NUREG/CR-6447
ORNL-6894

Results of Crack-Arrest Tests on Irradiated A 508 Class 3 Steel

Manuscript Completed: June 1995
Date Published: February 1998

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Prepared for
Division of Engineering Technology
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001
NRC Job Code L1098

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Abstract

Ten crack-arrest toughness values for irradiated specimens of A 508 class 3 forging steel have been obtained. The tests were performed according to the American Society for Testing and Materials (ASTM) Standard Test Method for Determining Plane-Strain Crack-Arrest Fracture Toughness, K_{Ia}, of Ferritic Steels, E 1221-88. None of these values are strictly "valid" in all five ASTM E 1221-88 validity criteria. However, they are useful when compared to unirradiated crack-arrest specimen toughness values since they show the small (averaging approximately 10°C) shifts in the mean and lower-bound crack-arrest toughness curves. This confirms that a low copper content in ASTM A 508 class 3 forging material can be expected to result in small shifts of the transition toughness curve. The shifts due to neutron irradiation of the lower bound and mean toughness curves are approximately the same as the Charpy V-notch (CVN) 41-J temperature shift. The nine crack-arrest specimens were irradiated at temperatures varying from 243 to 280°C, and to a fluence varying from 1.7 to 2.7 × 10^{19} neutrons/cm^2 (> 1 MeV). The test results were "normalized" to reference values that correspond to those of CVN specimens irradiated at 284°C to a fluence of 3.2 × 10^{19} neutrons/cm^2 (> 1 MeV) in the same capsule as the crack-arrest specimens. This adjustment resulted in a shift to lower temperatures of all the data, and in particular moved two data points that appeared to lie close to or lower than the American Society of Mechanical Engineers K_{Ia} curve to positions that seemed more reasonable with respect to the remaining data. A special fixture was designed, fabricated, and successfully used in the testing. For reasons explained in the text, special blocks to receive the Oak Ridge National Laboratory clip gage were designed, and greater-than-standard crack-mouth opening displacements measured were accounted for.

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Acknowledgments

The following individuals not only contributed to the various tasks mentioned but also made many useful and constructive suggestions. The authors acknowledge Eric T. Manneschmidt and John J. Henry, Jr., for modifications to and shakedown of the new fixture, temperature survey, and the testing in the hot cells; David L. Thomas and Ronald L. Swain for much assistance with equipment; Lloyd J. Turner, Robert K. Lawson, John R. Gilley, and A. Earl Parker for very significant contributions to the transportation and testing of the irradiated specimens (the three large irradiated specimens were particularly difficult to move into the hot cell, and the authors acknowledge the ingenuity displayed by them). The design of the new remote test fixture was a daunting task, since it is capable of handling ten different test configurations (five different specimen sizes in the normal and inverted positions), so thanks go to Kenneth W. Boling, who designed the original. Julia L. Bishop is gratefully acknowledged for her expert help to produce this manuscript, Kathy Spence for her thorough manuscript editing, and SAIC for final manuscript preparation.

The authors also gratefully acknowledge the help of Jim C. Newman, Jr., NASA Langley Research Center, with the adjustment of the crack-mouth opening displacement (CMOD). The authors wish to thank Randy K. Nanstad and John G. Merkle for their thorough and helpful reviews. John Merkle suggested the closed-form derivation of the adjustment to the CMOD. The authors also acknowledge Charles W. Marschall, Battelle Columbus Division (BCD), and Alan R. Rosenfield, formerly of BCD, who were consulted during the choice of test temperatures for the irradiated specimens, for their reviews and for the helpful comments, particularly with regard to the references to the development of state-of-the art crack-arrest testing methodology.

The authors are also grateful for the financial support and encouragement from the U.S. Nuclear Regulatory Commission, especially Alfred Taboada and Michael G. Vassilaros, the former and current Heavy-Section Steel Irradiation Program Monitors.

Foreword

The work reported here was performed at the 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 M. G. Vassilaros.

This report is designated HSSI Report 16. Reports in this series are listed below:

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1. Introduction

The exposure of some reactor pressure vessel (RPV) ferritic steels to neutron irradiation fluences of the order of 2×10^{19} neutrons/cm^2 (> 1 MeV) can cause changes in the shape and an increase in the transition temperature of the Charpy V-notch (CVN) impact energy curve.[1] The present procedure in Title 10, *Code of Federal Regulations*, Part 50 (10CFR50),[2] to account for the possible degradation of these steels is to shift the American Society of Mechanical Engineers (ASME) fracture toughness curves to a higher temperature by the amount of shift exhibited by CVN impact energy curves subjected to the same fluence. This procedure assumes that: (1) the ASME fracture toughness curves of the same material would have shifted by the same amount as the CVN impact energy had they been exposed to the same irradiation fluence and irradiation temperature, and (2) the fracture toughness curves of the irradiated material are of the same shape as those of unirradiated material. Since correlations exist between CVN impact energy and toughness,[3] and the CVN impact energy curves for these steels show changes in shape and an increase in the transition temperature, it might be expected that the fracture toughness curves for irradiation-sensitive RPV steels would also show changes in shape. A relatively small shape change of the crack-initiation toughness, K_{Jc}, versus temperature curve has been observed for Heavy-Section Steel Irradiation (HSSI) Program weld 73W (ref. 4).

For more than two decades, the U.S. Nuclear Regulatory Commission (NRC) has sponsored much research at the Oak Ridge National Laboratory (ORNL) and elsewhere to study the effects of neutron irradiation on the fracture toughness of RPV steels. The first data on irradiated crack-arrest specimens were obtained at Battelle under sponsorship of the NRC.[5] Battelle and Westinghouse researchers performed a more extensive study under sponsorship of the Electric Power Research Institute.[6,7] The NRC-supported HSSI Program has performed considerable research into the irradiated behavior of RPV steels, namely, the Fourth,[8] Fifth,[4] Sixth,[9,10] and Seventh[11] Irradiation Series. In particular, the HSSI Sixth Irradiation Series investigated the effects of irradiation on the temperature shift and shape change of the crack-arrest toughness, K_a,‡ versus temperature curve. The results of the Sixth Irradiation Series showed that the shift of the lower bound to the data was about the same as the shift in transition temperature, and no shape change was observed.

The number of published** K_a data points for irradiated RPV steels is about 73, of which 39 were generated in the Sixth Irradiation Series. Due to this paucity of data, the NRC has arranged for ORNL to test the nine irradiated crack-arrest specimens belonging to the Italian Agenzia Nazionale per la Protezione dell'Ambiente (ANPA).†† The material is of a type that is also used in U.S. RPVs, thus the results have usefulness and applicability to the integrity assessment of U.S. RPVs.

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*Research sponsored by the Office of Nuclear Regulatory Research, Division of Engineering Technology, U.S. Nuclear Regulatory Commission, under Interagency Agreement DOE 1886-8109-8L with the U.S. Department of Energy under contract DE-AC05-96OR22464 with Lockheed Martin Energy Research Corporation.

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‡American Society for Testing and Materials Test for Determining Plane-Strain Crack-Arrest Fracture Toughness, K_{Ia}, of Ferritic Steels (E 1221-88) makes a distinction between the plane-strain crack-arrest toughness value, K_{Ia}, which meets all the validity criteria, and the observed value, K_a.

**The principal author has recently learned that the Staatliche Materialprüfungsanstalt (MPA), Stuttgart, Germany, is preparing a report on the results of tests on more than a dozen irradiated crack-arrest toughness specimens.

††Recent changes have moved the Italian Nuclear Safety Authority, formerly known as ENEA-DISP, to the Agenzia Nazionale per la Protezione dell'Ambiente (ANPA).

The general purpose of this report is to document in detail the material of the test specimens, the equipment used, and the results of the tests performed on the nine irradiated crack-arrest specimens. For the reason explained below, the observed values of crack-mouth opening displacement (CMOD) were adjusted. To account for the differences in irradiation temperature and fluence values between the nine crack-arrest specimens, the test temperatures of the crack-arrest specimens were "adjusted" to correspond to those of reference irradiation temperature and fluence values. The raw data, the details of the adjustments, the final results, and the comparison between the curve shift due to irradiation for the crack-arrest specimens and that of reference CVN specimens will then be presented. A future report is planned that will perform more data analyses and compare the results to other data.

2. Materials, Test Specimens, and Equipment

The specimens were machined from a forging material produced in Italy that conforms to the American Society for Testing and Materials (ASTM) Specification for Quenched and Tempered Vacuum-Treated Carbon and Alloy Steel Forgings for Pressure Vessels, Class 3 (A 508 Class 3), A 508-81. All toughness specimens were machined in the C-R orientation.* Some time ago, ANPA started an extensive research program to characterize this forging.[12] The research program encompassed mechanical property data from the following types of unirradiated and irradiated specimens: tensile, Charpy impact (both standard and precracked), compact tensile, and crack arrest. Several institutions were involved in the irradiation and testing of these specimens: ENEA CRE Casaccia Laboratories, Battelle, and two laboratories of the French Commissariat a l'Energie Atomique. Previously reported crack initiation data for this steel indicated that the irradiation-induced shift of K_{Jc} was less than the CVN curve shift for fluences of 1 and 5.5 × 10^{19} neutrons/cm^2 (> 1 MeV).[13] ANPA tested the unirradiated crack-arrest specimens and originally planned to have the irradiated crack-arrest specimens tested at Battelle, but the hot cell facilities at Battelle were decommissioned before the testing could be performed. In this report, for brevity, the unirradiated and nine irradiated crack-arrest specimens are sometimes referred to as the "ANPA specimens."

Details of the tensile and Charpy results are in a report by Marschall et al.† from which the following data were excerpted. The room-temperature tensile yield and ultimate strengths for unirradiated specimens were 463 and 605 MPa, respectively, and increased ≈ 9 and 4%, respectively, when irradiated at a nominal temperature and fluence of 288°C and 3 × 10^{19} neutrons/cm^2 (> 1 MeV), respectively. The 41-J Charpy transition temperature and upper shelf for the unirradiated specimens were –58°C and 260 J, respectively, and changed by +11 and –6%, respectively, for the same irradiation conditions just mentioned. In particular, the 41-J Charpy transition temperature shift for this material and the same irradiation conditions was 11 C.‡ These small changes are due to the relatively small copper and moderate nickel contents (0.06 and 0.74%, respectively).

The irradiated tensile yield strength and Young's modulus, E, as a function of temperature are needed to evaluate the experimental data. The values of the 0.2% offset yield strength at several temperatures are given in Table 1 and were also excerpted from the report by Marschall et al.† Only the values at 25 and 150°C were used, and the

* Nomenclature for fracture toughness specimen orientation is described in ASTM Standard Test Method for Plane-Strain Fracture Toughness of Metallic Materials, E 399-90; for hollow cylinders, the first letter is the direction of the load relative to the crack plane, and the second corresponds to the direction of propagation of the flaw. Thus, for a C-R orientation, the normal to the crack plane is in the circumferential direction and propagates radially.

† C. W. Marschall, W. J. Zielenbach, R. W. Tayloe, Jr., and A. R. Rosenfield, *Effects of Fast Neutron Irradiation on the Mechanical Properties of an SA508 Class 3 Ring Forging*, Battelle, Columbus, Ohio, 1995.

‡ A distinction is made in this report between *temperatures*, which are designated with a degree symbol, and temperature *intervals* in the same units, without the degree symbol.

Table 1. Tensile properties of the A 508 class 3 forging after irradiation in the Ford Nuclear Reactor at a nominal temperature of 288°C to a fluence of 3.2 × 10^{19} neutrons/cm^2 (> 1 MeV)

Specimen	Test temperature		0.2% Offset yield strength	
	(°C)	(°F)	(MPa)	(ksi)
BT5	25	77	499	72.4
BT3	150	302	450	65.3
BT4	200	392	439	63.7
BT1	250	482	445	64.5
BT2	290	554	445	64.5

Source: C. W. Marschall, W. J. Zielenbach, R. E. Tayloe, Jr., and A. R. Rosenfield, Battelle, Columbus, Ohio, *Effects of Fast-Neutron Irradiation on the Mechanical Properties of an SA-508 Class 3 Ring Forging*, 1995.

yield strength, $\sigma_{0.2\,yield}$, at any intermediate temperature, t, was calculated using a straight line between these two points by the following expression:

$$\sigma_{0.2\ yield} = 508.8 - 0.392t\ , \qquad 25 \le t \le 150°C\ , \qquad (1)$$

with (t) in °C and $\sigma_{0.2\,yield}$ in MPa. The corresponding expression for t in °F and $\sigma_{0.2\,yield}$ in ksi is:

$$\sigma_{0.2\ yield} = 74.83 - 0.03156t\ , \qquad 77 \le t \le 300°F\ . \qquad (2)$$

Young's modulus, E, in GPa and t in °C is

$$E = 207.2 - 0.0571t\ , \qquad -198 \le t \le 260°C\ , \qquad (3)$$

and for E in ksi and t in °F:

$$E = 30{,}200 - 4.6t\ , \qquad -325 \le t \le 500°F\ . \qquad (4)$$

Equation (3) for E in SI units was obtained from Equation (4), the latter given in ref. 14. Young's modulus is needed in the calculation of K_0 and K_a.

The HSSI Program has previously tested irradiated crack-arrest specimens using a specially designed and manufactured fixture.[9,10] However, this fixture was too small for the large ANPA specimens, and a larger remote crack-arrest fixture was designed, fabricated, and tested. This fixture, like its predecessor, included a simple specimen hold-down feature that permitted easy wedge extraction during the unloading portion of the test sequence.[15] Prior to its use with irradiated specimens, the operation of the new remote crack-arrest fixture was verified, using unirradiated crack-arrest specimens from the Midland weld WF-70.[16] Crack-arrest testing was performed according to ASTM Test for Determining Plane-Strain Crack-Arrest Fracture Toughness, K_{Ia}, of Ferritic Steels (E 1221-88). During the unirradiated specimen verification tests, thermocouples were tack-welded to the specimens to check the removable temperature indicator that was to be used in the hot cell. A survey of the temperature distribution in the crack-arrest specimens was performed over the temperature range within which the device was to be used and for the two testing positions allowed in ASTM E 1221-88, the "normal" and "inverted" crack-arrest specimen positions. In the so-called normal testing position, the flanges of the split pins that receive the loading wedge sit over the specimen, while in the inverted configuration, the specimen sits over the flanges. The inverted configuration was invented by Irwin* and is described in ref. 17. The inverted position minimizes friction and damping effects and is preferred for attaining crack-arrest toughness values at relatively higher temperatures.[18] The normal position is used in testing at low temperatures to aid in the arrest of the flaw. In the temperature survey, the maximum difference in reading between the removable temperature indicator and any of the seven thermocouples tack-welded to the specimen was less than 2°C. The data obtained from this survey are presented in Appendix A.

2.1 Description of the Irradiated Specimens

Nine crack-arrest specimens of two different sizes were manufactured by ANPA from the ASTM A 508 class 3 forging for the irradiation effects studies. The chemical compositions of the specimens are given in Table 2. Note the very low copper content of this forging, 0.06%, which reflects state-of-the-art steelmaking practice and conforms to a specific requirement issued by ANPA for new reactors. The external dimensions of the three "large" specimens are 25 × 200 × 192 mm, while the dimensions of the six "small" specimens are 12.5 × 100 × 96 mm. The nine

Table 2. Chemical composition of the A 508 class 3 forging used in this study

Element	Composition (wt %)		
	Melt analysis	Product analysis	ASTM A 508 Class 3 specifications
Carbon	0.21	0.18	0.25 max
Manganese	1.41	1.33	1.20 to 1.50
Phosphorus	0.011	0.010	*a*
Sulfur	0.006	0.004	0.025 max
Silicon	0.28	0.27	0.15 to 0.40
Nickel	0.75	0.735	0.40 to 1.0
Chromium	0.10	0.10	0.25 max
Molybdenum	0.52	0.495	0.45 to 0.60
Copper	0.06	0.06	*a*

[a]ASTM A 508-81 Supplementary Requirement S9.1.1: P 0.012 maximum heat and 0.015 maximum product; Cu 0.10 maximum heat and product.

ANPA crack-arrest specimens were encapsulated at Battelle and irradiated in the Ford Nuclear Reactor (FNR) at the University of Michigan (irradiation was supervised by Battelle). Details of the irradiation are presented in a report

*A. R. Rosenfield, Rosenfield and Rosenfield, Columbus, Ohio, telephone conversation with S. K. Iskander, Oak Ridge National Laboratory, Oak Ridge, Tennessee, October 14, 1995.

by Marschall et al.* The fluences for the nine specimens varied between approximately 1.8 to 2.7 × 10^{19} nuetrons/ cm^2 (> 1 MeV), and the irradiation temperatures varied from 240 to 280°C.† Following completion of the irradiation, the specimens were shipped from the FNR to ORNL for testing.

A schematic of the geometry of the ANPA specimens is shown in Figure 1, and the dimensions corresponding to the symbols in this figure are given in Table 3. The crack-starter notch was embrittled using a special technique introduced by Milella and pioneered by ENEA.[19] In this special technique, a large current, in the 2- to 3-kA range, is discharged into the crack-arrest specimen notch area to heat, self-quench, and embrittle the material in the vicinity of the crack-tip region. The process is similar to that used for spot welding, but in this case, the crack-arrest specimen is placed between the two spot-welding electrodes. Figure 2 is a photograph, taken through the Kollmorgen periscope, of an irradiated specimen crack-tip region after a test and shows the circular imprint of the "spot-welder electrode," as well as the propagated crack at the bottom of the side grooves.

2.2 Adjustment of the Measured Crack-Mouth Opening Displacement

In the design of the ANPA crack-arrest specimens, the measurement of the CMOD had originally been intended to be performed by a clip gage seated on knife edges located on the front face of the specimen. At ORNL, the CMOD of crack-arrest specimens is measured using clip-gage blocks with conical recesses that receive the conical points of the clip gage. In the case of unirradiated specimens, the clip-gage blocks are attached by driving split pins into slightly undersize holes. If the specimens are to be irradiated, the clip-gage blocks are attached in the same manner as unirradiated specimens, and to minimize the possibility of the clip-gage blocks becoming detached, they are tack-welded to the specimens.

Since ORNL has considerable experience with the clip gages having conical points, after discussions between all interested parties, it was decided to use the ORNL method. Clip-gage blocks were designed, manufactured, and attached remotely to the ANPA specimens. Detailed drawings of the clip-gage blocks are shown in Appendix B, and a perspective view of the clip gage attached to a mounting block is shown in Figure 3. The CMOD measurements were made at distances of 0.29 and 0.27W from the load line (LL) for the small and large specimens, respectively, rather than the 0.25W location prescribed in the crack-arrest standard. According to ASTM E 1221-88, the CMOD should be measured at a distance of X_0 = 0.25W, and on the opposite side of the crack tip from the LL, where W is the nominal width of the specimen, as shown in Figure 4. Hence, the measured CMOD values were greater than those that would have been measured at the recommended distance. To calculate the stress-intensity factors for crack-initiation and crack-arrest, K_0 and K_a, respectively, using the expressions given in ASTM E 1221-88, the measured displacements were adjusted to values that would have been measured at a distance of 0.25W from the LL, using the method described below.

The method to determine the required adjustment uses the experimentally measured CMODs at a distance > 0.25W and those determined analytically by Newman[20] to interpolate for the required CMOD at 0.25W. Newman calculated the crack-line displacements for a crack-line wedge-loaded specimen, the geometry of which corresponds to the ASTM specimen, i.e., one for which 2H/W = 1.2, where 2H is the total specimen height and W is the nominal width. Plane stress conditions and a Poisson's ratio of 0.3 were assumed. The crack-line displacements were calculated by Newman at several locations from the LL. Two of these distances are 0.25 and 0.1576W, where W is the nominal specimen width that corresponds to the distance from the LL to the back face of the specimen. The 0.25W location is the front-face location corresponding to that prescribed in ASTM E 1221-88 Referring to Figure 4, the conical recesses of the clip-gage blocks are located at the distance, X_M, from the LL.

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*C. W. Marschall, W. J. Zielenback, R. W. Tayloe, Jr., and A. R. Rosenfield, *Effects of Fast Neutron Irradiation on the Mechanical Properties of an SA 508 Class 3 Ring Forging*, Battele, Columbus, Ohio, 1995.

†The irradiation temperature and neutron exposure for each specimen will be given together with the measured crack-arrest toughness values in a later section.

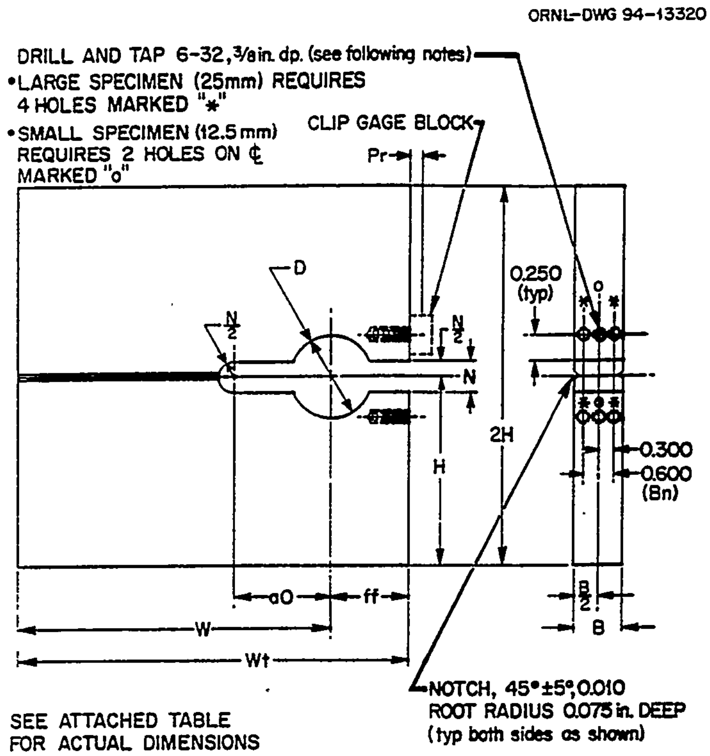

Figure 1. Schematic of the irradiated crack-arrest specimens tested for ANPA. The dimensions corresponding to the symbols for the two specimen sizes are given in Table 3.

Table 3. Nominal dimensions of the two sizes of irradiated crack-arrest specimens from the Italian Agenzia Nazionale per la Protezione dell'Ambiente (symbols correspond to Figure 1)

Dimensions	Small specimen		Large specimen	
	(mm)	(in.)	(mm)	(in.)
Nominal width, W	80.0	3.150	160.0	6.299
Total width, Wt	100.0	3.937	200.0	7.874
Total height, 2H	96.0	3.780	192.0	7.559
Specimen thickness, B	12.5	0.492	25.0	0.984
Thickness between side grooves, minimum, Bn	9.4	0.370	19.4	0.764
Thickness between side grooves, average, Bn	9.8	0.386	19.7	0.776
Thickness between side grooves, average, Bn	9.6	0.378	19.6	0.770
Initial crack depth, a0	28.0	1.102	56.0	2.205
Loading hole diameter, D	21.2	0.834	42.4	1.671
Notch width, N	8.0	0.315	16.0	0.630

Figure 2. Irradiated crack-arrest specimen BK7 showing crack-tip region, circular imprint of the "spot-welder" electrodes, and the propagated crack at the bottom of the side grooves after test completion.

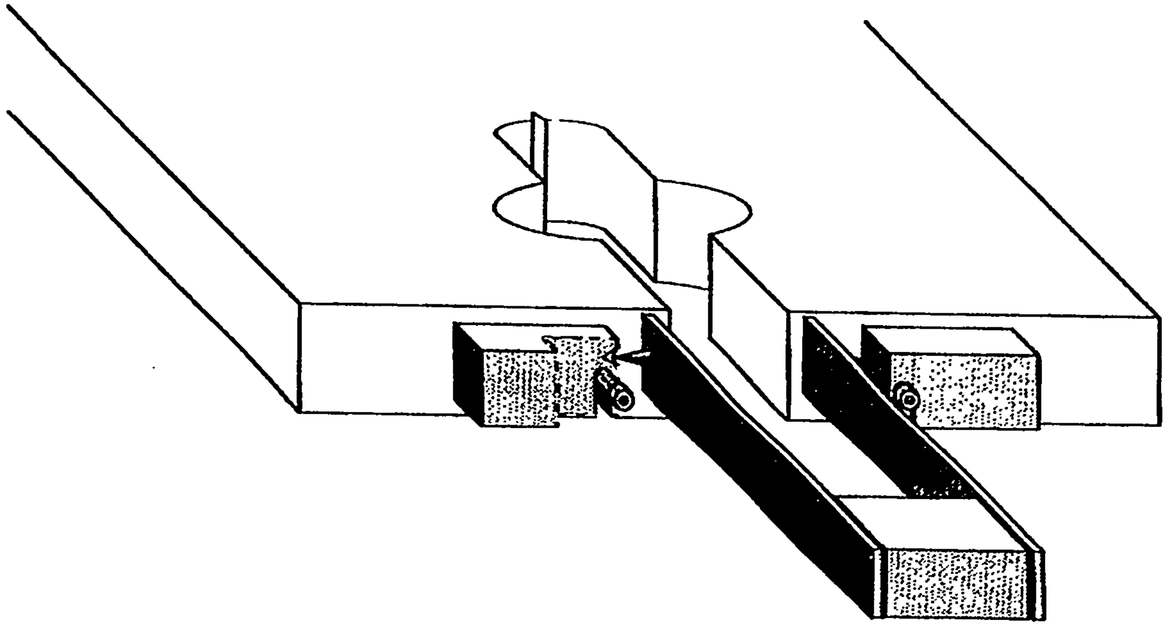

Figure 3. Perspective view of the clip gage attached to mounting blocks.

ORNL-DWG 94-13363

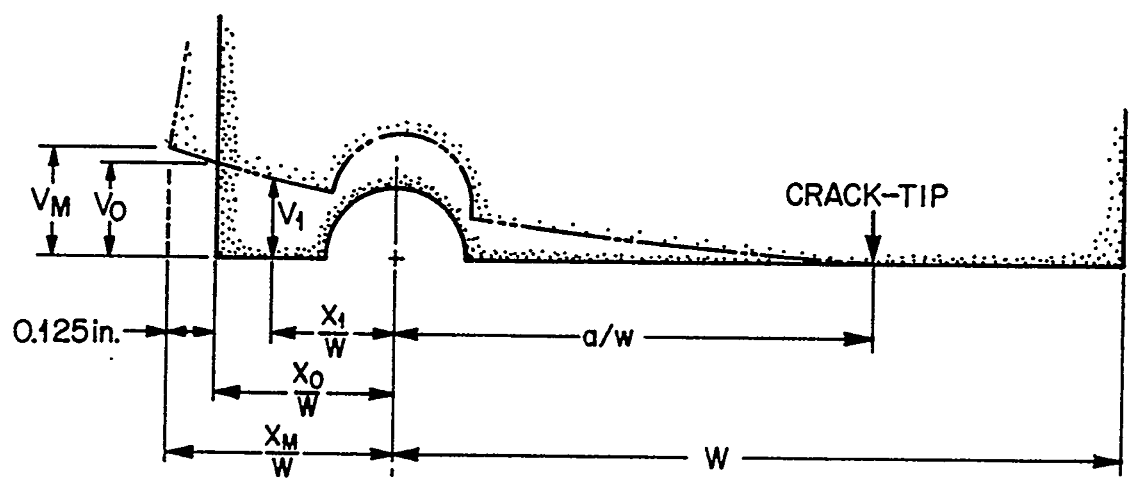

Figure 4. Locations M, 0, and 1 at which one-half the crack-line displacements V_M, V_0, and V_1, respectively, were calculated.

The point at which the CMODs were measured in the ANPA specimens is 3.2 mm (0.125 in.) from the front face of the specimen, and results in CMODs measured at distances of 0.29 and 0.27W for the small and large specimens, respectively, rather than the 0.25W prescribed in ASTM E 1221-88.

