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Results of Crack-Arrest Tests on Two Irradiated High-Copper Welds

Prepared by
S. K. Iskander, W. R. Corwin, R. K. Nanstead

Oak Ridge National Laboratory

Prepared for
U.S. Nuclear Regulatory Commission

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Prepared by
S. K. Iskander, W. R. Corwin, R. K. Nanstead

Oak Ridge National Laboratory
Operated by Martin Marietta Energy Systems, Inc.

Oak Ridge National Laboratory
Oak Ridge, TN 37831-6285

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NOMENCLATURE

ACRONYMS

ASME	American Society of Mechanical Engineers
CMOD	crack mouth opening displacement
CVN	Charpy V-notch
dpa	displacements per atom
DX	duplex
EPRI	Electric Power Research Institute
HSSI	Heavy-Section Steel Irradiation
ORNL	Oak Ridge National Laboratory
NDT	nil-ductility-transition temperature, as determined by the drop-weight test according to ASTM E 208
NRC	U.S. Nuclear Regulatory Commission
RPVs	reactor pressure vessels
RT_{NDT}	reference nil-ductility-transition temperature, determined in accordance with Subarticle NB-2330 of *ASME Boiler and Pressure Vessel Code, Sect. III*
WE	weld-embrittled

SYMBOLS

a	initial slot length a_o or final crack length a_a
a_a	arrested crack length
a_o	initial slot length
B	specimen thickness (Fig. 2)
B_N	specimen thickness at crack plane (Fig. 2)
D	split-pin hole diameter (Fig. 2)
δ	crack mouth opening displacement
$\Delta TT_{41\text{-}J}$	shift in the 41-J CVN-impact energy level
E	Young's modulus
$f(x)$	crack-arrest specimen calibration function [Eq. (2)]
ϕ	fluence, neutrons/cm^2
$2H$	specimen height (Fig. 2)
K_a	value of the stress intensity factor shortly after arrest*
K_o	value of the stress intensity factor at crack initiation
K_I	stress intensity factor
K_{Ia}	value of the crack-arrest fracture toughness K_a for a crack that arrests under conditions of crack front plane-strain*
K_{Ic}	plane-strain fracture toughness
K_{Jc}	a measure of fracture toughness calculated from the J-integral J_c at the point of cleavage using the relationship $(K_{Jc})^2 = EJ_c$
K_o	value of the stress intensity factor at crack initiation
L, L'	(See Fig. 2)

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*Excerpted from ASTM E 1221-88.

SYMBOLS

N	slot width
T	test temperature
W	nominal width of a crack-arrest specimen
W_t	total width of a crack-arrest specimen (Fig. 2)
x	fractional crack depth a/W

FOREWORD

The work reported here was performed at Oak Ridge National Laboratory (ORNL) under the Heavy-Section Steel Irradiation (HSSI) Program, W. R. Corwin, Program Manager. The program is sponsored by the Office of Nuclear Regulatory Research of the U.S. Nuclear Regulatory Commission (NRC). The technical monitor for the NRC is A. Taboada.

This report is designated HSSI Report 3. Reports in this series are listed below:

1. F. M. Haggag, W. R. Corwin, and R. K. Nanstad, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., Oak Ridge, Tenn., *Irradiation Effects on Strength and Toughness of Three-Wire Series-Arc Stainless Steel Weld Overlay Cladding*, NUREG/CR-5511 (ORNL/TM-11439), December 1989.

2. L. F. Miller, C. D. Baldwin, F. W. Stallman, and F. B. K. Kam, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., Oak Ridge, Tenn., *Neutron Exposure Parameters for the Metallurgical Test Specimens in The Sixth Heavy-Section Steel Irradiation Series*, NUREG/CR-5409 (ORNL/TM-11267), May 1990.

3. This report.

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RESULTS OF CRACK-ARREST TESTS ON TWO IRRADIATED HIGH-COPPER WELDS*

S. K. Iskander
W. R. Corwin
R. K. Nanstad

ABSTRACT

The objective of this study was to determine the effect of neutron irradiation on the shift and shape of the lower-bound curve to crack-arrest data. Two submerged-arc welds with copper contents of 0.23 and 0.31 wt % were commercially fabricated in 220-mm-thick plate. Crack-arrest specimens fabricated from these welds were irradiated at a nominal temperature of 288°C to an average fluence of 1.9×10^{19} neutrons/cm^2 (>1 MeV). Evaluation of the results shows that the neutron-irradiation-induced crack-arrest toughness temperature shift is about the same as the Charpy V-notch impact temperature shift at the 41-J energy level. The shape of the lower-bound curves (for the range of test temperatures covered) did not seem to have been altered by irradiation compared to those of the ASME K_{Ia} curve.

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1. INTRODUCTION

In the fracture mechanics integrity analysis of reactor pressure vessels (RPVs), the initiation and arrest fracture toughness curves as described in Sect. XI of *ASME Boiler and Pressure Vessel Code* are often used. These curves are used also for the normal operation of RPVs. The effects of neutron irradiation on toughness are accounted for by shifting the curves upward in temperature without change in shape by an amount equal to the temperature shift of the Charpy V-notch (CVN) impact energy curve at the 41-J level ($\Delta TT_{41\text{-}J}$). Such a procedure implies that the shifts in the fracture toughness curves are the same as that of the CVN $\Delta TT_{41\text{-}J}$ and that irradiation does not change the shapes of the fracture toughness curves.

It is well known that irradiation of some RPV ferritic steels to fluences on the order of 2×10^{19} neutrons/cm^2 (>1 MeV) can cause changes in the shape of the CVN impact energy curve. To determine whether similar changes in shape can occur in the fracture toughness curves, particularly if such changes could lead to non-conservative determinations of the irradiated fracture toughness, research programs are sponsored by the U.S. Nuclear Regulatory Commission (NRC) within the Heavy-Section Steel Irradiation (HSSI) Program at Oak Ridge National Laboratory (ORNL).

Two of these programs are the Fifth and Sixth Irradiation Series. The objective of the Fifth Series was to determine the effect of neutron irradiation on the shift and shape of the K_{Ic} vs (T-RT_{NDT}) curve, where K_{Ic} is the plane-strain fracture toughness, T is the temperature, and RT_{NDT} is the reference nil-ductility-transition temperature. Although the objective is similar, the Sixth Series investigates the effect on K_{Ia}, the plane-strain crack-arrest fracture toughness. Both programs investigate the effects of irradiation on the fracture toughness of welds, since some pressure vessels in operation have welds with copper contents and end-of-life fluences which make them susceptible to severe degradation in toughness. The amount of experimental data on the effects of irradiation on crack-arrest fracture toughness is rather meager (Refs. [1] and [2]).

Two submerged-arc welds with copper contents of 0.23 and 0.31 wt % were commercially fabricated in 220-mm-thick plate. In the Fifth Irradiation Series, irradiated CVN impact, tensile, drop-weight, and compact specimens, made from the weldment were tested and the results are given in Refs. [3] and [4].

Crack-arrest specimens fabricated from these welds were irradiated at a nominal temperature of 288°C to an average fluence of 1.9×10^{19} neutrons/cm^2 (>1 MeV). This report compares the results of crack-arrest tests on 36 irradiated weld-embrittled-type specimens with those from unirradiated control specimens. Since this is only the first phase of a two-phase program, the conclusions presented here are preliminary.

2. DESCRIPTION OF MATERIALS AND PROCEDURES

The weld wire for both programs was produced commercially in one melt. The melt was split to allow for copper additions and resulted in two weld wires that were comparable in chemical composition except for copper. Several meters of weldment were commercially fabricated from each weld wire and were designated 72W (0.23 wt % Cu) and 73W (0.31 wt % Cu). The welds were commercially fabricated in A 533, grade B, class 2 plate of 220-mm (8 5/8-in.) thickness by using the submerged-arc weld process with one lot of Linde 0124 flux. A macrograph of weld 72W is shown in Fig. 1, and the chemical compositions of both welds are given in Table 1. The welds were given a postweld heat treatment of 607°C for 40 h, typical of that given commercial RPVs.

Two capsules, each containing 30 compact crack-arrest specimens of the two weldments, have been irradiated at a nominal temperature of 288°C to a fluence of approximately 1.9×10^{19} neutrons/cm^2 (>1 MeV) in the Oak Ridge Research Reactor located at the ORNL. The irradiated specimen complement is given in Table 2, which gives the overall specimen dimensions. The complete nominal specimen dimensions are given in Fig. 2 and Table 3. For administrative purposes, the program was conducted in two phases. This report presents results of Phase 1 which consisted of crack-arrest tests on the 36 weld-embrittled-type specimens. In Phase 2, the results from remaining 24 duplex-type crack-arrest specimens will be reported.

2.1 Testing Procedures

Testing was performed according to the ASTM "Test for Determining Plane-Strain Crack-Arrest Fracture Toughness, K_{Ia}, of Ferritic Steels" (E 1221-88). Crack-arrest testing of the irradiated specimens was performed in a hot cell by using a servohydraulic machine and the test chamber shown schematically in Fig. 3, and photographically in Fig. 4. This equipment allows specimens to be tested with the split pins in either the so-called "normal" or "inverted" configuration at test temperatures ranging from -100 to 260°C.* In the "normal" configuration, the lateral surfaces of the specimen are in contact with the test-machine platen and friction decreases the crack-driving force somewhat compared with the "inverted" configuration in which the specimen sits on the narrow shoulders of the split pin. The "inverted" configuration is used at testing temperatures above NDT. For further information on the "normal" and "inverted" test configuration in crack-arrest testing, see Note 5 of ASTM E 1221-88.

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*This temperature range was chosen during the design phase of the test chamber on the basis of the anticipated test temperature. The maximum temperature is limited by the Teflon™ insert in the contact thermocouple.

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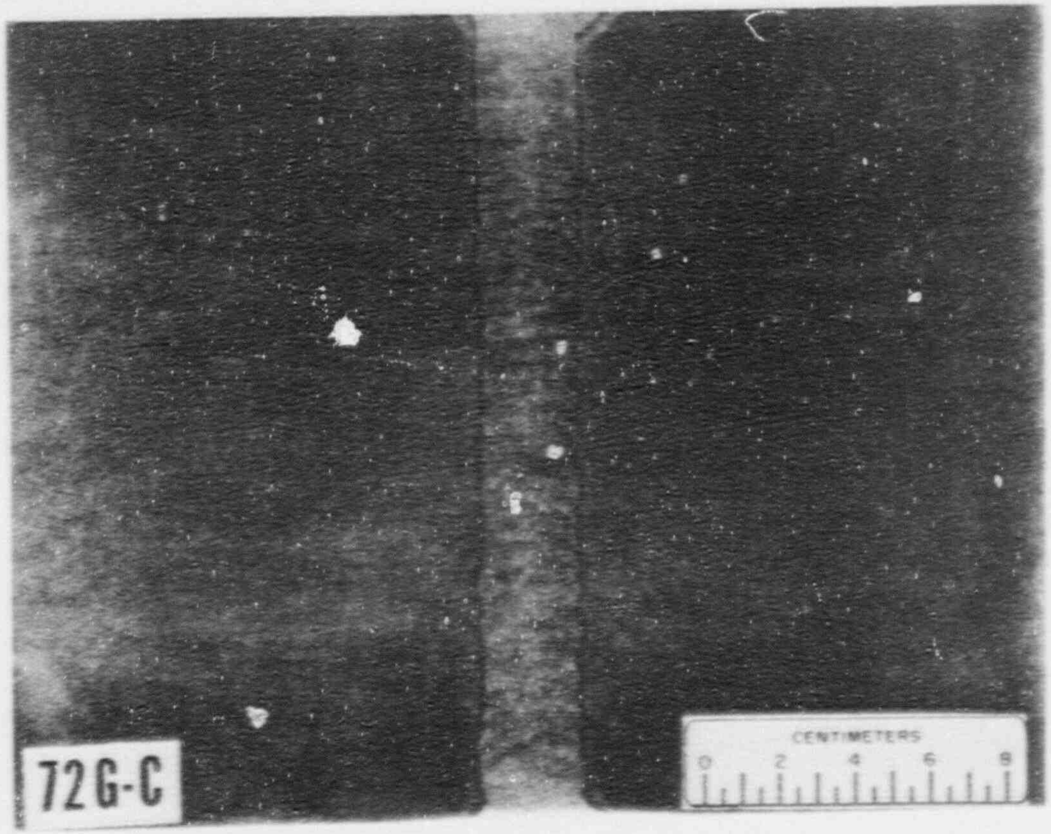

Fig. 1. Cross section of typical submerged-arc weld used in the 72W and 73W welds used in the Fifth and Sixth Irradiation Series.

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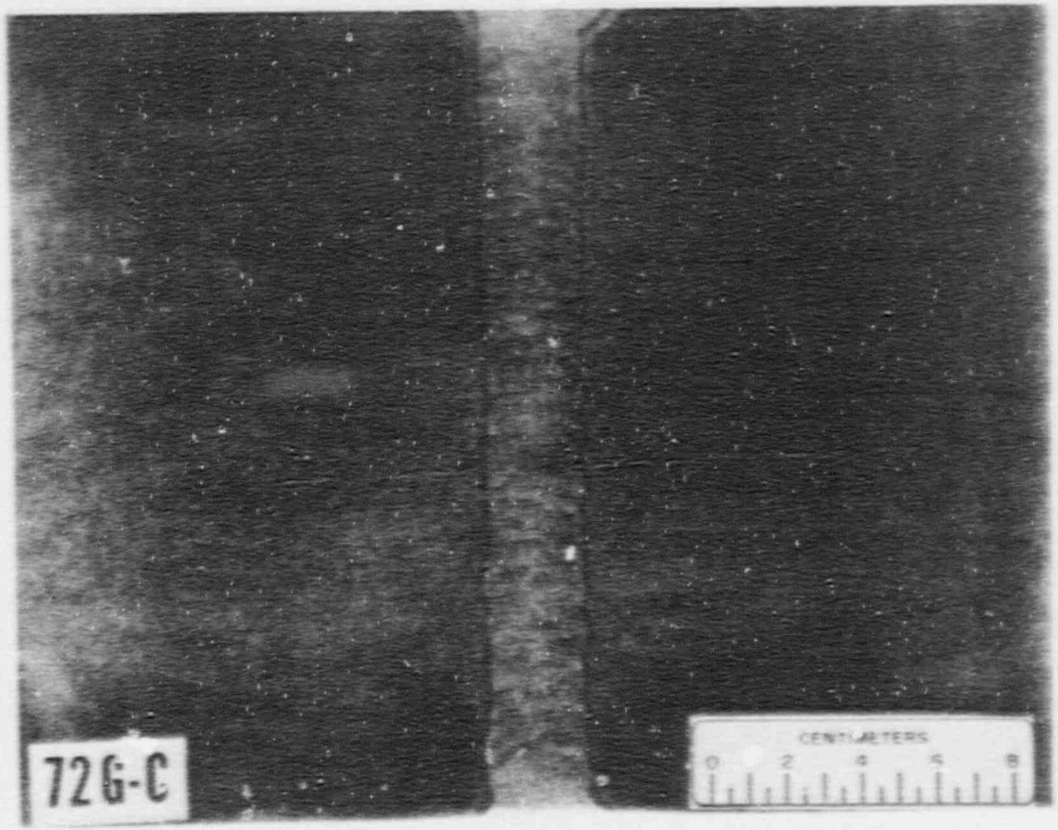

Fig. 1. Cross section of typical submerged-arc weld used in the 72W and 73W welds used in the Fifth and Sixth Irradiation Series.

Table 1. Chemical composition of the two submerged-arc welds in the Fifth and Sixth Irradiation Series

Material	Composition (wt %)									
	C	Mn	P	S	Si	Cr	Ni	Mo	Cu	V
72W	0.093	1.60	0.006	0.006	0.44	0.27	0.60	0.58	0.23	0.003
73W	0.098	1.56	0.005	0.005	0.45	0.25	0.60	0.58	0.31	0.003

Source: Values based on formula from R. K. Nanstad et al., "Effects of Irradiation on K_{Ic} curves for High-Copper Welds," pp. 214-33 in *Effects of Radiation on Materials, 14th International Symposium*, ASTM STP 1046, Vol. II, ed. N. H. Packan, R. E. Stoller, and A. S. Kumar, American Society for Testing and Materials, Philadelphia, 1990.

Table 2. Irradiated crack-arrest specimen complement for each of the 72W and 73W weldments

Specimen type	Dimensions (mm)	Quantity per weld
Weld embrittled	25 × 76 × 76	8
Weld embrittled	25 × 152 × 152	7
Weld embrittled	33 × 152 × 152	3
Duplex	33 × 152 × 152	12

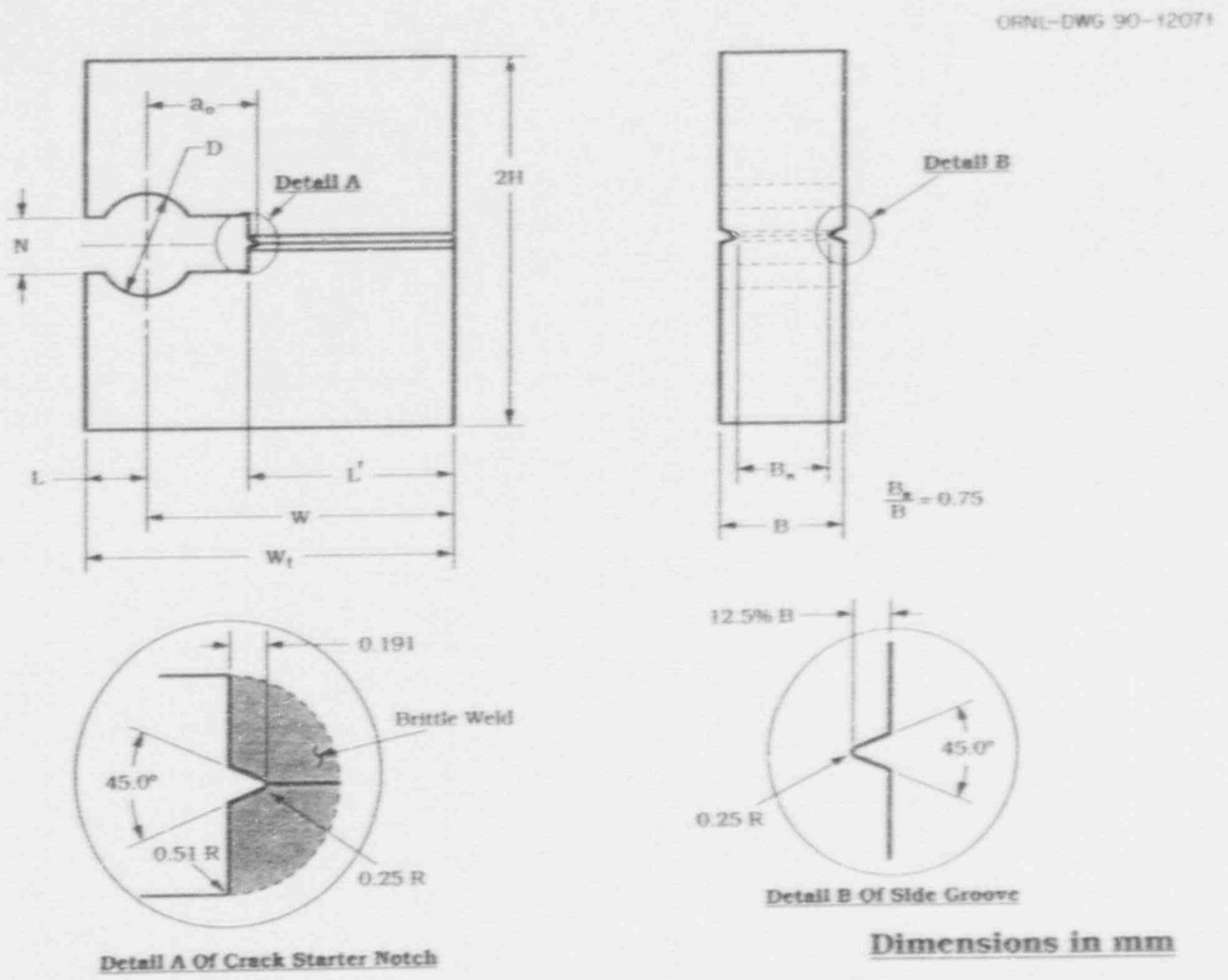

Fig. 2. Nominal dimensions in millimeters of weld-embrittled crack-arrest specimens used in the Sixth Irradiation Series.

Table 3. Nominal dimensions of weld-embrittled crack-arrest specimens used in the Sixth Irradiation Series

(All dimensions are in millimeters)

Nominal specimen size	W	a_o	a_o/W	B	W_t	2H	L	D	L'
72W and 73W weldments									
25 × 76 × 76	63.50	20.96	0.33	25.40	76.20	76.20	12.70	21.06	44.45
72W weldment									
25 × 152 × 152		43.82-44.45	0.345-0.350						84.46-85.09
33 × 152 × 152		43.82-45.09	0.345-0.355						83.82-85.09
73W weldment									
25 × 152 × 152	127.00	49.53	0.39	25.40	152.40	152.40	25.40	31.75	79.38
33 × 152 × 152	127.00	49.53	0.39	33.02	152.40	152.40	25.40	31.75	79.38

[a] To accommodate the crack-starter notch within the brittle weld, L' had to be adjusted. The values shown reflect the range for the a_o, a_o/W, and L' dimensions. All other dimensions are the same for both the 72W and 73W weldments.

NOTE:

- a_o – initial slot length.
- B – specimen thickness.
- D – split-pin hole diameter.
- 2H – specimen height.
- L,L' – see fig. 2.
- W – nominal width of crack-arrest specimen.
- W_t – total width of crack-arrest specimen.

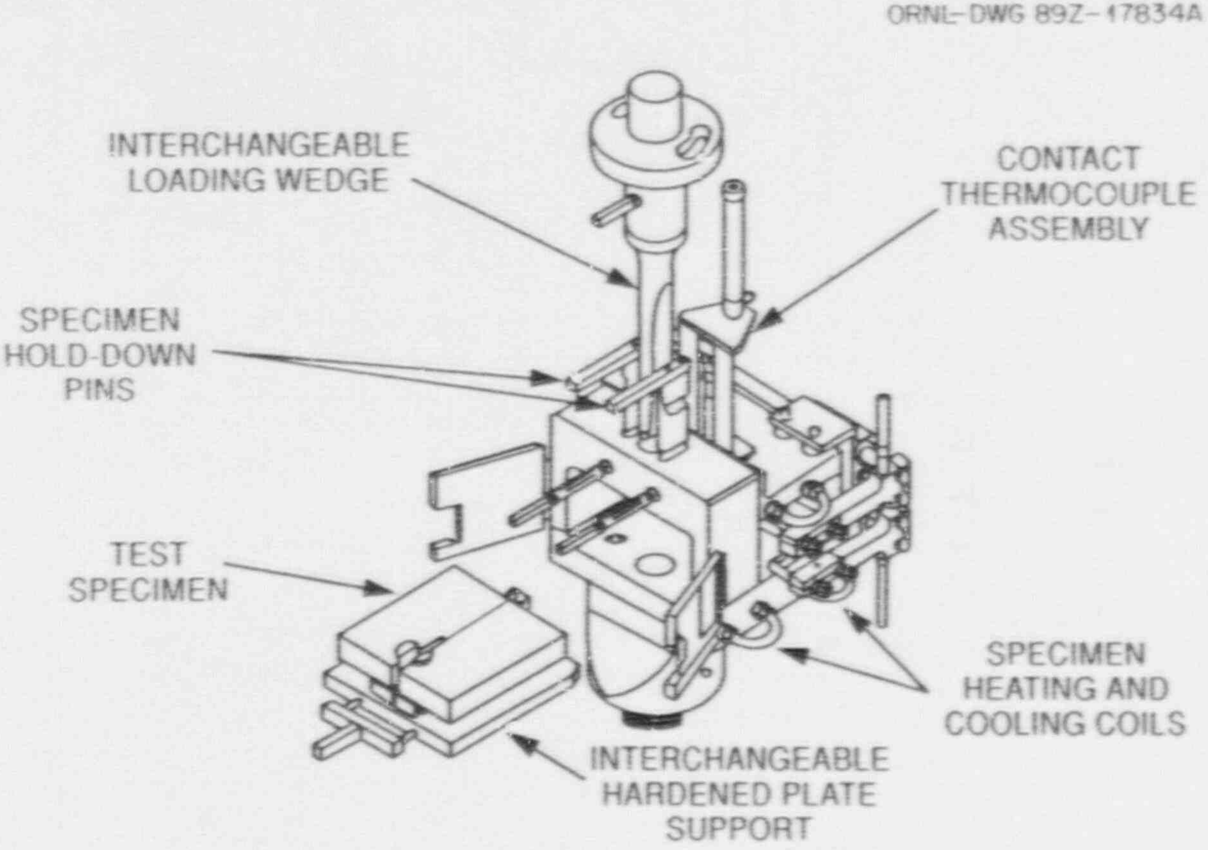

Fig. 3. Schematic drawing of equipment used to perform crack-arrest testing of irradiated specimens before set-up in the hot-cell 500-kN testing machine.

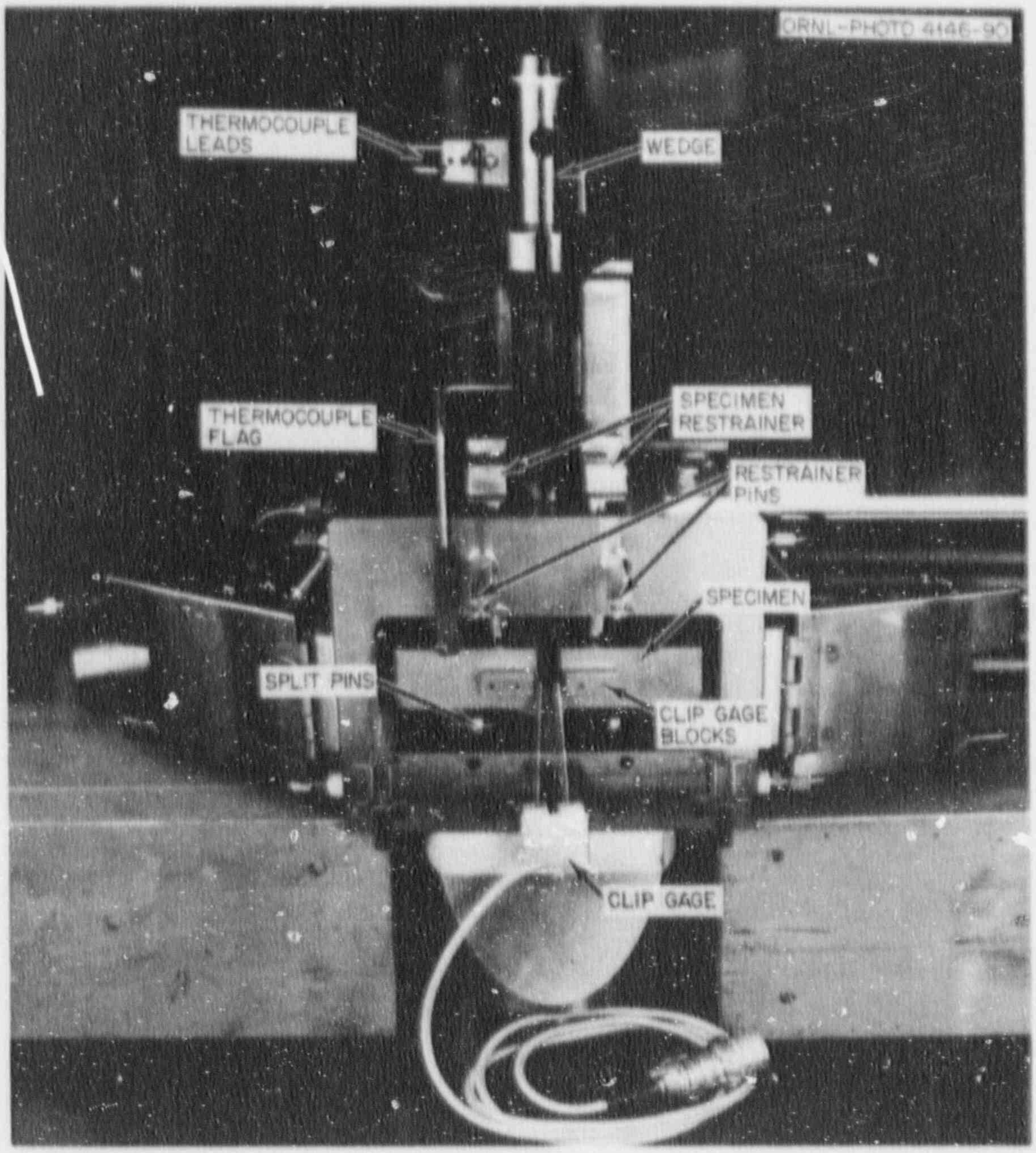

Fig. 4. Photograph of equipment used to perform crack-arrest testing of irradiated specimens before set-up in the hot-cell 500-kN testing machine.

Figure 5 shows a closeup view of the environmental chamber used for temperature conditioning of the crack-arrest specimens after it was installed in the hot cell 500-kN tensile testing machine. Figure 6 gives a general view of the test system as it is being prepared for a crack-arrest test.

Temperature conditioning below ambient is obtained by venting cold nitrogen gas into the chamber containing the crack-arrest specimen. Above ambient, temperature control is achieved by means of six heater elements. Four of these elements are cartridge type and are embedded in the base of the fixture. Two U-shaped heater elements can be moved into place below or above the specimen. After the specimen is positioned in the fixture, a contact thermocouple is lowered onto the specimen surface near the midpoint of the crack path to measure the specimen temperature.

Considerable effort was made to ensure temperature uniformity and accuracy in each crack-arrest specimen. Specimens of A 533B steel and of the same three sizes as those to be tested were instrumented with thermocouples and thermally conditioned in the fixture over the relevant temperature range in both normal and inverted configurations. The uniformity and accuracy of the temperature throughout the specimen were within ±1°C when compared to the values measured by the contact thermocouple used during testing.

The clip gage used for the irradiated specimen tests was specially designed and fabricated at ORNL. Long clip-gage arms were incorporated in the design to measure the crack mouth opening displacement (CMOD) from outside the temperature conditioning chamber. The arms are instrumented with temperature-compensated electrical resistance strain gages. Moreover, tests outside the hot cell have shown that the clip-gage temperature is $< 35°C$ when the specimen temperature[*] is 350°C. Since the maximum test temperature for this series of tests is under 150°C, the clip-gage is calibrated at room temperature with no significant loss in accuracy. The clip-gage was calibrated in the hot cell with a Boekler micrometer before and after every test since the CMOD (not the load) measured during the test is central to the determination of the crack-arrest toughness K_a. The error in K_a due to errors in the measurement of CMOD is estimated to be less than 2%.

An irradiated specimen to be tested is placed in the conditioning chamber, and special "knives" are used to center the specimen beneath the loading wedge. The sides of the loading wedge were covered with a replaceable strip of Teflon™ to reduce the friction between the wedge and the split pins. The testing machine ram was then raised until the loading wedge just touches the split pins (a load of about 40 N); then the ram is lowered until no-load is indicated. The centering "knives" were then removed since the proper position of the specimen is maintained by the inserted load wedge. The clip-gage is then seated in conical grooves of gage blocks welded (prior to irradiation) to the crack-arrest

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[*] For the purposes of this test, thermocouples were tack-welded to the test specimen.

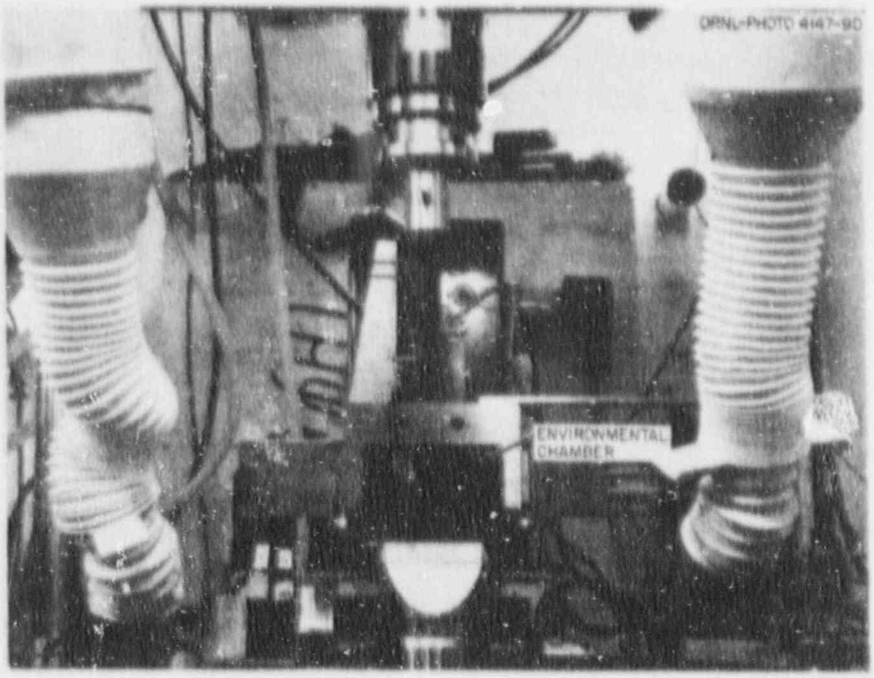

Fig. 5. Closeup view of the environmental chamber used for temperature conditioning of the crack-arrest specimens after installation in the hot-cell 500-kN tensile testing machine.

Fig. 6. General view of the test system as it is being prepared for a crack-arrest test.

specimen. The load vs CMOD is recorded on an X-Y plotter together with the clip-gage calibration marks; a typical chart from a test is shown in Fig. 7. The charts from all the irradiated tests are included in Appendix E. As mentioned above, the value of the load is not used in the calculation of K_a. However, the plot of load vs CMOD is indispensable in the conduct of the test and determination of the CMOD at various points in the loading-unloading cycles (see ASTM E 1221-88).

2.2 Analysis Procedures

The arrested crack front is marked by heat-tinting the specimen after testing. The specimen is then cooled with liquid nitrogen and broken open. The length of the remaining ligament for each specimen is obtained by measuring the position of the arrested crack front by using the averaging procedure prescribed in ASTM E 1221-88. In the case of irradiated specimens, a digitizing tablet was used to measure the length of the remaining ligament on a photograph taken through a Kollmorgan™ periscope of the broken specimen half. Typical fracture surfaces for two 33- × 152-mm specimens are shown in Fig. 8 (photographs of the fracture surfaces of all the specimens tested are given in Appendix E). Numerous unbroken ligaments, typical for pressure vessel steels at these test temperatures, can be observed on the fracture surface of the specimens. The known dimensions of the specimen serve as the scale for these measurements. In the case of the unirradiated specimens, the length of the remaining ligament is directly measured by a digital measuring microscope. The errors due to the *measurement method* are estimated to be less than those due to the *shape* of the crack front.

To estimate accuracy of the crack-arrest toughness, two values of the stress intensity factor (K_o and K_a) are calculated. The former is the stress intensity factor at crack initiation, and the latter is the value shortly after arrest. Both values are calculated by substituting appropriate values in the following expressions given in ASTM E 1221-88:

$$K = E \delta f(x) \sqrt{[B/(B_N W)]} \ , \qquad (1)$$

where f(x) = crack-arrest specimen calibration function defined as follows:

$$f(x) = \frac{2.24 (1.72 - 0.9x + x^2) \sqrt{(1 - x)}}{(9.85 - 0.17x + 11x^2)} \ , \qquad (2)$$

and

$x = a/W$,

E = Young's modulus,

a = initial slot length a_o or arrested (final) crack length a_a,

W = specimen width,

B = specimen thickness,

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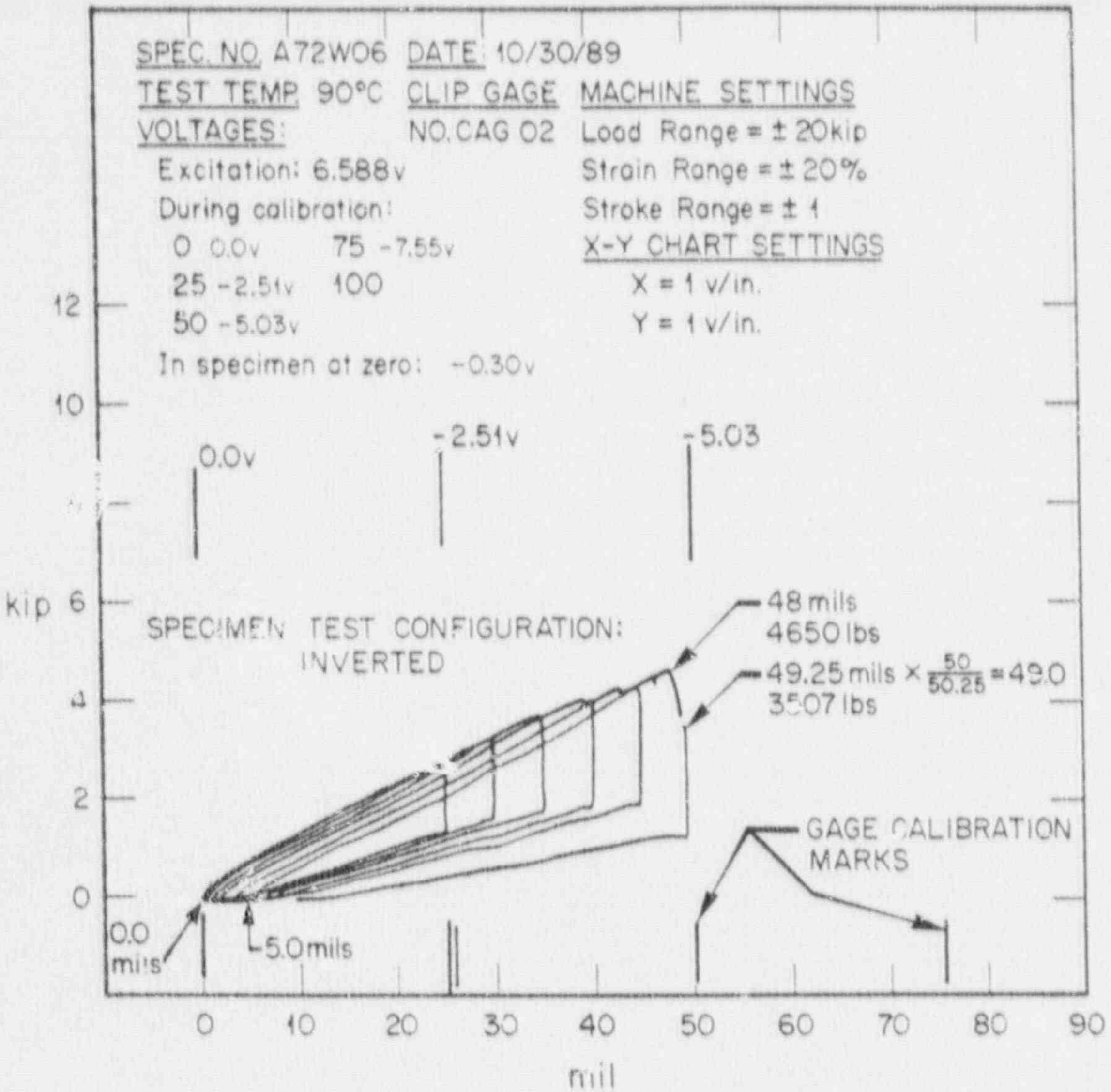

Fig. 7. Chart produced on an X-Y plotter during a typical crack-arrest test of an irradiated specimen.

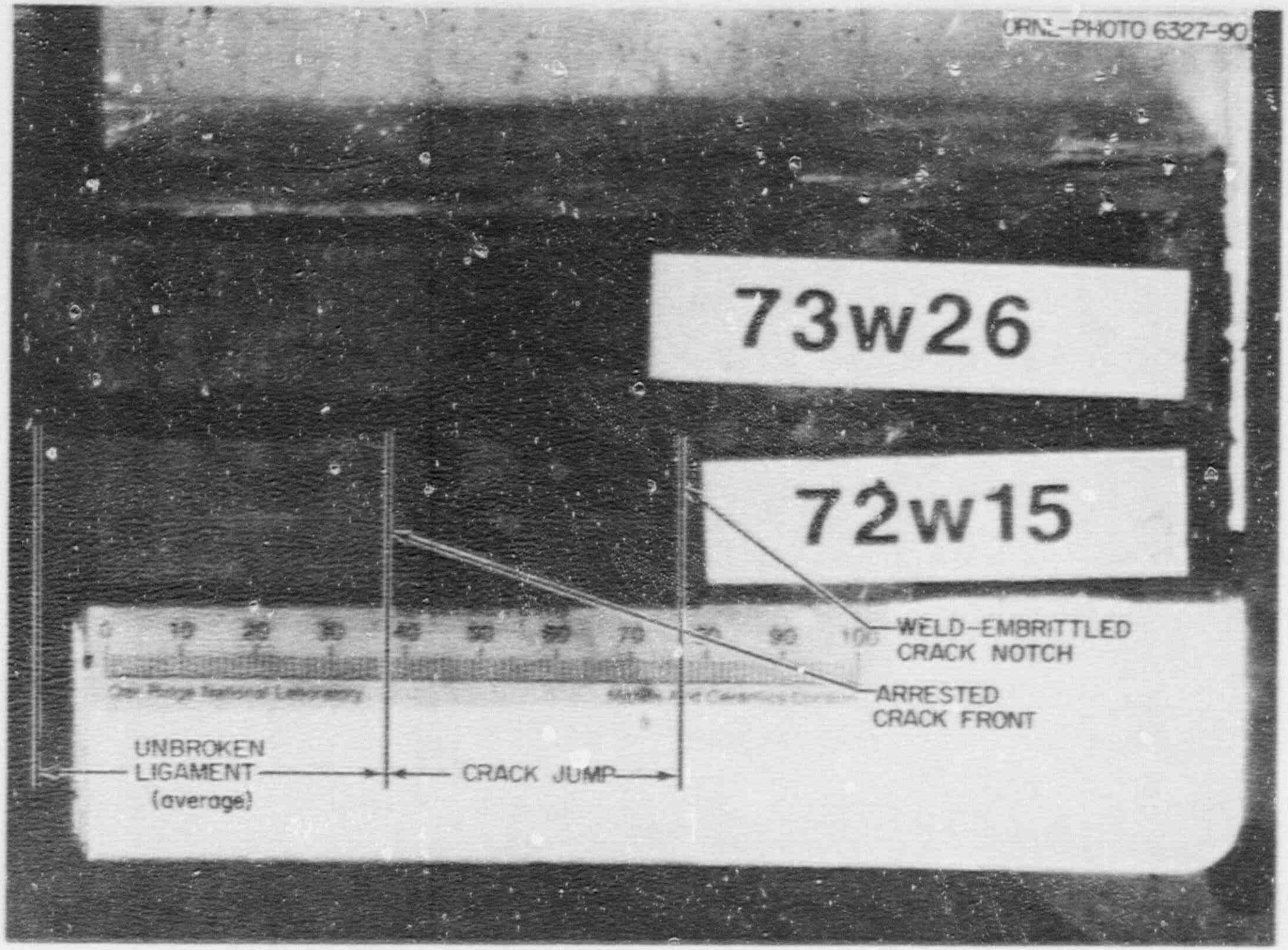

Fig. 8. Photograph taken through a Kollmorgen periscope of the fracture surfaces of two typical crack-arrest specimens after heat-tinting and splitting them open. The 2- or 3-mm, darker, transverse strips near the initial crack front are the brittle crack-starter weld beads.

B_N = specimen thickness at crack plane,

δ = CMOD.

If all other values are unchanged the error in K is directly proportional to the error in δ (given above). The error in K due to errors in crack length is estimated as described below.

In Eq. (1), if all other values are constant, the error in K is equal to that of f(x) due to the error in the fractional crack length x. Table 4 shows various estimates of the errors in f(x) resulting from the measurement of the initial slot length a_0 and arrested crack length a_a and for the various specimen sizes. A plot of f(x) vs fractional crack length x, shown in Fig. 9, is nearly linear in x. However, because f(x) decreases as x increases, the absolute value of the average relative error in f(x) increases as x increases. The average relative error is defined as:

$$\frac{1}{2}\;\frac{f[(1+e)\,x] - f[(1-e)\,x]}{f(x)}$$

Two relevant values of x are 0.33 for the initial slot length and 0.85 for the final crack length. The former is the minimum value for the crack-arrest specimens manufactured for the Sixth Series program, and the latter is the maximum valid value allowed by ASTM E 1221-88. A ±1% change for $x = 0.33$ results in a ∓0.5% change in f(x), while the same +1% change for $x = 0.85$ results in an approximately ∓3% change in f(x).

The determination of a_0 is performed with a digital measuring microscope, and the error is estimated to be < 0.2 mm, irrespective of the specimen size. Hence the maximum error in f(x) (and K_0) for the initial slot length is ±0.5% for a small specimen and even less for a large specimen. In both cases, the initial slot length is used to estimate K_0, which gives an estimate of K at the onset of rapid fracture. It is an estimate at best because the crack at initiation is not a sharp one and has a finite root radius. Moreover, K_0 is of interest to the experimenter only.

As mentioned, the measurement of the final crack length a_a is performed according to ASTM E 1221-88 by an averaging procedure. Since it is rare that the arrested crack front is square or straight (Fig. 8), it is difficult to estimate the error in such a determination. From the expression for K_a given in ASTM E 1221-88, estimates of the error were made by using different values of the arrested crack length to obtain bounds on the error. A maximum value of a_a is 54 mm for a small 25 × 76 × 76 mm specimen since this is the maximum length permitted in E 1221-88 for this specimen size. Errors of ±1 or ±2 mm in a_a for this case result in errors of ∓6.5% or ∓13%, respectively, in K_a. A similar procedure was followed for the large (33 × 152 × 152 mm) specimen. The error estimates are summarized in Table 4. The total maximum error in K_a from all sources is estimated to be approximately ±10% for the small specimens and ±5% for the large ones.

Table 4. Estimate of the average relative error[a] in f(x) (and thus in K_a) due to errors in the determination of initial and final crack lengths $x = a_o/W = 0.33$ and $x \simeq a_a/W = 0.85$, respectively, for the various specimen sizes

	Inital crack length a_o					Final crack length a_a			
			Errors in				Errors in		
Specimen size[b]	W (mm)	a_o (mm)	a_o (mm)	a_o/W (%)	f(x) (%)	a_a (mm)	a_a (mm)	a_a/W (%)	f(x) (%)
Small	63.5	21	0.2	±1	∓0.5	54	±1 ±2	±2 ±4	∓6.5 ∓13
Large	127	44	0.2	±0.5	∓0.2	108	±1 ±2	±1 ±2	∓ 3 ∓6.5

[a] Defined as $\frac{1}{2}\{f[(1+e)\bullet x] - f[(1-e)\bullet x]\}/f(x)$.

[b] The 25 × 76 × 76 mm specimens are the small specimens, while the 25 (or 33) × 152 × 152 mm ones are the large ones.

NOTE:

a_a - arrested crack length.
a_o - initial slot length.
f(x) - crack-arrest specimen specimen calibration function.
k_a - value of stress intensity factor shortly after arrest.
W - width.

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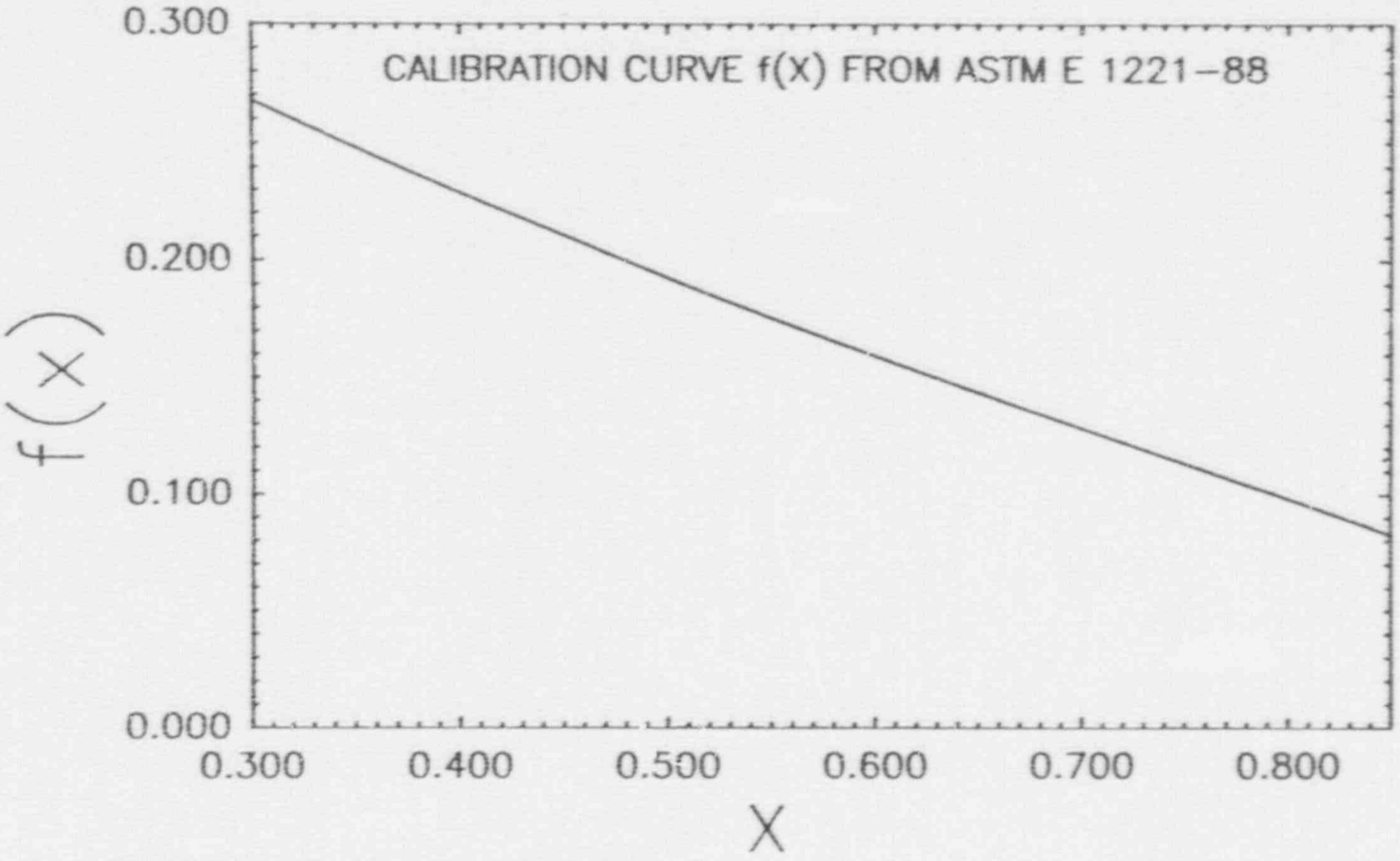

Fig. 9. Calibration function for crack arrest specimens as given in ASTM E 1221-88.

3. RESULTS AND DISCUSSION

The temperature control for the two irradiation capsules, each containing 30 specimens, was excellent. The temperature most of both weld-embrittled and duplex-type specimens (22 in one capsule and 23 in the other) ranged from 286 to 290°C, while the few remaining specimens were irradiated at temperatures ranging from 280 to 286°C. The average irradiation temperature of the weld-embrittled-type crack-arrest specimens is 286 and 285°C for the 72W and 73W specimens, respectively. For both 72W and 73W specimens, the fluences to which the weld-embrittled-type crack-arrest specimens were irradiated ranged from approximately 1.4 to 2.4 × 10^{19} neutrons/cm^2 (>1 MeV), and the average fluence and standard deviation is approximately 1.9 and 0.3 × 10^{19} neutrons/cm^2 (>1 MeV), respectively. Bar charts showing the distribution of fluence of the specimens successfully tested, 18 and 17 from the 72W and 73W weldments, respectively, are given in Figs. 10 and 11, respectively. The average irradiation temperature and the exposure values of each specimen are given later in this report. A summary of the irradiation data for the weld-embrittled specimens tested in Phase 1 is given in Table 5. Detailed reports on the dosimetry and operating history of the two capsules will be published separately.

The yield strength and Young's modulus of the test material are required in crack-arrest testing. Young's modulus is calculated from the following expression, from Ref. [5]: $E = 207.2 - 0.0571T$, where E = Young's modulus in GPa, and T = temperature in °C (discussed also in Appendix C). The unirradiated and irradiated tensile strengths have been reproduced from Ref. [3] in Figs. 12 and 13 for welds 72W and 73W, respectively. The average fluence of the tensile samples, approximately 1.6 × 10^{9} neutrons/cm^2 (>1 MeV), is about 15% less than that for the crack-arrest specimens. This difference will not affect the values of the crack-arrest toughnesses K_a but <u>could</u> have a small effect on the validity of each specimen as it is prescribed in ASTM E 1221-88. The observations in this report are preliminary.

The RT_{NDT} values for both weldments in the unirradiated and irradiated conditions are given in Table 6 (from Refs. [3] and [4]). The initial RT_{NDT} values were determined in accordance with Subarticle NB-2330 of *ASME Boiler and Pressure Vessel Code*, Sect. III, and are the same as the drop-weight NDT values. The "adjusted" RT_{NDT} values were determined according to paragraph 10.2.2 of ASTM E 185-82 by adding the CVN $\Delta TT_{41\text{-}J}$ values to the initial RT_{NDT} values. The CVN $\Delta TT_{41\text{-}J}$ shifts have been determined from a relatively large number of specimens, as shown in Fig. 14 (also from Refs. [3] and [4]). Approximately 84 and 56 unirradiated and irradiated CVN specimens were tested from each of the 72W and 73W welds respectively. The average fluence of CVN-impact energy specimens for both the 72W and 73W weldments is 1.51 × 10^{19} neutrons/cm^2,

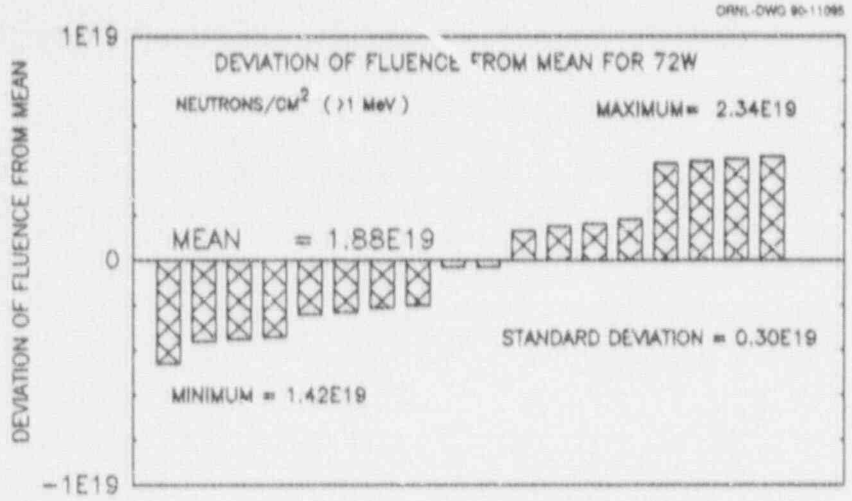

Fig. 10. Distribution of fluence in the 18 irradiated weld-embrittled-type crack specimens tested from the 72W weld.

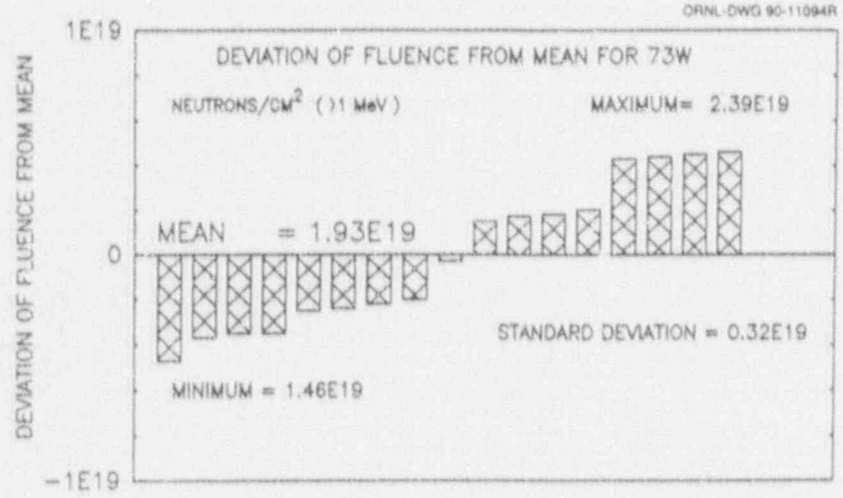

Fig. 11. Distribution of fluence in the 17 irradiated crack specimens of the 73W weld that were tested successfully.

