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Crack-Arrest Tests on Two Irradiated High-Copper Welds

Phase II: Results of Duplex-Type Experiments

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Abstract

The objective of the Heavy-Section Steel Irradiation Program Sixth Irradiation Series is to determine the effect of neutron irradiation on the shift and shape of the lower-bound curve to crack-arrest toughness data. Two submerged-arc welds with copper contents of 0.23 and 0.31 wt % were commercially fabricated in 220-mm-thick plate. Crack-arrest specimens fabricated from these welds were irradiated at a nominal temperature of 288°C to an average fluence of 1.9×10^{19} neutrons/cm^2 (>1 MeV). This is the second report giving the results of the tests on irradiated duplex-type crack-arrest specimens. A previous report gave results of tests on irradiated weld-embrittled-type specimens. Charpy V-notch (CVN) specimens irradiated in the same capsules as the crack-arrest specimens were also tested, and a 41-J transition temperature shift was determined from these specimens. "Mean" curves of the same form as the American Society of Mechanical Engineers (ASME) K_{Ia} curve were fit to the data with only the "reference temperature" as a parameter. The shift between the mean curves agrees well with the 41-J transition temperature shift obtained from the CVN specimen tests. Moreover, the four data points resulting from tests on the duplex crack-arrest specimens of the present study did not make a significant change to mean curve fits to either the previously obtained data or all the data combined.

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Nomenclature

Acronyms

ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
EB	electron beam
CVN	Charpy V-notch
dpa	displacements per atom
EPRI	Electric Power Research Institute
4340	a medium-carbon, low-alloy, ultrahigh-strength steel
HAZ	heat-affected zone
HSSI	Heavy-Section Steel Irradiation
ORNL	Oak Ridge National Laboratory
NDT	nil-ductility-transition temperature, as determined by the drop-weight test according to ASTM E 208
NRC	U.S. Nuclear Regulatory Commission
RPVs	reactor pressure vessels
RT_{NDT}	reference nil-ductility-transition temperature, determined in accordance with Subarticle NB-2330 of *ASME Boiler and Pressure Vessel Code, Sect. III*
SAWs	submerged arc welds
UT	ultrasonic non-destructive examination
WE	weld-embrittled

SYMBOLS

°C	temperature in degrees Celsius*
$\Delta TT_{41\text{-}J}$	shift in the 41-J CVN-impact energy level
Φ	fluence, neutrons/cm^2
K_a	value of the stress-intensity factor shortly after arrest**
K_{Ia}	value of the crack-arrest fracture toughness K_a for a crack that arrests under conditions of crack front plane-strain**
K_{Ic}	plane-strain fracture toughness
T	test temperature
$TT_{41\text{-}J}$	temperature at the 41-J CVN-impact energy level

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*Note that errors may arise because of the traditional use of the same symbol for both the temperature and for a temperature interval. The errors arise when converting a temperature ***interval*** from the SI system into the U.S. customary units. The correct conversion is 1°C = 1.8° F (without adding 32).

**Excerpted from ASTM E 1221-88.

Previous Reports In Series

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

This report is designated HSSI Report 8. Reports in this series are listed below:

1. F. M. Haggag, W. R. Corwin, and R. K. Nanstad, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., Oak Ridge, Tenn., *Irradiation Effects on Strength and Toughness of Three-Wire Series-Arc Stainless Steel Weld Overlay Cladding*, NUREG/CR-5511 (ORNL/TM-11439), February 1990.

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

3. S. K. Iskander, W. R. Corwin, and R. K. Nanstad, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., Oak Ridge, Tenn., *Results of Crack-Arrest Tests on Two Irradiated High-Copper Welds*, NUREG/CR-5584 (ORNL/TM-11575), December 1990.

4. R. K. Nanstad and R. G. Berggren, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., *Irradiation Effects on Charpy Impact and Tensile Properties of Low Upper-Shelf Welds, HSSI Series 2 and 3*, USNRC Report NUREG/CR-5696 (ORNL/TM-11804), August 1991.

5. R. E. Stoller, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., *Modeling the Influence of Irradiation Temperature and Displacement Rate on Radiation-Induced Hardening in Ferritic Steels*, USNRC Report NUREG/CR-5859 (ORNL/TM-12073), August 1992.

6. R. K. Nanstad, D. E. McCabe, and R. L. Swain, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., *Chemical Composition and RT_{NDT} Determinations For Midland Weld WF-70*, USNRC Report NUREG/CR-5914 (ORNL/TM-12157), to be published.

7. R. K. Nanstad, F. M. Haggag, D. E. McCabe, S. K. Iskander, K. O. Bowman, and B. H. Menke, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., *Irradiation Effects on Fracture Toughness of Two High-Copper Submerged-Arc Welds, HSSI Series 5*, USNRC Report NUREG/CR-5913 (ORNL/TM-12156/V1), October 1992.

8. This report.

The HSSI Program includes both follow-on and the direct continuation of work that was performed under the Heavy-Section Steel Technology (HSST) Program. The HSST reports related to irradiation effects in pressure vessel materials and those containing unirradiated properties of materials used in HSSI and HSST irradiation programs are tabulated below as a convenience to the reader.

C. E. Childress, Union Carbide Corp. Nuclear Div., Oak Ridge Natl. Lab., Oak Ridge, Tenn., *Fabrication History of the First Two 12-in.-Thick A-533 Grade B, Class 1 Steel Plates of the Heavy Section Steel Technology Program*, ORNL-4313, February 1969.

T. R. Mager and F. O. Thomas, Westinghouse Electric Corporation, PWR Systems Division, Pittsburgh, Pa., *Evaluation by Linear Elastic Fracture Mechanics of Radiation Damage to Pressure Vessel Steels*, WCAP-7328 (Rev.), October 1969.

P. N. Randall, TRW Systems Group, Redondo Beach, Calif., *Gross Strain Measure of Fracture Toughness of Steels*, HSSTP-TR-3, Nov. 1, 1969.

L. W. Loechel, Martin Marietta Corporation, Denver, Colo., *The Effect of Testing Variables on*

the Transition Temperature in Steel, MCR-69-189, Nov. 20, 1969.

W. O. Shabbits, W. H. Pryle, and E. T. Wessel, Westinghouse Electric Corporation, PWR Systems Division, Pittsburgh, Pa., *Heavy-Section Fracture Toughness Properties of A533 Grade B Class 1 Steel Plate and Submerged Arc Weldment*, WCAP-7414, December 1969.

C. E. Childress, Union Carbide Corp. Nuclear Div., Oak Ridge Natl. Lab., Oak Ridge, Tenn., *Fabrication History of the Third and Fourth ASTM A-533 Steel Plates of the Heavy Section Steel Technology Program*, ORNL-4313-2, February 1970.

P. B. Crosley and E. J. Ripling, Materials Research Laboratory, Inc., Glenwood, Ill., *Crack Arrest Fracture Toughness of A533 Grade B Class 1 Pressure Vessel Steel*, HSSTP-TR-8, March 1970.

F. J. Loss, Naval Research Laboratory, Washington, D.C., *Dynamic Tear Test Investigations of the Fracture Toughness of Thick-Section Steel*, NRL-7056, May 14, 1970.

T. R. Mager, Westinghouse Electric Corporation, PWR Systems Div., Pittsburgh, Pa., *Post-Irradiation Testing of 2T Compact Tension Specimens*, WCAP-7561, August 1970.

F. J. Witt and R. G. Berggren, Union Carbide Corp. Nuclear Div., Oak Ridge Natl. Lab., Oak Ridge, Tenn., *Size Effects and Energy Disposition in Impact Specimen Testing of ASTM A533 Grade B Steel*, ORNL/TM-3030, August 1970.

D. A. Canonico, Union Carbide Corp. Nuclear Div., Oak Ridge Natl. Lab., Oak Ridge, Tenn., *Transition Temperature Considerations for Thick-Wall Nuclear Pressure Vessels*, ORNL/TM-3114, October 1970.

T. R. Mager, Westinghouse Electric Corporation, PWR Systems Div., Pittsburgh, Pa., *Fracture Toughness Characterization Study of A533, Grade B, Class 1 Steel*, WCAP-7578, October 1970.
W. O. Shabbits, Westinghouse Electric Corp., PWR Systems Div., Pittsburgh, Pa., *Dynamic Fracture Toughness Properties of Heavy Section A533 Grade B Class 1 Steel Plate*, WCAP-7623, December 1970.

C. E. Childress, Union Carbide Corp. Nuclear Div., Oak Ridge Natl. Lab., Oak Ridge, Tenn., *Fabrication Procedures and Acceptance Data for ASTM A-533 Welds and a 10-in.-Thick ASTM A-543 Plate of the Heavy Section Steel Technology Program*, ORNL-TM-4313-3, January 1971.

D. A. Canonico and R. G. Berggren, Union Carbide Corp. Nuclear Div., Oak Ridge Natl. Lab., Oak Ridge, Tenn., *Tensile and Impact Properties of Thick-Section Plate and Weldments*, ORNL/TM-3211, January 1971.

C. W. Hunter and J. A. Williams, Hanford Eng. Dev. Lab., Richland, Wash., *Fracture and Tensile Behavior of Neutron-Irradiated A533-B Pressure Vessel Steel*, HEDL-TME-71-76, February 6, 1971.

C. E. Childress, Union Carbide Corp. Nuclear Div., Oak Ridge Natl. Lab., Oak Ridge, Tenn., *Manual for ASTM A533 Grade B Class 1 Steel (HSST Plate 03) Provided to the International Atomic Energy Agency*, ORNL/TM-3193, March 1971.

P. N. Randall, TRW Systems Group, Redondo Beach, Calif., *Gross Strain Crack Tolerance of A533-B Steel*, HSSTP-TR-14, May 1, 1971.

C. L. Segaser, Union Carbide Corp. Nuclear Div., Oak Ridge Natl. Lab., Oak Ridge, Tenn., *Feasibility Study, Irradiation of Heavy-Section Steel Specimens in the South Test Facility of the Oak Ridge Research Reactor*, ORNL/TM-3234, May 1971.

H. T. Corten and R. H. Sailors, University of Illinois, Urbana, Ill., *Relationship Between Material Fracture Toughness Using Fracture Mechanics and Transition Temperature Tests*, T&AM Report 346, August 1, 1971.

L. A. James and J. A. Williams, Hanford Eng. Dev. Lab., Richland, Wash., *Heavy Section Steel Technology Program Technical Report No. 21, The Effect of Temperature and Neutron Irradiation Upon the Fatigue-Crack Propagation Behavior of ASTM A533 Grade B, Class 1 Steel*, HEDL-TME 72-132, September 1972.

P. B. Crosley and E. J. Ripling, Materials Research Laboratory, Inc., Glenwood, Ill., *Crack Arrest in an Increasing K-Field*, HSSTP-TR-27, January 1973.

W. J. Stelzman and R. G. Berggren, Union Carbide Corp. Nuclear Div., Oak Ridge Natl. Lab., Oak Ridge, Tenn., *Radiation Strengthening and Embrittlement in Heavy-Section Steel Plates and Welds*, ORNL-4871, June 1973.

J. M. Steichen and J. A. Williams, Hanford Eng. Dev. Lab., Richland, Wash., *High Strain Rate Tensile Properties of Irradiated ASTM A533 Grade B Class 1 Pressure Vessel Steel*, HEDL-TME 73-74, July 1973.