It is assumed that the crack-line displacements, at locations ranging from the LL to beyond the front face of the specimen, vary linearly with distance from the LL.* Referring to Figure 4 and recalling that:

$$\frac{X_0}{W} = 0.25 \ , \tag{5}$$

$$\frac{X_1}{W} = 0.1576 \ , \tag{6}$$

and

$$\frac{X_M}{W} = M \ . \tag{7}$$

Then, by using similar triangles, the following relation may be written:

$$\frac{2V_M - 2V_0}{M - 0.25} = \frac{2V_0 - 2V_1}{0.25 - 0.1576} \ , \tag{8}$$

and simplifying the denominator of the right-hand side, the above equation becomes:

$$\frac{2V_M - 2V_0}{M - 0.25} = \frac{2V_0 - 2V_1}{0.0924} \ , \tag{9}$$

where $2V_M$, $2V_0$, and $2V_1$ are the relative crack-face displacements at locations M, 0, and 1, respectively, as indicated in Figure 4. Solving for the front-face displacement V_0, see Equation (9), becomes:

$$2V_0 = \frac{0.0924(2V_M) + (2V_1)(M - 0.25)}{0.0924 + (M - 0.25)} \ . \tag{10}$$

The crack-line displacements given by Newman are normalized with respect to the applied force, P, and are thus the specimen compliances at the respective locations. These compliances, C, are of the form:

$$C = \frac{2VEB}{P} \ , \tag{11}$$

*This is approximately true, as can be seen in Figure 11 of ref. 20, since this part of the specimen is not subjected to any loads.

where B is the specimen thickness, and E is Young's Modulus. Solving for the relative crack-face displacement 2V yields:

$$2V = \frac{CP}{EB} . \qquad (12)$$

Following the method used in ASTM 1221 to account for side grooves, the above expression can be multiplied by a square-root term as follows:

$$2V = \frac{CP}{EB} \sqrt{\frac{B}{B_N}} , \qquad (13)$$

where B_N is the net specimen thickness at the root of the side grooves. The correction factor in Equation (13) can also be of the form (B/B_e) where B_e is from ASTM Standard Test Method for Determining J-R Curves (E 1152-87):

$$B_e = B - \frac{(B - B_N)^2}{B} . \qquad (14)$$

It should be noted that either form gives the same value for the adjusted CMOD, since the compliances are only used to "calibrate" the measured CMOD, but the opening force, P, is about 10% higher when (B/B_e) is used rather than the $\sqrt{(B/B_N)}$.

The specimen compliances at locations 0 and 1, excerpted from Newman's reference, are given in Table 4. To interpolate the compliances at crack lengths other than those tabulated, the following function was regression fit to the tabulated values:

$$C^{0.5} = A + \frac{B}{\ln \frac{a}{W}} , \qquad (15)$$

where A and B are fitting parameters, and a is the crack length. The parameters A and B are given in Table 5, and the resulting fits are shown in Figure 5. The form of Equation (15) was chosen as the simplest from a large number of other trial candidate equations. The degree-of-freedom adjusted coefficient of determination (DOF-r^2) was better than 0.9999.

The opening force, P, applied at the LL, is not directly known from the experiment, since the load recorded during the crack-arrest test is the wedge load and includes various friction forces, such as that between the wedge and the split pins. For each initiation and arrested crack depth, a_0/W and a_a/W, respectively, the force P was previously

Table 4. Normalized crack-line displacements (or compliances) at specimen front face, x = 0.25W, and at x = 0.1576W as a function of crack length (plane stress conditions and Poisson's ratio = 0.3 were assumed)

Normalized crack length (a/W)	Normalized crack-line displacement at x = 0.25W ($2EBV_o/P$)	Normalized crack-line displacement at x = 0.1576W ($2EBV_1/P$)
0.20	12.18	11.15
0.25	15.64	14.26
0.30	19.90	18.14
0.35	25.12	22.80
0.40	31.58	28.64
0.45	39.73	36.05
0.50	50.33	45.70
0.55	64.59	58.73
0.60	84.63	77.07
0.65	114.30	104.20
0.70	161.00	147.20
0.75	240.80	220.60
0.80	392.40	360.20

Source: Excerpted from Table III, J. C. Newman, Jr., NASA Langley Research Center, Hampton, Virginia, *Crack-Opening Displacements in Center-Crack, Compact, and Crack-Line Wedge-Loaded Specimens*, NASA TN D-8268, July 1976.

Table 5. Results of regression fitting Equation (7) to the compliances at positions 0 and 1 for various crack lengths

Position	A	B
0 front face	0.977241836225	–4.195700426660
1 intermediate	0.888013907529	–4.029889833442

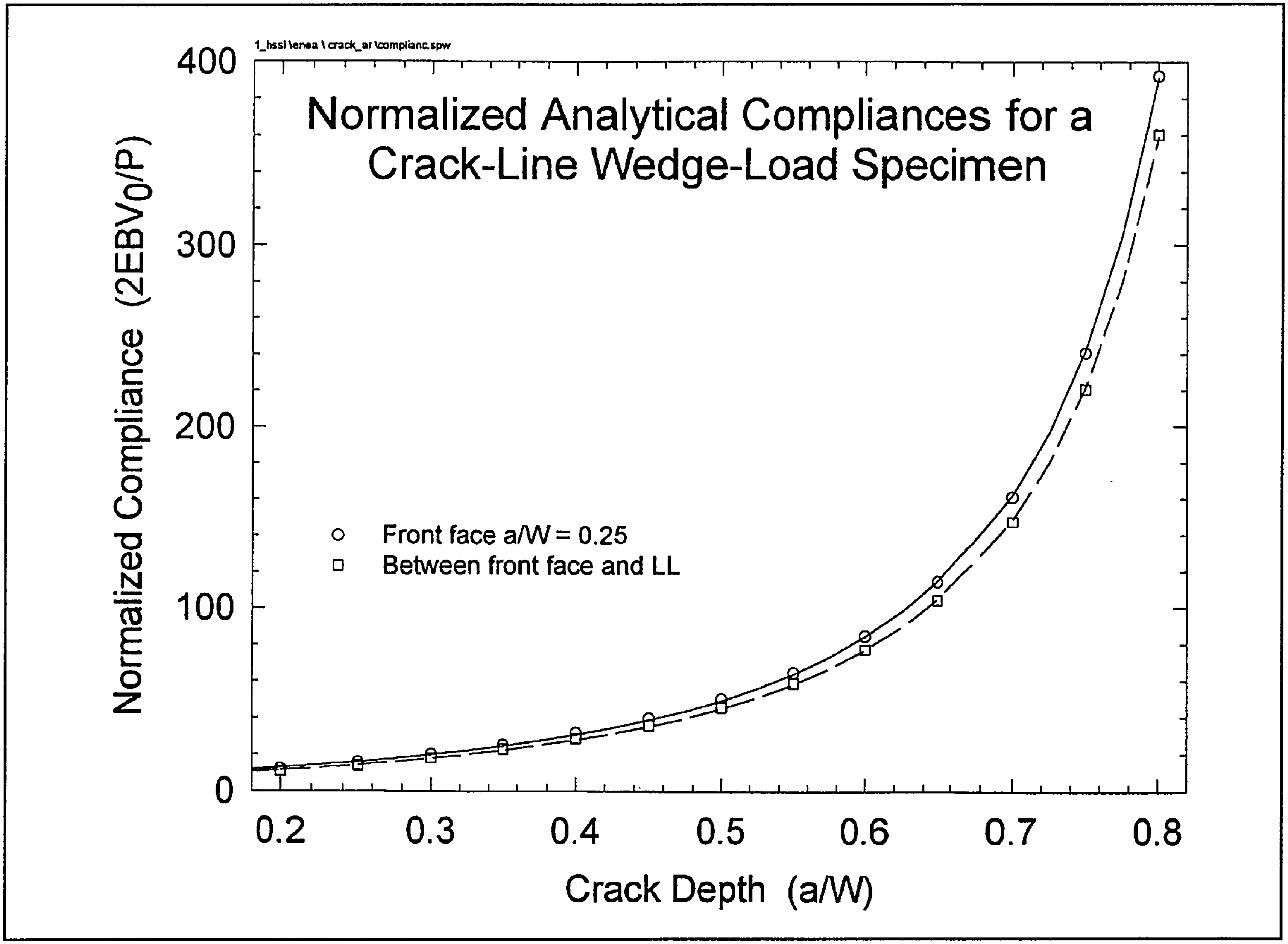

Figure 5. Crack-line wedge-loaded specimen compliances and regression fit of Equation (2.5). *Source*: J. C. Newman, Jr., NASA Langley Research Center, Hampton, Virginia, *Crack-Opening Displacements in Center-Crack, Compact, and Crack-Line Wedge-Loaded Specimens*, NASA TN D-8268, July 1976.

calculated iteratively. However, it can be calculated in the following manner suggested by J. G. Merkle.*
Equation (9) can be rewritten in the following form:

$$0.0924(2V_M) - 0.0924(2V_0) = (M - 0.25)(2V_0 - 2V_1) \ . \qquad (16)$$

Let

$$\alpha = \frac{1}{EB}\sqrt{\frac{B}{B_N}} \ , \qquad (17)$$

then Equation (12) may be written as

$$2V = CP\alpha \ , \qquad (18)$$

or

$$\frac{2V}{\alpha} = CP \ , \qquad (19)$$

and Equation (16), expressed in terms of the measured CMOD, compliances, specimen geometry, and the force P, becomes:

$$\frac{0.0924}{\alpha}\,2V_M - 0.0924C_0P = (M - 0.25)(C_0 - C_1)P \ , \qquad (20)$$

which may be solved for the force P in terms of known quantities:

$$P = \frac{0.0924(2V_M)}{\alpha[(M - 0.25)(C_0 - C_1) + 0.0924C_0]} \ . \qquad (21)$$

Using Equation (18), the front-face CMOD, $2V_0$, may now be expressed in terms of the compliances and the relative distances from the LL as:

$$2V_0 = \frac{0.0924\ C_0\ (2V_M)}{[(M - 0.25)(C_0 - C_1) + 0.0924C_0]} \ . \qquad (22)$$

Note that the $\sqrt{(B/B_N)}$ correction term that accounts for the side grooves does not appear explicitly in Equation (22) but is implicit in $2V_M$. The results of the above calculations to adjust the initiation and arrested crack depths, a_0/W and a_a/W, respectively, are shown in Table 6. It may be seen that the relative difference between the measured values and the adjusted ones is ≤ 4% for the smaller and ≤ 2% for the larger specimens. These adjustments could

*Memorandum, J. G. Merkle, Oak Ridge National Laboratory, to S. K. Iskander, Oak Ridge National Laboratory, August 2, 1995.

Table 6. Details of calculations to adjust the measured initiation and arrest crack-mouth opening displacement (CMOD) values to account for the $X_M/W > 0.25W$ location at which they were measured

Specimen	a_0/W, a_a/W	C_0	C_1	E (ksi)	Measured CMOD, $2V_M$ or d_0 (mils)	B (in.)	Bn (in.)	X_M/W	P (kips)	$2V_0$ from $2V_M$, M, C_0, C_1 (mils)	$(V_M - V_0)/V_M$ (%)
Initiation											
BK7	0.350	24.722	22.326	29821	33.3	0.492	0.378	0.290	16.633	31.97	4.0
BK8	0.350	24.722	22.326	19821	33.3	0.492	0.378	0.290	16.633	31.97	4.0
BK9	0.350	24.722	22.326	29722	30.1	0.492	0.378	0.290	14.985	28.90	4.0
BK10	0.350	24.722	22.326	29639	33.6	0.492	0.378	0.290	16.680	32.26	4.0
BK11	0.350	24.722	22.326	29556	28.2	0.492	0.378	0.290	13.961	27.08	4.0
BK12	0.350	24.722	22.326	29639	26.5	0.492	0.378	0.290	13.156	25.45	4.0
BK13 retest	0.350	24.739	22.341	29838	80.3	0.984	0.770	0.270	82.610	78.68	2.0
BK16 pop-in	0.350	24.739	22.341	29639	57.2	0.984	0.770	0.270	58.453	56.04	2.0
BK16 final	0.350	24.739	22.341	30053	78.3	0.984	0.770	0.270	81.134	76.72	2.0
BK18	0.350	24.739	22.341	29639	59.0	0.984	0.770	0.270	60.293	57.807	2.0
Arrest											
BK7	0.617	93.155	85.002	29821	34.5	0.492	0.378	0.290	4.584	33.21	3.6
BK8	0.637	105.787	96.593	19821	34.5	0.492	0.378	0.290	4.038	33.22	3.6
BK9	0.593	81.122	73.964	29722	31.4	0.492	0.378	0.290	4.781	30.26	3.6
BK10	0.592	80.532	73.423	29639	35.8	0.492	0.378	0.290	5.479	34.52	3.6
BK11	0.616	92.623	84.514	29556	29.2	0.492	0.378	0.290	3.867	28.10	3.6
BK12	0.629	100.275	91.535	29639	28.3	0.492	0.378	0.290	3.472	27.23	3.6
BK13 retest	0.768	283.663	260.051	29838	88.1	0.984	0.770	0.270	7.923	86.52	1.7
BK16 pop-in	0.678	138.260	126.407	29639	64.0	0.984	0.770	0.270	11.721	62.80	1.8
BK16 final	0.903	1790.906	1648.041	30053	82.8	0.984	0.770	0.270	1.189	81.42	1.7
BK18	0.658	121.239	110.778	29639	66.4	0.984	0.770	0.270	13.877	65.202	1.8

also be estimated by assuming that the rotation point for the specimens is at the tip of the flaw and was approximately the same as those obtained using the above procedure. However, the errors of the latter procedure would have been unknown.

2.3 Crack-Arrest Toughness Values of Unirradiated and Irradiated Specimens

The crack-arrest toughness (K_a) of the unirradiated specimens, which were tested by ANPA from 1986 to 1987, are given in Table 7. The thickness of the specimens used in these unirradiated tests ranged from 12.5 to 50 mm. The test temperatures, which ranged from –20 to 40°C, were also normalized with respect to the reference temperature, RT_{NDT}, of –12.5°C (10°F); both are also given in Table 7. In accordance with Subarticle NB-2330 of the 1986 Edition of ASME *Boiler and Pressure Vessel Code*, Sect. III, RT_{NDT} is the highest of three temperatures: T_{NDT}, $T_{CVN-68J} - 33$, and $T_{LE-89mm} - 33$, where T_{NDT} is the drop weight nil-ductility-transition temperature (DWT-NDT), $T_{CVN-68J}$ is the temperature at which the CVN impact energy is 68 J (50 ft-lb), and $T_{LE-89mm}$ is the temperature at which the CVN lateral expansion (LE) is 0.89 mm (35 mils). The temperatures are in °C, and the CVN specimens must be in the T-L orientation. The RT_{NDT} was determined by Terni, the Italian steel manufacturer that produced the forging. The DWT and crack-arrest specimens were machined from the same region of the forging. The DWT-NDT, T_{NDT}, was determined by Terni to be –12.5°C. Two sets, each set consisting of three T-L orientation CVN specimens, were tested at T_{NDT} + 33°C. The results indicated that the 68-J energy criterion was easily met. The minimum CVN impact energy from all six tests was 124 J, and the average energy of each set was 141 and 132 J, respectively. The LE values for these six specimens are not available. In order to estimate the LE, the CVN impact energy was plotted against the LE from the test results on specimens in the T-L orientation (see Figure 6). It may be seen that at the 124-J energy level the LE is » 0.89 mm. Thus, the 0.89-mm criterion was also met, and the RT_{NDT} is –12.5°C, and was dictated by the DWT test results.

Table 7 also shows which of the five ASTM E 1221-88 validity criteria were fulfilled. These criteria are described in Table 8, and a ratio ≥ 1 in Table 7 indicates that the particular criterion is met. In cases were a criterion fails to meet the ASTM requirements, its closeness to a value of one allows some judgment to be made about the margin with which it failed to meet the respective criterion. This is the first edition of the crack-arrest standard, and the validity criteria may be overly conservative; hence, it is of value to indicate the degree with which all five criteria are met. It is possible that useful data be obtained for a specimen without all five criteria being met. Such was the case with the results of the unirradiated and irradiated crack-arrest tests performed in the Sixth HSSI Series.[9,10] The design of large structural tests was successfully performed using "invalid data."[21] It is interesting to note that all 12 specimens have met the crack-jump length validity criteria D and E. This indicates that the ANPA crack-tip embrittling technique is successful since other crack-starter preparation techniques often produce a tough heat-affected zone that prevents the crack from propagating into the test section.[22]

The unirradiated specimen crack-arrest toughness values, (K_a), have been plotted in Figure 7. In Figure 7, a distinction has been made between K_{Ia} data, which fulfill all five ASTM 1221 validity criteria, and K_a data, which only partially fulfill the validity criteria. It may be seen that no obvious differences between the two are apparent. This is further evidence that the five ASTM E1221 criteria may be overly conservative. The ASME K_{Ia} curve, indexed to an RT_{NDT} = –12.5°C, has also been plotted in Figure 7. The ASME K_{Ia} equation,* in SI units, is:

$$K_{Ia} = 29.4 + 13.675\exp[\,0.0261(T - RT_{NDT})\,]\,, \qquad (23)$$

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*The previous ASME equation was:

$$K_{Ia} = 29.4 + 1.344\exp[\,0.0261(T - RT_{NDT} + 89)\,]\,.$$

The new ASME equation given in the December 31, 1992, addenda of the ASME *Boiler Pressure and Vessel Code* did not change the curve but has simply factored out the constant "89" in the exponent. The equation is based on the one appearing in *WRC Bulletin 175* (August 1972), with NDT replacing RT_{NDT}.

Table 7. Crack-arrest toughness values for <u>unirradiated</u> A 508 class 3 forging material with an $RT_{NDT} = -12.5°C$ (all unirradiated crack-arrest tests conducted by ANPA)

Specimen	Thickness (mm)	Test temperature (°C)	$T - RT_{NDT}$ (°C)	K_a (MPa√m)	Valid according to ASTM E 1221-88 if ≥ 1 for each of the following criteria[a]					Valid for all criteria
					A	B	C	D	E	
BK5	12.5	–20	–7.5	83	0.92[b]	0.62[b]	0.89[b]	2.13	1.40	
BK6	12.5	–20	–7.5	65	0.74[b]	9.81[b]	1.38	2.34	1.47	
BK1	12.5	–19	–6.5	64	0.61[b]	0.68[b]	1.47	2.61	1.54	
A5B	25	–10	2.5	90	1.93	2.21	1.49	1.62	1.90	Yes
A3B	25	18	30.5	145	1.58	0.69[b]	0.57[b]	1.76	1.39	
B5	50	23	35.5	129	1.21	0.68[b]	1.47	2.33	1.59	
A7C	25	24	36.5	128	1.06	0.61[b]	0.74[b]	2.09	1.61	
B2	50	25	37.5	105	0.85	0.71[b]	2.18	2.56	1.49	
B1	50	25	37.5	112	1.34	0.99	1.94	2.19	2.06	Yes
A2B	25	26	38.5	142	1.24	0.57[b]	0.60[b]	2.89	1.63	
B4	50	40	52.5	105	0.98	0.83[b]	2.22	2.43	1.44	
A4B	25	41	53.5	147	1.32	0.57[b]	0.56[b]	1.92	1.20	

[a]See Table 8 for validity criteria.
[b]Invalid.

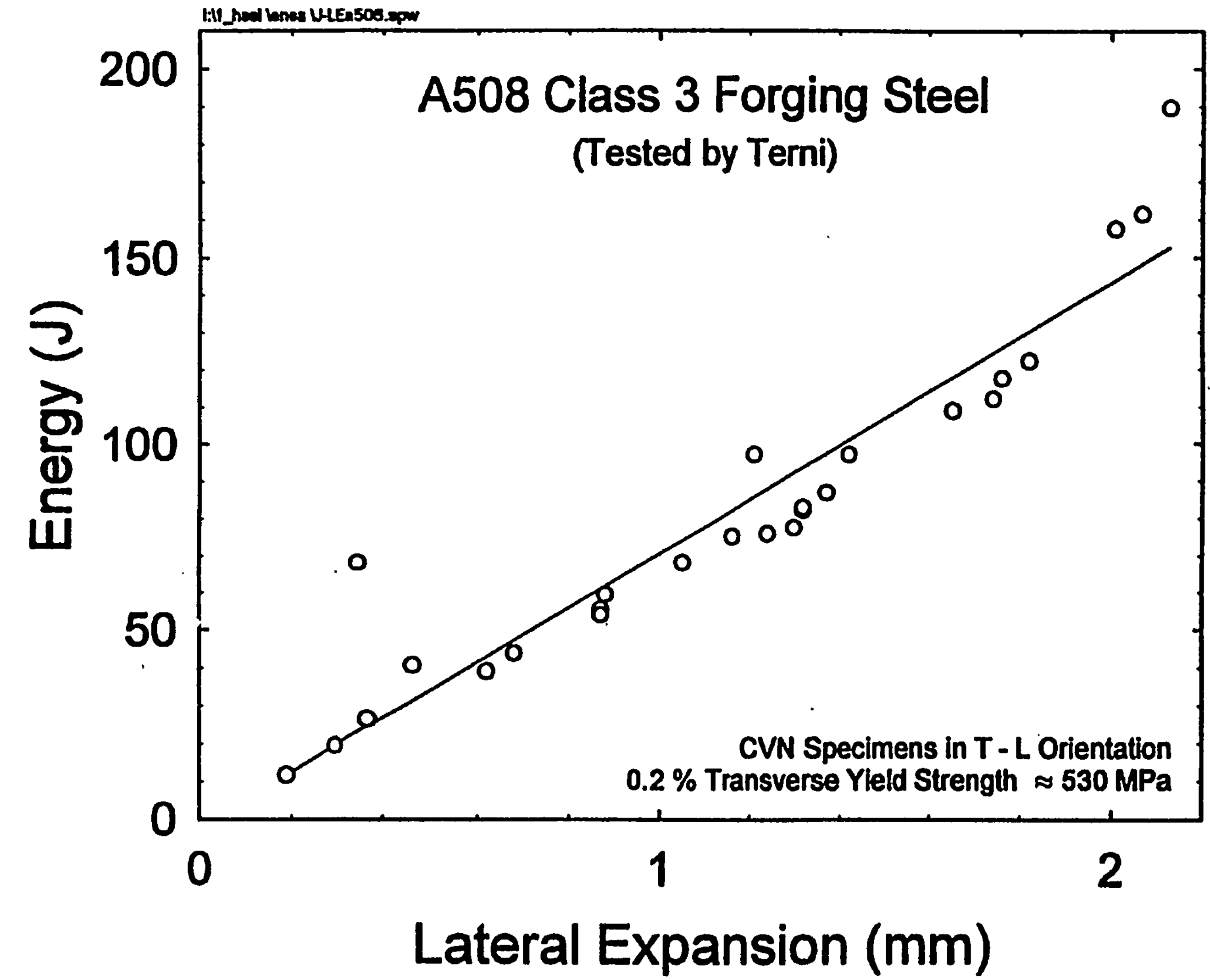

Figure 6. Energy versus lateral expansion of Charpy V-notch in the T-L orientation for A 508 class 3 steel. This figure was used to estimate the lateral expansion at an energy level of 120 J and shows that a 0.89-mm criterion is easily met.

Table 8. Validity criteria (from ASTM E 1221-88) used to ensure that K_a is a linear elastic, plane-strain value (symbols and nomenclature of E 1221-88 have also been adopted)

Feature	Criterion[a]
Unbroken ligament	A. $W - a_a \geq 0.15W$
Unbroken ligament	B. $W - a_a \geq 1.25\ (K_a/\sigma_{Yd})^2$
Thickness	C. $B \geq 1.0\ (K_a/\sigma_{Yd})^2$
Crack jump length	D. $a_a - a_a \geq 2N$
Crack jump length	E. $a_a - a_o \geq (K_o/\sigma_{Yd})^2/2\pi$

[a]Where

- W = nominal width of a crack-arrest specimen,
- a_a = arrested crack length,
- a_o = for duplex specimens, distance from centerline of loading hole to furthest edge of crack-starter hole,
- σ_{Yd} = a formal dynamic yield strength estimate for appropriate loading times at the test temperature [for structural steels, it is assumed to be 205 MPa (30 ksi) greater than σ_{YS}],
- σ_{YS} = static yield strength of the specimen material (or, in the case of a duplex specimen, of the crack-starter section material),
- B = specimen thickness,
- N = slot width,
- K_a = value of the stress-intensity factor shortly after arrest,
- K_o = value of the stress-intensity factor at crack initiation.

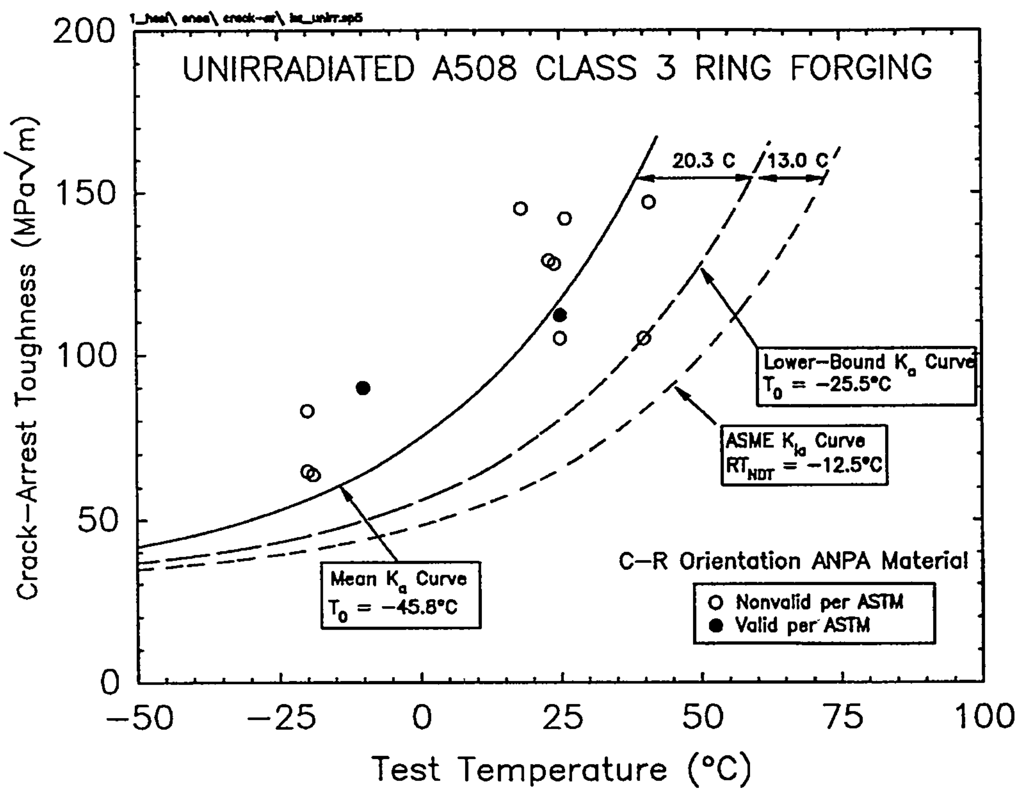

Figure 7. Crack-arrest toughness values (K_a) of <u>unirradiated</u> A 508 class 3 forging material with an $RT_{NDT} = -12.5°C$, together with the lower bound and the ASME K_{Ia} curves. A distinction is made between K_{Ia} values that satisfy all five ASTM E 1221-88 validity criteria that ensure plane-strain conditions are met, and K_a values that do not meet all five criteria.

where K_{Ia} is the crack-arrest toughness in MPa$\sqrt{m}$, and T is the test temperature in °C. The second curve, labeled as the "Mean K_a Curve" on the same figure, is based on the ASME K_{Ia} curve and is of the following form:

$$K_a = 29.4 + 13.675\exp[\,0.0261(T - T_0)\,] \; . \tag{24}$$

Here, T_0 is a parameter* obtained by nonlinear regression through all the data points. Thus, this curve may be interpreted as a mean curve in the least-squares sense. This mean curve will be used to adjust the irradiated data to a common irradiation temperature and fluence, as will be described below. The difference between the T_0 for the irradiated and unirradiated curves may also be used as a measure of the average shift of the crack-arrest toughness, and then compared to the shift at 41-J energy level for CVN specimens. The third curve in Figure 7 is a lower-bound curve that is also based on the ASME K_{Ia} curve and may be thought to be obtained by shifting the ASME curve toward a lower temperature until it passes through the first data value that is encountered. The T_0 value for the curve is actually obtained by calculating it, using the temperature and K_a values for the data point that lies on the lowest bound curve in the following expression:

$$T_0 = T - \frac{\ln \dfrac{(K_a - 29.4)}{13.675}}{0.0261} \; . \tag{25}$$

As mentioned previously, the testing of the irradiated specimens was performed at ORNL and closely coordinated with ANPA and Battelle. The testing of all nine irradiated specimens was performed in the inverted position. The tests were conducted at a sufficiently high temperature that the results should be unaffected by the split-pin configuration.[23] The results of the irradiated tests are given in Table 9 and are presented in the order in which they were tested. Results have not been sorted with respect to test temperature because the test temperature will be adjusted as described below. The toughness of the crack-arrest specimens is plotted in Figure 8 as a function of test temperature. The ASME K_{Ia} curve was also plotted on Figure 8 for an $RT_{NDT} = -1.5$°C that was obtained from the shift at the 41-J energy level for CVN specimens irradiated to 3.2×10^{19} neutrons/cm^2 (> 1 MeV) and an irradiation temperature of 284°C. As may be seen in Table 7, there are significant differences in the irradiation temperatures and fluences between the crack-arrest specimens, and in order to account for these differences and to compare the CVN shift to that of the crack-arrest specimens due to irradiation, an adjustment was made as explained below.