Table 5. Summary of the irradiation temperature and fluence for Series 72W and 73W crack-arrest specimens

	72W (18 specimens)		73W (17 specimens)	
	Temperature (°C)	Fluence[a]	Temperature (°C)	Fluence[a]
Mean	286	1.88	285	1.93
Standard Deviation	3	0.30	3	0.32
Minimum	281	1.42	280	1.46
Maximum	289	2.34	289	2.39

[a] In units of 10^{19} neutrons/cm^2 (>1 MeV).

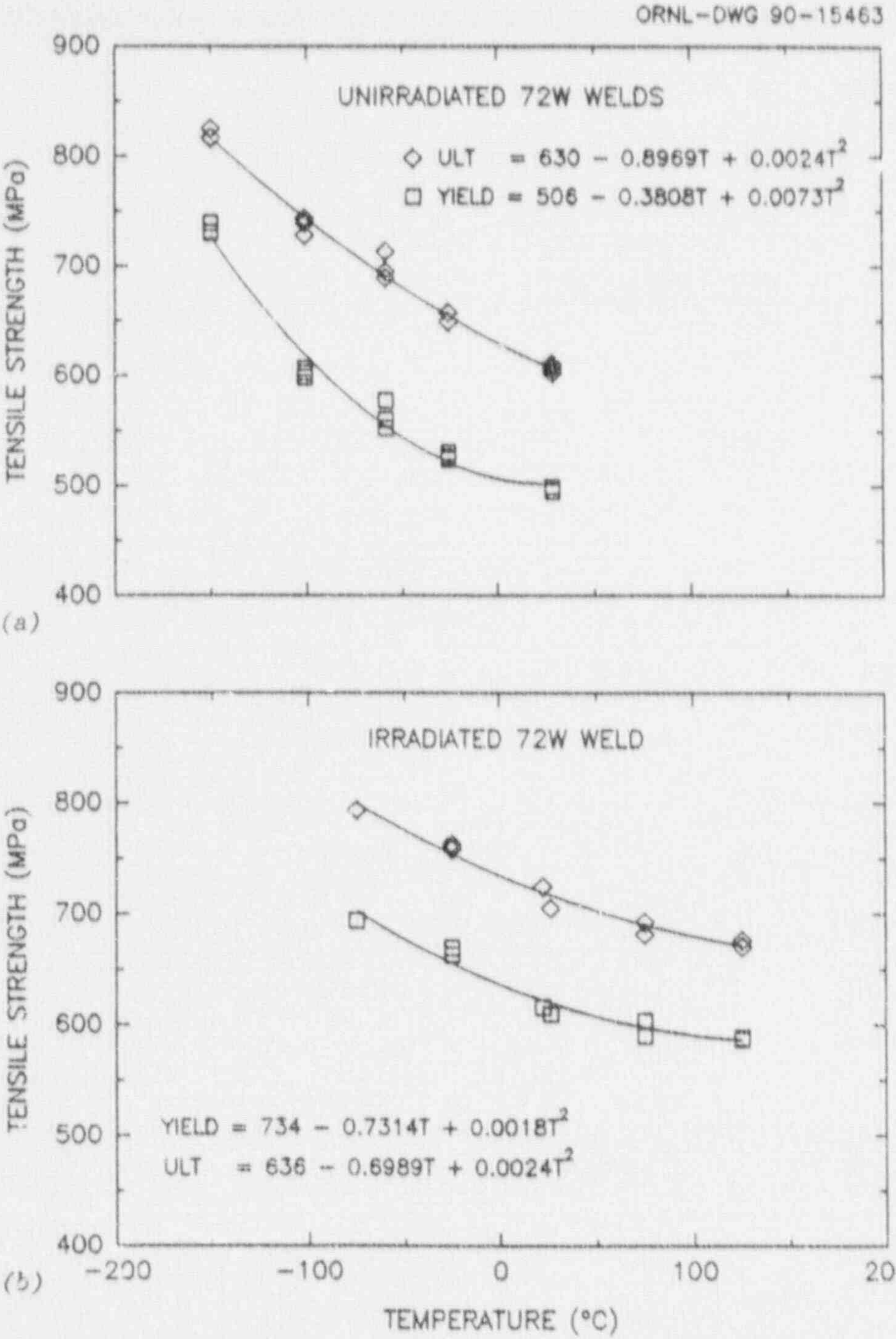

Fig. 12. Yield and ultimate strengths vs test temperature for weld 72W *(a)* unirradiated and *(b)* irradiated at a nominal temperature of 288°C to 1.57 × 10^{19} neutrons/cm^2 (>1 MeV).

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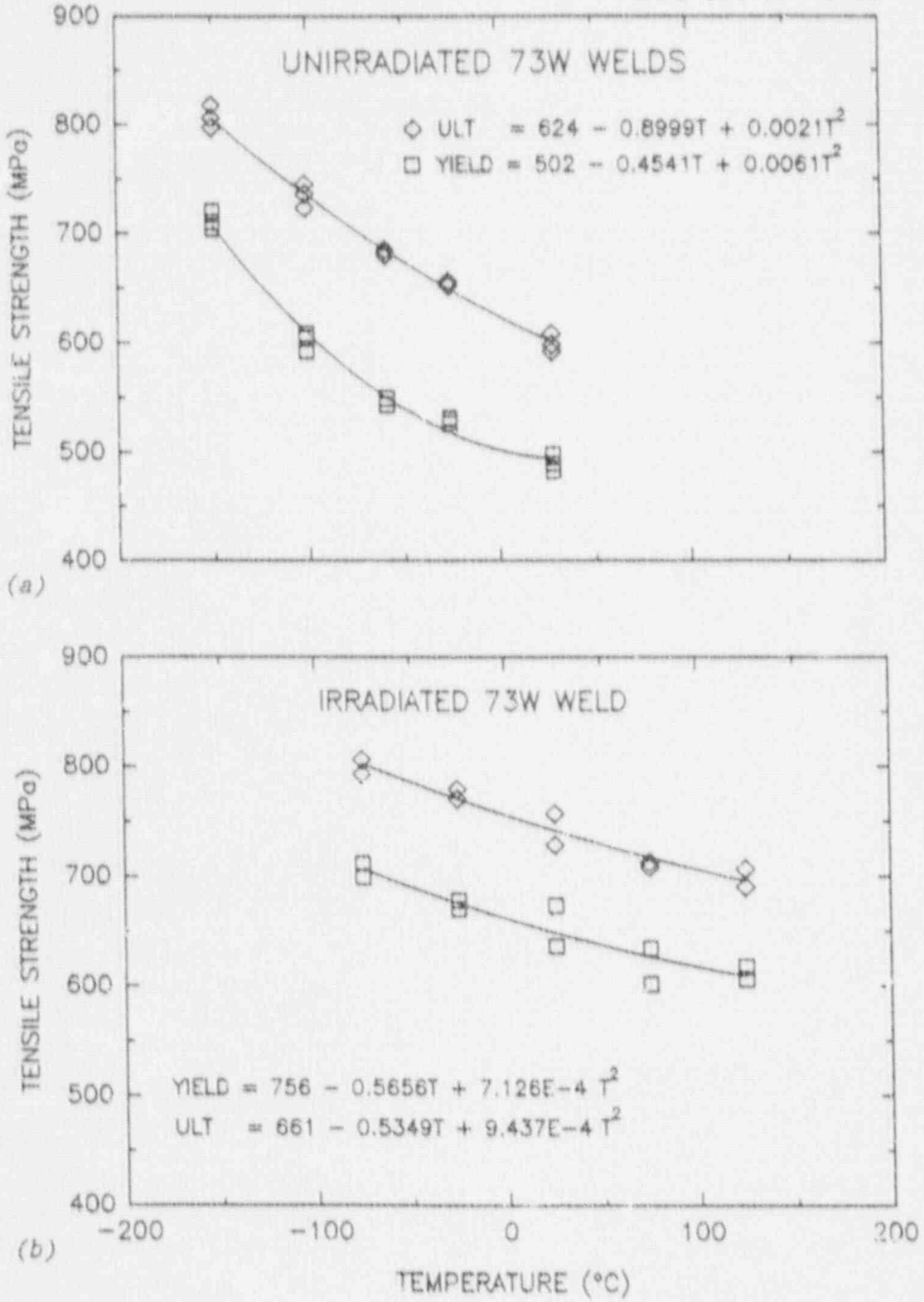

Fig. 13. Yield and ultimate strengths vs test temperature for weld 73W *(a)* unirradiated and *(b)* irradiated at a nominal temperature of 288°C to 1.56×10^{19} neutrons/cm^2 (>1 MeV).

Table 6. Initial, adjusted, and normalized reference temperatures (RT_{NDT}) for the 72W and 73W weldments

	Initial RT_{NDT} (°C)	Charpy impact[a] observed results		Adjusted[a] RT_{NDT} (°C)	Crack-arrest normalized results		Normalized[b] adjusted RT_{NDT} (°C)
		F (10^{19} n/cm^2) (>1 MeV)	ΔTT_{41-J} (K)		F' (10^{19} n/cm^2) (>1 MeV)	ΔTT_{41-J} (K)	
72W	-23	1.51	72	49	1.88	80	57
73W	-34	1.51	82	48	1.93	93	59

[a] *Source:* Data from R. K. Nanstad et al., "Effects of Irradiation on K_{Ic} curves for High-Copper Welds," pp. 214-33 in *Effects of Radiation on Materials, 14th International Symposium*, ASTM STP 1046, Vol. II, ed. N. H. Packan, R. E. Stoller, and A. S. Kumar, American Society for Testing and Materials, Philadelphia, 1990.

[b] Normalization: $(\Delta TT_{41-J})(F'/F)^{0.5}$. *Source:* Adopted with permission from G. R. Odette and G. E. Lucas, "Irradiation Embrittlement of Reactor Pressure Vessel Steels: Mechanisms, Models, and Data Correlations," pp. 206-41 in *Radiation Embrittlement of Nuclear Pressure Vessel Steels: An International Review (Second Volume)*, ASTM STP 909, ed. L. E. Steel, American Society for Testing and Materials, Philadelphia.

NOTE:

F = fluence for Charpy V-notch impact specimens.
F' = fluence for crack-arrest specimens.
n = neutrons.
ΔTT_{41-J} = shift in 41-J Charpy V-notch impact energy level.

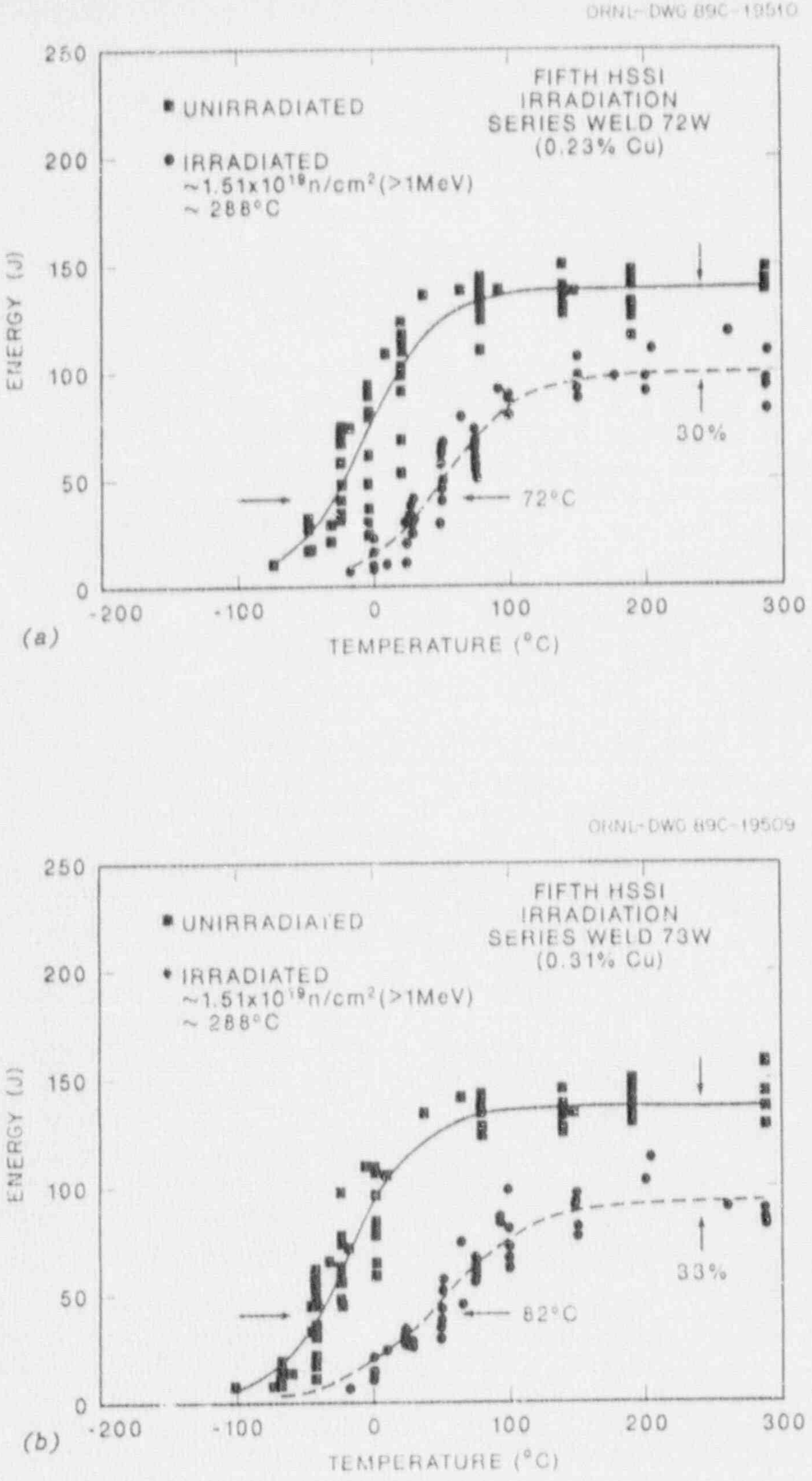

Fig. 14. Charpy V-notch-impact energy vs test temperature for welds 72W and 73W *(a)* unirradiated *(b)* irradiated at a nominal temperature of 288°C to 1.51×10^{19} neutrons/cm^2 (>1 MeV).

while that for the crack-arrest specimens is approximately 1.9×10^{19} neutrons/cm^2. To normalize the RT$_{NDT}$ shift, an average trend curve applicable to the behavior of test reactor data and having a slope of 0.5 was used (Ref. [6]). It is of the form:

$$\text{Normalized } \Delta TT_{41\text{-}J} = (\Delta TT_{41\text{-}J})(\phi'/\phi)^{0.5} ,$$

where ϕ' and ϕ are the average fluences for the crack-arrest and the CVN-impact specimens, respectively, in neutrons per square centimeter (>1 MeV). Both shifts for each weldment are given in Table 6. The normalized RT$_{NDT}$ values were used to shift the ASME K_{Ia} curves shown later in this report.

Tables 7 and 8 give the results of testing the unirradiated crack-arrest specimens of the 72W and 73W Series, respectively, and Tables 9 and 10 give data for the irradiated specimens of these two series. These tables also give for each specimen the irradiation temperature and the exposure value [fluence for energies > 1 MeV and > 0.1 MeV as well as displacements per atom (dpa)]. The K_a values have not been normalized to a single average fluence to account for the variation of fluence from one specimen to another.

In testing of one specimen, A73W17 (listed in Table 10), the crack failed to initiate in a cleavage mode and exhibited tearing. It was retested at 30°C, but the crack did not arrest, and the specimen broke. The K_a value from specimen A73W37 (tested at -25°C) is recognized as too low because the arrested crack length a_a is 96% of the nominal specimen width W. The expression in ASTM E 1221-88 used to calculate K_a is limited to $a_a/W \leq 0.85$. While other specimens may be slightly invalid and hence may or may not necessarily represent plane-strain behavior, the authors believe this specimen to be so far beyond the validity limits as to be clearly nonrepresentative of plane-strain crack-arrest toughness of the weld. Hence, its position below the ASME K_{Ia} curve is of no significance. In general, even though some of the other individual specimens may not strictly meet all of the ASTM validity criteria, the authors believe the data to be representative of the arrest toughness that would exist within a thick-walled RPV.

The task group responsible for crack-arrest test procedure ASTM E 1221-88 recognized the need for the data to represent plain-strain conditions. Conservative validity criteria were selected on the basis of existing analytical and experimental results (Ref. [7]) to ensure that specimens meeting those criteria would indeed be representative of plane-strain conditions. Even at the time ASTM E 1221-88 was written, however, it was recognized that those criteria might be overly restrictive; they were, nonetheless, chosen to be used until more evidence justifying their relaxation could be amassed. More data are now available; for example, Ref. [8] shows crack-arrest test results clearly violating the size criteria of ASTM E 1221-88, that still accurately predict the arrest behavior of a thick-walled pressure vessel under simulated pressurized-thermal-shock loading. On the bases of these and other considerations, the ASTM task group will be asked to reconsider relaxation of the validity criteria.

Table 7. Unirradiated crack-arrest toughness data obtained from testing weldment 72W (RT_{NDT} = -23°C)

Specimen	Test temperature (°C)	K_a (MPa·$\sqrt{m}$)	Validity[a]
Weld-embrittled 25 × 76 × 76 mm specimens			
A72W37	-61	66	
A72W35	-60	53	
A72W38	-59	57	
A72W36	-47	71	
A72W34	-45	73	
A72W24	-30	61	
A72W28	-30	60	
A72W25	-30	79	B
A72W31	-15	108	B,E
Weld-embrittled 25 × 152 × 152 mm specimens			
A72W44	-60	76	
A72W39	-60	45	A
A72W20	-47	67	
A72W41	-45	74	
A72W46	-45	92	
A72W43	-32	92	
A72W08	-30	104	
A72W05	-30	107	
A72W48	-30	98	
A72W01	-16	97	
A72W03	-14	128	C
Weld-embrittled 33 × 152 × 152 mm specimens			
A72W45	-45	76	
A72W47	-30	91	
A72W07	-15	103	
A72W04	-15	94	
A72W19	-15	94	
A72W02	0	93	
A72W12	0	114	
A72W40	0	114	B

Table 7. (continued)

Specimen	Test temperature (°C)	K_a (MPa·$\sqrt{m}$)	Validity[a]
Duplex 33 × 152 × 152 mm specimens			
A72W71	-14	91	
A72W66	-2	103	
A72W63	-1	125	
A72W64	1	108	
A72W65	4	125	
A72W68	5	115	
A72W73	5	142	C,D
A72W62	10	136	B,C
A72W57	21	146	C,D
Weld-embrittled 51 × 203 × 203 mm specimens			
A72W83	-30	85	
A72W85	-15	95	
A72W84	0	107	

[a] One or more letters for a specimen indicate that the results did not meet one of the minimum lengths of the ASTM E 1221-88 validity criteria. The letters correspond to those in Table 2 of ASTM E 1221-88, which can be paraphrased as:

A,B = unbroken ligament too short.
C = specimen too thin.
D,E = insufficient crack-jump length.

NOTE:

K_a = value of stress intensity factor shortly after arrest.
RT_{NDT} = reference nil-ductility-transition temperature.

Table 8. Unirradiated crack-arrest toughness data obtained from testing weldment 73W ($RT_{NDT} = -34°C$)

Specimen	Test temperature (°C)	K_a (MPa·$\sqrt{m}$)	Validity[a]
Weld-embrittled 25 × 76 × 76 mm specimens			
A73W38	-62	50	A
A73W42	-60	58	
A73W32	-59	56	A
A73W36	-59	72	
A73W01	-45	52	
A73W02	-45	75	
A73W03	-45	64	A,B
A73W06	-35	83	B
A73W04	-30	67	
A73W05	-30	70	A,B
Weld-embrittled 25 × 152 × 152 mm specimens			
A73W28	-61	69	
A73W43	-45	73	
A73W47	-45	85	
A73W30	-44	71	
A73W11	-32	85	
A73W48	-31	75	
A73W50	-30	80	
.73W16	-29	89	
A73W52	-29	77	
A73W20	-16	126	C
A73W25	-15	141	B,C
Weld-embrittled 33 × 152 × 152 mm specimens			
A73W29	-30	100	
A73W10	-16	77	A
A73W22	-16	110	
A73W46	-15	124	
A73W44	-15	123	
A73W49	-15	117	
A73W24	-13	89	A,B
A73W27	-12	111	

Table 8. (continued)

Specimen	Test temperature (°C)	K_a (MPa·$\sqrt{m}$)	Validity[a]
Duplex 33 × 152 × 152 mm specimens			
A73W86	-5	101	
A73W07	5	129	B
A73W08	5	119	
A73W09	5	112	
A73W85	5	137	C,D
A73W87	5	113	
A73W88	15	132	
Duplex 51 × 203 × 203 mm specimen			
A73W75	5	107	

[a] One or more letters for a specimen indicate that the test results did not meet one of the minimum lengths of the ASTM E 1221-88 validity criteria. The letters correspond to those in Table 2 of ASTM E 1221-88, which can be paraphrased as:

A,B = unbroken ligament too short.
C = specimen too thin.
D,E = insufficient crack-jump length.

NOTE:
K_a = value of stress intensity factor shortly after arrest.
RT_{NDT} = reference nil-ductility-transition temperature.

Table 9. Irradiated crack-arrest toughness data for the weld-embrittled type specimens from weldment 72W (normalized RT_{NDT} = 57°C). The average fluence and irradiation temperatures were 1.88×10^{19} neutrons/cm^2 (>1 MeV) and 286°C, respectively

Specimen	Test temperature (°C)	K_a (MPa·$\sqrt{m}$) (°C)	Irradiation temperature	Exposure values Fluences (>1 MeV) (neutrons/cm^2)	 Fluences (>0.1 MeV) (neutrons/cm^2)	Displacements per atom	Validity[a]
				25 × 76 × 76 mm specimens			
A72W26	-25	38	285	2.01E+19	1.24E+20	0.0470	
A72W30	-25	43	283	2.04E+19	1.26E+20	0.0478	
A72W27	29	61	283	2.06E+19	1.28E+20	0.0483	
A72W21	30	53	281	2.34E+19	1.41E+20	0.0538	
A72W32	32	66	285	2.31E+19	1.39E+20	0.0530	D
A72W22	60	62	284	2.03E+19	1.26E+20	0.0475	A
A72W23	60	74	282	2.32E+19	1.39E+20	0.0532	D
A72W29	60	70	286	2.33E+19	1.41E+20	0.0536	
				25 × 152 × 152 mm specimens			
A72W13	60	81	287	1.68E+19	1.11E+20	0.0415	
A72W10	75	101	289	1.64E+19	1.12E+20	0.0410	
A72W11	75	133	286	1.52E+19	1.01E+20	0.0376	
A72W15	75	114	289	1.54E+19	1.03E+20	0.0379	
A72W16	76	102	289	1.53E+19	1.02E+20	0.0377	
A72W06	90	160	289	1.65E+19	1.13E+20	0.0413	C,D
A72W18	90	132	287	1.42E+19	9.21E+19	0.0345	
				33 × 152 × 152 mm specimens			
A72W09	90	120	289	1.67E+19	1.14E+20	0.0418	
A72W14	100	144	289	1.85E+19	1.26E+20	0.0462	
A72W17	100	118	289	1.85E+19	1.26E+20	0.0463	

[a] One or more letters for a specimen indicate that the test results did not meet one of the minimum lengths of the ASTM E 1221-88 validity criteria. The letters correspond to those in Table 2 of ASTM E 1221-88, which can be paraphrased as:

A,B – unbroken ligament too short.
C – specimen too thin.
D,E – insufficient crack-jump length.

NOTE:
K_a – value of stress intensity factor shortly after arrest.
RT_{NDT} – reference nil-ductility-transition temperature.

Table 10. Irradiated crack-arrest toughness data for the weld-embrittled type specimens from weldment 73W (normalized RT_{NDT} = 59°C). The average fluence and irradiation temperatures were 1.93×10^{19} neutrons/cm^2 (>1 MeV) and 285°C, respectively

Specimen	Test temperature (°C)	K_a (MPa·$\sqrt{m}$) (°C)	Irradiation temperature	Exposure values		Displacements per atom	Validity[a]
				Fluences (>1 MeV) (neutrons/cm^2)	Fluences (>0.1 MeV) (neutrons/cm^2)		
				25 × 76 × 76 mm specimens			
A73W37[b]	-25	29	280	2.38E+19	1.44E+20	0.0548	A
A73W39	-25	41	282	2.13E+19	1.31E+20	0.0497	
A73W31	29	57	283	2.10E+19	1.29E+20	0.0490	D
A73W34	29	60	283	2.08E+19	1.28E+20	0.0484	D
A73W35	29	67	283	2.37E+19	1.42E+20	0.0544	D
A73W33	60	74	282	2.39E+19	1.44E+20	0.0550	D
A73W40	60	81	280	2.36E+19	1.42E+20	0.0542	D
A73W41	60	79	284	2.11E+19	1.30E+20	0.0492	D
				25 × 152 × 152 mm specimens			
A73W15	60	81	289	1.68E+19	1.15E+20	0.0421	
A73W13	75	150	289	1.69E+19	1.16E+20	0.0424	C,D
A73W18	75	131	287	1.56E+19	1.04E+20	0.0385	
A73W21	75	107	289	1.73E+19	1.14E+20	0.0426	
A73W26	75	88	288	1.58E+19	1.05E+20	0.0387	
A73W23	90	180	288	1.58E+19	1.05E+20	0.0389	B,C
A73W45	90	114	287	1.46E+19	9.45E+19	0.0354	
				33 × 152 × 152 mm specimens			
A73W14	90	159	289	1.71E+19	1.17E+20	0.0429	B,C
A73W17[c]	100		289	1.90E+19	1.29E+20	0.0474	
A73W51	100	184	289	1.90E+19	1.30E+20	0.0475	B,C

[a] One or more letters for a specimen indicate that the test results did not meet one of the minimum lengths of the ASTM E 1221-88 validity criteria. The letters correspond to those in Table 2 of ASTM E 1221-88, which can be paraphrased as:

A,B – unbroken ligament too short.
C – specimen too thin.
D,E – insufficient crack-jump length.

[b] Value of K_a is unrealistically low because remaining ligament is too small.

[c] Specimen exhibited tearing behavior when tested at this temperature, then broke without arresting when retested at 30°C.

NOTE:

K_a – value of stress intensity factor shortly after arrest.
RT_{NDT} – reference nil-ductility-transition temperature.

In Tables 7 through 10, the results of the crack-arrest tests that were "invalid" relative to the requirements of ASTM E 1221-88 are indicated by one or more letters, a blank implying a "valid" result. To judge the degree of "invalidity," see the detailed results given in Appendix A.

The crack-arrest toughnesses, K_a, as a function of test temperature for the different materials, specimen sizes, and specimen types are plotted in Figs. 15 through 18. Comparisons of the unirradiated and irradiated crack-arrest toughnesses for each of the 72W and 73W welds are shown in Figs. 19 and 20, respectively. These figures also show the unirradiated and irradiated ASME K_{Ia} curves for each weldment indexed to their respective RT_{NDT} values. In the plots showing the results of the irradiated crack-arrest testing for weldment 73W, the data point at -25°C below the ASME K_{Ia} curve is that of specimen A73W37, described above.

Lower-bound curves to the test results have been plotted as dotted curves in Figs. 19 through 21. The dotted curves are ASME curves that have been shifted downward in temperature until the first data point is encountered. The amount of the shift is shown for both the unirradiated and irradiated conditions. In the case of 72W, the temperature shift downward from the normalized curve for the irradiated specimens is 8 K smaller than that for unirradiated specimens. For the 73W specimens, however, the opposite is obtained; the downward shift for the irradiated specimens results is 11 K *greater* than that for the unirradiated specimens. With all the uncertainties involved, the differences between the downward shifts are not deemed to be significant. Thus, the preliminary observation is that the shift in K_a due to irradiation is about the same as the shift in the CVN-impact energy at the 41-J energy level, as can be judged by the dotted curves in Figs. 19 and 20.

All the crack-arrest toughnesses, both unirradiated and irradiated, for both welds have been plotted as a function of $T-RT_{NDT}$ in Fig. 21. The irradiated specimen A73W17 described above (whose remaining ligament was too small to yield an accurate result) is not included in this figure. Figure 21 includes a total of 77 unirradiated and 34 irradiated data points, many of which overlap. This figure indicates that the results form a reasonable trend when indexed to RT_{NDT}. The normalized RT_{NDT}s (Table 6) have been used to index the irradiated data. When shifted by the normalized CVN ΔTT_{41-J}, the ASME curve is a conservative estimate of the irradiated crack-arrest toughness of the 72W and 73W weldments in the transition region to approximately 40 K above RT_{NDT}. At temperatures below RT_{NDT}, there seems to be a smaller K_{Ia} margin between the lower-bound curves and the ASME K_{Ia} curves.

The shape of the lower-bound curves shown dotted in Figs. 19 and 20 for the data obtained in Phase 1 of the Sixth Irradiation Series do not seem to have been altered by irradiation. The CVN-impact energy curve for both welds, especially for 73W, changed shape when irradiated to a

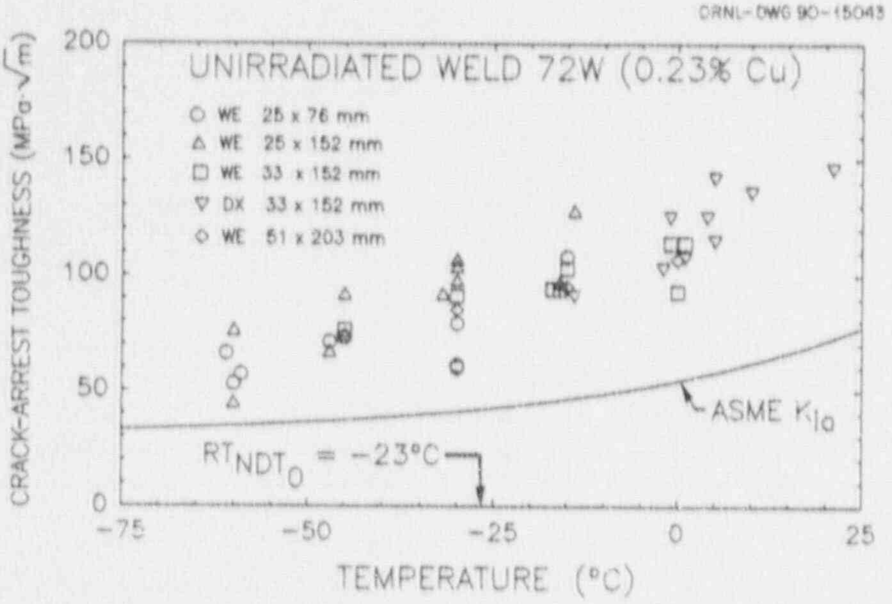

Fig. 15. Detailed crack-arrest toughness K_a vs test temperature for the *unirradiated* 72W weld showing the different specimen sizes and types used.

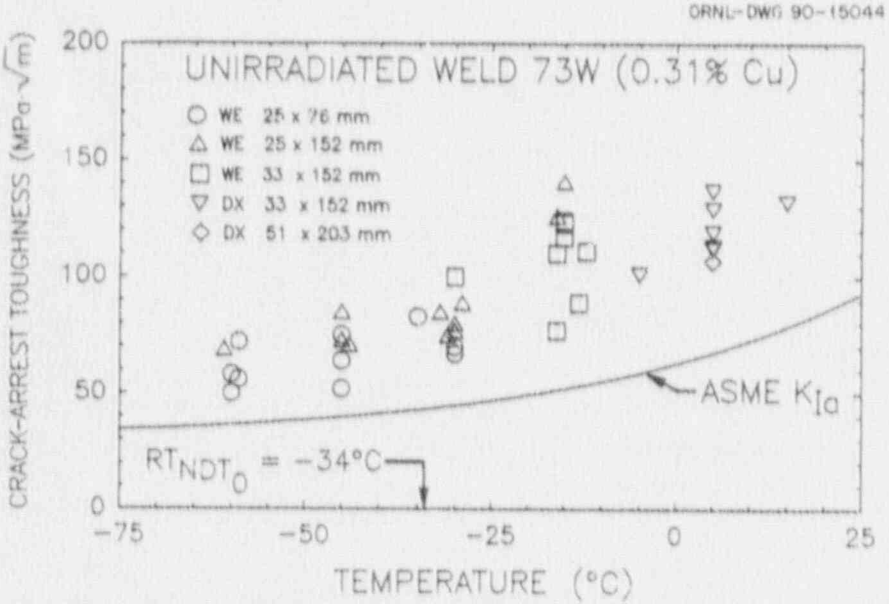

Fig. 16. Detailed crack-arrest toughness K_a vs test temperature for the *unirradiated* 73W weld showing the different specimen sizes and types used.

ORNL-DWG 90-15045

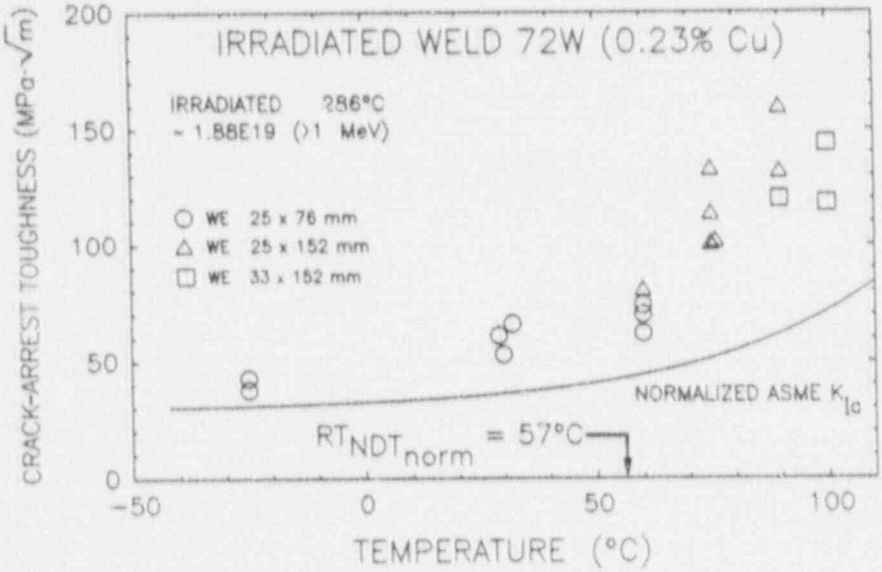

Fig. 17. Detailed crack-arrest toughness K_a vs test temperature for the *irradiated* 72W weld showing the different specimen sizes and types used.

ORNL-DWG 90-15046

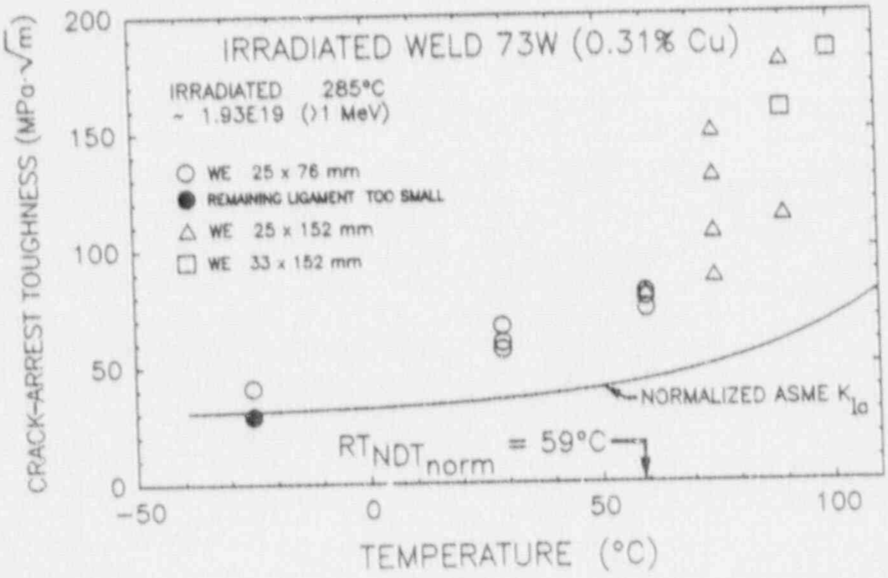

Fig. 18. Detailed crack-arrest toughness K_a vs test temperature for the *irradiated* 73W weld showing the different specimen sizes and types used.

ORNL-DWG 90-11089A

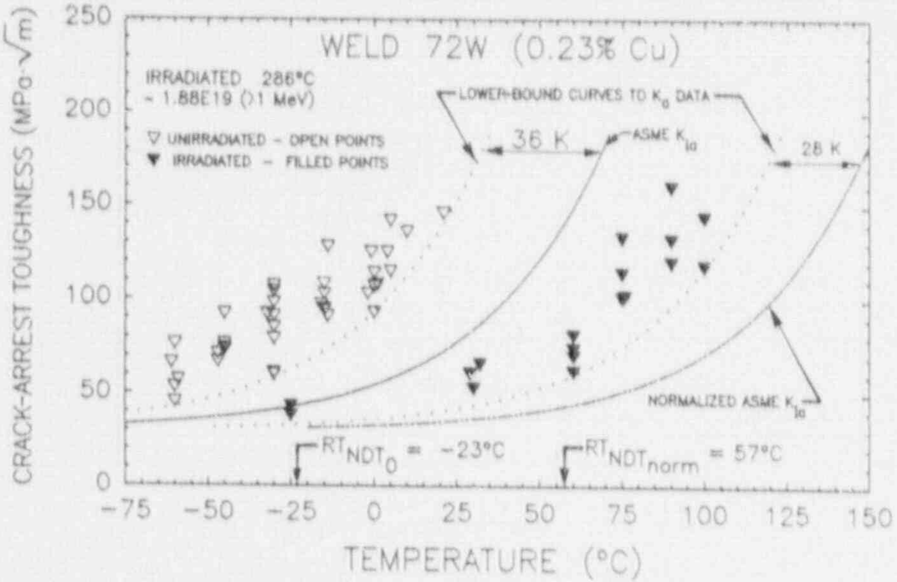

Fig. 19. Unirradiated and irradiated crack-arrest toughness K_a vs test temperature for the 72W weld.

ORNL-DWG 90-11090A

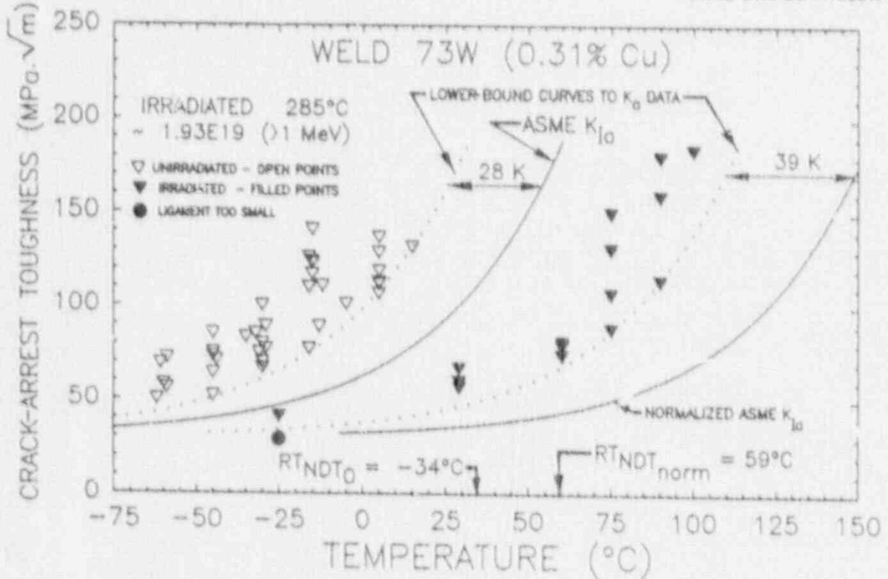

Fig. 20. Unirradiated and irradiated crack-arrest toughness K_a vs test temperature for the 73W weld.

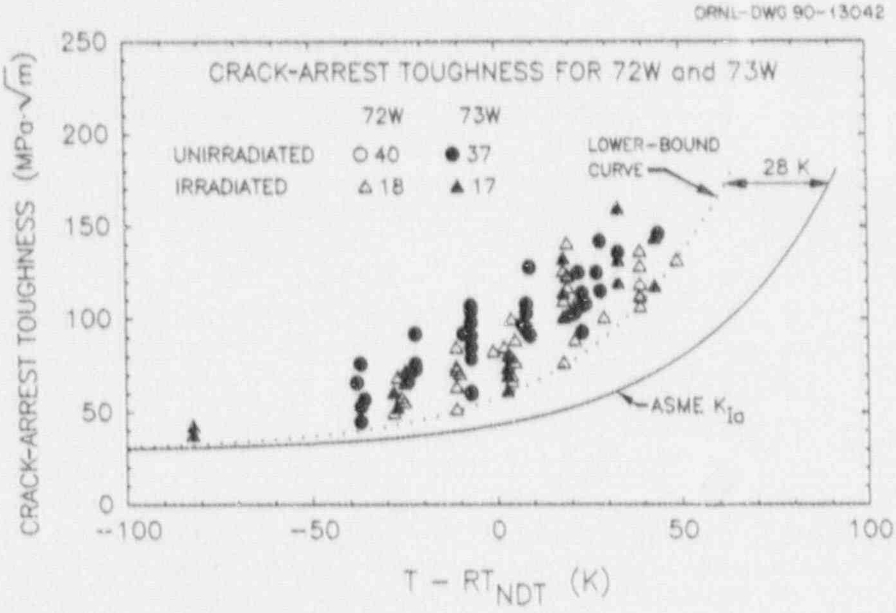

Fig. 21. All crack-arrest toughness K_a data for welds 72W and 73W plotted as a function of (T-RT_{NDT}).

fluence level of 1.51 × 10^{19} neutrons/cm^2 (>1 MeV), (see Ref. [3] and Fig. 14) Many empirical correlations exist between the CVN-impact energy and fracture toughness of *unirradiated* ferritic steels (Ref. [9]). If such a relationship also exists for *irradiated* ferritic steels and if the irradiated CVN curve changes shape, then the irradiated fracture toughness curve may also change shape correspondingly. One of the objectives of the Fifth and Sixth Irradiation Series research programs is to investigate whether irradiation can induce such a shape change in the toughness curves. Indeed, such a change has been observed in the lower-bound curve to the irradiated initiation toughness K_{Jc} data for the 73W weldment. Although no such change in shape has been observed in the K_a data obtained in tests to approximately 40 K above RT_{NDT}, further tests at higher temperatures are needed to ascertain whether a similar change in shape occurs in the arrest toughness curve. Moreover, statistical analyses of all the results will be performed to examine that question.

Successful cleavage crack initiation occurred in 35 of the 36 specimens tested. Such a success rate is unusual even for testing unirradiated specimens. Moreover, successful unstable crack initiation occurred in weld-embrittled-type specimens at test temperatures 40 K above NDT. A test temperature of approximately 20 K above NDT is generally considered to be the upper limit for a successful unstable crack to initiate in unirradiated weld-embrittled-type crack-arrest specimens for the steels and specimen thicknesses used here. It is likely that the radiation-induced increases in strength of the test material and the brittle-weld crack-starter material allows for a higher crack-driving force to enable testing at higher temperatures.

4. COMPARISON WITH OTHER DATA

Reference [2], which describes an Electric Power Research Institute (EPRI) project, contains almost all the published data on the effect of irradiation on crack-arrest toughness. Four steels were tested in the EPRI project: two welds and two plate materials. Both the plates and the welds included a low-copper as well as a high-copper steel. The total number of irradiated data points from all materials is 34. The results of the irradiated crack-arrest toughness tests were compared with the unirradiated data by shifting the irradiated data downward in temperature to achieve an approximate data coincidence. The EPRI downward shift is approximately comparable to the lower-bound shift that we used (obtained by shifting the ASME K_{Ia} curve downwards in temperature until the first data point was encountered). The EPRI shift in K_{Ia} due to irradiation for high-copper materials is less than ΔTT_{41-J}, whereas the shift in K_{IA} for the low-copper materials is slightly greater or equal to ΔTT_{41-J} (in the EPRI program, the CVN shifts were also evaluated in several other ways). A similar trend is obtained in this study, although the range of copper contents is quite different. In the EPRI program, the copper contents ranged from approximately 0.03 to 0.23 % by weight. In our study, the copper contents for the two materials were 0.23 and 0.31% and the normalized ΔTT_{41-J} values were 80 and 93 K, the shifts of the *lower-bound* K_a curves were 88 and 82 K for the 72W and 73W welds respectively. We also increased the maximum values of irradiated crack-arrest toughness obtained when compared with those of the EPRI program from approximately 130 to 185 $MPa \cdot \sqrt{m}$. Irradiated crack-arrest toughness data for both welds in our study were also obtained at higher temperatures with respect to the normalized adjusted RT_{NDT} (up to 40 K above RT_{NDT}) than were the EPRI data for the high-copper weld (up to approximately the adjusted RT_{NDT}).

5. SUMMARY

Crack-arrest testing of high-copper, submerged-arc welds was performed on unirradiated and irradiated weld-embrittled-type specimens 25- and 33-mm thick. Most of the crack-arrest test results are either valid or only marginally invalid according to ASTM E 1221-88. The 35 data points obtained by testing the irradiated crack-arrest specimens have approximately doubled the known data base of irradiated crack-arrest toughness and extended the data base coverage to higher levels of crack-arrest toughness and temperature relative to RT_{NDT}. Preliminary observations are:

1. Values of irradiated crack-arrest toughness K_{Ia} were obtained at temperatures 40 K above the irradiated RT_{NDT} of the welds. This accomplishment is experimentally significant because a temperature of 20 K above RT_{NDT} is generally considered to be the limit for obtaining useful results with the unirradiated weld-embrittled type of crack-arrest specimen.

2. The shifts of the lower-bound K_a curves for the 72W and 73W welds are approximately the same as the corresponding 41-J CVN-impact energy level shifts.

3. The ASME K_{Ia} curve, when shifted by $\Delta TT_{41\text{-}J}$, is a conservative estimate of the irradiated crack-arrest toughness <u>for welds 72W and 73W</u> in the transition region 40 K above RT_{NDT}. At temperatures below RT_{NDT}, a smaller margin of toughness is apparent between the lower-bound curves and the ASME K_{Ia} curves.

4. The shape of the lower-bound curves compared to those of the ASME K_{Ia} curves were apparently unaltered by irradiation for the temperature range covered by the tests.

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[*] Available in public technical libraries.

[†] Available for purchase from National Technical Information Service, Springfield, VA 22161.

APPENDIX A

DETAILED CRACK-ARREST SPECIMEN DATA AND TEST RESULTS

Flow and Processing of Crack-Arrest Data

The appendices document for archival and quality assurance purposes various aspects of the crack-arrest data. Appendix A traces the flow and processing of data on the crack-arrest specimens and also gives detailed crack-arrest specimen dimensions and results. The BASIC computer code "CA_TEST" used to process the test data is listed in Appendix B, and the Young's moduli used are discussed in Appendix C. Typical output from CA_TEST for weld-embrittled and duplex-type crack-arrest specimens is shown in Appendix D. The load vs crack mouth opening displacement (CMOD) charts obtained during the test and a photograph of the fracture surface for each irradiated specimen is reproduced in Appendix E.

It is not possible to legibly present the voluminous data about each specimen in one table without resorting to foldout pages. Thus, to limit table widths to a single page, the data are logically grouped and the specimen identification is used to tie the tables together. To facilitate their use, the crack-arrest data tables given in the appendices are sorted by specimen identification (in the main body of the text they are sorted by test temperature).

The dimensions of each crack-arrest specimen are measured and recorded on data sheets, a sample of which is shown in Fig. A.1. The data on crack-arrest specimens are then recorded on a Hewlett Packard Series 200/300 computer. The BASIC computer code used for this purpose is CA_TEST, (crack arrest test), which was specifically written to process the crack-arrest test data. A listing of CA_TEST is included in Appendix B. The pretest input data consist of the measured specimen dimensions, test temperature, yield strength, and Young's modulus at the test temperature. The measured specimen dimensions, for the unirradiated and irradiated crack arrest tests are given in Tables A-1 and A-2, respectively. The yield strength and Young's moduli used have not been included in these tables. The yield strength for each of the 72W and 73W weldments are presented as Figs. 10 and 11 in the main body of the test, and Young's moduli are given in Appendix C.

The ASTM E 1221-88 test procedure prescribes for weld-embrittled-type specimens only a series of loading and unloading cycles. The yield strength and Young's modulus are used to calculate the load increment for the loading and unloading cycles for weld-embrittled-type specimens as well as the validity criteria. Young's modulus is also used to evaluate the stress intensity factors.

The pretest output for CA_TEST is an echo of the input data. CA_TEST also calculates and prints the load increments for the loading and unloading steps in terms of clip-gage CMOD. For duplex specimens, no loading and unloading cycles are prescribed in ASTM E 1221-88, but a single cycle with a CMOD approximately equal to that for weld-embrittled specimens is performed to seat the clip gage and generally shake down the test equipment.

After the rapid crack propagation and arrest event, the specimen is heat-tinted, chilled, and broken open. The length of the remaining ligament is measured at three locations by the procedure given in paragraph 8.6.2 of E 1221-88. These three lengths as well as the clip-gage CMODs at the four points on the load vs CMOD chart as prescribed in ASTM E 1221-88 are provided as posttest input to CA_TEST.

The maximum and minimum loads registered just before and after the rapid crack propagation event are also recorded. During the development of ASTM E 1221-88, the ratio of these loads was one of the validity requirements. Although the latest revision of ASTM E 1221-88 does not prescribe this ratio, it is still recorded for consistency with the large number of existing files. Experience has also shown that the relative load drop is an approximate indicator of the crack-jump length at the time of the test. A small drop in load is an indication that the crack has not propagated a significant amount. At the other extreme, if the load drops to almost zero, it is likely that the remaining ligament is small. All the posttest data are given in Tables A-3 and A-4 for the unirradiated and irradiated specimens respectively.

The output of CA_TEST echoes the posttest data input and calculates K_a and K_0 as well as all the validity criteria prescribed in ASTM E 1221-88. The output also indicates which of the criteria have been met or not met. Typical output from CA_TEST for both a weld-embrittled and a duplex specimen is given in Appendix D.

The detailed values used to determine the validity of the crack-arrest results are given in Tables A-5 through A-8. Tables A-5 and A-6 are for the unirradiated 72W and 73W weldments respectively, and the corresponding information for the irradiated weldments is in Tables A-7 and A-8. In these four tables, the first row for each specimen contains the measured values required to judge the validity of the results. Below these values are the corresponding minimum values as prescribed in ASTM E 1221-88. Validity criteria are evaluated for weld-embrittled specimens (4 criteria) and duplex-type specimens (5 criteria).

In the right-hand column, the presence of one or more letters indicates that the specimen did not meet the validity criteria of ASTM E 1221-88. The arrested crack front is rarely straight or square. Thus, to allow for uncertainties in the measurement of the remaining ligament, the measured values were increased by 10% before they were compared with the ASTM criteria.

Other values included in the tables are the specimen type (whether weld embrittled or duplex) and nominal specimen thickness B and overall width (the height is equal to the width). Other parameters included are test temperature and stress intensity factors just before the rapid crack propagation event K_0 (a measure of the crack-driving force) and that shortly after arrest K_a.

During the processing of the data, it was not clear how the information will be eventually presented. To maintain some flexibility, the data are maintained in the relational data base computer code PARADOX. Such a data base allows any of the information stored in it to be selected, sorted, and formatted for presentation. All data (including that from the Hewlett Packard Series 200/300 computers) are maintained in PARADOX on an IBM-compatible computer. The tables in this report have been prepared by using a RDB computer code. The RDB code has also proven useful in the evaluation of the data. When the data are examined from different viewpoints, input data errors are often noticed.

Table A-1. Measured dimensions in millimeters of the *unirradiated* crack-arrest specimens from the 72W and 73W weldments[a]

Specimen	B	B_N	2H	W_t	Pr	Rs	Rt	Tu	Tv	N
A72W01	25.40	19.25	152.37	152.45	6.35	10.72	40.18	28.94	0.00	11.54
A72W02	33.05	24.73	152.37	152.45	6.35	10.69	40.24	28.89	0.00	12.98
A72W03	25.40	17.86	152.40	152.45	6.35	10.77	40.26	29.43	0.00	11.61
A72W04	33.05	24.94	152.37	152.45	6.35	10.73	40.26	28.90	0.00	11.53
A72W05	25.40	17.86	152.40	152.45	6.35	10.73	40.18	29.39	0.00	11.51
A72W07	33.02	25.12	152.37	152.43	6.35	10.67	40.33	28.91	0.00	11.52
A72W08	25.43	17.96	152.40	152.43	6.35	10.66	40.19	30.28	0.00	11.44
A72W12	33.05	25.07	152.40	152.43	6.35	10.68	40.32	28.77	0.00	11.45
A72W19	33.02	25.04	152.37	152.43	6.35	10.59	40.26	29.37	0.00	11.54
A72W20	25.37	18.15	152.43	152.43	6.35	10.47	40.52	28.68	0.00	11.49
A72W24	25.35	19.13	76.17	76.20	3.18	3.95	21.61	11.75	0.00	11.49
A72W25	25.35	19.15	76.17	76.17	3.18	3.77	21.54	11.58	0.00	11.46
A72W28	25.27	19.10	76.17	76.17	3.18	3.95	21.58	11.86	0.00	11.53
A72W31	25.27	19.20	76.17	76.17	3.18	3.95	21.60	11.80	0.00	11.41
A72W34	25.40	19.15	76.15	76.20	3.18	3.89	21.44	12.37	0.00	11.61
A72W35	25.40	19.08	76.20	76.23	3.18	3.93	21.66	11.86	0.00	11.57
A72W36	25.40	19.15	76.17	76.23	3.18	3.85	21.62	12.12	0.00	11.53
A72W37	25.40	19.02	76.17	76.23	3.18	4.00	21.68	12.03	0.00	11.52
A72W38	25.37	19.05	76.20	76.20	3.18	4.01	21.48	12.22	0.00	11.54
A72W39	25.40	19.00	152.37	152.40	6.35	10.62	40.44	28.54	0.00	11.53
A72W40	32.39	24.74	152.37	152.40	6.35	10.73	40.56	29.66	0.00	11.60
A72W41	25.4	19.00	152.37	152.43	6.35	10.74	40.50	28.39	0.00	11.55

Table A-1 (continued)

Specimen	B	B_w	2H	W_t	Pr	Rs	Rt	Tu	Tv	N
A72W43	25.43	19.00	152.40	152.37	6.35	10.62	40.44	28.42	0.00	11.50
A72W44	25.40	19.02	152.37	152.37	6.35	10.63	40.38	28.52	0.00	11.47
A72W45	32.99	24.74	152.40	152.40	6.35	10.56	40.40	28.89	0.00	11.41
A72W46	25.43	18.92	152.37	152.37	6.35	10.57	40.50	28.43	0.00	11.49
A72W47	33.02	24.74	152.37	152.40	6.35	10.70	40.51	28.52	0.00	11.50
A72W48	25.40	18.87	152.37	152.40	6.35	10.69	40.55	28.33	0.09	11.38
A72W57	32.97	24.79	152.40	152.40	6.35	9.40	41.13	27.07	42.67	1.43
A72W62	32.99	24.82	152.40	152.40	6.35	9.53	41.34	26.76	42.67	1.15
A72W63	32.99	24.84	152.35	152.37	6.35	9.55	41.39	26.50	42.67	1.04
A72W64	33.02	24.79	152.45	152.35	6.35	9.48	41.16	26.70	42.67	1.08
A72W65	33.05	24.79	152.40	152.40	6.35	9.53	41.38	26.89	42.67	1.17
A72W66	33.02	24.77	152.40	152.43	6.35	9.49	41.34	26.55	42.67	1.06
A72W68	32.99	24.79	152.40	152.40	6.35	9.45	41.33	27.22	42.67	1.10
A72W71	33.02	24.79	152.43	152.43	6.35	9.53	41.25	27.06	42.67	1.06
A72W73	33.05	24.82	152.43	152.40	6.35	9.46	41.20	30.19	42.67	1.13
A72W83	50.85	46.99	203.23	197.74	14.29	7.90	48.66	40.18	0.00	11.34
A72W84	50.90	46.99	203.20	197.71	14.29	7.76	48.74	40.19	0.00	11.33
A72W85	50.84	38.13	203.33	197.76	14.27	7.87	50.30	54.35	0.00	11.86
A73W01	25.45	19.02	76.15	76.15	3.18	3.65	21.65	11.82	0.00	11.52
A73W02	25.45	19.02	76.17	76.12	3.18	3.57	21.84	11.52	0.00	11.60
A73W03	25.45	19.10	76.15	76.12	3.18	3.70	21.58	11.74	0.00	11.52
A73W04	25.45	19.00	76.17	76.12	3.18	3.76	21.26	12.18	0.00	11.52
A73W05	25.45	19.13	76.17	76.10	3.18	3.84	21.64	11.70	0.00	11.51
A73W06	25.45	19.02	76.17	76.02	3.18	3.79	21.64	11.69	0.00	11.56
A73W07	32.97	24.93	152.35	152.27	6.35	9.54	41.12	26.74	43.18	2.37
A73W08	32.97	24.97	152.37	152.37	6.35	9.60	41.15	26.83	43.18	2.45
A73W09	32.94	24.94	152.35	152.37	6.35	9.57	41.11	27.00	43.18	2.36
A73W10	32.99	24.88	152.37	152.40	6.35	10.41	40.29	34.39	0.00	11.52

Table A.1 (continued)

Specimen	B	B_N	2H	W_t	Pr	Rs	Rt	Tu	Tv	N
A73W11	25.43	18.97	152.43	152.43	6.35	10.58	40.14	34.65	0.00	11.59
A73W16	25.40	18.95	152.35	152.37	6.35	10.50	40.30	34.59	0.00	11.56
A73W20	25.40	18.92	152.35	152.40	6.35	10.41	40.29	34.03	0.00	11.60
A73W22	33.05	24.78	152.40	152.37	6.35	10.37	40.14	34.60	0.00	11.52
A73W24	32.99	24.80	152.37	152.37	6.35	10.38	40.39	34.62	0.00	11.45
A73W25	25.40	19.02	152.35	152.40	6.35	10.52	40.45	34.19	0.00	11.57
A73W27	32.99	24.77	152.37	152.40	6.35	10.45	40.19	34.28	0.00	11.53
A73W28	25.40	18.97	152.35	152.40	6.35	10.43	40.43	34.38	0.00	11.58
A73W29	33.02	24.77	152.37	152.40	6.35	10.30	40.33	34.31	0.00	11.51
A73W30	25.40	18.95	152.43	152.45	6.35	10.51	40.30	34.48	0.00	11.59
A73W32	25.40	19.10	76.17	76.23	3.18	3.83	21.60	12.13	0.00	11.53
A73W36	25.40	19.02	76.17	76.23	3.18	4.02	21.56	11.81	0.00	11.49
A73W38	25.40	19.15	76.17	76.23	3.18	3.83	21.63	12.11	0.00	11.49
A73W42	25.40	19.08	76.20	76.23	3.18	3.85	21.46	12.17	0.00	11.55
A73W43	25.40	19.02	152.37	152.40	6.35	10.61	40.39	28.61	0.00	11.51
A73W44	33.05	24.79	152.40	152.40	6.35	10.61	40.46	29.62	0.00	11.52
A73W46	33.02	24.82	152.37	152.40	6.35	10.62	40.33	28.67	0.00	11.70
A73W47	25.43	18.95	152.40	152.40	6.35	10.73	40.41	28.65	0.00	11.48
A73W48	25.40	18.87	152.37	152.37	6.35	10.59	40.46	28.76	0.00	11.57
A73W49	33.02	24.74	152.32	152.37	6.35	10.59	40.43	28.52	0.00	11.37
A73W50	25.43	19.08	152.37	152.40	6.35	10.71	40.37	28.74	0.00	11.57
A73W52	25.43	19.05	152.40	152.37	6.35	10.76	40.59	28.64	0.00	11.55
A73W75	49.53	37.26	203.23	203.28	0.84	8.43	55.16	37.10	66.06	1.50
A73W85	33.05	24.87	152.32	152.43	6.27	9.58	41.30	27.97	42.57	1.34
A73W86	33.02	24.89	152.43	152.45	6.27	9.51	41.27	27.84	42.77	1.39
A73W87	32.99	24.89	152.45	152.43	6.27	9.53	41.26	28.69	44.19	1.38
A73W88	32.97	24.99	152.50	152.43	6.27	9.46	41.25	28.72	42.42	1.37

[a] See Fig. A.1 for definitions of nomenclature used in this table.