J. A. Williams, Hanford Eng. Dev. Lab., Richland, Wash., *The Irradiation and Temperature Dependence of Tensile and Fracture Properties of ASTM A533, Grade B, Class 1 Steel Plate and Weldment*, HEDL-TME 73-75, August 1973.

J. A. Williams, Hanford Eng. Dev. Lab., Richland, Wash., *Some Comments Related to the Effect of Rate on the Fracture Toughness of Irradiated ASTM A553-B Steel Based on Yield Strength Behavior*, HEDL-SA 797, December 1974.

J. A. Williams, Hanford Eng. Dev. Lab., Richland, Wash., *The Irradiated Fracture Toughness of ASTM A533, Grade B, Class 1 Steel Measured with a Four-Inch-Thick Compact Tension Specimen*, HEDL-TME 75-10, January 1975.

J. G. Merkle, G. D. Whitman, and R. H. Bryan, Union Carbide Corp. Nuclear Div., Oak Ridge Natl. Lab., Oak Ridge, Tenn., *An Evaluation of the HSST Program Intermediate Pressure Vessel Tests in Terms of Light-Water-Reactor Pressure Vessel Safety*, ORNL/TM-5090, November 1975.

J. A. Davidson, L. J. Ceschini, R. P. Shogan, and G. V. Rao, Westinghouse Electric Corporation, Pittsburgh, Pa., *The Irradiated Dynamic Fracture Toughness of ASTM A533, Grade B, Class 1 Steel Plate and Submerged Arc Weldment*, WCAP-8775, October 1976.

J. A. Williams, Hanford Eng. Dev. Lab., Richland, Wash., *Tensile Properties of Irradiated and Unirradiated Welds of A533 Steel Plate and A508 Forgings*, NUREG/CR-1158 (ORNL/SUB-79/50917/2), July 1979.

J. A. Williams, Hanford Eng. Dev. Lab., Richland, Wash., *The Ductile Fracture Toughness of Heavy Section Steel Plate*, NUREG/CR-0859, September 1979.

K. W. Carlson and J. A. Williams, Hanford Eng. Dev. Lab., Richland, Wash., *The Effect of Crack Length and Side Grooves on the Ductile Fracture Toughness Properties of ASTM A533 Steel*, NUREG/CR-1171 (ORNL/SUB-79/50917/3), October 1979.

G. A. Clarke, Westinghouse Electric Corp., Pittsburgh, Pa., *An Evaluation of the Unloading Compliance Procedure for J-Integral Testing in the Hot Cell, Final Report*, NUREG/CR-1070 (ORNL/Sub-7394/1), October 1979.

P. B. Crosley and E. J. Ripling, Materials Research Laboratory, Inc., Glenwood, Ill., *Development of a Standard Test for Measuring K_{Ia} with a Modified Compact Specimen*, NUREG/CR-2294 (ORNL/SUB-81/7755/1), August 1981.

H. A. Domian, Babcock and Wilcox Company, Alliance, Ohio, *Vessel V-8 Repair and Preparation of Low Upper-Shelf Weldment*, NUREG/CR-2676 (ORNL/Sub/81-85813/1), June 1982.

R. D. Cheverton, S. K. Iskander, and D. G. Ball, Union Carbide Corp. Nuclear Div., Oak Ridge Natl. Lab., Oak Ridge, Tenn., *PWR Pressure Vessel Integrity During Overcooling Accidents: A Parametric Analysis*, NUREG/CR-2895 (ORNL/TM-7931), February 1983.

J. G. Merkle, Union Carbide Corp. Nuclear Div., Oak Ridge Natl. Lab., Oak Ridge, Tenn., *An Examination of the Size Effects and Data Scatter Observed in Small Specimen Cleavage Fracture Toughness Testing*, NUREG/CR-3672 (ORNL/TM-9088), April 1984.

W. R. Corwin, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., Oak Ridge, Tenn., *Assessment of Radiation Effects Relating to Reactor Pressure Vessel Cladding*, NUREG/CR-3671 (ORNL-6047), July 1984.

W. R. Corwin, R. G. Berggren, and R. K. Nanstad, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., Oak Ridge, Tenn., *Charpy Toughness and Tensile Properties of a Neutron Irradiated Stainless Steel Submerged-Arc Weld Cladding Overlay*, NUREG/CR-3927 (ORNL/TM-9709), September 1984.

J. J. McGowan, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., Oak Ridge, Tenn., *Tensile Properties of Irradiated Nuclear Grade Pressure Vessel Plate and Welds for the Fourth HSST Irradiation Series*, NUREG/CR-3978 (ORNL/TM-9516), January 1985.

J. J. McGowan, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., Oak Ridge, Tenn., *Tensile Properties of Irradiated Nuclear Grade*

Pressure Vessel Welds for the Third HSST Irradiation Series, NUREG/CR-4086 (ORNL/TM-9477), March 1985.

W. R. Corwin, G. C. Robinson, R. K. Nanstad, J. G. Merkle, R. G. Berggren, G. M. Goodwin, R. L. Swain, and T. D. Owings, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., Oak Ridge, Tenn., *Effects of Stainless Steel Weld Overlay Cladding on the Structural Integrity of Flawed Steel Plates in Bending, Series 1*, NUREG/CR-4015 (ORNL/TM-9390), April 1985.

W. J. Stelzman, R. G. Berggren, and T. N. Jones, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., Oak Ridge, Tenn., *ORNL Characterization of Heavy-Section Steel Technology Program Plates 01, 02, and 03*, NUREG/CR-4092 (ORNL/TM-9491), April 1985.

G. D. Whitman, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., Oak Ridge, Tenn., *Historical Summary of the Heavy-Section Steel Technology Program and Some Related Activities in Light-Water Reactor Pressure Vessel Safety Research*, NUREG/CR-4489 (ORNL-6259), March 1986.

R. H. Bryan, B. R. Bass, S. E. Bolt, J. W. Bryson, J. G. Merkle, R. K. Nanstad, and G. C. Robinson, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., Oak Ridge, Tenn., *Test of 6-in.-Thick Pressure Vessels. Series 3: Intermediate Test Vessel V-8A — Tearing Behavior of Low Upper-Shelf Material*, NUREG-CR-4760 (ORNL-6187), May 1987.

D. B. Barker, R. Chona, W. L. Fourney, and G. R. Irwin, University of Maryland, College Park, Md., *A Report on the Round Robin Program Conducted to Evaluate the Proposed ASTM Standard Test Method for Determining the Plane Strain Crack Arrest Fracture Toughness, K_{Ia}, of Ferritic Materials*, NUREG/CR-4966 (ORNL/Sub/79-7778/4), January 1988.

L. F. Miller, C. A. Baldwin, F. W. Stallman, and F. B. K. Kam, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., Oak Ridge, Tenn., *Neutron Exposure Parameters for the Metallurgical Test Specimens in the Fifth Heavy-Section Steel Technology Irradiation Series Capsules*, NUREG/CR-5019 (ORNL/TM-10582), March 1988.

J. J. McGowan, R. K. Nanstad, and K. R. Thoms, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., Oak Ridge, Tenn., *Characterization of Irradiated Current-Practice Welds and A533 Grade B Class 1 Plate for Nuclear Pressure Vessel Service*, NUREG/CR-4880 (ORNL-6484/V1 and V2), July 1988.

R. D. Cheverton, W. E. Pennell, G. C. Robinson, and R. K. Nanstad, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., Oak Ridge, Tenn., *Impact of Radiation Embrittlement on Integrity of Pressure Vessel Supports for Two PWR Plants*, NUREG/CR-5320 (ORNL/TM-10966), February 1989.

J. G. Merkle, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., Oak Ridge, Tenn., *An Overview of the Low-Upper-Shelf Toughness Safety Margin Issue*, NUREG/CR-5552 (ORNL/TM-11314), August 1990.

R. D. Cheverton, T. L. Dickson, J. G. Merkle, and R. K. Nanstad, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., Oak Ridge, Tenn., *Review of Reactor Pressure Vessel Evaluation Report for Yankee Rowe Nuclear Power Station (YAEC No. 1735)*, NUREG/CR-5799 (ORNL/TM-11982), March 1992.

Crack-Arrest Tests on Two Irradiated High-Copper Welds. Phase II: Results of Duplex-Type Specimens*

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

1. Introduction

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

Two of these programs are the Heavy-Section Steel Irradiation (HSSI) Program Fifth and Sixth Irradiation Series. The objective of the Fifth Series was to determine the effect of neutron irradiation on the shift and shape of the K_{Ic} versus ($T - RT_{NDT}$) curve, where K_{Ic} is the plane-strain fracture toughness, T is the temperature, and RT_{NDT} is the reference nil-ductility-transition (NDT) temperature. Although the objective is similar, the Sixth Series investigates the effect on K_{Ia}, the plane-strain crack-arrest fracture toughness. Both programs investigate the effects of irradiation on the fracture toughness of welds, since some pressure vessels in operation have welds with copper contents and end-of-life fluences that make them susceptible to severe degradation in toughness. The amount of experimental data on the effects of irradiation on crack-arrest fracture toughness is still rather meager [1-3].

Two submerged-arc welds (SAWs) with copper contents of 0.23 and 0.31 wt % were commercially fabricated in 220-mm-thick plate. In the Fifth Irradiation Series, irradiated CVN impact, tensile, drop-weight, and compact specimens made from the weldment were tested, and the results are given in refs. [4-6].

Crack-arrest specimens fabricated from these welds were irradiated at a nominal temperature of 288°C to a nominal fluence of 1.9×10^{19} neutrons/cm^2 (>1 MeV). Complete details of the dosimetric calculations are given in ref. [7]. Testing was performed according to the American Society for Testing and Materials (ASTM) Test for Determining Plane-Strain Crack-Arrest Fracture Toughness, K_{Ia}, of Ferritic Steels (E 1221-88). In ASTM E 1221, a distinction is made between K_a, the value of the stress-intensity factor shortly after arrest, and K_{Ia}, the value of the crack-arrest fracture toughness, K_a, for a crack that arrests under conditions of crack front plane-strain.*

This report gives the results of tests on 24 duplex-type crack-arrest specimens (Phase II). A previous detailed report [3] and a summary paper [8] presented the results of Phase I of testing 36 weld-embrittled crack-arrest specimens, and a summary of these results is given below. A final report on both phases of this program is planned, and the conclusions presented here are preliminary.

1.1 Summary of Previous Results on the Weld-Embrittled Crack-Arrest Specimens

Crack-arrest testing of high-copper SAWs was performed on 77 unirradiated and 36 irradiated 25- and 33-mm-thick weld-embrittled specimens. Most of the crack-arrest test results are either valid or only marginally invalid according to ASTM E 1221-88. The 35 data points† obtained

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*All symbols and acronyms, in addition to their definition before their first use, have also been given in the nomenclature table at the beginning of this report.

†One of the specimens exhibited tearing, and no data were obtained.

by testing the irradiated crack-arrest specimens have approximately doubled the known data base of irradiated crack-arrest toughness and extended the data base coverage to higher levels of crack-arrest toughness and temperature relative to RT_{NDT}. Preliminary observations are:

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

2. The shifts of the lower-bound K_a curves for the 72W and 73W welds are approximately the same as the corresponding 41-J CVN impact energy level shifts, $\Delta TT_{41\text{-}J}$.

