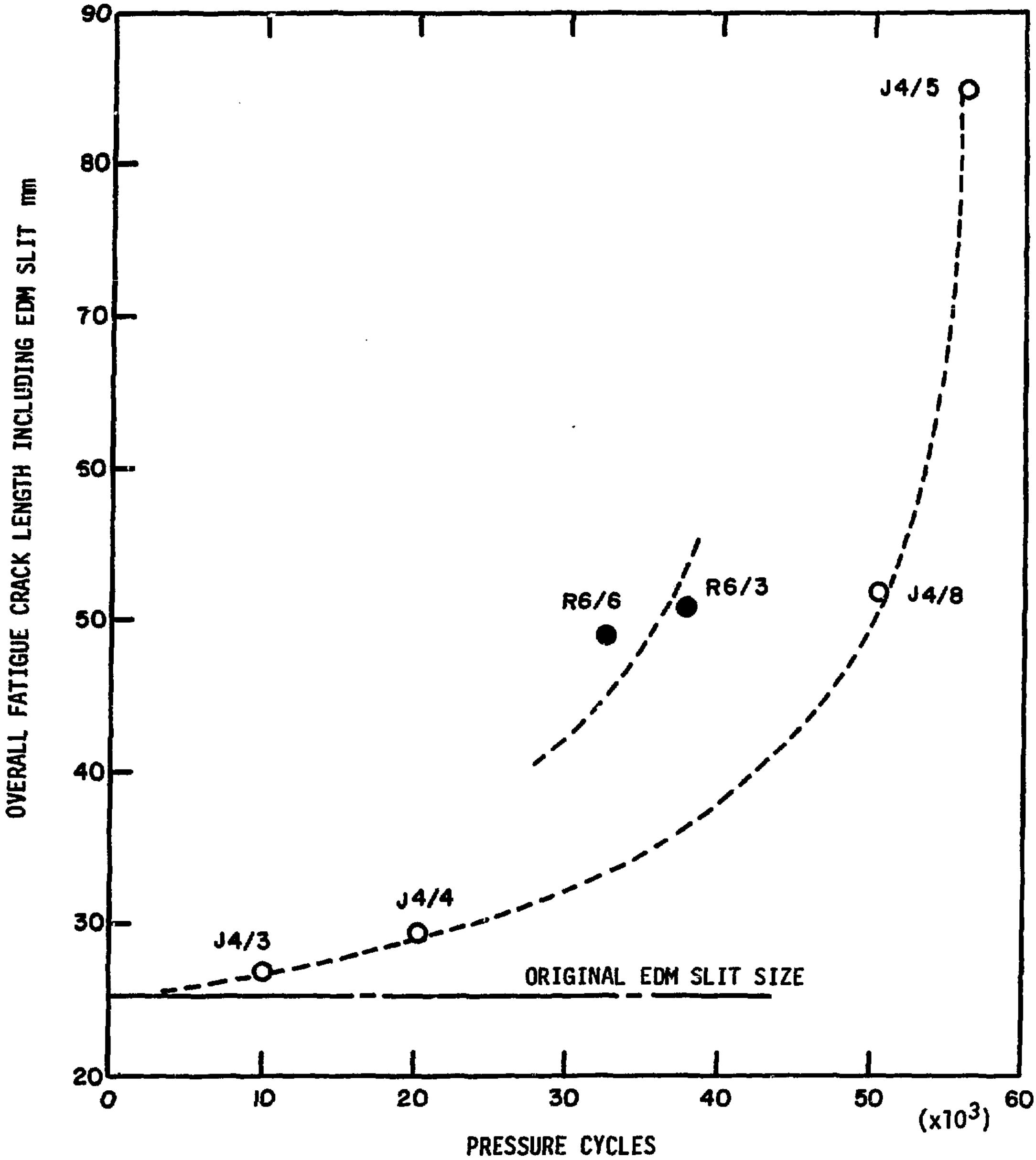

FIGURE 3: CRACK EXTENSION BY PRESSURE CYCLING AT 27°C

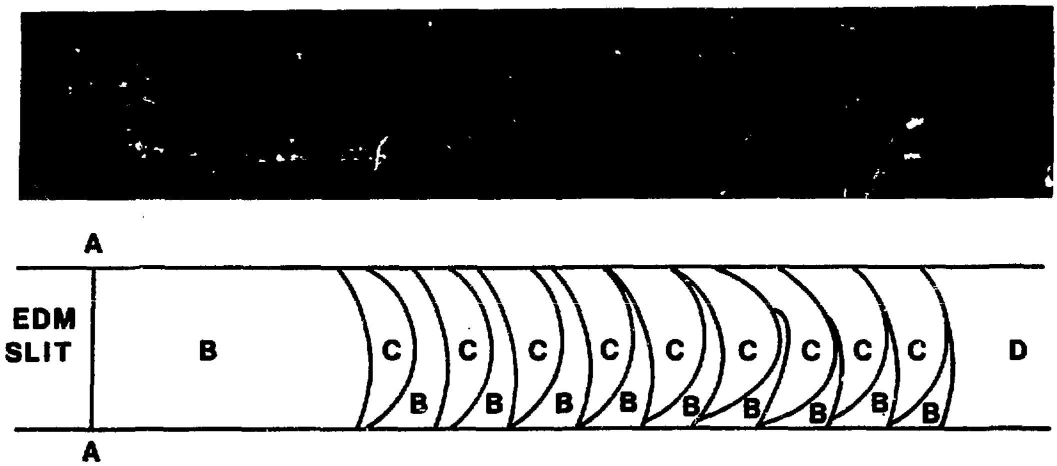

FIGURE 4: FRACTURE SURFACE IN J4/5 SHOWING TRANSITION FROM FATIGUE TO FAST FRACTURE. POINT A INDICATES ONE END OF ORIGINAL EDM SLIT, B ARE AREAS OF FATIGUE CRACK PROPAGATION AND C AND D ARE AREAS OF FAST FRACTURE