Table A-2. Measured dimensions in millimeters of the *irradiated* weld-embrittled crack-arrest specimens from the 72W and 73W weldments[a]

Specimen	B	B_N	2H	W_t	Pr	Rs	Rt	Tu	N
A72W06	25.40	17.88	152.40	152.40	6.35	10.51	40.22	29.56	11.65
A72W09	33.02	24.82	152.40	152.40	6.35	10.50	40.23	30.13	11.51
A72W10	25.40	17.93	152.40	152.40	6.35	10.52	40.31	28.85	11.53
A72W11	25.40	17.83	152.40	152.40	6.35	10.43	40.29	29.35	11.51
A72W13	25.40	17.83	152.40	152.40	6.35	11.87	41.68	28.79	11.39
A72W14	33.02	25.02	152.40	152.40	6.35	10.49	40.27	28.92	11.51
A72W15	25.40	17.81	152.40	152.40	6.35	10.54	40.34	28.96	11.55
A72W16	25.40	17.83	152.40	152.40	6.35	10.48	40.29	29.37	11.56
A72W17	33.02	24.79	152.37	152.40	6.35	10.49	40.34	28.97	11.15
A72W18	25.40	18.01	152.40	152.40	6.35	10.53	40.34	28.89	11.51
A72W21	25.40	19.08	76.20	76.20	3.18	3.59	21.45	11.60	11.59
A72W22	25.40	19.10	76.20	76.20	3.18	3.73	21.36	11.91	11.48
A72W23	25.40	19.10	76.20	76.20	3.18	3.82	21.48	11.81	11.48
A72W26	25.40	19.10	76.20	76.20	3.18	3.94	21.62	11.76	11.56
A72W27	25.40	19.13	76.20	76.20	3.18	3.91	21.54	11.80	11.51
A72W29	25.40	19.08	76.20	76.20	3.18	3.64	21.35	11.81	11.55
A72W30	25.40	19.15	76.20	76.20	3.18	3.98	21.43	11.90	11.66
A72W32	25.40	19.13	76.20	76.20	3.18	3.60	21.43	11.78	11.54

Table A-2 (continued)

Specimen	B	B_w	2H	W_t	Pr	Rs	Rt	Tu	N
A73W13	25.40	18.92	152.40	152.40	6.35	10.35	40.33	34.58	11.55
A73W14	33.02	24.77	152.40	152.40	6.35	10.45	40.32	34.54	11.52
A73W15	25.40	18.95	152.40	152.40	6.35	10.41	40.35	34.59	11.62
A73W17	33.02	24.77	152.40	152.40	6.35	10.41	40.35	34.49	11.53
A73W18	25.40	18.92	152.40	152.40	6.35	10.27	40.41	34.48	11.60
A73W21	25.40	18.90	152.40	152.40	6.35	10.13	40.33	34.49	11.52
A73W23	25.40	18.90	152.40	152.40	6.35	10.31	40.32	34.52	11.64
A73W26	25.40	18.87	152.46	152.40	6.35	10.38	40.21	34.67	11.55
A73W31	25.40	19.08	76.20	76.20	3.18	3.80	21.63	12.12	11.55
A73W33	25.40	19.08	76.20	76.20	3.18	3.75	21.62	12.10	11.49
A73W34	25.40	19.05	76.20	76.20	3.18	3.78	21.65	11.99	11.48
A73W35	25.40	19.10	76.20	76.20	3.18	3.87	21.59	12.18	11.58
A73W37	25.40	19.05	76.20	76.20	3.18	3.83	21.57	12.35	11.59
A73W39	25.40	19.13	76.20	76.20	3.18	3.80	21.65	12.07	11.53
A73W40	25.40	19.00	76.20	76.20	3.18	3.75	21.60	12.13	11.54
A73W41	25.40	19.02	76.20	76.20	3.18	3.79	21.60	12.05	11.56
A73W45	25.40	19.13	152.40	152.40	6.35	10.68	40.45	28.74	11.51
A73W51	33.02	24.71	152.40	152.40	6.35	10.50	40.55	28.57	11.47

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[a] See Fig. A.1 for the definition of the nomenclature used in this table.

Table A-3. Posttest values measured for *unirradiated* crack-arrest specimens from the 72W and 73W weldments

Specimen	W1	W2	W3	P1	P2	P3	P4	P_{max}	P_{min}
A72W01	33.01	30.94	33.66	0.056	0.163	1.351	1.369	52	4
A72W02	28.64	27.53	29.22	0.038	0.147	1.369	1.443	71	0
A72W03	42.67	42.52	42.70	0.051	0.165	1.405	1.455	54	17
A72W04	27.80	25.65	31.22	0.025	0.122	1.367	1.445	68	2
A72W05	36.73	36.13	42.57	0.046	0.165	1.265	1.326	54	11
A72W07	34.68	34.73	34.43	0.061	0.163	1.367	1.433	73	0
A72W08	35.86	34.64	34.81	0.030	0.145	1.283	1.346	52	4
A72W12	33.03	34.23	33.78	0.038	0.312	1.600	1.651	77	1
A72W19	33.09	36.33	33.54	0.051	0.142	1.224	1.326	71	0
A72W20	39.10	35.34	42.45	0.000	0.000	0.714	0.767	29	0
A72W24	10.58	10.37	10.35	0.020	0.058	0.742	0.815	27	0
A72W25	12.50	11.65	14.60	0.046	0.109	0.889	0.932	26	2
A72W28	9.82	10.54	9.45	0.018	0.079	0.762	0.828	33	0
A72W31	13.26	13.46	15.78	0.020	0.208	1.168	1.219	51	1
A72W34	14.77	13.69	15.95	0.013	0.043	0.732	0.737	28	2
A72W35	12.02	12.56	12.14	0.008	0.020	0.554	0.630	25	6
A72W36	13.67	14.84	11.82	0.010	0.069	0.737	0.800	31	2
A72W37	14.20	14.47	14.15	0.008	0.015	0.610	0.709	26	0
A72W38	11.65	11.74	11.15	0.020	0.028	0.620	0.699	28	0
A72W39	13.87	14.46	13.79	0.030	0.030	0.879	1.095	34	0
A72W40	24.79	27.18	23.77	0.051	0.320	1.892	1.956	87	0
A72W41	34.88	34.19	33.12	0.056	0.056	0.927	1.016	30	0
A72W43	33.35	31.12	34.07	0.025	0.066	1.184	1.245	49	0
A72W44	34.18	34.21	33.34	0.018	0.043	0.925	1.019	44	2
A72W45	38.29	38.93	36.84	0.058	0.058	0.889	0.980	38	2
A72W46	46.44	48.73	42.19	0.056	0.056	0.958	0.980	36	8
A72W47	33.36	38.38	29.52	0.061	0.097	1.189	1.255	56	2
A72W48	34.57	35.19	33.04	0.038	0.076	1.214	1.306	53	3
A72W57	54.48	54.34	56.69	0.018	0.000	1.283	1.316	78	4
A72W62	37.13	37.39	36.83	0.000	0.000	1.577	1.659	107	8
A72W63	39.81	40.04	41.37	0.005	0.000	1.361	1.427	143	1
A72W64	37.49	35.73	39.64	0.036	0.000	1.275	1.306	75	10
A72W65	34.33	34.35	38.15	0.010	0.000	1.509	1.554	84	8

Table A-3. (continued)

Specimen	W1	W2	W3	P1	P2	P3	P4	P_{max}	P_{min}
A72W66	31.37	32.20	30.64	0.018	0.000	1.346	1.402	87	3
A72W68	35.12	35.53	38.25	0.020	0.000	1.359	1.443	89	0
A72W71	23.22	22.16	25.71	0.025	0.000	1.392	1.504	106	0
A72W73	48.18	50.45	43.83	0.046	0.000	1.415	1.448	64	7
A72W83	59.33	60.56	56.02	0.079	0.079	1.209	1.224	66	26
A72W84	53.72	55.41	60.47	0.086	0.178	1.570	1.651	121	4
A72W85	32.98	39.89	28.27	0.102	0.163	1.745	1.816	76	6
A73W01	10.14	10.87	9.47	0.051	0.038	0.650	0.699	18	0
A73W02	14.24	12.53	15.76	0.025	0.038	0.732	0.808	27	0
A73W03	7.76	7.89	8.08	0.030	0.097	0.919	0.998	26	0
A73W04	10.36	9.00	11.43	0.030	0.102	0.838	0.909	38	0
A73W05	8.04	9.48	7.29	0.038	0.193	1.021	1.125	38	0
A73W06	12.99	13.00	12.67	0.043	0.254	0.996	1.052	37	9
A73W07	30.21	34.74	31.51	0.025	0.000	1.636	1.783	119	0
A73W08	39.08	38.93	40.81	0.025	0.000	1.313	1.417	88	1
A73W09	37.24	39.62	37.05	0.025	0.000	1.283	1.372	97	0
A73W10	16.62	16.62	16.31	0.030	0.229	1.605	1.671	66	0
A73W11	34.95	33.74	36.70	0.051	0.079	1.085	1.107	31	12
A73W16	32.55	34.35	31.80	0.013	0.051	1.143	1.186	48	0
A73W20	40.31	40.56	39.90	0.051	0.262	1.542	1.565	49	5
A73W22	27.44	26.80	29.91	0.013	0.173	1.651	1.671	54	0
A73W24	14.07	14.66	11.93	0.038	0.361	2.108	2.200	68	0
A73W25	35.53	35.93	39.76	0.038	0.229	1.781	1.819	48	12
A73W27	34.23	38.29	34.82	0.025	0.122	1.407	1.433	61	0
A73W28	29.54	30.73	28.66	0.051	0.051	0.968	1.003	30	2
A73W29	31.24	26.85	34.02	0.064	0.099	1.402	1.433	66	0
A73W30	25.60	28.52	23.98	0.025	0.053	1.067	1.118	31	0
A73W32	6.60	6.91	6.93	0.013	0.058	0.841	0.927	37	0
A73W36	13.84	13.75	12.90	0.013	0.043	0.716	0.792	31	1
A73W38	6.98	6.83	6.81	0.020	0.048	0.699	0.876	23	0
A73W42	8.80	8.09	9.36	0.025	0.053	0.726	0.874	34	0
A73W43	35.72	36.16	36.54	0.056	0.056	0.892	0.968	43	0
A73W44	41.77	44.87	42.95	0.064	0.150	1.372	1.433	75	18
A73W46	41.28	39.15	42.24	0.030	0.137	1.433	1.473	73	0
A73W47	39.58	41.03	39.26	0.056	0.056	0.968	1.031	38	8
A73W48	28.27	26.48	29.53	0.051	0.091	1.090	1.166	40	3
A73W49	35.39	33.42	38.65	0.030	0.206	1.516	1.539	64	0

Table A-3. (continued)

Specimen	W1	W2	W3	P1	P2	P3	P4	P_{max}	P_{min}
A73W50	18.05	18.28	22.52	0.036	0.152	1.435	1.560	67	0
A73W52	18.32	18.84	17.84	0.051	0.155	1.448	1.567	66	0
A73W75	40.84	37.67	45.12	0.000	0.000	1.613	1.765	181	0
A73W85	50.63	50.28	49.94	0.000	0.000	1.280	1.313	82	7
A73W86	34.19	35.10	32.86	0.000	0.000	1.245	1.285	83	1
A73W87	30.58	30.94	30.74	0.000	0.000	1.491	1.554	91	2
A73W68	42.81	46.58	42.56	0.000	0.000	1.387	1.407	82	3

NOTES:

W1,W2, and W3 = lengths in millimeters of the remaining ligament measured according to ASTM E 1221-88

P1 through P4 = displacements in millimeters measured from the load vs CMOD trace, see Fig. A.3.

P_{max}, P_{min} = maximum and minimum loads registered just before and just after the rapid crack propagation event.

Table A-4. Posttest values measured for *unirradiated* crack arrest specimens from the 72W and 73W weldments

Specimen	W1	W2	W3	P1	P2	P3	P4	P_{max}	P_{min}
A72W06	66.1	67.45	68.33	0	0.127	1.213	1.245	21	16
A72W09	46.34	45.59	52.86	0	0.152	1.246	1.308	50	15
A72W10	49.31	49.94	48.44	0	0.051	0.965	1.003	16	6
A72W11	60.43	60.25	62.5	0	0.159	1.124	1.149	18	12
A72W13	43.86	45.26	43.38	0	0.051	0.81	0.879	28	7
A72W14	59.19	68.53	56.84	0	0.14	1.232	1.283	58	29
A72W15	46.14	49.14	45.93	0	0.089	1.13	1.186	18	3
A72W16	54.8	57.81	52.31	0	0.102	0.919	0.958	15	8
A72W17	50.94	59.45	50.96	0	0.064	1.095	1.138	24	12
A72W18	52.18	66.86	52.02	0	0.038	1.138	1.138	39	1
A72W21	20.35	20.48	19	0	0	0.404	0.452	8	2
A72W22	6.682	7.145	7.406	0	0	0.957	0.97	2	1
A72W23	21.77	22.11	22.23	0	0	0.538	0.572	10	3
A72W26	15.57	14.19	15.03	0	0.013	0.34	0.406	7	2
A72W27	18.13	19.6	17.3	0	0	0.498	0.549	11	3
A72W29	20.23	22.09	19.94	0	0	0.538	0.574	11	3
A72W30	15.84	15.11	15.29	0	0	0.394	0.414	6	2
A72W32	24.77	24.78	24.97	0	0	0.434	0.472	10	5
A73W13	67.24	70.09	60.19	0	0.051	1.151	1.189	20	14
A73W14	29.69	24.59	33.03	0	0.218	2.355	2.398	58	1
A7315	45.23	47.6	44.04	0	0.013	0.828	0.859	16	5
A73W17	0	0	0	0	0	0	0	0	0
A73W18	48.72	54.82	50.23	0	0.083	1.273	1.285	15	5
A73W21	52.97	53.16	56.02	0	0.032	0.972	0.997	12	7
A73W23	43.73	50.62	41.69	0	0.286	2.037	2.045	60	9
A73W26	56.14	55.65	54.27	0	0.02	0.77	0.813	12	6
A73W31	19.97	22.84	21.64	0	0	0.408	0.464	8	3
A73W33	26.34	26.68	26.6	0	0	0.464	0.495	10	4
A73W34	22.15	21.2	22.88	0	0	0.414	0.48	10	3
A73W35	27.82	25.31	30.01	0	0	0.411	0.424	9	4
A73W37	2.738	3.18	2.556	0	0.025	0.732	0.732	1	0
A73W39	13.66	13.86	14.39	0	0	0.362	0.464	13	1
A73W40	25.99	26.32	26.62	0	0	0.508	0.546	10	4
A73W41	31.13	32.23	29.41	0	0	0.432	0.472	9	5
A73W45	52.69	52.84	60.23	0	0.07	1.034	1.082	26	10
A73W51	47.38	51.28	42.7	-0.013	0.343	2.019	2.057	41	16

NOTES:

W1,W2, and W3 = lengths in millimeters of the remaining ligament measured according to ASTM E 1221-88.

P1 through P4 = displacements in millimeters measured from the load vs crack mouth opening displacement trace, see Fig. A.1.

P_{max}, P_{min} = maximum and minimum loads registered just before and just after the rapid crack propagation event

Table A-5. Values measured during crack-arrest testing of the *unirradiated* weldment 72W and 73W

Specimen	Type	B	W_t	T	Ka	Ko	A	B	C	D	E	Validity
A72W01	WE	25	152	-16	97	199	33	33	25	51	51	
							19	23	18	23	24	
A72W02	WE	33	152	0	91	203	29	29	33	55	55	
							19	21	17	26	26	
A72W03	WE	25	152	14	128	214	43	43	25	40	40	C
							19	40	32	23	28	
A72W04	WE	33	152	-15	96	209	28	28	33	55	55	
							19	21	17	23	26	
A72W05	WE	25	152	-30	107	191	39	39	25	44	44	
							19	27	22	23	21	
A72W07	WE	33	152	-15	103	201	35	35	33	49	49	
							19	26	21	23	25	
A72W08	WE	25	152	-30	104	195	35	35	25	47	47	
							19	25	20	23	22	
A72W12	WE	33	152	0	114	215	34	34	33	50	50	
							19	32	26	23	29	
A72W19	WE	33	152	15	96	180	34	34	33	49	49	
							19	22	17	23	20	
A72W20	WE	25	152	-47	61	126	39	39	25	44	44	
							19	10	8	23	8	
A72W24	WE	25	76	-30	61	168	10	10	25	32	32	
							10	9	7	23	16	
A72W25	WE	25	76	10	79	192	13	13	25	30	30	B
							10	15	12	23	21	
A72W28	WE	25	76	-30	60	168	10	10	25	33	33	
							10	9	7	23	16	
A72W31	WE	25	76	15	108	234	14	14	25	29	29	B,E
							10	28	22	23	33	
A72W34	WE	25	76	-45	73	168	15	15	25	28	28	
							10	12	10	23	16	
A72W35	WE	25	76	-60	53	132	12	12	25	31	31	
							10	6	5	23	9	
A72W36	WE	25	76	-47	61	164	13	13	25	29	29	
							10	11	9	23	15	
A72W37	WE	25	76	-61	66	147	14	14	25	28	28	
							10	9	8	23	11	
A72W38	WE	25	76	-59	57	146	12	12	25	31	31	
							10	7	6	23	11	
A72W39	WE	25	152	-60	55	145	14	14	25	69	69	A
							19	4	4	23	41	
A72W40	WE	33	152	0	114	261	25	25	33	57	57	B
							19	32	26	23	42	
A72W41	WE	25	152	-45	74	149	34	34	25	50	50	
							19	12	10	23	12	
A72W43	WE	25	152	-12	92	190	33	33	25	51	51	
							19	20	16	23	21	
A72W44	WE	25	152	-60	76	151	34	34	25	50	50	
							19	13	10	23	12	
A72W45	WE	33	152	-45	66	141	38	38	33	45	45	
							19	13	11	23	11	
A72W46	WE	25	152	-45	93	154	46	46	25	38	38	
							19	19	15	23	13	
A72W47	WE	33	152	-30	91	186	34	34	33	50	50	
							19	20	16	23	20	
A72W48	WE	25	152	10	98	194	34	34	25	49	49	
							19	22	18	23	22	

Table A-5. (continued)

Specimen	Type	B	W_f	T	Ka	Ko	A	B	C	D	E	Validity
A72W57	DX	33	152	21	146	216	55	55	33	13	13	C,D
							19	54	43	25		
A72W62	DX	33	152	10	136	267	37	37	33	31	31	B,C
							19	46	37	25		
A72W63	DX	33	152	-1	125	232	40	40	33	28	28	
							19	39	31	25		
A72W64	DX	33	152	1	108	217	38	38	33	31	31	
							19	29	23	25		
A72W65	DX	33	152	4	125	256	36	36	33	33	33	
							19	39	31	25		
A72W66	DX	33	152	-2	103	229	31	31	33	37	37	
							19	26	21	25		
A72W68	DX	33	152	5	115	229	36	36	33	32	32	
							19	33	27	25		
A72W71	DX	33	152	-14	91	237	24	24	33	45	45	
							19	20	16	25		
A72W73	DX	33	152	5	142	230	48	48	33	21	21	C,D
							19	50	40	25		
A72W83	WE	51	203	-30	85	146	59	59	51	50	50	
							25	17	14	23	12	
A72W84	WE	51	203	0	107	178	57	57	51	52	52	
							25	28	23	23	20	
A72W85	WE	51	203	-15	95	195	34	34	51	59	59	
							25	22	17	24	23	
A73W01	WE	25	76	-45	52	151	10	10	26	33	33	
							10	6	5	23	13	
A73W02	WE	25	76	-45	75	172	14	14	26	29	29	
							10	13	10	23	16	
A73W03	WE	25	76	-45	64	203	8	8	26	35	35	A,B
							10	9	7	23	23	
A73W04	WE	25	76	-30	67	181	10	10	26	32	32	
							10	11	8	23	19	
A73W05	WE	25	76	-30	70	204	8	8	26	35	35	A,B
							10	12	9	23	24	
A73W06	WE	25	76	-35	83	184	13	13	26	30	30	B
							10	.6	13	23	19	
A73W07	DX	33	152	5	129	277	32	32	33	36	36	B
							19	42	34	25		
A7SW08	DX	33	152	5	119	222	40	40	33	28	28	
							19	36	29	25		
A73W09	DX	33	152	5	112	216	38	38	33	30	30	
							19	32	25	25		
A73W10	WE	33	152	-16	77	216	17	17	33	61	61	A
							19	15	12	23	28	
A73W11	WE	25	152	-32	85	159	35	35	25	43	43	
							19	17	14	23	15	
A73W16	WE	25	152	-29	89	172	13	33	25	45	45	
							19	19	15	23	17	
A73W20	WE	25	152	-16	126	203	40	40	25	38	38	C
							19	39	31	23	25	
A73W22	WE	33	152	-16	110	232	28	28	33	50	50	
							19	30	24	23	33	
A73W24	WE	33	152	-13	89	273	14	14	33	64	64	A,B
							19	20	16	23	46	
A73W25	WE	25	152	-15	141	243	37	37	25	41	41	B,C
							19	49	39	23	36	

Table A-5. (continued)

Specimen	Type	B	W_t	T	K_a	K_0	A	B	C	D	E	Validity
A73W27	WE	33	152	-12	111	202	36	36	33	42	42	
							19	10	24	23	25	
A73W28	WE	25	152	-61	69	146	30	30	25	48	48	
							19	10	8	23	11	
A73W29	WE	33	152	-30	100	205	31	31	33	47	47	
							19	24	19	23	25	
A73W30	WE	25	152	-44	71	161	26	26	25	52	52	
							19	12	9	23	14	
A73W32	WE	25	76	-59	56	192	7	7	25	36	36	A
							10	7	5	23	20	
A73W36	WE	25	76	-59	72	168	14	14	25	29	29	
							10	11	9	23	15	
A73W38	WE	25	76	-62	50	160	7	7	25	36	36	A
							10	5	4	23	13	
A73W42	WE	25	76	60	58	166	9	9	25	34	34	
							10	7	6	23	14	
A73W43	WE	25	152	-45	73	142	36	36	25	47	47	
							19	12	10	23	11	
A73W44	WE	33	152	-15	123	204	43	43	33	39	39	
							19	37	30	23	25	
A73W46	WE	33	152	-15	124	219	41	41	33	43	43	
							19	38	30	23	29	
A73W47	WE	25	152	-45	85	156	40	40	25	43	43	
							19	17	13	23	14	
A73W48	WE	25	152	-31	75	170	28	28	25	55	55	
							19	13	11	23	17	
A73W49	WE	33	152	-15	117	222	36	36	33	48	48	
							19	33	27	23	30	
A73W50	WE	25	152	-30	80	221	20	20	25	64	64	
							19	15	12	23	29	
A73W52	WE	25	152	-29	77	219	18	18	25	65	65	
							19	14	11	23	28	
A73W75	DX	51	203	5	107	229	41	41	50	41	41	
								38	19	23	33	
A73W85	DX	33	152	5	137	214	50	50	33	18	18	C,D
								19	47	38	25	
A73W86	DX	33	152	5	101	209	34	34	33	34	34	
								19	25	20	25	
A73W87	DX	33	152	5	113	247	31	31	33	36	36	
								19	32	26	25	
A73W88	DX	33	152	15	132	228	44	44	33	25	25	
								19	44	36	25	

NOTES:

Type: = either WE (weld-embrittled) or DX (duplex)
B, W_t = nominal overall specimen size, in millimeters, see Fig. 2
T = test temperature in °C
K_a,K_0 = stress intensity factor at crack arrest and at crack initiation, respectively, in MPa·$\sqrt{m}$

The letters A, B, ... E are the letters used in the ASTM E 1221-88 validity criteria. The top row of numbers are the measured values for each criterion, and those below are the minimums specified in the standard. The remaining ligament has to fulfill two criteria, and thus the same value is repeated for A and B. The same is true for the crack jump.

A,B = length of remaining ligament, millimeters.
C = specimen width, millimeters.
D,E = crack jump, millimeters. For duplex specimens, only D is applicable.

Validity = On or more letters in this column indicates that the specimen did not meet the validity criteria of E 1221-88. To allow for the uncertainty in the measurement of the crack front, the measured values were increased by 10% before comparing them with the criteria in the standard

Table A-6. Values measured during crack-arrest testing of *irradiated* weldment 72W and 73W

Specimen	Type	B	W_t	T	K_a	K_o	A	B	C	D	E	Validity
A72W06	WE	25	152	90	160	182	67 19	67 50	25 40	15 23	15 15	C,D
A72W09	WE	33	152	90	120	176	48 19	48 28	33 23	34 23	34 14	
A72W10	WE	25	152	75	101	155	49 19	49 20	25 16	34 23	34 11	
A72W11	WE	25	152	75	133	163	61 19	61 35	25 28	22 23	22 12	
A72W13	WE	25	152	60	81	130	44 19	44 13	25 10	38 23	38 7.3	
A72W14	WE	33	152	100	144	177	62 19	62 41	33 33	22 23	22 14	
A72W15	WE	25	152	75	114	177	47 19	47 25	25 20	36 23	36 14	
A72W16	WE	25	152	76	102	138	55 19	55 20	25 16	28 23	28 8.5	
A72W17	WE	33	152	100	118	168	54 19	54 28	33 22	29 22	29 13	
A72W18	WE	25	152	90	132	185	57 19	57 34	25 27	26 23	26 16	
A72W21	WE	25	76	30	53	98	20 9.6	20 5.2	25 4.2	23 23	23 4	
A72W22	WE	25	76	60	62	229	7.1 9.5	7.1 7.4	25 6	36 23	36 23	A
A72W23	WE	25	76	60	74	129	22 9.5	22 10	25 8.3	21 23	21 7.3	D
A72W26	WE	25	76	-25	38	81	15 9.5	15 2.5	25 2	28 23	28 2.4	
A72W27	WE	25	76	29	61	121	18 9.5	18 7	25 5.6	25 23	25 6.1	
A72W29	WE	25	76	60	70	129	21 9.6	21 9.5	25 7.6	22 23	22 7.3	
A72W30	WE	25	76	-25	43	97	15 9.5	15 3.1	25 2.5	28 23	28 3.5	
A72W32	WE	25	76	32	66	105	25 9.6	25 8.2	25 6.5	18 23	18 4.6	D
A73W13	WE	25	152	75	150	168	66	66 19	25 41	12 33	12 23	C,D 12
A73W14	WE	33	152	90	159	325	29	29 19	33 46	48 37	48 23	B,C 44
A73W15	WE	25	152	60	81	125	46	46 19	25 12	32 9.4	32 23	6.3
A73W17	WE	33	152	100								
A73W18	WE	25	152	75	131	182	51	51 19	25 31	26 25	26 23	14
A73W21	WE	25	152	75	107	144	54	54 19	25 21	24 17	24 23	8.4
A73W23	WE	25	152	90	180	263	45	45 19	25 60	32 48	32 23	B,C 29
A73W26	WE	25	152	75	88	115	55	55 19	25 14	22 11	22 23	5.4
A73W31	WE	25	76	29	57	98	22	22 9.5	25 5.7	21 4.6	21 23	D 3.7
A73W33	WE	25	76	60	74	110	27	27 9.5	25 9.7	16 7.8	16 23	D 4.8
A73W34	WE	25	76	29	60	100	22	22 9.5	25 6.2	21 5	21 23	D 3.8

Table A.6 (continued)

Specimen	Type	B	W_t	T	K_a	K_o	A	B	C	D	E	Validity
A73W35	WE	25	76	29	67	99	28	28	25	15	15	D
								9.5	7.8	6.2	23	3.7
A73W37	WE	25	76	-25	29	171	2.8	2.8	25	40	40	A
								9.5	1.4	1.1	23	10
A73W39	WE	25	76	-25	41	88	14	14	25	29	29	
								9.5	2.7	2.2	23	2.7
A73W40	WE	25	76	60	81	121	26	26	25	16	16	D
								9.5	12	9.3	23	5.8
A73W41	WE	25	76	60	79	103	31	31	25	12	12	D
								9.5	11	9	23	4.2
A73W45	WE	25	152	90	114	158	55	55	25	28	28	
								19	24	19	23	10
A73W51	WE	33	152	100	184	274	47	47	33	36	36	B,C
								19	63	50	23	31

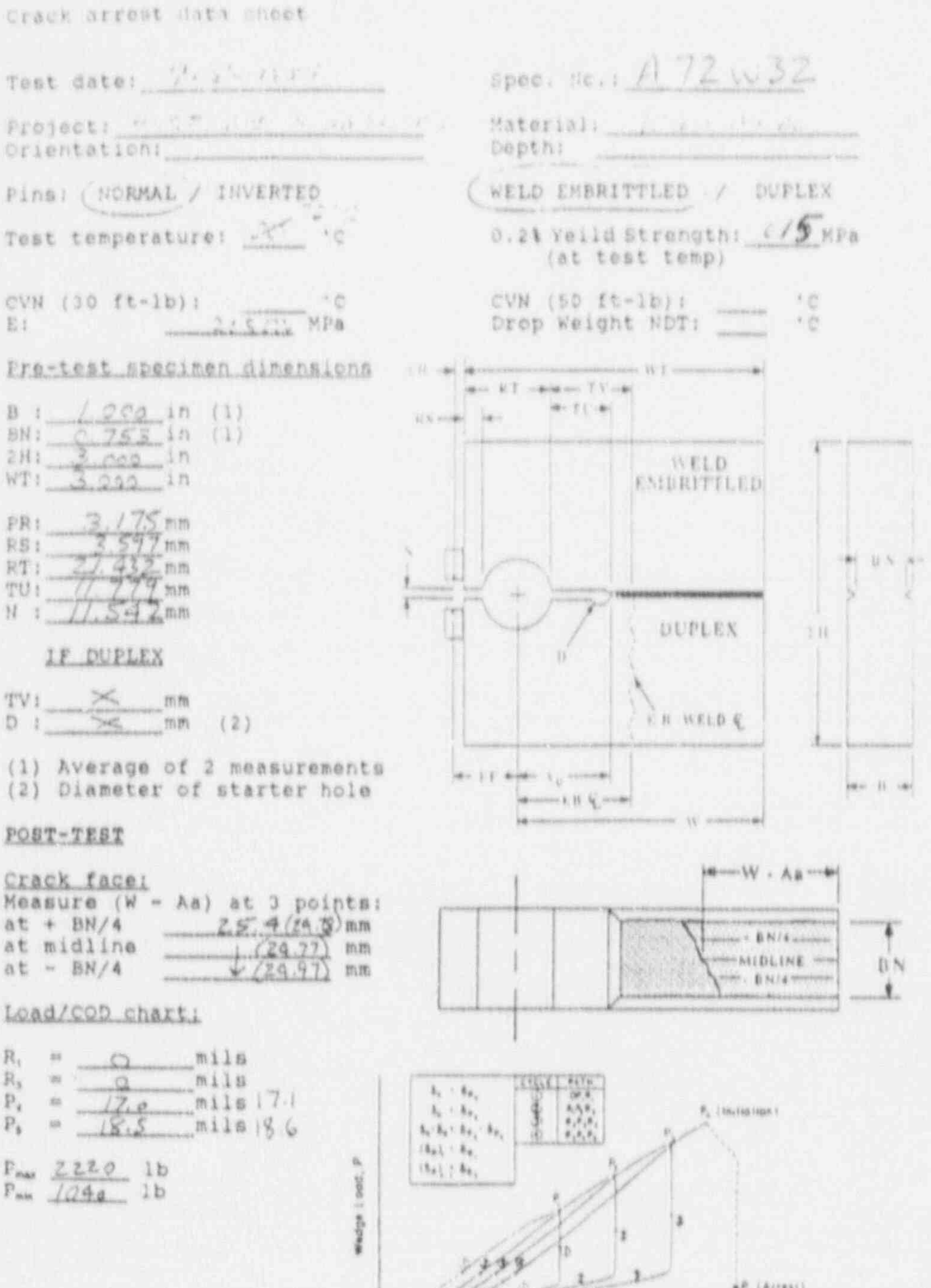
NOTES:

Type: = either WE (weld-embrittled) or DX (duplex)
B, W_t = nominal overall specimen size, in millimeters, see Fig. 2
T = test temperature in °C
K_a,K_o = stress intensity factor at crack arrest and at crack initiation, respectively, in MPa·$\sqrt{m}$.

The letters A, B, ... E are the letters used in the ASTM E 1221-88 validity criteria. The top row of numbers are the measured values for each criterion, and those below are the minimums specified in the standard. The remaining ligament has to fulfill two criteria, and thus the same value is repeated for A and B. The same is true for the crack jump.

A,B = length of remaining ligament, millimeters.
C = specimen width, millimeters.
D,E = crack jump, millimeters. For duplex specimens, only D is applicable.

Validity = On or more letters in this column indicates that the specimen did not meet the validity criteria of E 1221-8. To allow for the uncertainty in the measurement of the crack front, hte measured values were increased by 10% before comparing them with the criteria in the standard.



Crack arrest data sheet

Test date: [illegible]

Spec. No.: A72w32

Project: [illegible]

Orientation: ______

Material: [illegible]

Depth: ______

Pins: [✓ NORMAL] / INVERTED

[✓ WELD EMBRITTLED] / DUPLEX

Test temperature: [illegible] °C

0.2% Yeild Strength: 615 MPa
(at test temp)

CVN (30 ft-lb): ______ °C

E: [illegible] MPa

CVN (50 ft-lb): ______ °C

Drop Weight NDT: ______ °C

Pre-test specimen dimensions

B : 1.000 in (1)
BN: 0.755 in (1)
2H: 3.000 in
WT: 3.000 in

PR: 3.175 mm
RS: 3.597 mm
RT: 27.432 mm
TU: 11.779 mm
N : 11.542 mm

IF DUPLEX

TV: × mm
D : × mm (2)

(1) Average of 2 measurements
(2) Diameter of starter hole

POST-TEST

Crack face:
Measure (W - Aa) at 3 points:
at + BN/4 25.4 (24.75) mm
at midline ↓ (24.77) mm
at - BN/4 ↓ (24.97) mm

Load/COD chart:

R_1 = 0 mils
R_3 = 0 mils
P_4 = 17.0 mils 17.1
P_5 = 18.5 mils 18.6

P_{max} 2220 lb
P_{min} 1048 lb

[illegible]
February 24, [illegible]

Fig. A-1. Comparison of values of Young's moduli as calculated from an American Society of Mechanical Engineers table and an Electric Power Research Institute expression.

APPENDIX B

LISTING OF BASIC COMPUTER CODE CA_TEST

Documentation of Computer Code CA TEST

The listing of the computer code CA_TEST has been included solely for purposes of QA. It details in a concise manner the computational details that were performed with the crack arrest data. Moreover, the methodology in crack-arrest testing is still evolving. The standard test method used in this work, ASTM Test for Determining Plane-Strain Crack-Arrest Fracture Toughness, K_{Ia}, of Ferritic Steels (E 1221-88), is in its first issue and will probably be modified. It is therefore important that the precise details of the algorithms used to calculate K_a as well as the validity criteria be documented. If crack-arrest methodology does change, that data can be re-evaluated using the new methodology.

```
10  ! THE NAn." OF THIS PROGRAM IS CA_TEST
20  !
30  DIM Banner$[40]
40  Banner$ = "Version 5.1  Revised February 14, 1990)"
50  !
60  !
70  ! THIS PROGRAM PERFORMS CRACK ARREST TEST COMPUTATIONS
80  !
90  !
100  INTEGER Cycle,Nrec,Nbytes,Nvar
110  !
120  !
130  ! INITIALIZATION OF VARIABLES
140  !
150  ! Data_stored = 0 (FALSE) (DEFAULT) data for specimen have NOT been stored
160  !             = 1 (TRUE)  data for this spec. have been stored previously
170  !                 This is set in subprogram Load after succesful input
180  !
190  !   For     DUPLEX specimens,  Tv = measured value, and for
200  !   WELD-EMBRITTLED specimens  Tv = 0
210  !
220  !   Yso = Dynamic yield strength increment is set at 205 MPa
230  !       per ASTM 1221-88 Para.
240  !
250  ON ERROR GOTO Error_sub
260   !
270  Yso=205
280  Data_stored=0
290  Msus$=":,700,1"
300  PRINTER IS 1
310  !
320  PRINT "CRACK ARREST CALCULATIONS      "&Banner$
330  PRINT "THIS PROGRAM LOADS DATA PREVIOUSLY STORED ON 3.5"" DISKS"
340! WAIT 2
350  !
360  !
370  !                           **************** Begin  ******
380 Begin:   !
390  M$="Y"
400  INPUT "LOAD DATA FROM DISKETTE? (Y/N) Y",M$
410  IF M$="Y" THEN
420     PRINTER IS 1
430     DISP "INSERT DATA SOURCE AND PRESS CONTINUE"
440     PAUSE
450     GOSUB Load
460     GOTO Print_dta
470  END IF
480  !
490  !
500  !                           ********* Start *******
510  !  Starts data input from Keyboard
520 Start:   !
530  PRINTER IS 1
540  PRINT USING "@"
550  INPUT " ENTER SPECIMEN NO.",File$
560  PRINT USING """SPECIMEN NO. =  "",10A";File$
570  PRINT
580  INPUT "ENTER TEST TEMPERATURE IN C",Tp
590  INPUT "ENTER YIELD STRENGTH AT TEST TEMPERATURE IN MPa",Ys
600  INPUT "ENTER TEST DATE IN THE FORM 072989 (6 CHARACTERS MAX)",Test_date
```

```
610  PRINT USING "3X,""TEST DATE = "",1X,6Z";Test_date
620  PRINT USING """YS =  "",10D,2X,9A,5D,4A  ";Ys,"MPa at",Tp,"C"
630  INPUT "ENTER E IN MPa",E
640  PRINT USING """E  =  "",10D   ,2X,4A";E,"MPa "
650  PRINT
660  INPUT "ENTER B IN INCHES",B
670  FRINT USING """B  =  "",3D.3D,2X,4A";B,"inch"
680  INPUT "ENTER BN IN INCHES",Bn
690  PRINT USING """BN =        D.3D,2X,4A";Bn,"inch"
700  INPUT "ENTER 2H IN       S",H
710  PRINT USING ""                .3D,2X,4A";H,"inch"
720  INPUT "ENTER W            S",Wt
730  PRINT USING """W             3D.3D,2X,4A";Wt,"inch"
740  PRINT
750  INPUT "ENTER PR IN mm",Pr
760  PRINT USING """PR =  "",3D.2D,3X,4A";Pr,"mm  "
770  INPUT "ENTER RS IN mm",Rs
780  PRINT USING """RS =  "",3D.2D,3X,4A";Rs,"mm  "
790  INPUT "ENTER RT IN mm",Rt
800  PRINT USING """RT =  "",3D.2D,3X,4A";Rt,"mm  "
810  INPUT "ENTER TU IN mm",Tu
820  PRINT USING """TU =  "",3D.2D,3X,4A";Tu,"mm  "
830  PRINT
840  INPUT "ENTER N IN  mm",N
850  PRINT USING """N  =  "",3D.2D,3X,4A";N,"mm  "
860  !
870  INPUT "ENTER TV IN mm, (= 0 for WELD-EMBRITTLED !!!)",Tv
880  PRINT USING "/,K,3D.2D,2X,2A";"TV   = ",Tv,"mm"
890  !
900  !                                  **** Cortec_0 ****
910 Cor ec_0:   !
920  C  $="Y"
930  IN UT "CORRECTIONS? (Y/N) Y",Cor$
940  IF  PC$(Cor$)="Y" THEN GOTO Start
950  !
960  !
970  Sto $="Y"
980  NP T "STORE DATA ON DISKETTE? (Y/N) Y",Store$
990  IF  PC$(Store$)="Y" THEN GOSUB Store
1000  !
1010 !
1020 !
1030 !                                  ***** Print_dta ******
1040 Print_dta:  !
1050 !  Prints input data if required
1060 GOSUB Hardcopy
1070 !
1080 !
1090 !  READ LABEL Label$ FROM Msus$
1100 !
1110 !
1120 GOSUB Specimen
1130 !
1140 !
1150 PRINT USING "/,9X,""YIELD STRENGTH = "",5D,1X,3A,#";Ys,"MPa"
1160 PRINT USING "8X,""YOUNG'S MODULUS = "",7D,1X,3A,#";E,"MPa"
1170 PRINT USING """    INCR. TO YIELD (DYN) (Yso) ="",4D,1X,3A";Yso,"MPa"
1180 !
1190 !
1200 PRINT USING "/,""Pre-test specimen dimension measurements"""
```

```
1210 !
1220 !
1230 PRINT USING "/,9X,""B    =  "",3D.3D,2X,4A";B,"inch"
1240 PRINT USING "9X,""BN   =  "",3D.3D,2X,4A";Bn,"inch"
1250 PRINT USING "9X,""2H   =  "",3D.3D,2X,4A";H,"inch"
1260 PRINT USING "9X,""WT   =  "",3D.3D,2X,4A";Wt,"inch"
1270 PRINT
1280 PRINT USING "9X,""PR   =  "",3D.2D,2X,4A";Pr,"mm"
1290 PRINT USING "9X,""RS   =  "",3D.2D,2X,4A";Rs,"mm"
1300 PRINT USING "9X,""RT   =  "",3D.2D,2X,4A";Rt,"mm"
1310 PRINT USING "9X,""TU   =  "",3D.2D,2X,4A";Tu,"mm"
1320 PRINT USING "9X,""N    =  "",3D.2D,2X,7A,D.6D,2A";N,"mm"
1330 !
1340 PRINT USING "/,9X,K,3D.2D,2X,2A";"TV   =  ",Tv,"mm"
1350 !
1360 !
1370 PRINT USING "/,""Pre-test specimen dimension calculations"""
1380 !
1390 W=Wt*25.4-(Rs+Rt)/2
1400 Ao=Tu+(Rt-Rs)/2
1410 Ro=Ao/W
1420 !
1430 PRINT USING "/,9X,""W        ="",4X,6D.2D,2X,2A";W,"mm"
1440 PRINT USING "9X,""Ao       ="",4X,6D.2D,2X,2A";Ao,"mm"
1450 PRINT USING "9X,""Ao/w     ="",4X,D.3D";Ro
1460 !
1470 !
1480 Faow=(2.24*(1.72-.9*Ro+Ro^2)*(1-Ro)^.5)/(9.85-.17*Ro+11*Ro^2)
1490 PRINT USING "9X,""F(Ao/W)  ="",4X,D.4D";Faow
1500 !
1510 Ff=Pr+(Rt+Rs)/2
1520 Ffoverw=Ff/W
1530 PRINT USING "/,9X,""Clip gage is located at (FF/W) ="",4X,D.2D";Ffoverw
1540 !
1550 Ffow_cor=.25
1560 IF (Ffoverw>.98*Ffow_cor) AND (Ffoverw<1.02*Ffow_cor) THEN
1570   GOTO Proceed
1580 ELSE
1590   PRINT "WARNING !!!  Do not proceed to test this specimen"
1600   PRINT "Check input data, particularly PR, RS, and RT"
1610   PRINT "Clip gage location blocks are NOT located at FF/W = 0.25 !"
1620   DISP "INCORRECT (FF/W)!  IF POSSIBLE CORRECT DATA BEFORE PROCEEDING"
1630   Que$="Y"
1640   INPUT "DO YOU WANT TO CORRECT INPUT DATA? (Y/N) Y",Que$
1650   IF UPC$(Que$)="Y" THEN GOTO Start
1660   Que$="Y"
1670   INPUT "Do you want to QUIT now ?  (Y/N) Y",Que$
1680   IF UPC$(Que$)="Y" THEN GOTO Finish
1690 END IF
1700 !
1710 !
1720 Proceed:  !
1730 IF Tv<>0 THEN
1740   Ebcl=(Rt-Rs)/2+Tv
1750   PRINT USING "/,9X,""EBCL="",10X,4D.2D,4A";Ebcl,"  mm"
1760 END IF
1770 !
1780 !
1790 PRINT USING "/,K,/";"Pre-test loading calculations"
1800 !
```

```
1810 ! Fact is in mils. W is in mm
1820 Fact=1.E+3*(Ys*W/25.4*(Bn/B)^.5)/(E*Faow)
1830 Deltaoinit=.69*Fact
1840 !
1850 Num_cycles=10
1860 IF Tv< >0 THEN
1870    Num_cycles=1
1880    PRINT USING "/,K,/";"This is a DUPLEX specimen, only one loading cycle
needed"
1890 END IF
1900 FOR Cycle=1 TO Num_cycles
1910    Del_max=(1+.25*(Cycle-1))*Deltaoinit
1920   !
1930   ! 100 mils = 10 volts
1940    Volts=.1*Del_max
1950    PRINT USING "11X,""FOR CYCLE No. ="",5D,"",  maximum COD ="",5D.D,"" m
ils"",15D.2D,"" Volts""";Cycle,Del_max,Volts
1960 NEXT Cycle
1970 Deltaomax=1.5*Fact
1980 !
1990 IF Tv=0 THEN PRINT USING "/,11X,""Probable maximum COD for useful results"
",5D.D,""  Mils""";Deltaomax
2000 !
2010 Cor$="Y"
2020 INPUT "DO YOU WANT TO MAKE CORRECTIONS IN THE STORED DATA? (Y/N) Y",Cor$
2030 IF Cor$="Y" THEN GOTO Start
2040 !
2050 Print$="Y"
2060 INPUT "DO YOU WANT TO PRINT OUT DATA (SCREEN/PRINTER) ? (Y/N) Y",Print$
2070 IF UPC$(Print$)="Y" THEN GOTO Print_dta
2080 !
2090 Ptc$="Y"
2100 INPUT "DO YOU WANT TO DO POST TEST CALCULATIONS? (Y/N) Y",Ptc$
2110 IF UPC$(Ptc$)="Y" THEN Post_tcalc
2120 GOSUB Hardcopy
2130 Que$="Y"
2140 INPUT "DO YOU WANT TO DO MORE PRE TEST CALCULATIONS? (Y/N) Y",Que$
2150 IF UPC$(Que$)="Y" THEN Begin
2160 Que$="N"
2170 INPUT "DO YOU WANT TO STORE THE DATA (Y/N) N",Que$
2180 IF UPC$(Que$)="Y" THEN GOSUB Store
2190 Que$="Y"
2200 INPUT "DO YOU WANT TO DO MORE? (Y/N) Y",Que$
2210 IF UPC$(Que$)="Y" THEN GOTO Begin
2220 GOTO Finish
2230 STOP
2240 !
2250 !
2260 !                                    ****** Post_tcalc   ****
2270 Post_tcalc: !
2280 PRINTER IS 1
2290 ! Check if only pre-test data was stored, but no post-test data
2300 Pstsdta$="Y"
2310 INPUT "HAS POST TEST DATA FOR THIS TEST BEEN PREVIOUSLY STORED? (Y/N) Y",P
stsdta$
2320 IF UPC$(Pstsdta$)="Y" THEN
2330 !
2340 ! CODs have been stored in inches. Initialize variables R1,R3,P4 & P5
2350 ! for printing out in mils.
2360 !
```

```
2370    R1=Deltapsb1*1.E+3
2380    R3=Sdeltap*1.E+3
2390    P4=Deltao*1.E+3
2400    P5=Deltaa*1.E+3
2410    GOTO Pr_dta2
2420  END IF
2430  !
2440  !                                  **** Correc_1 ****
2450  ! Pst-test data input from keyboard
2460 Correc_1:  !
2470  INPUT "ENTER W-Aa AT  +BN/4  IN mm",Waat
2480  PRINT USING """   W-Aa AT  +BN/4    = "",4X,3D.2D,2X,4A";Waat,"mm  "
2490  INPUT "ENTER W-Aa AT MIDLINE IN mm",Waam
2500  PRINT USING """   W-Aa AT MIDLINE    = "",4X,3D.2D,2X,4A";Waam,"mm  "
2510  INPUT "ENTER W-Aa AT  -BN/4  IN mm",Waab
2520  PRINT USING """   W-Aa AT  -BN/4    = "",4X,3D.2D,2X,4A";Waab,"mm  "
2530  PRINT
2540  PRINT
2550  INPUT "ENTER R1 IN mils",R1
2560  PRINT USING """R1     = "",2X,4D.D,"" mils""";R1
2570  INPUT "ENTER R3 IN mils",R3
2580  PRINT USING """R3     = "",2X,4D.D,"" mils""";R3
2590  INPUT "ENTER P4 IN mils",P4
2600  PRINT USING """P4     = "",2X,4D.D,"" mils""";P4
2610  INPUT "ENTER P5 IN mils",P5
2620  PRINT USING """P5     = "",2X,4D.D,"" mils""";P5
2630  PRINT
2640  INPUT "ENTER Pmax IN pounds",Pmax
2650  PRINT USING """   Pmax              = "",4X,6D,2X,4A";Pmax,"lbs "
2660  INPUT "ENTER Pmin IN pounds",Pmin
2670  PRINT USING """   Pmin              = "",4X,6D,2X,4A";Pmin,"lbs "
2680  Cor$="Y"
2690  INPUT "CORRECTIONS? (Y/N) Y",Cor$
2700  IF Cor$="Y" THEN
2710    PRINT USING "@"
2720    GOTO Correc_1
2730  END IF
2740  !
2750  !
2760  ! For compatibility with previous data stored on diskettes, CODs
2770  !  are stored in inches
2780  Deltapsb1=R1*1.E-3
2790  Sdeltap=R3*1.E-3
2800  Deltao=P4*1.E-3
2810  Deltaa=P5*1.E-3
2820  !
2830  !
2840  Store$="Y"
2850  INPUT "STORE DATA ON DISKETTE? (Y/N) Y",Store$
2860  IF Store$="Y" THEN GOSUB Store
2870    !
2880    !                                 ***** Pr_dta2 ****
2890 Pr_dta2:    !
2900  GOSUB Hardcopy
2910  !
2920  GOSUB Specimen
2930  !
2940  !
2950  PRINT USING "/,""Post-test crack arrest measurements"""
2960  PRINT USING "/,9X,""W-Aa AT  +BN/4    = "",4X,3D.3D,"" mm""";Waat
```

```
2970 PRINT USING "9X,""W-Aa AT MIDLINE   =""",4X,3D.3D,"" mm""";Waam
2980 PRINT USING "9X,""W-Aa AT -BN/4    =""",4X,3D.3D,"" mm""";Waab
2990 !
3000 !
3010 PRINT USING "/,9X,""Zero load disp. offset at end of cycle 1       (R1) ="
",4D.D,""  mils""";R1
3020 PRINT USING "9X,""Total disp.offset at end of cycle n-1         (R3) ="",
4D.D,"" mils""";R3
3030 PRINT USING "9X,""Displacement at onset of unstable crack growth (P4) ="",
4D.D,"" mils""";P4
3040 PRINT USING "9X,""Displacement approx. .1 s after arrest         (P5) ="",
4D.D,"" mils""";P5
3050 !
3060 !
3070 PRINT USING "/,9X,""Pmax =""",6D,2X,3A";Pmex,"lbs"
3080 PRINT USING "  9X,""Pmin =""",6D,2X,3A";Pmin,"lbs "
3090 Rp=(Pmax-Pmin)/Pmax
3100 PRINT USING "9X,""(Pmax-Pmin)/Pmex  =""",5D.2D";Rp
3110 IF Rp>.5 THEN
3120    PRINT USING "9X,""Load drop guideline met"""
3130 ELSE
3140    PRINT "**********Load drop guideline NOT met*******************"
3150 END IF
3160 !
3170 !
3180 !
3190 PRINT USING "/,""Post-test crack arrest calculations"""
3200 !
3210 W_aa_avg=(Waam+Waat+Waab)/3
3220 PRINT USING "/,9X,""Length of remaining ligament W-Aa(average) =""",4D.D,""
 mm""";W_aa_avg
3230 !
3240 ! Aa = arrested crack length per ASTM Paragr. 8.6
3250 Aa=W-W_aa_avg
3260 Crakjmp=Aa-Ao
3270 PRINT USING "/,9X,""Crack jump Aa - Ao""",24X,""  =""",4D.D,1X,2A";Crakjmp,"m
m"
3280 !
3290 !
3300 ! Do and Da are "net" CODs per ASTM (in m)
3310 Do=(Deltao-Sdeltap)*25.4  1.E-3
3320 ! For duplex specimens, there is only one unload cycle
3330 ! $ Deltapsb1 (R1) is equal to Sdeltap (R3)
3340 !
3350 Da=.5*(Deltao+Deltaa-Deltapsb1-Sdeltap)*25.4*1.E-3
3360 Rf=Aa/W
3370 Fafw=(2.24*(1.72-.9*Rf+Rf^2)*(1-Rf)^.5)/(9.85-.17*Rf+11*Rf^2)
3380 Fac=E*(B/(Bn*W*.001))^.5
3390 Ko=Do*Faow*Fac
3400 Kf=Da*Fafw*Fac
3410 !
3420 !
3430 PRINT USING "/,9X,""Net COD at initiation per ASTM =""",2X,1D.3DE,"" m""";D
o
3440 PRINT USING "9X,""Net COD at arrest per ASTM     =""",2X,1D.3DE,"" m""";Da
3450 !
3460 !
3470 PRINT USING "/,9X,""Arrested crack length (Aa)             =""",5D.D,"" mm
""";Aa
3480 PRINT USING "9X,""Fractional arrested crack length (Aa/w) =""",4X,D.3D";Rf
```

```
3490 PRINT USING "9X,""Geometry factor F(Aa/W)              = "",4X,D.4D";Faf
w
3500 !
3510 !
3520 PRINT USING "/,9X,""*******************************"""
3530 PRINT USING "9X,""*  "",""Ko = "",5D,"" MPa.m^0.5"",""  *""";Ko
3540 PRINT USING "9X,""*  "",""Ka = "",5D,"" MPa.m^0.5"",""  *""";Kf
3550 PRINT USING "9X,""********************************"""
3560 !
3570 !
3580 !                  VALIDITY CRITERIA
3590 !
3600 !
3610 W015=.15*W
3620 Liga_b=1.25*1000*(Kf/(Ys+Yso))^2
3630 Liga_c=1000*(Kf/(Ys+Yso))^2
3640 Nvalid=2*N
3650 Minjmp=1000*(Ko/Ys)^2/(2*PI)
3660 !
3670 !
3680 PRINT USING "/,1X,""VALIDITY CRITERIA PER ASTM 1221-88  PARA. 9.3"""
3690 PRINT USING "1/,40X,""ACTUAL VALUES"",40X,""ASTM CRITERIA MINIMUMS"""
3700 !
3710 !          aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa
3720 !          *  REMAINING LIGAMENT CRITERIA "A" & "B" PER ASTM    *
3730 !          *bbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbbb
3740 !
3750 PRINT USING "/,1X,""Length of remaining ligament (W - Aa) = "",4D.D,1X,4A,#
";W_aa_avg,"mm"
3760 PRINT USING "1/X,""Remaining ligament (0.15W)"",17X,"" = "",4D.D,1X,2A";W015
,"mm"
3770 IF W_aa_avg>W015 THEN
3780    PRINT USING "1X,K";"REMAINING LIGAMENT CRITERION ""A"" MET"
3790 ELSE
3800    PRINT "***REMAINING LIGAMENT CRITERION ""A"" NOT MET***"
3810 END IF
3820 !
3830 PRINT USING "/,1X,""Length of remaining ligament (W - Aa) = "",4D.D,1X,4A,#
";W_aa_avg,"mm"
3840 PRINT USING "15X,""Remaining ligament  1.25*[Ka/(YS + YSo)]^2   = "",4D.D,1X,
4A";Liga_b,"mm"
3850 IF W_aa_avg>Liga_b THEN
3860    PRINT USING "1X,K";"REMAINING LIGAMENT CRITERION ""B"" MET"
3870 ELSE
3880    PRINT "***REMAINING LIGAMENT CRITERION ""B"" NOT MET***"
3890 END IF
3900 !
3910 ! ____________________________________________________________________
3920 !
3930 !          cccccccccccccccccccccccccccccc
3940 !          c  THICKNESS CRITERION  (C)  c
3950 !          cccccccccccccccccccccccccccccc
3960 !
3970 Bmm=B*25.4
3980 PRINT USING "/,1X,""Specimen width B = "",3D.3D,"" inches"",6X,"" = "",4D.D,"
" mm"",#";B,Bmm
3990 PRINT USING "17X,""Specimen width [Ka/(YS + YSo)]^2"",12X,"" = "",4D.D,"" mm"
"";Liga_c
4000 IF Bmm>Liga_c THEN
4010    PRINT USING "11X,K";"THICKNESS CRITERION ""C"" MET"
```

```
4020 ELSE
4030   PRINT "***THICKNESS CRITERION ""C"" NOT MET***"
4040 END IF
4050 !
4060 ! ________________ ______________________________________ ____________________
4070 !
4080 !             dddddddddddddddddddddddddddddddddddddddddddddddd
4090 !             d   Crack jump length criteria (D, and (E)   d
4100 !             eeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeee
4110 !
4120 !
4130 !
4140 !
4150 !
4160 IF Tv=0 THEN
4170   PRINT USING "/,1X,""Crack jump Aa - Ao"",20X,"" = "",1X,3D.D,1X,2A,#";Cra
kjmp,"mm"
4180   PRINT USING "17X,""ASTM 2N"",36X,"" = "",3D.D,1X,2A";Nvalid,"mm"
4190   IF Crakjmp > Nvalid THEN
4200     PRINT USING "11X,K";"WELD EMBRITTLED SPEC. CRACK JUMP-LENGTH CRITERI
ON ""D"" MET"
4210   ELSE
4220     PRINT "***WELD EMBRITTLED SPEC. CRACK JUMP-LENGTH CRITERION ""D"" NO
T MET***"
4230   END IF
4240   !
4250   !
4260   PRINT USING "/,1X,""Crack jump Aa - Ao"",20X,"" = "",1X,3D.D,1X,2A,#";Cra
kjmp,"mm"
4270   PRINT USING "17X,""Min. crack jump (Ko/YS)^2/2PI"",12X,"" = "",3D.D,1X,
2A";Minjmp,"mm"
4280   IF Crakjmp > Minjmp THEN
4290     PRINT USING "1X,K";"WELD EMBRITTLED SPEC. CRACK-JUMP LENGTH CRITERIO
N ""E"" MET"
4300   ELSE
4310     PRINT "***CRACK-JUMP LENGTH CRITERION ""L"" NOT MET***"
4320   END IF
4330 !
4340 ELSE              ! DUPLEX SPECIMEN CRITERION "D" + "E"
4350 !
4360 !                 ("D" & "E" ARE REPLACED WITH A SINGLE ONE)
4370   Dpxjmp = Aa-Ebcl
4380   PRINT USING "/,1X,""Crack jump beyond EB weld (Aa - EBCL) = "",1X,3D.D,2
X,4A,#";Dpxjmp,"mm"
4390 !
4400 !
4410   Bnmm = Bn*25.4
4420   PRINT USING "14X,""Specimen width at notch (Bn) = "",D.3D,"" inches = ""
,3D.D,"" mm""";Bn,Bnmm
4430   IF Dpxjmp > Bnmm THEN
4440     PRINT "DUPLEX SPECIMEN CRACK JUMP CRITERION ""D"" + ""E"" MET"
4450   ELSE
4460     PRINT "***DUPLEX SPEC. CRACK JUMP CRITERION ""D"" + ""E"" NOT MET***
"
4470   END IF
4480 END IF
4490 !  END OF CRITERIA "D" & "E" DETERMINATIONS
4500 !
4510 !
4520 Cor$ = "Y"
```

```
4530 INPUT "DO YOU WANT TO CORRECT POST TEST DATA (Y/N) Y",Cor$
4540 IF UPC$(Cor$)="Y" THEN
4550    PRINTER IS 1
4560    GOTO Correc_1
4570 END IF
4580 Ques$="Y"
4590 INPUT "DO YOU WANT TO DO MORE (Y/N) Y",Ques$
4600 IF UPC$(Ques$)="Y" THEN Begin
4610 GOTO Finish
4620 !
4630 !
4640 !                              ******** Store  ********
4650 Store: !
4660    !ON ERROR GOSUB Error
4670 DISP "INSERT INITIALIZED AND LABELLED DISC IN DRIVE AND PRESS CONTINUE"
4680 PAUSE
4690 !
4700 READ LABEL Label$ FROM Msus$
4710 !
4720    !
4730    ! Data_stored = 1 (TRUE) if data has been previously stored.
4740 ON ERROR GOTO 4770 !**************************************************
4750 IF Data_stored THEN PURGE File$&Msus$
4760 GOTO 4810 !**************************************************************
4770 IF (ERRN=56) THEN GOTO 4810 !NO PROBLEM !*****************************
4780 GOTO Error_sub !*******************************************************
4790    !
4800    ! There are 26 variables. Round up to 30
4810 Nrec=1
4820 Nvar=30
4830 Nbytes=8*Nvar
4840 CREATE BDAT File$&Msus$,Nrec,Nbytes
4850 ASSIGN @Path TO File$&Msus$;FORMAT OFF
4860 !
4870 ! Note:  Bmet,Hmet,Wtmet, and Wn are not used, but for compatability
4880 !        with previously written output, its location is reserved.
4890 !        It can be used for other purposes.
4900 !        Following line is one used to date (July 8, 1989)
4910 ! OUTPUT @Path;File$,Ys,Tp,E,B,Bmet,Bn,H,Hmet,Wt,Wtmet,Wn,Pr,Rs,Rt,Tu,Tv,N
,Waam,Waat,Waab,Deltapsb1,Sdeltap,Deltao,Deltaa,Pmax,Pmin
4920 OUTPUT @Path;File$,Ys,Tp,E,B,Test_date,Bn,H,Hmet,Wt,Wtmet,Wn,Pr,Rs,Rt,Tu,T
v,N,Waam,Waat,Waab,Deltapsb1,Sdeltap,Deltao,Deltaa,Pmax,Pmin
4930 ASSIGN @Path TO *
4940 Data_stored=1
4950 DISP "DATA STORAGE SUCCESSFUL"
4960 WAIT 1
4970 DISP " "
4980 RETURN
4990 !
5000 !                                  *********** Load *******
5010 Load:!
5020 !
5030 !
5040 INPUT "SPECIMEN NO.",File$
5050 READ LABEL Label$ FROM Msus$
5060 !
5070 ASSIGN @Path1 TO File$&Msus$;FORMAT OFF
5080 ! Bmet, Hmet, Wtmet, & Wn is no longer used, but location is kept for com
patability
5090 ! See comment in Store routine
```

```
5100 READ LABEL Label$ FROM Msus$
5110 ENTER @Path1;File$,Ys,Tp,E,B,Test_date,Bn,H,Hmet,Wt,Wtmet,Wn,Pr,Rs,Rt,Tu,T
v,N,Waam,Waat,Waab,Deltapsb1,Sdeltap,Deltao,Deltaa,Pmax,Pmin
5120 ASSIGN @Path1 TO *
5130   ! If data input from storage was successful, then data is actually
5140   !          there. Initialize Data_stored = 1 (TRUE)
5150 Data_stored = 1
5160 DISP "DATA LOA'' FROM DISK "&Msus$&"  "&Label$&" SUCCESSFUL"
5170 WAi f 3
5180 RETURN
5190 !
5200 !                              ***** Advance *****
5210 Advance:  !
5220 P$ = "N"
5230 INPUT "ADVANCE PAPER? (Y/N) N",P$
5240 IF UPC$(P$) = "Y" THEN PR' 'IT USING "@"
5250 RETURN
5260 !
5270 !
5280 !                              ***** Hardcopy *****
5290 Hardcopy:  !
5300 H$ = "N"
5310 INPUT "NEED HARDCOPY? (Y/N) N",H$
5320 IF UPC$(H$) = "Y" THEN
5330    ?RINTER IS 9
5340    GOSUB Advance
5350    PRINT USING "K,2X,K,3X,K,2X,K";"CRACK ARREST CO\ . JTER CODE CA_TEST "&Ba
nner$,"Time of this run: ",DATE$(TIMEDATE),TIME$(TIMEDATE)
5360 ELSE
5370    PRINTER IS 1
5380 END IF
5390 RETURN
5400 !
5410 !                              **** Error_sub ****
5420 Error_sub:  !
5430 PRINT ERRM$
5440 PRINT "POSSIBLE INPUT DATA ERROR: CHECK INPUT"
5450 DISP "HIT CONTINUE"
5460 PAUSE
5470 GOTO Begin
5480 !
5490 !                              **** Specimen ****
5500 Specimen:  !
5510 PRINT USING "2/,1X,""SPECIMEN NO.  "",7A,#";File$
5520 IF Tv< >0 THEN
5530    PRINT USING """ (DUPLEX)"",#"
5540 ELSE
5550    PRINT USING """ (WELD EMBRITTLED)"",#"
5560 END IF
5570 !
5580 !
5590 PRINT USING "9X,""TEST TEMPERATURE = "",4D,1X,A,#";Tp,"C"
5600 PRINT USING "3X,K,#";" from disk   "&Label$
5610 PRINT USING "3X,""TEST DATE = "",1X,6Z";Test_date
562^ RETURN
5630 !
5640 !                              **** Dpx_we ****
5650 ! Dpx_we:    ! This subprogam prints out whether specimen
5660            ! is a duplex or weld-embrittled type and value of Tv
5670            ! Note that Tv is set equal to zero for weld-embrittled
```

```
5680          !  specimens, and is the measured value for duplex specimens
5690! IF Dpxspm$="Y" THEN
5700!   PRINT USING "/,""This is a DUPLEX specimen"""
5710! ELSE
5720!   PRINT USING "/,K";"This is a WELD EMBRITTLED specimen and TV is set = 0
by program"
5730! END IF
5740! PRINT USING "/,9X,K,3D.2D,2X,2A";"Tv   =  ";Tv,"mm"
5750! RETURN
5760 !
5770 !                               **** Finish ****
5780 Finish:       ! End of Program
5790  PRINTER IS 1
5800  DISP "Crack arrest program ended."
5810  STOP
3820  END
```