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

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

1.2 Reasons for Use of Duplex Crack-Arrest Specimens

Crack-arrest toughness testing is intrinsically difficult. It is complicated by the conflicting goals of initiating a brittle mode (or fast-running crack), then the requirement of its arrest in a relatively short distance. The initiation and arrest are accomplished by applying a crack-driving force to a brittle region using a wedge. The relatively stiff wedge minimizes the elastic energy stored in the loading system; thus, after a crack starts to run, it relieves the load on the wedge. This limits the crack-driving force to the elastic energy stored in the specimen and, thus, the crack may stop without running out the back side of the specimen, breaking the specimen in two.

Furthermore, the range of temperatures for a weld-embrittled crack-arrest specimen in which a brittle-mode crack can initiate and run is generally limited to about 20°C above the drop-weight NDT.* At temperatures above this range, stable tearing occurs and, at times, is accompanied by a drop in the maximum load. This drop in load distinguishes stable tearing from crack blunting that often occurs near the upper limits of the possible test temperature range.

In order to increase the range of temperature for which a fast-running crack can initiate, duplex-type crack-arrest specimens are necessary. In the unirradiated crack-arrest tests on both 72W and 73W welds, the highest test temperatures attained with weld-embrittled crack-arrest specimens were about 20 to 25°C above the NDT. By using duplex-type specimens, values at 45 to 50°C above the NDT have been obtained, as shown in Figures 1 and 2. Duplex crack-arrest specimens allow testing at higher temperatures because the higher yield strength of the crack-starter portion of the specimen minimizes yielding near the crack starter. Furthermore, the higher yield strengths and the use of a crack-starter hole create higher driving forces than those possible with a notch in a weld-embrittled crack-arrest specimen. These attributes of the crack-starter material, in combination with its resistance to slow, stable tearing, result in a higher probability of obtaining a fast-running, highly loaded crack-initiation event at higher temperatures.

Figure 3 is a schematic of a typical duplex crack-arrest specimen. A key feature of this specimen is the crack-starter hole. The hole diameter, D, is important since the crack-initiation force increases as the diameter increases in a non-linear manner. This topic will be discussed in more detail in Appendix F.

1.3 Outline of Report

Chapter 2 of this report documents a very significant effort undertaken to modify the

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*Recent testing has indicated that the RT_{NDT} may be somewhat higher than that estimated at the time of the previous report.

*For both welds 72W and 73W, the RT_{NDT} was equal to the NDT.

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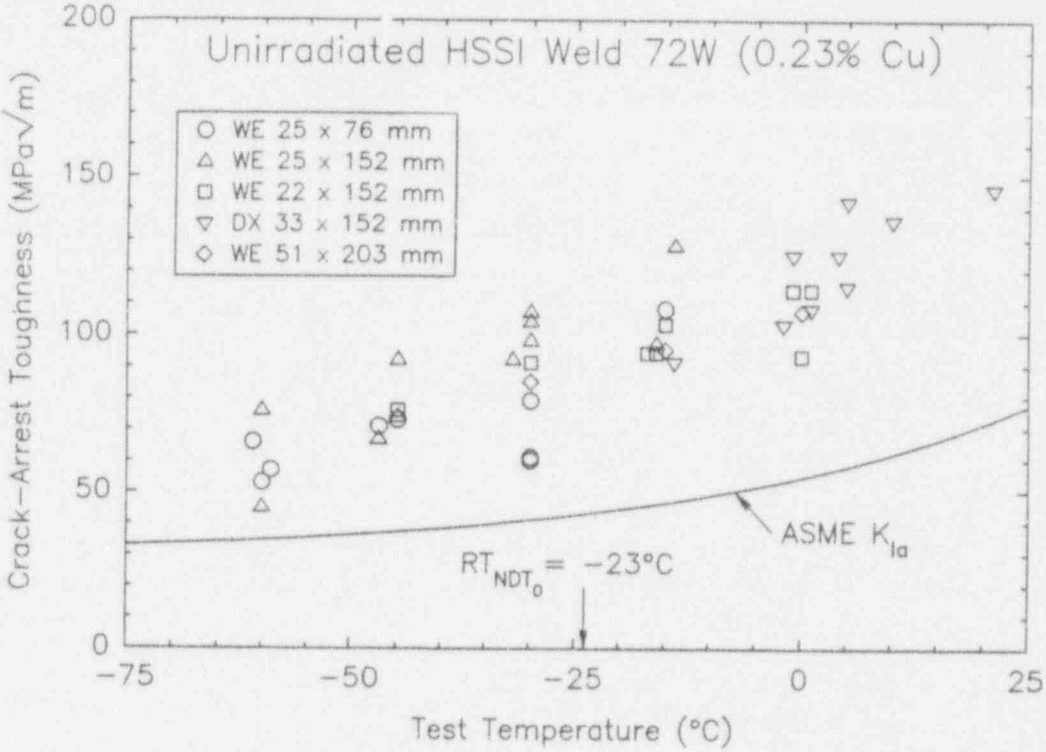

Figure 1. The crack-arrest toughness for unirradiated 72W weld-embrittled specimens.

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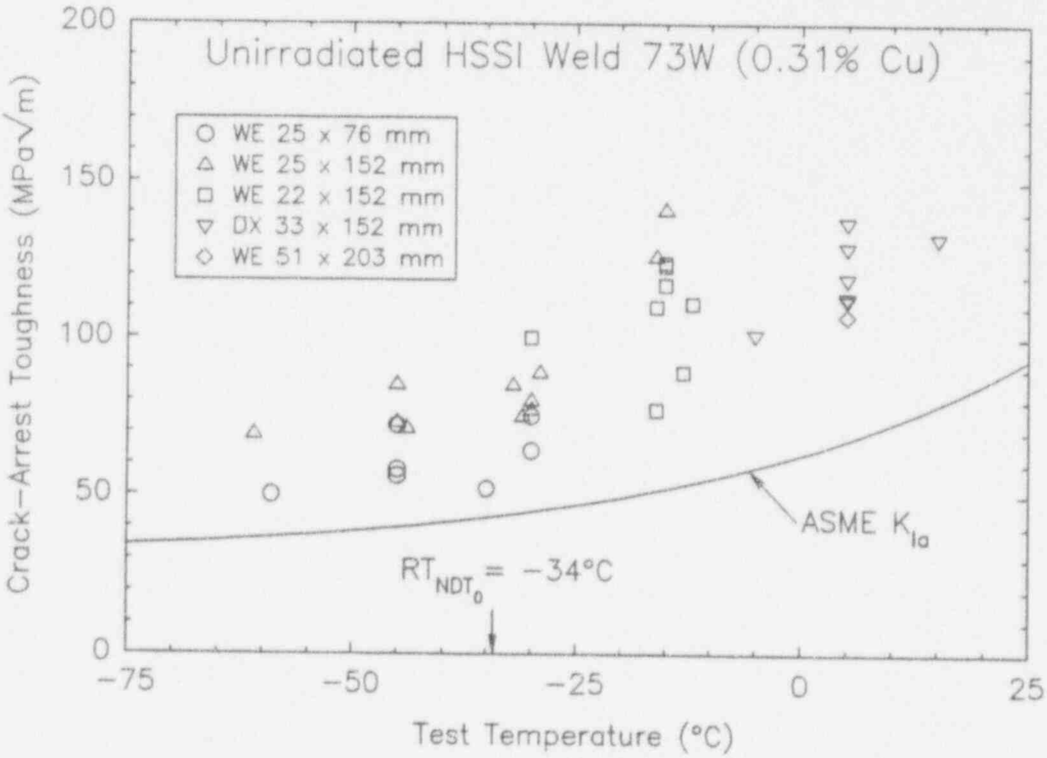

Figure 2. The crack-arrest toughness for unirradiated 73W weld-embrittled specimens.

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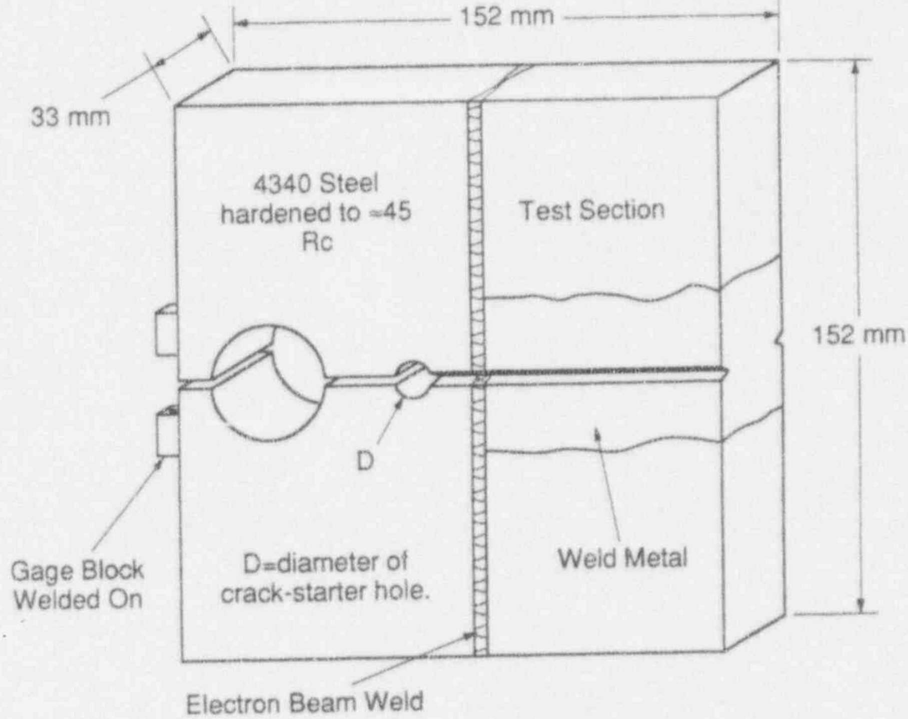

Figure 3. Schematic of the duplex-type crack-arrest specimen used in the Sixth Irradiation Series for welds 72W and 73W.

irradiated duplex specimens because of a lack of fusion between the weld metal test section and the hardened 4340 crack-starter section that was discovered after the specimens were irradiated.

The modifications were complicated by the geometry of the specimen and the hardened and irradiated condition of the specimens themselves. During irradiation, the diameter of the crack-starter hole for the irradiated specimens was approximately 4 mm. For the reasons given in Chapter 2, the diameter of the hole was increased to either 16 or 19 mm.

Chapter 3 is limited to details of the test results since much of the description of the test equipment and method, as well as error analysis and a summary of other investigators' results, were given in the Phase I report [3].

Chapter 4 is a discussion of the results and some preliminary conclusions, since a final report on the results of Phases I and II is planned that will include detailed analyses. Also included are several appendices that document various details.

A great deal of valuable experience has been gained in this program, and many important details have been documented in the appendices. Appendix A gives strip charts and photographs of the fracture surfaces of all 24 irradiated duplex crack-arrest specimens tested. Appendix B gives similar information as Appendix A for the unirradiated trial specimens that were used to verify the modification contemplated for the irradiated specimens. One of the difficult phases in this program was the actual modification of the irradiated duplex crack-arrest specimens, and Appendix C documents the equipment used. The detailed results of the successful tests on the irradiated duplex crack-arrest specimens, the mathematical expressions used to calculate the stress-intensity factors, and the evaluation of the validity criteria are given in Appendix D.