FIGURE 5: FRACTURE SURFACE IN R6/3 SHOWING FEATURES SIMILAR TO THOSE IN J4/5 IN FIGURE 4

FIGURE 6: FATIGUE STRIATIONS SEEN IN AREAS B IN FIGURES 4 AND 5

FIGURE 7: DIMPLES INDICATING TENSILE RUPTURE SEEN IN AREAS C AND D IN FIGURES 4 AND 5

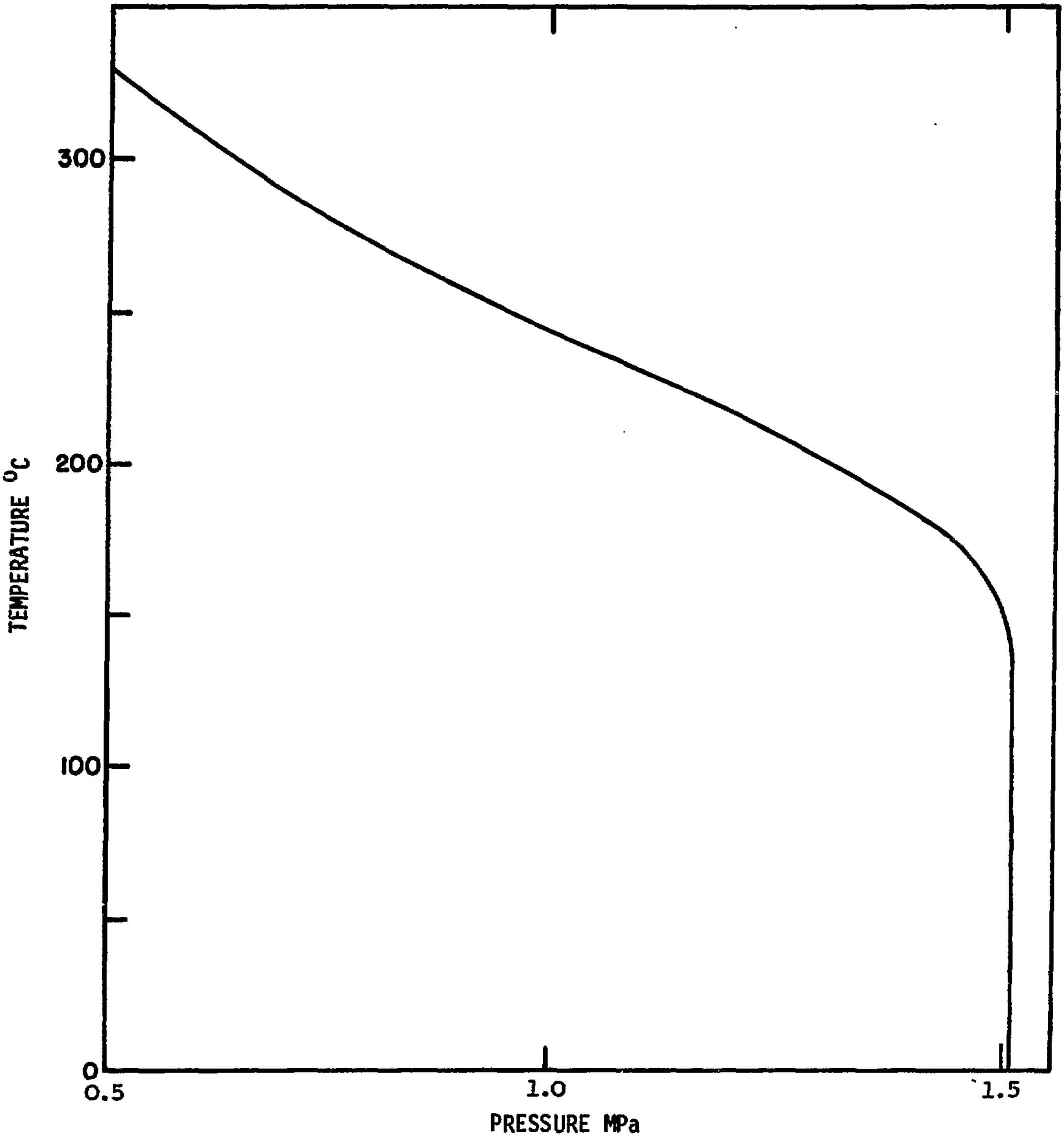

FIGURE 8: BURST TEST PRESSURE CORRECTION, BASED ON LINER WITH OD OF 103.38 mm AND WALL THICKNESS OF 0.889 mm