APPENDIX C

YOUNG'S MODULUS USED IN THE EVALUATION OF THE CRACK ARREST DATA

Young's modulus is used to calculate the stress intensity factors K_o and K_a, both of which are directly proportional to the value of E used [see Eq. (C.1)]. Young's modulus together with the yield strength are used to calculate the load increment for the loading and unloading cycles for weld-embrittled type specimens as well as the validity criteria.

The Young's modulus used to evaluate both unirradiated and irradiated crack arrest data is calculated from the following expression [1]:

$$E = 207.2 - 0.0571T , \qquad (C.1)$$

where E = Young's modulus in GPa, and T = temperature in °C. Reference [1] in turn cites Subsection NB 2300, *ASME Boiler and Pressure Vessel Code*, Sect. III. The current version of NB 2300 does not give this equation, so it is of interest to compare it with values in the recent edition of the ASME Code [2]. Figure C.1 and Table C.1 compare Young's modulus calculated at the tabular temperatures given in the American Society of Mechanical Engineers Code. In the temperature range used for testing both the unirradiated and irradiated crack arrest specimens, -75 to 100°C, Eq. (C.1) gives values that are about 2% higher than those in Ref. [2]. It is planned to measure Young's modulus for the weldments and reanalyze the crack-arrest data.

Table C.1. Comparison of Young's modulus calculated using values given in the ASME Code and Eq. (C.1)

Temperature (°C)	Young's modulus (GPa)		% Difference [(E-A)/A]
	ASME (A)	EPRI (E)	
-198	216.5	218.5	1
-129	212.4	214.6	1
-73	208.2	211.4	2
21	203.4	206.0	1
93	198.6	201.9	2
149	195.1	198.7	2
204	191.0	195.5	2
260	188.2	192.4	2
316	184.1	189.2	3
371	175.8	186.0	6
427	166.9	182.9	10

NOTE:

ASME = American Society of Mechanical Engineers
EPRI = Electric Power Research Institute

REFERENCES FOR APPENDIX C

1. W. L. Server, J. W. Sheckherd, and R. A. Wullaert, Electric Power Research Institute, Palo Alto, Calif., *Fracture Toughness Data for Ferritic Nuclear Pressure Vessel Materials*, EPRI NP-119, April 1976.

2. *ASME Boiler and Pressure Vessel Code*, Sect. III, Div. 1, Appendix I, Table I-6.0, American Society of Mechanical Engineers, July 1, 1989.

APPENDIX D

TYPICAL OUTPUT FROM CA_TEST FOR A WELD-EMBRITTLED AND DUPLEX SPECIMEN

```
CRACK ARREST COMPUTER CODE CA_TEST Version 5.1  Revised February 14, 1990)  Time of this run   12 Sep 1990  16:02:48

SPECIMEN NO. A72W48  (WELD EMBRITTLED)       TEST TEMPERATURE = -30 C   from disk  CAN01  TEST DATE = 000

   YIELD STRENGTH =  539 MPa       YOUNG'S MODULUS =  208900 MPa   INCR. TO YIELD (DYN) (Yso) = 205 MPa

Pre-test specimen dimension measurements

      B   =   1.000  inch
      BN  =    .743  inch
      2H  =   5.999  inch
      WT  =   6.000  inch

      PR  =   6.35  mm
      RS  =  10.69  mm
      RT  =  40.55  mm
      TU  =  28.33  mm
      N   =  11.38  mm

      TV  =   0.00  mm

Pre-test specimen dimension calculations

      W        =     126.78  mm
      Ao       =      43.27  mm
      Ao/w     =     .341
      F(Ao/W)  =      .2511

      Clip gage is located at (FF/W) =     .25

Pre-test loading calculations

        FOR CYCLE No. =   1,  maximum COD =  30.5  mils          3.05 Volts
        FOR CYCLE No. =   2,  maximum COD =  38.1  mils          3.81 Volts
        FOR CYCLE No. =   3,  maximum COD =  45.8  mils          4.58 Volts
        FOR CYCLE No. =   4,  maximum COD =  53.4  mils          5.34 Volts
        FOR CYCLE No. =   5,  maximum COD =  61.0  mils          6.10 Volts
        FOR CYCLE No. =   6,  maximum COD =  68.6  mils          6.86 Volts
        FOR CYCLE No. =   7,  maximum COD =  76.3  mils          7.63 Volts
        FOR CYCLE No. =   8,  maximum COD =  83.9  mils          8.39 Volts
        FOR CYCLE No. =   9,  maximum COD =  91.5  mils          9.15 Volts
        FOR CYCLE No. =  10,  maximum COD =  99.1  mils          9.91 Volts

        Probable maximum COD for useful results  66.3  Mils
```

```
CRACK ARREST COMPUTER CODE CA_TEST Version 5.1  Revised February 14, 1990)  Time of this run:   12 Sep 1990  16:03:09

SPECIMEN NO.  A72W48  (WELD EMBRITTLED)        TEST TEMPERATURE = -30 C    from disk   CAN01   TEST DATE = 0000

Post-test crack arrest measurements

        W-Aa AT  +BN/4    =     35.192 mm
        W-Aa AT MIDLINE   =      34.573 mm
        W-Aa AT  -BN/4    =     33.037 mm

        Zero load disp. offset at end of cycle 1       (R1) =   1.5  mils
        Total disp.offset at end of cycle n-1          (R3) =   3.0 mils
        Displacement at onset of unstable crack growth (P4) =  47.8 mils
        Displacement approx. .1 s after arrest         (P5) =  51.4 mils

        Pmax = 12000  lbs
        Pmin =   750  lbs
        (Pmax-Pmin)/Pmax  =     .94
        Load drop guideline met

Post-test crack arrest calculations

        Length of remaining ligament W-Aa(average) =  34.3 mm

        Crack jump Aa - Ao                    =  49.2 mm

        Net COD at initiation per ASTM  =  1.138E-03 m
        Net COD at arrest per ASTM      =  1.203E-03 m

        Arrested crack length (Aa)            =  92.5 mm
        Fractional arrested crack length (Aa/w) =    .730
        Geometry factor F(Aa/W)               =    .1193

        ***************************
        *  Ko =  194 MPa.m^0.5   *
        *  Ka =   98 MPa.m^0.5   *
        ***************************

 VALIDITY CRITERIA PER ASTM 1221-88, PARA. 9.3

                     ACTUAL VALUES                                    ASTM CRITERIA MINIMUMS

 Length of remaining ligament (W - Aa) =  34.3 mm          Remaining ligament (0.15W)               =  19.0 mm
 REMAINING LIGAMENT CRITERION "A" MET

 Length of remaining ligament (W - Aa) =  34.3 mm          Remaining ligament  1.25*[Ka/(YS+YSo)]^2  =  21.5 mm
 REMAINING LIGAMENT CRITERION "B" MET

 Specimen width B =  1.000 inches     =  25.4 mm          Specimen width  [Ka/(YS+YSo)]^2          =  17.2 mm
      THICKNESS CRITERION "C" MET

 Crack jump Aa - Ao              =  49.2 mm          ASTM 2N                              = 22.8 mm
      WELD EMBRITTLED SPEC. CRACK JUMP-LENGTH CRITERION "D" MET

 Crack jump Aa - Ao              =  49.2 mm          Min. crack jump  (Ko/YS)^2/2PI          = 20.7 mm
 WELD EMBRITTLED SPEC. CRACK-JUMP LENGTH CRITERION "E" MET
```

```
CRACK ARREST COMPUTER CODE CA_TEST Version 5.1  Revised February 14, 1990)  Time of this run:   12 Sep 1990  16:06:07

 SPECIMEN NO.  A72W57  (DUPLEX)        TEST TEMPERATURE =  21 C    from disk   CAN02   TEST DATE = 000000

      YIELD STRENGTH =   496 MPa        YOUNG'S MODULUS =  206100 MPa    INCR. TO YIELD (DYN) (Yso) = 205 MPa

Pre-test specimen dimension measurements

      B    =   1.298  inch
      BN   =     .976  inch
      2H   =   6.000  inch
      WT   =    6.000  inch

      PR   =   6.35  mm
      RS   =   9.40  mm
      RT   =  41.13  mm
      TU   =  27.07  mm
      N    =   1.43  mm

      TV   =  42.66  mm

Pre-test specimen dimension calculations

      W         =       127.14  mm
      Ao        =        42.94  mm
      Ao/w      =      .338
      F(Ao/W)  =      .2525

      Clip gage is located at (FF/W) =      .25

      EBCL=             58.53  mm

Pre-test loading calculations


This is a DUPLEX specimen, only one loading cycle needed

       FOR CYCLE No. =    1,  maximum COD =   28.5  mils              2.85 Volts
```

```
CRACK ARREST COMPUTER CODE CA_TEST Version 5.1  Revised February 14, 1990)  Time of this run:   12 Sep 1990  16:05:03

SPECIMEN NO.  A72W57  (DUPLEX)        TEST TEMPERATURE =  21 C    from disk   CAN02   TEST DATE = 000000

Post-test crack arrest measurements

      W-Aa AT  +BN/4     =     54.341 mm
      W-Aa AT MIDLINE    =     54.484 mm
      W-Aa AT  -BN/4     =    56.693 mm

      Zero load disp. offset at end of cycle 1       (R1) =    .7  mils
      Total disp.offset at end of cycle n-1          (R3) =   0.0 mils
      Displacement at onset of unstable crack growth (P4) =  50.5 mils
      Displacement approx. .1 s after arrest         (P5) =  51.8 mils

      Pmax = 17600  lbs
      Pmin =  1000  lbs
      (Pmax-Pmin)/Pmax  =     .94
      Load drop guideline met

Post-test crack arrest calculations

      Length of remaining ligament W-Aa(average) =  55.2 mm

      Crack jump Aa - Ao                       =  29.0 mm

      Net COD at initiation per ASTM  =  1.283E-03 m
      Net COD at arrest per ASTM      =  1.290E-03 m

      Arrested crack length (Aa)             =   72.0 mm
      Fractional arrested crack length (Aa/w) =     .566
      Geometry factor F(Aa/W)              =     .1701

      ****************************
      *  Ko =  216 MPa.m^0.5   *
      *  Ka =  146 MPa.m^0.5   *
      ****************************

  VALIDITY CRITERIA PER ASTM 1221-88, PARA. 9.3

                    ACTUAL VALUES                                ASTM CRITERIA MINIMUMS

  Length of remaining ligament (W - Aa) =  55.2 mm          Remaining ligament (0.15W)              =  19.1 mm
  REMAINING LIGAMENT CRITERION "A" MET

  Length of remaining ligament (W - Aa) =  55.2 mm          Remaining ligament  1.25*[Ka/(YS+YSo)]^2  =  54.5 mm
  REMAINING LIGAMENT CRITERION "B" MET

  Specimen width B =  1.298 inches      =  33.0 mm         Specimen width  [Ka/(YS+YSo)]^2          =  43.6 mm
  ***THICKNESS CRITERION "C" NOT MET***

  Crack jump beyond EB weld (Aa - EBCL) =  13.4  mm          Specimen width at notch (Bn) =  .976 inches =  24.8 mm
  ***DUPLEX SPEC. CRACK JUMP CRITERION "D" + "E" NOT MET***
```

APPENDIX E

STRIP CHARTS AND FRACTURE SURFACES

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Specimen Identification - A72W06
Test Temperature - 90°C
Crack Arrest Toughness - 160 MPa·√m
Length of Remaining Ligament - 67.3 mm

SPEC. # A 72 W 06 **DATE:** Oct. 30, 1979 ~~Normal~~ / [✓ Inverted] ~~Non~~ ·N [✓ radiated]

TEST TEMP. 90°C

CLIP GAGE
CAG Ø2

VOLTAGES:

Excitation - 6.588

During calibration-

0 0.0

25 - 2.5~~01~~

50 - 5.03

75 - 7.55

100

In specimen at zero- -0.30 (0.0)

MACHINE SETTINGS

Load Range = ± 20 KIPS

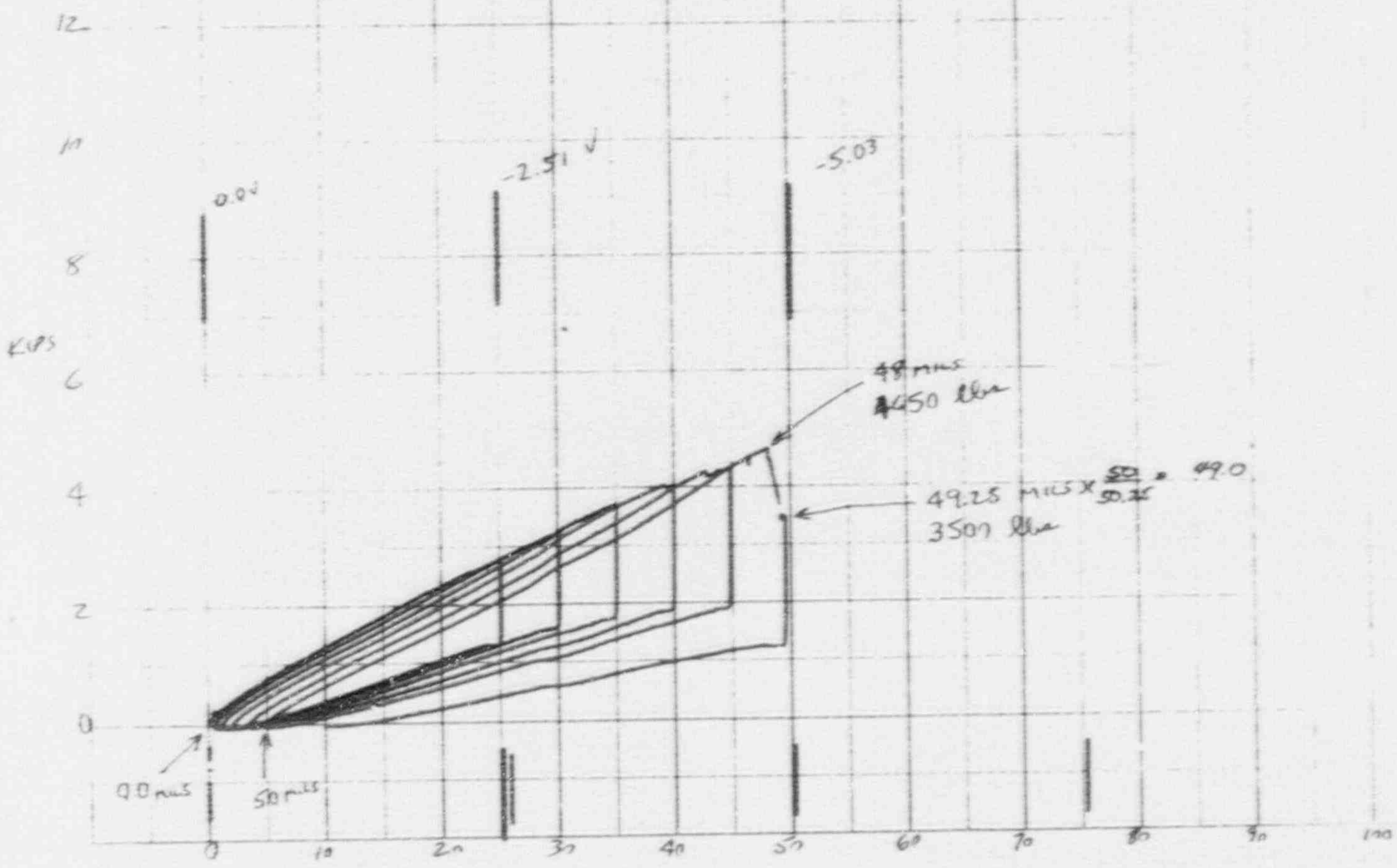
Strain Range = ~~± [illegible]~~

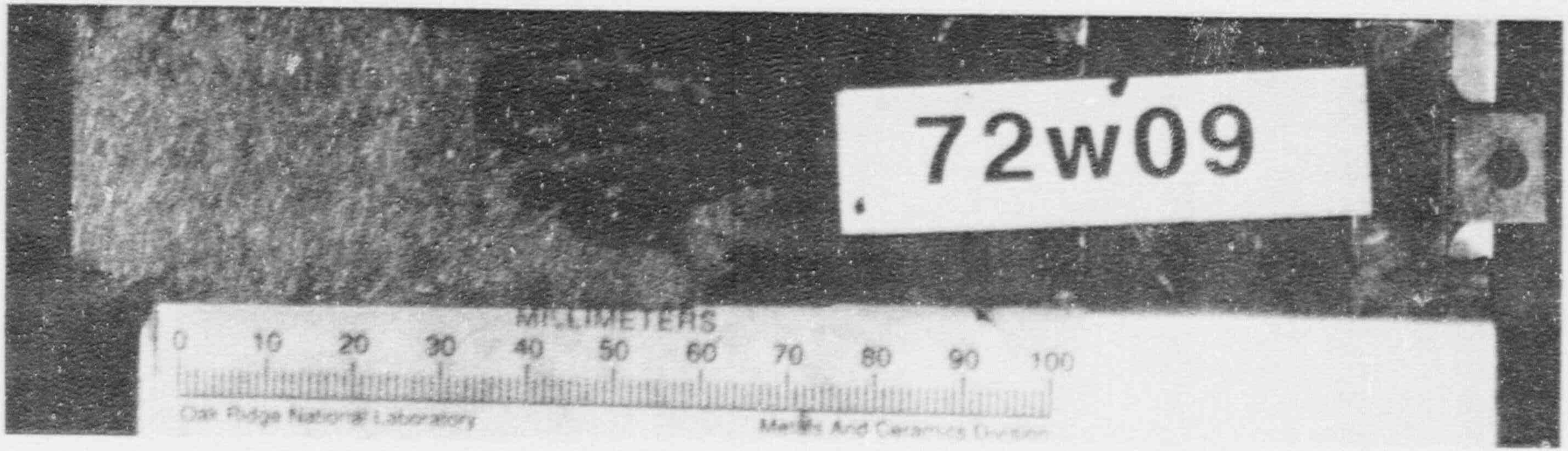
Stroke Range = ± 1"

X-Y CHART SETTINGS

X= 1 "/in

Y= 1 "/in





Specimen Identification - A72W09
Test Temperature - 90°C
Crack Arrest Toughness - 120 MPa·√m
Length of Remaining Ligament - 48.0 mm

SPEC. # A72W09 **DATE:** 9-25-89 ~~Normal~~/ [✓ Inverted] ~~Non~~- [✓ Irradiated]

TEST TEMP. 90 °C

CLIP GAGE #CAG#2

VOLTAGES:

Excitation - 6.543

During calibration-

0 0.0 75

25 -2.449 100

50 -4.978

In specimen at zero- +0.680

MACHINE SETTINGS

Load Range = ±10 KIPS

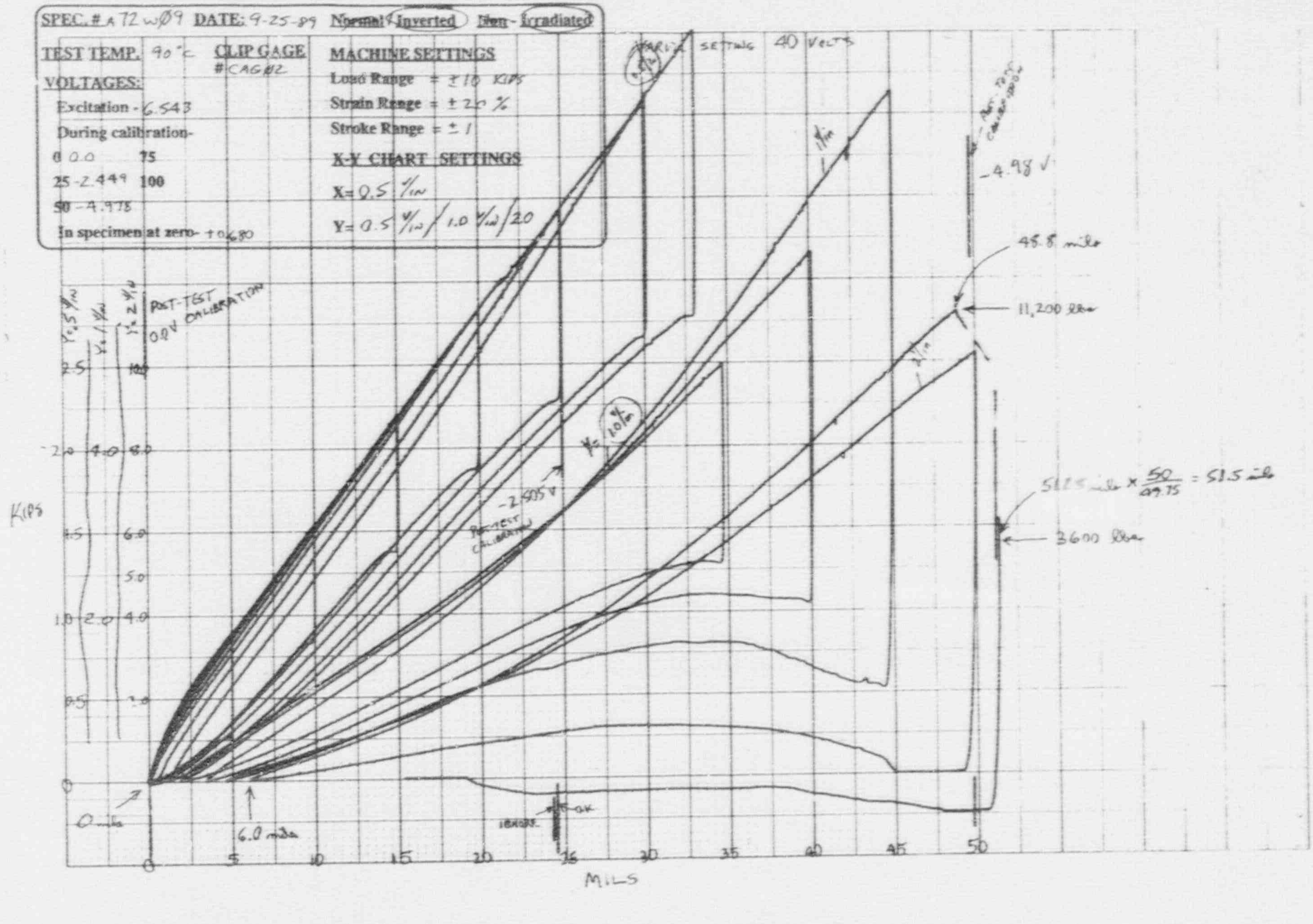
Strain Range = ± 20 %

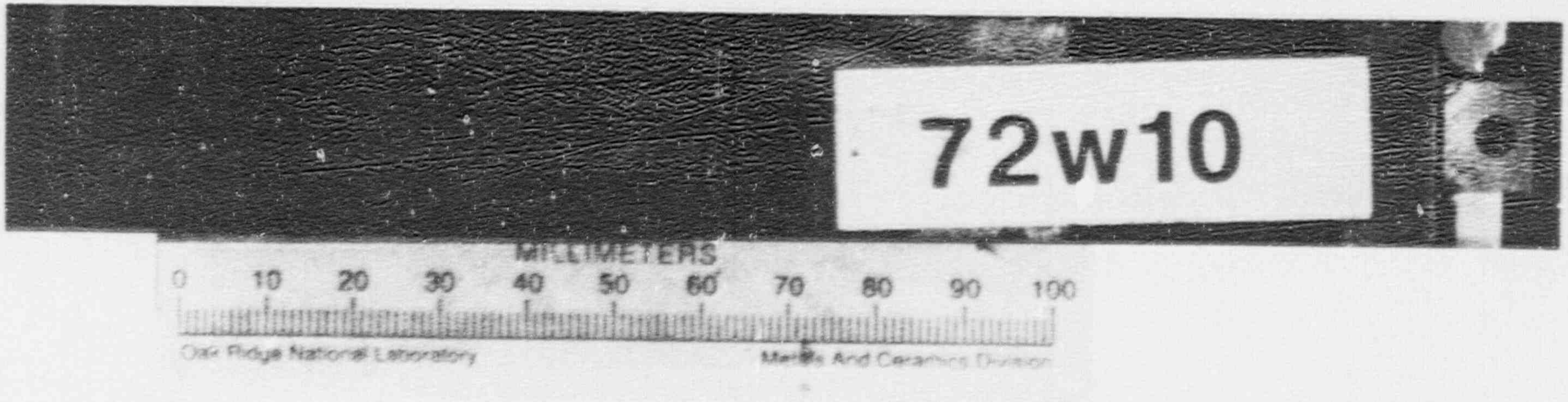
Stroke Range = ± 1

X-Y CHART SETTINGS

X= 0.5 "/in

Y= 0.5 "/in / 1.0 "/in / 20





Specimen Identification - A72W10
Test Temperature - 75°C
Crack Arrest Toughness - 101 MPa·$\sqrt{m}$
Length of Remaining Ligament - 49.2 mm

SPEC. # A12W10 **DATE:** 9/22/89 Normal [✓ Inverted] Non [✓ Irradiated]

TEST TEMP. 75 °C **CLIP GAGE** #CAG#2

MACHINE SETTINGS

Load Range = ± 10 Kips

Strain Range = ± 20 %

Stroke Range = ± 1"

VOLTAGES:

Excitation - 6.543

During calibration-

0 0.0 25

25 -2.47 100

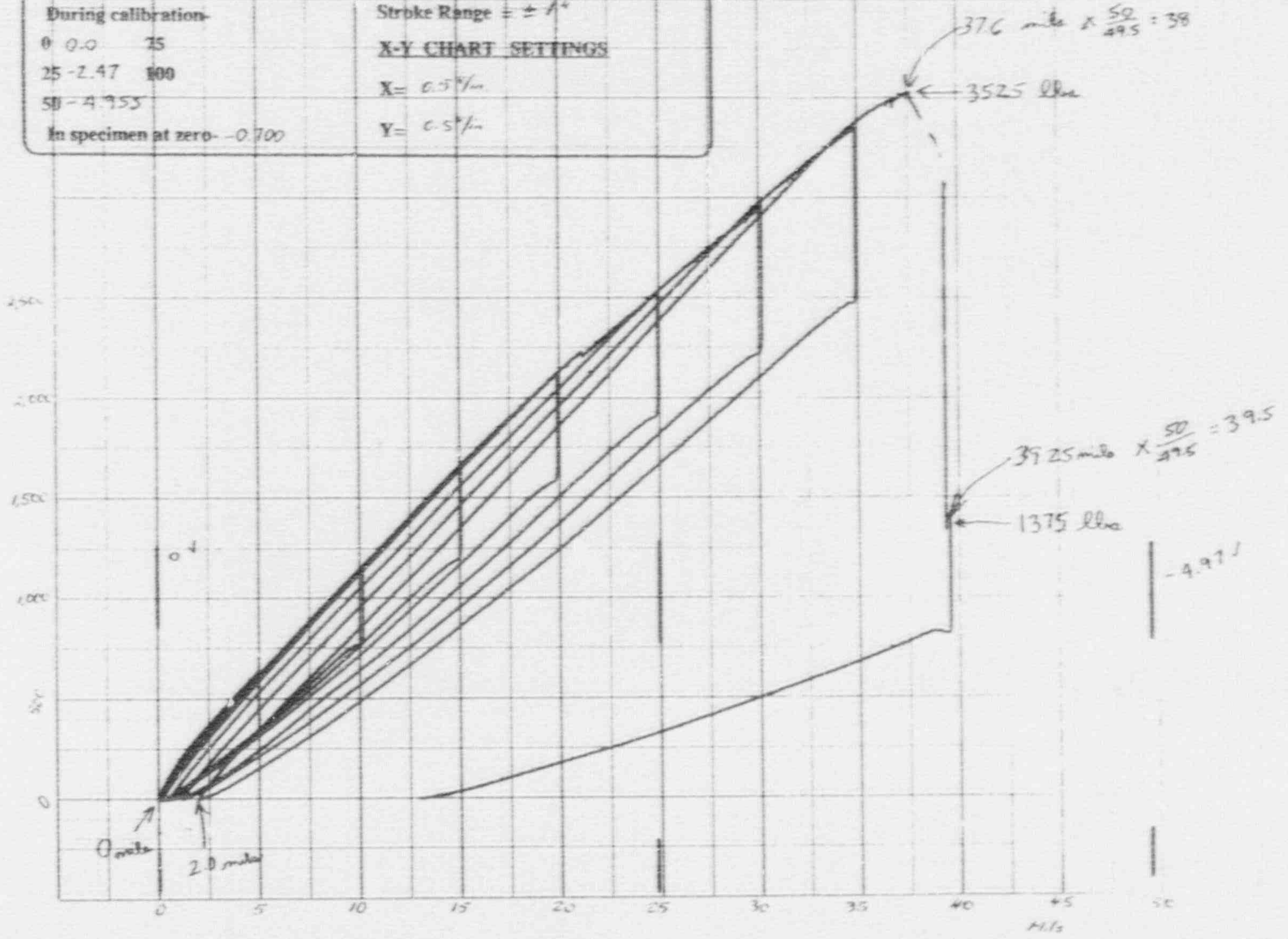
50 -4.955

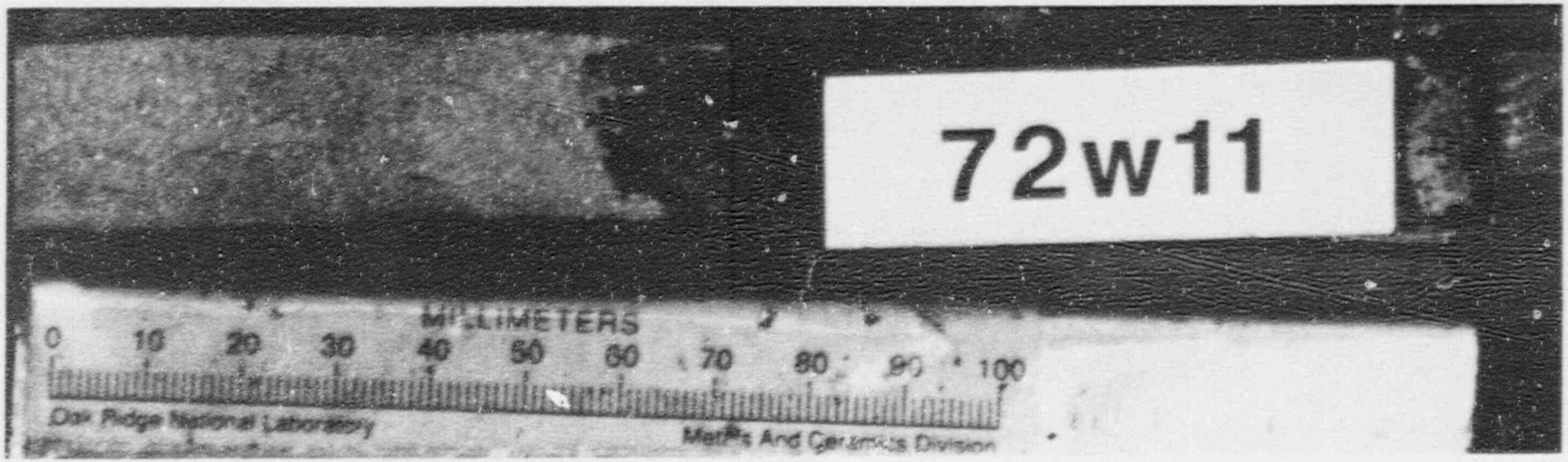
In specimen at zero- -0.700

X-Y CHART SETTINGS

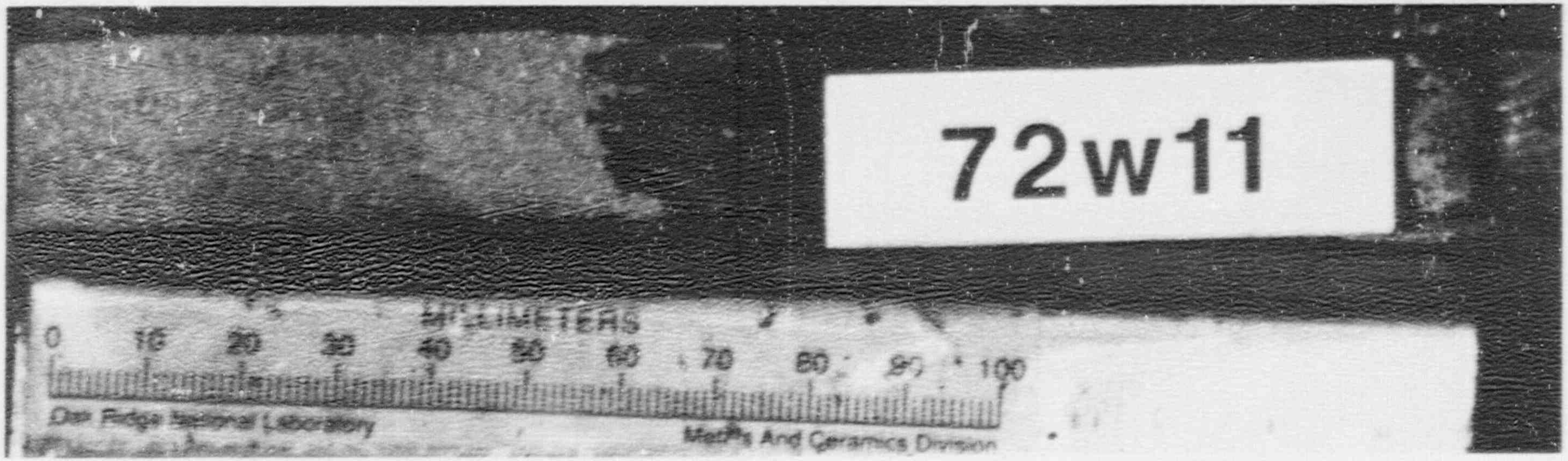
X= 0.5"/in

Y= 0.5"/in





Specimen Identification - A72W11
Test Temperature - 75°C
Crack Arrest Toughness - 133 MPa·√m
Length of Remaining Ligament - 61.1 mm



Specimen Identification - A72W11
Test Temperature - 75°C
Crack Arrest Toughness - 133 MPa·√m
Length of Remaining Ligament - 61.1 mm

SPEC. # A72W11 **DATE:** Oct. 25, 1995 Normal / [✓ Inverted] Non - [✓ Irradiated]

TEST TEMP. 75 °C

CLIP GAGE
#CAG 02

VOLTAGES:

Excitation - 6.588

During calibration-

0	0.0	75	-7.57
25	-2.53	100	-10.09
50	-5.04		

In specimen at zero- -0.299 (0.0)

MACHINE SETTINGS

Load Range = ± 20 KIPS

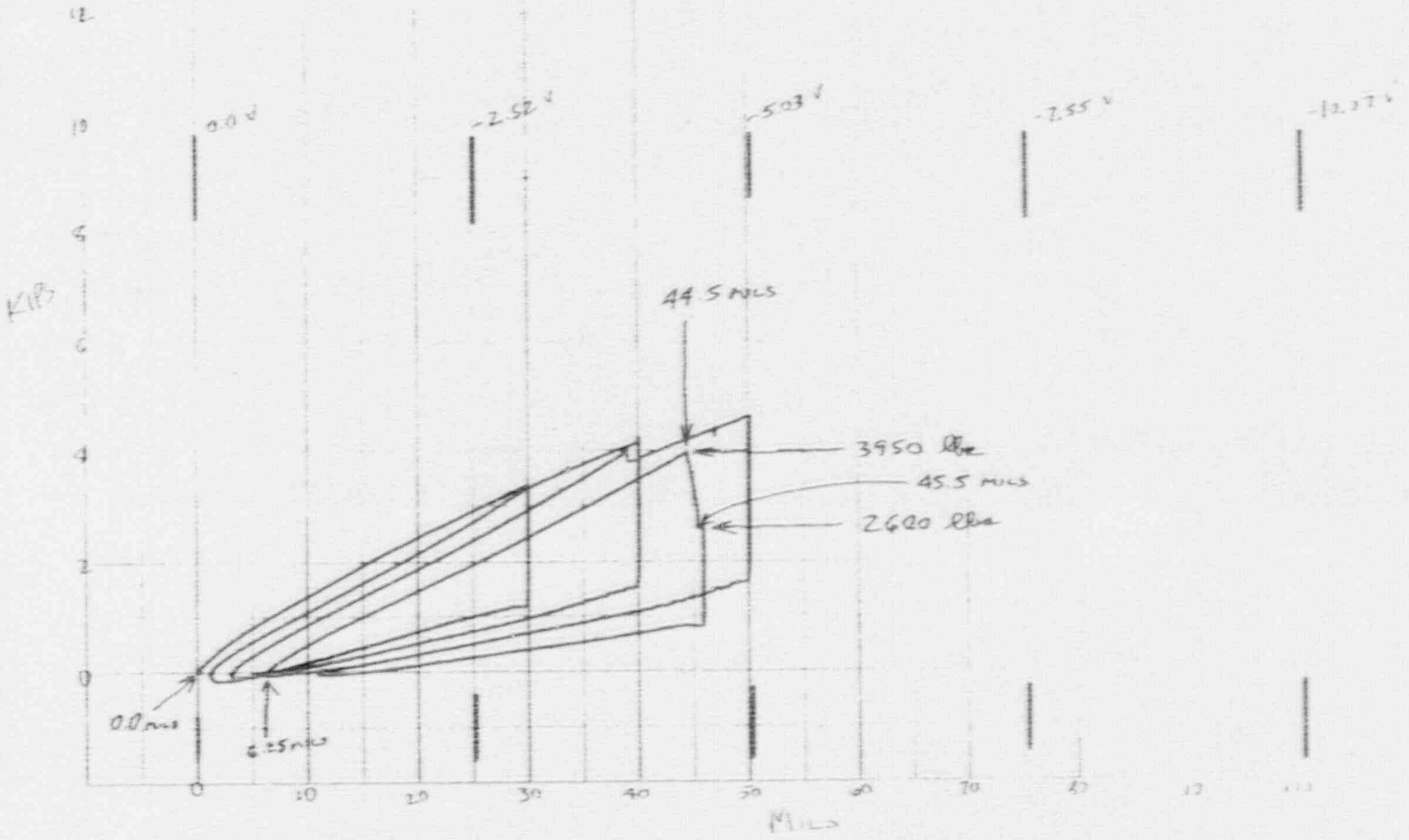
Strain Range = ± 20 %

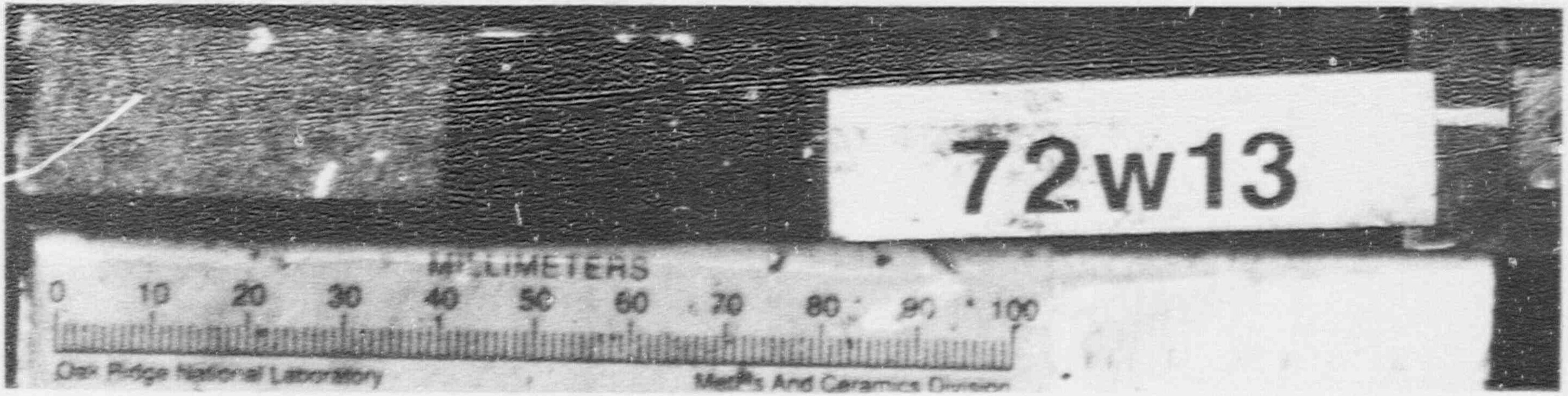
Stroke Range = ± 1

X-Y CHART SETTINGS

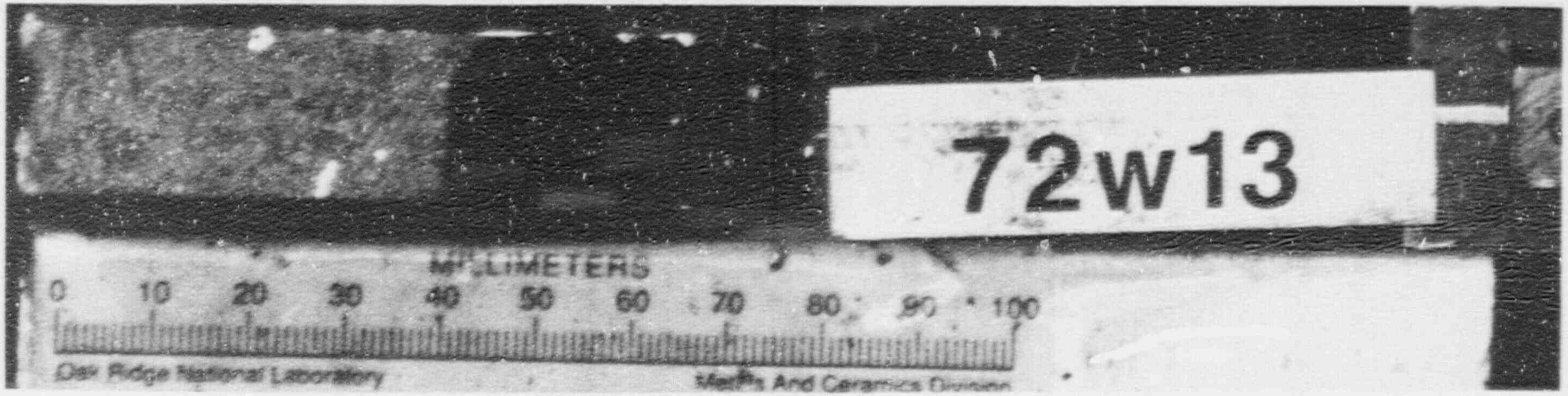
X= 1 %/in

Y= 1 %/in





Specimen Identification - A72W13
Test Temperature - 60°C
Crack Arrest Toughness - 81 MPa·√m
Length of Remaining Ligament - 44.2 mm



Specimen Identification - A72W13
Test Temperature - 60°C
Crack Arrest Toughness - 81 MPa·√m
Length of Remaining Ligament - 44.2 mm

SPEC. # A72W13 **DATE:** Oct. 31, 1989 ~~**Normal**~~/[✓ **Inverted**] ~~**Non**~~ - [✓ **Irradiated**]

TEST TEMP. 60°C **CLIP GAGE** # CAG02 **MACHINE SETTINGS**

VOLTAGES:

Excitation - 6.588

During calibration-

0 0.0 **75**

25 -2.51 **100**

50 -5.03

In specimen at zero- -0.27 (0.0)