The difference between the test temperature of each specimen and that corresponding to the K_a toughness value on the *unirradiated* ASME K_{Ia} curve is the basis used to adjust the values of the test temperatures to account for the variations in irradiation temperature and irradiation fluence. As may be seen in Figure 8, there are two K_a points either on or below the ASME curve. This is most likely due to the low irradiation temperature for these specimens.

Complete details of the specimen dimensions and pretest and post-test data are given in Appendix C. The X-Y plotter output from these tests and the fracture surfaces of the irradiated specimens are given in Appendix D. The uneven crack front of the arrested crack, as well as the unbroken ligaments, is probably the largest source of error in the calculation of the crack-arrest toughness values. It has been estimated that an error of approximately ±1 to 2% in the measurement of the length of the arrested crack length can lead to an error of 5 to 10% in the calculated K_a value.[9]

*This T_0 should not be confused with the reference temperature used in the ASTM Test Practice (Method) for Fracture Toughness in the Transition Range, Draft 9, May 2, 1995.

Table 9. Results of testing irradiated crack-arrest specimens machined from A 508 class 3 forging material

Specimen	Exposure values		Test temperature (°C)	Stress-intensity factors				ASTM validity criteria[a]				
	Irradiation temperature (°C)	Fluence, > 1 MeV (10^{19} n/cm^2)		Initiation, K_0		Arrest, K_a		A	B	C	D	E
				(ksi√in.)	(MPa√m)	(ksi√in.)	(MPa√m)					
12.5-mm-thick specimens												
BK7	272	2.5	28	151.8	166.8	98.0	107.7	2.56	1.05	0.54[b]	1.33	1.19
BK8	265	2.2	28	151.8	166.8	93.9	103.2	2.42	1.08	0.58[b]	1.44	1.29
BK9	268	2.5	40	136.8	150.3	93.3	102.5	2.71	1.21	0.58[b]	1.22	1.32
BK10	271	2.2	50	152.3	167.4	106.4	116.9	2.72	0.93[b]	0.44[b]	1.21	1.04
BK11	244	1.8	60	127.4	140.0	82.3	90.4	2.56	1.44	0.73[b]	1.33	1.61
BK12	243	1.8	50	120.1	132.0	77.9	85.6	2.58	1.57	0.83[b]	1.39	1.93
25-mm-thick specimens												
BK13 retest	280	2.7	26	261.9	287.8	125.4	137.8	1.55	0.78[b]	0.66[b]	2.09	1.26
BK16 pop-in	280	2.7	50	185.3	203.6	113.2	124.4	2.15	1.29	0.78[b]	1.64	1.90
BK16 final	280	2.7	0	257.2	257.2	70.8	77.8	0.64[b]	1.05	2.12[b]	2.77	1.80
BK18	274	2.3	50	191.1	210.0	122.7	134.8	2.28	1.17	0.67[b]	1.54	1.68

[a]Values ≥ 1, corresponding criterion is valid. See Table 8 for ASTM E 1221-88 validity criteria.
[b]Invalid.

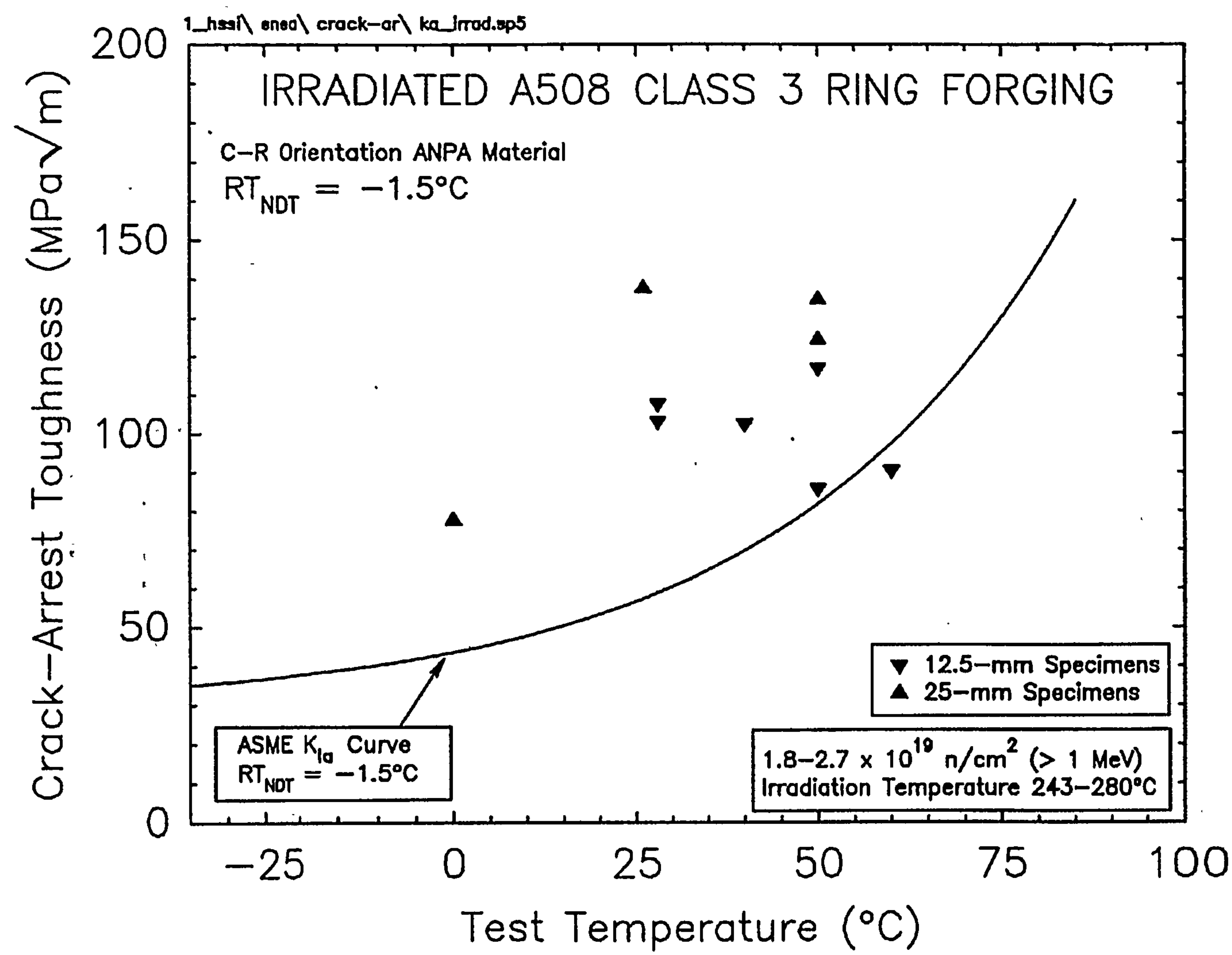

Figure 8. Crack-arrest toughness values (K_a) vs test temperature of irradiated A 508 class 3 forging material with an RT_{NDT} = −1.5°C. The points near or below the ASME K_{Ia} curve are due to the low irradiation temperature of these two specimens compared to the other specimens.

2.4 Adjustment to Account for Differences in Irradiation Temperature and Exposure

To account for the different exposure parameters of each specimen, the test data have been referenced to the fluence and irradiation temperature of the CVN specimens irradiated in the same capsule as the crack-arrest specimens, thus reducing spectrum effects. The fluence for these CVN data is 3.2×10^{19} neutrons/cm^2 (> 1 MeV), and the irradiation temperature is 284°C. The data were "adjusted" using observations from Odette.[24] The test temperature was decreased by 1°C for every 1°C of irradiation temperature less than the reference temperature and vice versa, i.e., an adjustment of ±1°C to the test temperature per ±1°C difference in irradiation temperature.

Odette's observations were also used to adjust the actual fluence to the reference fluence by first determining the temperature shift at the measured K_a level, ΔTK_a, between the test temperature and the mean *unirradiated* K_a curve as given in Equation (24). An adjusted shift was then calculated as follows:

$$\Delta TK'_a = \Delta TK_a \left(\frac{\Phi'}{\Phi}\right)^{0.5} , \qquad (26)$$

where

$\Delta TK'_a$ = shift adjusted to the reference fluence, Φ',
ΔTK_a = shift between the test temperature and the mean unirradiated curve,
Φ' = the reference fluence, 3.2×10^{19} neutrons/cm^2 (> 1 MeV),
Φ = the fluence of the specimen.

The adjusted test temperature, T′, was then calculated as follows:

$$T' = T + (\Delta TK'_a - \Delta TK_a) + (T_{irr} - T_{ref}) , \qquad (27)$$

where

T, = adjusted test temperature,
T = actual test temperature,
T_{irr} = temperature at which the specimen was irradiated,
T_{ref} = reference temperature, 284°C.

The details of the test temperature adjustment calculations are given in Table 10, and the effect of the above adjustments on the distribution of the crack-arrest values with respect to the ASME K_{Ia} curve may be seen in Figure 9. In all cases, the adjusted temperature is less than the actual test temperature. In particular, the two points that were close to or below the ASME K_{Ia} curve are now at about the same relative distance from the curve as the rest of the data. The results of the tests on the nine irradiated crack-arrest specimens have been summarized in Table 11, which shows the adjusted temperature and the crack-arrest fracture toughness K_a.

The fit of a mean curve, see Equation (24), to the ten irradiated and test temperature-adjusted specimen crack-arrest toughness values using the same computer-based method used to fit the unirradiated specimen data was not satisfactory, probably due to the scatter of the data. A fit was obtained by first choosing a trial T_0, then calculating the algebraic sum of the differences in K_a between the specimen toughness and that of the trial mean curve. From the trial T_0s, the value of −37.6°C was chosen since it gave a sum of approximately zero to the desired precision.*

*This is the same process performed by computer codes that implement least-squares regression fitting.

Table 10. Details of the adjustment of testing temperature to a reference temperature of 284°C and a fluence of 3.2×10^{19} neutrons/cm^2 (> 1 MeV) for the irradiated A 508 class 3 forging crack-arrest specimens

Specimen	Exposure values		Test temperature, T (°C)	Crack-arrest toughness (MPa√m)	Shift from mean unirradiated curve (C)	Shift adjusted for fluence (C)	Adjustment due to fluence (C)	Adjustment due to irradiation temperature (C)	Adjusted shift (C)	Adjusted test temperature, T (°C)
	Irradiation temperature (°C)	Fluence, > 1 MeV (10^{19} n/cm^2)								
BK7	272	2.5	28	107.7	7.14	8.08	0.94	−12.0	−11.1	16.9
BK8	265	2.2	28	103.2	9.41	11.35	1.94	−19.0	−17.1	10.9
BK9	268	2.5	40	102.5	21.78	24.64	2.86	−16.0	−13.1	26.9
BK10	271	2.2	50	116.9	24.89	30.01	5.13	−13.0	−7.9	42.1
BK11	244	1.8	60	90.4	48.71	64.94	16.24	−40.0	−23.8	36.2
BK12	243	1.8	50	85.6	41.85	55.80	13.95	−41.0	−27.1	22.9
BK13 retest	280	2.7	26	137.8	−7.32	−7.97	0.65	−4.0	−3.4	22.6
BK16 pop-in	280	2.7	50	124.4	21.74	23.66	1.93	−4.0	−2.1	47.9
BK final	280	2.7	0	77.8	−2.43	−2.64	0.22	−4.0	−3.8	−3.8
BK18	274	2.3	50	134.8	17.76	20.94	3.19	−10.0	−6.8	43.2

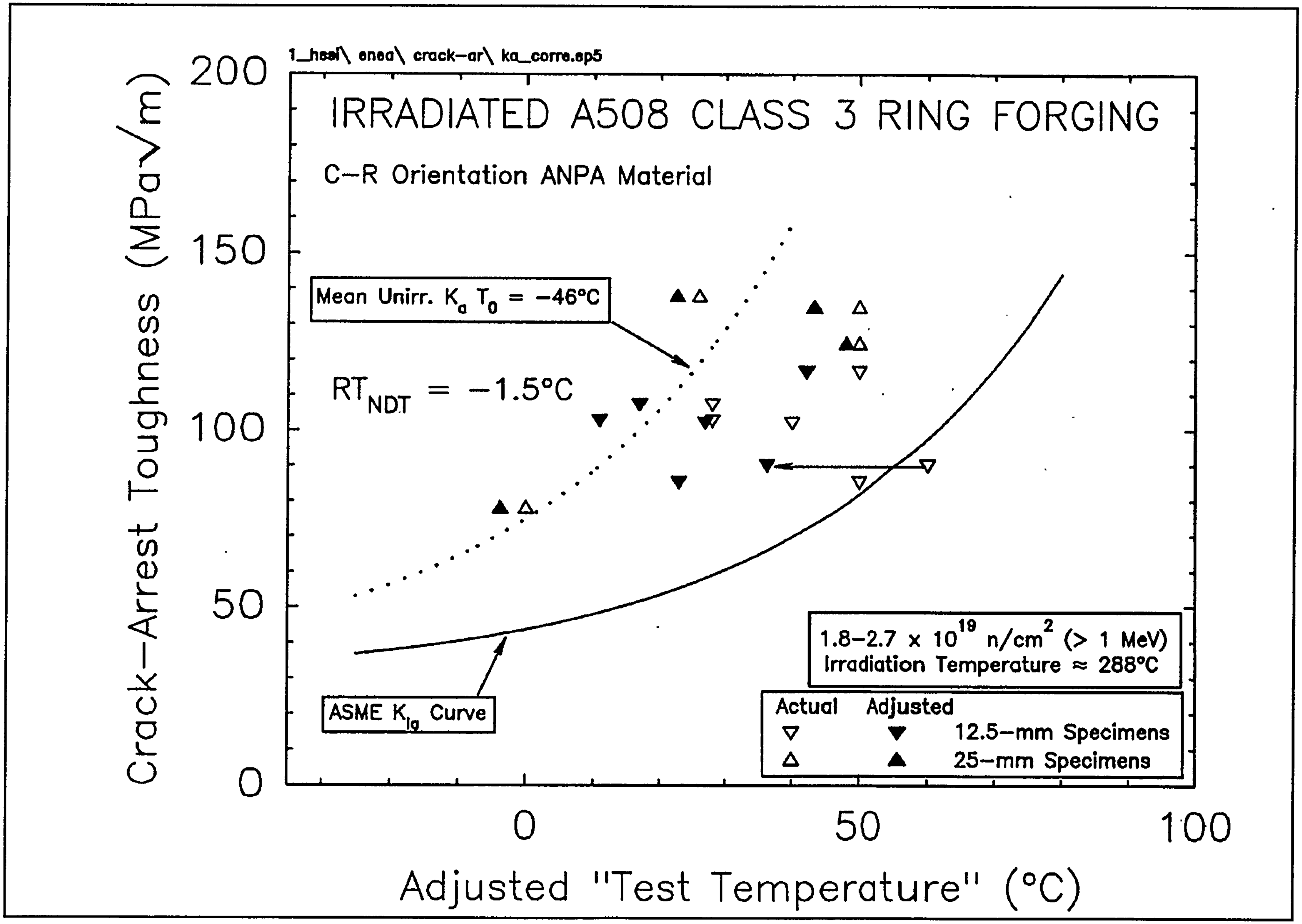

Figure 9. Effect of the test temperature adjustment on the distribution of the crack-arrest toughness with respect to the ASME K_{Ia} curve. The arrow is one example of a typical adjustment.

Table 11. Results of testing irradiated crack-arrest specimens machined from A 508 class 3 forging material

Specimen	Adjusted test temperature (°C)	$T_{adj} - RT_{NDT}$ (C)	Crack-arrest toughness, Ka (MPa√m)	ASTM 1221-88 validity criteria not met[a]
12.5-mm-thick specimens				
BK7	16.9	18.4	107.7	c
BK8	10.9	12.4	103.2	c
BK9	26.9	28.4	102.5	c
BK10	42.1	43.6	116.9	b,c
BK11	36.2	37.7	90.4	c
BK12	22.9	24.4	85.6	c
25-mm-thick specimens				
BK13 retest	22.6	24.1	137.8	b,c
BK16 pop-in	47.9	49.4	124.4	c
BK16 final	–3.8	–2.3	77.8	a
BK18	43.2	44.7	134.8	c

[a]For description of ASTM 1221-88 validity criteria, see Table 8.

The irradiated specimen crack-arrest toughness values plotted as a function of the *adjusted* test temperature, together with the lower-bound, mean curve, and the ASME K_{Ia} curves are shown in Figure 10. The ASME K_{Ia} curve RT_{NDT} has been adjusted by adding to the unirradiated specimen value of RT_{NDT} the amount of the CVN 41-J temperature shift (ΔTT_{41J}) due to neutron irradiation. A lower-bound curve is also included that was derived in the same way as that for the unirradiated specimen curve [see the explanation just before Equation (25)]. It may be seen that the specimen crack-arrest toughness values are now in a reasonable relationship to the ASME K_{Ia} curve than that shown for the unadjusted test temperatures in Figure 8.

The crack-arrest toughness values of the unirradiated and irradiated specimens, as well as the mean and ASME K_{Ia} curves, are given in Figure 11, and show the small shift due to neutron irradiation. The mean, lower-bound, and ASME K_{Ia} curves for the unirradiated and irradiated specimen crack-arrest toughness have been plotted in Figure 12 to show the relationships between the various unirradiated and irradiated specimen curves. The experimental data have been omitted from Figure 12 for purposes of clarity, since they were given in detail in previous figures. A summary of the various T_0 and RT_{NDT} values for the unirradiated and irradiated specimen crack-arrest toughness results is given in Table 12. The shift between the unirradiated and irradiated specimen ASME K_{Ia} curves corresponds to that of the ΔTT_{41J} due to neutron irradiation. It may be seen that the shifts of the lower-bound and mean curves due to neutron irradiation are about the same as the ΔTT_{41J}. This agrees with the results obtained from the HSSI Sixth Irradiation Series.[9,10] A different perspective on the shifts may also be obtained by plotting the unirradiated and irradiated specimen crack-arrest toughness values as a function of ($T - RT_{NDT}$); see Figure 13. The unirradiated and irradiated specimen crack-arrest toughness values seem to form similar sets of data; thus, the CVN ΔTT_{41J} shift seems to agree with the experimental crack-arrest toughness data. It is not possible to draw final conclusion about potential shape changes of the crack-arrest toughness curve from the small amount of data available for the irradiated ANPA material.

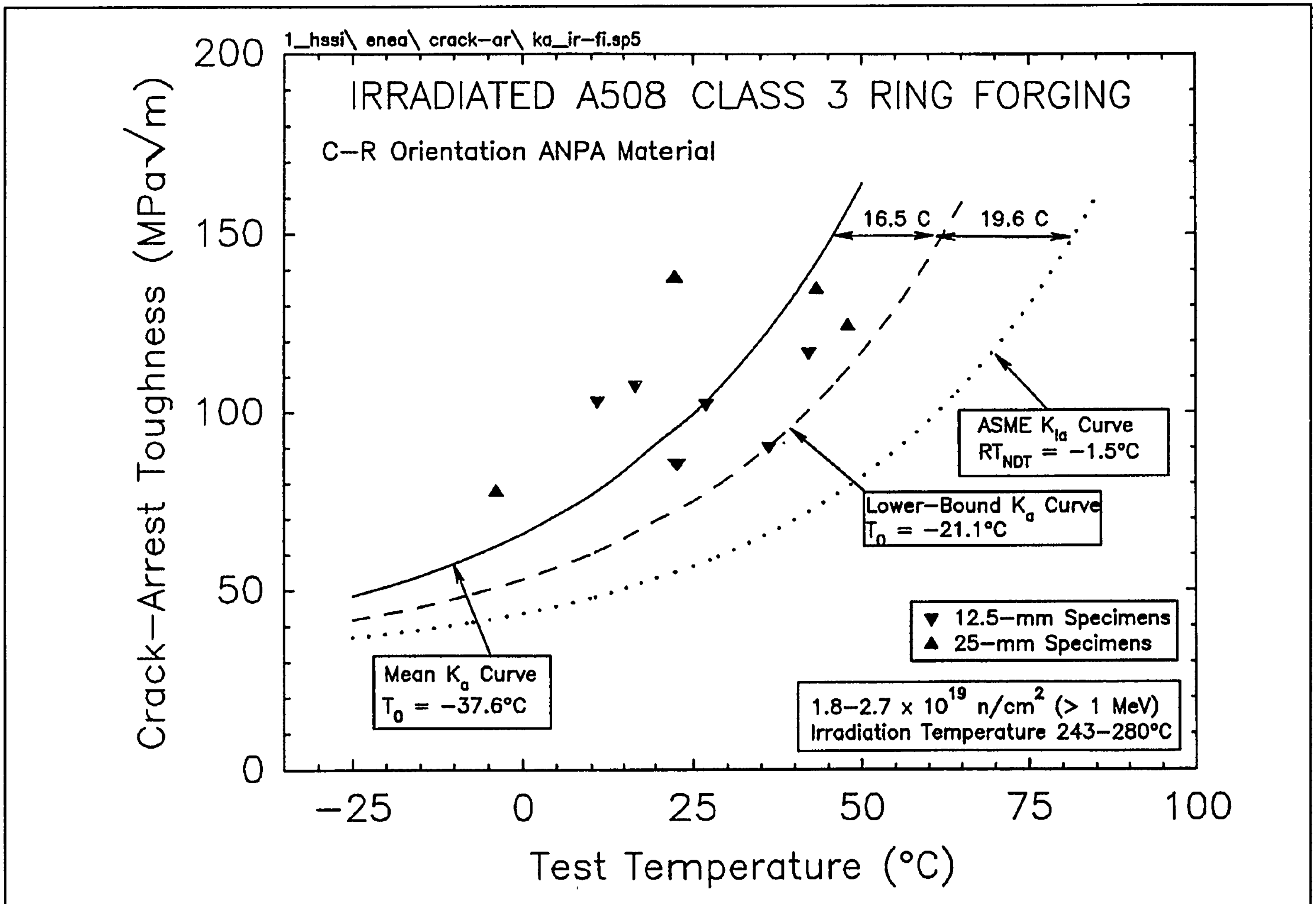

Figure 10. Crack-arrest toughness values (K_a) of irradiated A 508 class 3 forging material with an RT_{NDT} = -1.5°C, plotted as a function of the adjusted test temperature, together with the lower-bound and the ASME K_{Ia} curves.

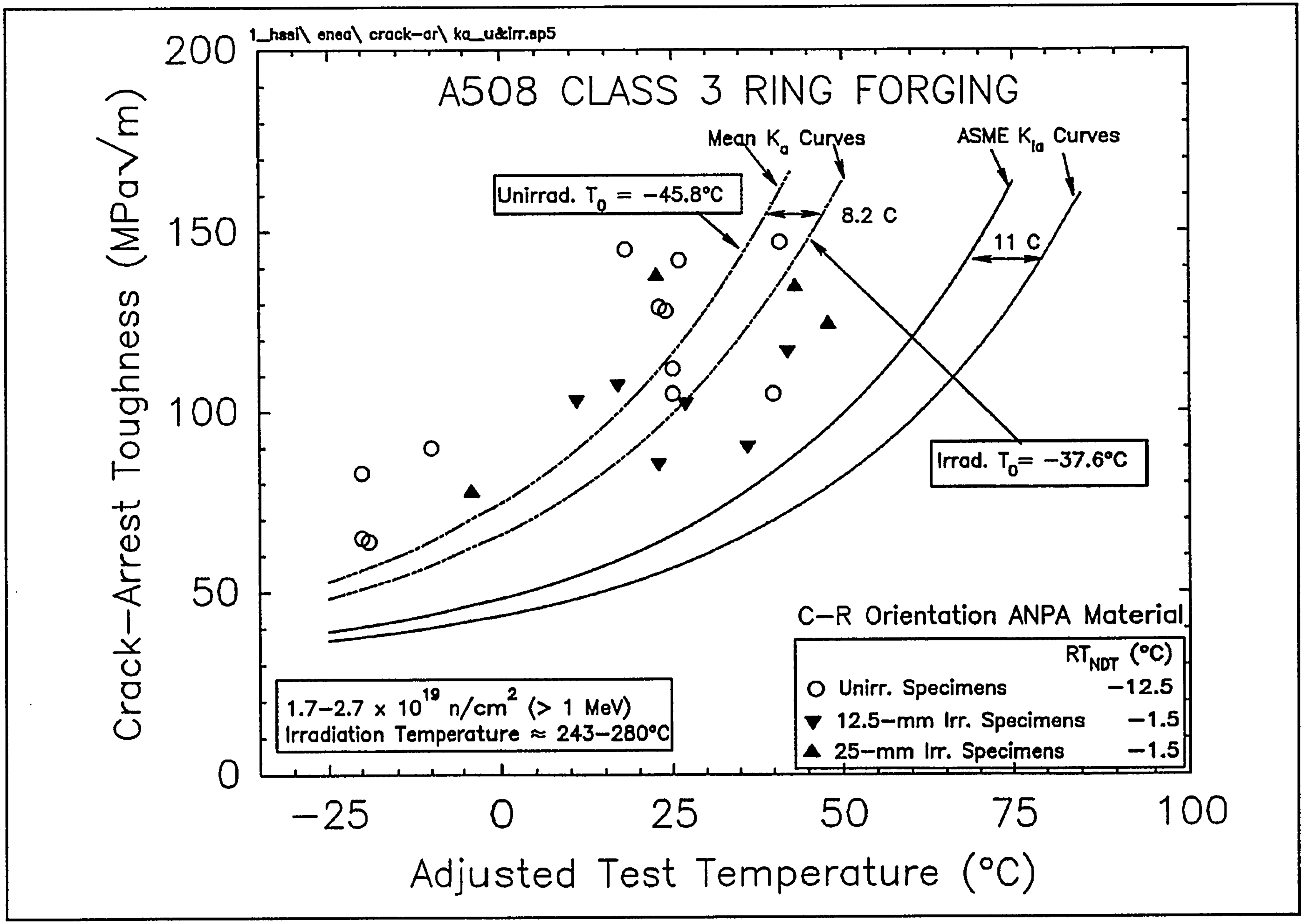

Figure 11. Toughness of unirradiated and irradiated crack-arrest specimens from the ANPA A 508 class 3 forging material.