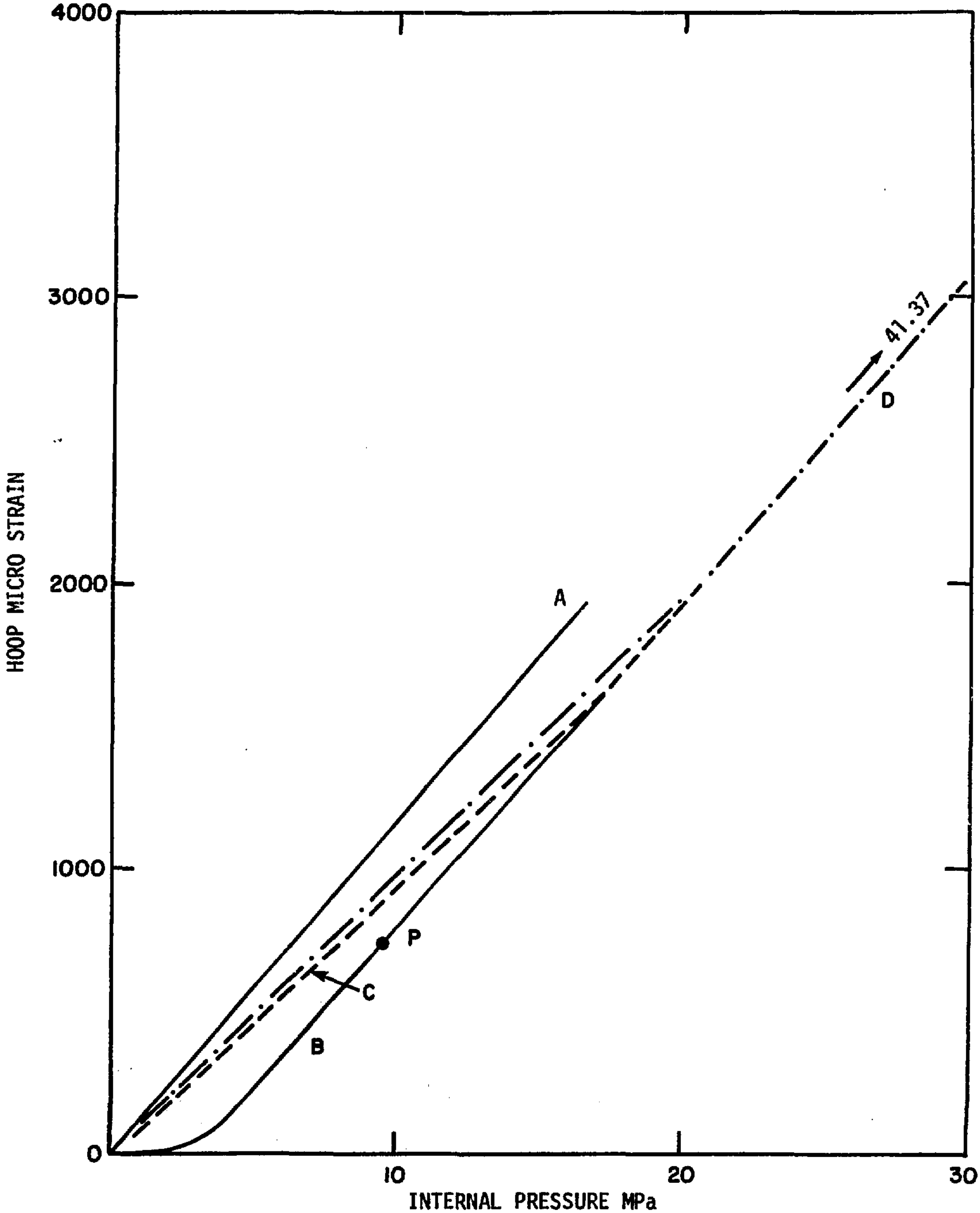

FIGURE 9: HOOP MICRO STRAIN (OD OF PRESSURE TUBE SECTION) VERSUS INTERNAL PRESSURE DURING INFLUENCE OF LINER TESTS