Correlating the transition temperature shift of irradiated crack-arrest specimens to that of CVN specimens is one of the objectives of the Sixth Irradiation Series. A large number of CVN specimens from the same welds have already been tested in the Fifth Series; their shift can be adjusted to the slightly larger fluence to which the crack-arrest specimens were irradiated. However, a smaller number of CVN specimens were irradiated in the same capsules as the crack-arrest specimens, and their 41-J impact energy level transition temperature shift should be taken into account in the final analysis of the results of this program. Appendix E presents the detailed results of tests recently completed on these Sixth Series CVN specimens.

Increasing the crack-driving force by increasing the diameter of the crack-starter hole was the reason for modifying the duplex crack-arrest specimens. Appendix F compares the increase in the force indicated at the instant of crack initiation with the increase in crack-starter hole diameter.

References

1. C. W. Marschall and A. R. Rosenfield, "Crack-Arrest Tests of Irradiated High-Copper ASTM A508 Submerged-Arc Weld Metal," pp. 2467-75 in *International Conference on Fracture, Advances in Fracture Research,* Vol. 5, April 1981.*

2. T. R. Mager and C. W. Marschall, *Development of Crack-Arrest Toughness Data Bank for Irradiated Reactor Pressure Vessel Materials,* EPRI NP-3616, Electric Power Research Institute, Palo Alto, Calif., July 1984.

3. S. K. Iskander, W. R. Corwin, and R. K. Nanstad, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab, *Results of Crack-Arrest Tests on Two Irradiated High-Copper Welds,* USNRC Report NUREG/CR-5584 (ORNL/TM-11575), December 1990.†

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

5. R. K. Nanstad, F. M. Haggag, and S. K. Iskander, "Radiation-Induced Temperature Shift of the ASME K_{Ic} Curve," pp. 143-48 in *Transactions of the 10th International Conference on Structural Mechanics in Reactor Technology (SMiRT),* Vol. S, ed. H. Hadgjian, Anaheim, Calif., August 1989.*

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*Available in public technical libraries.

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

6. R. K. Nanstad, F. M. Haggag, D. E. McCabe, S. K. Iskander, K. O. Bowman, and B. H. Menke, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., *Irradiation Effects on Fracture Toughness of Two High-Copper Submerged-Arc Welds, HSSI Series 5,* USNRC Report NUREG/CR-5913, Vol. 1 (ORNL/TM-12156/V1), August 1992.*

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

8. S. K. Iskander, W. R. Corwin, and R. K. Nanstad, "Effects of Irradiation on Crack-Arrest Toughness of Two High-Copper Welds," pp. 251-69 in *Effects of Radiation on Materials: 15th International Symposium, ASTM STP 1125,* ed. R. E. Stoller, A. S. Kumar, and D. S. Gelles, American Society for Testing and Materials, Philadelphia, 1992.†

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

†Available in public technical libraries.

2. Modification of the Irradiated Duplex Crack-Arrest Specimens

At the conclusion of tests on the weld-embrittled-type crack-arrest specimens for Phase I of this program, four duplex-type crack-arrest specimens were tested. In all four specimens, the crack did initiate but arrested in the fusion zone between the hard 4340 crack-starter section and the weld metal test section. Figure 4 shows a photograph* of the fracture surface of one of these four irradiated specimens. Photographs of the fracture surfaces of all the specimens are included in Appendix A. The most likely cause of the arrest is the lack of fusion between the two sections. The gap between the two regions acts like an arrester hole that is sometimes introduced in structures to stop a growing crack.

Prior to irradiation, all the duplex crack-arrest specimens were examined using X-ray radiography. The examination did not reveal the presence of any discontinuities. Furthermore, the area of interest is one whose morphology is complicated by the presence of several materials of different properties; see Figure 3. On one side of the fusion zone is a hardened 4340 (a medium-carbon, low-alloy, ultrahigh-strength steel), and on the other side is the section that contains the weld metal to be tested. The manufacture of duplex crack-arrest specimens of weld metal has traditionally been more difficult than that of base metal. The region of the weld metal test section destined to be joined to the 4340 is "buttered" by melting a thin layer of weld metal to minimize the entrapped slag, gases, etc., then remachined before it is electron-beam (EB) welded to the 4340. At the present time, ORNL is using newly acquired equipment that uses the recently developed "B-scanning" ultrasonic technique in order to examine the interface region for flaws that other techniques have failed to reveal. This is performed before the side grooves are machined. If lack of fusion is discovered, it can be rewelded. It is anticipated that B-scan method will enhance the capability to detect such flaws in duplex crack-arrest specimens.

It should be noted that the heat-affected zone (HAZ) is generally tougher than the surrounding material, and thus it is not uncommon for it to arrest a running flaw in duplex-type specimens. The test section is EB welded to the 4340 crack-starter section from one side, then turned to complete the weld from the other side. The specimens are 33 mm thick, and the EB equipment has enough power to weld up to 100-mm-thick sections. The welding is performed from both sides to minimize the heat input and to reduce the width of the HAZ. In the case of the subject irradiated duplex crack-arrest specimens, unexpected changes in the welding procedure produced EB welds that did not penetrate to the desired 60% of the specimen thickness obtained in previous specimen fabrication.

From the tests of the first four specimens, it seemed highly probable that this lack of fusion existed in all the remaining specimens. In retrospect, this was indeed the case. In order to utilize these specimens, various options were considered. One was to store the specimens until such time that the irradiated weld metal could be used for some other task, as yet unknown. It was worthwhile to try to obtain data from these specimens, even at the risk of a large percentage of unsuccessful tests, always a possibility in crack-arrest testing. Another option was to reweld the specimens, but this did not appear feasible because of the difficulty of locating EB equipment capable of handling irradiated specimens. Even if such equipment was located, the presence of the side grooves would make it difficult to focus the EB to the precise location of the interface. Previous experience of rewelding unirradiated specimens shows that this may be successful *before* the side grooves are machined.

The only option that seemed feasible was to increase the crack-starter hole diameter. The theory behind this modification is that a sufficiently large crack-driving force may cause the propagating flaw to "jump" through the sound material on either side of the unfused zone. Appendix B gives details of the trial tests made to verify this option using unirradiated specimens with an intentionally unfused zone. The tests indicated that such a process could be successful provided that the unfused region is no larger than approximately one-third of the net specimen thickness.

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*Photographs of irradiated materials are necessarily taken through the many lenses and mirrors of a Kollmorgen viewer and are not as sharp as normal ones taken directly of unirradiated specimens; see, for example, the photographs of unirradiated specimens shown in Appendix B.

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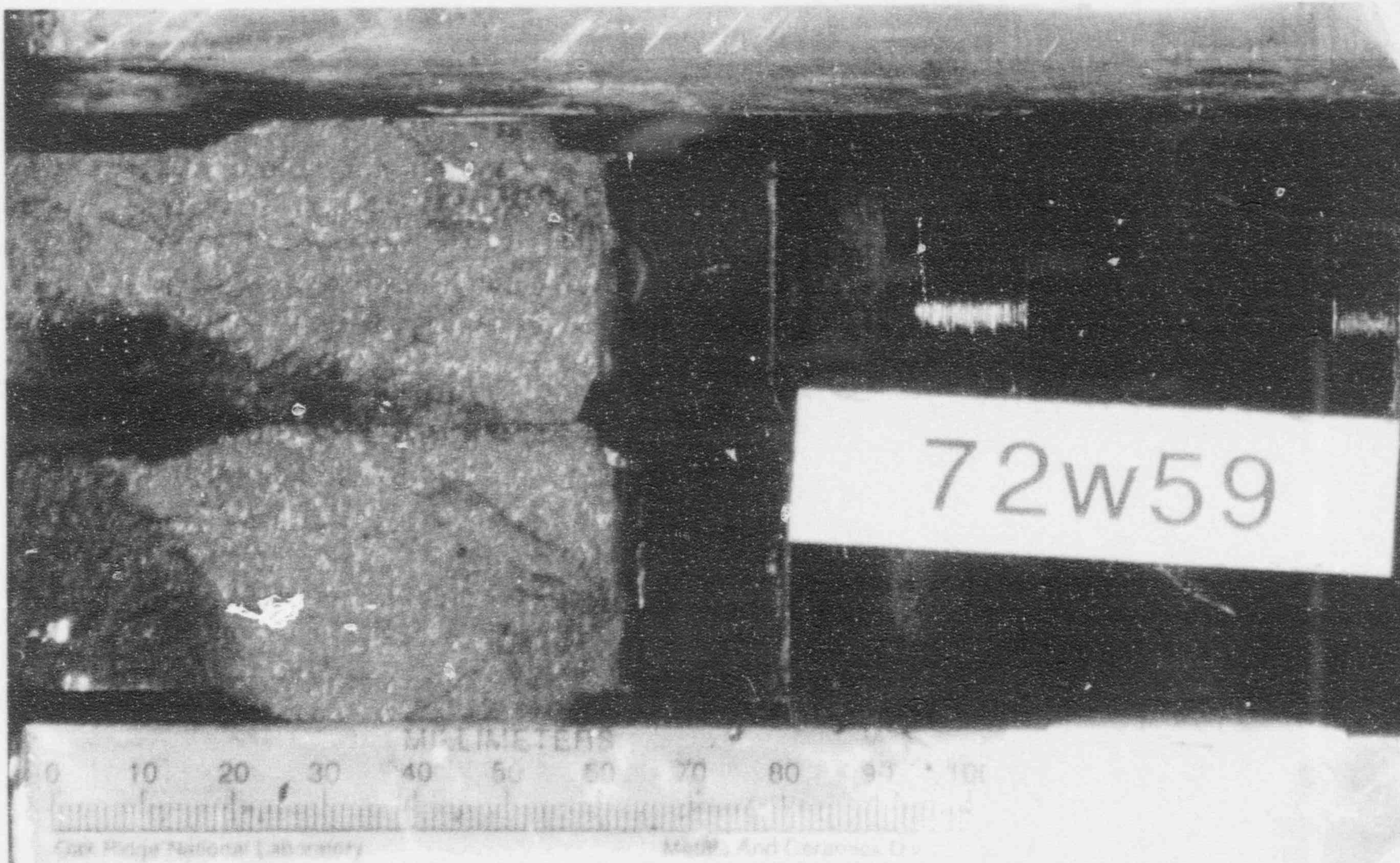

Figure 4. Fracture surfaces of one of the first of four unmodified irradiated duplex-type crack-arrest specimens tested.

Based on this limited success, a method had to be developed to increase the diameter of an existing hole with an adjoining slot. The problem of modifying this geometry in a hardened irradiated steel had to be addressed. The new hole must be tangential to the old one to preserve the initial crack length-to-width ratio. As is well known, it is not possible to use a drill, since the existing hole would have the tendency to force the centerline of the new hole to be concentric with the old one. The flutes of the drill would also catch on the edges of the slot, possibly stalling the equipment. The problem was solved by using a carbide-tipped end mill hole-trepanning cutter. Appendix C gives more details about this cutter and details about the lathe that was "configured" into a milling machine in order to perform this modification.