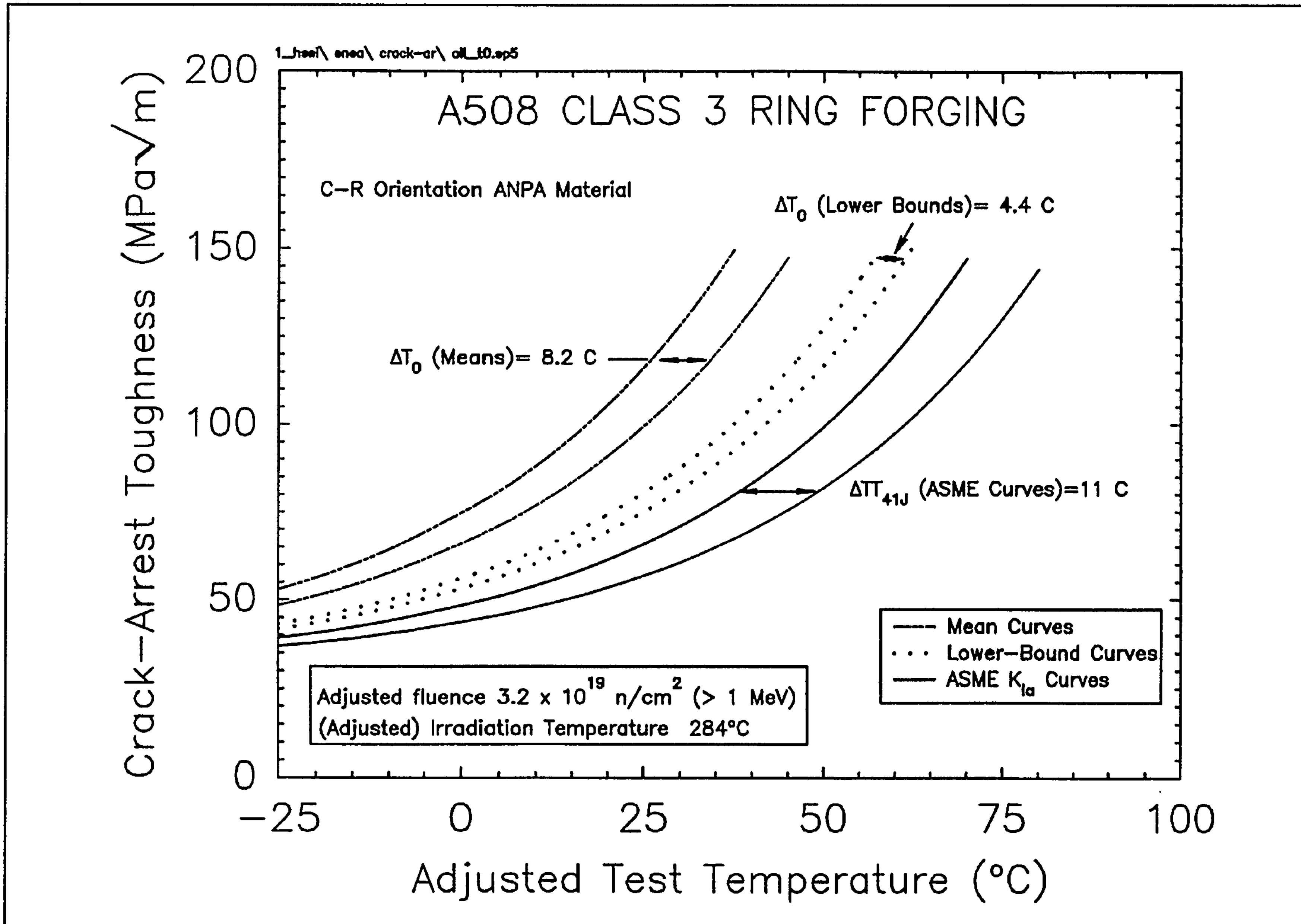

Figure 12. Unirradiated and irradiated crack-arrest toughness lower-bound, mean, and ASME K_{Ia} curves for the ANPA A 508 class 3 forging material.

Table 12. Mean and lower-bound T_0 and RT_{NDT} values derived from unirradiated and irradiated crack-arrest toughness results of ANPA A 508 class 3 forging material (shift of 41-J Charpy V-notch impact energy level was 11 C)

	Unirradiated	Irradiated	Shift (C)
Lower-bound values:			
Temperature (°C)	40.0	36.2	
K_a (MPa√m)	105.0	90.4	
Lower-bound T_0 (°C)[a]	–25.5	–21.1	4.4
Mean T_0 (°C)	–45.8	–37.6	8.2
ASME RT_{NDT} (°C)	–12.5	–1.5	11.0
Difference between mean and data lower-bound curves	20.3	16.5	
Difference between data lower-bound and ASME K_{Ia} curves	13.0	19.6	

[a]Calculated by substituting the lower-bound values of T and K_a in

$$T_0 = T - \frac{\ln \frac{(K_a - 29.4)}{13.675}}{0.0261} .$$

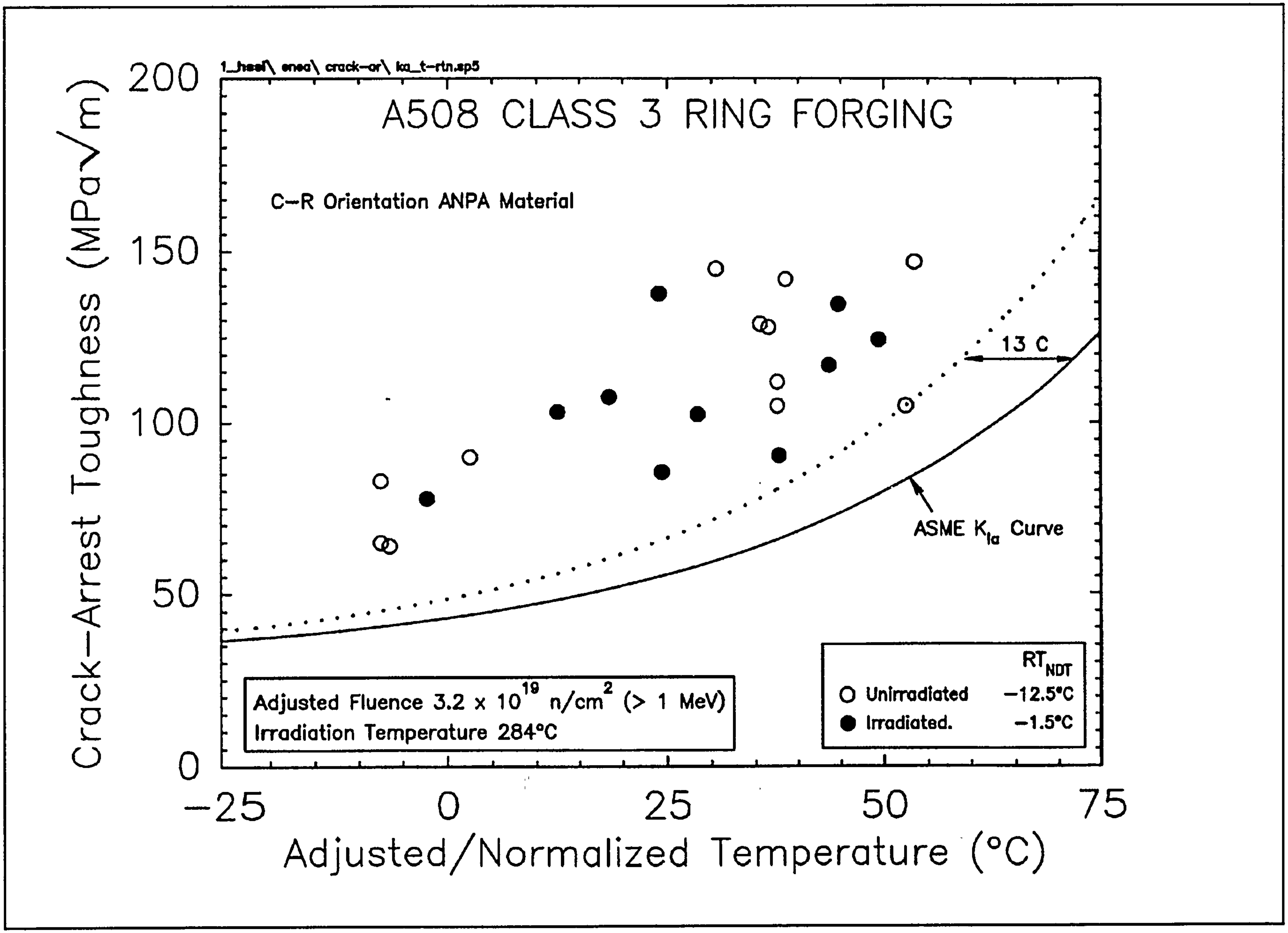

Figure 13. Toughness of unirradiated and irradiated crack-arrest specimens from the ANPA A 508 class 3 forging material, plotted as a function of ($T - RT_{NDT}$).

3. Summary and Conclusions

A special fixture was designed, fabricated, and used successfully for testing nine irradiated crack-arrest specimens fabricated from A 508 class 3 forging material irradiated at 243 to 280°C to a fluence of 1.7 to 2.7 × 10^{19} neutrons/cm^2 (> 1 MeV). Special mounting blocks to receive the ORNL clip gage were designed, and the greater-than-standard CMODs were accounted for. The test temperatures were adjusted to account for the variations in irradiation temperature and fluence in the crack-arrest specimens with respect to the toughness reference values that correspond to those of CVN specimens irradiated at 284°C to a fluence of 3.2 × 10^{19} neutrons/cm^2 (> 1 MeV) in the same capsule as the crack-arrest specimens. This adjustment resulted in a shift to lower effective test temperatures of all the data and, in particular, moved two data points that appeared to lie close to or below the ASME K_{Ia} curve to positions that seemed more reasonable with respect to the remaining data. The shifts of the lower-bound and mean curves due to neutron irradiation are approximately the same as the CVN 41-J temperature shift. It is significant to note that the small (averaging approximately 10°C) shifts in the mean and lower-bound crack-arrest toughness curves confirm that a low copper content in A 508 class 3 forging material can be expected to result in small shifts of the transition toughness curve.

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*Available for purchase from National Technical Information Service, Springfield, VA 22161.

†Available in public technical libraries.

Appendix A

Results of Temperature Survey

Appendix A
Results of Temperature Survey

This appendix contains the detailed results of the temperature survey conducted to ensure that the reading of the removable thermocouple (TC) reflects that of the specimen. The TCs were tack-welded at various locations, designated 1, 2, 3, etc. The TC locations are shown in Figure A-1. The temperature conditioning medium is liquid nitrogen vapor for temperatures below room temperature (RT). At higher than RT, the specimen was heated by both electrically heated cartridges embedded in the fixture and heater elements below and above the specimen. The general procedure was to (1) turn on the heating or cooling medium, (2) take the reading of the removable TC labeled "Probe" in Tables A-1 through A-8, (3) record the various TC readings, and (4) re-record the probe temperature. If the probe temperature had changed significantly from the first reading, then the conditioning medium was turned on again. The time at which the conditoning was started was also recorded as a guide to the time required for the specimen to achieve the recorded temperature distribution.

In general, if the probe temperature remained steady, within 1 or 2°, for about 2 min, this was a good indication that a steady state of temperature was achieved in the specimen. Each of the tables in this appendix gives the results of a temperature distribution in a specimen for a particular nominal temperature and for specimens in both the so-called "normal" and "inverted" positions.

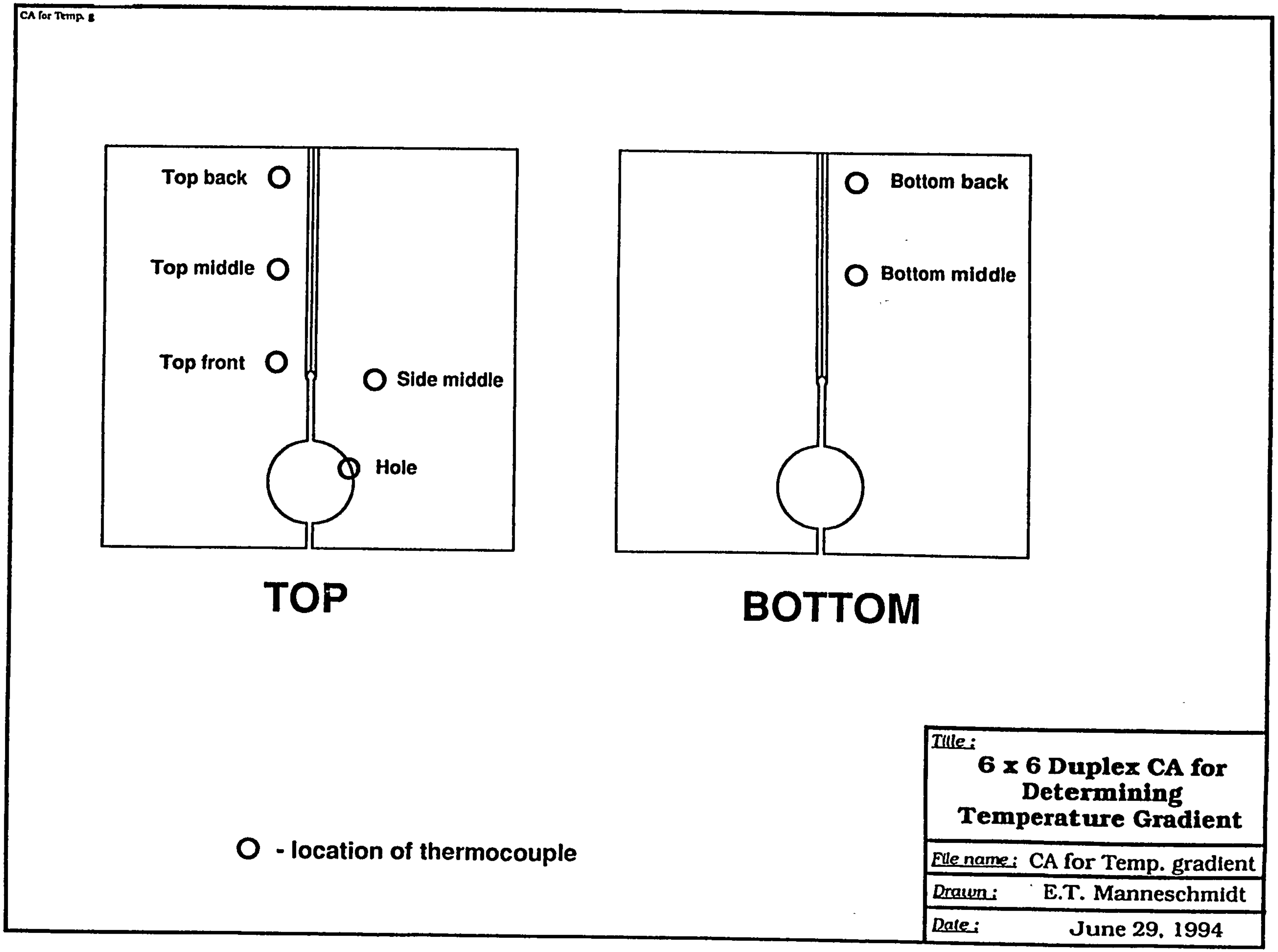

Figure A-1. A 6 x 6 duplex CA for determining temperature gradient.

Table A-1.

CA Fix. N Eval -50°/wedge

Crack Arrest Fixture Temperature Gradient

Thermocouple locations **(TEMP PROB RESEATED)**

1=Top Front 2=Top Middle 3=Top Rear 4=Bottom front **Room Temp. 77°F**

5=Bottom middle 6=Bottom back 7=Side middle 8=Diff. between last probe temp. vs probe with wt.

Target Temp. -50°C / -58°F **R=reseat of probe**

OA Temp & W1	Probe Temp	Thermocouples °F 1	2	3	4	5	6	7	8	Time	Probe Temp
-80	-47.6	-25	-31	-34	-23	-31	-35	-21.8	NA	37	-41.8
-100	-62.0	-41	-46	-50	-39	-47	-50	-38.9	2.3	41	-60.2
-100	-65.4	-47	-51	-55	-45	-52	-55	-45.3	1.7	44	-62.2
-90	-64.0	-51	-55	-58	-49	-56	-59	-49.8	1.2	47	-62.2
-70	-63.7	-53	-57	-60	-51	-58	-60	-52.8	0.7	49	-62.2
-65	-63.0	-55	-58	-60	-52	-59	-61	-54.6	.4 R	51	-62.8
-65	-63.6	-56	-59	-60	-54	-60	-61	-55.8	0.3	35	-62.9
-65	-63.5	-56	-59	-60	-54	-60	-62	-56.9	.2 R	55	-63.3
-65	-63.8	-57	-59	-61	-55	-60	-62	-57.9	-	57	-61.4
W1	-61.9	-56	-58	-59	-54	-60	-60	-57.4	-	58	-63.1
-65	-63.9	-57	-59	-60	-55	-60	-61	-58.4	-	60	-61.1
W1	-61.7	-56	-58	-59	-54	59	-60	-57.8	-0.2	62	-60.6
-62	-61.1	-56	-57	-58	-53	-59	-59	-57.4	-0.1	63	-60.5
-62	-61.0	-55	-57	-58	-53	-58	-59	-57.2	-0.1	65	-60.4
-62	-61.0	-55	-57	-58	-53	-58	-59	-56.9	-	67	-62.9
-65	-63.0	-57	-58	-59	-54	-59	-60	-58.2	R	69	-63.3
-65	-63.9	-57	-59	-60	-55	-60	-60	-58.9	-	71	-63.3
-65	-63.8	-57	-59	-60	-55	-60	-61	-59.3	R	73	-63.4
-65	-64.0	-58	-59	-60	-55	-60	-61	-59.7	-	75	-61.3
-63	-61.8	-57	-58	-58	-54	59	-59	-58.9	-0.1	77	-61.7
-63	-62.1	-56	-58	-58	-54	-59	-59	-58.8	-0.1	79	-61.1
-63	-61.5	-56	-57	-58	-53	-58	-59	-58.4	R	81	-61.0
-63	-60.6	-56	-57	-58	-53	-58	-59	-58.2	NA	83	-60.6
-63	-62.1	-56	-57	-58	-53	-58	-59	-58.2	NA	84	60.6

Comments: OA Temp & W1 - SPECIMEN IN NORMAL POSITION

OA = Off At, the temperature the LN was turned off. Each time the nitrogen was turned off, temperature readings were not taken until 1 minute had elapsed.

W1=Wait 1 minute before recording temperatures. After the first temps. were recorded and before the nitrogen was turned back on another recording was made 60 seconds after the first.

Test wedge WAS in the specimen during temperature evaluations.
Readings were taken from left to right starting and finishing with the "control" thermocouple.

Table A-2.

CA Fix. N Eval 50°/wedge

Crack Arrest Fixture Temperature Gradient

Test Wedge Inserted

Thermocouple locations (TEMP PROB RESEATED)

1=Top Front | 2=Top Middle | 3=Top Rear | 4=Bottom front
5=Bottom middle | 6=Bottom back | 7=Side middle | 8=Hole

Target Temp. 50°C / 122°F

% POWER	OA Temp. & W1	Probe Temp	Thermocouples °F 1	2	3	4	5	6	7	8	Time	Probe Temp
80	90 W1	99.9	93	101	104	96	102	108	93.6	NA	5	103.0
OFF	W5	105.6	101	106	109	102	105	109	99.1	NA	10	105.3
OFF	W1	105.0	101	105	108	101	105	108	99.2	NA	11	104.6
30	W20	110.7	109	111	113	109	111	113	107.4	NA	33	110.8
50	115 W1	118.7	115	119	121	116	120	123	114.0	NA	37	119.5
OFF	W5	119.2	117	120	121	117	120	122	115.3	NA	42	119.0
OFF	W1	118.7	117	119	121	117	119	121	115.0	NA	43	118.4
30	W1	117.8	116	119	120	117	119	121	114.6	NA	44	117.8
30	W3	119.4	118	120	122	119	121	123	116.6	NA	47	119.8
20	W3	122.4	121	124	125	121	124	126	119.1	NA	51	122.4
OFF	W3	122.4	121	123	125	122	123	125	119.3	NA	55	122.1
OFF	W1	121.7	121	123	124	121	123	125	119.0	NA	56	121.5
15	W1	121.0	121	122	123	121	122	124	118.7	NA	57	120.9
15	W1	120.7	120	122	123	121	122	124	118.5	NA	58	120.6
15	W1	120.5	120	122	123	122	122	123	118.5	NA	59	120.5
15	W2	120.6	120	122	123	121	122	123	118.8	NA	61	120.8
15	W2	121.2	120	122	123	121	122	123	119.0	NA	63	121.2
15	W3	121.5	121	122	123	121	122	123	119.3	NA	66	121.5
15	W5	122.0	121	123	124	121	122	124	119.7	NA	71	122.0
10	W15	122.1	120	121	121	120	121	121	118.8	NA	86	122.1
10	W1	219.9	120	121	121	120	121	121	118.6	NA	87	119.9

Comments: OA Temp & W1 - **SPECIMEN IN NORMAL POSITION**

OA = **Off At**, the temperature the LN was turned off. Each time the nitrogen was turned off, temperature readings were not taken until 1 minute had elapsed.

W1=Wait 1 minute before recording temperatures. After the first temps. were recorded and before the nitrogen was turned back on another recording was made 60 seconds after the first.

Readings were taken from left to right starting and finishing with the "Probe" thermocouple.

Table A-3.

CA Fix. N Eval 100°/wedge

Crack Arrest Fixture Temperature Gradient

Test Wedge Inserted **Thermocouple locations** **(TEMP PROB RESEATED)**

1=Top Front 2=Top Middle 3=Top Rear 4=Bottom front

5=Bottom middle 6=Bottom back 7=Side middle 8=See note below

Target Temp. 100°C / 212°F

% POWER	OA Temp. & W1	Probe Temp	Thermocouples °F 1	2	3	4	5	6	7	8	Time	Probe Temp
100%	240											
LN	212 W2	210.3	207	213	215	208	212	215	206.7		44	210.0
	W1	209.5	206	212	214	208	211	214	206.0		45	209.1
20	W1	207.8	205	210	212	206	208	212	204.7		47	207.4
	W2	205.7	204	208	210	205	207	210	203.2	0.3	49	205.5
30	W1	204.8	202	207	209	205	206	208	202.2	R	50	204.7
	W2	204.3	202	206	208	203	205	208	201.5	0.2	52	204.3
	W2	204.4	202	206	208	203	205	208	201.4		54	204.5
50	W2	207.1	203	207	211	204	207	210	202.8		57	207.7
25	W3	210.4	206	211	213	207	210	213	205.3	-0.1	60	210.6
	W2	211.0	207	211	214	208	211	214	206.1	0	62	211.0
	W2	211.1	207	212	214	208	211	214	206.7	0	64	211.1
	W2	211.0	207	212	214	209	211	214	206.9	0	66	211.0
	W2	210.9	208	212	214	209	211	214	207.1	0.1	68	210.9
	W20	210.2	208	211	213	209	211	213	207.5	0.1	88	210.3

Thermocouple #8 shows the change in temp. reading when weight is applied to the probe thermocouple. "R" indicates that the probe was reseated.

Comments: **SPECIMEN IN NORMAL POSITION**

OA = Power Off At temperature. W1=Wait 1 minute before recording temperatures.

Readings were taken from left to right starting and finishing with the "control" thermocouple.

Table A-4.

CA Fix. N Eval 0°/wedge

Crack Arrest Fixture Temperature Gradient

Room Temp. **Thermocouple locations** **(TEMP PROB RESEATED)**

1=Top Front 2=Top Middle 3=Top Rear 4=Bottom front

5=Bottom middle 6=Bottom back 7=Side middle 8=Hole

Target Temp. 0°C / 32°F

OA Temp & W1	Probe Temp	Thermocouples °F 1	2	3	4	5	6	7	8	Time	Probe Temp
32 W1	35.1	44	40	36	44	40	36	47.?	NA	1	35.8
32 W1	33.8	41	38	35	41	38	35	43.2	NA	3	34.3
30 W1	31.5	38	35	33	38	35	33	39.7	NA	5	32.0
30 W1	31.5	36	34	32	37	34	32	38.0	NA	7	31.5
W1	32.4	37	35	33	38	34	33	37.9	NA	8	32.7
30 W1	32.9	35	34	32	37	33	32	36.4	NA	10	31.3
30 W1	32.6	35	33	32	36	33	31	35.5	NA	12	31.0
30 W1	32.8	34	33	32	36	33	31	35.2	NA	14	31.0
29 W1	29.4	34	32	31	35	32	30	34.2	NA	15	29.7
28 W1	28.4	33	31	30	34	31	29	33.2	NA	17	28.7
W1	29.3	33	32	31	34	31	30	33.2	NA	18	29.5
29 W1	29.5	33	32	31	34	31	30	33.1	NA	20	29.7
W1	30.2	33	32	32	35	32	31	33.2	NA	21	30.4
29 W1	29.5	33	32	31	34	31	31	32.8	NA	22	29.8

Comments: OA Temp & W1 - **SPECIMEN IN NORMAL POSITION**

OA = Off At, the temperature the LN was turned off. Each time the nitrogen was turned off, temperature readings were not taken until 1 minute had elapsed.

W1=Wait 1 minute before recording temperatures. After the first temps. were recorded and before the nitrogen was turned back on another recording was made 60 seconds after the first.

Test wedge WAS inserted into the specimen during temperature evaluations.

Readings were taken from left to right starting and finishing with the "control" thermocouple.

Table A-5.

CA Fix. I Eval 100°/wedge

Crack Arrest Fixture Temperature Gradient

2/13/95

Test Wedge Inserted

Thermocouple locations (TEMP PROB RESEATED)

1=Top Front 2=Top Middle 3=Top Rear 4=Bottom front

5=Bottom middle 6=Bottom back 7=Side middle 8=Hole

Target Temp. 100°C / 212°F

% POWER	OA Temp. & W1	Probe Temp	Thermocouples °F 1	2	3	4	5	6	7	8	Time	Probe Temp
100-0	190 W1	212.6	186	206	227	187	204	NA	180.0	152	18	216.6
POWER OFF	OFF W1	220.1	199	217	232	201	215	NA	193.5	167	20	220.1
	W1	219.7	203	218	230	204	216	NA	197.0	172	21	218.4
	W1	218.4	210	218	228	206	217	NA	200.1	178	22	217.9
	W1	217.2	206	217	226	207	216	NA	201.7	182	23	216.7
	W1	215.7	207	217	224	208	215	NA	202.8	185	24	215.1
	W1	214.2	207	216	222	208	215	NA	203.6	188	25	213.7
	W1	212.8	207	215	220	208	214	NA	204.1	190	26	212.4
20% POWER	20% W1	211.1	207	213	218	208	213	NA	204.7	193	28	210.8
	W1	211.4	207	213	217	208	212	NA	205.0	194	29	210.3
	W1	210.0	207	213	216	208	212	NA	205.5	195	30	210.0
	W1	209.9	207	212	216	208	212	NA	205.6	196	31	209.9
	W1	209.8	208	212	216	209	212	NA	205.9	197	31	209.9
	W1	209.9	208	212	216	209	212	NA	206.2	198	32	209.9
	W1	210.0	208	213	216	209	212	NA	206.7	198	34	210.0
	W1	210.2	209	213	216	209	212	NA	207.2	199	35	210.3
15% POWER	15% W2	210.5	209	213	216	210	213	NA	207.8	200	38	210.6
	W1	210.5	209	213	216	200	213	NA	207.9	200	39	210.5
	W1	210.5	209	213	216	200	212	NA	207.9	200	40	210.4
	W1	210.3	209	213	216	200	212	NA	208.1	201	41	210.3
	W1	210.2	209	213	215	200	212	NA	208.1	201	42	210.1
	W1	210.1	209	213	215	200	212	NA	208.1	201	43	210.0
	W1	210.0	209	213	215	200	212	NA	208.1	201	44	209.9
	W1	209.8	209	212	215	200	212	NA	208.0	201	45	209.7
	W10	208.1	208	211	213	208	210	NA	206.9	200	55	208.0
17%	W10	207.4	207	210	212	207	209	NA	206.0	199	65	207.4
20%	W15	210.1	208	212	214	209	211	NA	207.7	200	80	210.1

Comments: SPECIMEN IN INVERTED POSITION

OA = Power Off At temperature. W1=Wait 1 minute before recording temperatures.