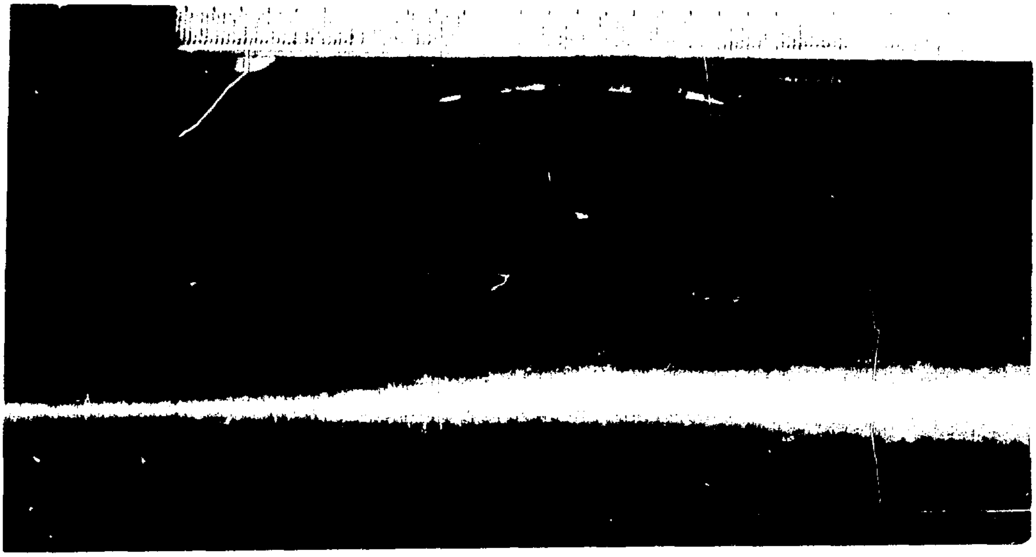

FIGURE 10: OUTWARD BULGING OF TUBE AT THROUGH-WALL AXIAL CRACK

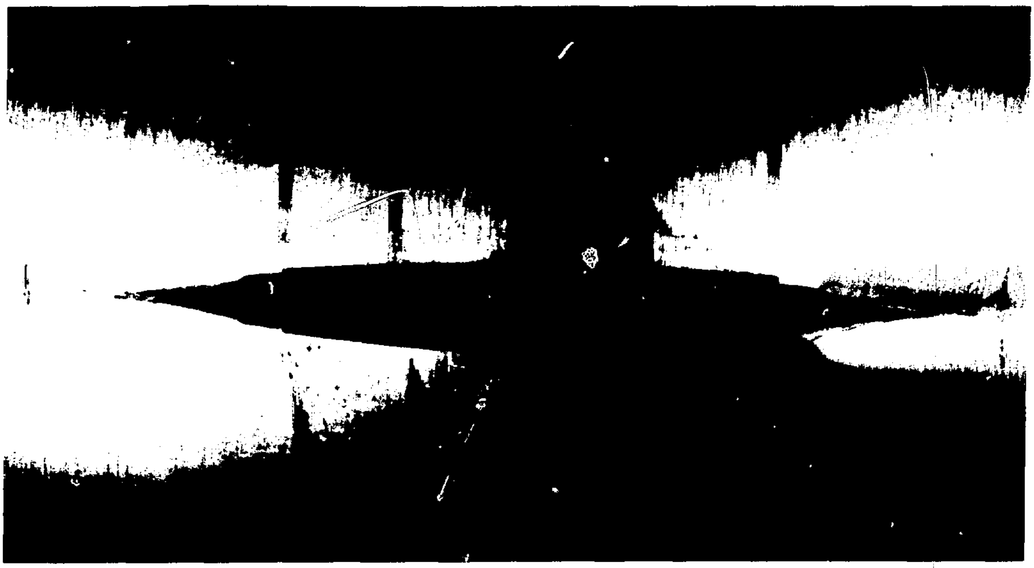

FIGURE 11: CRACK OPEN-MOUTHING