Following development of a technique to make an EB weld with a predetermined "defective zone," about ten unirradiated duplex crack-arrest specimens ("dummy specimens") were manufactured with an intentionally unfused EB weld zone, an approximate duplication of the duplex specimens previously tested. The crack-initiation force increases with diameter in a non-linear manner. The diameter of the hole in the irradiated duplex specimens was approximately 4 mm. Specimens with two different hole diameters, 16 and 19 mm (5/8 and 3/4 in.), were manufactured to determine the optimum hole diameter. The dummy specimens were machined from A 533 grade B base metal whose crack-arrest behavior was already known.

Only 5 of the 10 specimens with 16-mm-diam crack-starter holes were successfully tested. In the unsuccessful tests, the unfused region was too large to allow the crack to jump across it. However, in the five successful tests, a fast-running crack propagated across the unfused EB weld region and well into the test section. It was concluded that if the unfused region is no larger than about one-third of the net section at the root of the side grooves,* increasing the crack-starting hole diameter to 16 or 19 mm would increase the probability of obtaining useful data from the 20 irradiated crack-arrest specimens. The detailed results of these tests are given in Appendix B.

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*Which is indeed the case in some of the four irradiated 72W and 73W specimens already tested and mentioned above.

3. Results of Testing the Modified Duplex Crack-Arrest Specimens

Twelve each of HSSI welds 72W and 73W duplex crack-arrest specimens were irradiated in HSSI Capsules 6-1 and 6-2, respectively. Four were tested before the unfused EB weld region problem was discovered. Because all four specimens showed lack of fusion, it was considered to be a likely condition in all the specimens. The remaining 20 were eventually modified and tested, and this chapter presents the test results.

Of the ten specimens from each of welds 72W and 73W, there were four successful tests, all with specimens from weld 72W.* The crack-arrest toughness values, K_a; the irradiation exposures; and the validity criteria according to the ASTM Test for Determining Plane-Strain Crack-Arrest Fracture Toughness, K_{Ia}, of Ferritic Steels (E 1221 - 88) are given in Table 1. The K_a values for the duplex crack-arrest specimens have been plotted, together with those of the weld-embrittled specimens previously obtained, [1] against the test temperature in Figure 5. It may be seen that the K_a values of the duplex crack-arrest specimen all fall near the upper end of the scatter band of the K_a values of the previously tested 18 weld-embrittled crack-arrest specimens. It should be noted, however, that the average fluence of these four duplex crack-arrest specimens, 1.56 × 10^{19} neutrons/cm^2 (>1 MeV), is somewhat lower than that of the weld-embrittled crack-arrest specimens, 1.88 × 10^{19} neutrons/cm^2 (>1 MeV). Thus, the toughness values obtained from these specimens being somewhat higher than those of the weld-embrittled specimens seems reasonable.

*There was a single successful crack-initiation and run event in a specimen from weld 73W. Unfortunately, there is sufficient reason to question the accuracy of temperature indicated, and the result has not been used in this report. This particular specimen is shown in Appendix A.

The figure also shows two curves based on the ASME K_{Ia} equation*, which in SI units is:

$$K_a = 29.4 + 1.344\exp[0.0261(T - T_0 + 89)], \qquad (1)$$

where K_a is the crack-arrest toughness in MPa$\sqrt{m}$; T is the test temperature in °C; and T_0 is a parameter, in °C. The crack-arrest toughness data were fit to the above equation with T_0 as the unknown parameter. The process was performed once with the 18 weld-embrittled crack-arrest toughness values obtained previously, [1] then a second time with the results of both the 18 weld-embrittled and four duplex crack-arrest specimens. The T_0s were 14 and 12°C for the weld-embrittled and both specimen types, respectively. The smaller T_0 value reflects the influence of the higher K_a values of the duplex crack-arrest specimens compared to those of the weld-embrittled specimens.

The experimentally obtained crack-arrest toughness values for both unirradiated and irradiated 72W weld metal and for weld-embrittled and duplex-type specimens are plotted in Figure 6. Also shown on the same figure are two "mean"† American Society of Mechanical Engineers (ASME) curves with a T_0 determined by fitting the ASME equation to the K_a data for the 72W weld. The shift between the two curves is 84°C, within 1° of that or the CVN specimens irradiated to 1.8 × 10^{19} neutrons/cm^2 (>1 MeV). The shift of the $TT_{41\text{-}J}$ obtained from testing the CVN specimens of the Sixth Series and their scatter is discussed below. It should be recalled that the four duplex

*In the 1992 Addenda (issued December 31, 1992) of the ASME Boiler Pressure and Vessel Code, the following equation (converted to SI units) for K_{Ia} is given in Article A-4000 of Section XI :

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

The equation appears to be the simplification of the one given in WRC Bulletin 175 (August 1972) and not that of the K_{IR} equation given in Article G-2000 of Section III.

†All curve-fitting methods rely on minimizing the residual between the fitted curve and the data in some manner. In this report, such curves are sometimes referred to as "mean" curves.

Table 1. Irradiated crack-arrest toughness data for four duplex specimens from weld 72W. The average fluence and irradiation temperatures were 1.56 × 10^{19} neutrons/cm^2 (>1 MeV) and 288°C.

Specimen	Test temperature (°C)	K_a[a] (MPA√m)	Irradiation temperature (°C)	Exposure values			Validity[b]
				Fluence (neutrons/cm^2)		Displacements per atom	
				(>1 MeV)	(>0.1 MeV)		
A72W50	50	82.2	288	1.53E+19	1.020E+20	0.0379	
A72W51	75	133.0	289	1.67E+19	1.150E+20	0.0419	
A72W61	91	137.4	287	1.56E+19	1.040E+20	0.0385	
A72W72	75	152.8	287	1.49E+19	0.978E+20	0.0363	C,D

[a] K_a = value of stress intensity shortly after arrest.

[b] One or more letters for a specimen indicate that the test results did not meet one of the minimum lengths of the ASTM E 1221-88 validity criteria. The letters correspond to those in Table 2 of ASTM E 1221-88; in particular, C = specimen too thin - the standard prescribes (based on plastic zone size considerations) 37 mm (1.46 in.), and the actual thickness was 33 mm (1.3 in.); and D = insufficient crack-jump length - the standard prescribes (based on twice the crack-starter hole diameter) 38 mm (1.5 in.), and the actual jump was 31 mm (1.23 in.).

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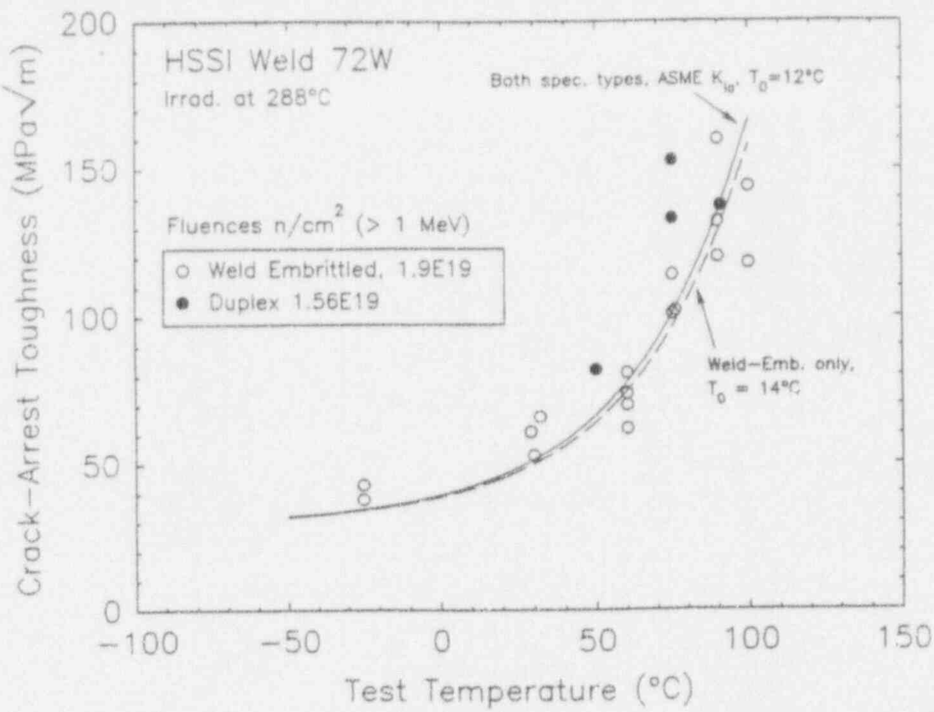

Figure 5. Crack-arrest toughness, K_a, for irradiated HSSI weld 72W showing the results of both weld-embrittled and duplex-type specimens.

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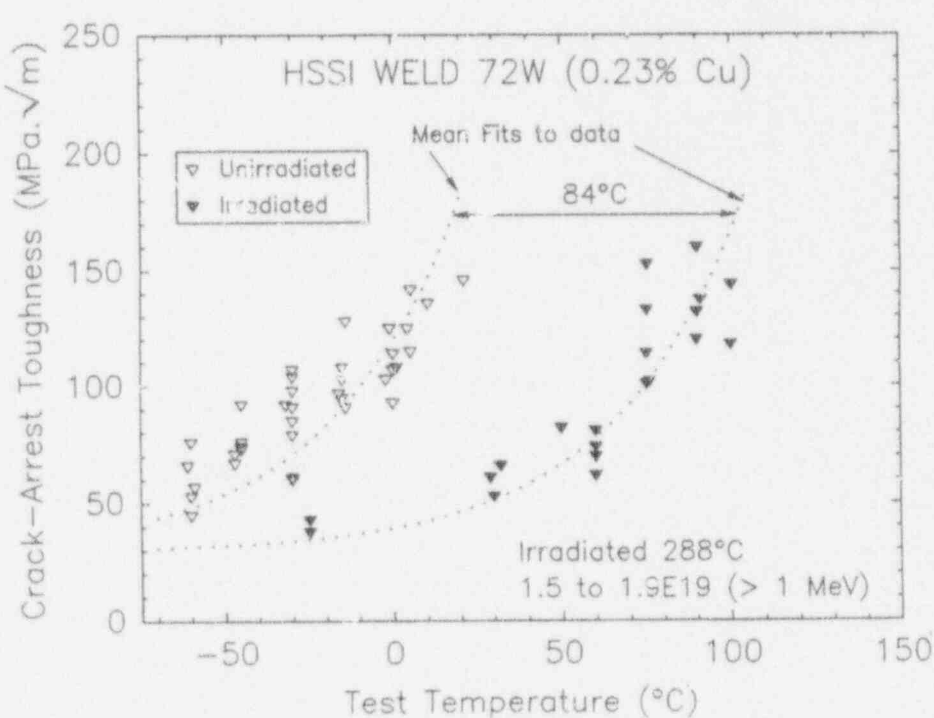

Figure 6. Crack arrest toughness values for both unirradiated and irradiated 72W weld metal and for weld-embrittled and duplex-type specimens.

crack-arrest specimens were irradiated to 1.6×10^{19} neutrons/cm^2 (>1 MeV) compared to 1.9×10^{19} neutrons/cm^2 (>1 MeV) for the weld embrittled specimens. No adjustment was made when they were considered as one set with the weld-embrittled specimens. Such adjustments may be made in the final report on the Sixth Series. The calculation of stress-intensity factor, K_a, is performed according to ASTM E 1221-88. The exact specimen dimensions, intermediate calculations, and outcome of calculations of the validity criteria according to ASTM E 1221-88, etc., are given in Appendix D.