Readings were taken from left to right starting and finishing with the "control" thermocouple.

Table A-6.

CA Fix. I Eval -50°

Crack Arrest Fixture Temperature Gradient

Room Temp. 77°F **Thermocouple locations** **(TEMP PROB NOT RESEATED)**

1=Top Front 2=Top Middle 3=Top Rear 4=Bottom front

5=Bottom middle 6=Bottom back 7=Side middle 8=Hole

Target Temp. -50°C / -58°F

OA Temp. & W1	Control Temp	Thermocouples °F 1	2	3	4	5	6	7	8	Time	Control Temp
-58	-54.7	-45	-51	-54	-43	-51	NA	-46.1	-34	9	-52.7
W1	-50.7	-44	-49	-51	-42	-49	NA	-44.9	-35	10	-49.3
-58	-55.9	-48	-52	-55	-46	-53	NA	-49.8	-40	12	-54.2
W1	-52.4	-48	-51	-52	-46	-51	NA	-49.0	-41	13	-51.5
-59	-56.8	-51	-54	-56	-49	-55	NA	-52.0	-45	15	-55.6
W1	-53.9	-50	-53	-53	-48	-53	NA	-51.5	-45	16	
-59	-57.6	-52	-55	-56	-50	-56	NA	-54.0	-48	18	-56.4
W1	-54.8	-52	-53	-54	-49	-54	NA	-53.4	-47	19	-54
-60	-58.1	-54	-56	-57	-51	-57	NA	-55.4	-49	22	-57.2
W1	-55.5	-53	-55	-55	-51	-55	NA	-54.7	-49	23	
-60	-58.4	-54	-56	-57	-52	-57	NA	-56.4	-51	25	-57.7
W1	-56.1	-54	-55	-55	-51	-56	NA	-55.8	-50	26	-55.6
-61	-60.1	-56	-58	-59	-54	-59	NA	-57.8	-52	28	-59.1
W1	-57.8	-55	-57	-57	-53	-57	NA	-57.2	-52	29	-57.3
-61	-60	-56	-58	-58	-54	-59	NA	-58.4	-53	31	-59.2
W1	-58	-55	-57	-57	-53	-57	NA	-57.8	-53	32	-57.4
-61	-60.1	-56	-58	-58	-54	-59	NA	-58.8	-54	34	-59.3
W1	-58	-56	-57	-57	-53	-57	NA	-58.0	-53	35	-57.5
-62	-60.8	-58	-58	-59	-56	-60	NA	-60.2	-55	38	-60.2
W1	-59.1	-57	-57	-57	-54	-58	NA	-59.5	-54	39	-58.5
-62	-61.4	-57	-59	-59	-55	-60	NA	-59.9	-55	42	-60.7
W1	-59.1	-57	-57	-57	-54	-58	NA	-59.4	-55	43	-58.5
-62	-61.4	-58	-59	-59	-55	-60	NA	-60.4	-55	45	-60.7
W1	-59.1	-57	-58	-58	-54	-59	NA	-59.8	-55	46	-59

Comments: OA Temp & W1 - SPECIMEN IN INVERTED POSITION

OA = Off At, the temperature the LN was turned off. Each time the nitrogen was turned off, temperature readings were not taken until 1 minute had elapsed.

W1=Wait 1 minute before recording temperatures. After the first temps. were recorded and before the nitrogen was turned back on another recording was made 60 seconds after the first.

Test wedge WAS NOT inserted into the specimen during temperature evaluations.

Readings were taken from left to right starting and finishing with the "control" thermocouple.

Table A-7.

CA Fix. I Eval 0°

Crack Arrest Fixture Temperature Gradient

Room Temp. 77°F **Thermocouple locations** **(TEMP PROB NOT RESEATED)**

1=Top Front 2=Top Middle 3=Top Rear 4=Bottom front

5=Bottom middle 6=Bottom back 7=Side middle 8=Hole

Target Temp. 0°C / 32°F

OA Temp & W1	Control Temp	Thermocouples °F 1	2	3	4	5	6	7	8	Time	Control Temp
31.5	31.9	35	33	32	36	33	NA	34.8	38	034	32.1
31.5	31.8	35	33	32	36	33	NA	34.7	37	36	32.0
31.5	31.7	34	33	32	36	33	NA	34.3	37	38	31.8
W1	32.0	35	34	33	36	33	NA	34.4	37	39	32.2
31.5 (W2)	31.9	35	34	33	36	33	NA	34.2	36	42	32.0
31.0	31.7	34	32	32	35	32	NA	33.2	36	44	30.9
W1	31.1	34	33	32	35	32	NA	33.2	36	45	31.3
W1	31.5	34	33	33	35	33	NA	33.4	36	46	31.7
W1	31.9	34	34	34	36	33	NA	33.7	36	47	32.0
30.0	31.3	33	32	32	35	32	NA	32.5	35	51	30.5
W1	31.7	33	32	32	35	32	NA	32.7	35	52	30.9
30.0	31.4	33	32	32	35	32	NA	32.4	34	54	30.4
W1	31.8	33	33	33	35	32	NA	32.6	34	55	31.0
30.0	31.4	33	32	32	35	32	NA	32.2	34	57	30.5
W1	31.8	33	33	33	35	32	NA	32.5	34	58	30.9

Comments: OA Temp & W1 - SPECIMEN IN INVERTED POSITION

OA = **Off At**, the temperature the LN was turned off. Each time the nitrogen was turned off, temperature readings were not taken until 1 minute had elapsed.

W1=Wait 1 minute before recording temperatures. After the first temps. were recorded and before the nitrogen was turned back on another recording was made 60 seconds after the first.

Test wedge WAS NOT inserted into the specimen during temperature evaluations.

Readings were taken from left to right starting and finishing with the "control" thermocouple.

Table A-8.

CA Fix. I Eval -50°/wedge

Crack Arrest Fixture Temperature Gradient

Room Temp. 77°F **Thermocouple locations** **(TEMP PROB RESEATED)**

1=Top Front 2=Top Middle 3=Top Rear 4=Bottom front

5=Bottom middle 6=Bottom back 7=Side middle 8=Hole

Target Temp. -50°C / -58°F

OA Temp & W1	Control Temp	Thermocouples °F 1	2	3	4	5	6	7	8	Time	Control Temp
-62	-57.9	-56	-59	-60	-54	-59	NA	-57.8	-50	52	-55.7
W1	-52.8	-56	-57	-57	-53	-58	NA	6.8	-50	53	-51.3
-62	-58.1	-56	-58	-59	-54	-59	NA	7.9	-51	55	-56.1
W1	-53.0	-55	-57	-57	-53	-58	NA	7.1	-51	56	-51.8
-62	-57.6	-56	-58	-59	-54	-59	NA	8.2	-52	58	-55.7
W1	-53.2	-55	-57	-57	-53	-58	NA	7.5	-52	59	-51.8
-62	-58.9	-57	-59	-59	-55	-60	NA	9.0	-53	63	-56.7
W1	-55.0	-56	-58	-58	-54	-59	NA	8.6	-53	64	-53.3
-62	-58.8	-58	-59	-59	-55	-60	NA	9.8	-54	67	-56.4
W1	-53.4	-57	-58	-58	-55	-59	NA	9.0	-54	68	-52.0
-62	-59.1	-58	-59	-60	-56	-60	NA	60.4	-55	70	-57.0
W1	-53.9	-57	-58	-58	-56	-59	NA	59.6	-54	71	-52.7
-62	-58.9	-58	-60	-60	-56	-61	NA	60.7	-56	74	-57.1
W1	-54.3	-58	-59	-59	-55	-60	NA	0.2	-55	75	-53.2

Comments: OA Temp & W1 - SPECIMEN IN INVERTED POSITION

OA = Off At, the temperature the LN was turned off. Each time the nitrogen was turned off, temperature readings were not taken until 1 minute had elapsed.

W1=Wait 1 minute before recording temperatures. After the first temps. were recorded and before the nitrogen was turned back on another recording was made 60 seconds after the first.

Test wedge WAS in the specimen during temperature evaluations.

Readings were taken from left to right starting and finishing with the "control" thermocouple.

Appendix B

Design Details of Clip-Gage Blocks

Appendix B
Design Details of Clip-Gage Blocks

This appendix gives details about the clip-gage blocks that were designed to be attached remotely to the irradiated crack-arrest specimens. Figures B-1 and B-2 show these blocks and their attachment screws for the small and large specimens, respectively. In the case of the small specimen, the conical recess intended to receive the clip-gage points had to be offset from the centerline of the specimen so as not to interfere with the hole for attaching the block to the specimen. The reduced shank of the socket-head cap screw for the smaller block was also necessitated by dimensional constraints, but it also considerably facilitated the assembly of the blocks. The cap screws for both sizes of clip-gage blocks were made from a high-strength steel and then hardened to minimize the possibility of inadvertently twisting off the head of such a small screw while it is being tightened by the manipulators. After attaching the clip-gage blocks to the specimen and tightening the screws snugly, the assembly was placed flat
on a plane surface and, if necessary, the gage blocks were tapped so that they were in proper alignment on the specimen; then the final tightening of the screws of gage blocks was performed.

The gap between the faces containing the conical recesses on the installed clip-gage blocks is smaller than the distance over the completely compressed clip-gage points. To insert the clip-gage, it was first completely compressed until both arms were in contact, then one of the conical points was inserted. This allowed the other point to be inserted. The depth of the conical recesses and the dimension over the completely compressed clip-gage points were such that even after a crack-mouth opening displacement of 2.5 mm (100 mils), the completely compressed gage had to be manipulated for removal in the same manner used to insert the gage. The purpose of this design is to minimize the probability of the clip-gage jumping out of the blocks during a sudden crack jump, which would make the test useless.

The sequence for attaching the clip-gage block to the small specimens is as follows. The cap screw is first screwed into the specimen until the threaded part is below the front face of the specimen. The U-shaped opening in the clip-gage block is then slipped onto the reduced shank of the cap screw, which is then tightened.

The design of the clip-gage blocks for large specimens was slightly different from that for the small specimens. It was believed that their relatively larger size would make them easier to handle, and two U-openings for the cap screws were thought to be unnecessary. In hindsight, this was a mistake, and such openings would have made their mounting much easier.

To minimize the amount of contaminated waste generated, only a minimum number of clip-gage blocks were placed in the hot cell. This necessitated the removal of these blocks after the handling of the specimen was completed. Incidentally, the blocks were also useful as pickup points for removing the specimen from the pan containing liquid nitrogen and back-putting it into the test machine to break it open to measure the crack jump.

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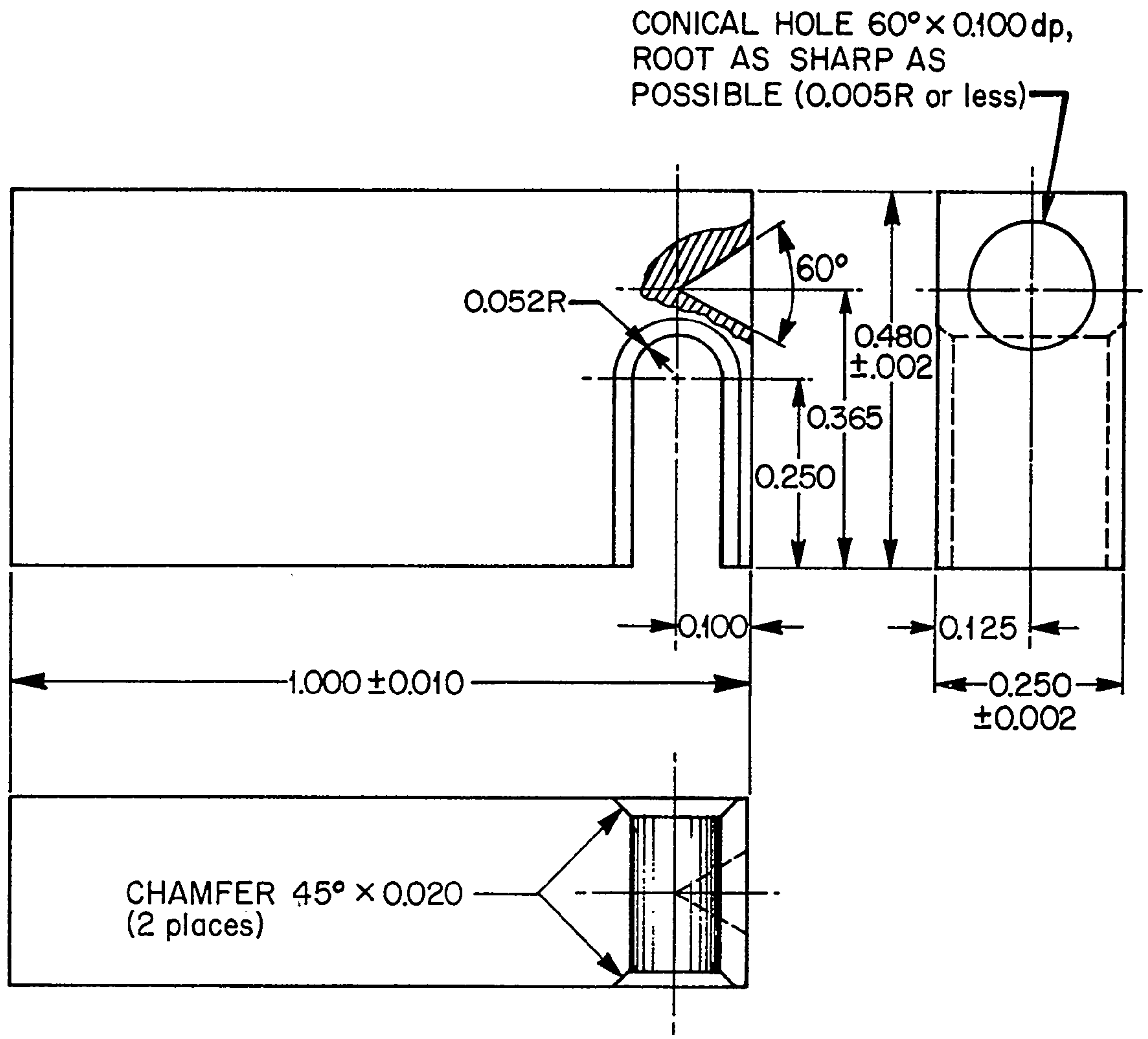


CLIP GAGE BLOCK FOR ½ in. ENEA CRACK-ARREST SPECIMEN

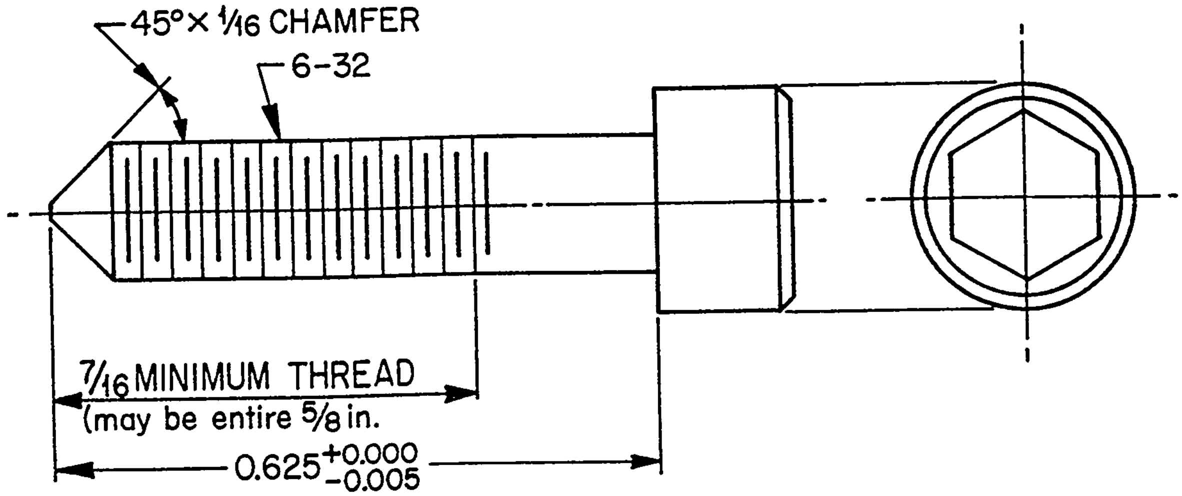
ALL DIMENSIONS IN INCHES

MATERIAL: ANY STRUCTURAL STEEL (A-36 for example)

NUMBER REQUIRED: 4

Figure B-1*(a)*.

ORNL-DWG 94-12365



6-32 ALLEN SOCKET HEAD CAP SCREW

MATERIAL: HARDENED STEEL

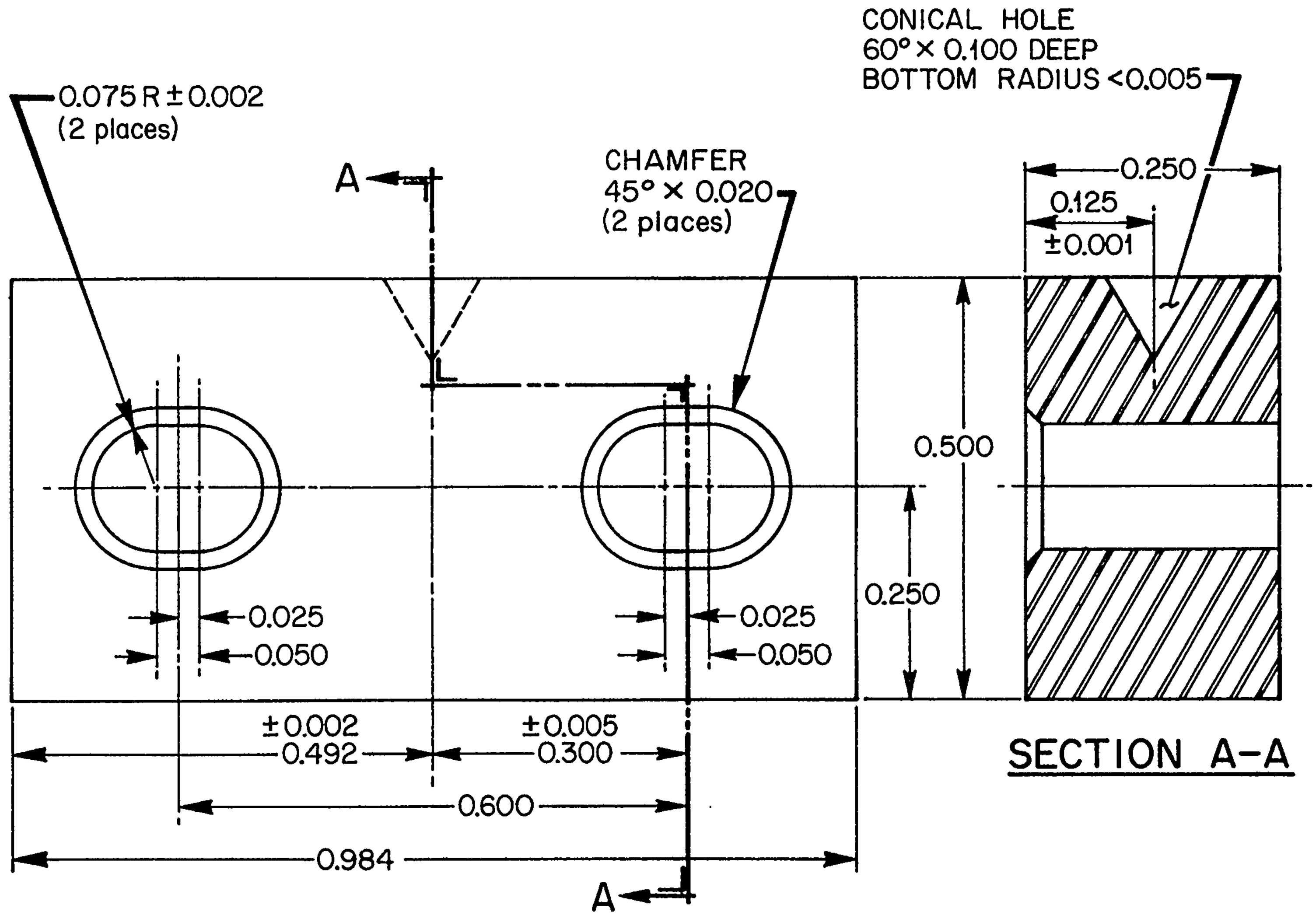
NUMBER REQUIRED: 18

ALL DIMENSIONS IN INCHES

FOR USE WITH 1" ENEA IRRADIATED CRACK-ARREST SPECIMEN CLIP GAGE BLOCKS

Figure B-1(*b*).

ORNL-DWG 94-12366



CLIP GAGE BLOCK FOR 1 in. ENEA SPECIMENS

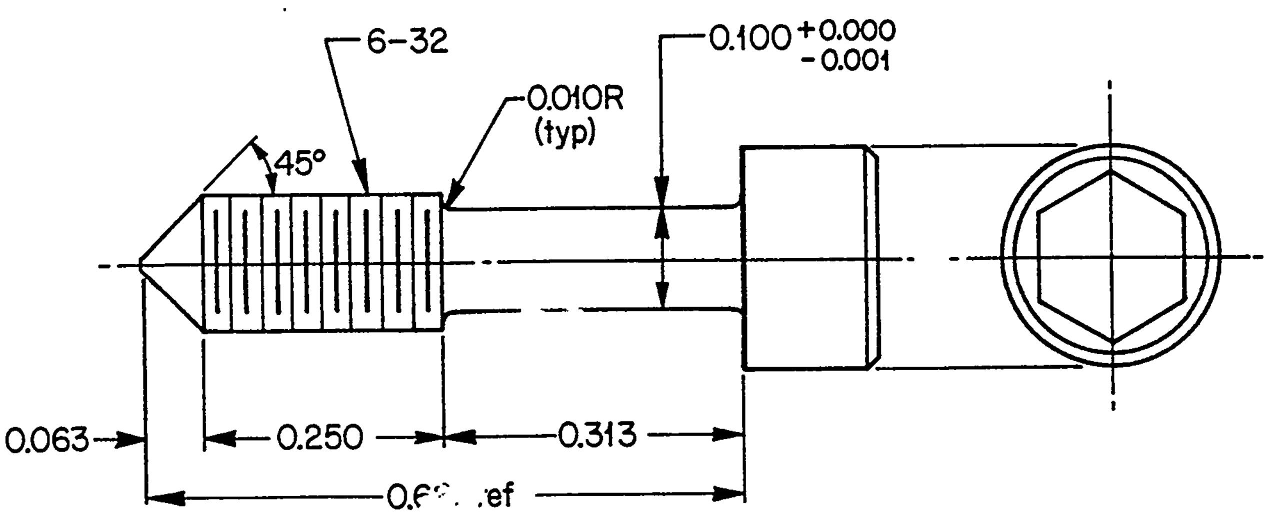
NUMBER REQUIRED: 4

ALL DIMENSIONS IN INCHES

MATERIAL: ANY STRUCTURAL STEEL
(A-36 for example)

Figure B-2(*a*).

ORNL-DWG 94-12364



SPECIAL 6-32 ALLEN SOCKET HEAD CAP SCREW

MATERIAL: HARDENED STEEL

NUMBER REQUIRED: 18

ALL DIMENSIONS IN INCHES

FOR USE WITH 1" ENEA IRRADIATED CRACK-ARREST SPECIMEN CLIP GAGE BLOCKS

Figure B-2(*b*).

Appendix C

Pretest and Post-Test Calculations According to ASTM E 1221-88

Appendix C
Pretest and Post-Test Calculations According to ASTM E 1221-88

The specimen dimensions; the intermediate calculations of crack-mouth opening displacement (CMOD) at initiation and arrest; and the outcome of calculations of the validity criteria according to ASTM E 1221-88, K_0, and K_a, etc., are shown in this appendix in Table C-1 in the form of a spreadsheet. The nomenclature used in the column headings for the specimen dimensions is defined in Figure 1 in the main body of this report. The validity criteria used in Table C-1 and excerpted from ASTM E 1221-88 were given in Table 8 of this report. The BASIC routines for the formulae for calculating the yield strength, Young's modulus, the specimen compliance calibration function, and the maximum CMOD during loading are shown in Table C-2. Tables C-3 and C-4 give other BASIC routines used to adjust the measured CMOD and the test temperature, respectively.

Table C-1. Detailed pre- and post-test data for the ANPA crack-arrest specimens, test results, and validity criteria

MPa_ksi= 6.895 ksi_in_MPa_m_ = 1.099 mm_in= 25.4

	Specimen	Specimen Dimensions											
Spec	Type	B		Bn		2H		Wt		Pr		N	
Id	WE / DX	(in)	(mm)	(in)	(mm)	(in)	(mm)	(in)	(mm)	(in)	(mm)	(in)	(mm)
BK7	WE	0.492	12.50	0.378	9.60	3.780	96.01	3.937	100.00	0.125	3.18	0.315	8.00
BK8	WE	0.492	12.50	0.378	9.60	3.780	96.01	3.937	100.00	0.125	3.18	0.315	8.00
BK9	WE	0.492	12.50	0.378	9.60	3.780	96.01	3.937	100.00	0.125	3.18	0.315	8.00
BK10	WE	0.492	12.50	0.378	9.60	3.780	96.01	3.937	100.00	0.125	3.18	0.315	8.00
BK11	WE	0.492	12.50	0.378	9.60	3.780	96.01	3.937	100.00	0.125	3.18	0.315	8.00
BK12	WE	0.492	12.50	0.378	9.60	3.780	96.01	3.937	100.00	0.125	3.18	0.315	8.00
BK13 *retest*	WE	0.984	25.00	0.770	19.56	7.560	192.02	7.874	200.00	0.125	3.18	0.630	16.00
BK16 *pop-in*	WE	0.984	25.00	0.770	19.56	7.560	192.02	7.874	200.00	0.125	3.18	0.630	16.00
BK16 *final*	WE	0.984	25.00	0.770	19.56	7.560	192.02	7.874	200.00	0.125	3.18	0.630	16.00
BK18	WE	0.984	25.00	0.770	19.56	7.560	192.02	7.874	200.00	0.125	3.18	0.630	16.00

Check on tabular values of yield

Temperature		Yield Strength	
(°C)	(°F)	(ksi)	(MPa)
25	77	72.4	499.2
150	302	65.3	450.2

Check on tabular values of E

Temperature		Young's Modulus	
(°C)	(°F)	(ksi)	(MPa)
21.1	70.0	29.88	206.0

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Table C-1 (continued)

Spec Id	Preliminary Calculations							Dimensional Checks					
	Dist to CL (in)	Hole dia (in)	W (in)	a0 (in)	ff (in)	a0/W	f(a0/W)	ff / W		a0 / W		Bn / B	
BK7	0.787	0.834	3.150	1.102	0.912	0.350	0.2477	0.290	Check!!	0.350	OK	0.768	Check!!
BK8	0.787	0.834	3.150	1.102	0.912	0.350	0.2477	0.290	Check!!	0.350	OK	0.768	Check!!
BK9	0.787	0.834	3.150	1.102	0.912	0.350	0.2477	0.290	Check!!	0.350	OK	0.768	Check!!
BK10	0.787	0.834	3.150	1.102	0.912	0.350	0.2477	0.290	Check!!	0.350	OK	0.768	Check!!
BK11	0.787	0.834	3.150	1.102	0.912	0.350	0.2477	0.290	Check!!	0.350	OK	0.768	Check!!
BK12	0.787	0.834	3.150	1.102	0.912	0.350	0.2477	0.290	Check!!	0.350	OK	0.768	Check!!
BK13 *retest*	1.574	1.671	6.300	2.205	1.699	0.350	0.2477	0.270	Check!!	0.350	OK	0.782	Check!!
BK16 *pop-in*	1.574	1.671	6.300	2.205	1.699	0.350	0.2477	0.270	Check!!	0.350	OK	0.782	Check!!
BK16 *final*	1.574	1.671	6.300	2.205	1.699	0.350	0.2477	0.270	Check!!	0.350	OK	0.782	Check!!
BK18	1.574	1.671	6.300	2.205	1.699	0.350	0.2477	0.270	Check!!	0.350	OK	0.782	Check!!