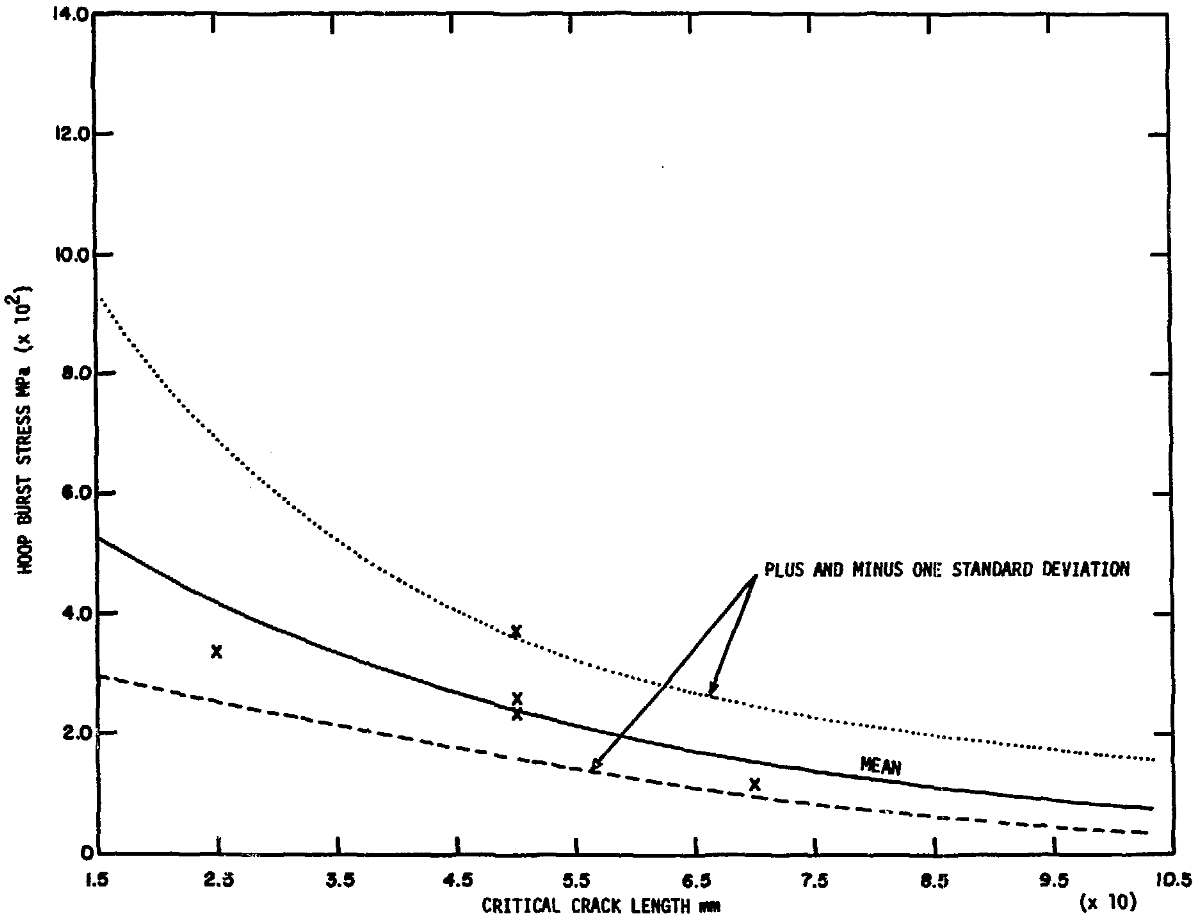

FIGURE 12: BURST HOOP STRESS VERSUS CRITICAL CRACK LENGTH FOR BLUNT CRACKS AT 23-27°C

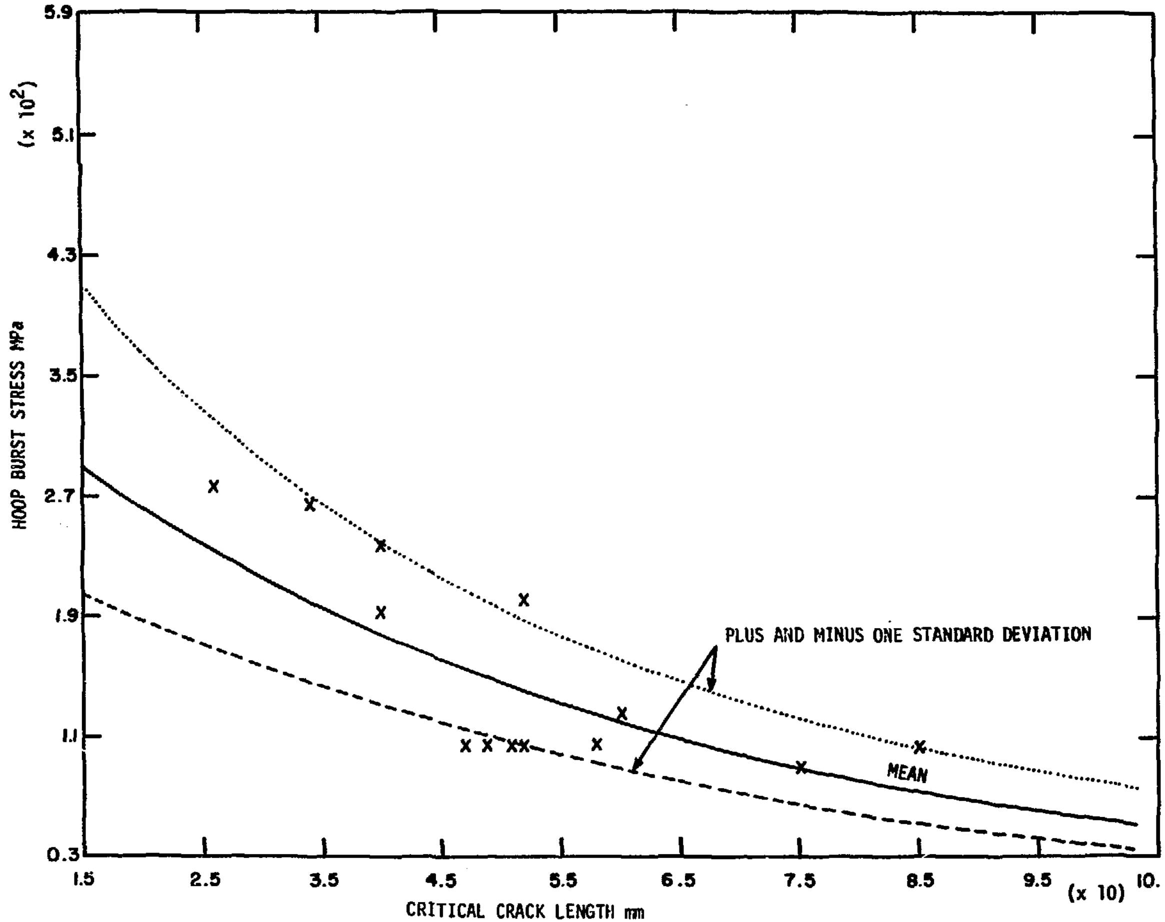