3.1 The Shift in $TT_{41\text{-}J}$ and Scatter of Sixth Series CVN Specimens

Correlating the transition temperature shift of irradiated crack-arrest specimens to that of CVN specimens is one of the important objectives of the Sixth Irradiation Series. The determination of RT_{NDT}, $TT_{41\text{-}J}$, and its shift is based on a large number of drop-weight and CVN specimens that were tested as part of the Fifth Irradiation Series. In order to make some judgment about the possible differences in shift between the Fifth and Sixth Series, 22 CVN specimens were included in each of the two Sixth Irradiation Series capsules. These 44 CVN specimens were recently tested, and the detailed results are given in Appendix E. The exposures of CVN specimens were such that they were tested in two groups from each of the 72W and 73W welds. A "*high fluence*" group consisted of 7 specimens with an average fluence of approximately 1.8 to 1.9×10^{19} neutrons/cm^2 (>1 MeV), while a "*low fluence*" group consisted of 15 specimens with an average fluence of approximately 1.2 to 1.3×10^{19} neutrons/cm^2 (>1 MeV).

The seven specimens from the "high fluence" group from each of HSSI welds 72W and 73W were insufficient to obtain a full CVN impact energy curve, so they were divided into two subgroups of three and four specimens. One subgroup was tested at a temperature estimated to be lower than $TT_{41\text{-}J}$ and the other at a temperature higher than the estimated $TT_{41\text{-}J}$. A straight line was fit to the CVN impact energy values using linear regression and the $TT_{41\text{-}J}$ calculated from the equation of the straight line.

In the case of the 15 specimens from the "low fluence" group of each weld, a full CVN impact energy curve was obtained, and the results were analyzed using two approaches. One approach was to fit a hyperbolic tangent equation to the CVN impact energy values using non-linear regression. Since a straight line has already been used to analyze the high fluence results, it was of interest to use it also on a subset of the "low fluence" group. Thus, the second approach was to fit a straight line to the CVN impact energy values chosen at two temperatures that bracket the $TT_{41\text{-}J}$. The $TT_{41\text{-}J}$s from the straight-line fit for both 72W and 73W welds could then be compared to those obtained from the hyperbolic tangent equation.

A summary of the analysis of the CVN test results is given in Tables 2(*a*) and (*b*). Also included in Table 2(*a*) is the $TT_{41\text{-}J}$ for the CVN specimens from the Fifth Irradiation Series capsules and whose average fluence is approximately 1.5×10^{19} neutrons/cm^2 (>1 MeV). A comparison of the $TT_{41\text{-}J}$ at the three fluence levels shows that the $TT_{41\text{-}J}$ from the Sixth Irradiation Series capsules is higher than the $TT_{41\text{-}J}$ from the Fifth Irradiation Series capsules. For the higher fluence specimens, this was to be expected but not for the lower fluence ones. As may be seen from Table 2(*b*), the use of a straight-line or a hyperbolic fit did not have a significant change to the value of $TT_{41\text{-}J}$.

In order to determine whether scatter or the smaller number of specimens in the Sixth Series could account for this discrepancy (56 specimens were tested in the Fifth Series), a statistical analysis was performed. As a measure of scatter, two intervals are used: the confidence and prediction. As described in the user's manual for TableCurve [2] (the computer software that was used to perform the statistical analysis), confidence intervals "are a measure of how accurately the average curve for repeated experiments is determined." Reference 2 also gives the following explanation of confidence intervals. The 95% **confidence limits** give the limits in which 95 out of 100 ***average*** curves would fall if the experiment were repeated a large number of times, say 100 times. On the other hand, the "**prediction limits** define the confidence intervals for an ***individual curve fit***" (also quoted from the TableCurve manual).

The confidence and prediction intervals for all six sets of data are shown in Table 3. The values shown in Table 3 for the fluence of 1.5×10^{19} neutrons/cm^2 agree with those in Table 10, p. 58 of ref. [3], which were generated with a different software package. The mean $TT_{41\text{-}J}$ and *temperature* span of the 95% confidence

Table 2(*a*). Transition temperatures at the 41-J impact energy level ($TT_{41\text{-}J}$), the $TT_{41\text{-}J}$ shifts, the temperature at the 68-J impact energy level, parameters of the hyperbolic tangent equation used to fit the Charpy V-notch (CVN) test results, and the number of CVN specimens tested for the Fifth and Sixth Irradiation Series.

Material	Transition temperature			Tanh fit parameters[a]			Number of specimens
	41 J (°C)	Shift (°C)	68 J (°C)	USE (J)	MTT (°C)	TZW (°C)	
72W unirradiated and irradiated at 288°C to values shown (neutrons/cm², >1 MeV)							
Unirradiated	-28		-6	136.3	-4.5	103.6	84
Irradiated:							
1.2×10^{19}	59	87	88	92.0	65.4	88.5	15
1.5×10^{19}	44	72	77	95.9	53.7	110.0	56
1.8×10^{19}	55	83	80[b]	[c]	[c]	[c]	7
73W unirradiated and irradiated at 288°C to values shown (neutrons/cm², >1 MeV)							
Unirradiated	-40		-18	134.6	-17.0	101.1	83
Irradiated:							
1.3×10^{19}	56	96	104	98.4	72.9	162.5	15
1.5×10^{19}	42	82	87	90.7	51.1	135.1	56
1.9×10^{19}	63	103	108[b]	[c]	[c]	[c]	7

[a]The following equation was used to fit the data: Energy = (USE + 2.7)/2 + [(USE - 2.7)/2] Tanh (T - MTT)/(TZW/2), where USE = upper-shelf energy, 2.7 = lower-shelf energy, MTT = mid-transition temperature, and TZW = transition zone width. The 2.7 J is the lower-shelf energy and was determined experimentally from five tests conducted at liquid nitrogen temperature, -196°C, on a submerged-arc weld from the Midland reactor pressure vessel.

[b]Extrapolated from available data.

[c]Not enough specimens to generate a complete curve in order to fit a hyperbolic tangent equation. A straight line was fit, and the parameters are given in Table 2(*b*).

Table 2(*b*). Comparison of the $TT_{41\text{-}J}$ obtained from fitting either a straight line or a hyperbolic tangent to the Charpy V-notch impact energy test results of the Sixth Series specimens. The parameters for the straight-line fit are also given. At the lower fluence, the straight line was fit to the test results at only the two temperatures that bracketed the $TT_{41\text{-}J}$.

Material	$TT_{41\text{-}J}$ (°C) obtained using		Parameters for a + bT	
	Straight line	Hyperbolic tangent	a (°C)	b (J/°C)
72W irradiated at 288°C to values shown (neutrons/cm², >1 MeV)				
1.2×10^{19}	60	59	-37.3	1.304
1.8×10^{19}	55	[a]	-18.4	1.078
73W irradiated at 288°C to values shown (neutrons/cm², >1 MeV)				
1.3×10^{19}	53	56	19.99	0.394
1.9×10^{19}	63	[a]	2.90	0.603

[a]Insufficient data for a hyperbolic tangent fit.

Table 3. Temperatures at the 41-J Charpy V-notch impact energy level for mean, confidence, and prediction intervals for specimens machined from HSSI welds 72W and 73W and irradiated in the Fifth and Sixth Series

Fluence, 10^{19} neutrons/cm^2 (>1 MeV)	Number of specimens	$TT_{41\text{-}J}$ (°C)	95% confidence interval (°C)			95% prediction interval (°C)		
			Lower	Upper	Span	Lower	Upper	Span
HSSI weld 72W								
1.2	15	59	54	65	11	41	76	35
1.5	56	44	39	49	10	15	68	53
1.8	7	55	46	80	34	24	102	78
HSSI weld 73W								
1.3	15	56	35	69	34	3	94	91
1.5	56	42	35	48	13	−1	78	79
1.9	7	63	54	83	29	35	102	67

intervals have been plotted in Figure 7. The overlap of the 95% confidence intervals on the means (which were used to calculate the $TT_{41\text{-}J}$) of the low fluence results of the 73W weld could explain the reason that the $TT_{41\text{-}J}$ at a fluence level of 1.3×10^{19} neutrons/cm^2 (>1 MeV) is greater than the $TT_{41\text{-}J}$ for 1.5×10^{19} neutrons/cm^2. However, this is not the case for the low fluence results of the 72W weld. This matter will be investigated further and, if resolved, the reasons for this anomaly given in the final report on the Sixth Irradiation Series on crack-arrest specimens.

Noteworthy are the relatively large temperature spans (given in Table 3) for the ±95% prediction intervals at the 41-J energy level for the two welds. These results are surprising, particularly since the fabrication of HSSI 72W and 73W welds was very carefully controlled in the sense that the copper was added to the melt prior to drawing of the weld wire and did not originate from a dip coating.

References

1. S. K. Iskander, W. R. Corwin, and R. K. Nanstad, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., *Results of Crack-Arrest on Two Irradiated High-Copper Welds*, USNRC Report NUREG/CR-5584 (ORNL/TM-11575), December 1990.*

2. *User's Manual for TableCurve for Windows*, Version 1.0, Jandel Scientific, San Rafael, California, 1992, pp. 4-126.†

3. R. K. Nanstad, F. M. Haggag, D. E. McCabe, S. K. Iskander, K. O. Bowman, and B. H. Menke, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., *Irradiation Effects on Fracture Toughness of Two High-Copper Submerged-Arc Welds, HSSI Series 5*, USNRC Report NUREG/CR-5913, Vol. 1 (ORNL/TM-12156/V1), August 1992.*

ORNL-DWG 93-11680

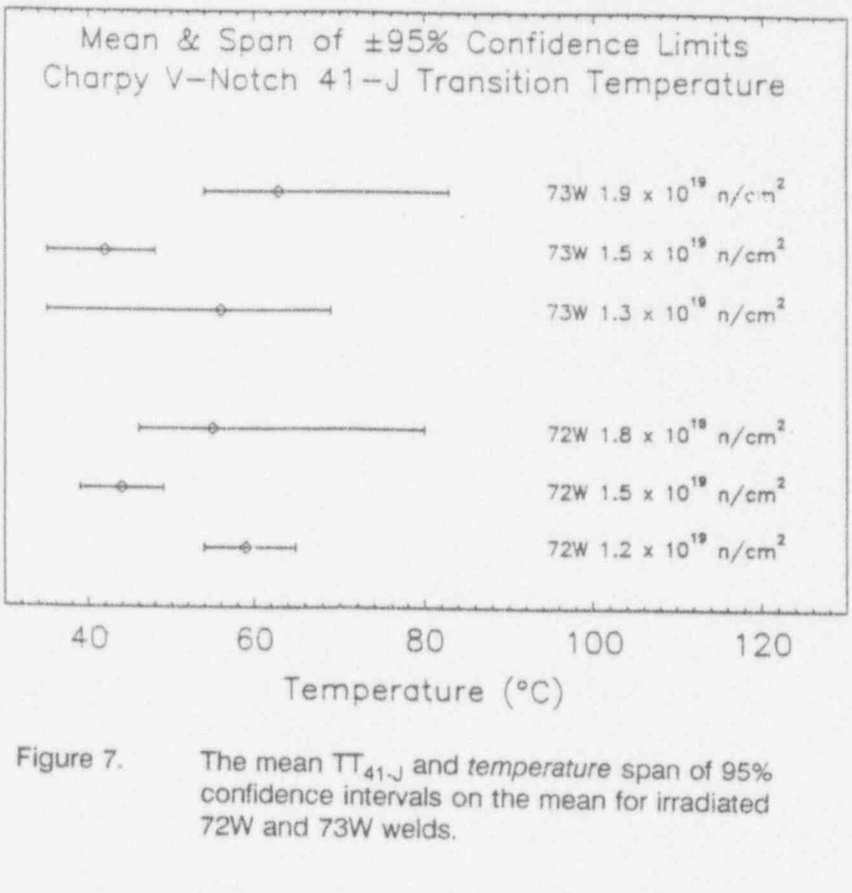

Figure 7. The mean $TT_{41\text{-}J}$ and *temperature* span of 95% confidence intervals on the mean for irradiated 72W and 73W welds.