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Table C-1 (continued)

Spec Id	Test Date	Temperature (°F)	Temperature (°C)	Position (I/N)	Maximum Crack-Mouth-Opening Displacement during recycling — Cycle No: CMODmax & 1	2	3	4	5	6	7	8	9	10	Limit
BK7	26-Jul-94	82	28	I	19	23	28	33	37	42	47	51	56	61	40
BK8	27-Jul-94	82	28	I	19	24	29	33	38	43	48	52	57	62	41
BK9	27-Jul-94	104	40	I	19	24	29	33	38	43	48	52	57	62	41
BK10	28-Jul-94	122	50	I	18	23	27	32	36	41	45	50	54	59	39
BK11	29-Jul-94	140	60	I	18	23	27	32	36	41	45	50	54	59	39
BK12	29-Jul-94	122	50	I	18	23	27	32	36	41	45	50	54	59	39
BK13 *retest*	3-Aug-94	79	26	I	38	48	57	67	76	86	95	105	114	124	83
BK16 *pop-in*	5-Aug-94	122	50	I	37	46	56	65	74	83	93	102	111	120	80
BK16 *final*	5-Aug-94	32	0	I	38	48	57	67	76	86	95	105	114	124	83
BK18	5-Aug-94	122	50	I	37	46	56	65	74	83	93	102	111	120	80

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Table C-1 (continued)

Test Results

Spec Id	Length of Remaining Ligament (in)				CODs (mils)				aa	aa/W	f(aa/W)
	+Bn/4	Mid	-Bn/4	Avg	R1	R3	P4	P5	(in)		
BK7	1.186	1.301	1.138	1.208	0.2	2.3	35.6	35.8	1.942	0.617	0.1539
BK8	0.946	1.447	1.036	1.143	0.2	2.3	35.6	35.8	2.007	0.637	0.1475
BK9	1.221	1.354	1.272	1.282	0.0	0.6	30.7	32.7	1.868	0.593	0.1614
BK10	1.173	1.472	1.213	1.286	0.2	2.0	35.6	38.3	1.864	0.592	0.1618
BK11	1.081	1.426	1.126	1.211	0.0	0.5	28.7	30.1	1.939	0.616	0.1542
BK12	1.046	1.426	1.039	1.170	0.0	0.5	27.0	30.0	1.980	0.629	0.1501
BK13 *retest*	1.437	1.303	1.652	1.464	0.0	14.5	94.8	95.8	4.836	0.768	0.1079
BK16 *pop-in*	2.248	1.691	2.153	2.031	0.0	13.2	70.4	70.7	4.269	0.678	0.1350
BK16 *final*	0.712	0.461	0.651	0.608	0.0	7.0	85.3	87.3	5.692	0.903	0.0642
BK18	2.510	1.403	2.546	2.153	0.0	11.9	70.9	73.8	4.147	0.658	0.1409

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Table C-1 (continued)

Final Calculations RTndt= -1.5 °C

Spec Id	Yield Static (ksi)	Yield Dyn (ksi)	E ksi	Measured *d0* (mils)	Measured *da* (mils)	Adjusted d0 (mils)	Adjusted da (mils)	Stress Intensity Factors K0 (ksi|in)	K0 (MPa|m)	Test Temperature T (°C)	T-RTndt(K)	Ka (ksi|in)	Ka (MPa|m)	Loads Pmax (lb)	Pmin (lb)	Pmin/Pmax
BK7	72.2	102.2	29821	33.3	34.5	32.0	33.2	151.8	166.8	28.0	29.5	98.0	107.7	1625	450	0.28
BK8	72.2	102.2	29821	33.3	34.5	32.0	33.2	151.8	166.8	28.0	29.5	93.9	103.2	1625	450	0.28
BK9	71.5	101.5	29722	30.1	31.4	28.9	30.3	136.8	150.3	40.0	41.5	93.3	102.5	1655	620	0.37
BK10	71.0	101.0	29639	33.6	35.8	32.3	34.5	152.3	167.4	50.0	51.5	106.4	116.9	2590	650	0.25
BK11	70.4	100.4	29556	28.2	29.2	27.1	28.1	127.4	140.0	60.0	61.5	82.3	90.4	1460	600	0.41
BK12	71.0	101.0	29639	26.5	28.3	25.4	27.2	120.1	132.0	50.0	51.5	77.9	85.6	1460	550	0.38
BK13 *retest*	72.3	102.3	29838	80.3	88.1	78.7	86.5	261.9	287.8	26.0	27.5	125.4	137.8	15600	3000	0.19
BK16 *pop-in*	71.0	101.0	29639	57.2	64.0	56.0	62.8	185.3	203.6	50.0	51.5	113.2	124.4	6300	5800	0.92
BK16 *final*	73.8	103.8	30053	78.3	82.8	76.7	81.4	257.2	282.7	0.0	1.5	70.8	77.8	12430	0	0.00
BK18	71.0	101.0	29639	59.0	66.4	57.8	65.2	191.1	210.0	50.0	51.5	122.7	134.8	7960	3400	0.43

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in file: \1_hssi \enea \crack_ar \KA.XLS

Table C-1 (continued)

Validity Criteria

Spec Id	Unbroken Ligament								Thickness				Crack-jump length							
	(A) 0.15W				(B) $1.25(Ka/sigyd)^2$				(C) $1.0(Ka/sigyd)^2$				(D) 2N or 2D				(E) $(K0/sigys)^2/(2*PI)$			
	W-aa	(a)	Valid ?*		W-aa	(b)	Valid ?*		B	(c)	Valid ?*		aa-a0	(d)	Valid ?*		aa-a0	(e)	Valid ?*	
BK7	1.21	0.47	2.56	OK	1.21	1.15	1.05	OK	0.49	0.92	0.54	Fails	0.84	0.63	1.33	OK	0.84	0.70	1.19	OK
BK8	1.14	0.47	2.42	OK	1.14	1.05	1.08	OK	0.49	0.84	0.58	Fails	0.91	0.63	1.44	OK	0.91	0.70	1.29	OK
BK9	1.28	0.47	2.71	OK	1.28	1.06	1.21	OK	0.49	0.84	0.58	Fails	0.77	0.63	1.22	OK	0.77	0.58	1.32	OK
BK10	1.29	0.47	2.72	OK	1.29	1.39	0.93	Fail	0.49	1.11	0.44	Fails	0.76	0.63	1.21	OK	0.76	0.73	1.04	OK
BK11	1.21	0.47	2.56	OK	1.21	0.84	1.44	OK	0.49	0.67	0.73	Fails	0.84	0.63	1.33	OK	0.84	0.52	1.61	OK
BK12	1.17	0.47	2.48	OK	1.17	0.74	1.57	OK	0.49	0.60	0.83	Fails	0.88	0.63	1.39	OK	0.88	0.46	1.93	OK
BK13 *retest*	1.46	0.95	1.55	OK	1.46	1.88	0.78	Fail	0.98	1.50	0.66	Fails	2.63	1.26	2.09	OK	2.63	2.09	1.26	OK
BK16 *pop-in*	2.03	0.95	2.15	OK	2.03	1.57	1.29	OK	0.98	1.26	0.78	Fails	2.06	1.26	1.64	OK	2.06	1.08	1.90	OK
BK16 *final*	0.61	0.95	0.64	Fails	0.61	0.58	1.05	OK	0.98	0.47	2.12	OK	3.49	1.26	2.77	OK	3.49	1.93	1.80	OK
BK18	2.15	0.95	2.28	OK	2.15	1.85	1.17	OK	0.98	1.48	0.67	Fails	1.94	1.26	1.54	OK	1.94	1.15	1.68	OK

*The degree with which the particular validity criterion was met or not may be judged by the closeness to unity of ratio of values in the two previous columns. If the ratio ≥ 1, validity is "OK", otherwise it "Fails"

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Table C-2. Basic routines to calculate yield strength, Young's modulus, ASTM E 1221-88 compliance function, stress-intensity factor, maximum crack-mouth opening displacements during recycling, and temperature conversions

```
Function Yield(T)
' Calculates yield strenght for irradiated ANPA A508 Cl 3 forging steel
'   Uses the straight line between the two data points
'   (25,499) and (150,450), in (degr.C, MPa) after convertion to degr_F and ks.
'   as shown in Table 1 and Eq. (1) of this report
'   Argument for this function is temperature (t) is in Degr. F,
'   and returns yield in ksi
'   Valid for 25 <= t <= 150
'
Yield = 74.83 - 0.03156 * T
End Function

Function E(T)
' Calculates Young's Modulus using an expression in an EPRI report by
'   Server et al. See Eq. (3) of this report for more details.
'   Temperature (t) is in Degr. F, and E is in ksi
'
E = 30200 - 4.6 * T
End Function

Function f(x)
' Function to calculate ASTM 1221-88 para. 9.2, Eq. (5) compliance
'    functionf(x) where x is a/W
f = (2.24 * (1.72 - 0.9 * x + x ^ 2) * Sqr(1 - x)) / _
 (9.85 - 0.17 * x + 11 * x ^ 2)
End Function

Function K_(E, del, fx, Bn_B, W)
' Calculates K. the stress-intensity factors Ko & Ka according
'   to ASTM 1221-88 para. 9.2, using appropriate values for del & fx
'   fx is compliance f(a/W), where a is either ao or aa
'   Uses E in ksi, del in mils, returns K in ksi*sqr(in)
K_ = E * del * 0.001 * fx * Sqr(1 / (Bn_B * W))
End Function

Function CMOD_max(Sigy, W, Bn_B, E, fx)
' Calculate max. CMOD during recycling, according to ASTM-1221
'   para. 8.4.6, Eq. 1
CMOD_max = 1000# * 0.69 * Sigy * W * Sqr(Bn_B) / (E * fx)
End Function

Function DegF_C(T)
' Converts temperature from Degr. F to Degr. C
DegF_C = (T - 32) / 1.8
End Function

Function DegC_F(T)
' Converts temperature from Degr. C to Degr. F
DegC_F = T * 1.8 + 32
End Function
```

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Table C-3. Basic routines to adjust measured crack-mouth opening displacement to front-face

```
Function Compliance(x, a, B)
' Interpolates for Compliance, between tabluar values given by
'   Newman, (see main report), using a function whose parameters were
'   evaluated by non-linear regression.
'
'   x is a measured relative crack length a/W
'   a, B, the parameters resulting from the regression fit.

Compliance = (a + B / Log(x)) ^ 2
End Function


Function V(C, P, E, B, Bn, Iflag)
'   V is the "measured" CMOD Displacement, in mils,
'   from Compliance  [ CP/(EB) ] * Be. See Eq. (8) in the report
'   N.B. Although the Function name is "V", but the value it returns is 2V!
'   not one-half the CMOD V.
'   where Be is the effective thickness in the presence of side grooves
'   If Iflag is 1, B_e is calculated using ASTM 1221-88 thickness correction
'   used in Eq. 4 (para. 9.2)
If Iflag = 1 Then
    B_e = Sqr(B / Bn)
ElseIf Iflag = 2 Then
'   If Iflag is 2, B_e is calculated using ASTM 1152-87 thickness correction
'   in para. 9.2.1
    B_e = B / (B - (B - Bn) ^ 2 / B)
End If
V = ((C * P) / (E * B)) * B_e * 1000#
End Function


Function P(V2m, E, B, Bn, C_0, C_1, M)
'   Calculates the crack opening force in kips
'   V2 is the relative crack-face displacement in mils
'   E = Young's modulus, B = spec. thickness, Bn = net spec. thickness, all in inche
s
'   C_0 and C_1 compliances at the spec. face and at 0.1576W from LL
'   M is XM/W, the normalized location at which the CMOD was measured
alpha = 1 / (E * B) * Sqr(B / Bn)
P = (0.0924 * V2m * 0.001) / (alpha * ((M - 0.25) * (C_0 - C_1) + (0.0924 * C_0)))
End Function


Function V0(V2m, C_0, C_1, M)
'   Calculates the crack face CMOD using closed form derived in report
'   V0 and V2m are the full relative crack-face displacements in mils
'        at front face and measured locations, respectively
'   C_0 and C_1 compliances at the spec. face and at 0.1576W from LL
'   M is XM/W, the normalized location at which the CMOD was measured
V0 = (0.0924 * C_0 * V2m) / ((M - 0.25) * (C_0 - C_1) + (0.0924 * C_0))
End Function
```

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1_hssi \enea \crack-arr \KA.XLS worksheet "Macros for Displ"

Table C-4. Basic routines to adjust test temperature to the reference fluence and temperatures

```
Function Shift(Test_temp, Ka_irr)

'Calculates the unirradiated "temperature" T_eq corresponding
'   to the irradiated Ka_unirr from the mean curve

' TO is the mean value obtained by fitting the
'   unirrad. crack-arrest test results
TO = -46
' Note that in Visual Basic, Log() is the natural logarithm

T_eq = Log((Ka_irr - 29.4) / 13.675) / 0.0261 + TO

Shift = Test_temp - T_eq

End Function


Function Flu_corr(DelT, Ref_flu, Act_flu)

'Corrects for actual fluence irradiation conditons

Flu_corr = DelT * (Ref_flu / Act_flu) ^ 0.5

End Function


Function Adj_flu(Shift_mean, Adj_shift, Actual_flu, Ref_flu)

'Calculates adjustment due to fluence correction
'   In case the shift from mean curve is negative, then the corrected fluence is
'       also negative, see above Flu_corr function, and reference fluence > actual,
'       then the adjustment must be positive

If Ref_flu > Actual_flu Then

    Adj_flu = Abs(Adj_shift - Shift_mean)

    Else

    Adj_flu = Adj_shift - Shift_mean

End If

End Function


Function Temp_corr(Ref_Irr_temp, Irr_temp)

' Corrects for actual temperature irradiation conditons

Temp_corr = (Irr_temp - Ref_Irr_temp)

End Function
```

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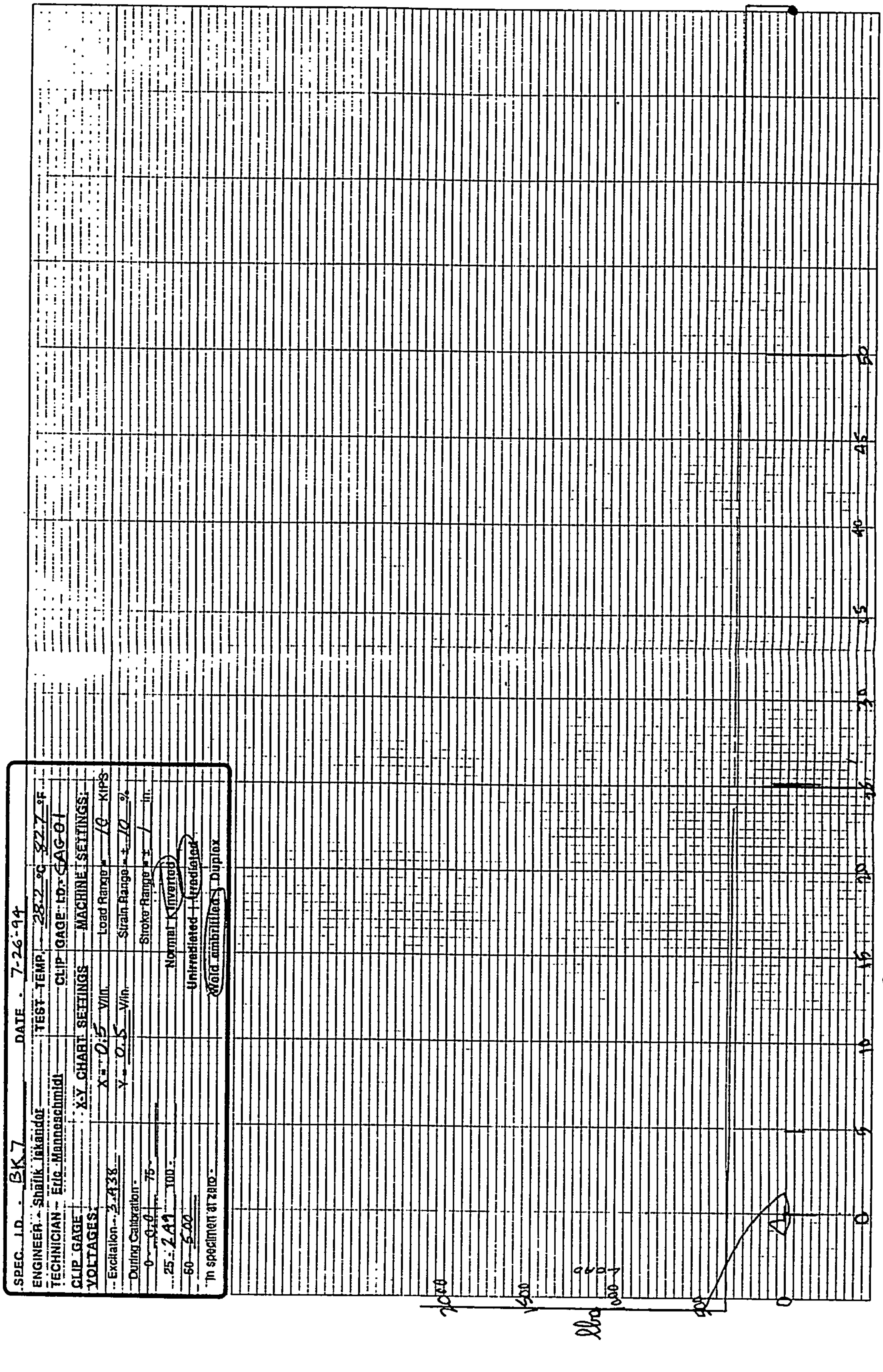
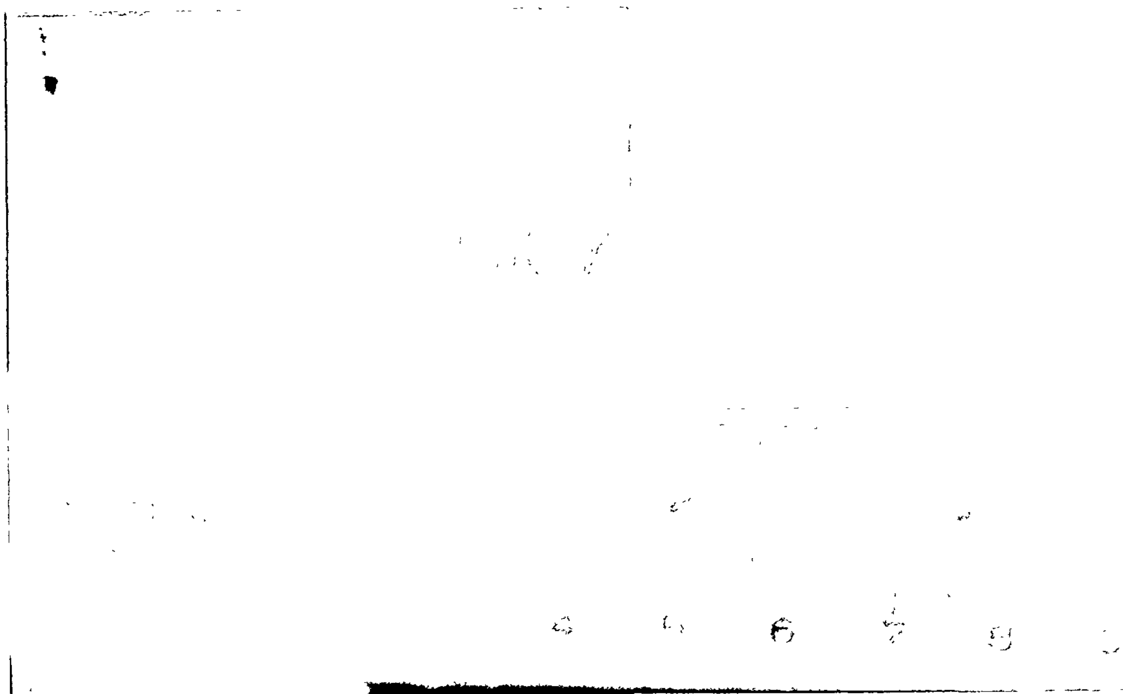
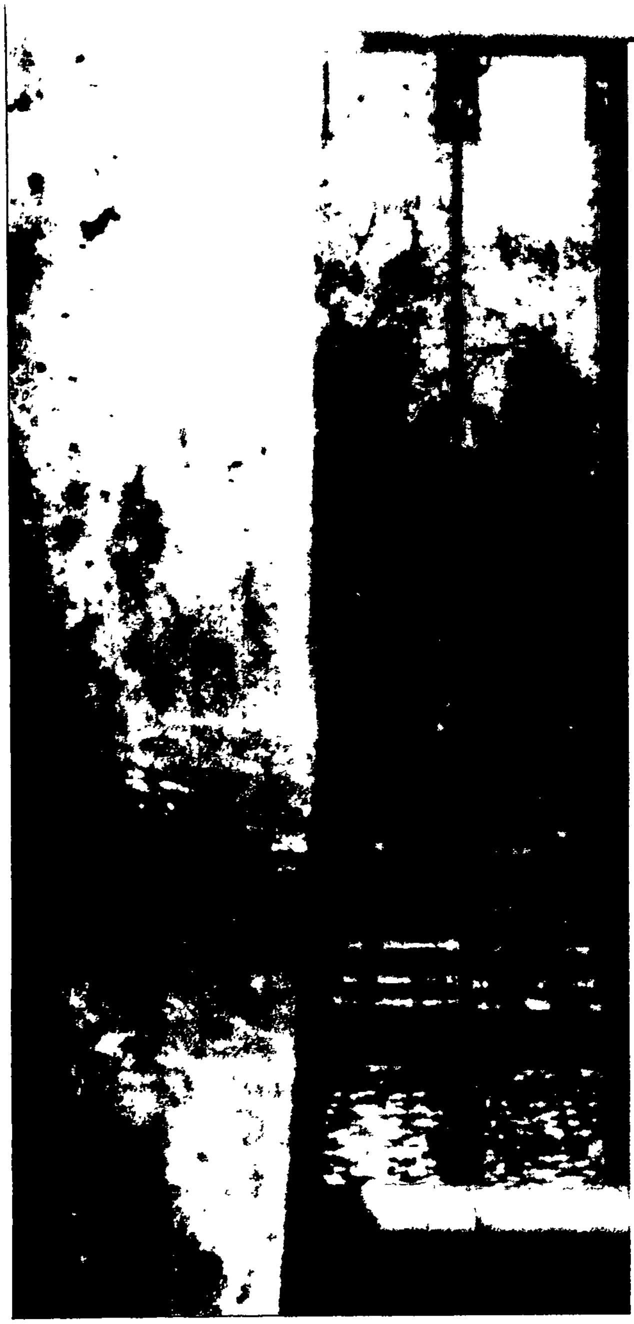
1_hssi \enea \crack-arr \KA.XLS worksheet "Exp Adj Macros"

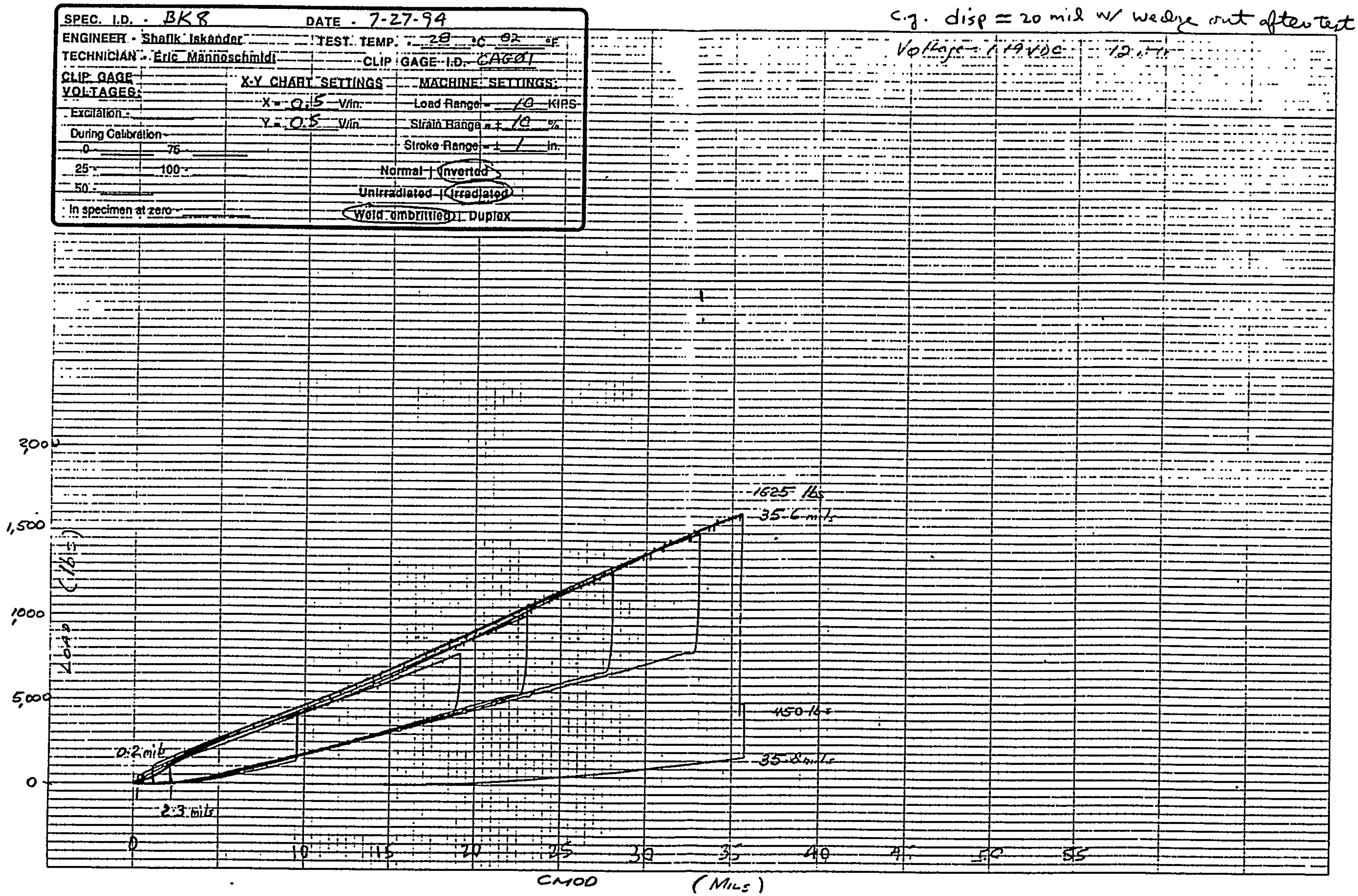
Appendix D

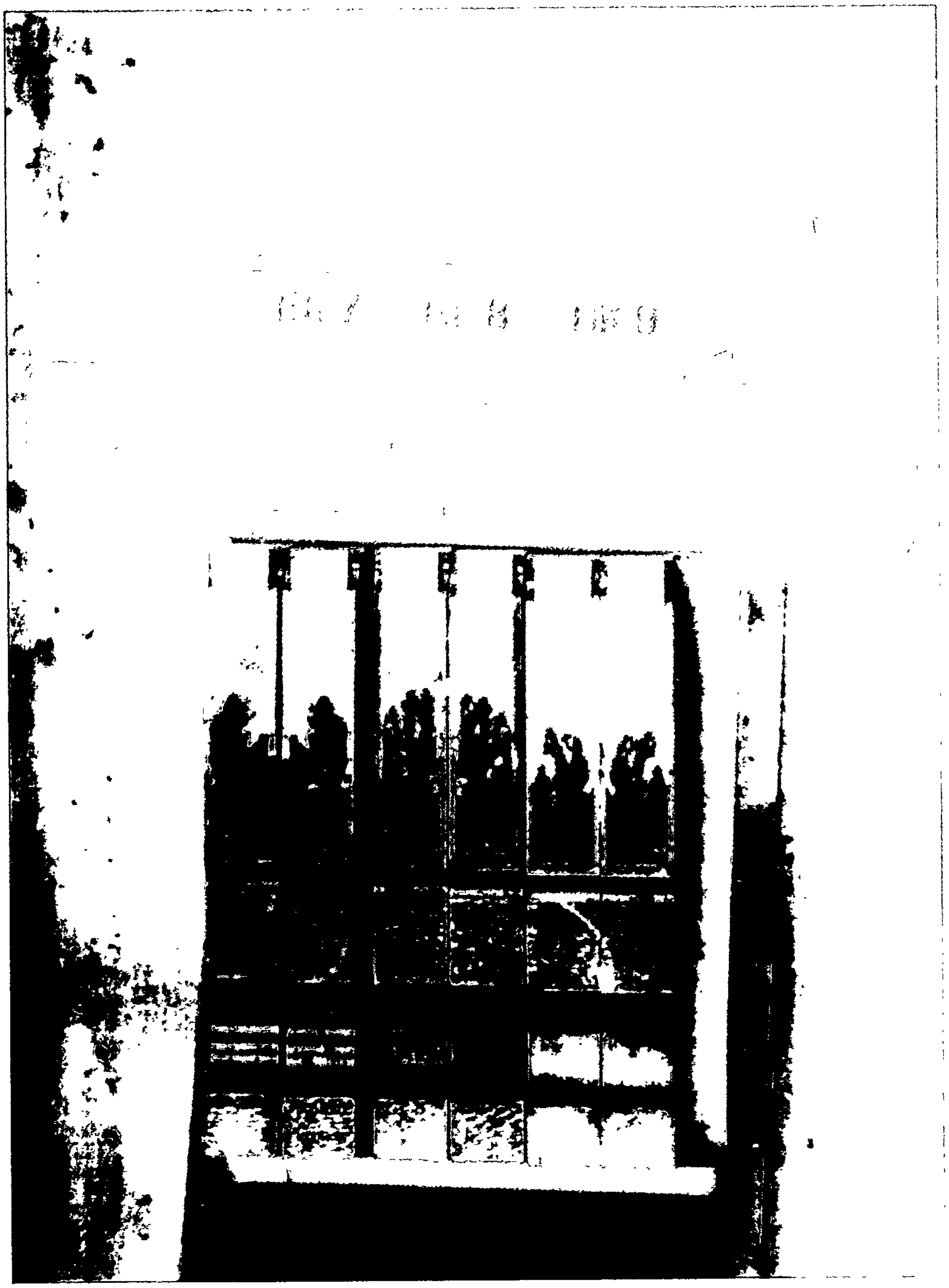
X-Y Plotter Output and Fracture Surfaces