FIGURE 13: BURST HOOP STRESS VERSUS CRITICAL CRACK LENGTH FOR SHARP CRACKS AT 23-32°C

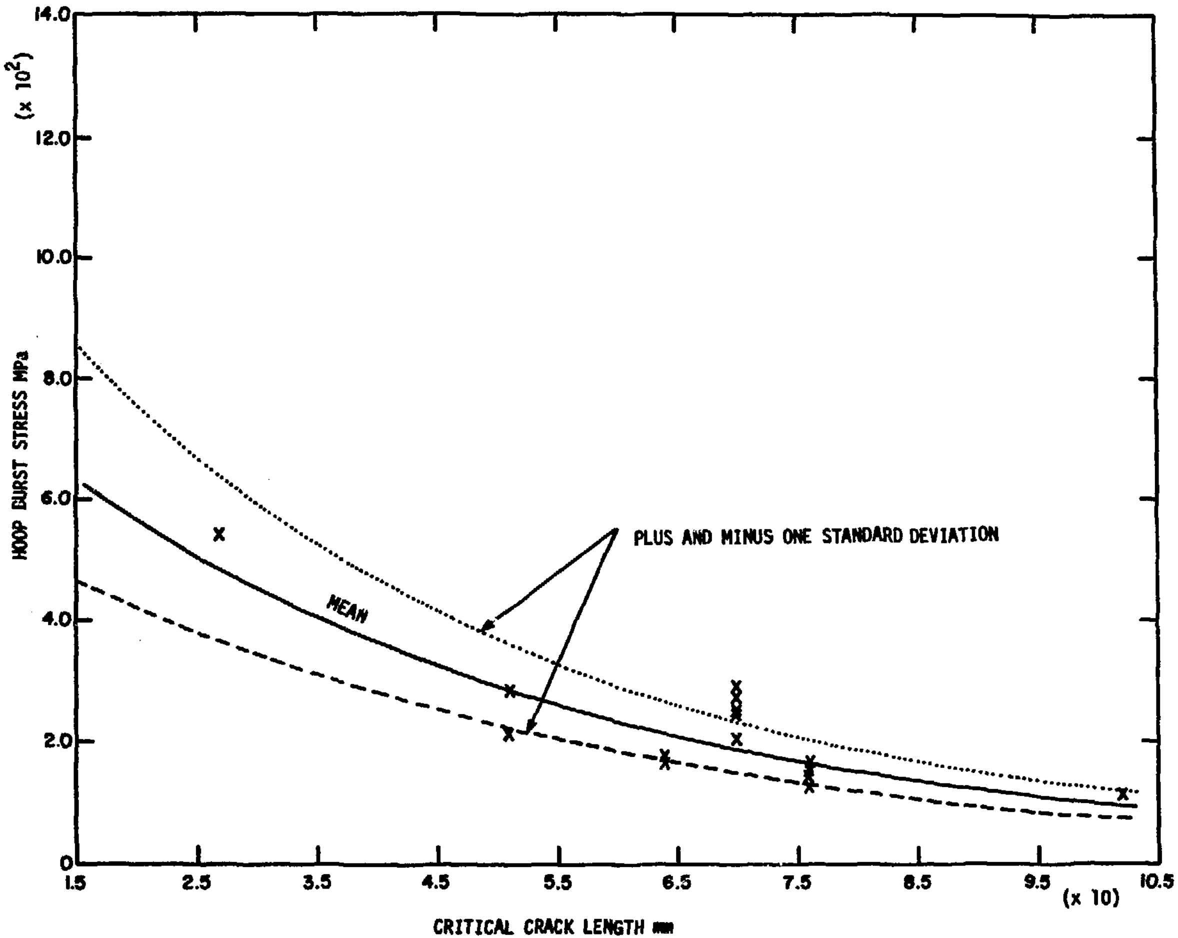

FIGURE 14: BURST HOOP STRESS VERSUS CRITICAL LENGTH FOR BLUNT CRACKS AT 240-300°C