Load Range = ±2.0 KIPS

Strain Range = ~~±2.0~~ %

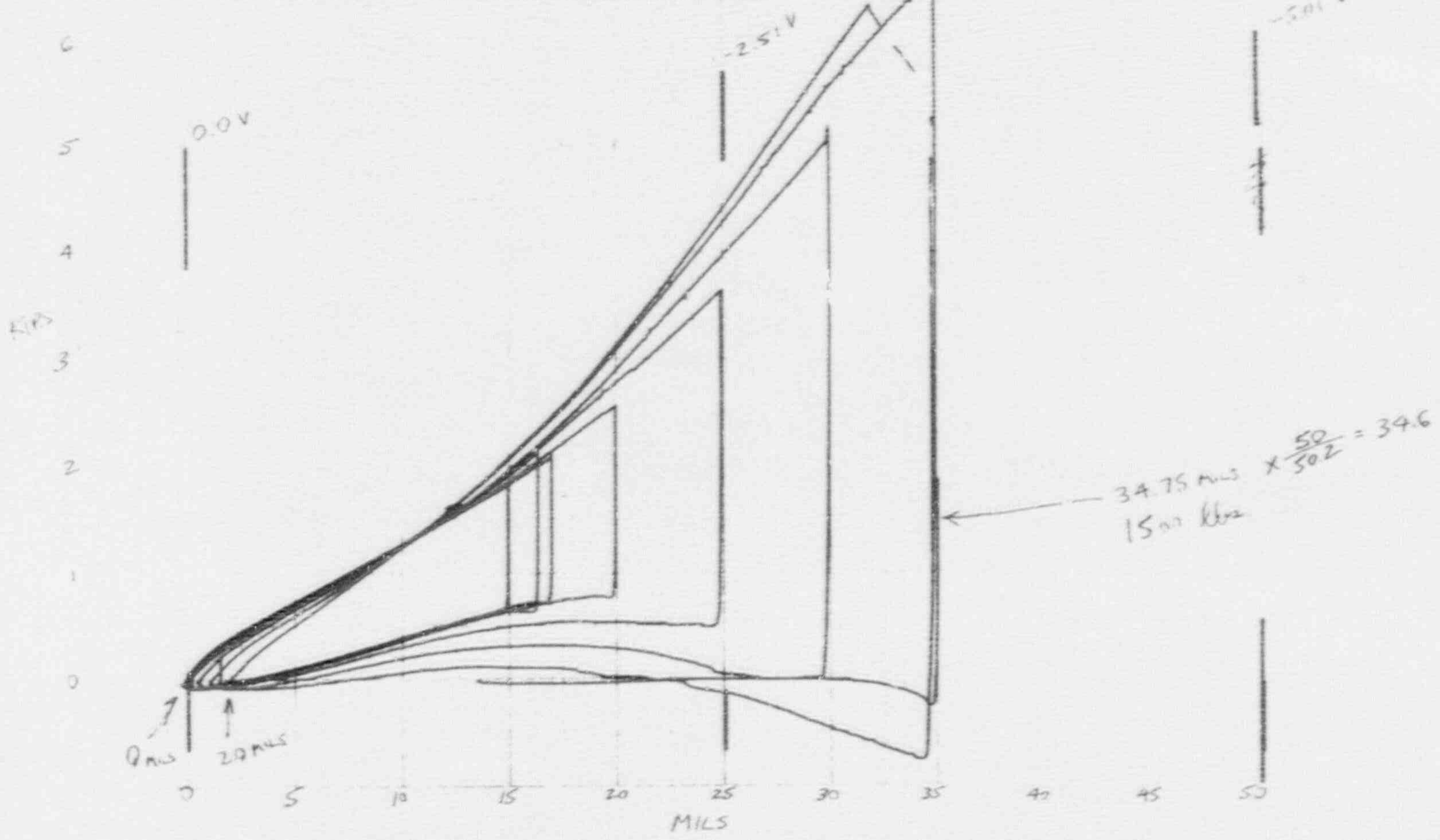
Stroke Range = ±1

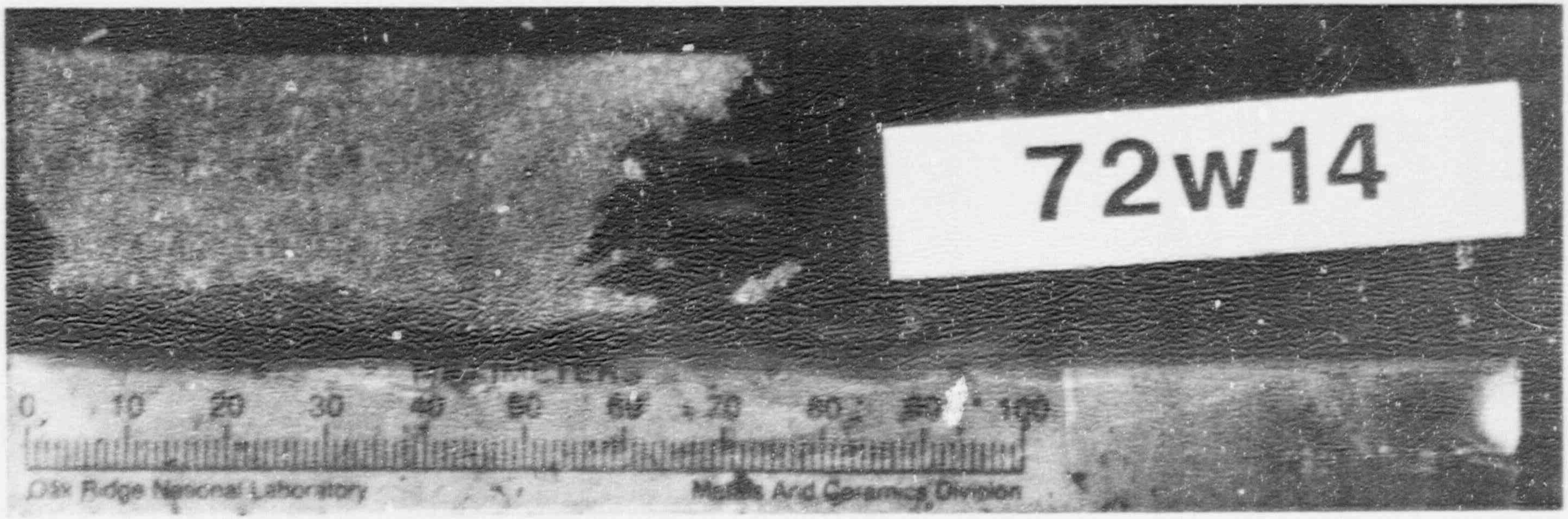
X-Y CHART SETTINGS

X= 0.5 "/in

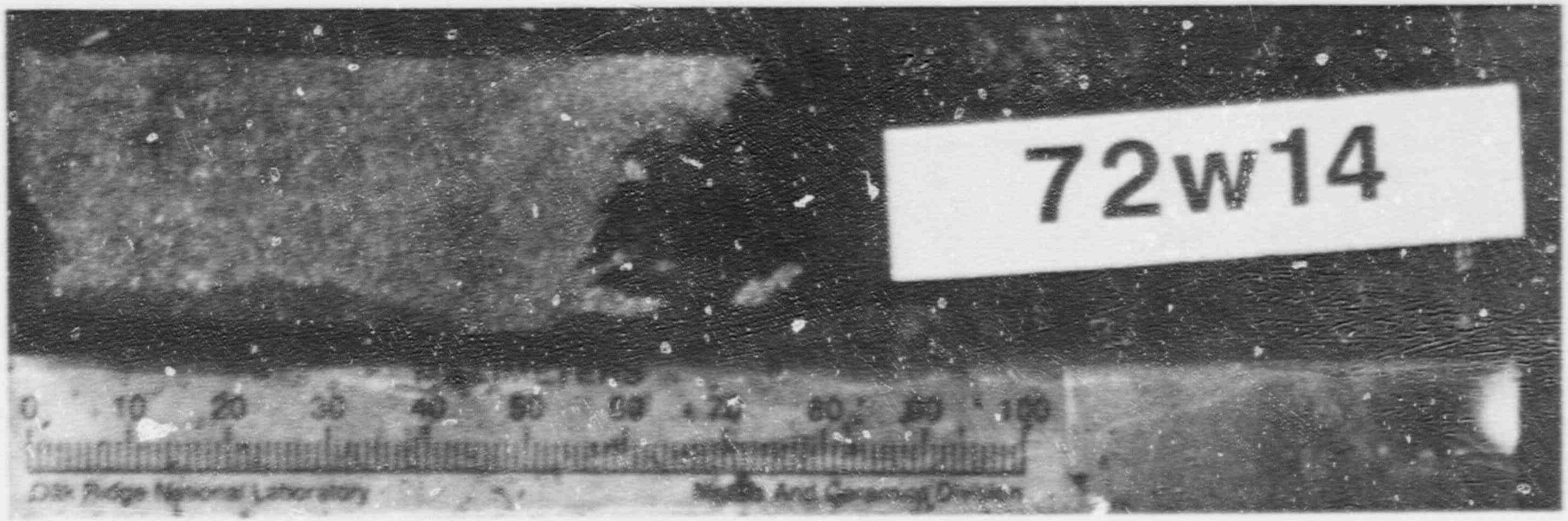
Y= 0.5 "/in

32.0 mils = 31.9
6350 lbs

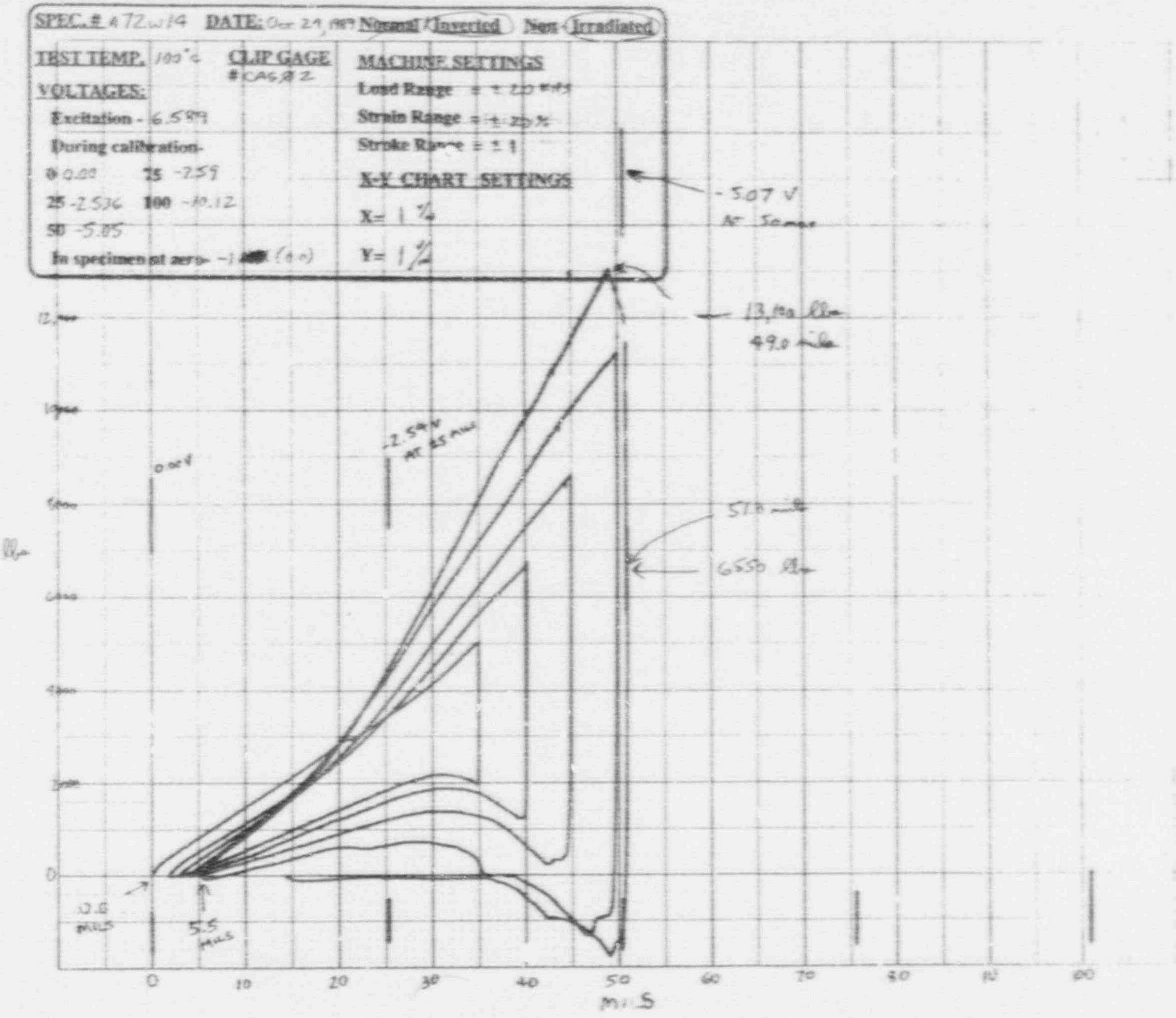




Specimen Identification - A72W14
Test Temperature - 100°C
Crack Arrest Toughness - 144 MPa·√m
Length of Remaining Ligament - 61.5 mm



Specimen Identification - A72W14
Test Temperature - 100°C
Crack Arrest Toughness - 144 MPa·$\sqrt{m}$
Length of Remaining Ligament - 61.5 mm



SPEC. # A72W14 **DATE:** Oct 29, 1989 Normal / [✓ Inverted] Non-[✓ Irradiated]

TEST TEMP. 100°C

CLIP GAGE #CAG#2

VOLTAGES:

Excitation - 6.589

During calibration-

0 0.00 75 -7.59

25 -2.536 100 -10.12

50 -5.85

In specimen at zero- -1[illegible] (4.0)

MACHINE SETTINGS

Load Range = ± 20 kips

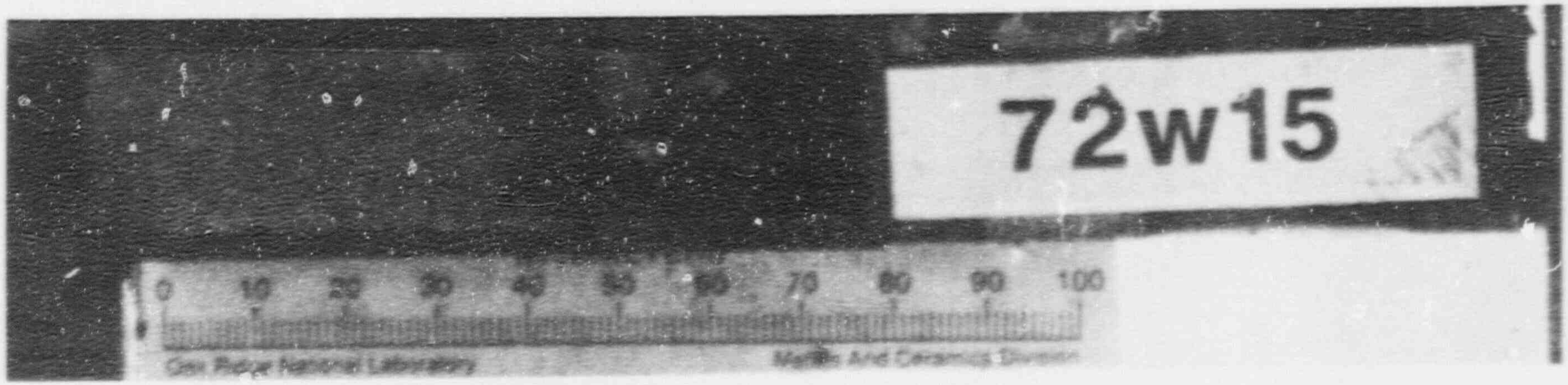
Strain Range = ± 20%

Stroke Range = ± 1

X-Y CHART SETTINGS

X= 1 %

Y= 1 %

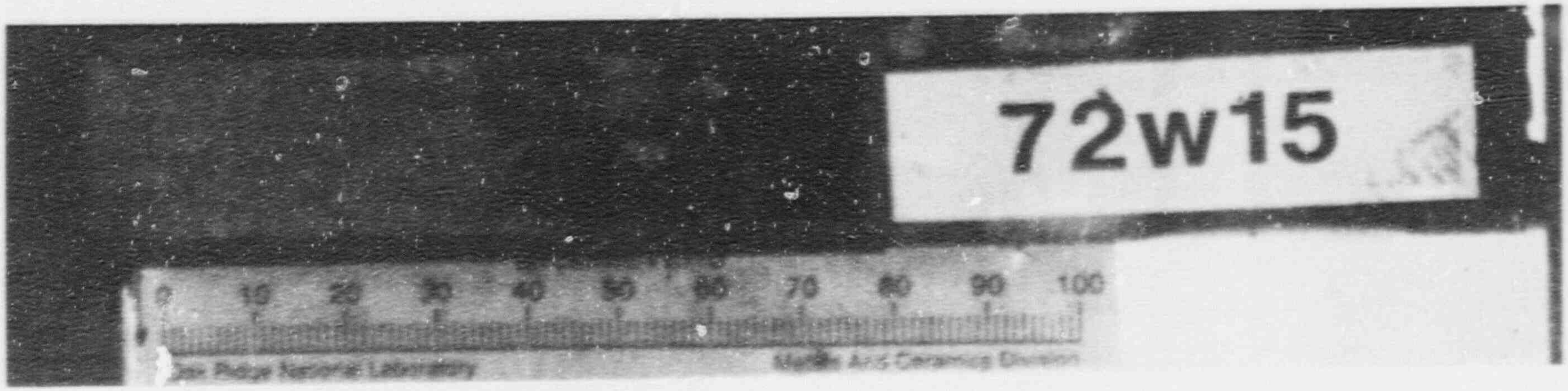


Specimen Identification - A72W15

Test Temperature - 75°C

Crack Arrest Toughness - 114 MPa·√m

Length of Remaining Ligament - 47.1 mm



Specimen Identification - A72W15
Test Temperature - 75°C
Crack Arrest Toughness - 114 MPa·√m
Length of Remaining Ligament - 47.1 mm

SPEC. # A72-15 **DATE:** 9-19-89 **Normal** [✓ **Inverted**] **Non** - [✓ **Irradiated**]

TEST TEMP. 75°C **CLIP GAGE** #CAG Ø2

VOLTAGES:

Excitation - 6.543

During calibration-

0 0.00 75

25 100

50 -4.978

In specimen at zero- +0.234

MACHINE SETTINGS

Load Range = ± 10 KIPS

Strain Range = ± 20 %

Stroke Range = ± 1

X-Y CHART SETTINGS

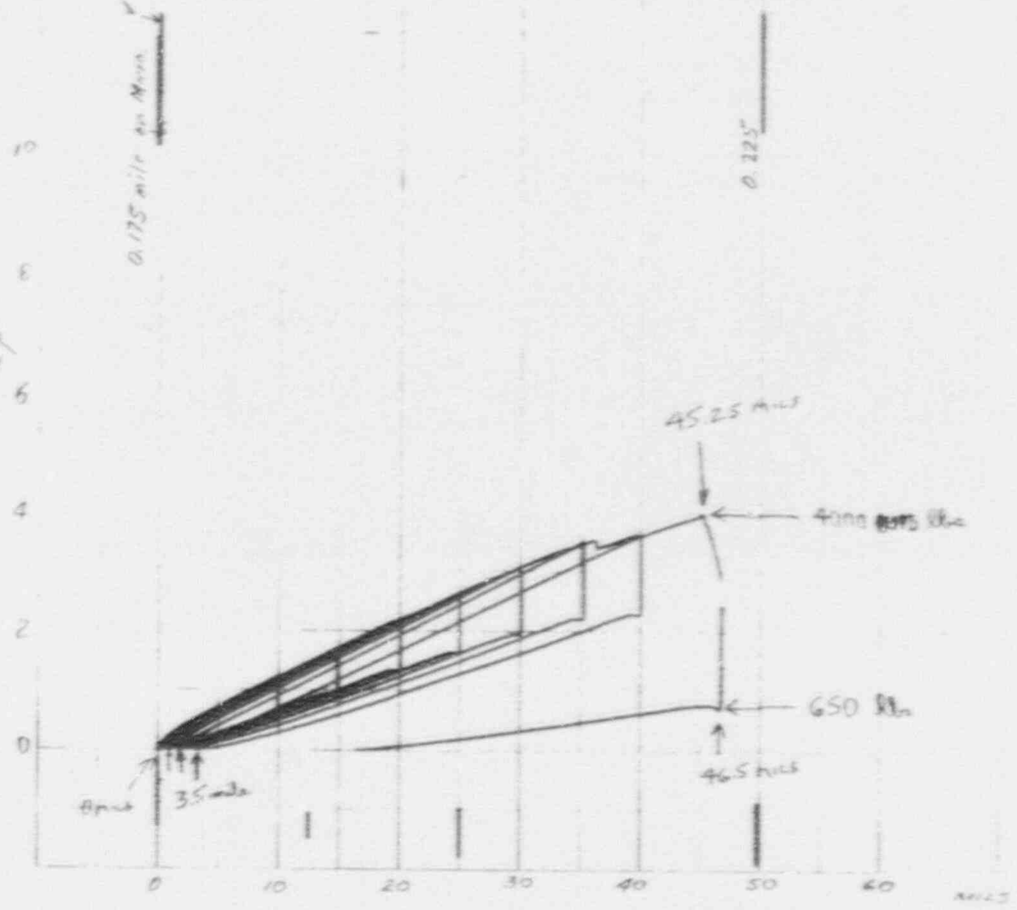
X= 1.0 v/in

Y= 2.0 v/in

[illegible] Setting 30

Loading Rate 150 sec.

Unloading Rate 30 sec



Specimen Identification - A72W16
Test Temperature - 76°C
Crack Arrest Toughness - 102 MPa·√m
Length of Remaining Ligament - 55.0 mm

Specimen Identification - A72W16
Test Temperature - 76°C
Crack Arrest Toughness - 102 MPa·√m
Length of Remaining Ligament - 55.0 mm

SPEC.# A72W16 **DATE:** 9-21-89 ~~Normal~~ [✓ Inverted] ~~Non~~-[✓ Irradiated]

TEST TEMP. ~~75~~°C 76°C **CLIP GAGE** #CAG#2

VOLTAGES:

Excitation - 6.543

During calibration-

0 0.0 75

25 -2.497 100

50 4.990

In specimen at zero- +0.776

MACHINE SETTINGS

Load Range ± ±10 KIPS

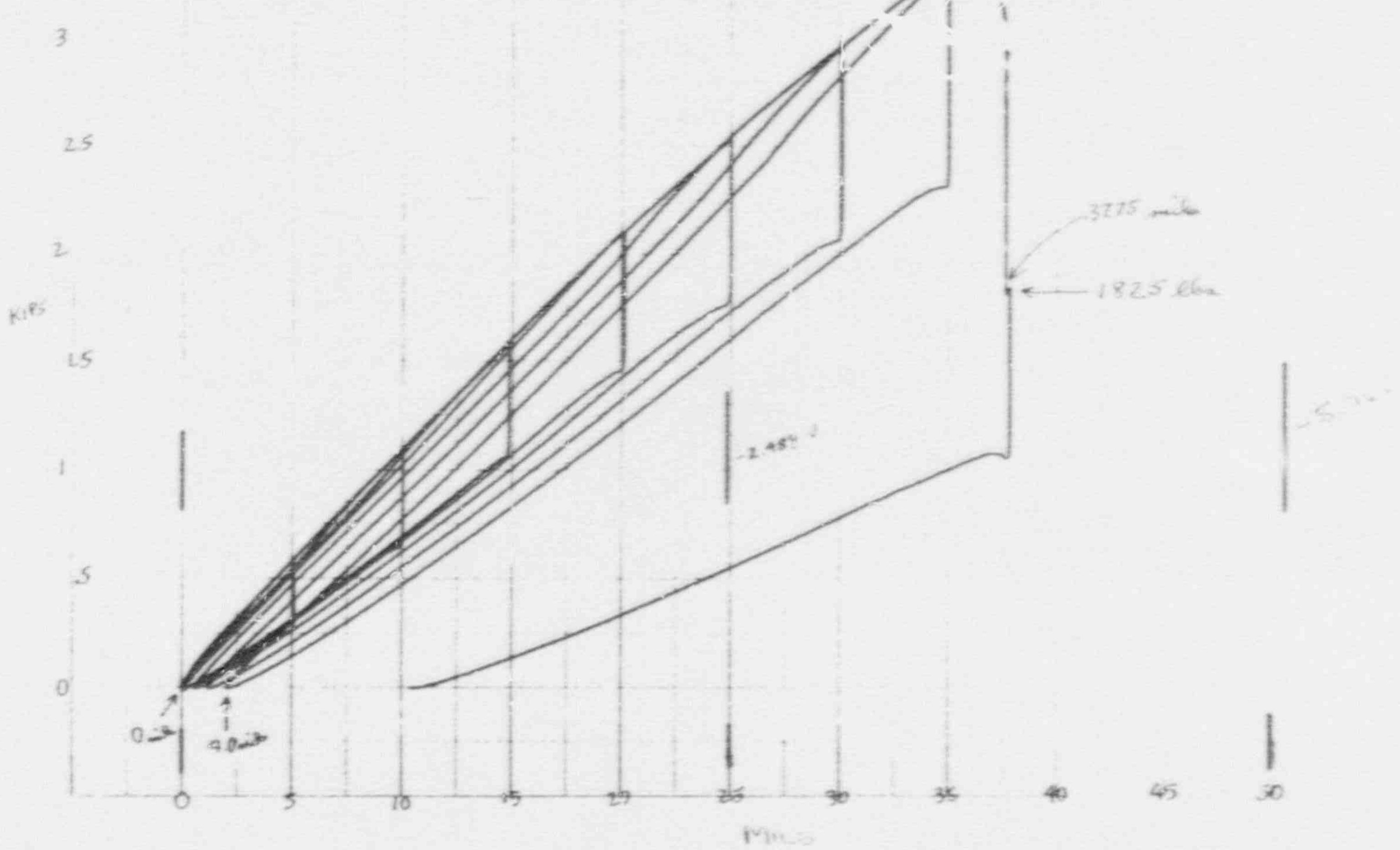
Strain Range ± ±20%

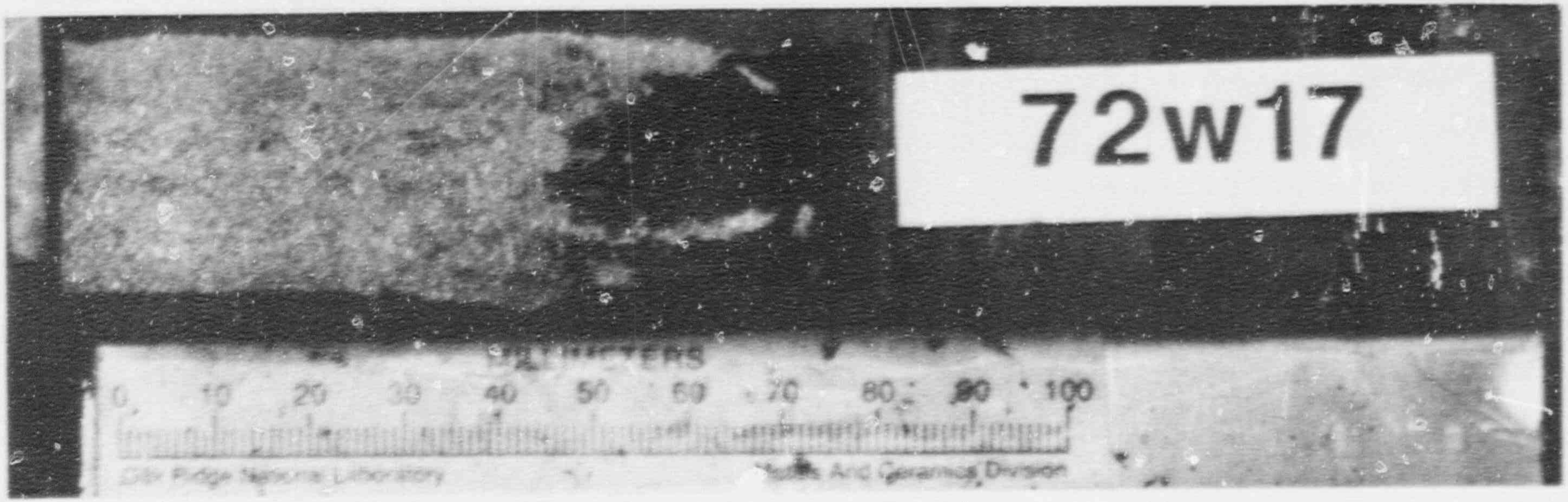
Stroke Range ± ±1"

X-Y CHART SETTINGS

X= 0.5 "/in

Y= 0.5 "/in





Specimen Identification - A72W17
Test Temperature - 100°C
Crack Arrest Toughness - 118 MPa·√m
Length of Remaining Ligament - 53.8 mm

Specimen Identification - A72W17
Test Temperature - 100°C
Crack Arrest Toughness - 118 MPa·$\sqrt{m}$
Length of Remaining Ligament - 53.8 mm

SPEC. # F72W17 **DATE:** ~~[illegible]~~ Oct. 22, 1989 ~~Normal~~ [✓ Inverted] ~~[illegible]~~ [✓ Irradiated]

TEST TEMP. 100°C **CLIP GAGE** #[illegible]

VOLTAGES:

Excitation - 16.590

During calibration-

0 0.00 75 - 7.692

25 -2.537 100 -10.22

50 -5.16

In specimen at zero- -0.683 (0.0)

MACHINE SETTINGS

Load Range ± ±20 kips

Strain Range ± ±20%

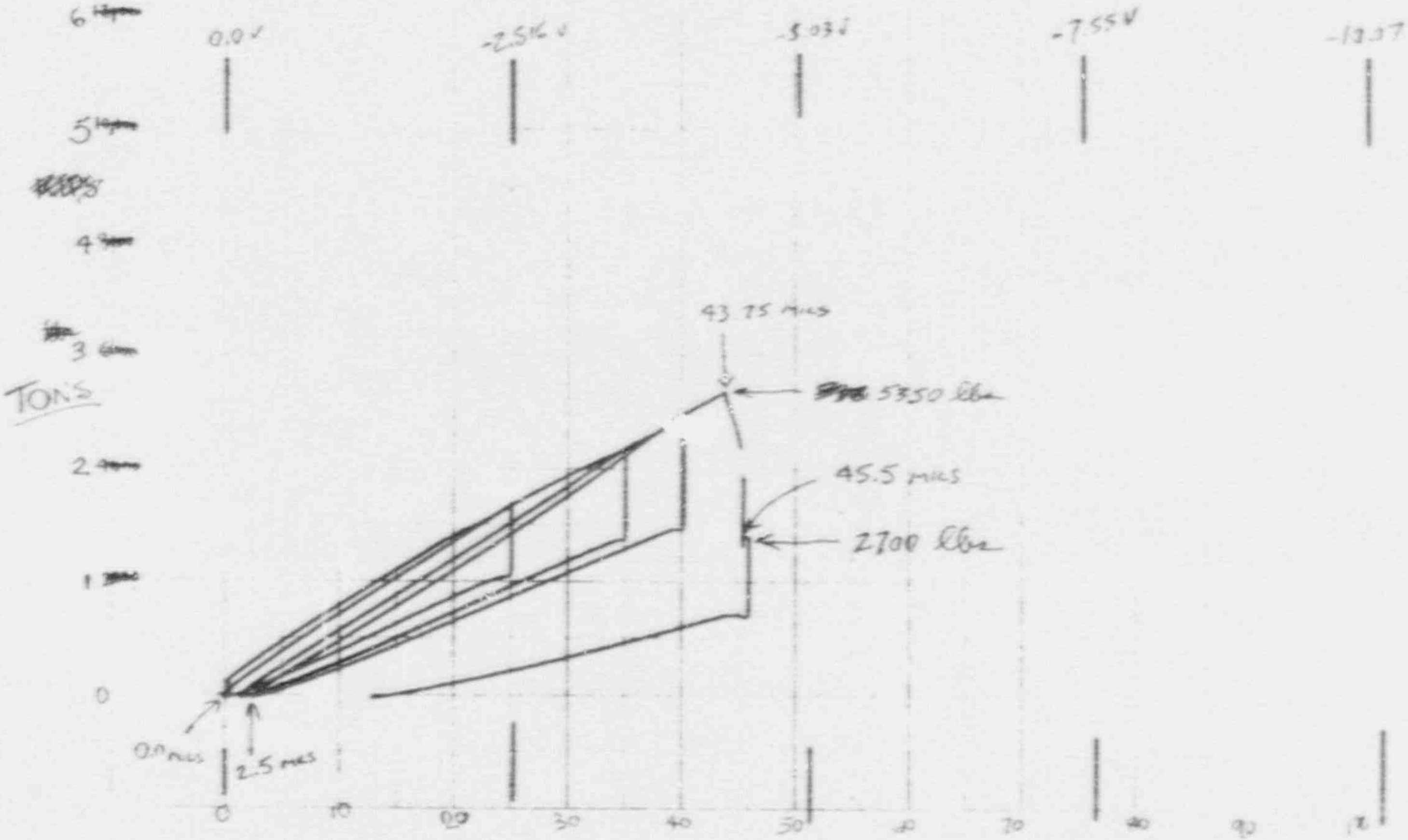
Stroke Range ± ±1

X-Y CHART SETTINGS

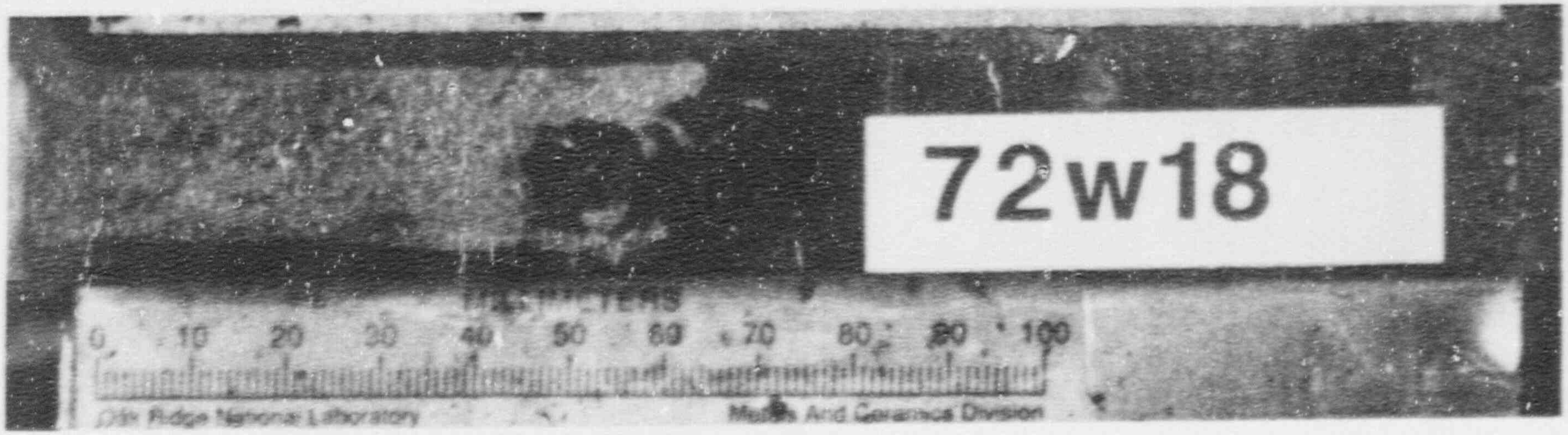
X= 1"/in

Y= 1"/in

Brake at 99°C



Specimen Identification - A72W18
Test Temperature - 90°C
Crack Arrest Toughness - 132 MPa·$\sqrt{m}$
Length of Remaining Ligament - 57.0 mm



Specimen Identification - A72W18
Test Temperature - 90°C
Crack Arrest Toughness - 132 $\text{MPa}\cdot\sqrt{\text{m}}$
Length of Remaining Ligament - 57.0 mm

SPEC. # ATZW18 **DATE:** Nov 13, 1989 Normal [✓ Inverted] Non-[✓ Irradiated]

TEST TEMP. 90°C **CLIP GAGE** #CAG02

VOLTAGES:

Excitation - 6.588

During calibration-

0 0.2 75 -7.55

25 -2.52 100 -10.05

50 -5.03

In specimen at zero- -0.380 (0.0)

MACHINE SETTINGS

Load Range = ± 20 KIPS

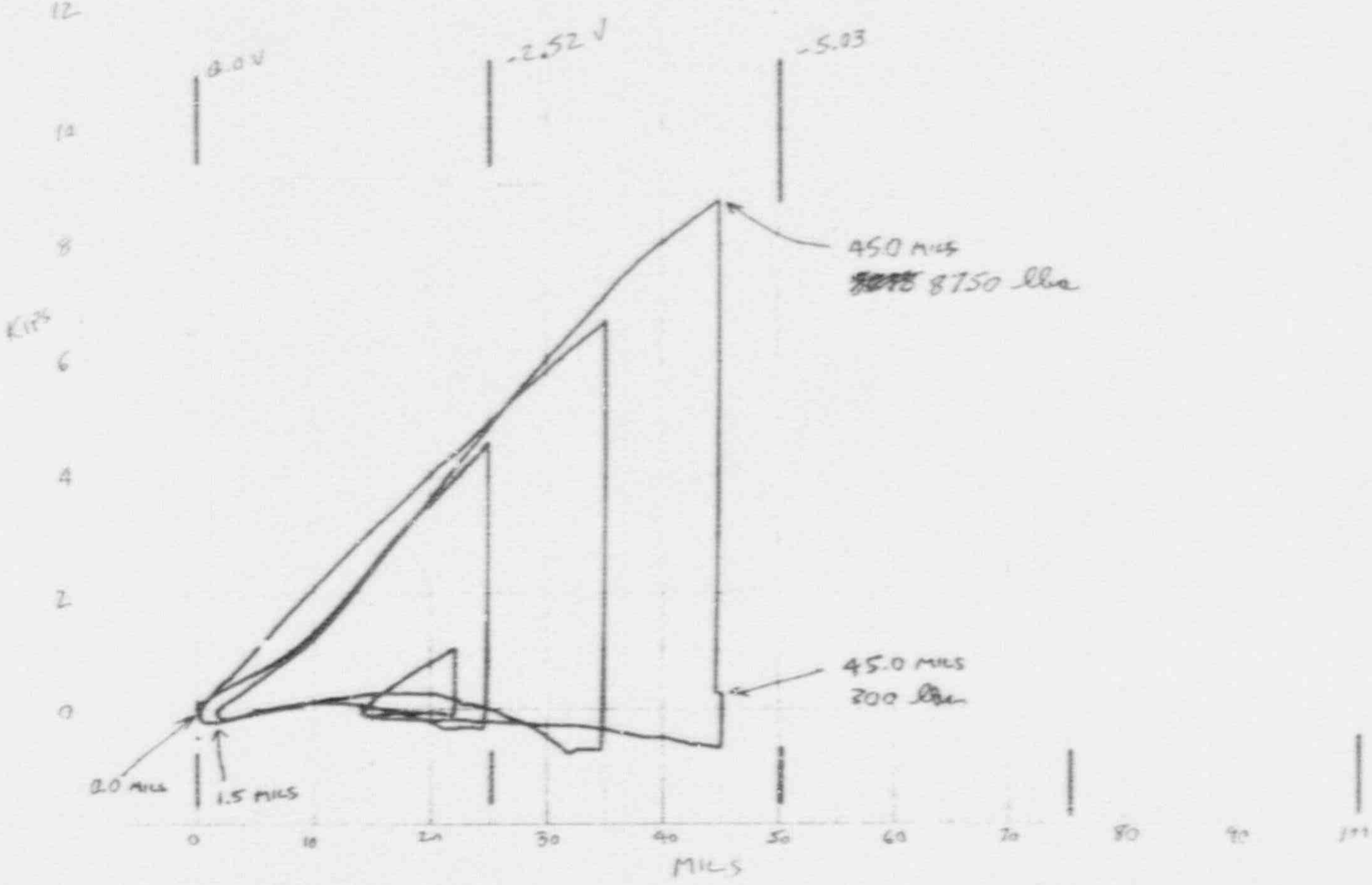
Strain Range = ± 20%

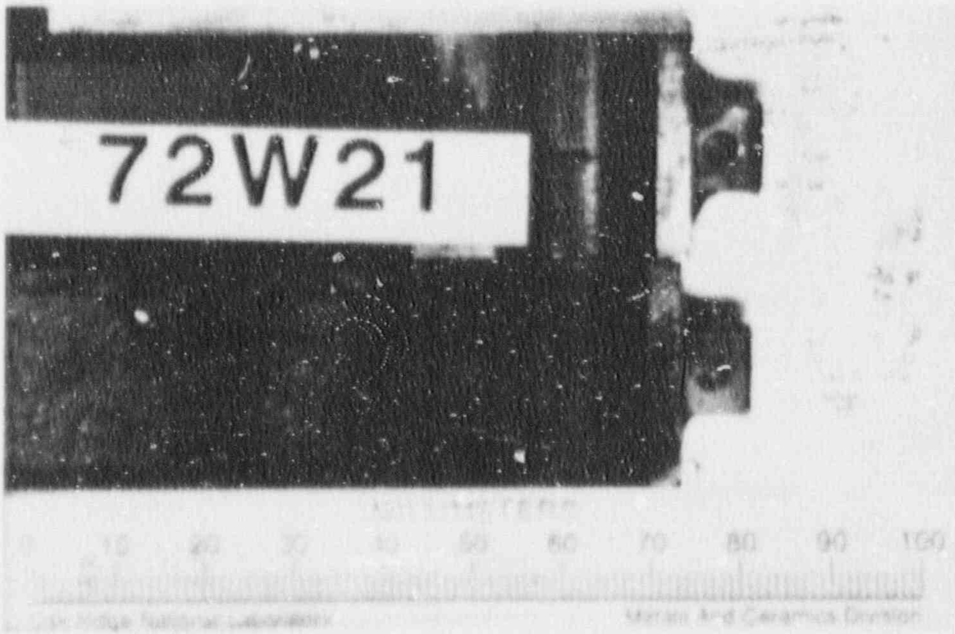
Stroke Range = ± 1

X-Y CHART SETTINGS

X= 1 $^{K}/_{in}$

Y= 1 $^{K}/_{in}$





Specimen Identification = A72W21
Test Temperature = 30°C
Crack Arrest Toughness = $53\ \mathrm{MPa}\cdot\sqrt{\mathrm{m}}$
Length of Remaining Ligament = 19.9 mm

SPEC. IRRAD A72W21 X=.5%/in TEMP. 30°C

Y=.5K/in

DATE 8-23-89

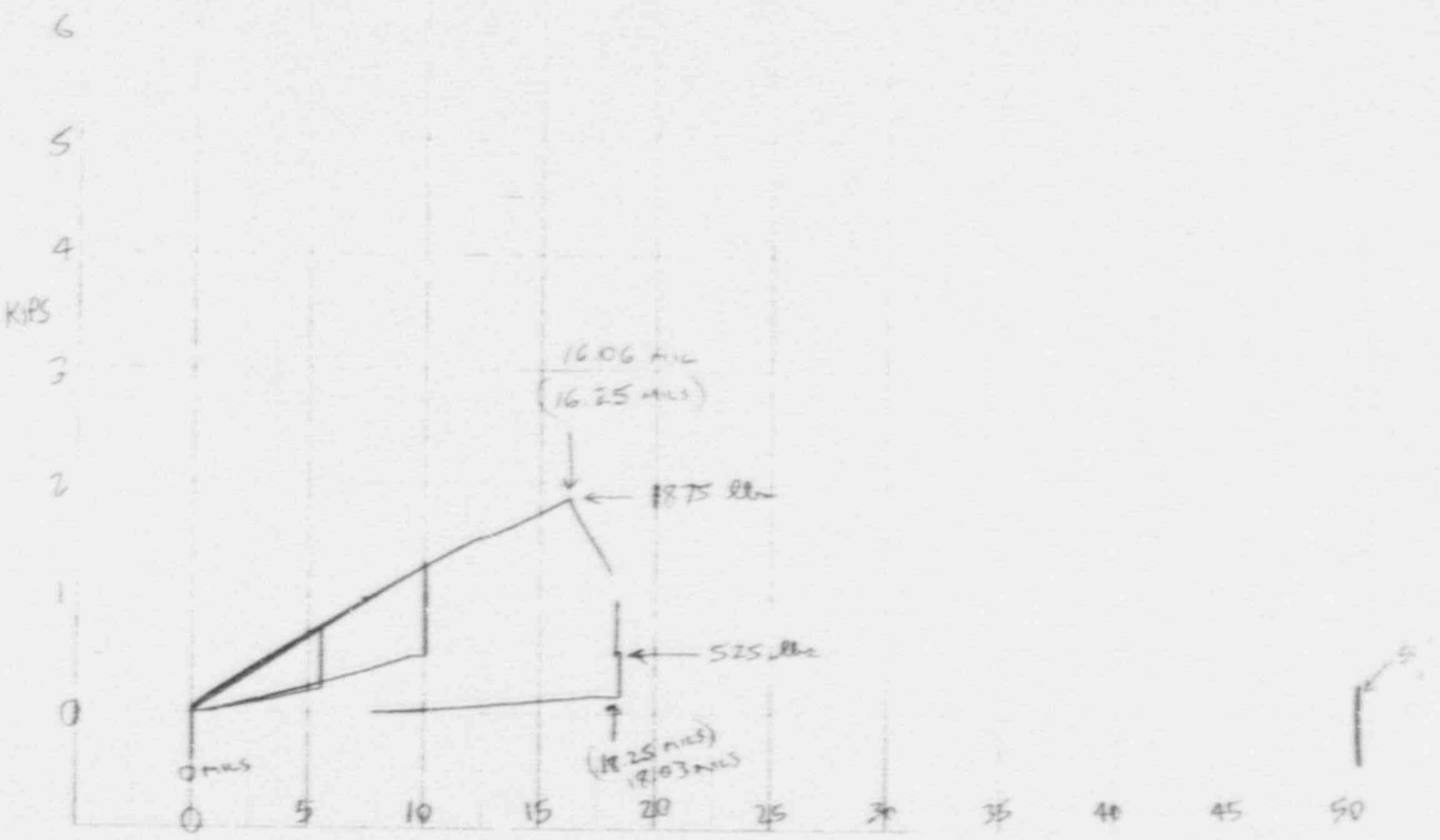
LOAD RANGE ± 20 KIPS

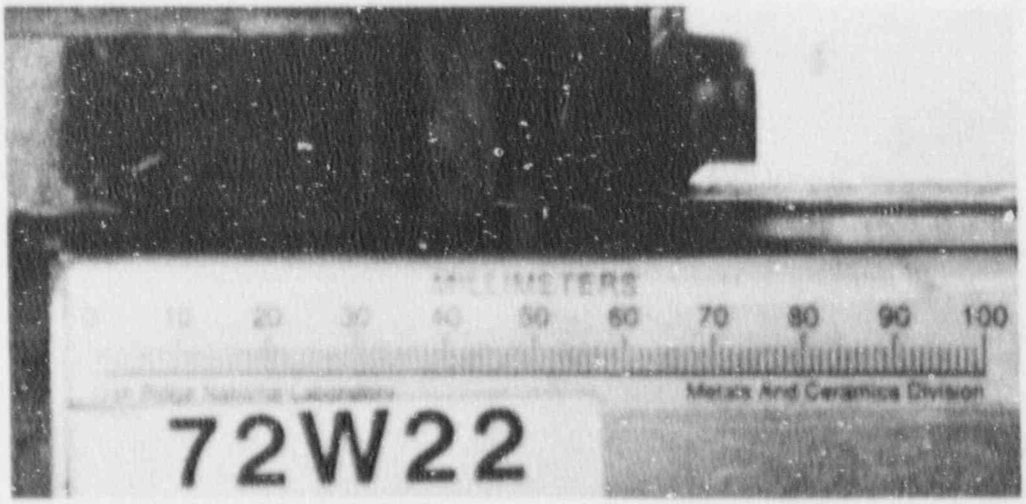
STRAIN RANGE ± 10%

STROKE RANGE 3 (±1")

NORMAL POSITION

CLIP GAGE EXC = 3.436" DC





Specimen Identification = A72W22
Test Temperature = 60°C
Crack Arrest Toughness = 62 $\text{MPa}\cdot\sqrt{m}$
Length of Remaining Ligament = 7.1 mm

SPEC A72W22 8-25-89

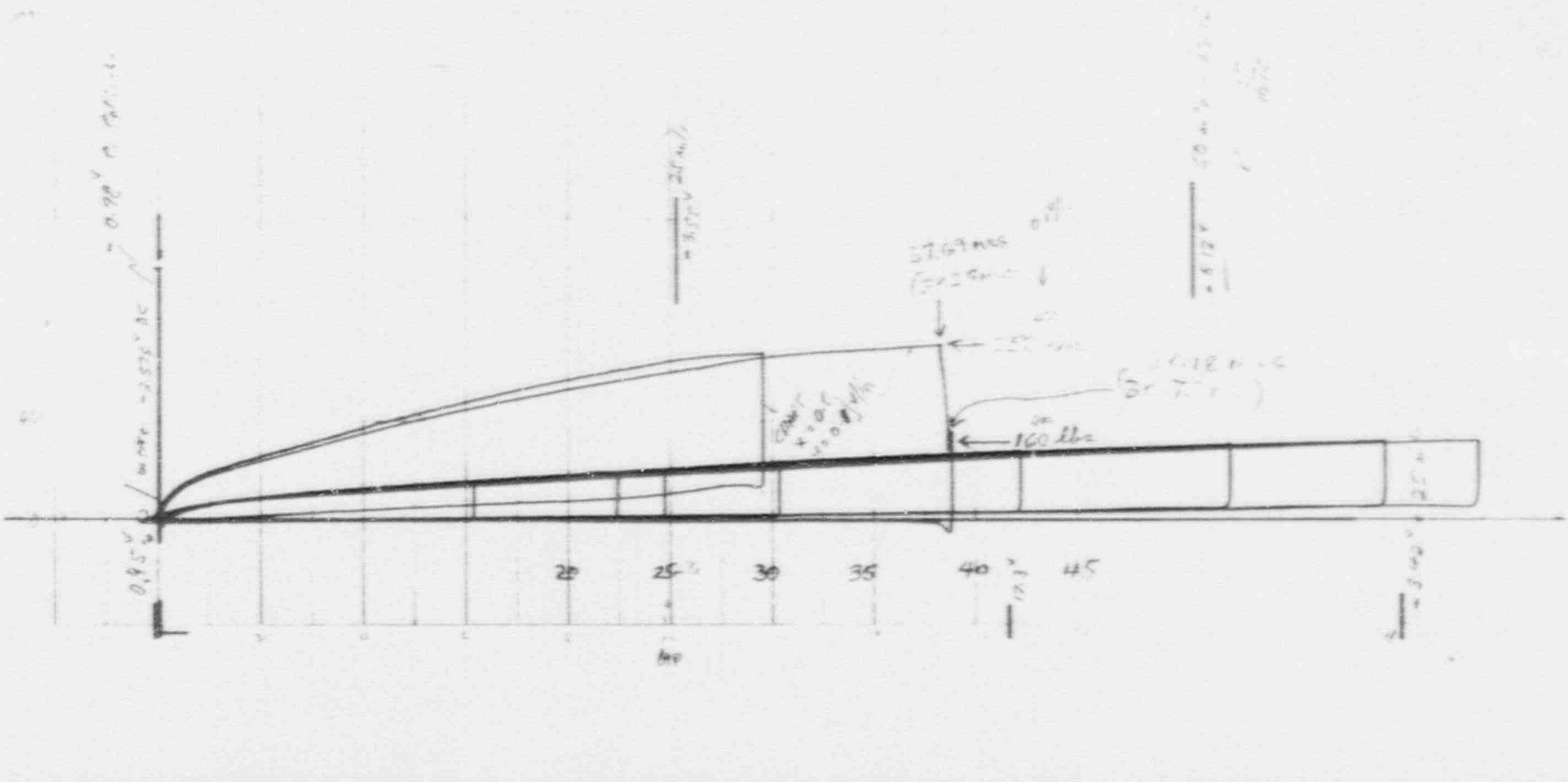
TEST TEMP 60°C

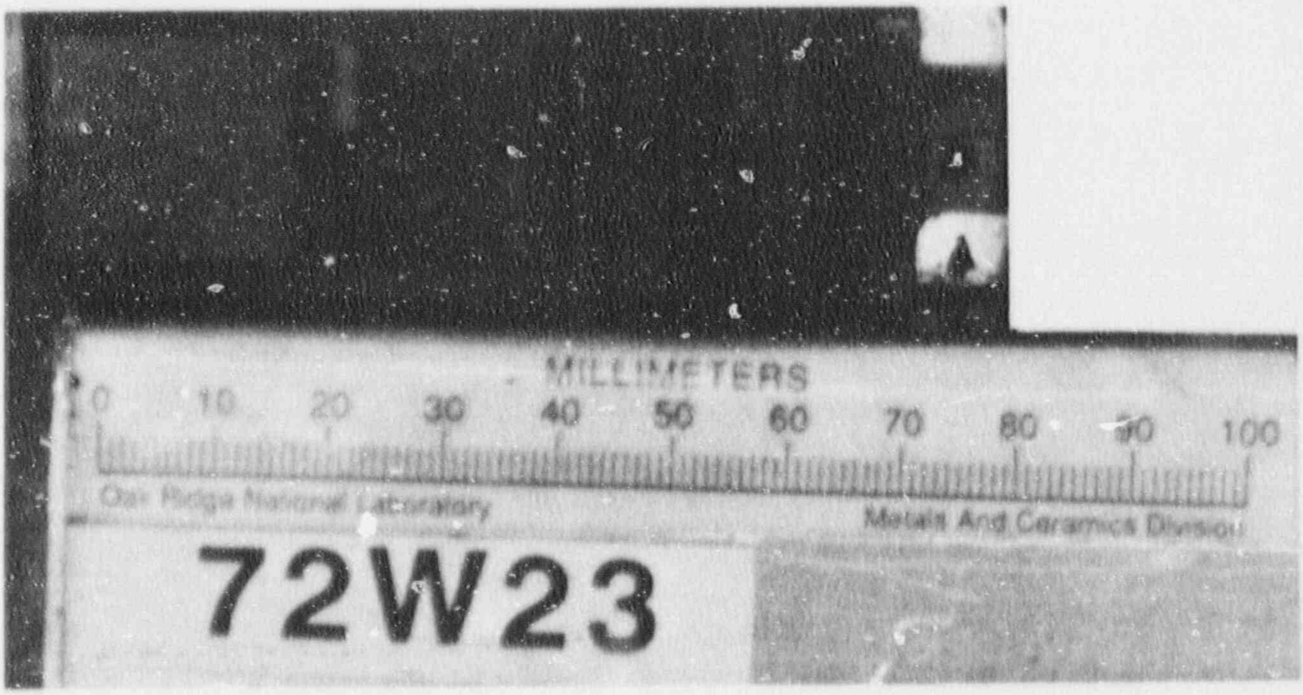
IRRADIATED

INHIBITED

X = 0.2"/in
Y = 0.2"/in

CLIP GAGE B 2X501
EXC. = .3436"
MACH CONTROL
LOAD ± 20 kip
STRAIN ± 10%
STROKE No 3 (± 1")





Specimen Identification = A72W23
Test Temperature = 60°C
Crack Arrest Toughness = 74 MPa·√m
Length of Remaining Ligament = 22.0 mm

SPEC. # 72W23 **DATE:** 8-27-87 Normal [✓ Inverted] ~~Non~~ - [✓ Irradiated]

TEST TEMP. 60°c **CLIP GAGE** #CAGØ1

VOLTAGES:

Excitation - 3.436

During calibration-

0 -2.27 75

25 -4.79 100

50 -7.36

In specimen at zero- ~~[illegible]~~ -2.10

MACHINE SETTINGS

Load Range = ±10 KIPS

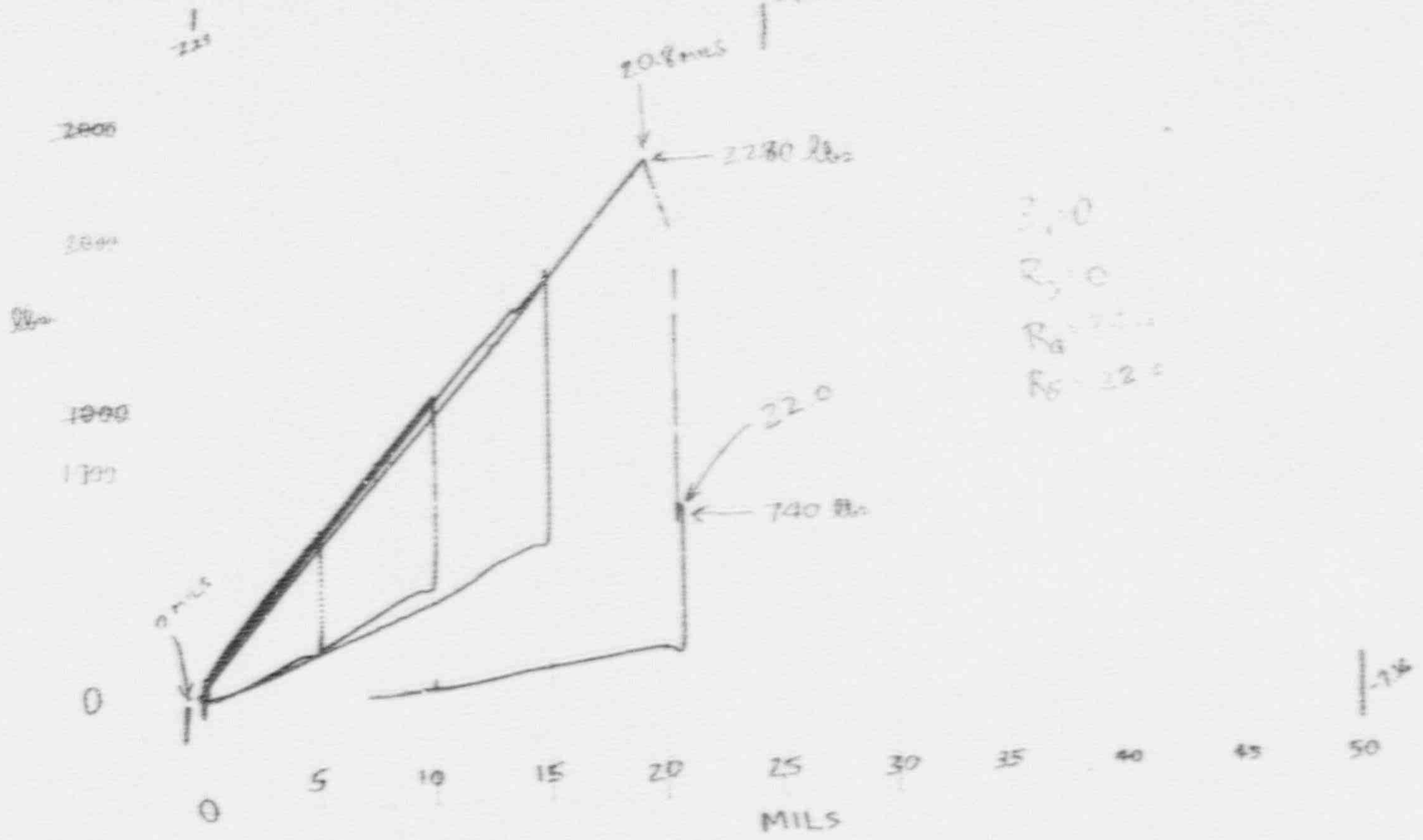
Strain Range = ±10%

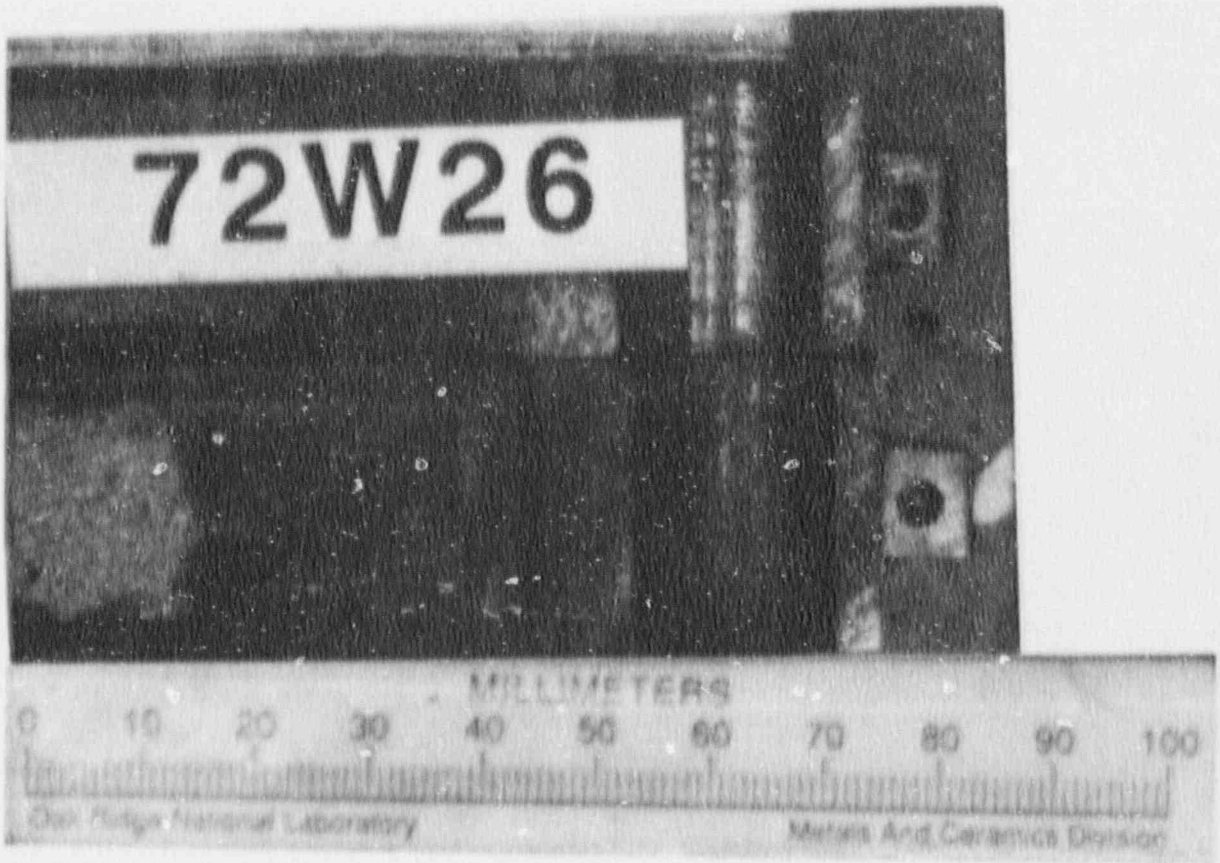
Stroke Range = 3 (±1)

X-Y CHART SETTINGS

X= 0.5 "/in

Y= 0.2 "/in





Specimen Identification = A72W26
Test Temperature = -25°C
Crack Arrest Toughness = 38 MPa·$\sqrt{m}$
Length of Remaining Ligament = 14.9 mm

SPEC.# TZW26 **DATE:** 8-30-87 [✓ **Normal**]/ **Inverted** **Non**-[✓ **Irradiated**]

TEST TEMP. -25°C **CLIP GAGE** #CAG01

VOLTAGES:

Excitation - 3.436

During calibration-

0 -7.40 75

25 -9.91 100

50 -12.47

In specimen at zero- ~~-2.18~~ -2.03

MACHINE SETTINGS

Load Range = ±10 kips

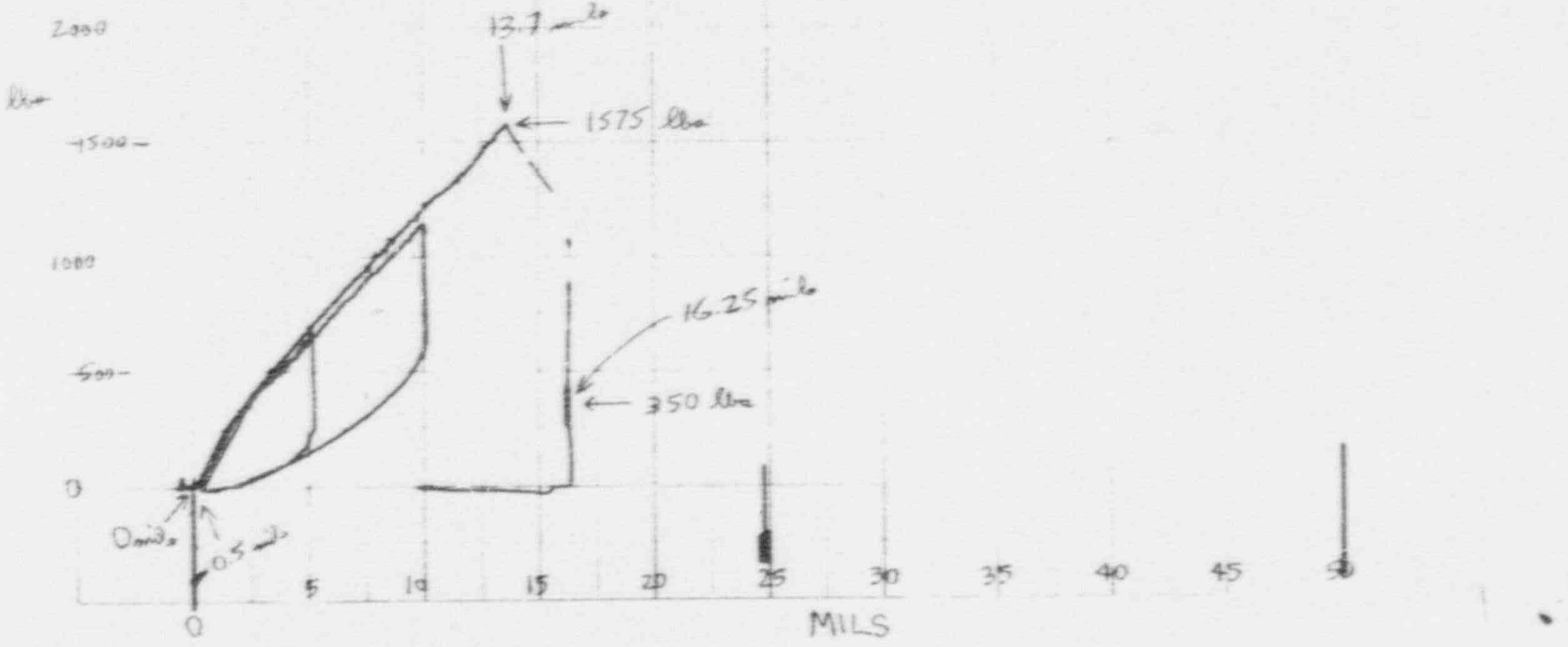
Strain Range = ±10%

Stroke Range = 3(±1)

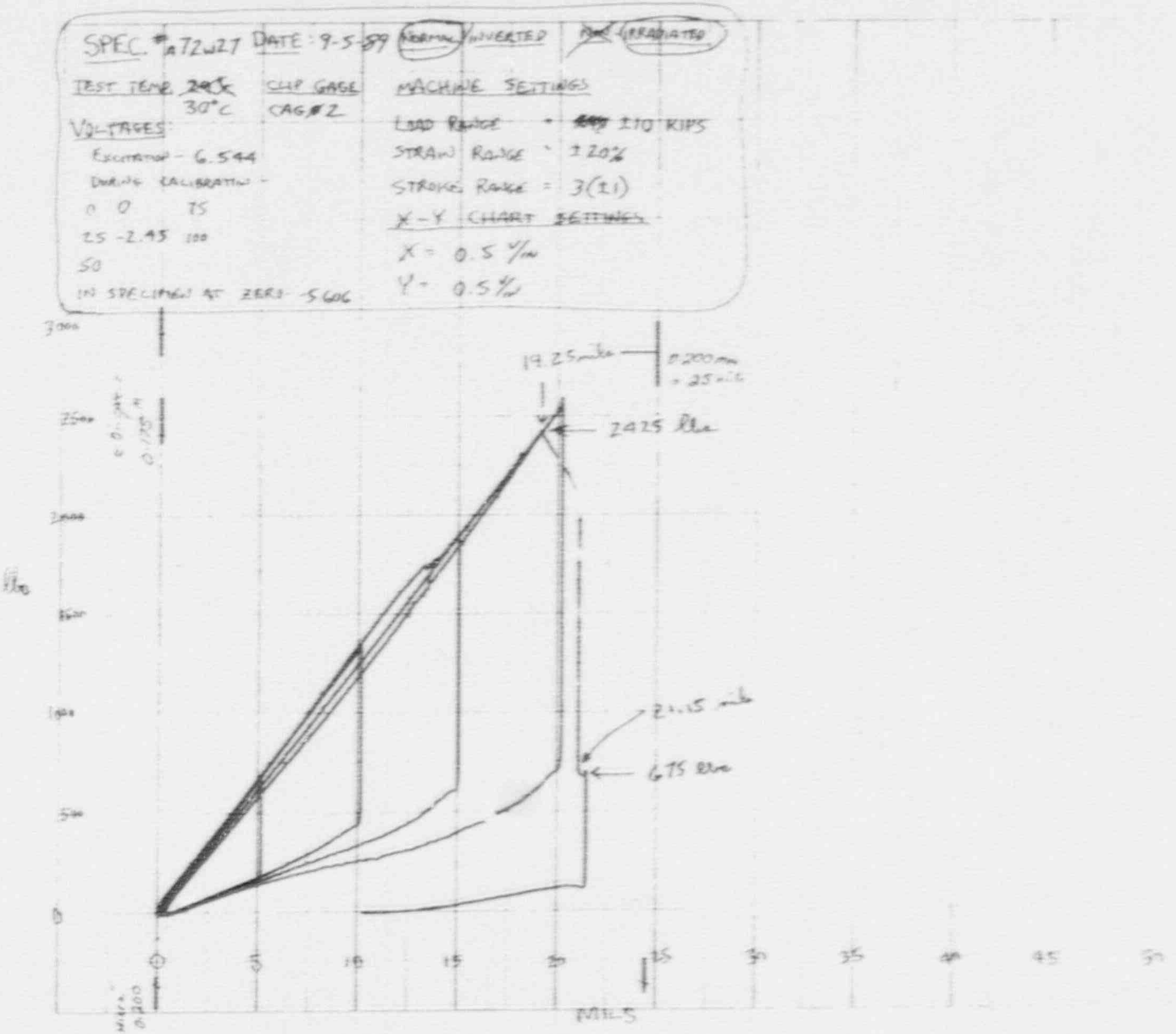
X-Y CHART SETTINGS

X= 0.5 $\frac{\%}{in}$

Y= 0.5 $\frac{\%}{in}$



Specimen Identification - A72W27
Test Temperature - 29°C
Crack Arrest Toughness - 61 $\text{MPa}\cdot\sqrt{\text{m}}$
Length of Remaining Ligament - 18.3 mm



SPEC. #A72W27 DATE: 9-5-89 [✓ NORMAL] / INVERTED [illegible] [✓ IRRADIATED]

TEST TEMP. ~~24°C~~ 30°C

CLIP GAGE CAG#2

VOLTAGES:

EXCITATION - 6.544

DURING CALIBRATION -

0 0 75

25 -2.45 100

50

IN SPECIMEN AT ZERO -5.606

MACHINE SETTINGS

LOAD RANGE = ~~[illegible]~~ ±10 KIPS

STRAIN RANGE = ±20%

STROKE RANGE = 3(±1)

X-Y CHART SETTINGS

X = 0.5 "/in

Y = 0.5 "/in

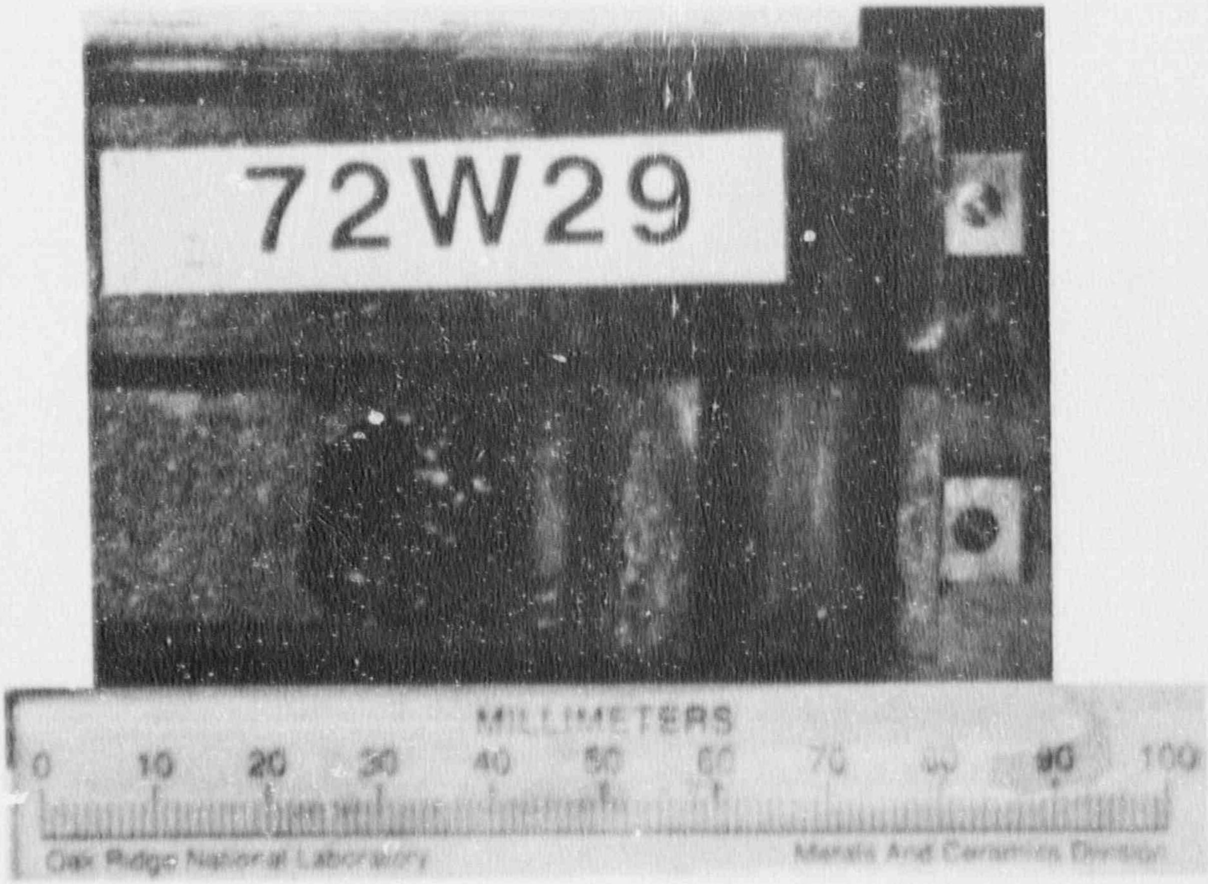
19.25 mils

0.200 mm = 25 mils

2425 lbs

21.15 mils

675 lbs



Specimen Identification = A72W29
Test Temperature = 60°C
Crack Arrest Toughness = 70 MPa·$\sqrt{m}$
Length of Remaining Ligament = 20.8 mm

SPEC. # A72W29 **DATE:** 8-25-89 ~~Normal~~ [✓ Inverted] ~~Wet~~ [✓ Irradiated]

TEST TEMP. 60°C **CLIP GAGE** #CAG01

MACHINE SETTINGS

Load Range = ± 20 KIPS

Strain Range = ± 10%

Stroke Range = 3 (±1)

X-Y CHART SETTINGS

X= 0.5 ‰in

Y= 0.2 ‰in

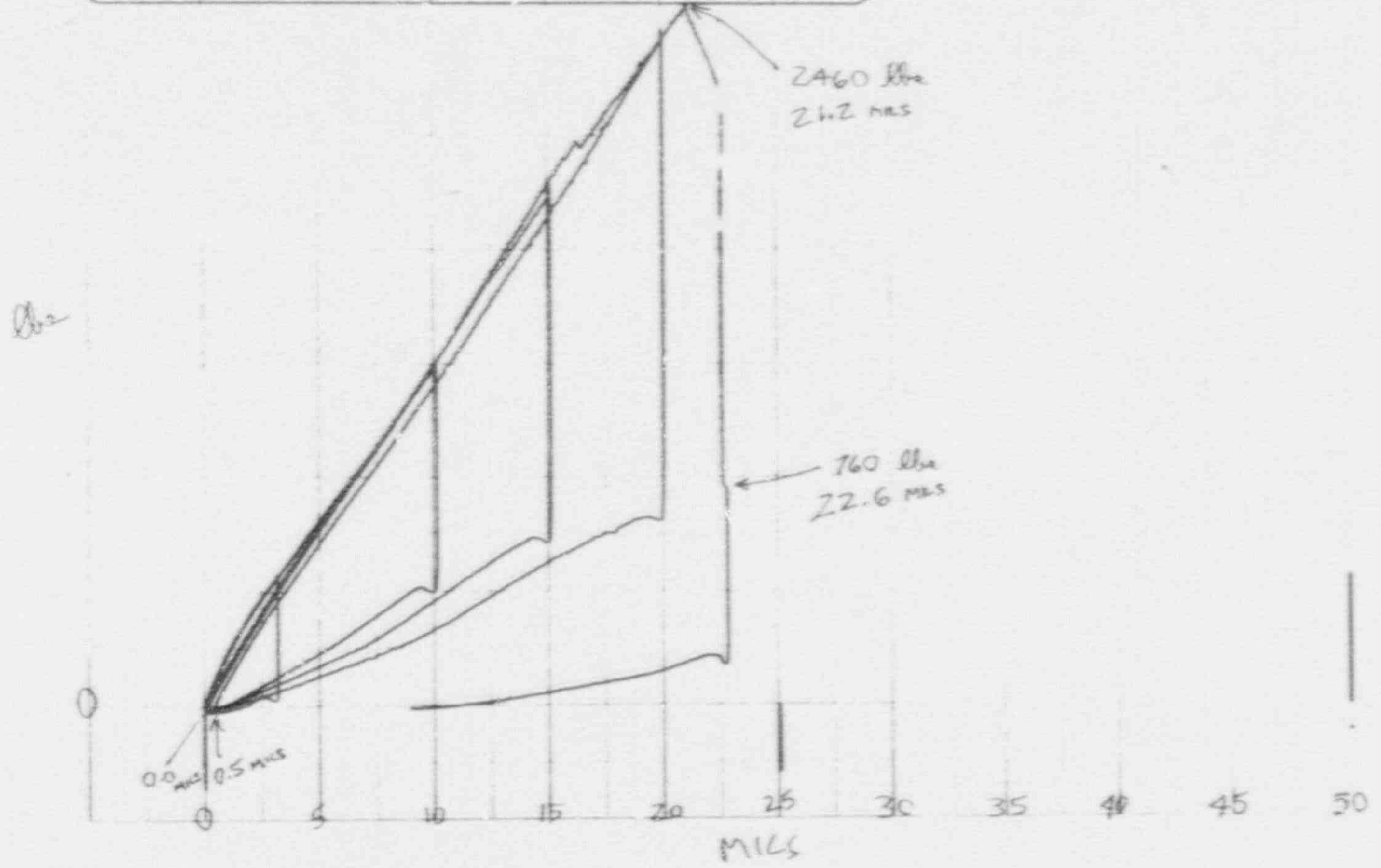
VOLTAGES:

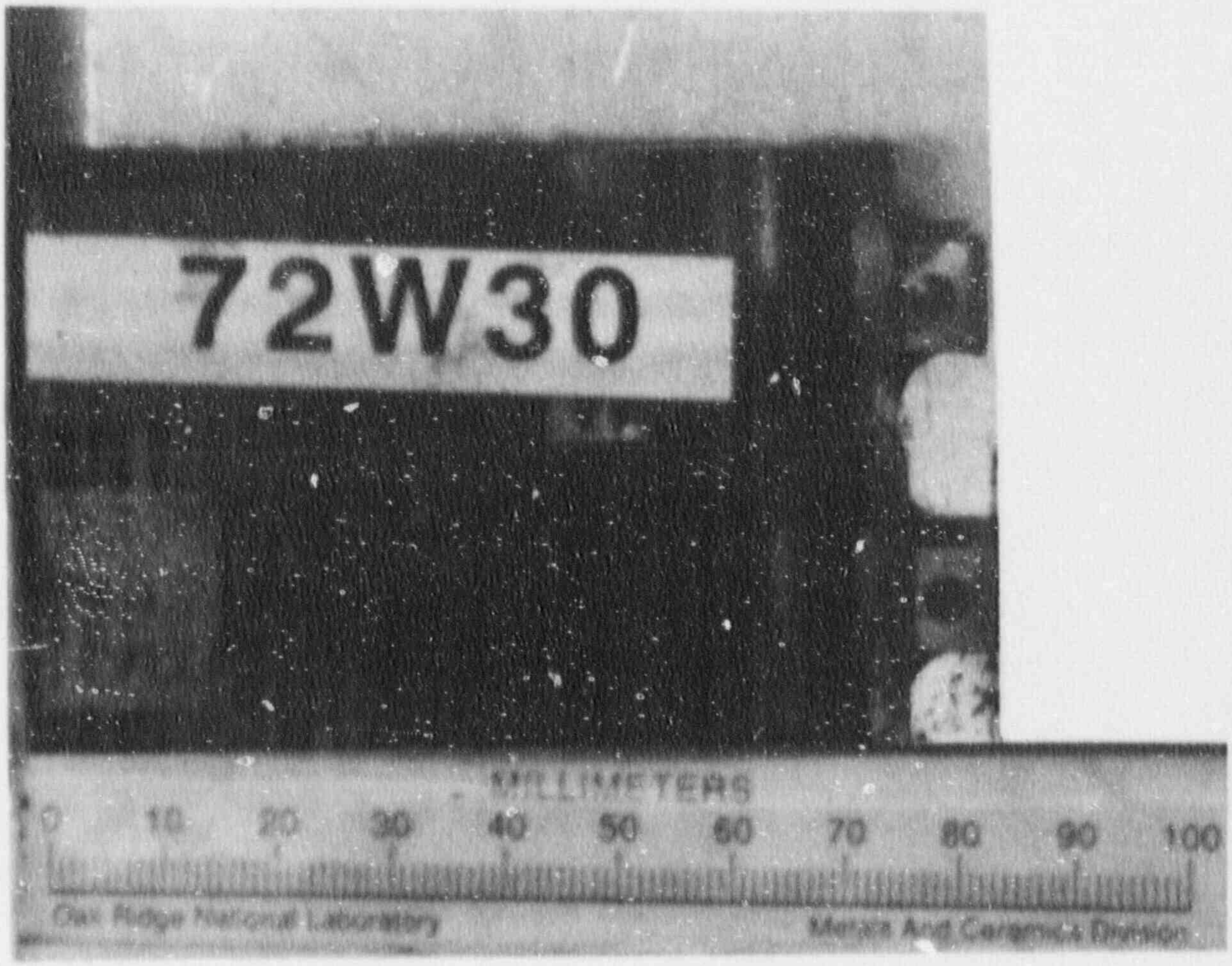
Excitation - 3.436

During calibration-

0	3.08	75
25	0.544	100
50	-1.99	

In specimen at zero- -1.37





Specimen Identification = A72W30
Test Temperature = -25°C
Crack Arrest Toughness = 43 MPa·√m
Length of Remaining Ligament = 15.4 mm

SPEC.# A72W30 **DATE:** 8-30-89 [✓ Normal] Inverted ~~Non~~ - [✓ Irradiated]

TEST TEMP. -25°C **CLIP GAGE** #CAG01

VOLTAGES:

Excitation - 3.436

During calibration

0 -1.66 75

25 - 4.20 100

50 - 6.75

In specimen at zero- .750

MACHINE SETTINGS

Load Range = ±10 KIPS

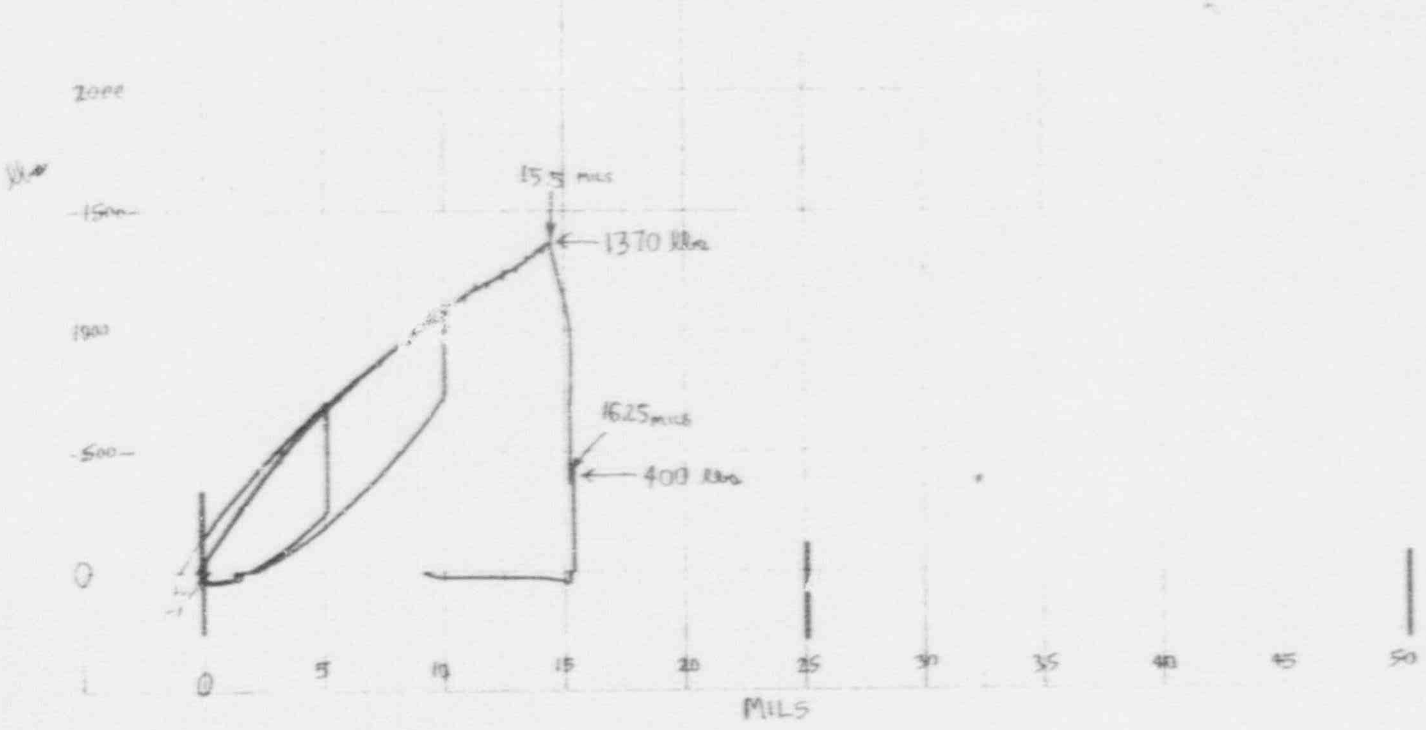
Strain Range = ±10%

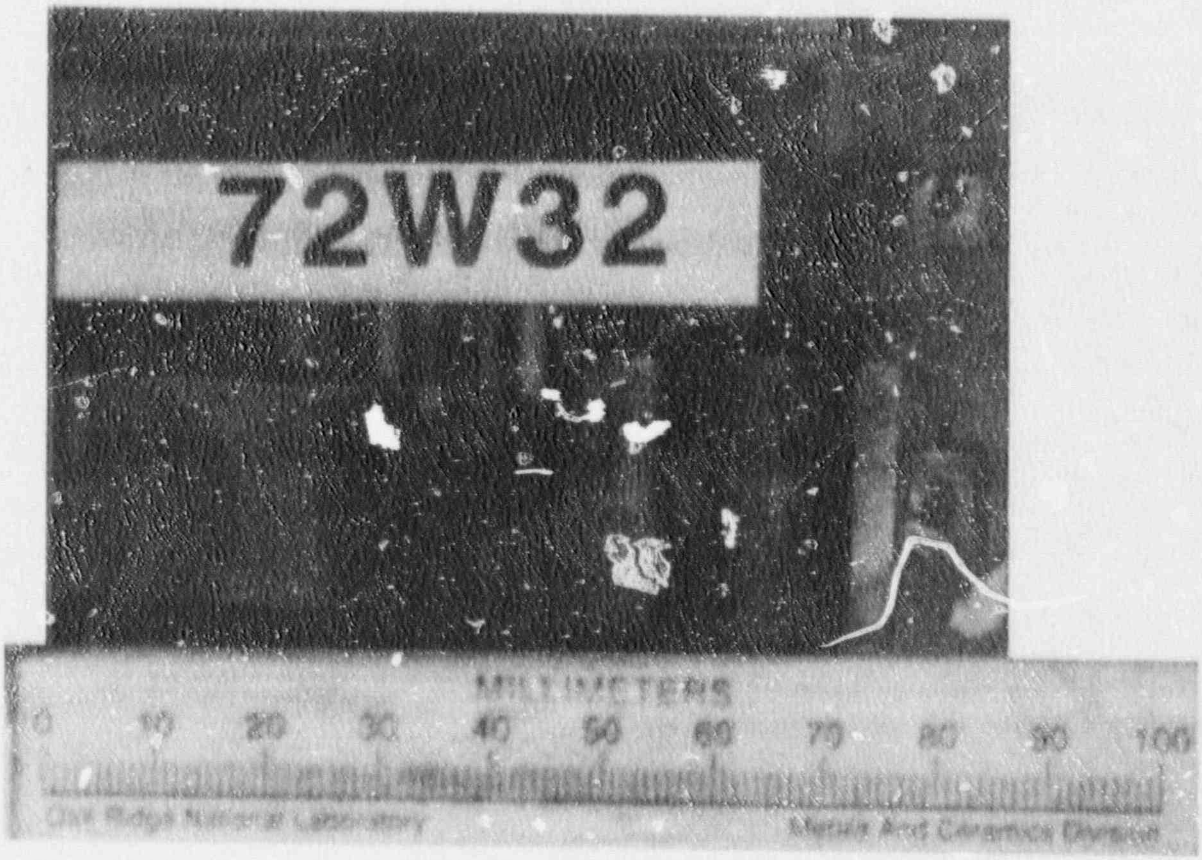
Stroke Range = 3(±1)

X-Y CHART SETTINGS

X= 0.5 %/in

Y= 0.5 %/in





Specimen Identification - A72W32
Test Temperature - 32°C
Crack Arrest Toughness - 66 MPa·$\sqrt{m}$
Length of Remaining Ligament - 24.8 mm

SPEC. # A72 w32 **DATE:** 9-5-89 [✓ **Normal**] / **Inverted** ~~**Non**~~-[✓ **Irradiated**]

TEST TEMP. ~~20°C~~ 32°C **CLIP GAGE** #CAG 2

VOLTAGES:

Excitation - 6.542

During calibration-

0 0 75

25 -2.47 100

50 ~~3.98~~ -5.04

In specimen at zero- (+1.41) 0

MACHINE SETTINGS

Load Range = ±10 KIPS

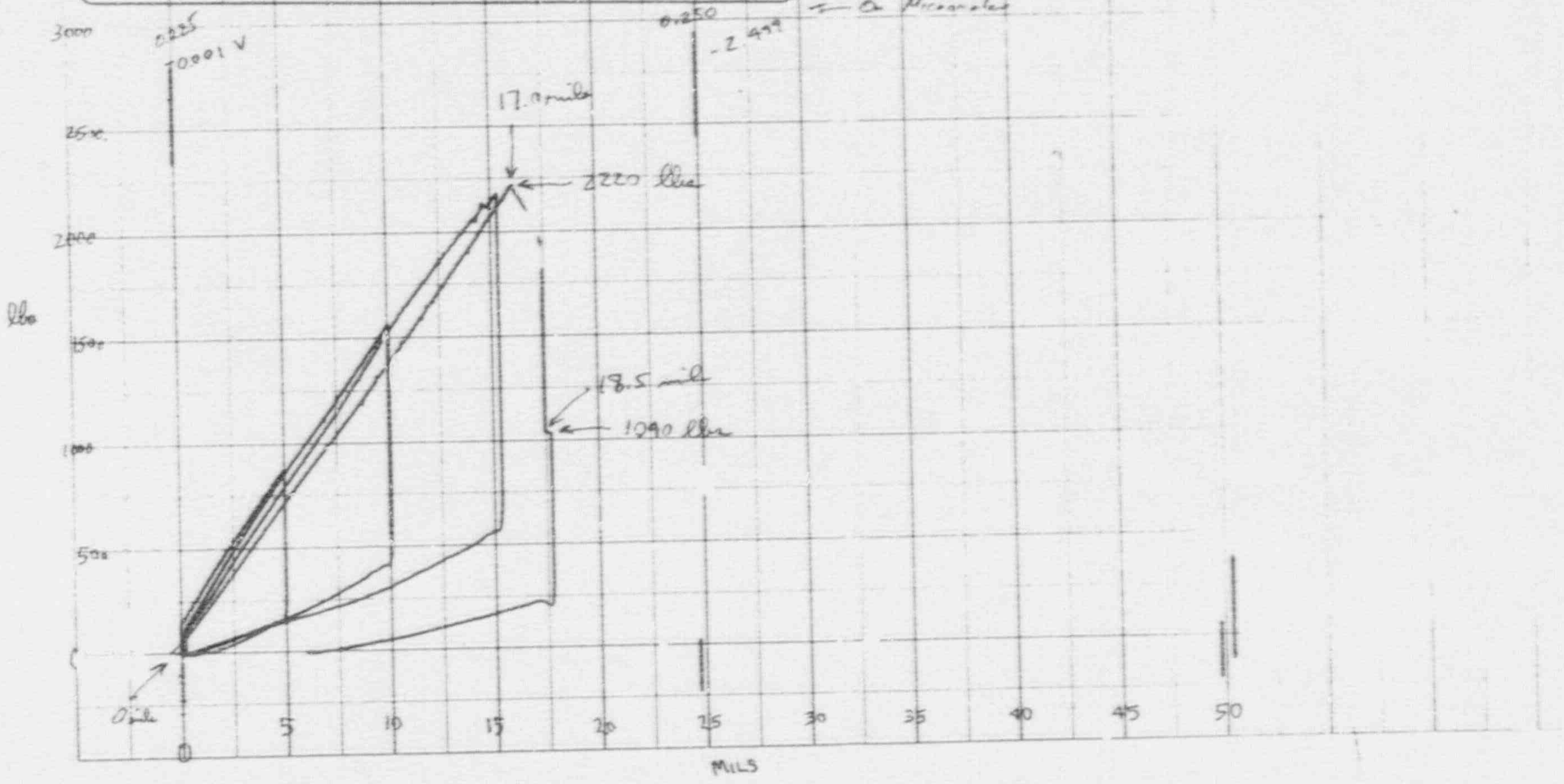
Strain Range = ±2.8%

Stroke Range = 3 (±1)

X-Y CHART SETTINGS

X= 0.5 "/in

Y= 0.5 "/in



Specimen Identification = A73W13
Test Temperature = 75°C
Crack Arrest Toughness = 150 MPa·√m
Length of Remaining Ligament = 65.8 mm

Specimen Identification - A73W13
Test Temperature - 75°C
Crack Arrest Toughness - 150 MPa·$\sqrt{m}$
Length of Remaining Ligament - 65.8 mm

SPEC. # A73W13 **DATE:** OCT. 25, 1997 ~~Normal~~ [✓ Inverted] ~~Non~~- [✓ Irradiated]

TEST TEMP. 75°C **CLIP GAGE** #CAG02

MACHINE SETTINGS

Load Range = ±20 KIPS

Strain Range = ±20 %

Stroke Range = ±1

VOLTAGES:

Excitation - 6.588

During calibration-

0 0.0 75 -7.55

25 -2.52 100 -10.07

50 -5.03

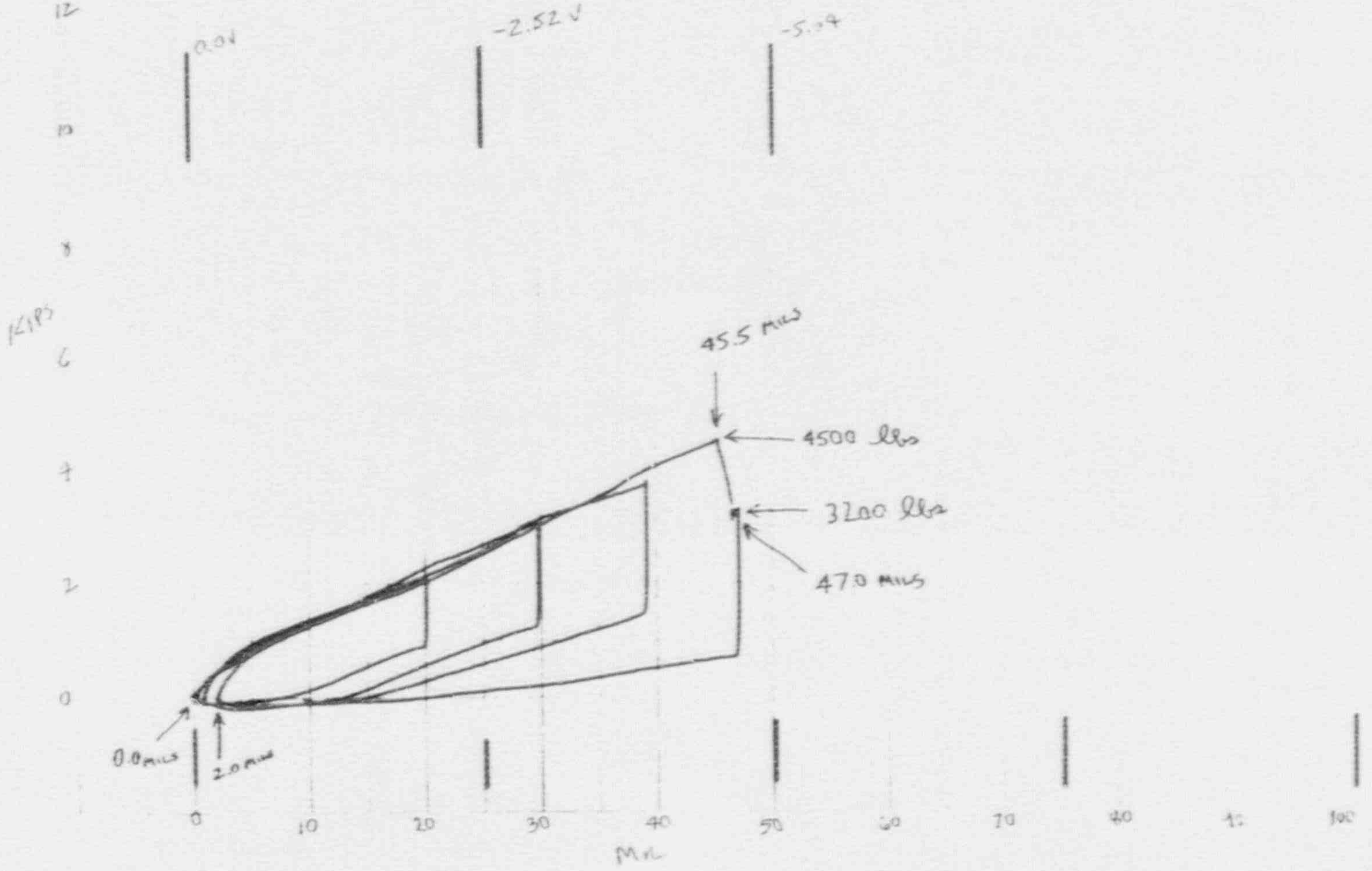
In specimen at zero- -0.05 (2.0)

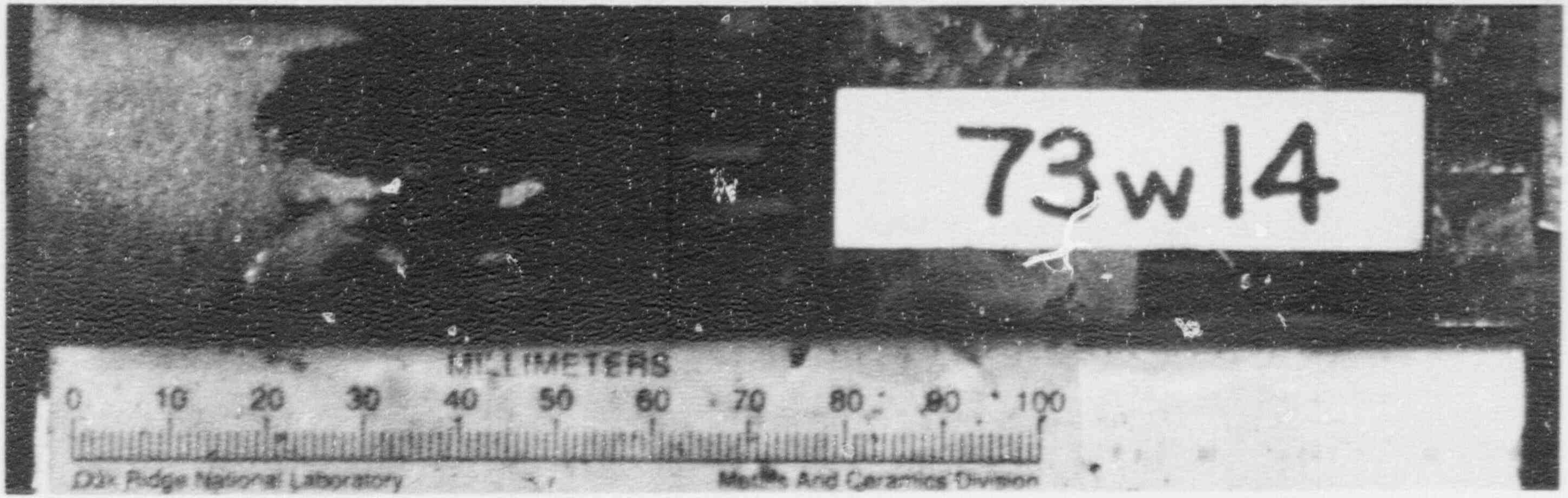
X-Y CHART SETTINGS

X= 1 %/in

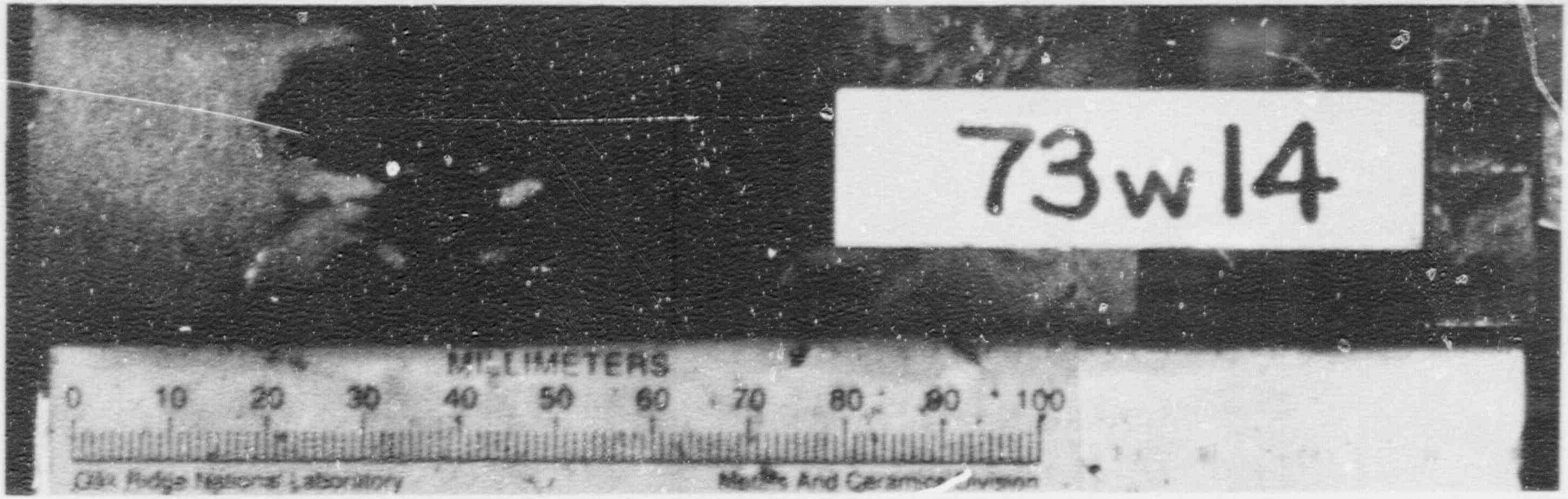
Y= 1 %/in

BROKE AT 76°C





Specimen Identification - A73W14
Test Temperature - 90°C
Crack Arrest Toughness - 159 MPa·√m
Length of Remaining Ligament - 29.1 mm



Specimen Identification - A73W14
Test Temperature - 90°C
Crack Arrest Toughness - 159 MPa·$\sqrt{m}$
Length of Remaining Ligament - 29.1 mm

SPEC. # A73W14 **DATE:** 9-25-89 ~~**Normal**~~ [✓ **Inverted**] ~~**Non**~~ **-** [✓ **Irradiated**]

TEST TEMP. 90°c 91°C **CLIP GAGE** #CAG02

VOLTAGES:

Excitation - 6.542

During calibration-

0 0.00 75

25 -2.49 100

50 - 4.97

In specimen at zero- -0.875

MACHINE SETTINGS

Load Range = ± 10 KIPS

Strain Range = ± 20 %

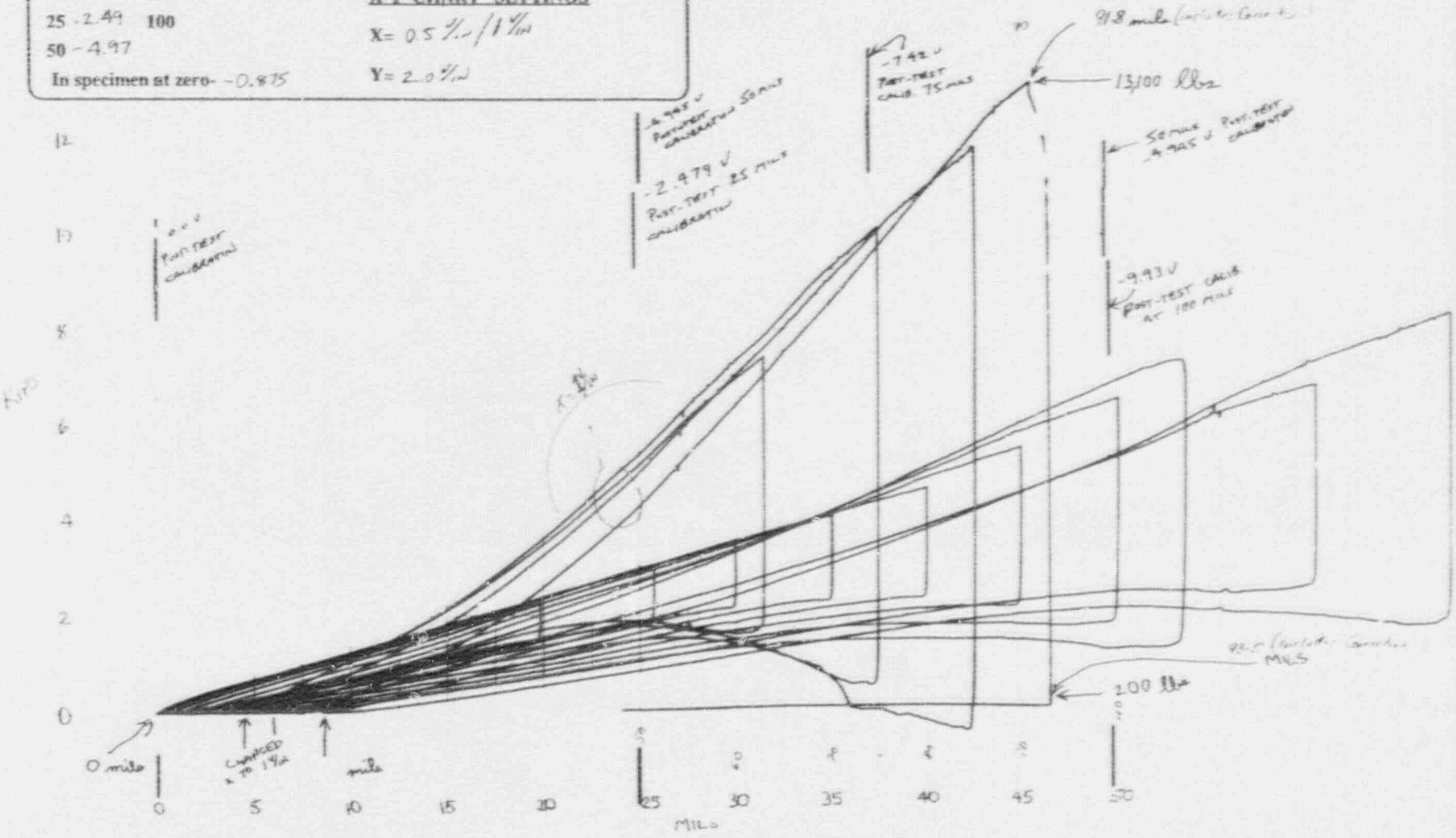
Stroke Range = ± 1

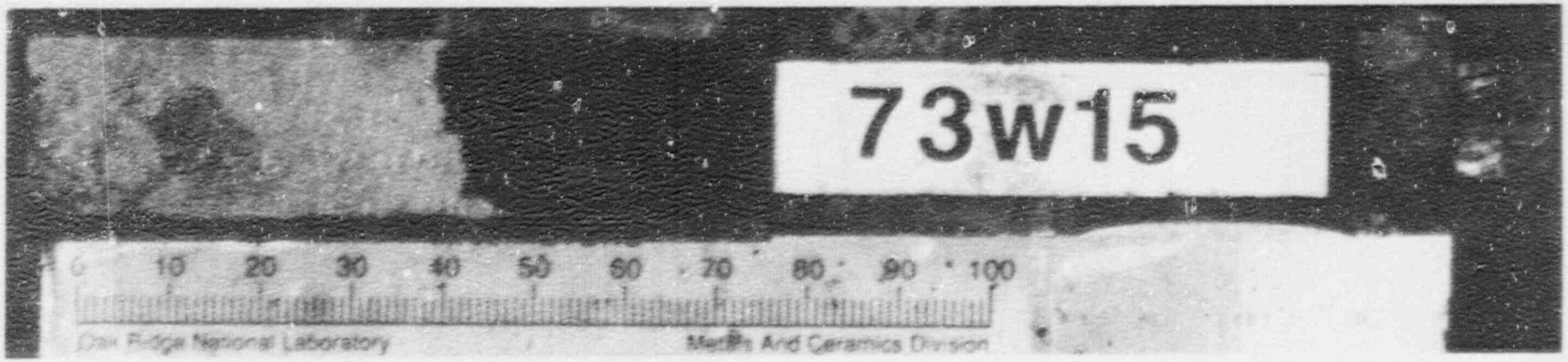
X-Y CHART SETTINGS

X= 0.5 %/in / 1 %/in

Y= 2.0 %/in

VARIAC SETTING 40 VOLTS





Specimen Identification - A73W15
Test Temperature - 60°C
Crack Arrest Toughness - 81 MPa·√m
Length of Remaining Ligament - 45.6 mm

Specimen Identification = A73W15
Test Temperature = 60°C
Crack Arrest Toughness = 81 MPa·√m
Length of Remaining Ligament = 45.6 mm

SPEC. # [illegible] **DATE:** [illegible] **Normal / [✓ Inverted]** **Non - Irradiated**

TEST TEMP. [illegible] **CLIP GAGE # CAG Ø2**

MACHINE SETTINGS

VOLTAGES:

Excitation - 6.585

Load Range = ± 20 KIP

Strain Range = ± ~~20~~ %

During calibration-

Stroke Range = ± 1

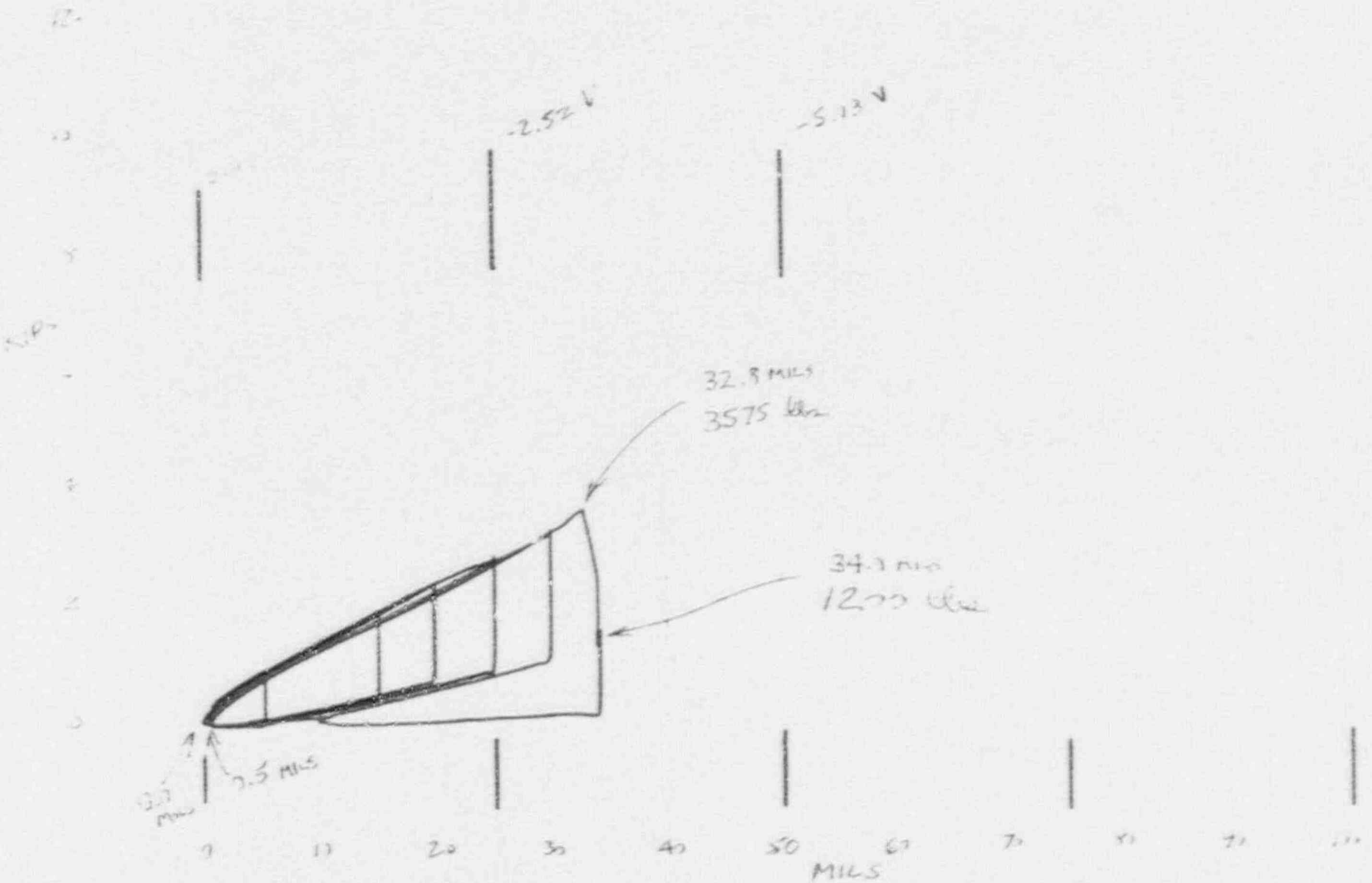
0	0.0?	75	- 7.55
25	- 2.52	100	- 10.0?
50	- 5.0?		