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

†Available for purchase from the publisher.

4. Discussion

Twenty-four duplex crack-arrest specimens were tested. Lack of fusion was discovered after testing the first four specimens, and considerable efforts were made to obtain data from the remaining specimens. By increasing the crack-driving force, a propagating crack was able in five instances to bridge the gap created by the lack of fusion. Four of these specimens were of HSSI weld 72W, and the results of the tests have been incorporated into the data base on irradiated crack-arrest toughness. This brings the number of irradiated toughness values to 39 for welds 72W and 73W and more than doubles the previously known values of irradiated crack-arrest toughness. Unfortunately, the temperature measurement of the only duplex crack-arrest specimen from weld 73W in which a crack was successfully initiated is suspect, and it was not included in the preliminary analysis performed.

The average fluence of the four duplex crack-arrest specimens for weld 72W is slightly smaller than that of the weld-embrittled specimens. Thus, the toughness values obtained from these four duplex crack-arrest specimens being somewhat higher than those of the weld-embrittled specimens seems reasonable. However, data from CVN specimens irradiated to two different fluences with the crack-arrest specimens give results that require further analyses. The data from the Sixth Irradiation Series capsules will be reexamined for the final report on the Sixth Series.

Preliminary analyses seem to indicate that the shift between the ***mean*** curves of the 72W weld metal for the unirradiated and irradiated crack-arrest toughness values agree well with the 41-J energy level shift from the CVN specimens irradiated together with the crack-arrest specimens.

Appendix A

Load Displacement Records and Fracture Surfaces

Appendix A

Load Displacement Records and Fracture Surfaces

This appendix gives the fracture surface and load displacement output (from X-Y recorder charts) of every specimen tested, whether it was successful or not (4 of the 24 duplex specimens tested were successful*). It is still believed that crack-arrest testing can yield valuable "valid" lower-bound toughness data in the transition and lower mid-transition regions for reactor pressure vessel steels. This may be accomplished by using both dimensionally smaller specimens and a smaller number of specimens than would be otherwise possible using K_{Ic} specimens of sufficient capacity to give valid values according to American Society for Testing and Materials (ASTM) E 399. It is also believed that the so-called validity criteria in the ASTM Test for Determining Plane-Strain Crack-Arrest Fracture Toughness, K_{Ia}, of Ferritic Steels (E 122-88) may be overly conservative because they do not take into account the time dependence of plastic flow. Most of the plastic flow that occurs in crack-arrest specimens develops *after* the crack has arrested. Thus, some of the validity criteria on specimen thickness and length of remaining ligament may be overly conservative.

One of the problems of crack-arrest testing arises from the difficulties in making a judgment about the extent of crack propagation after a sudden load drop has occurred. In the case where the crack has arrested in the heat-affected zone (HAZ) [particularly duplex-type crack-arrest specimens], and it is decided to discontinue the test, the likely result will be the loss of a specimen. However, if it was decided that the observed crack jump was just to the HAZ, it may still be possible to obtain useful data by testing at a lower temperature.† Unirradiated weld-embrittled specimens can be reused by removing the brittle bead and some of the adjoining area, rewelding, remachining, and retesting the specimen. One method available for judging the extent of crack propagation is the ratio of the minimum load just after arrest to maximum load prior to crack propagation. A rule of thumb is that if this ratio is about 0.40 or less, then the crack has propagated sufficiently for a successful test. A useful area of future investigation would be the development of a simple and more reliable method of judging the amount of crack extension without breaking open the specimen.

Much of the experience gained during crack-arrest testing is obtained by examining the X-Y plotter output and relating it to features on the fracture surface, information that is important to document. All photographs lose some resolution after they are printed. Photographs of fracture surfaces of irradiated specimens are often made through a Kollmorgen periscope whose optical system deteriorates with time because of the radiation to which it is subjected. Hence, the fracture surfaces of irradiated specimens are not as detailed as those of unirradiated specimens.* A special video camera was recently investigated for use in the hot cell, and the results were not much better.

Following are five subsections (Tables A-1 through A-5) with the fracture surfaces and X-Y charts for the following groups of specimens: (1) the first four specimens tested, with original approximately 4-mm-diam crack-starter hole, followed by the fracture surfaces and X-Y charts after crack-hole modification; (2) successful tests on 72W weld metal; (3) the only 73W weld metal specimen with a crack to have run into the test section; (4) unsuccessful tests on 72W weld metal; and (5) unsuccessful tests on 73W weld metal. Since storage of irradiated materials is becoming difficult, most of the specimen halves will eventually be disposed of. These tables also document the present status of the specimen remains, that is, whether they will be stored or disposed of.†

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*In Phase 1 of this program, 35 of the 36 specimens tested were successful.

†See, for example, test on specimen A72W50 whose fracture surfaces and test charts are shown in Table A-2 of this appendix.

*Compare the photos of the irradiated specimens shown in this appendix with those of unirradiated ones in Appendix B.

†The Oak Ridge National Laboratory has often received requests from other institutions for specimen halves. This is particularly true for materials such as the 72W and 73W weld metal because of the very significant amount of characterization performed on these two materials.

Table A-1. First four specimens tested with original 3- to 4-mm crack-starter hole diameter

Specimen	Hole diameter mm (in.)	Test temperature (°C)	Figure No.[a]	Remarks and status
A72W59	3.56 (0.14)	120	A.1	Both halves of these four specimens have been marked for disposal.
A72W67	4.32 (0.17)	120	A.2	
A73W67	3.56 (0.14)	120	A.3	
A73W71	4.32 (0.17)	120	A.4	

[a]There are two figures for each of these numbers, except where indicated; a = fracture surface and b = output from X-Y recorder.

Table A-2. Successful tests on 72W weld metal after crack-starter hole modification

Specimen	Hole diameter mm (in.)	Test temperature (°C)	Figure No.[a]	Remarks and status
A72W50	16 (5/8)	50	A.5	Successfully retested at 50°C.
		120	A.5c	This is the chart for first test at 120°C. Only one-half of
A72W51	19 (3/4)	75	A.6	all these specimens will be stored until the final report is
A72W61	19 (3/4)	91	A.7	published. They will then be disposed of. The other
A72W72	19 (3/4)	75	A.8	half has already been marked for disposal.

[a]There are two figures for each of these numbers, except where indicated; a = fracture surface and b = output from X-Y recorder.

Table A-3. Successful crack-run event on 73W weld metal after crack-starter hole modification

Specimen	Hole diameter mm (in.)	Test temperature (°C)	Figure No.[a]	Remarks and status
A73W53	19 (3/4)	Temperature indicator malfunction	A.9	Only one-half of this specimen will be kept until the final report is published. It will then be disposed of. The other half has already been marked for disposal.

[a]There are two figures for each of these numbers, except where indicated; a = fracture surface and b = output from X-Y recorder.

Table A-4. Unsuccessful tests on 72W weld metal

The crack-initiation force drops very rapidly during propagation from the crack-starter hole to the electron beam (EB) weld. Thus, an attempt was made to warm prestress specimen A72W49 by allowing the crack to propagate to the EB weld at 150°C, then reloading it at 95°C. By blunting the crack, the crack-initiation force would also be increased. This was not successful in forcing the flaw to jump over the unfused region. This specimen was then heat tinted, chilled, and broken open as usual, but the specimen did not break along the side grooves as usual. Rather, it broke into 1/4 and 3/4 pieces as shown below. This particular specimen reveals very clearly the unfused region running along the entire specimen height.

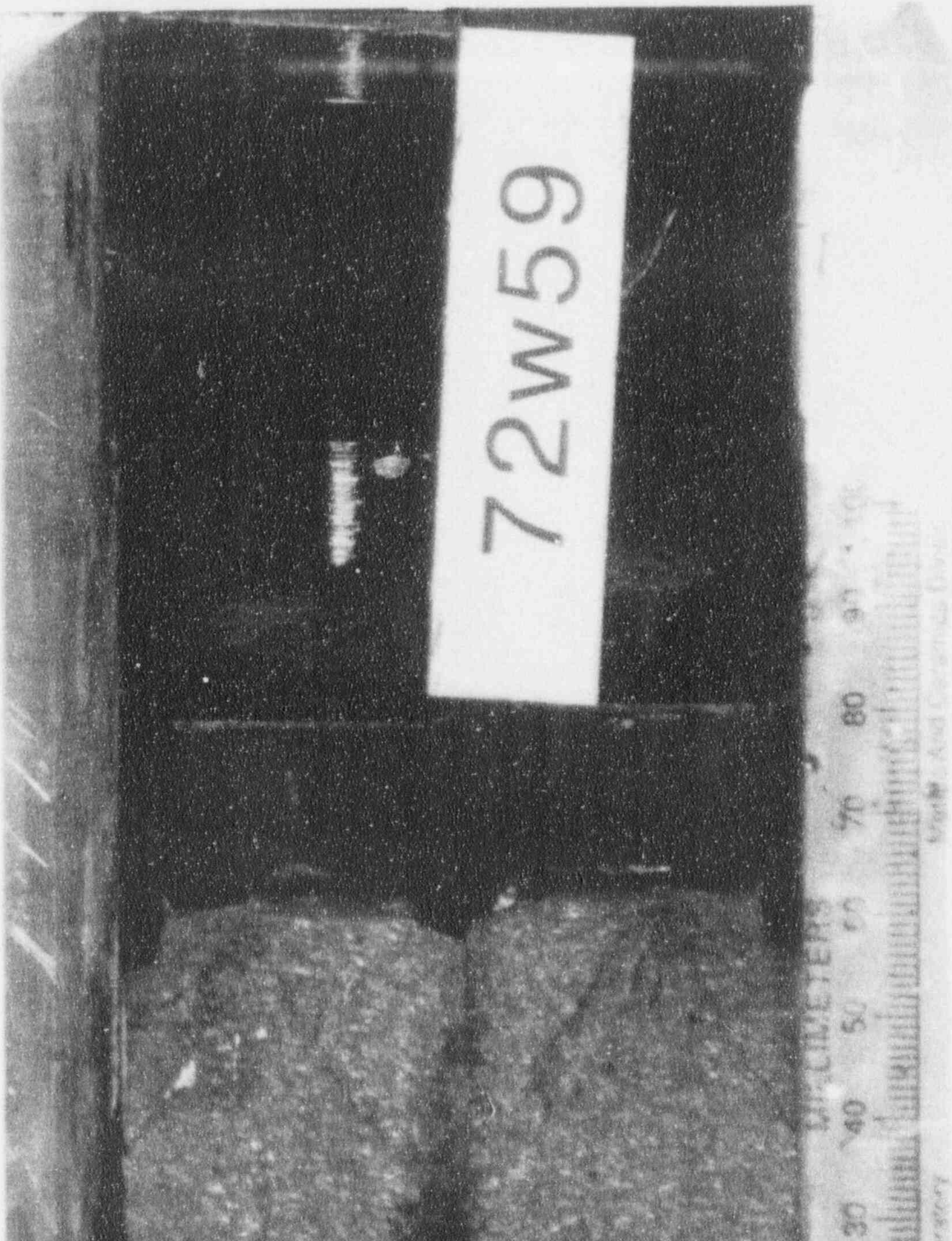
Specimen	Hole diameter mm (in.)	Test temperature (°C)	Figure No.[a]	Remarks and status
A72W49	16 (5/8)	150 and 95	A-10	Only one-half of specimen A72W55 will be kept until the final report is published. It will then be disposed of. All others have been marked for disposal.
A72W52	19 (3/4)	112	A-11	
A72W53	19 (3/4)	90	A-12	
A72W54	19 (3/4)	90	A-13	
A72W55	19 (3/4)	95	A-14	
A72W58	19 (3/4)	100	A-15	

[a]There are two figures for each of these numbers, except where indicated; a = fracture surface and b = output from X-Y recorder.