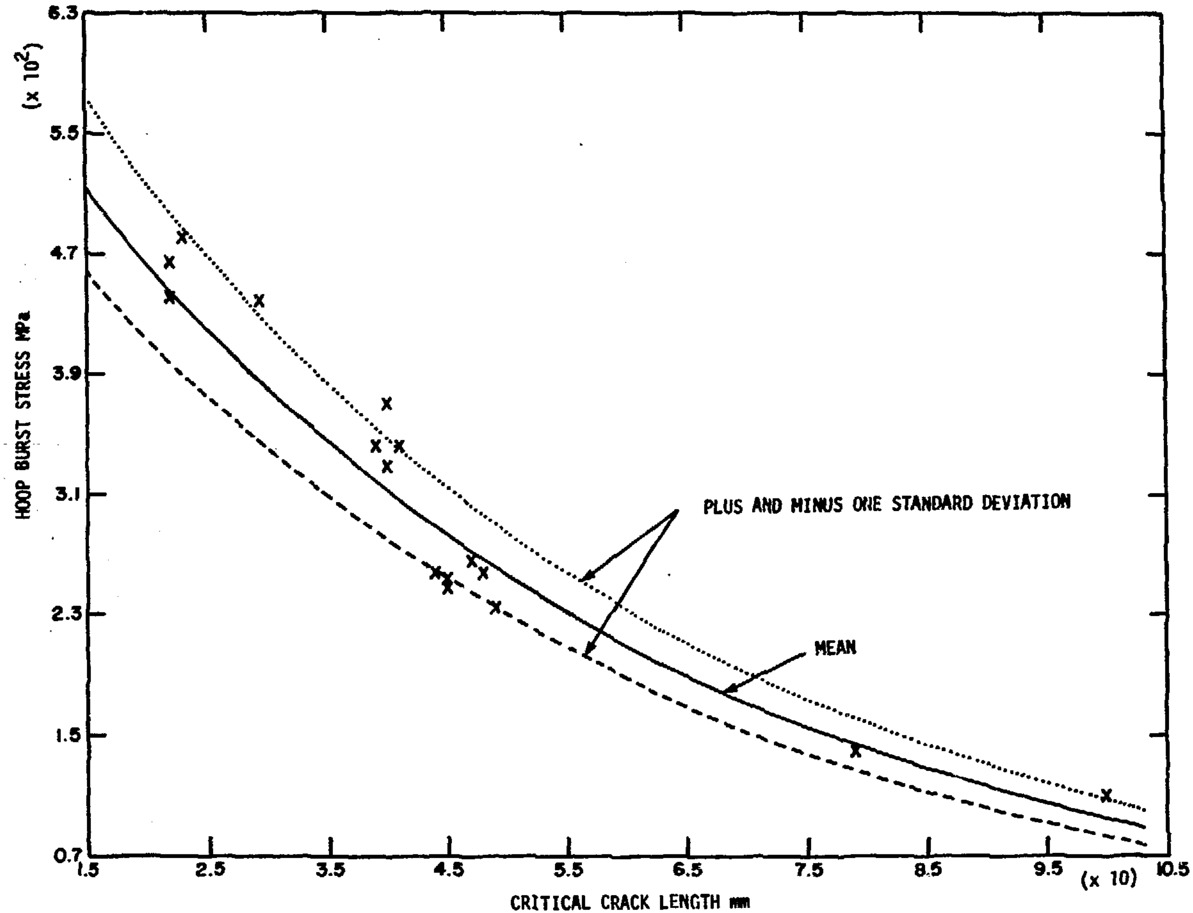

FIGURE 15: BURST HOOP STRESS VERSUS CRITICAL CRACK LENGTH FOR SHARP CRACKS AT 237-300°C

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