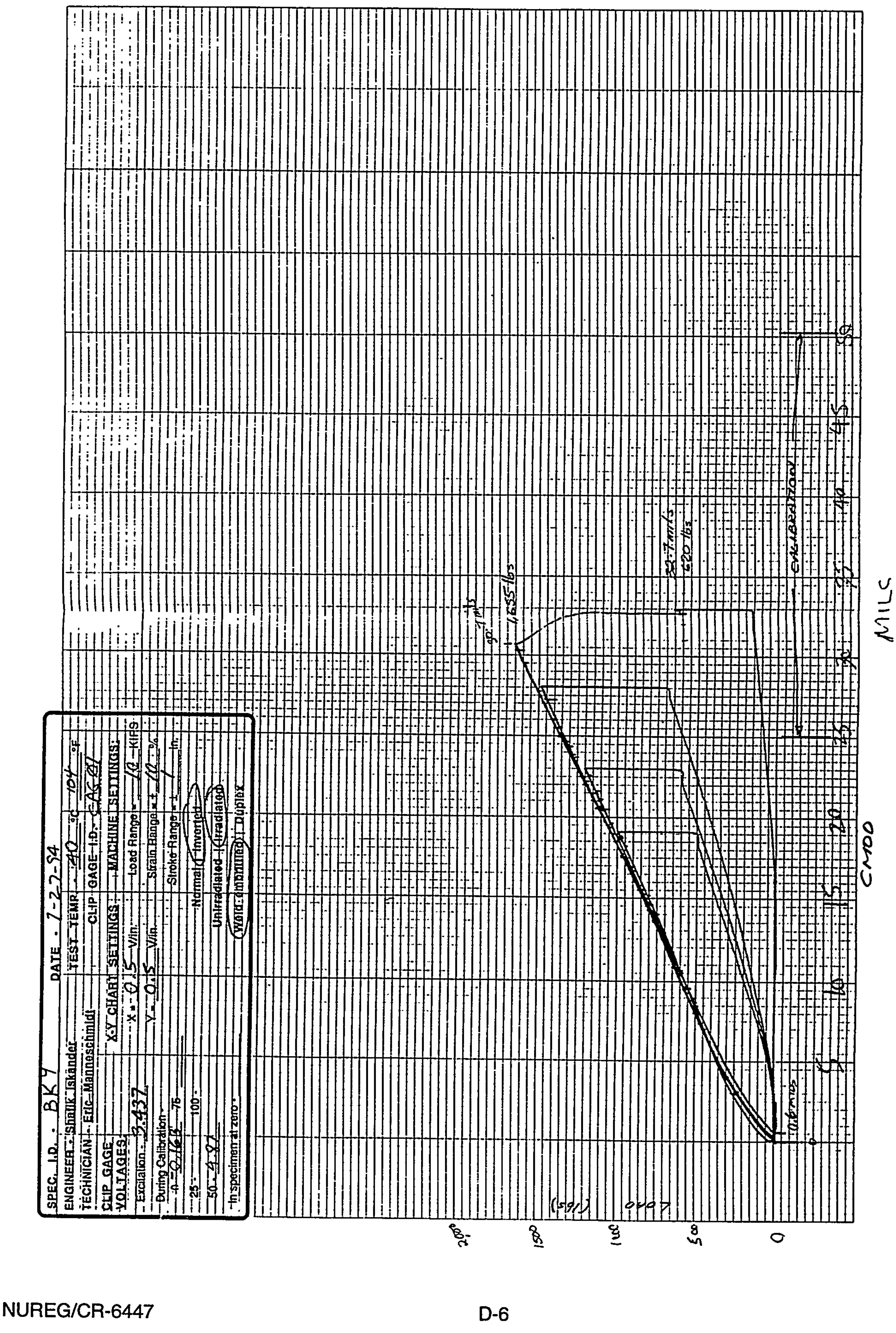

SPEC. I.D. - BK7
DATE - 7-26-94
ENGINEER - Shafik Iskandar
TECHNICIAN - Eric Manneschmidt
TEST TEMP. 28.2 °C 82.7 °F
CLIP GAGE I.D. GAG 01
CLIP GAGE VOLTAGES:
Excitation - 3.438
During Calibration -
0 - 0.0
75 -
25 - 2.49
100 -
50 - 5.00
In specimen at zero -
X-Y CHART SETTINGS
X = 0.5 V/in.
Y = 0.5 V/in.
MACHINE SETTINGS:
Load Range = 10 KIPS
Strain Range = ± 10 %
Stroke Range = ± 1 in.
Normal | Inverted
Unirradiated | Irradiated
Weld embrittled | Duplex
2000
1500
1000
500
0
lbs
0
5
10
15
20
25
30
35
40
45
50
CMOD
MILS

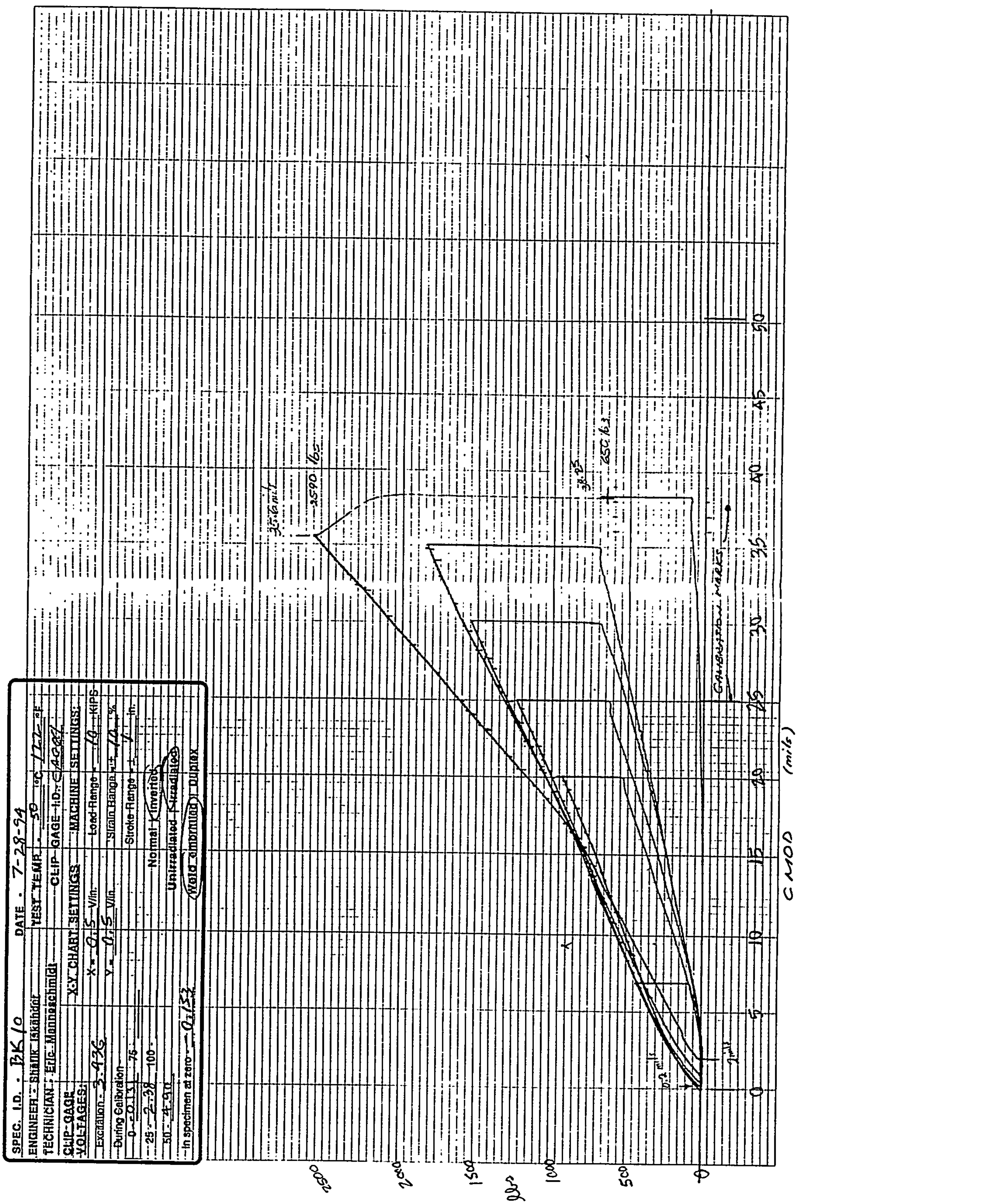


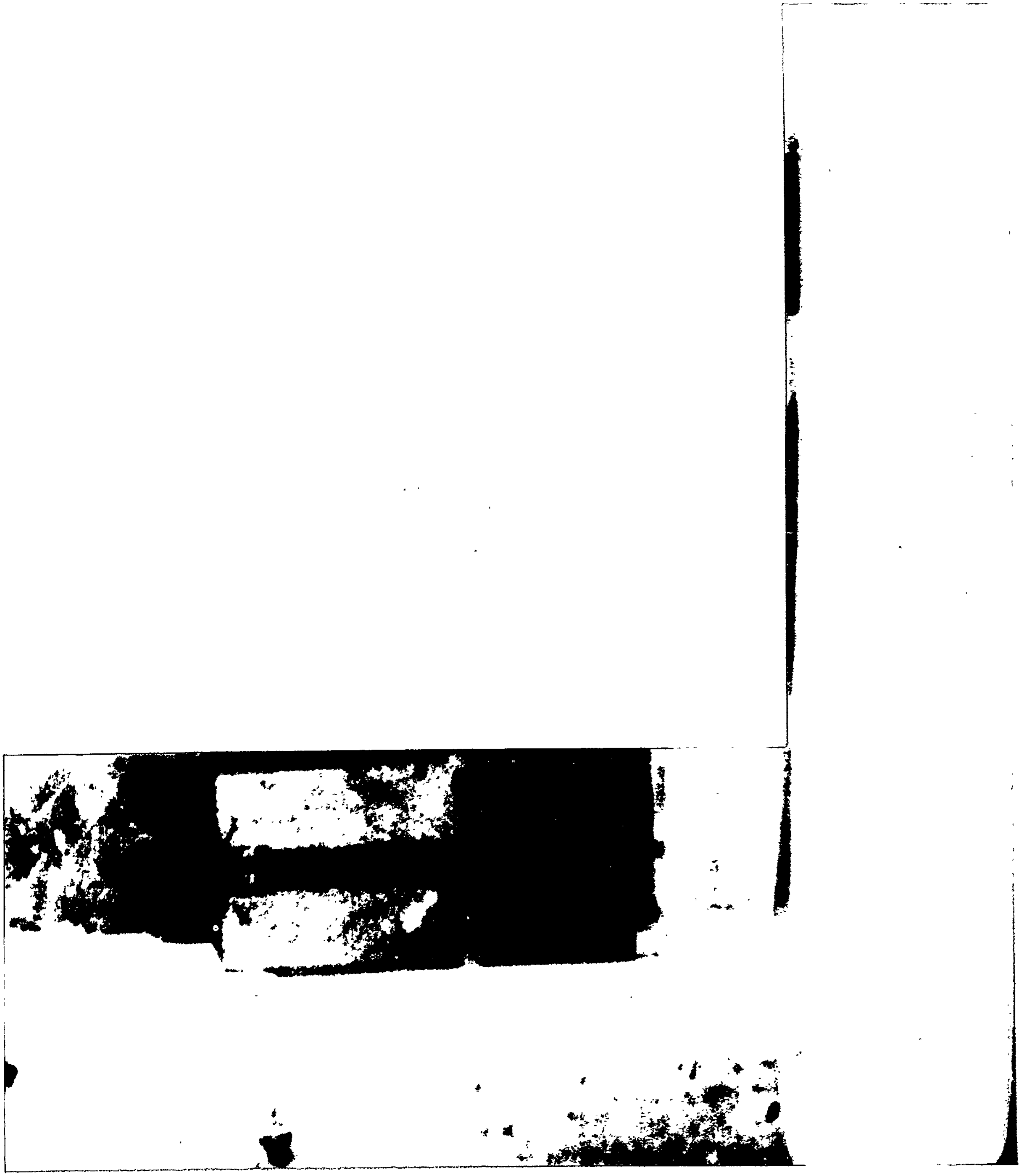


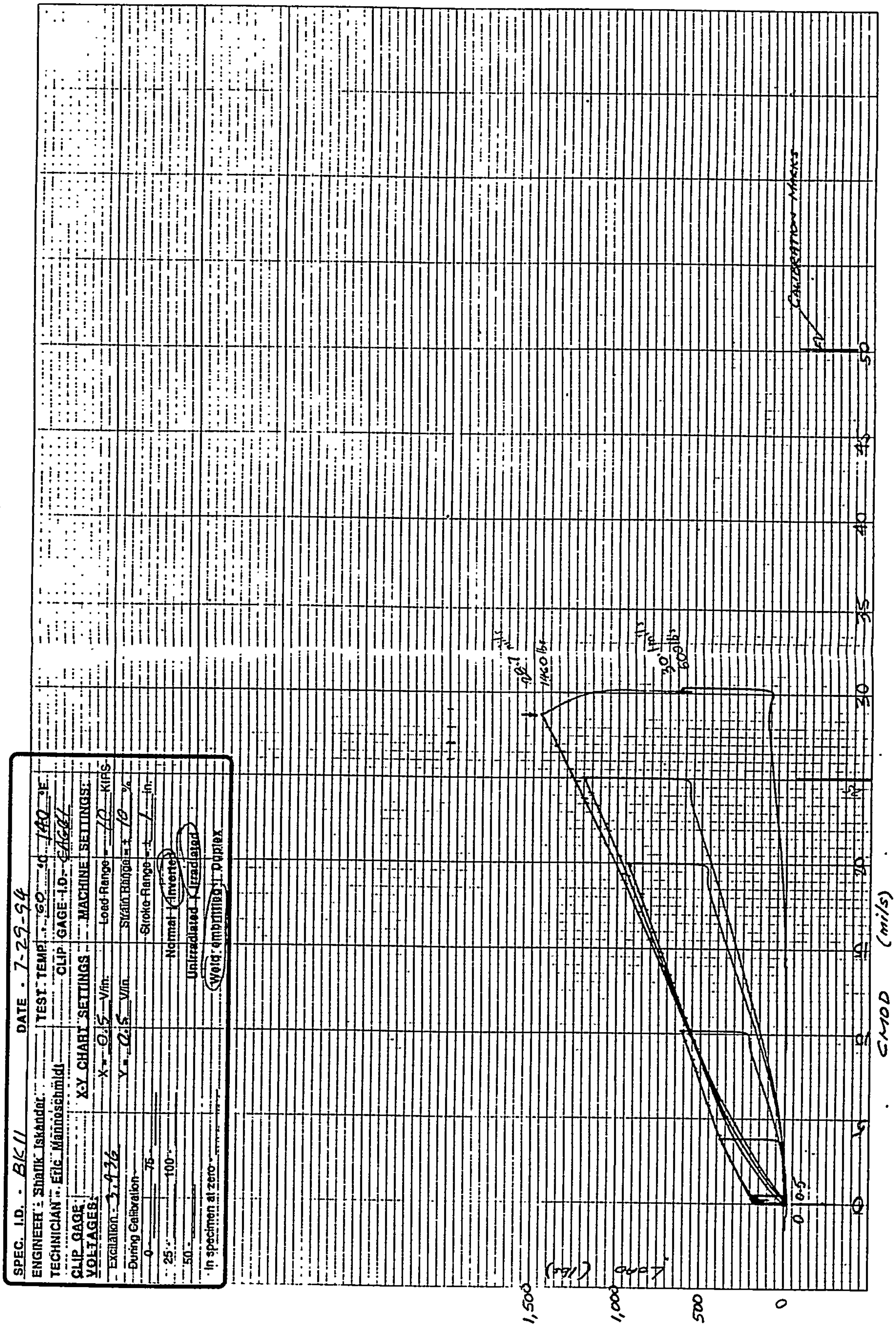

SPEC. I.D. - BK8
DATE - 7-27-94
ENGINEER - Shafik Iskander
TEST. TEMP. - 28 °C 82 °F
TECHNICIAN - Eric Mannoschmidt
CLIP GAGE I.D. CAG01
CLIP GAGE VOLTAGES:
Excitation -
During Calibration -
0 - 75 -
25 - 100 -
50 -
In specimen at zero -
X-Y CHART SETTINGS
X = 0.5 V/in.
Y = 0.5 V/in.
MACHINE SETTINGS:
Load Range = 10 KIPS
Strain Range = ± 10 %
Stroke Range = ± 1 in.
Normal | Inverted
Unirradiated | Irradiated
Weld embrittled | Duplex
c.g. disp = 20 mil w/ wedge out after test
Voltage - 1.19 VDC
1625 lbs
35.6 mils
450 lbs
35.8 mils
0.2 mils
2.3 mils
Load (lbs)
CMOD (Mils)

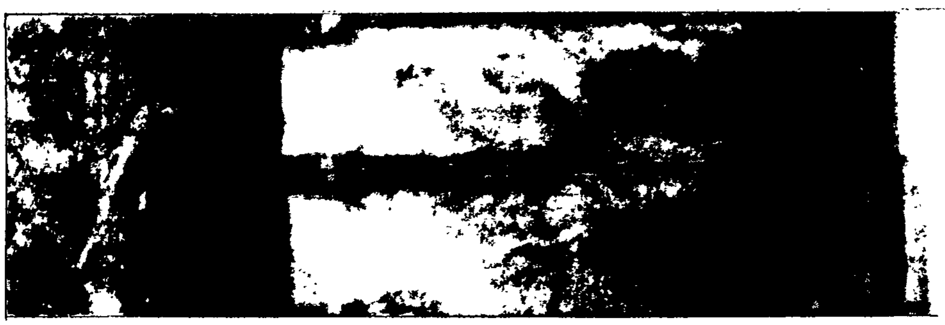


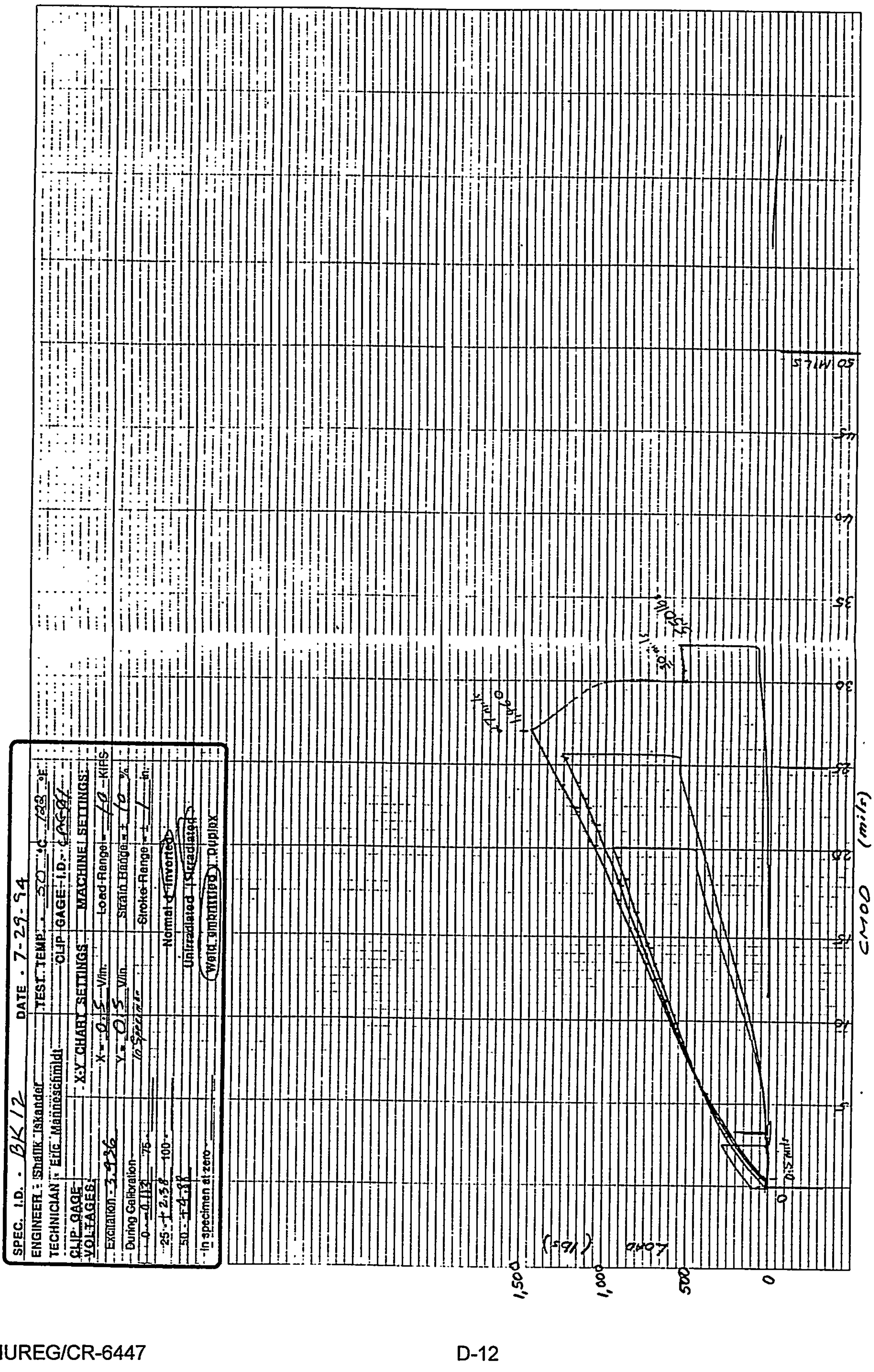

SPEC. I.D. BK7
DATE 7-27-94
ENGINEER Shaik Iskander
TECHNICIAN Eric Manneschmidt
TEST TEMP 40 °C 104 °F
CLIP GAGE I.D. CAS-01
CLIP GAGE VOLTAGES
X-Y CHART SETTINGS
MACHINE SETTINGS
Excitation 3.437
X = 0.15 V/in.
Load Range 10 KIPS
During Calibration
Y = 0.15 V/in.
Strain Range ± 10 %
0 -0.168 75
Stroke Range ± 1 in.
25 100
Normal Inverted
50 4.81
Unirradiated Irradiated
In specimen at zero
Weld Unirradiated Duplex
1655 lbs
30.1 mils
33.7 mils
620 lbs
CALIBRATION
0.6 mils
0
5
10
15
20
25
30
35
40
45
50
CMOD
MILS
0
500
1000
1500
2000
LOAD (lbs)