X-Y CHART SETTINGS

X= 1 %/in

In specimen at zero- - 2.0C (0.3)

Y= 1 %/in



Specimen Identification - A73W17 (no test)
Test Temperature - 100°C
Crack Arrest Toughness - -
Length of Remaining Ligament - -

Specimen Identification - A73W17 (no test)
Test Temperature - 100°C
Crack Arrest Toughness - -
Length of Remaining Ligament - -

SPEC. # A 13[illegible] **DATE:** Jan 24, 19[illegible] **Normal** / [✓ **Inverted**] **Non** - [✓ **Irradiated**]

TEST TEMP. [illegible]°C **CLIP GAGE** #CAG2L

MACHINE SETTINGS

Load Range = ± 20 KIPS

Strain Range = ± 2.0 %

Stroke Range = ± 1

VOLTAGES:

Excitation - 6.589

During calibration-

0 0.0 75 - 7.59

25 - 2.53 100 - 10.[illegible]4

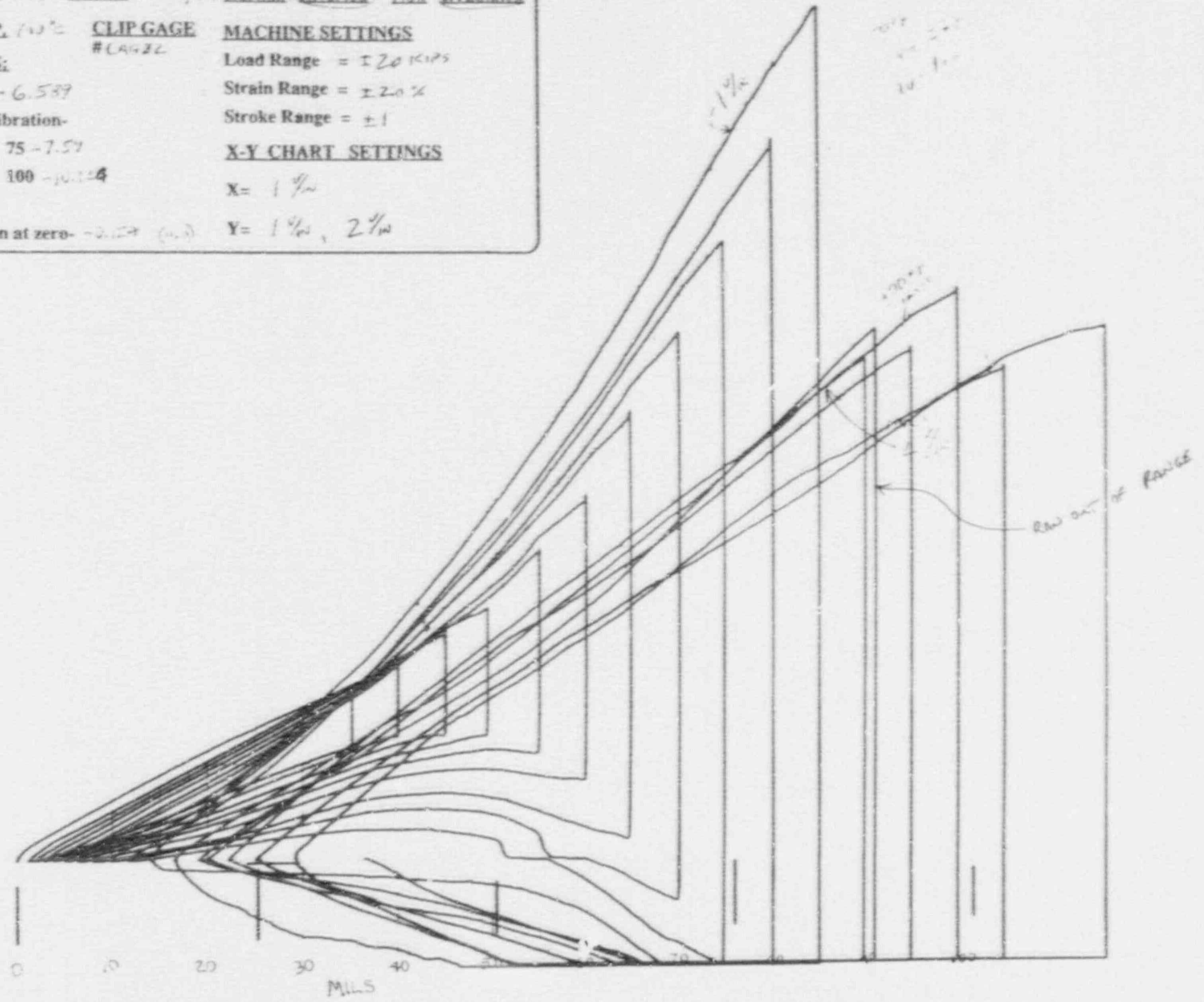
50 - 5.[illegible]

In specimen at zero- - 0.[illegible] [illegible]

X-Y CHART SETTINGS

X= 1 "/in

Y= 1 "/in, 2 "/in



SPEC. # A73W17 **DATE:** 10-25-89 ~~Normal~~ / [✓ Inverted] ~~Non~~ - [✓ Irradiated]

TEST TEMP. 30°C **CLIP GAGE** # CAG02

VOLTAGES:

Excitation - 6.588

During calibration-

0 0.0 75 -7.55

25 -2.52 100 -12.10

50 -5.07

In specimen at zero- -3.77 (0.0)

MACHINE SETTINGS

Load Range = ± 20 KIPS/50KIP

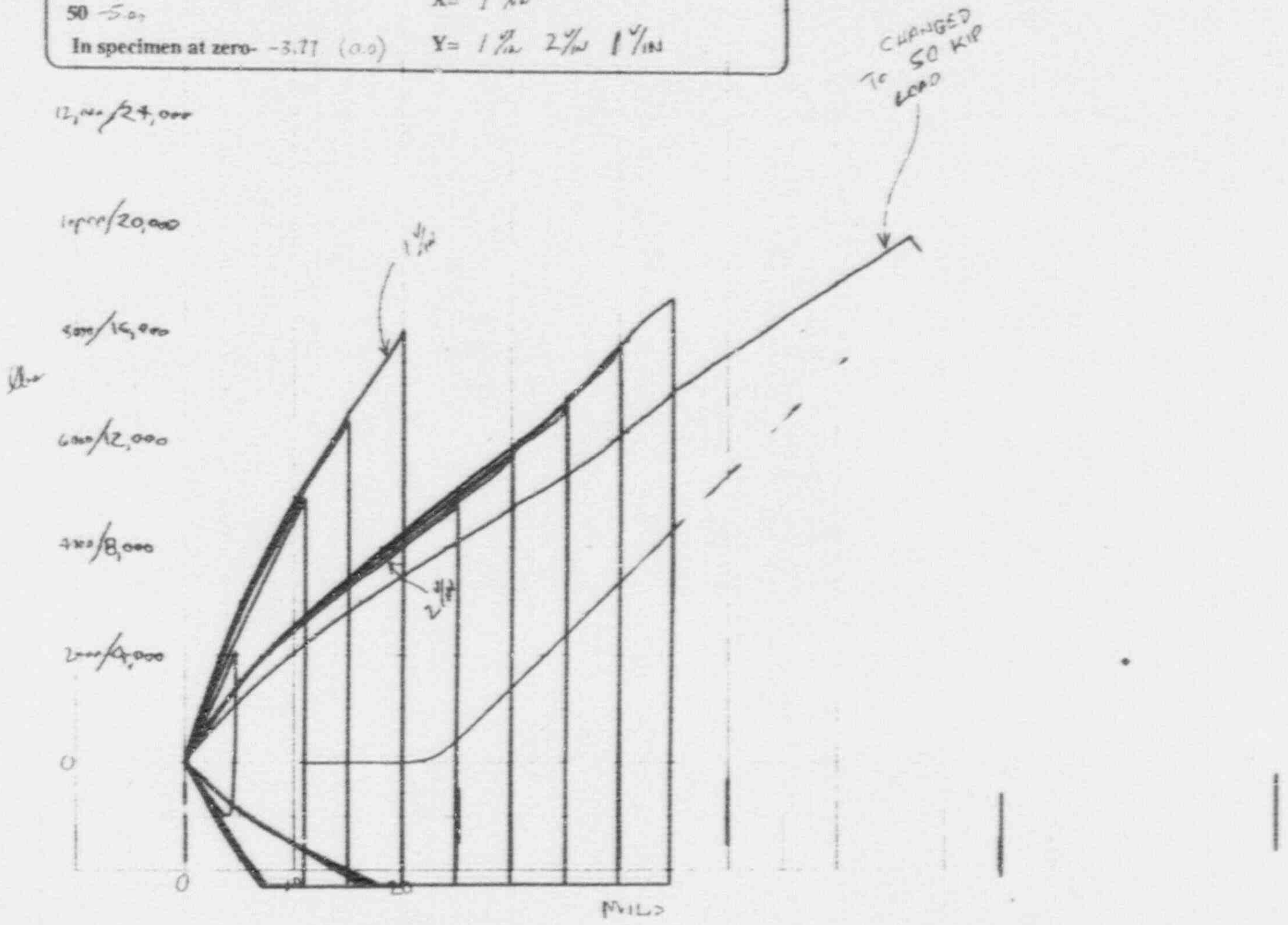
Strain Range = ± 20%

Stroke Range = ± 1

X-Y CHART SETTINGS

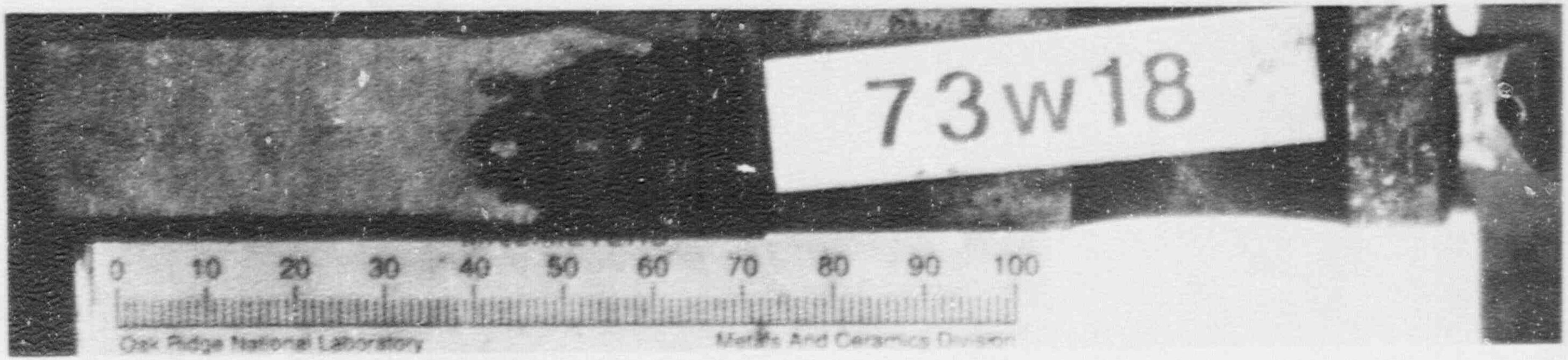
X= 1 %/in

Y= 1 %/in 2%/in 1%/in



CHANGED TO 50 KIP LOAD

Specimen Identification - A73W18
Test Temperature - 75°C
Crack Arrest Toughness - 131 MPa·√m
Length of Remaining Ligament - 51.3 mm



Specimen Identification = A73W18
Test Temperature = 75°C
Crack Arrest Toughness = 131 $\text{MPa}\cdot\sqrt{m}$
Length of Remaining Ligament = 51.3 mm

SPEC. # A73W18 **DATE:** 9-28-89 ~~Normal~~ / [✓ Inverted] ~~Non~~-[✓ Irradiated]

TEST TEMP. 75°C **CLIP GAGE** #CAG02

VOLTAGES:

Excitation - 6.543

During calibration-

0 0.00 75

25 -2.56 100

50 -5.06

In specimen at zero- -0.415

MACHINE SETTINGS

Load Range = ± 10 KIPS

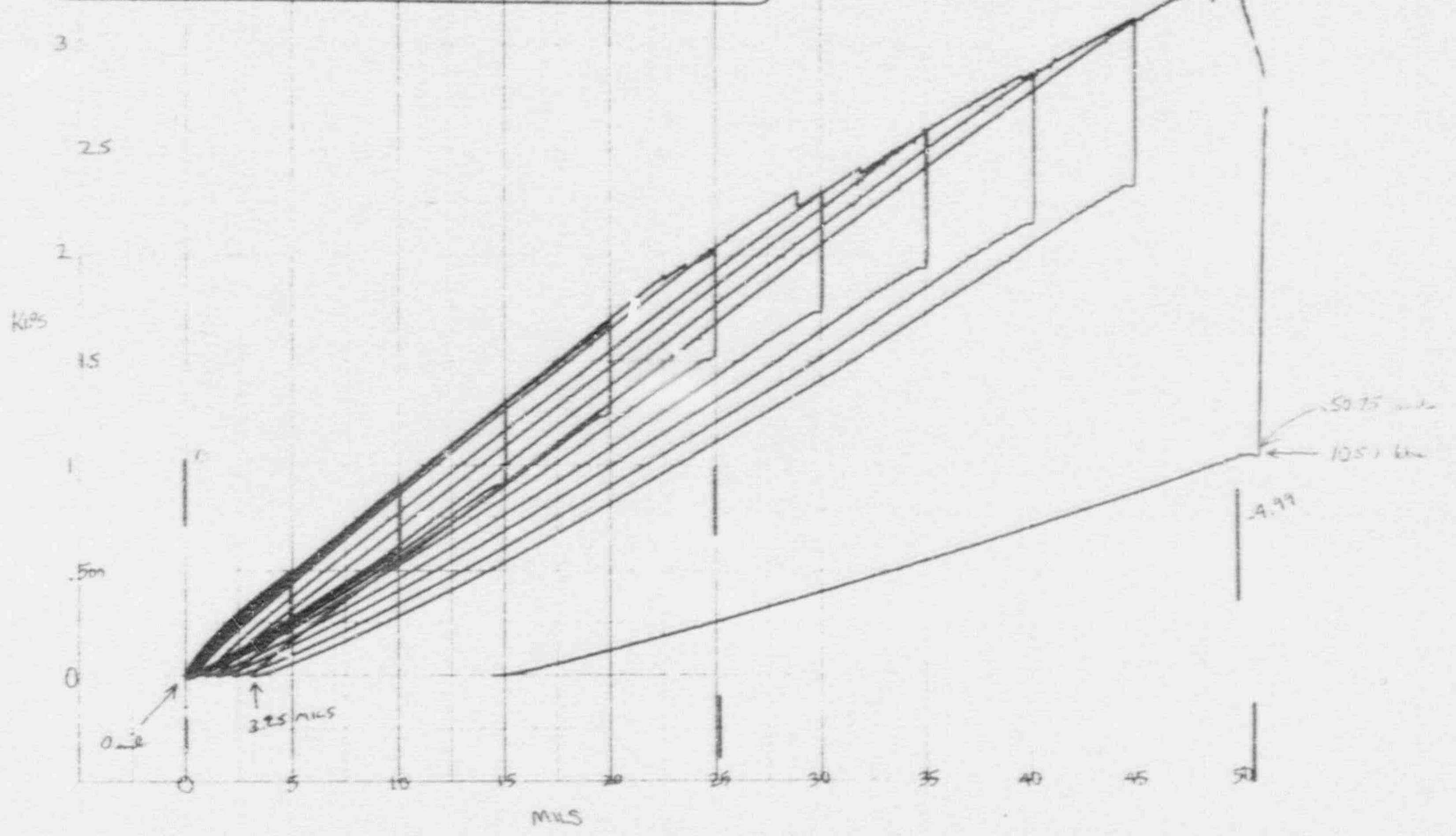
Strain Range = ± 2.0%

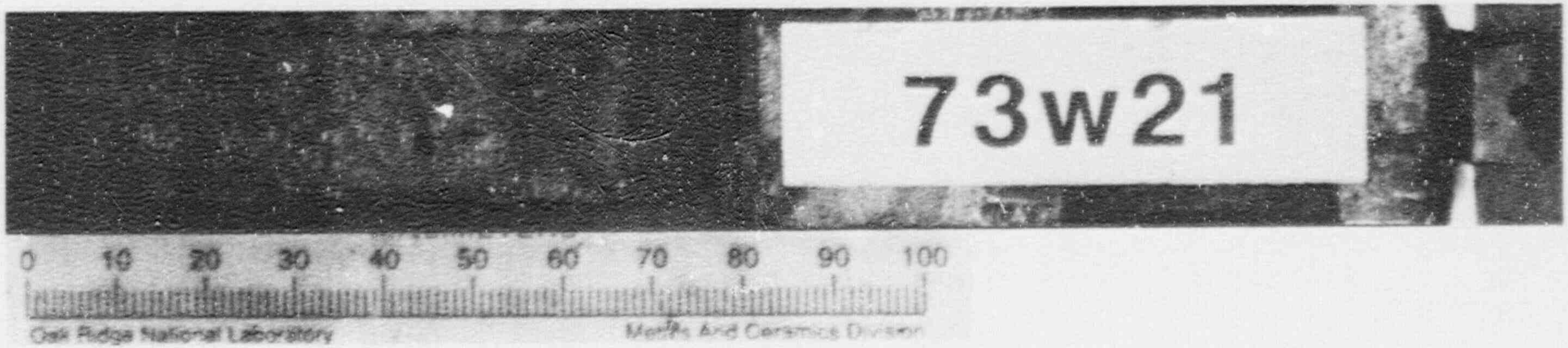
Stroke Range = ± 1

X-Y CHART SETTINGS

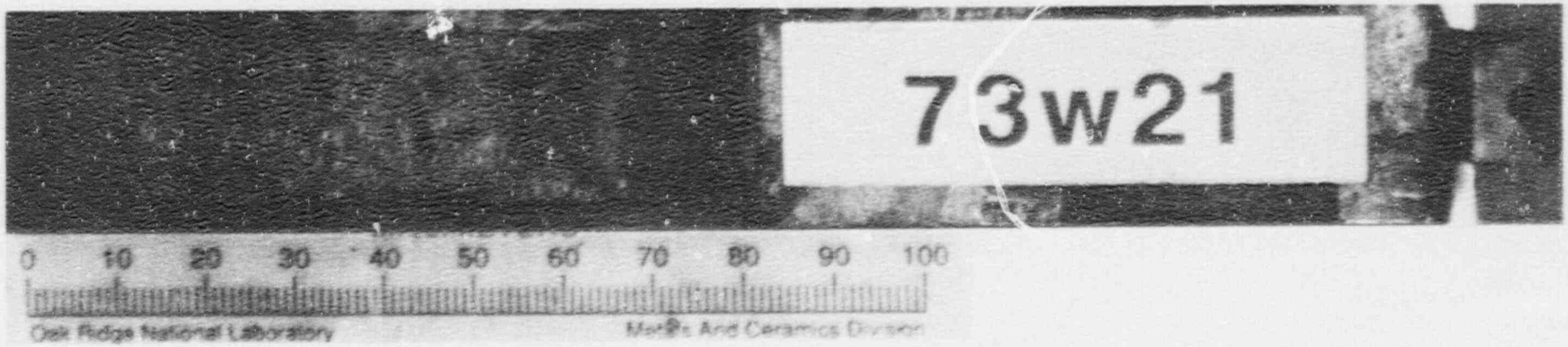
X= 0.5 V/in

Y= 0.5 V/in





Specimen Identification - A73W21
Test Temperature - 75°C
Crack Arrest Toughness - 107 $\mathrm{MPa}\cdot\sqrt{m}$
Length of Remaining Ligament - 54.1 mm



Specimen Identification - A73W21
Test Temperature - 75°C
Crack Arrest Toughness - 107 MPa·√m
Length of Remaining Ligament - 54.1 mm

SPEC. # A73W21 **DATE:** 9-22-89 **Normal** / [✓ **Inverted**] **Non** - [✓ **Irradiated**]

TEST TEMP. 75°C

CLIP GAGE
CAGØ2

VOLTAGES:

Excitation - 6.543

During calibration-

0 0.00 75

25 -2.49 100

50 -4.977

In specimen at zero- +0.351

MACHINE SETTINGS

Load Range = ± 10 KIPS

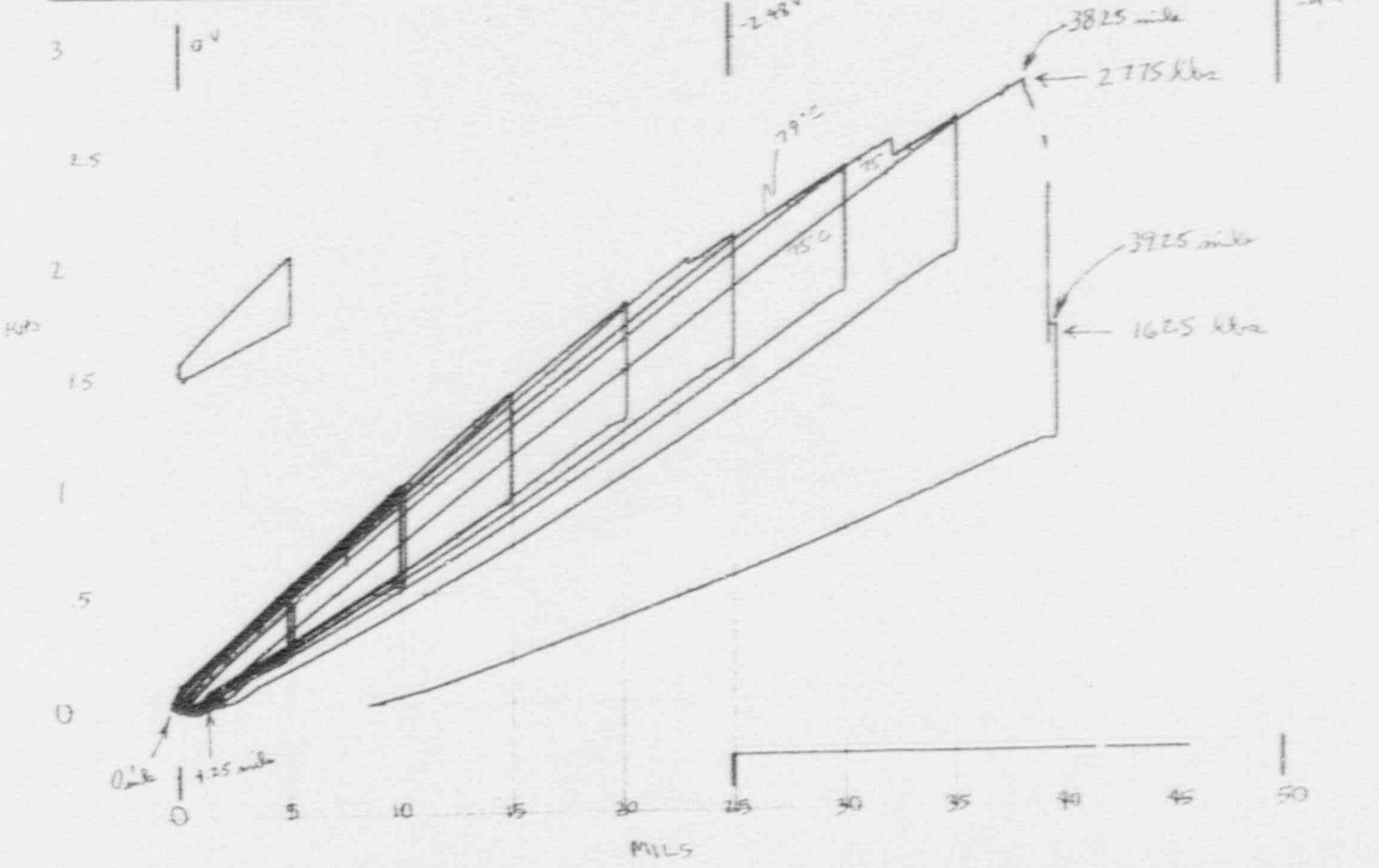
Strain Range = ± 20 %

Stroke Range = ± 1

X-Y CHART SETTINGS

X= 0.5 "/in

Y= 0.5 "/in



Specimen Identification - A73W23
Test Temperature - 90°C
Crack Arrest Toughness - 180 MPa·√m
Length of Remaining Ligament - 45.3 mm

Specimen Identification - A73W23
Test Temperature - 90°C
Crack Arrest Toughness - 180 MPa·√m
Length of Remaining Ligament - 45.3 mm

SPEC. # A73W23 **DATE:** Nov. 9, 1989 **Normal / [✓ Inverted]** **Non - [✓ Irradiated]**

TEST TEMP. 92°C **CLIP GAGE** #CAG02 **MACHINE SETTINGS**

VOLTAGES:

Load Range = ±20 KIPS

Excitation - 6.588

Strain Range = ±20%

Stroke Range = ±1

During calibration-

X-Y CHART SETTINGS

0 0.000

25 -2.47 -2.53

50 -4.94 -5.05

75 -7.49 -7.58

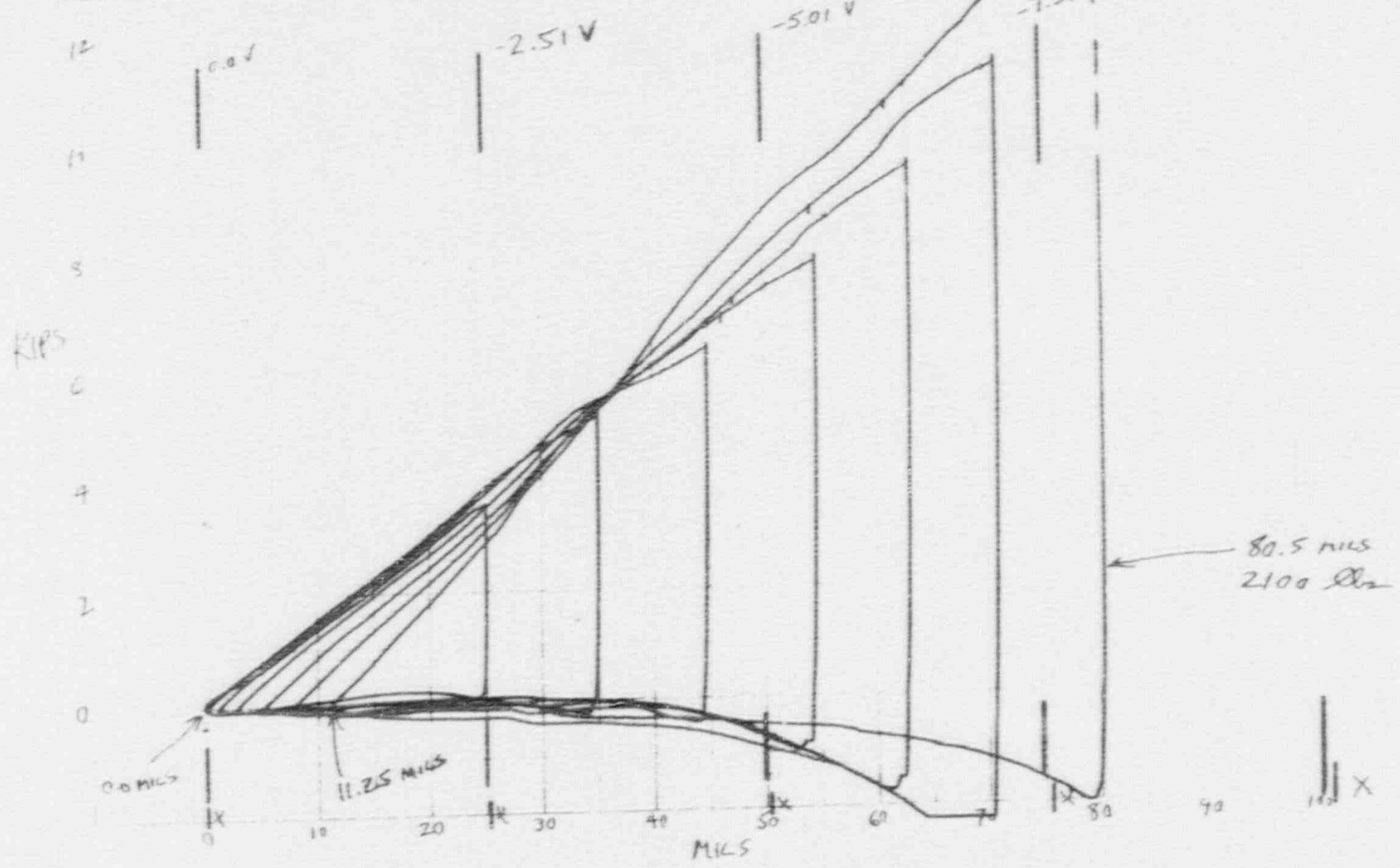
100 -9.99 -10.10

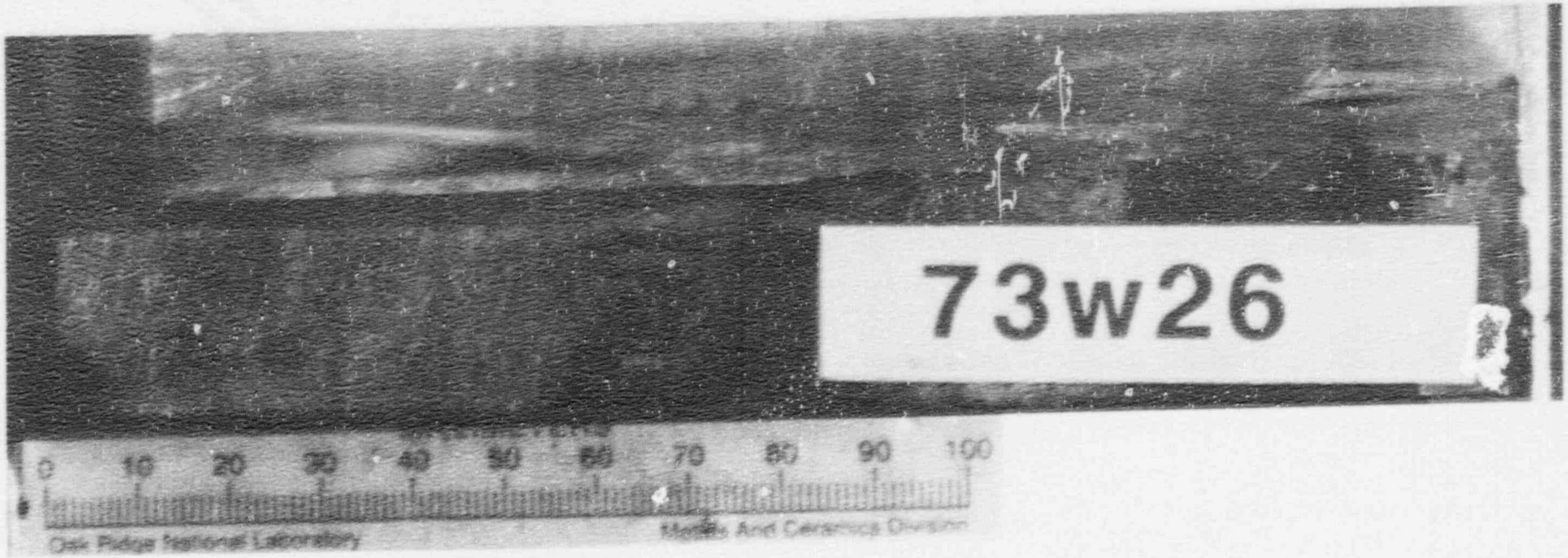
X= 1"/in

Y= 1"/in

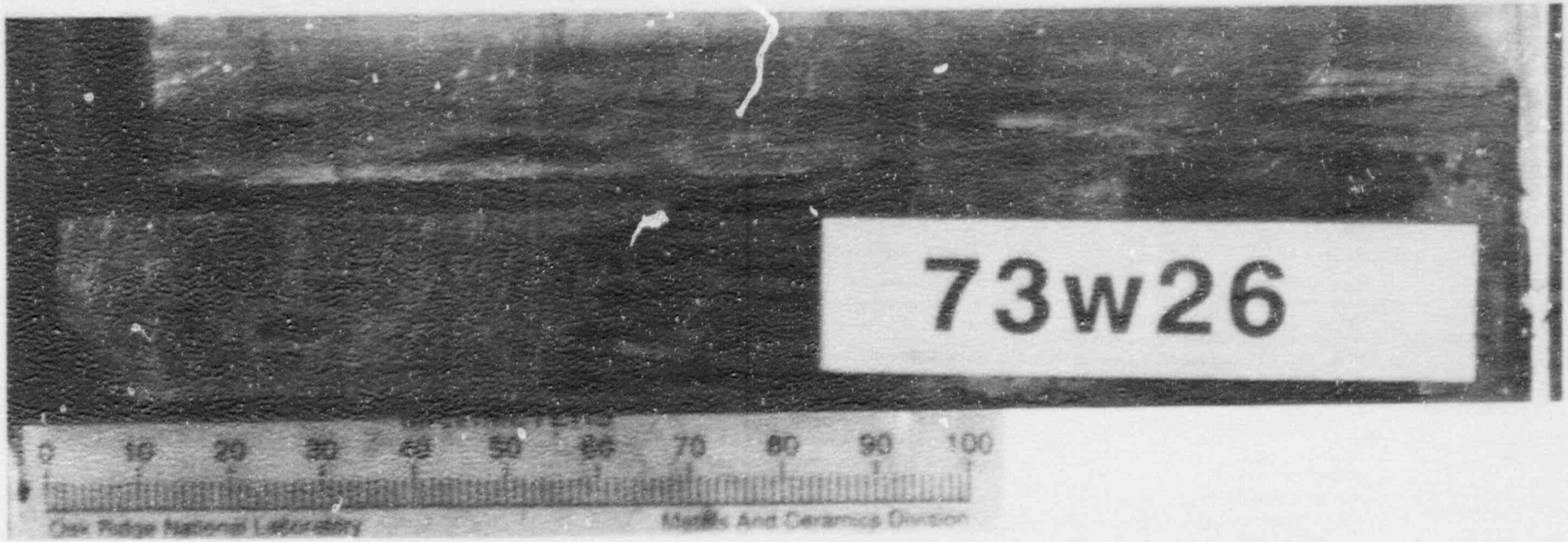
In specimen at zero- -0.474 (0.0)

VARIAC SETTING IS 45





Specimen Identification = A73W26
Test Temperature = 75°C
Crack Arrest Toughness = 88 MPa·√m
Length of Remaining Ligament = 55.4 mm



Specimen Identification - A73W26
Test Temperature - 75°C
Crack Arrest Toughness - 88 $\mathrm{MPa}\cdot\sqrt{m}$
Length of Remaining Ligament - 55.4 mm

SPEC. # A73W26 **DATE:** 9-19-89 Normal [✓ Inverted] Non - [✓ Irradiated]

TEST TEMP. 75°C **CLIP GAGE** # AG02

MACHINE SETTINGS

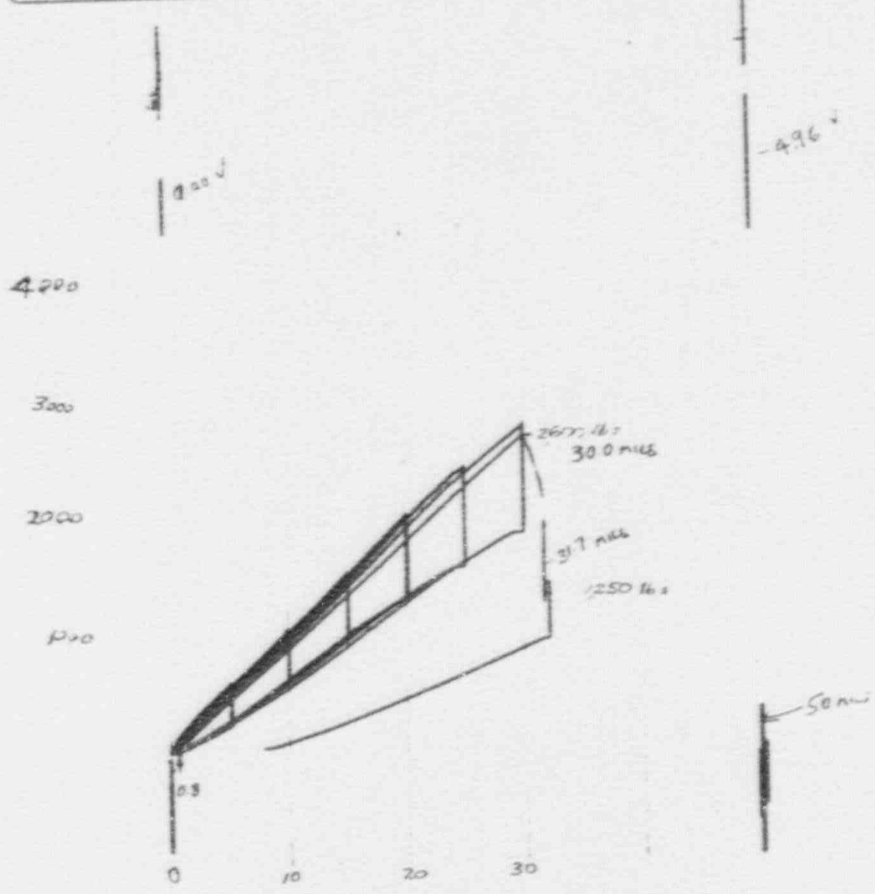
Load Range = ±10 KIPS
Strain Range = ±20%
Stroke Range = ±1

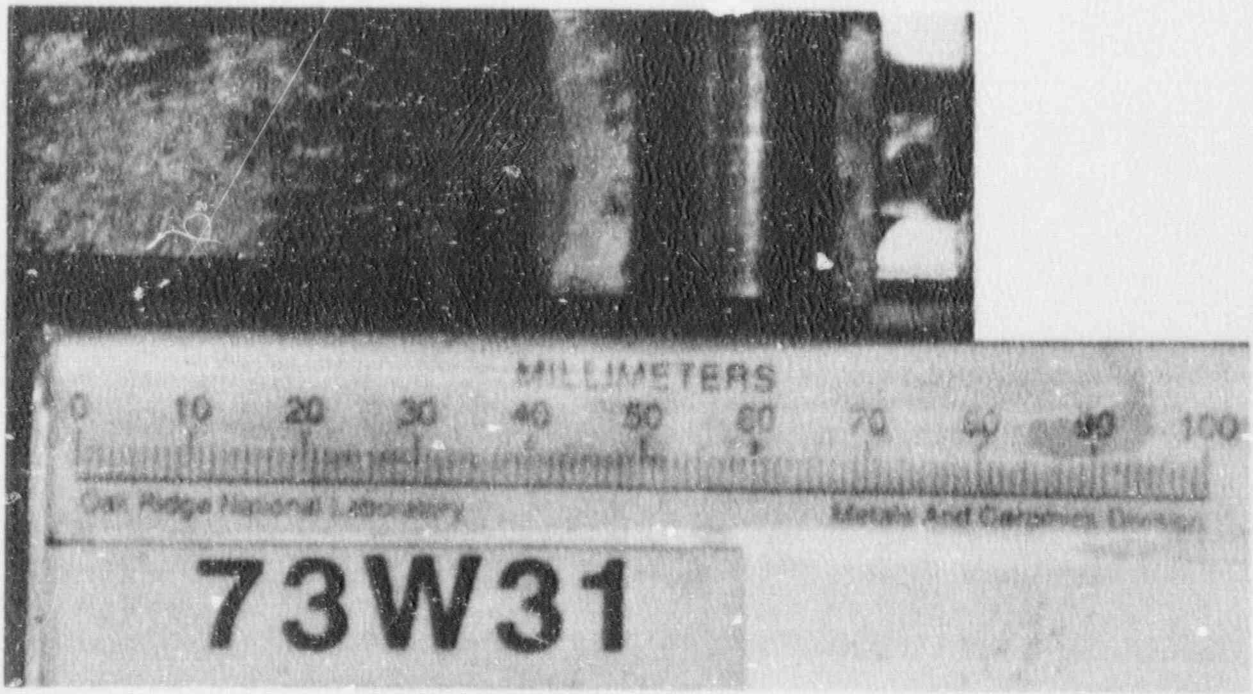
VOLTAGES:

Excitation - 6.543
During calibration-
0-0.02 75
25 100
50 -5.023
In specimen at zero- 0.00

X-Y CHART SETTINGS

X= 1.0 %/in
Y= 1.0 %/in





Specimen Identification - A73W31
Test Temperature - 29°C
Crack Arrest Toughness - 57 MPa$\cdot\sqrt{m}$
Length of Remaining Ligament - 21.5 mm

IRRAD

SPEC. A73-131 X: 5 V/in TEMP. 29°C [illegible]

DATE 8-23-75 Y: 10 V/in (1) [illegible]

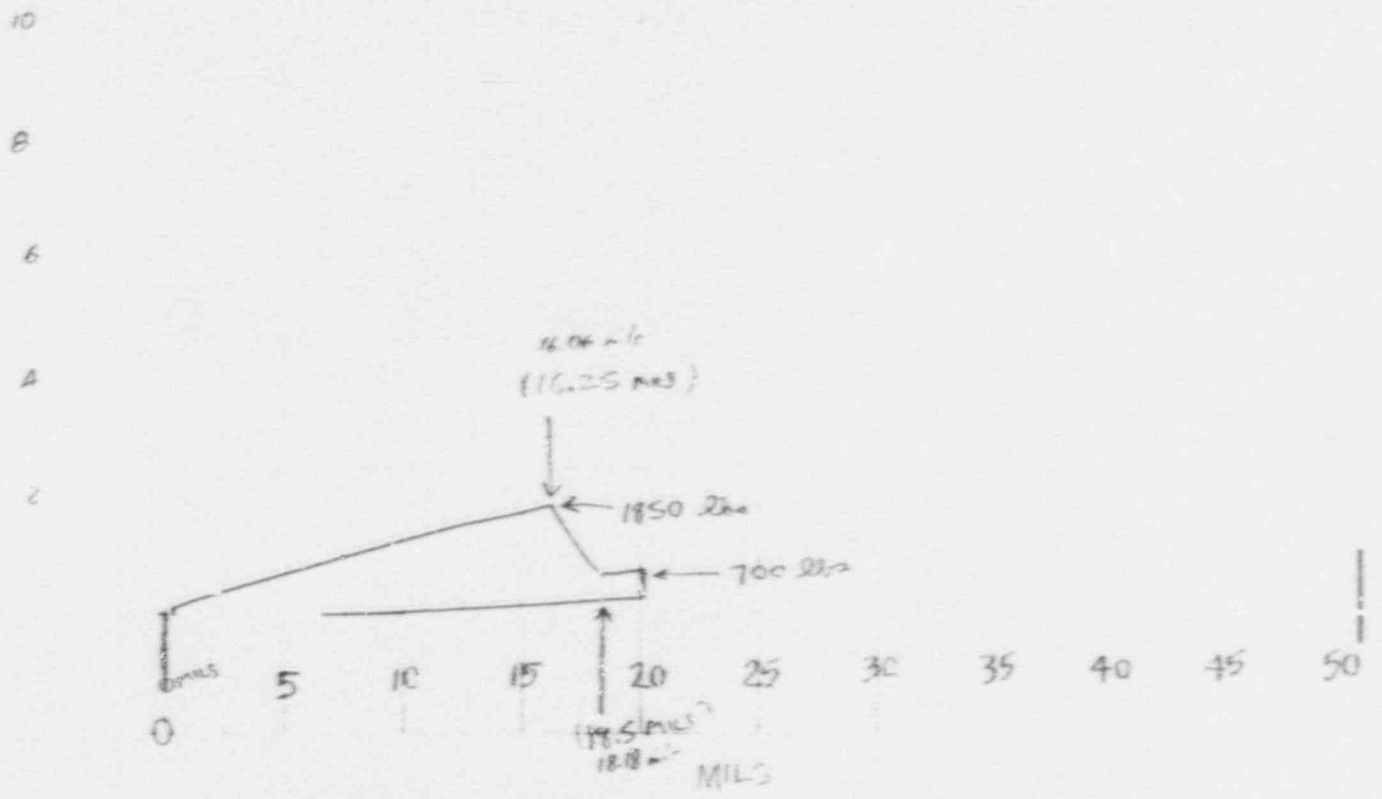
LOAD RANGE ±20 kips

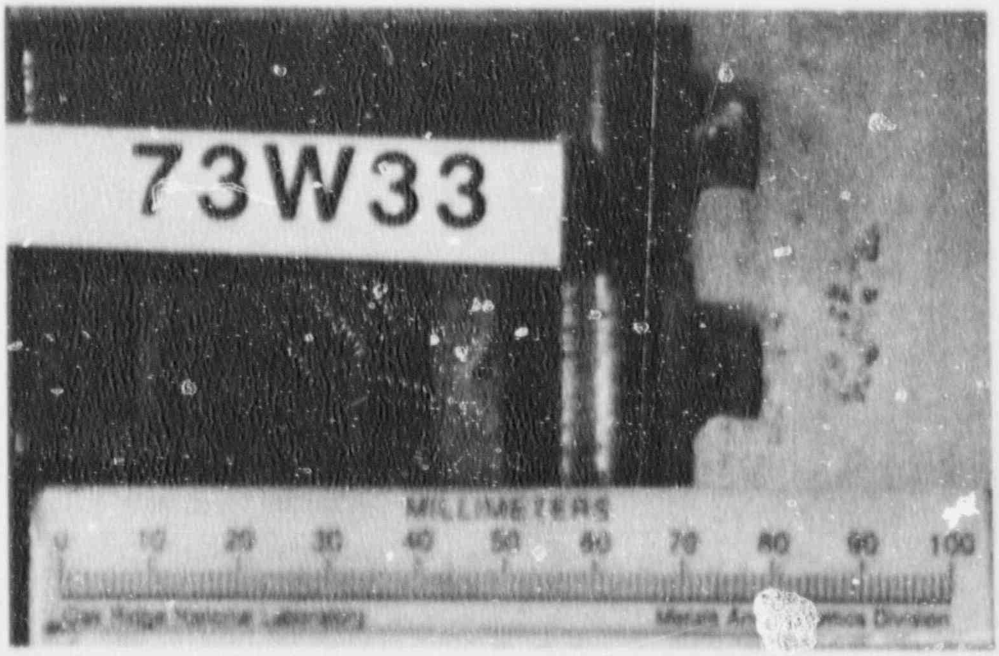
STRAIN RANGE ±10 %

Stroke = 3 (±1")

Normal Split Pin

Excitation Voltage for Clip Gage = 036" DC

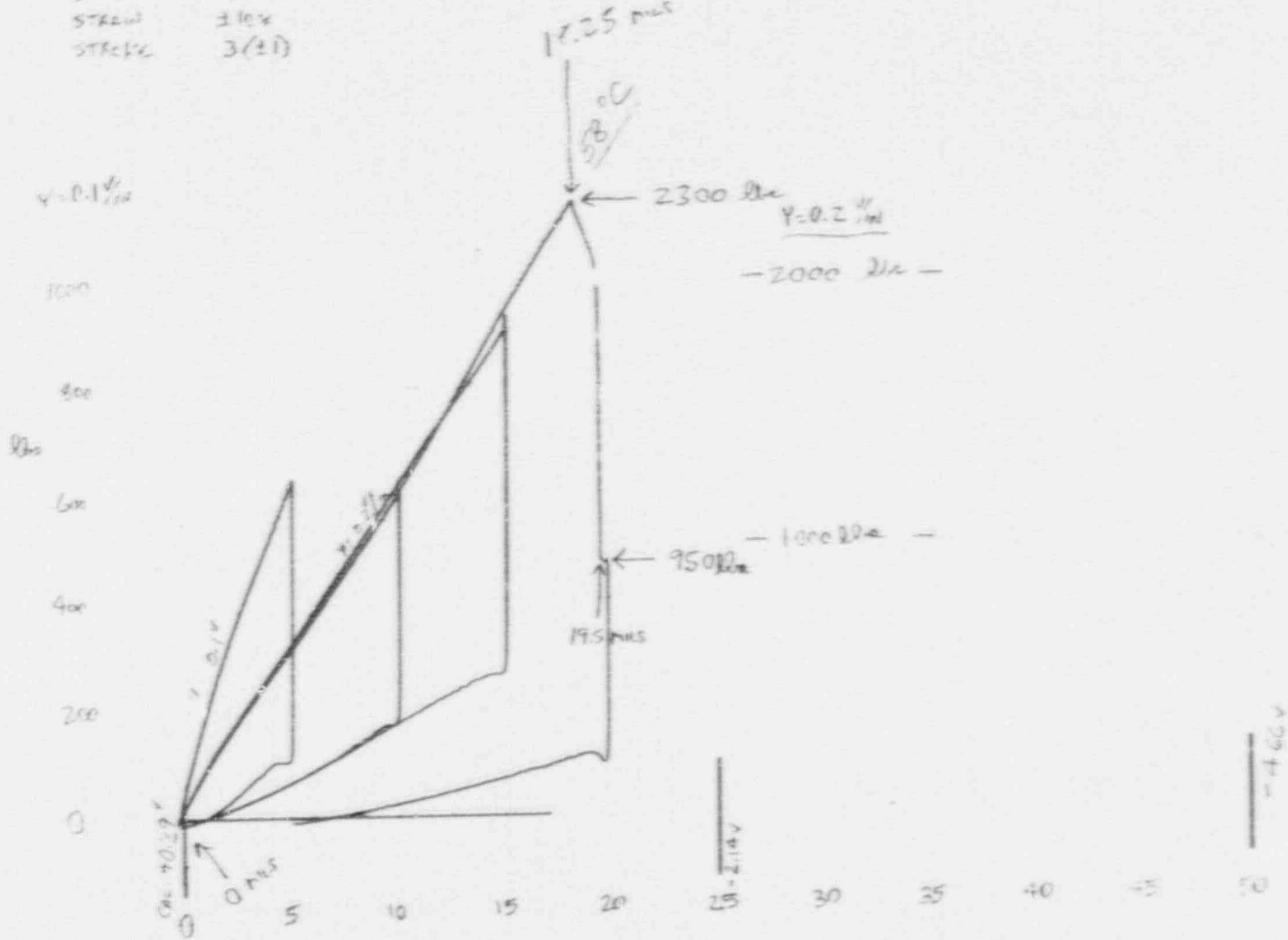


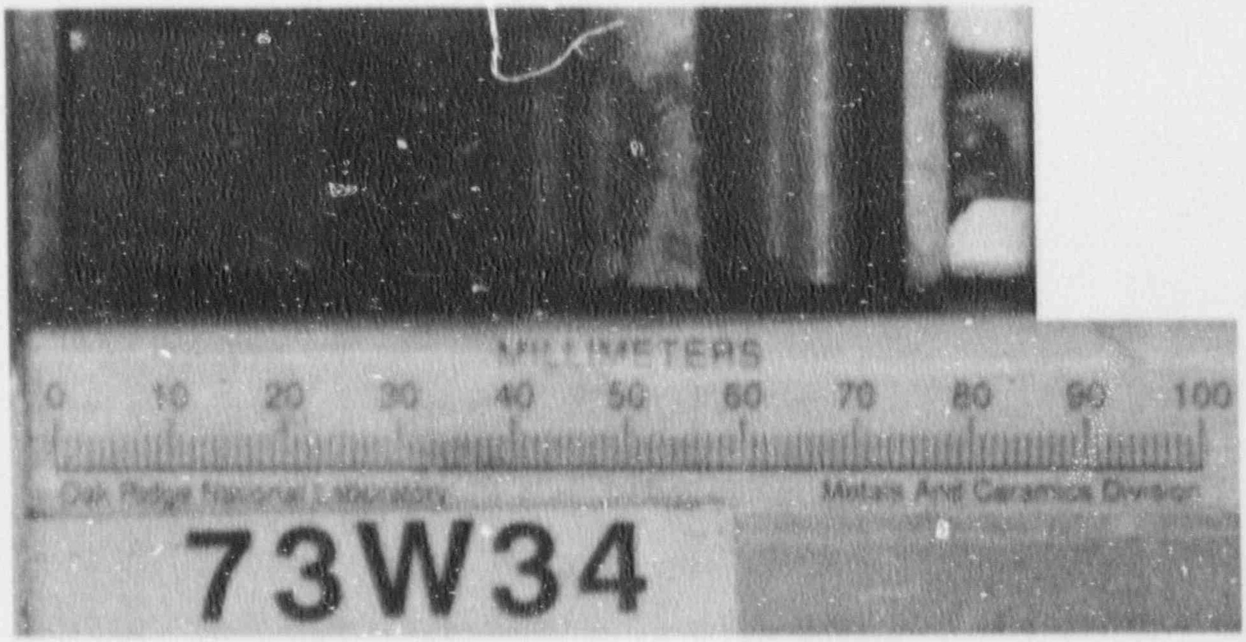


Specimen Identification = A73W33
Test Temperature = 60°C
Crack Arrest Toughness = 74 MPa·√m
Length of Remaining Ligament = 26.5 mm

SPEC #73-33 DATE 7-24 [illegible]
TI = TEMP (60°) X = 0.5 "/in 60°K ~ 25° [illegible]
[illegible] Y = 0.1 "/in / 0.2"/

LOAD RANGE ±20 KIP
STRAIN ±10%
STROKE 3(±1)





Specimen Identification = A73W34
Test Temperature = 29°C
Crack Arrest Toughness = 60 MPa·$\sqrt{m}$
Length of Remaining Ligament = 22.1 mm

SPEC.# A73W34 **DATE:** ~~9-1-89~~ 8-31-89 [✓ Normal] / Inverted ~~Non~~-[✓ Irradiated]

TEST TEMP. ~~75~~ +29°C

CLIP GAGE #CAG02

VOLTAGES:

Excitation - ~~3.436~~ 6.53

During calibration-

0 0.0 75

25 -2.49 100

50 -4.977

In specimen at zero- 7.84

MACHINE SETTINGS

Load Range = ±10 KIPS

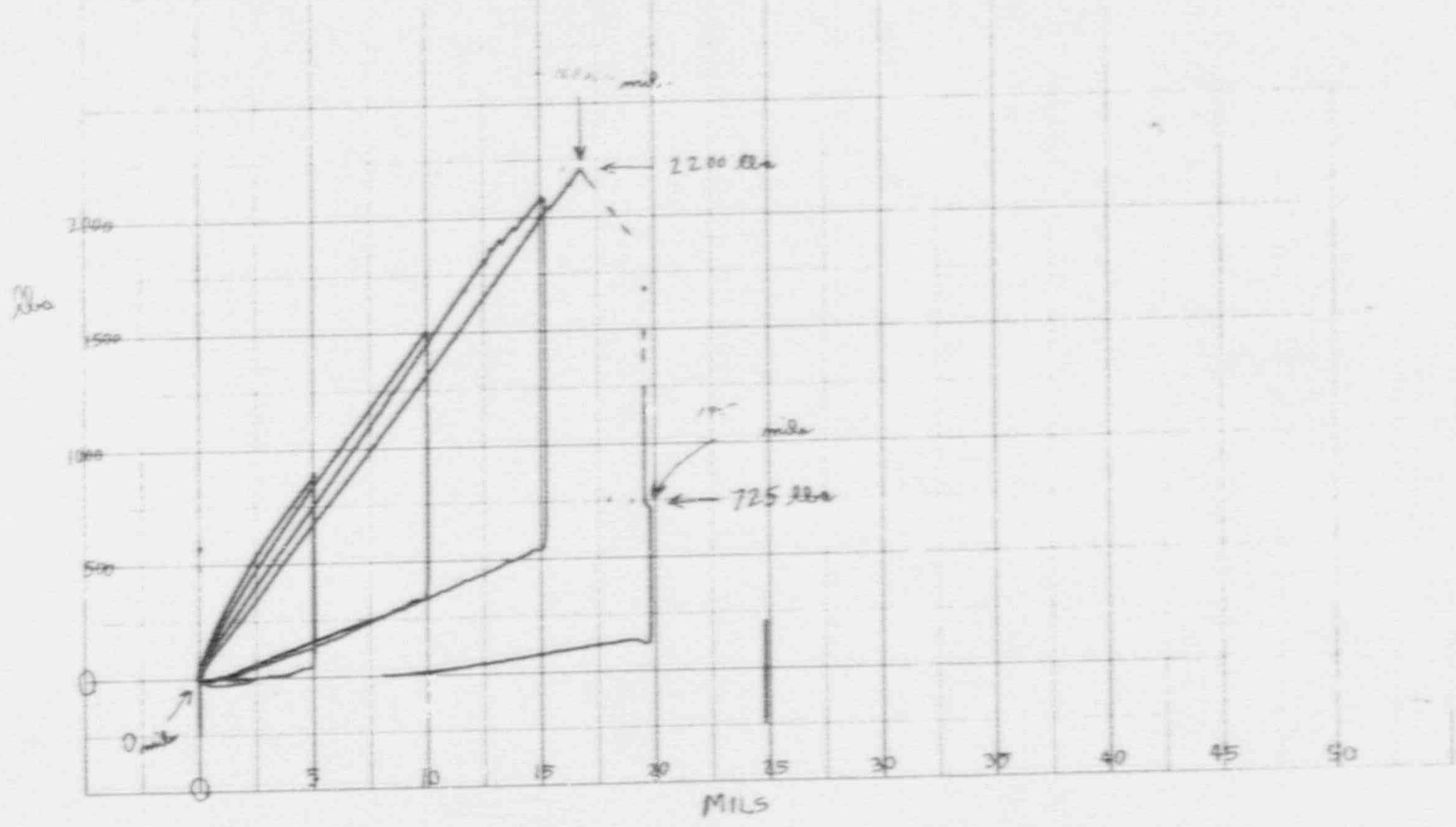
Strain Range = [✓ ±10%] ±20%

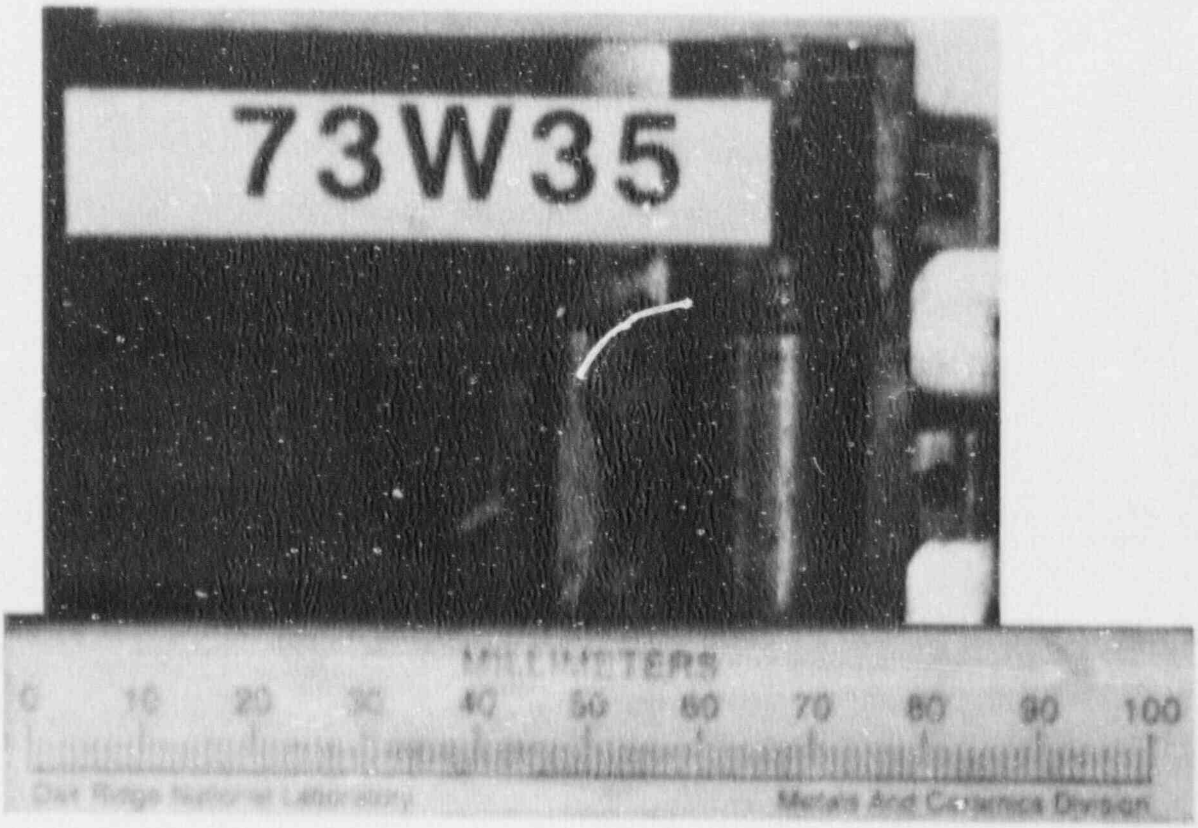
Stroke Range = 3 (±1)

X-Y CHART SETTINGS

X= 0.5 "/in

Y= 0.5 "/in





Specimen Identification = A73W35
Test Temperature = 29°C
Crack Arrest Toughness = 67 $\mathrm{MPa}\cdot\sqrt{\mathrm{m}}$
Length of Remaining Ligament = 27.7 mm

SPEC.# A75-35 **DATE:** 9-5-89 [✓ Normal] / Inverted Non-[✓ Irradiated]

TEST TEMP. 29°C

CLIP GAGE
#CAG#2

MACHINE SETTINGS

Load Range = ±10 KIPS

Strain Range = ±20%

Stroke Range = 3(±1)

VOLTAGES:

Excitation - 6.544

During calibration-

0 (0.285—) 75

25 - 2.49 100

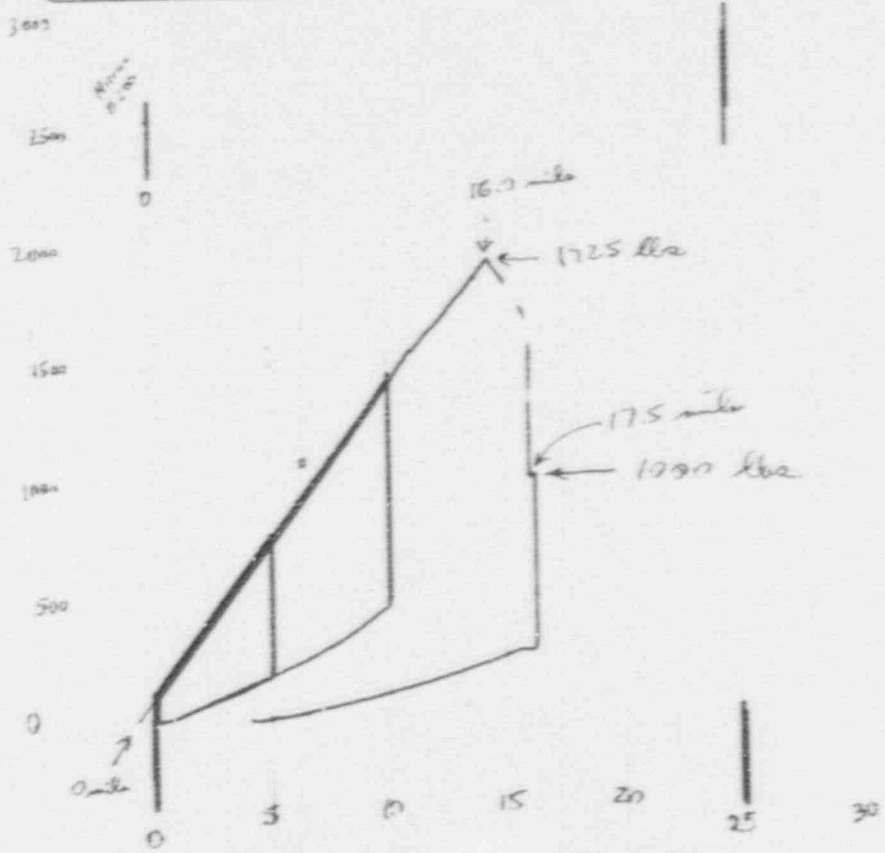
50

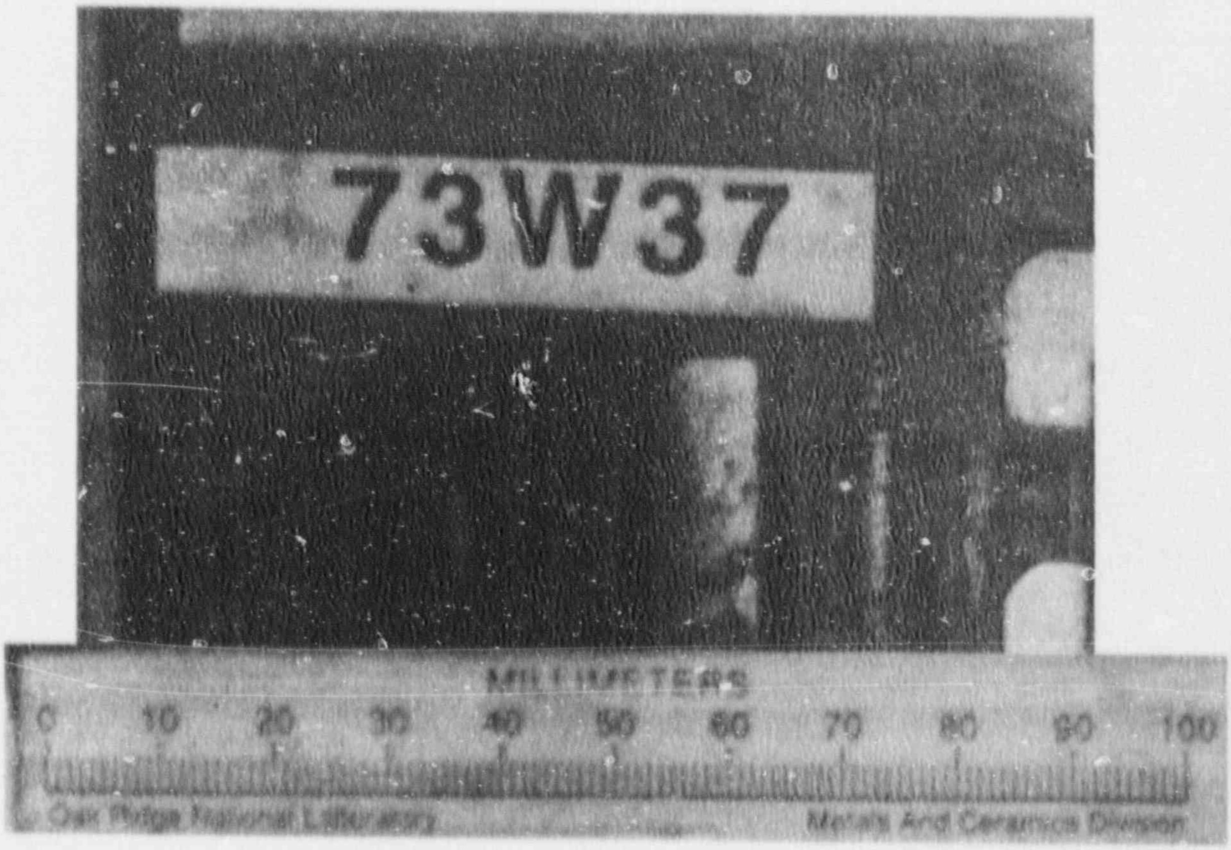
In specimen at zero- .04

X-Y CHART SETTINGS

X= 0.5 V/in

Y= 0.5 V/in





Specimen Identification = A73W37
Test Temperature = -25°C
Crack Arrest Toughness = 29 MPa·$\sqrt{m}$
Length of Remaining Ligament = 2.8 mm

SPEC.# A73 W37 **DATE:** 8-30-89 [✓ Normal] / Inverted ~~Non~~-[✓ Irradiated]

TEST TEMP. -25°C **CLIP GAGE** # CAGS#1 **MACHINE SETTINGS**

VOLTAGES:

Excitation - 3.436

During calibration-

0 -3.92 75

25 -[illegible] 100

50 -[illegible]

In specimen at zero- -

Load Range = ±10 KIPS

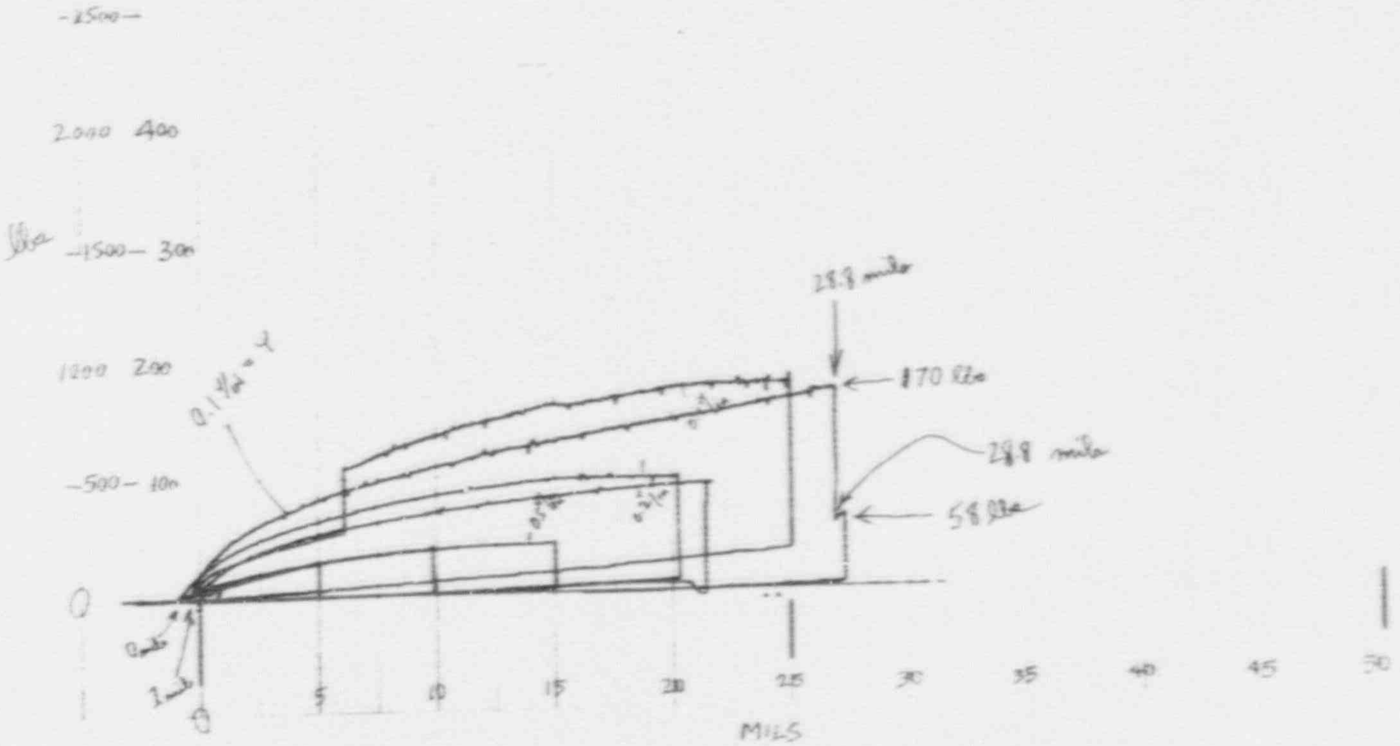
Strain Range = ±#/10%

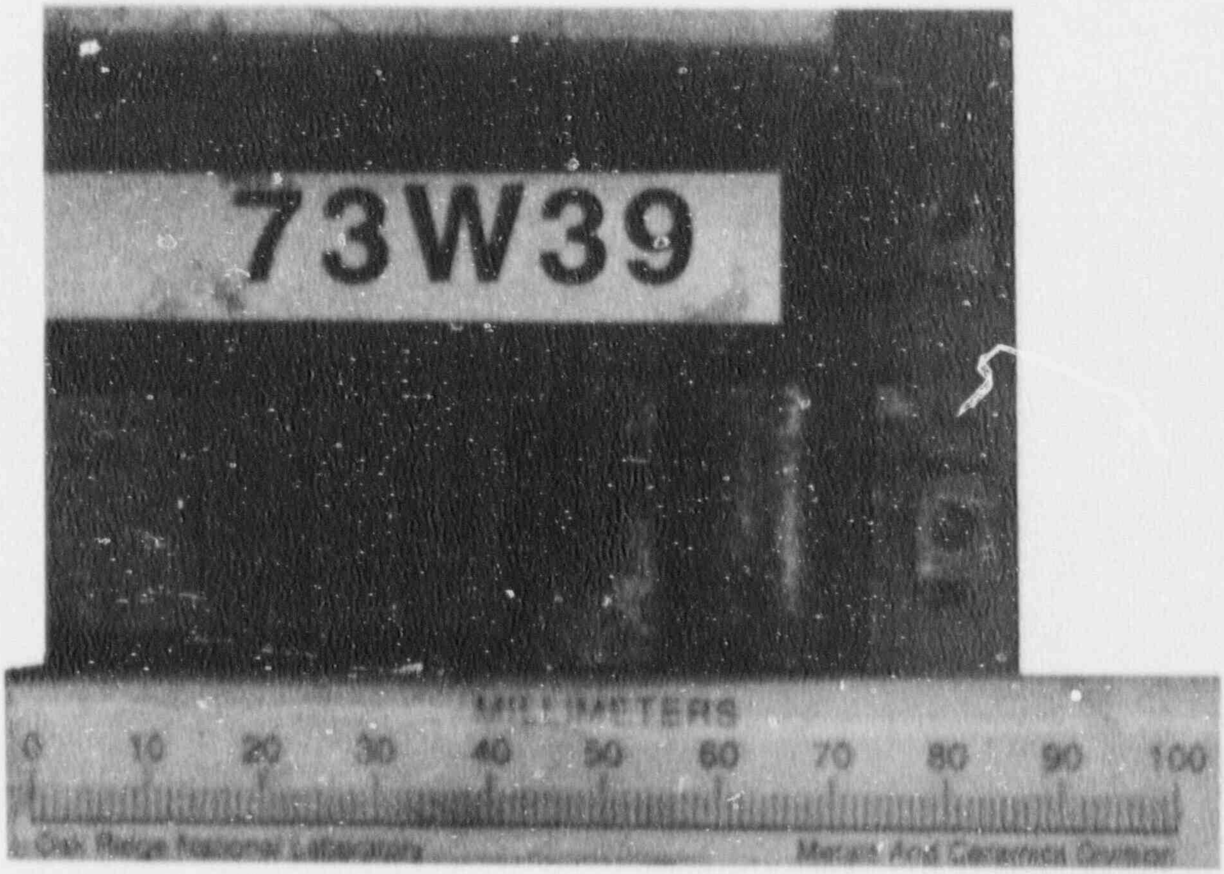
Stroke Range = 3(±1)

X-Y CHART SETTINGS

X= 0.5 V/in

Y= 0.5 V/in ⟹ 0.1V/in





Specimen Identification - A73W39
Test Temperature - -25°C
Crack Arrest Toughness - $41\ \mathrm{MPa}\cdot\sqrt{m}$
Length of Remaining Ligament - 14.0 mm

[illegible]

SPEC. # 75N-34 **DATE:** [illegible] [✓ Normal] / ~~Inverted~~ ~~Non~~ [✓ Irradiated]

TEST TEMP. -25 C **CLIP GAGE** #CPL-C-2 **MACHINE SETTINGS**

VOLTAGES:

Excitation - 6.40 [illegible]

During calibration-

0 -0.200 75

25 -2.483 100

50 -4.575

In specimen at zero- -0.453

Load Range = ±10 kips

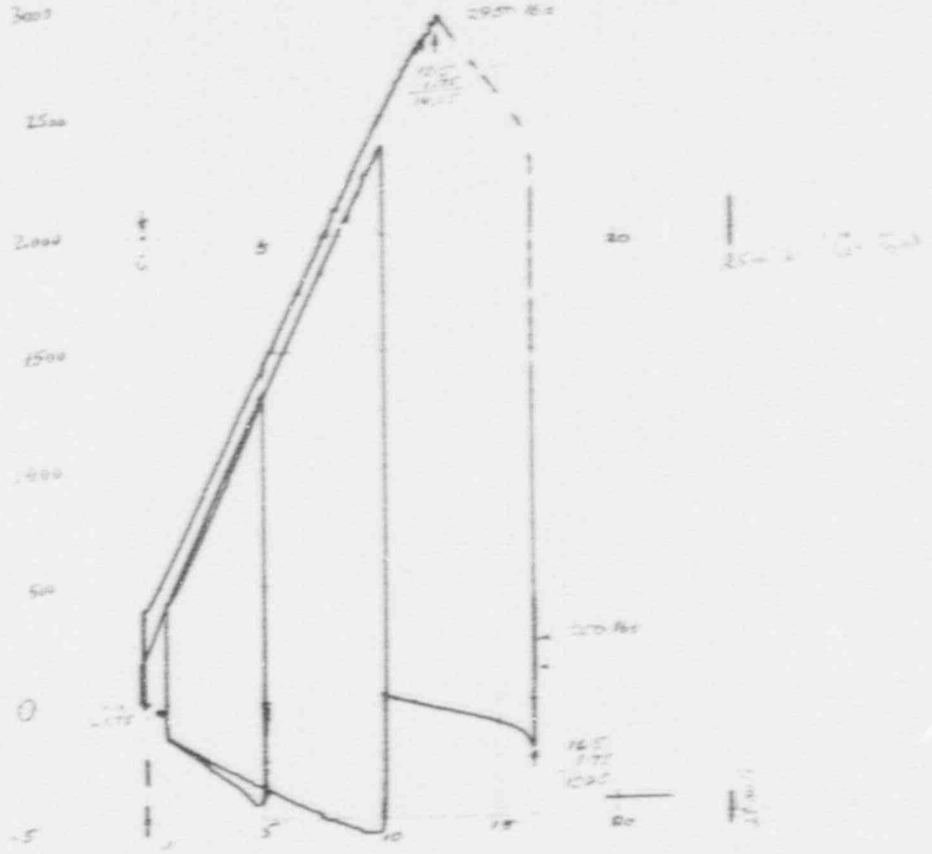
Strain Range = ±20%

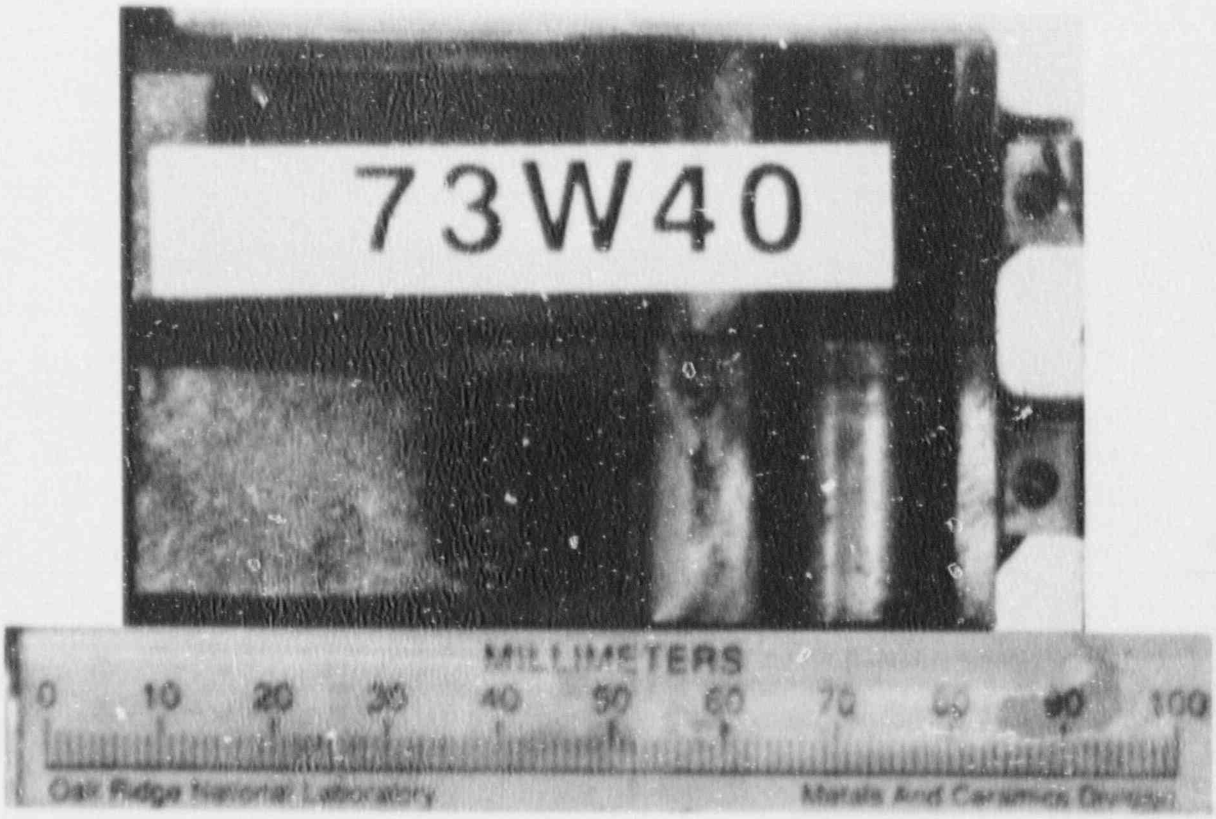
Stroke Range = ±1 in

X-Y CHART SETTINGS

X= 0.5"/in

Y= 0.5"/in





Specimen Identification = A73W40
Test Temperature = 60°C
Crack Arrest Toughness = 81 MPa·√m
Length of Remaining Ligament = 26.3 mm

SPEC.# 73w40 **DATE:** 8-25-89 ~~Normal~~ [✓ Inverted] ~~Not~~ [✓ Irradiated]

TEST TEMP. 60°c **CLIP GAGE** #CAG01

VOLTAGES:

Excitation - 3.436

During calibration-

0	-4.98	75
25	-4.51	100
50	-7.06	

In specimen at zero- -1.80

MACHINE SETTINGS

Load Range = ±20 KIPS

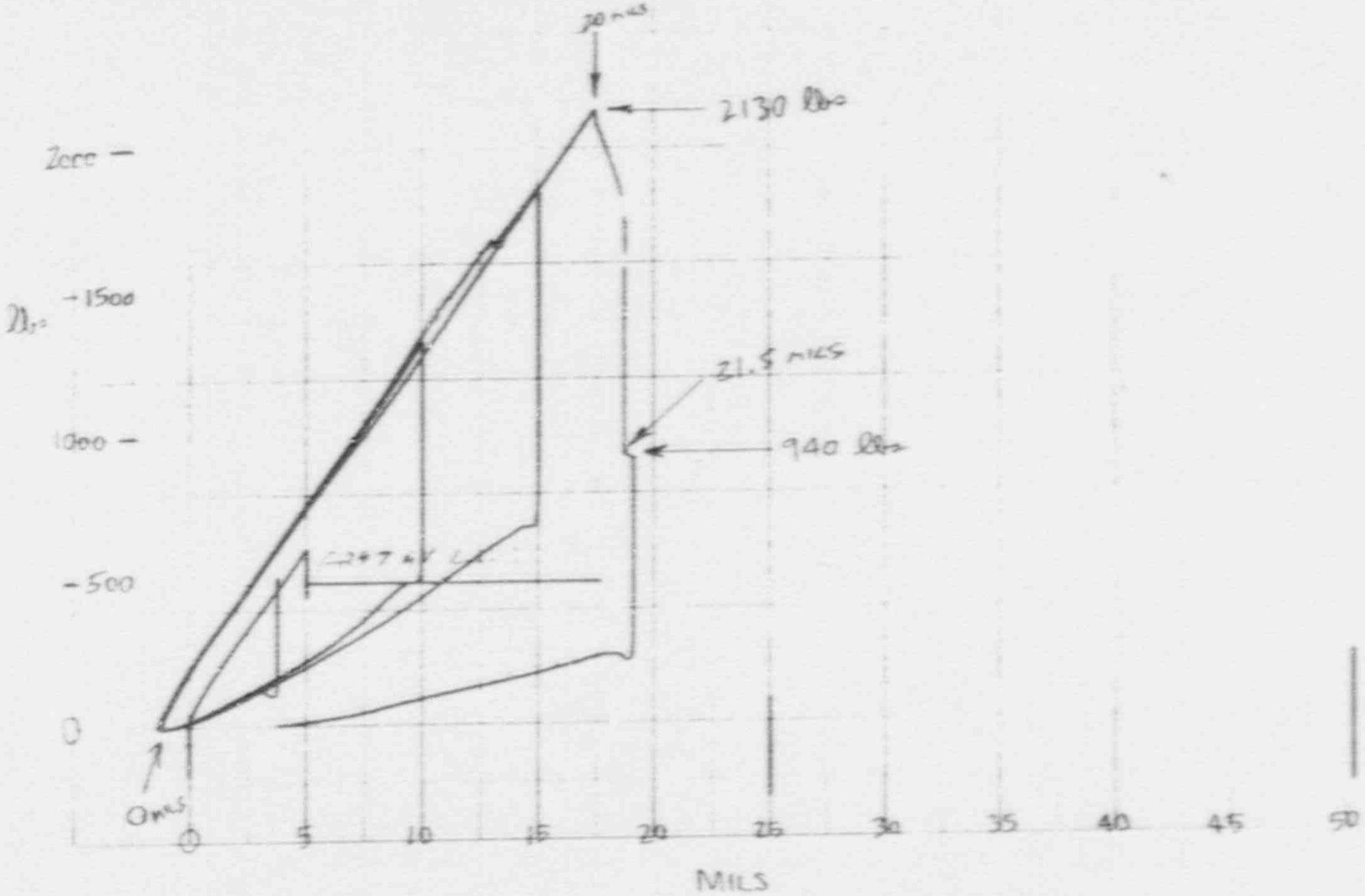
Strain Range = ±10%

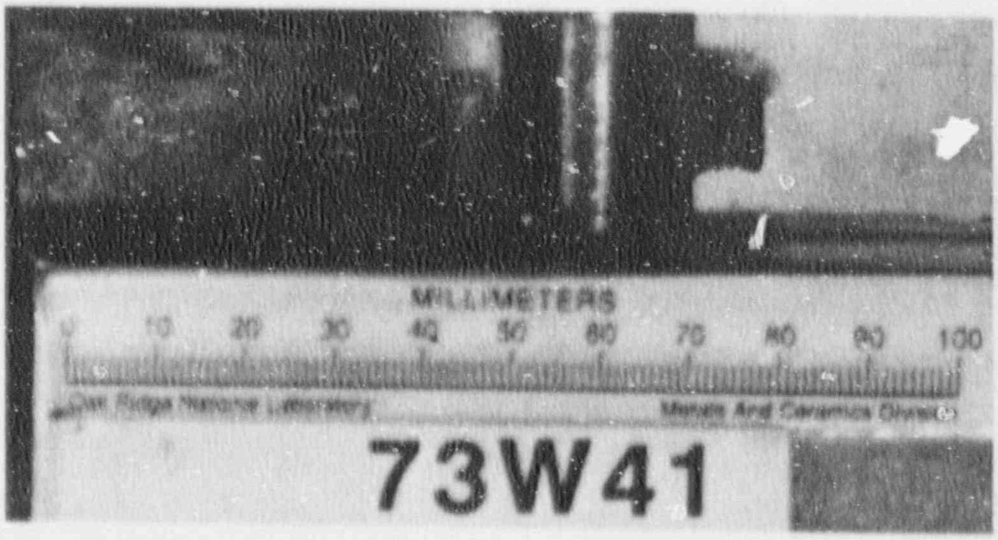
Stroke Range = 3(±1)

X-Y CHART SETTINGS

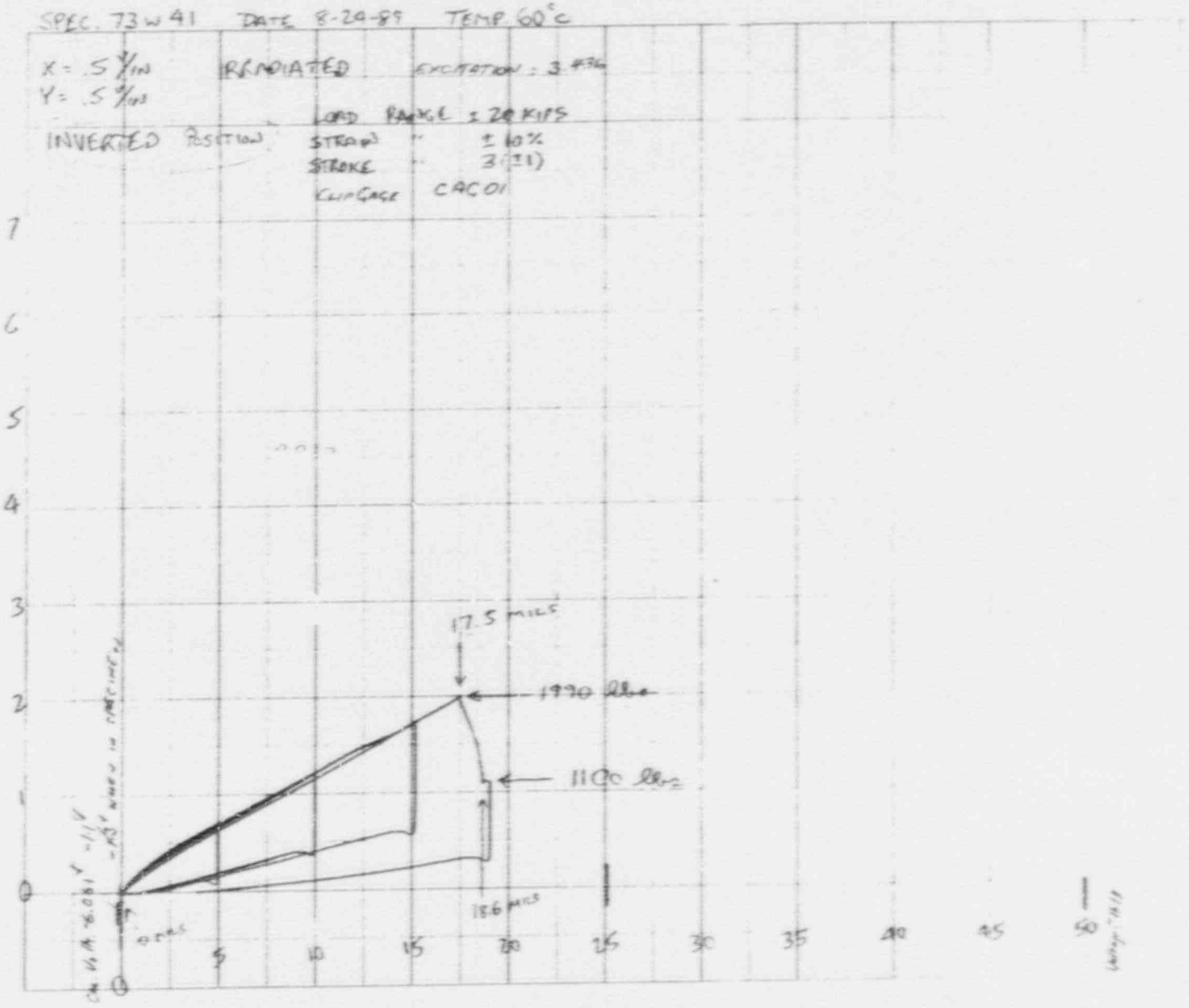
X= 0.5 "/in

Y= 0.2 "/in





Specimen Identification = A73W41
Test Temperature = 60°C
Crack Arrest Toughness = 79 MPa·$\sqrt{m}$
Length of Remaining Ligament = 30.9 mm


SPEC. 73W41 DATE 8-29-89 TEMP. 60°C
X = .5 V/IN
Y = .5 V/IN
IRRADIATED
EXCITATION : 3 #36
INVERTED POSITION
LOAD RANGE ± 20 KIPS
STRAIN " ± 10%
STROKE " 3(±1)
KLIPGAGE CAC01
7
6
5
4
3
2
1
0
17.5 MILS
1990 lbs
1100 lbs
18.6 MILS
0 MILS
0
5
10
15
20
25
30
35
40
45
50
mils down
-6.081 V
-11 V

Specimen Identification - A73W45
Test Temperature - 90°C
Crack Arrest Toughness - 114 MPa·$\sqrt{m}$
Length of Remaining Ligament - 55.3 mm

Specimen Identification - A73W45
Test Temperature - 90°C
Crack Arrest Toughness - 114 MPa·√m
Length of Remaining Ligament - 55.3 mm

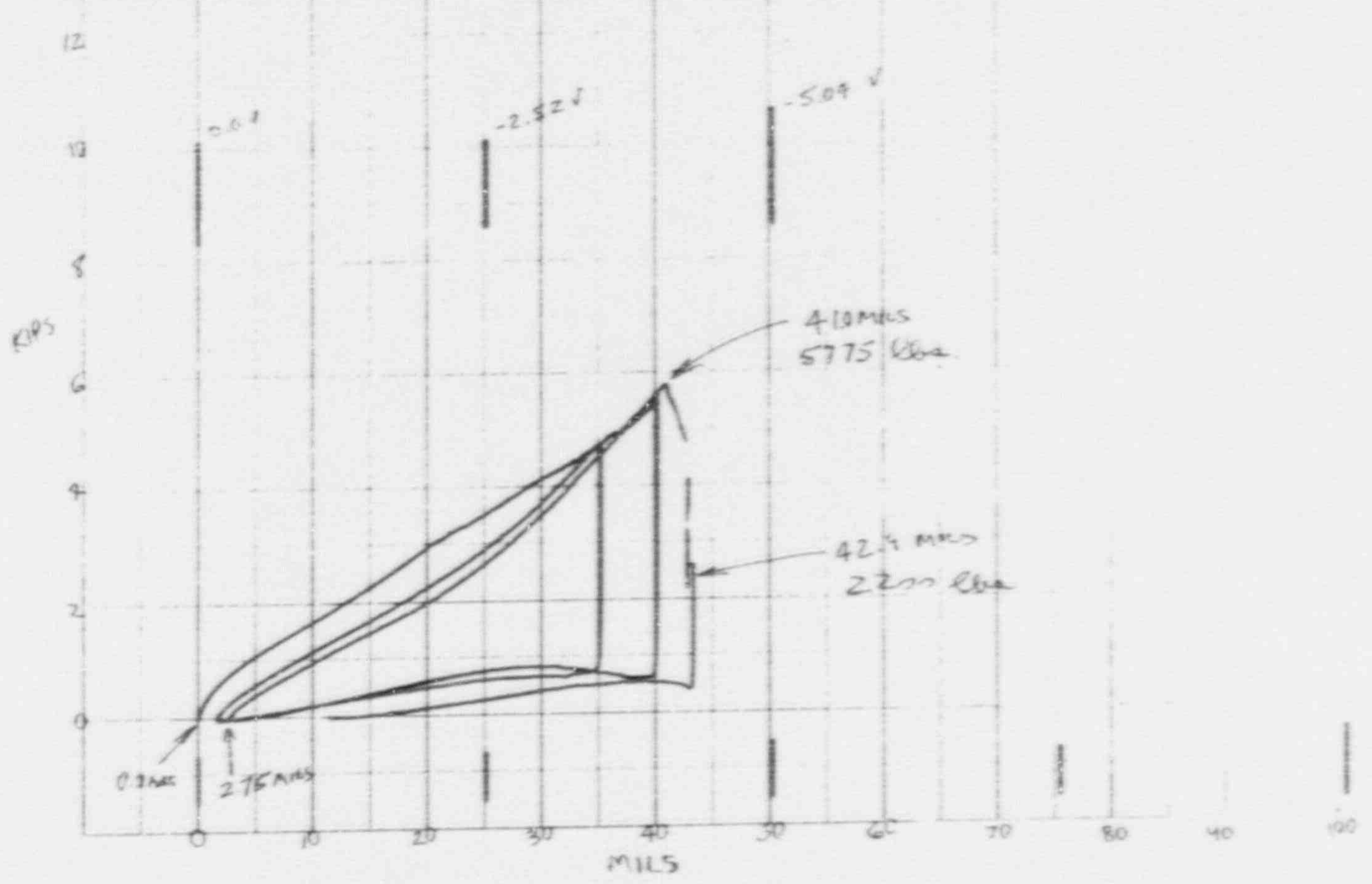
SPEC.# A73W45 **DATE:** Oct 30,1987 **Normal** [✓ **Inverted**] **Non-**[✓ **Irradiated**]

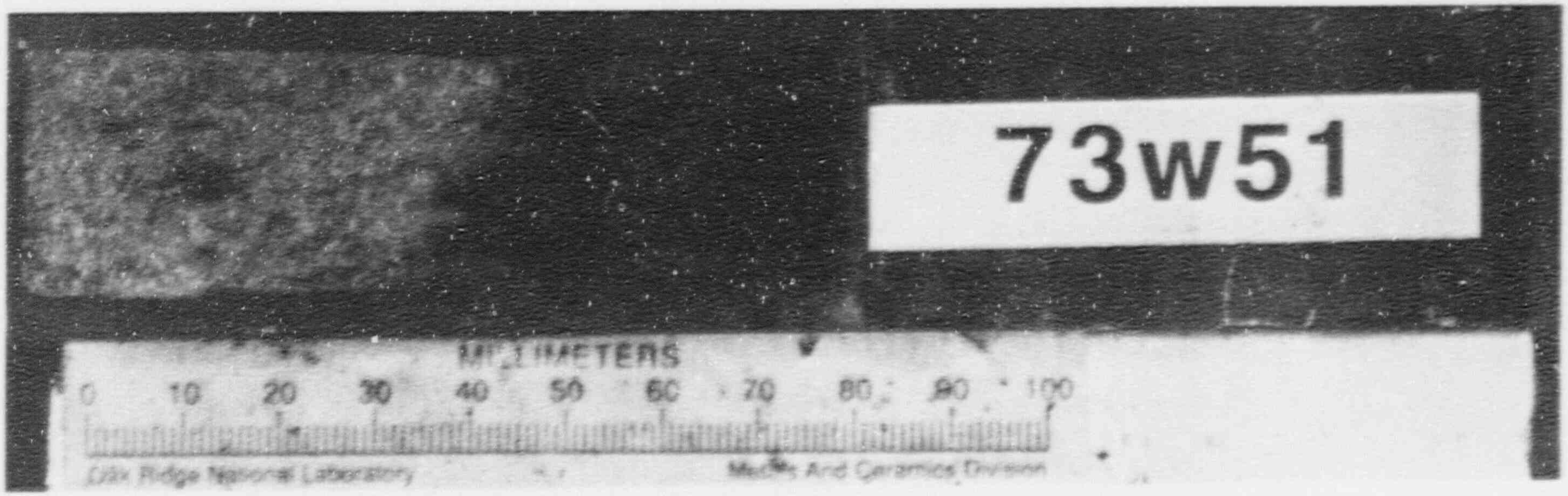
TEST TEMP. ~~75°C~~ 90°C
CLIP GAGE #CAG 02

VOLTAGES:
Excitation - 6.588
During calibration-
0 0.0
25 -2.52
50 -5.04
75 -7.56
100 -10.08
In specimen at zero- -0.854 (0.0)

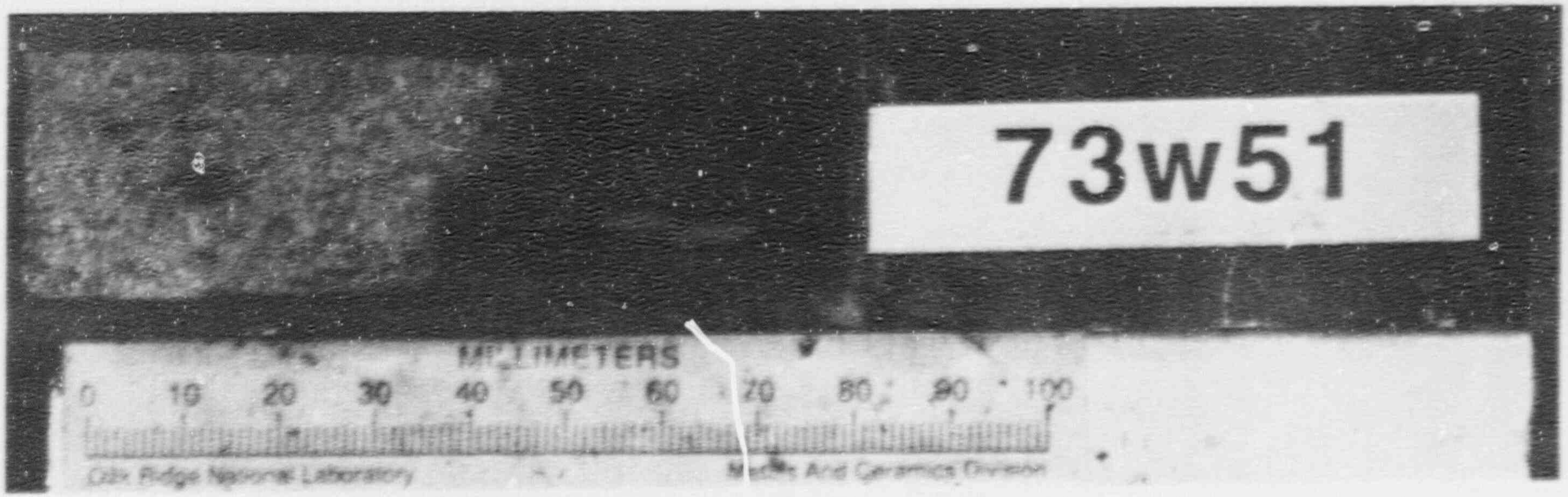
MACHINE SETTINGS
Load Range ± 12 KIPS
Strain Range ~~± 2.5~~
Stroke Range ± 1

X-Y CHART SETTINGS
X= 1 V/in
Y= 1 V/in





Specimen Identification - A73W51
Test Temperature - 100°C
Crack Arrest Toughness - 184 MPa$\cdot\sqrt{m}$
Length of Remaining Ligament - 47.1 mm



Specimen Identification - A73W51
Test Temperature - 100°C
Crack Arrest Toughness - 184 MPa·$\sqrt{m}$
Length of Remaining Ligament - 47.1 mm

SPEC. # A73-51 **DATE:** 9-27-89 ~~Normal~~ / [✓ Inverted] ~~Non~~ - [✓ Irradiated]

TEST TEMP. 100°c

CLIP GAGE # CACO2

VOLTAGES:

Excitation - 6.588 v

During calibration-

0 0.0 75 -7.48

25 -2.51 100 -9.97

50 -5.01

In specimen at zero- -3.40

MACHINE SETTINGS

Load Range = ± 20 KIPS

Strain Range = ± 10%

Stroke Range = ±1

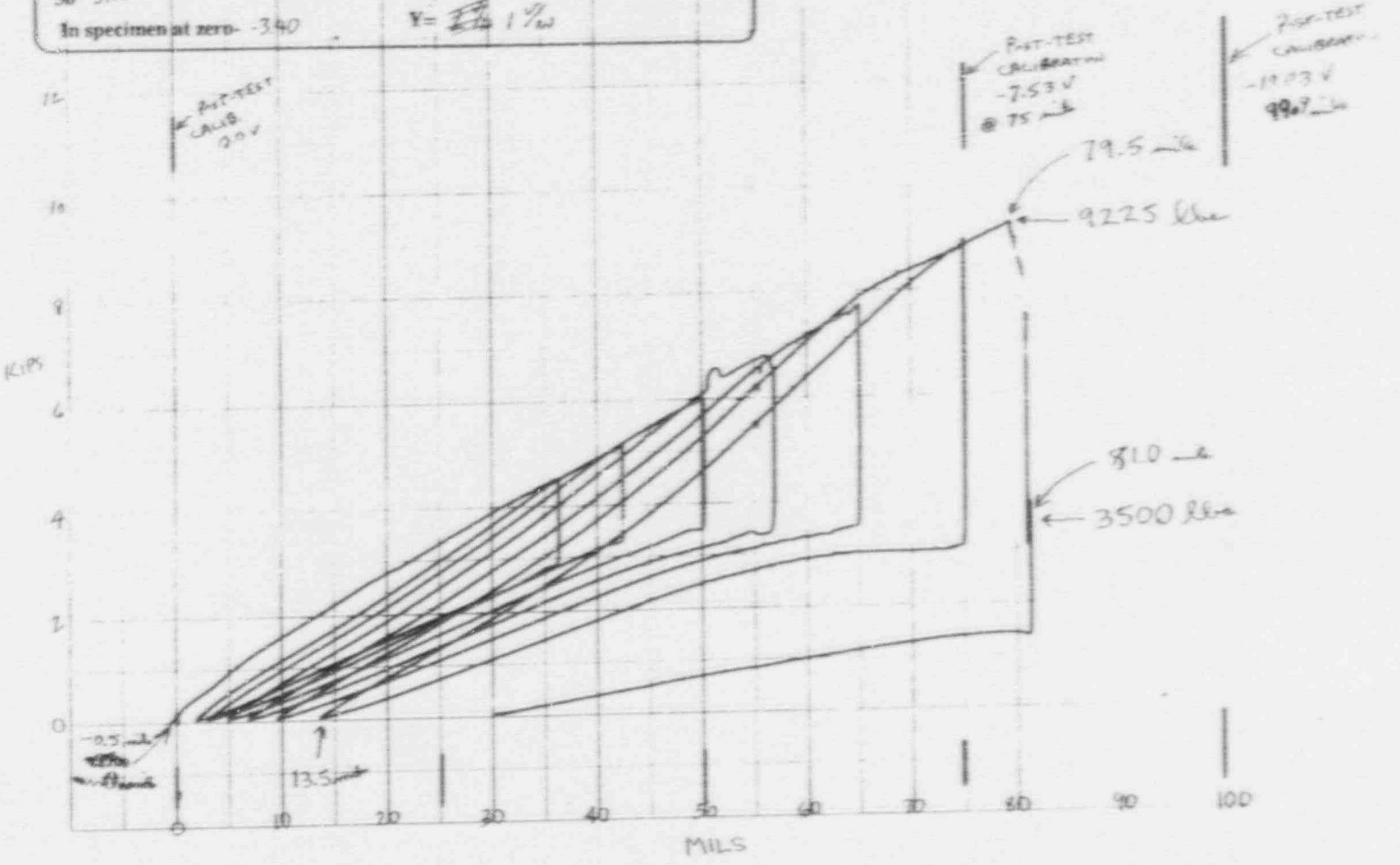
X-Y CHART SETTINGS

X= 1 V/in

Y= ~~2 V/in~~ 1 V/in

Varian Setting 43

sweep rate 150 = (up)
30 = (Down)



SPEC. # A73-51 **DATE:** 9-27-89 Normal [✓ Inverted] Non - [✓ Irradiated]

TEST TEMP. 100°C

CLIP GAGE #CACO2

VOLTAGES:

Excitation - 6.588 V

During calibration-

0	0.0	75	-7.48
25	-2.51	100	-9.97
50	-5.01		

In specimen at zero- -3.40

MACHINE SETTINGS

Load Range = ± 20 KIPS

Strain Range = ± 10%

Stroke Range = ±1

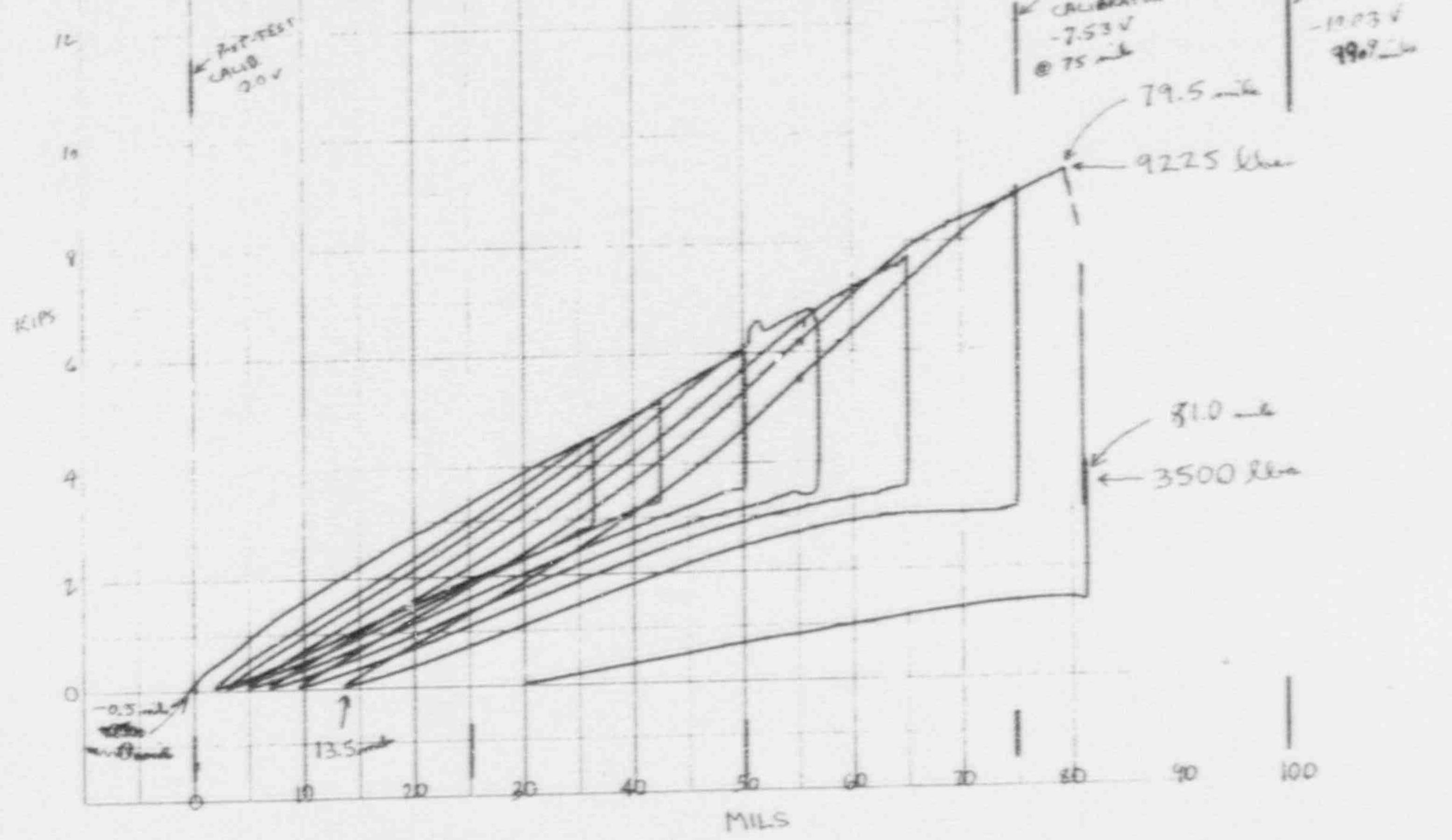
X-Y CHART SETTINGS

X= 1 V/in

Y= ~~[illegible]~~ 1 V/in

Variac Setting 43#

sweep rate 150 s (up)
30 s (down)



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3. DATE REPORT PUBLISHED

MONTH	YEAR
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4. FIN OR GRANT NUMBER

L1098

5. AUTHOR(S)

S.K. Iskander, W.R. Corwin. P [illegible]. Nanstad

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10. SUPPLEMENTARY NOTES

11. ABSTRACT *(200 words or less)*

The objective of this study was to determine the effect of neutron irradiation on the shift and shape of the lower-bound curve to crack-arrest data. Two submerged-arc welds with copper contents of 0.23 and 0.31 wt % were commercially fabricated in 220-mm-thick plate. Crack-arrest specimens fabricated from these welds were irradiated at a nominal temperature of 288°C to an average fluence of 1.9×10^{19} neutrons/cm^2 (>1 MeV). Evaluation of the results shows that the neutron-irradiation-induced crack-arrest toughness temperature shift is about the same as the Charpy V-notch impact temperature shift at the 41-J energy level. The shape of the lower-bound curves (for the range of test temperatures covered) did not seem to have been altered by irradiation compared to those of the ASME K_{Ia} curve.

12. KEY WORDS/DESCRIPTORS *(List words or phrases that will assist researchers in locating the report.)*

Charpy V-notch impact toughness
copper content
crack arrest
drop-weight
fracture toughness
irradiation
K_{Ia}
light-water reactors
neutron fluence
nil-ductility transition temperature
reactor pressure vessels
submerged arc welds
temperature shift
ΔRT_{NDT}

13. AVAILABILITY STATEMENT

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14. SECURITY CLASSIFICATION

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