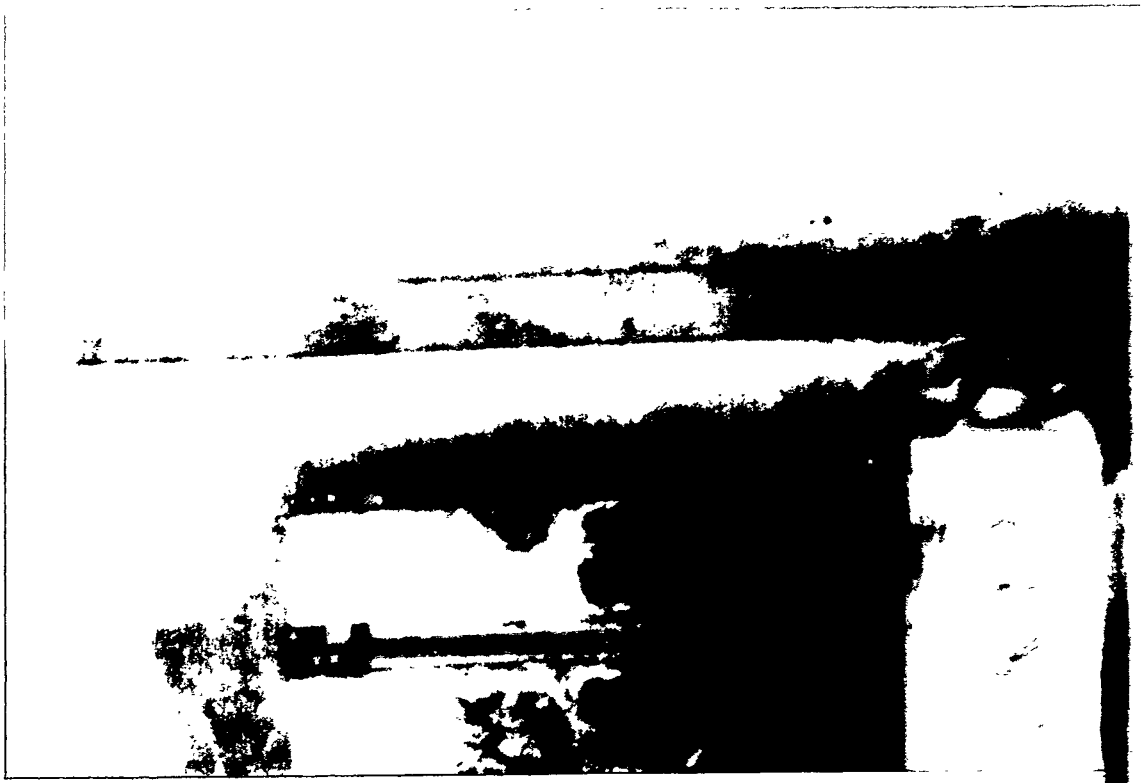

SPEC. I.D. - BK10
DATE - 7-28-94
ENGINEER - Shafik Iskander
TEST TEMP. - 50 °C 122 °F
TECHNICIAN - Eric Manneschmidt
CLIP GAGE I.D. - CAG84
CLIP-GAGE VOLTAGES:
X-Y CHART SETTINGS:
MACHINE SETTINGS:
Excitation - 3.936
X = 0.5 V/in.
Y = 0.5 V/in.
Load Range - 10 KIPS
Strain Range ± 10 %
Stroke Range ± 1 in.
During Calibration
0 - 0.131
75 -
25 - 2.38
100 -
50 - 4.90
Normal
Inverted
Unirradiated
Irradiated
Weld embrittled
Duplex
In specimen at zero - 0.133
2590 lbs
35.6 mils
38.25
2500 lbs
GALIBRATION MARKS
0.3 mils
2 mils
0
5
10
15
20
25
30
35
40
45
50
C MOD (mils)
0
500
1000
1500
2000
2500
lbs

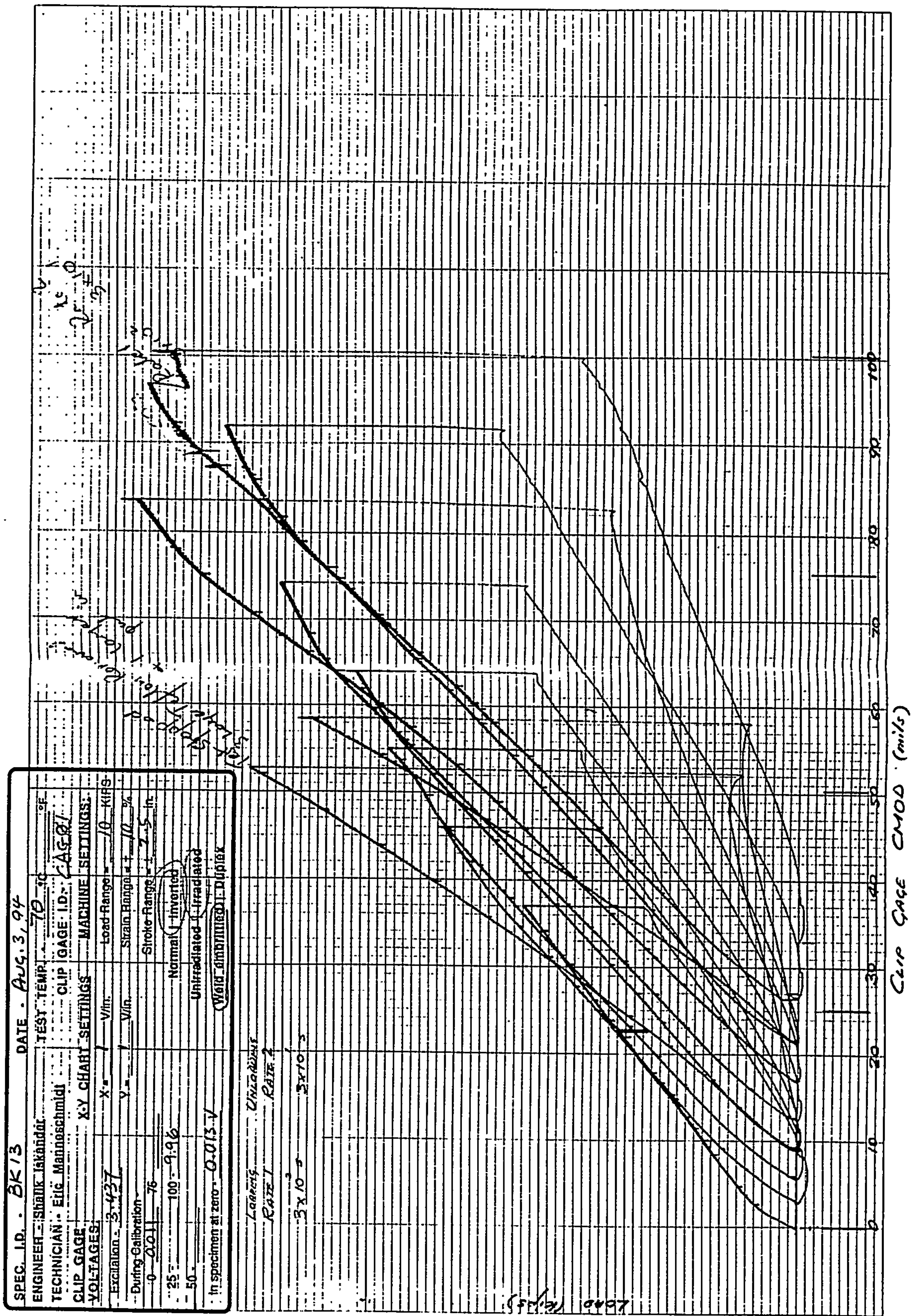


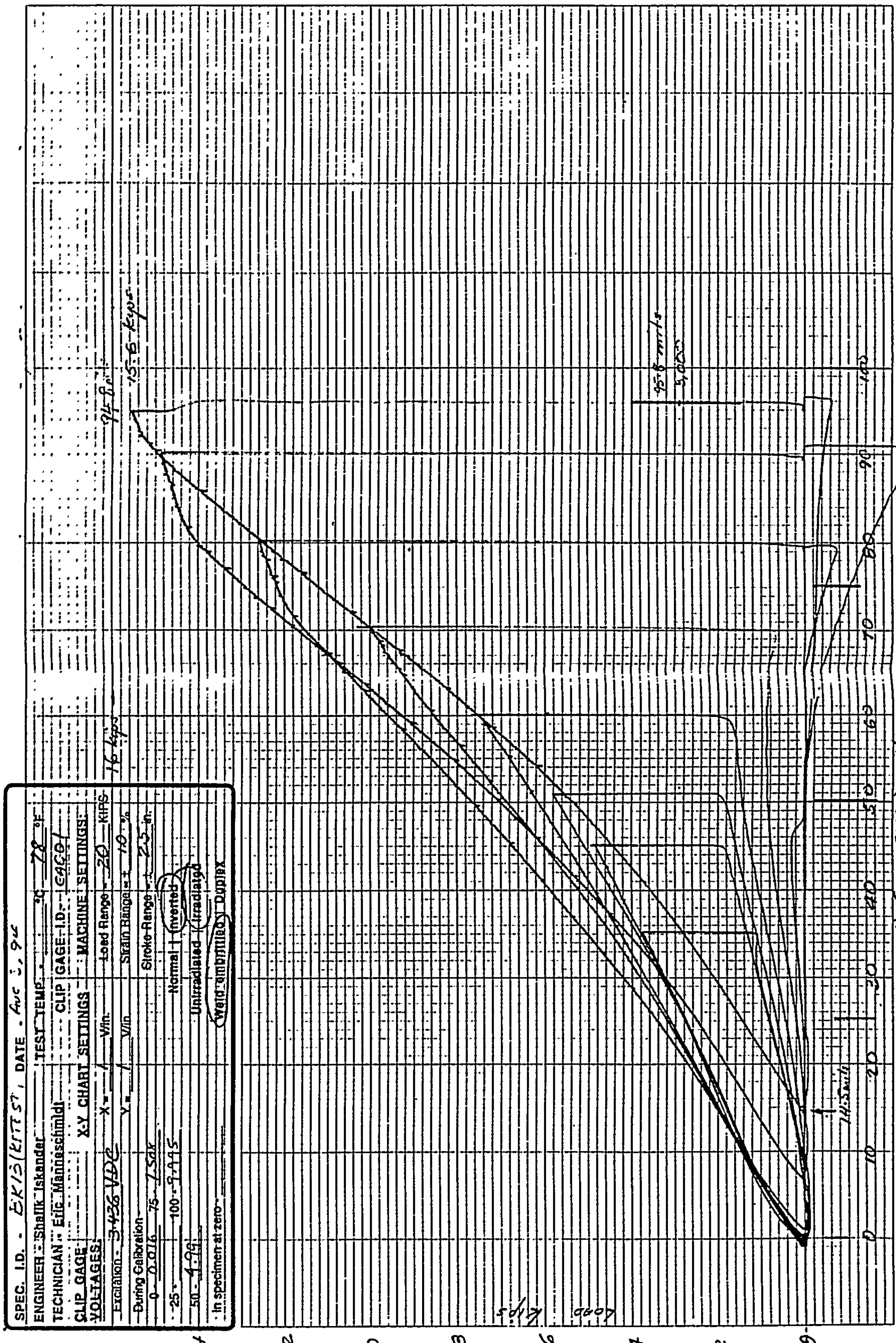

SPEC. I.D. - BK11
DATE - 7-29-94
ENGINEER - Shafik Iskander
TECHNICIAN - Eric Manneschmidt
TEST TEMP. 60 °C 140 °F
CLIP GAGE I.D.
CLIP GAGE VOLTAGES:
Excitation 3.436
During Calibration
0
25
50
75
100
In specimen at zero
XY CHART SETTINGS
X = 0.5 V/in.
Y = 0.5 V/in.
MACHINE SETTINGS:
Load Range 10 KIPS
Strain Range ± 10 %
Stroke Range ± 1 in.
Normal Inverted
Unirradiated Irradiated
Weld embrittling Duplex
CALIBRATION MARKS
1400 lbs
600 lbs
CMOD (mils)
LOAD (lbs)
0
5
10
15
20
25
30
35
40
45
50
500
1,000
1,500




SPEC. I.D. - BK12
DATE - 7-29-94
ENGINEER: Shafik Iskander
TECHNICIAN: Eric Manneschmidt
TEST TEMP: 50 °C 122 °F
X-Y CHART SETTINGS
MACHINE SETTINGS
Load Range 10 KIPS
Normal
Inverted
Unirradiated
Irradiated
Weld
Duplex
In specimen at zero
50 MILS
CMOD (mils)
LOAD (lbs)
1,500
1,000
500
0

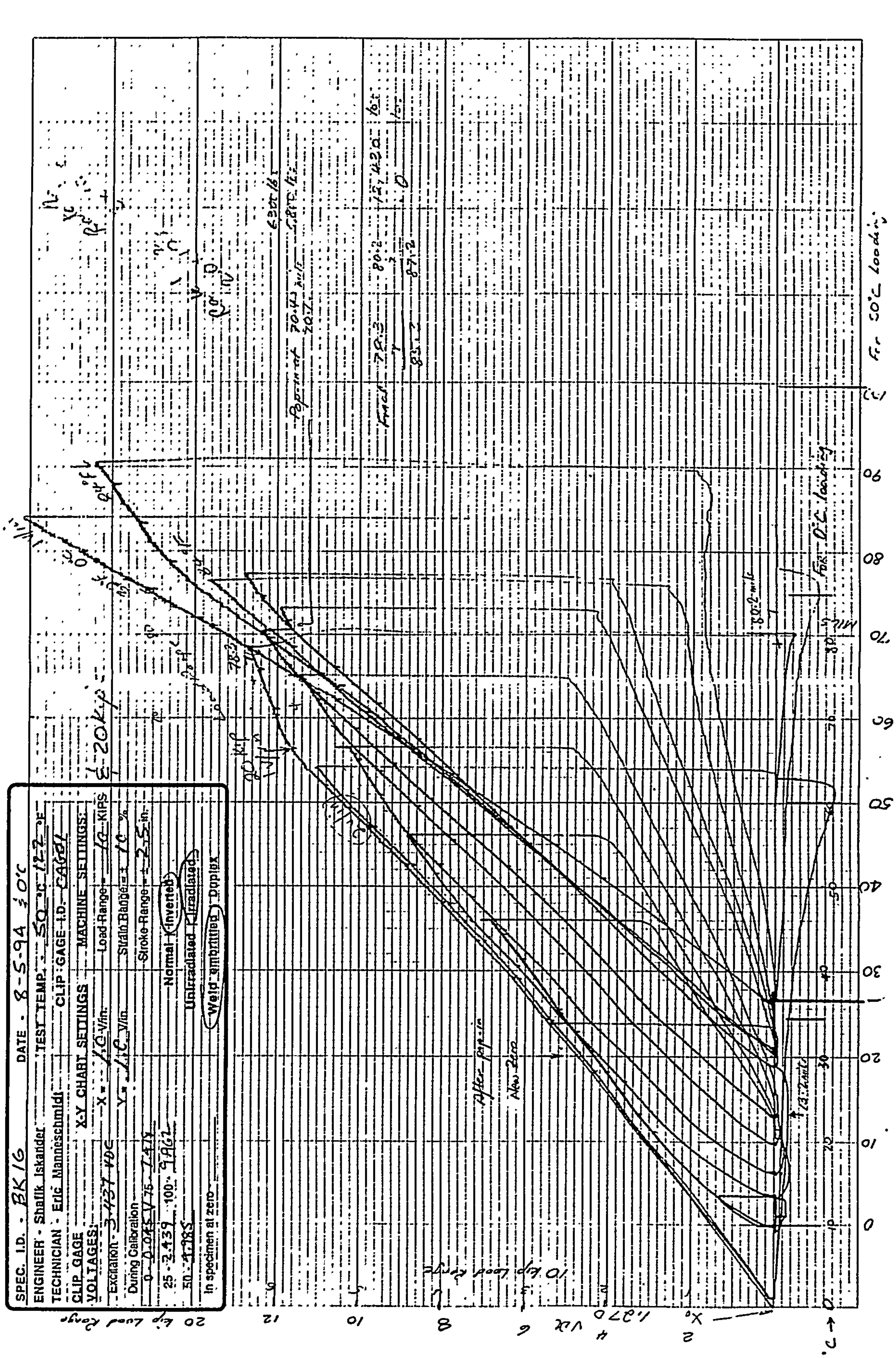



SPEC. I.D. - BK13
DATE - Aug. 3, 94
ENGINEER - Shafik Iskander
TEST TEMP. - 70 °F
TECHNICIAN - Eric Manneschmidt
CLIP GAGE I.D. - CAG01
CLIP GAGE VOLTAGES:
X-Y CHART SETTINGS
MACHINE SETTINGS:
Excitation - 3.437
X = 1 V/in.
Load Range = 10 KIPS
Y = 1 V/in.
Strain Range = ± 10 %
Stroke Range = ± 2.5 in.
During Calibration
0 - 0.011
75
25 -
100 - 9.96
50 -
Normal / Inverted
Unirradiated / Irradiated
Weld / Duplex
In specimen at zero - 0.013 V
Loading Rate 1 3x10^-3
Unloading Rate 2 3x10^-3
Clip Gage CMOD (mils)
0
10
20
30
40
50
60
70
80
90
100
0
1
2
3
4
5
6
7
8

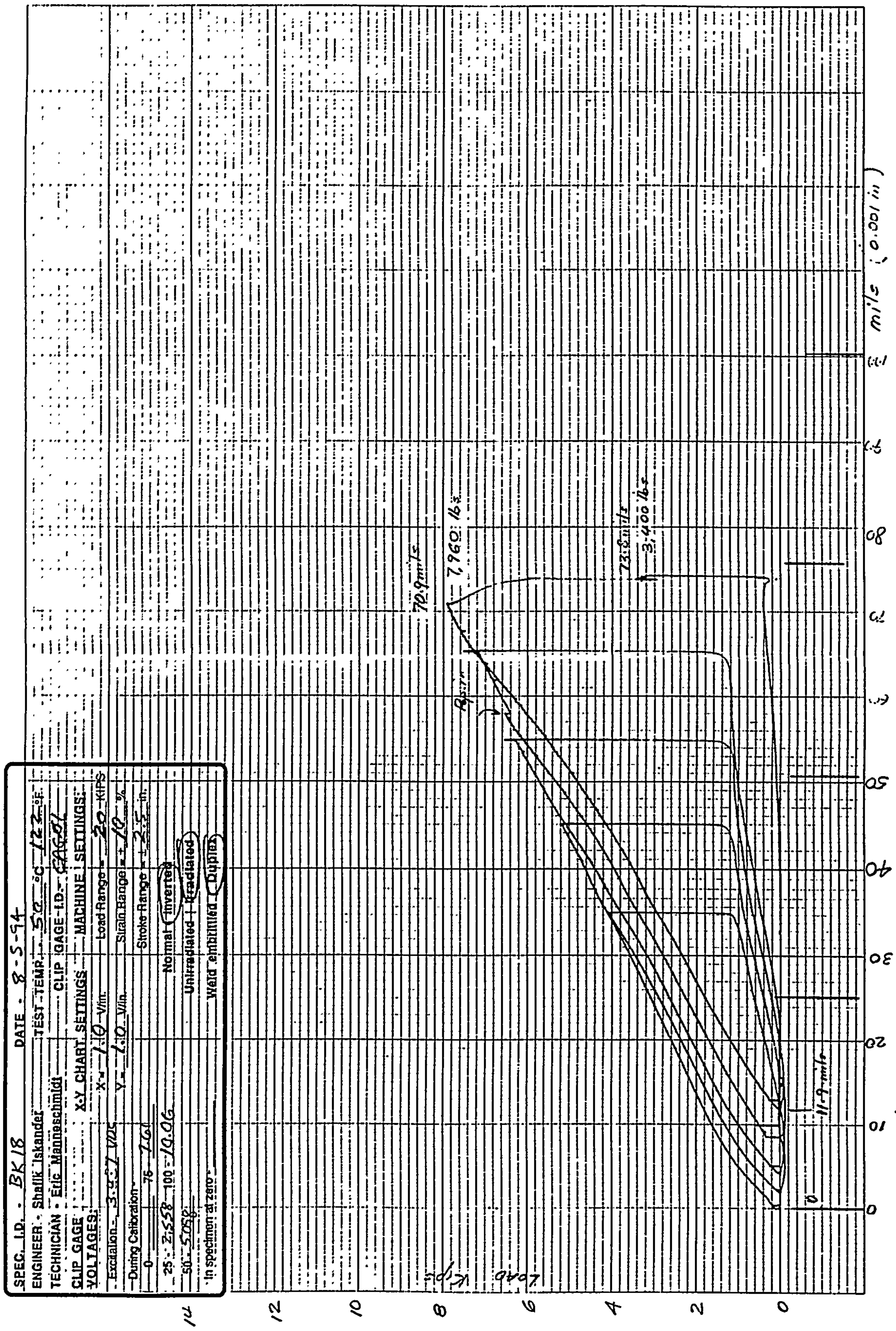


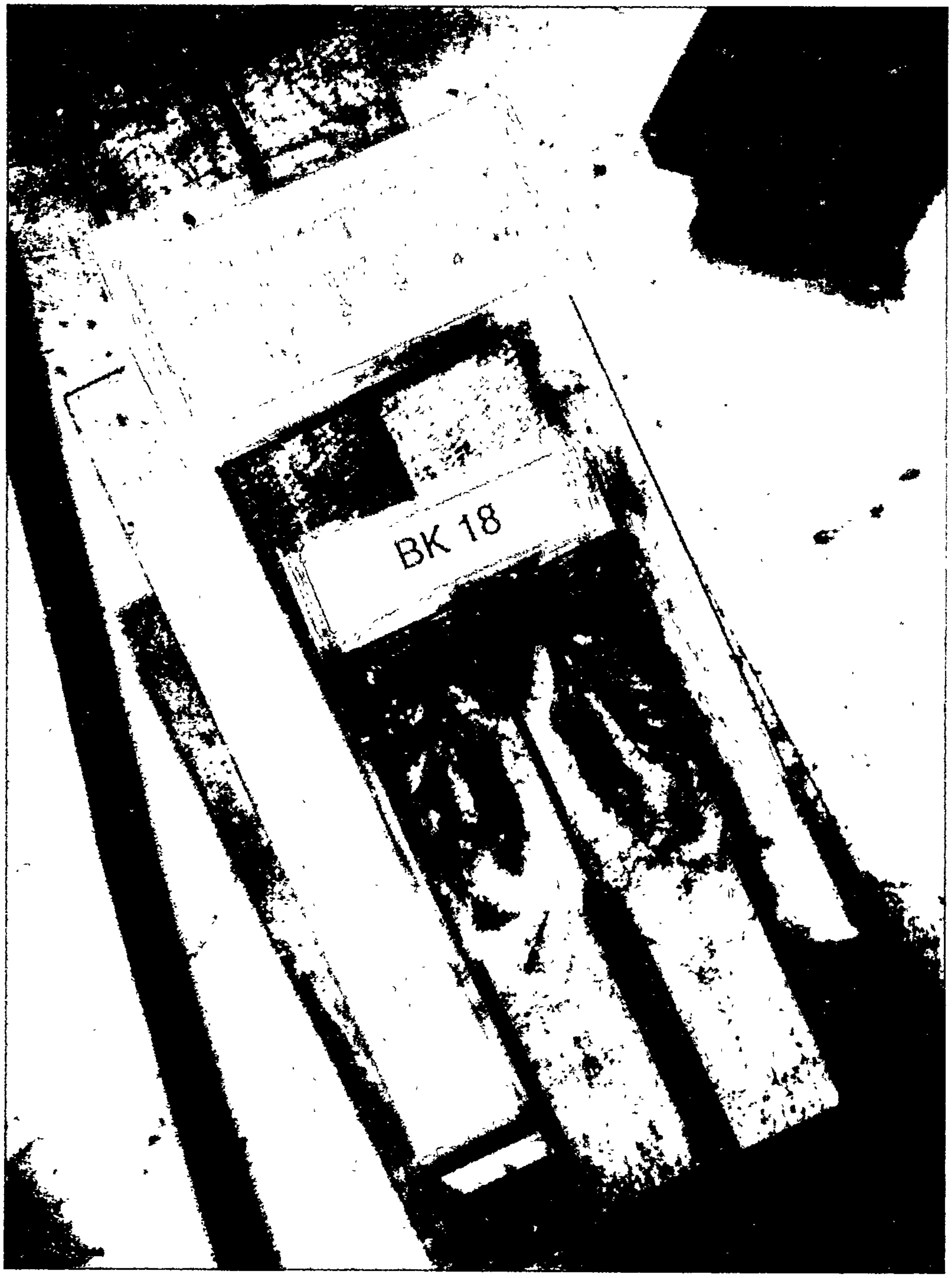
SPEC. I.D. - EK13(KITT ST, DATE - Aug 3, 94
ENGINEER - Shafik Iskander
TEST TEMP. - °C 78 °F
TECHNICIAN - Eric Manneschmidt
CLIP GAGE I.D. - CAGO1
CLIP GAGE VOLTAGES:
X-Y CHART SETTINGS
MACHINE SETTINGS:
Excitation - 3.436 VDC
X = 1 V/in.
Y = 1 V/in.
Load Range - 20 KIPS
Strain Range = ± 10 %
Stroke Range - ± 25 in.
During Calibration
0 - 0.016
25 -
50 - 4.99
75 - 7.50
100 - 9.995
Normal | Inverted
Unirradiated | Irradiated
Weld embrittled | Duplex
In specimen at zero -
16 kips
15.6 kips
14.5 mils
95.8 mils
Load Kips
clip Gage CMOD . mils
0
2
4
6
8
10
12
14
0
10
20
30
40
50
60
70
80
90
100


YPC-2021sas



SPEC. I.D. - BK16
DATE - 8-5-94 & 0°C
ENGINEER - Shafik Iskander
TEST TEMP. - 50 °C 122 °F
TECHNICIAN - Eric Manneschmidt
CLIP GAGE I.D. - CAG01
CLIP GAGE VOLTAGES:
Excitation - 3.437 VDC
During Calibration
0 - 0.045 V 75 - 7.419
25 - 2.439 100 - 9.962
50 - 4.985
In specimen at zero
X-Y CHART SETTINGS
X = 1.0 V/in.
Y = 1.0 V/in.
MACHINE SETTINGS:
Load Range - 10 KIPS
Strain Range = ± 10 %
Stroke Range = ± 2.5 in.
Normal / Inverted
Unirradiated / Irradiated
Weld embrittled / Duplex
20 kip Load Range
10 kip Load Range
After pop-in
New Zero
Pop-in at 70.4 mils
Fract. 78.3
For 0°C loading
For 50°C loading


SPEC. I.D. - BK18
DATE - 8-5-94
ENGINEER - Shafik Iskander
TEST TEMP. - 50 °C 122 °F
TECHNICIAN - Eric Manneschmidt
CLIP GAGE I.D. - CAG01
CLIP GAGE VOLTAGES
X-Y CHART SETTINGS
MACHINE SETTINGS
Load Range - 20 KIPS
Strain Range - ± 10 %
Stroke Range - ± 2.5 in.
Normal - Inverted
Unirradiated - Irradiated
Weld embrittled - Duplex
In specimen at zero
70.9 mils
7,960 lbs
72.8 mils
3,400 lbs
11.9 mils
mils (0.001 in)
Load Kips


BK 18

NRC FORM 335 (2-89) NRCM 1102, 3201, 3202

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

(See instructions on the reverse)

1. REPORT NUMBER (Assigned by NRC, Add Vol., Supp., Rev., and Addendum Numbers, if any.)

NUREG/CR-6447
ORNL-6894

2. TITLE AND SUBTITLE

Results of Crack-Arrest Tests on Irradiated A 508 Class 3 Steel

3. DATE REPORT PUBLISHED

MONTH	YEAR
February	1998

4. FIN OR GRANT NUMBER

L1098

5. AUTHOR(S)

S. K. Iskander, P. P. Milella, and A. Pini

6. TYPE OF REPORT

Technical

7. PERIOD COVERED *(Inclusive Dates)*

8. PERFORMING ORGANIZATION — NAME AND ADDRESS *(If NRC, provide Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.)*

Oak Ridge National Laboratory
Oak Ridge, TN 37831-6285

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Division of Engineering Technology
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

10. SUPPLEMENTARY NOTES

M.G. Vassilaros, NRC Project Manager

11. ABSTRACT *(200 words or less)*

Crack-arrest specimens of irradiated A 508 class 3 forging steel were tested and evaluated according to the American Society for Testing and Materials Standard Test Method for Determining Plain-Strain Crack-Arrest Fracture Toughness, K_{Ia}, of Ferritic Steels, E 1221-88. The irradiation-induced shifts while small, averaging only about 10 K, are approximately the same as the Charpy 41-J temperature shifts. The specimens were irradiated at temperatures ranging from 243 to 280°C to fluences varying from 1.7 to 2.7 × 10^{19} neutrons/cm^2 (>1 MeV).

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

crack arrest
fracture toughness
Charpy V-notch toughness
embrittlement
irradiation effects
transition temperature shift
ferritic steel
A 508 class 3 steel

13. AVAILABILITY STATEMENT

Unlimited

14. SECURITY CLASSIFICATION

(This Page) Unclassified

(This Report) Unclassified

15. NUMBER OF PAGES

16. PRICE