Table A-5. Unsuccessful tests on 73W weld metal

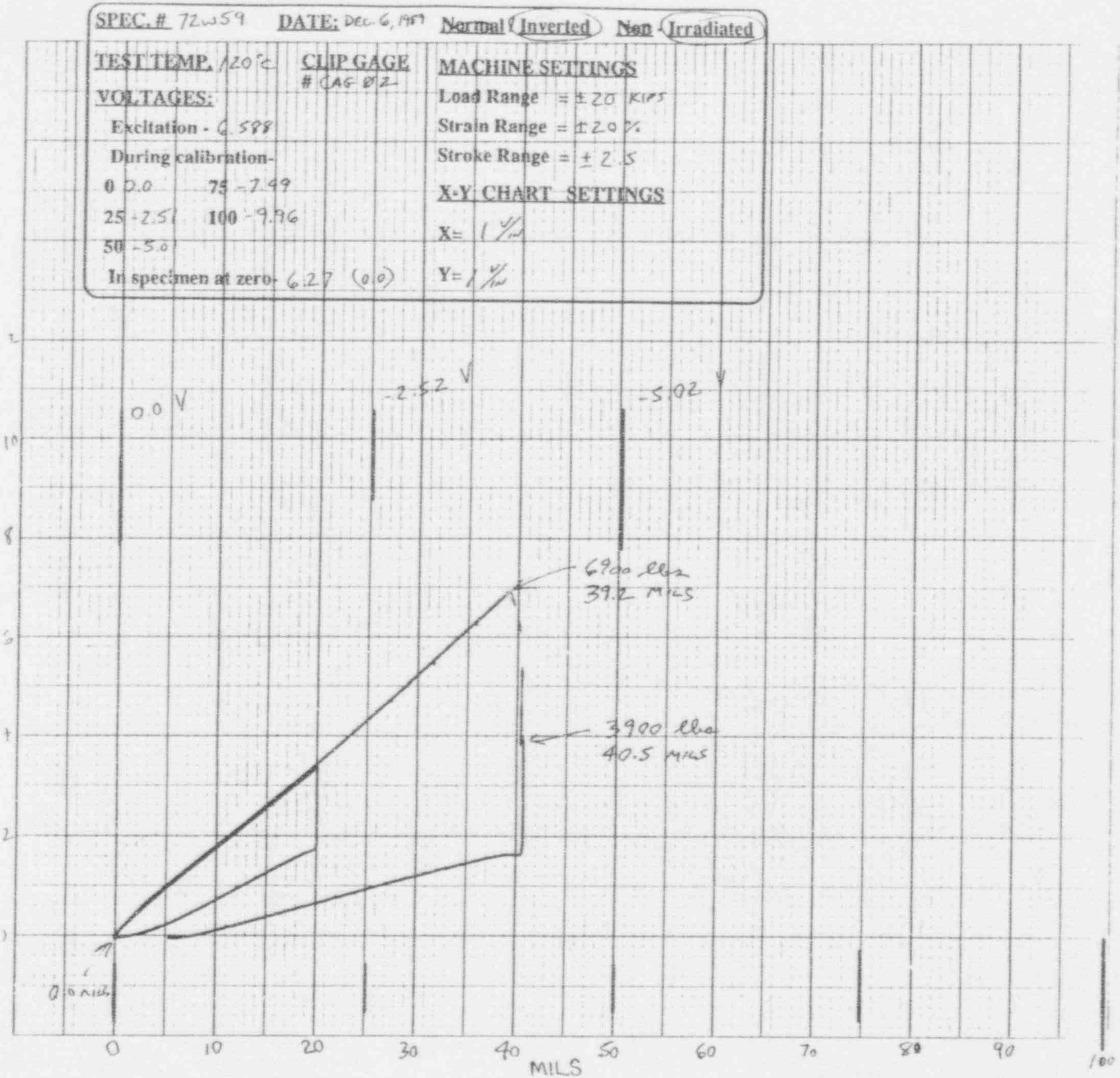
Specimen	Hole diameter mm (in.)	Test temperature (°C)	Figure No.[a]	Remarks and status
A73W54	16 (5/8)	92	A-16	Only one-half of specimens A73W53, A73W59, and A73W66 will be kept until the final report is published. They will then be disposed of. All others have been marked for disposal.
A73W55	19 (3/4)	100	A-17	
A73W56	19 (3/4)	75	A-18	
A73W59	19 (3/4)	60 and 30	A-19	
A73W61	19 (3/4)	100	A-20	
A73W63	19 (3/4)	60	A-21	
A73W66	19 (3/4)	110 and 60	A-22	
A73W69	19 (3/4)	101	A-23	
A73W72	16 (5/8)	80	A-24	

[a]There are two figures for each of these numbers, except where indicated; a = fracture surface and b = output from X-Y recorder.



a

b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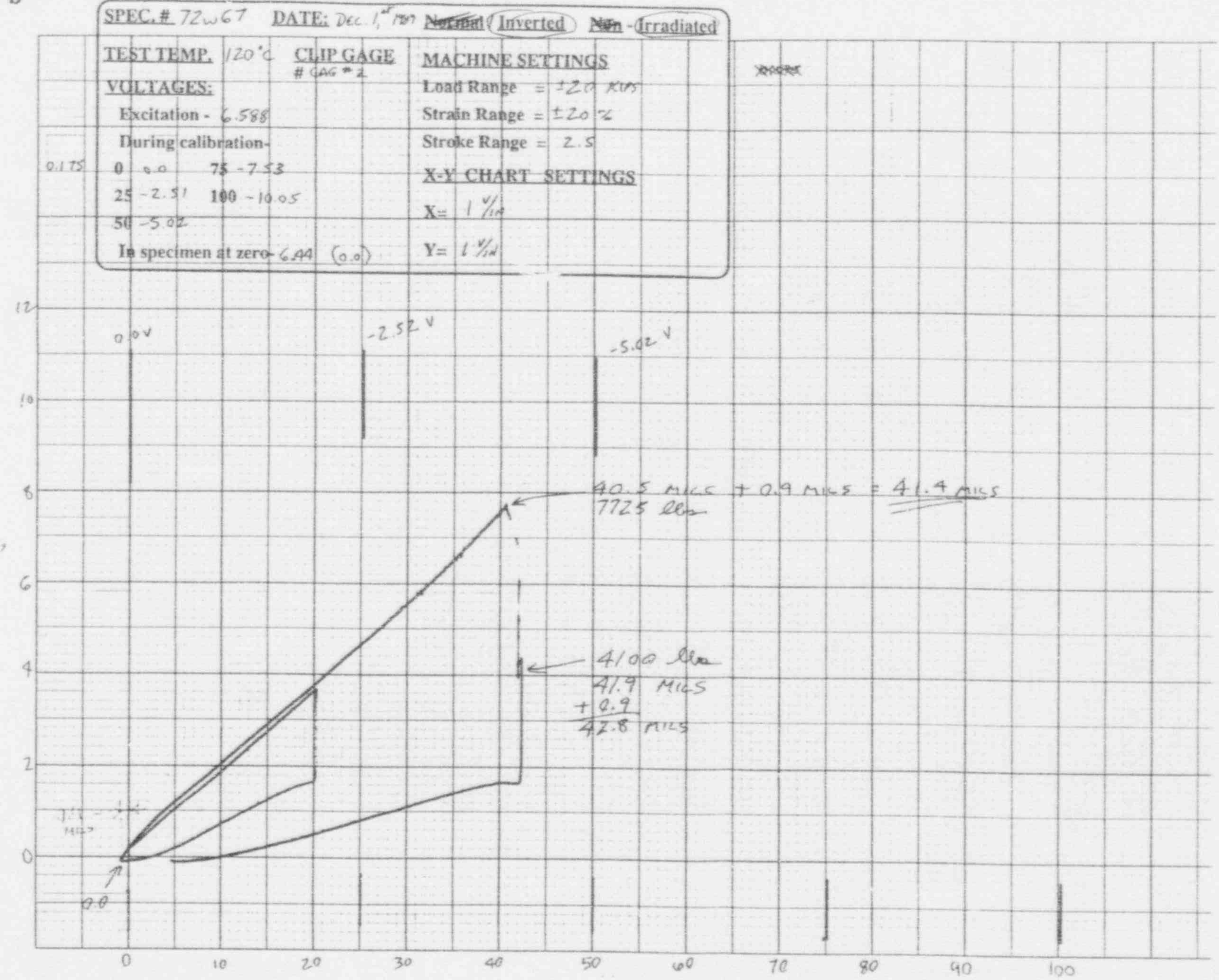
25 -2.51 100 -9.96
50 -5.0
In specimen at zero- 6.27 (0.0)
MACHINE SETTINGS
Load Range = ±20 KIPS
Strain Range = ±20%
Stroke Range = ±2.5
X-Y CHART SETTINGS
X= 1 V/in
Y= 1 V/in
0.0 V
-2.52 V
-5.02 V
6900 lbs 39.2 MILS
3900 lbs 40.5 MILS
MILS


72w67
Oak Ridge National Laboratory
Metals And Ceramics Division

a

b



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VOLTAGES:
Excitation - 6.588
During calibration-
0 0.0 75 -7.53
25 -2.51 100 -10.05
50 -5.02
In specimen at zero -6.44 (0.0)
MACHINE SETTINGS
Load Range = ±20 KIPS
Strain Range = ±20 %
Stroke Range = 2.5
X-Y CHART SETTINGS
X= 1 V/in
Y= 1 V/in
0.175
0.0 V
-2.52 V
-5.02 V
40.5 MILS + 0.9 MILS = 41.4 MILS
7725 lbs
4100 lbs
41.9 MILS
+ 0.9
42.8 MILS
0.0
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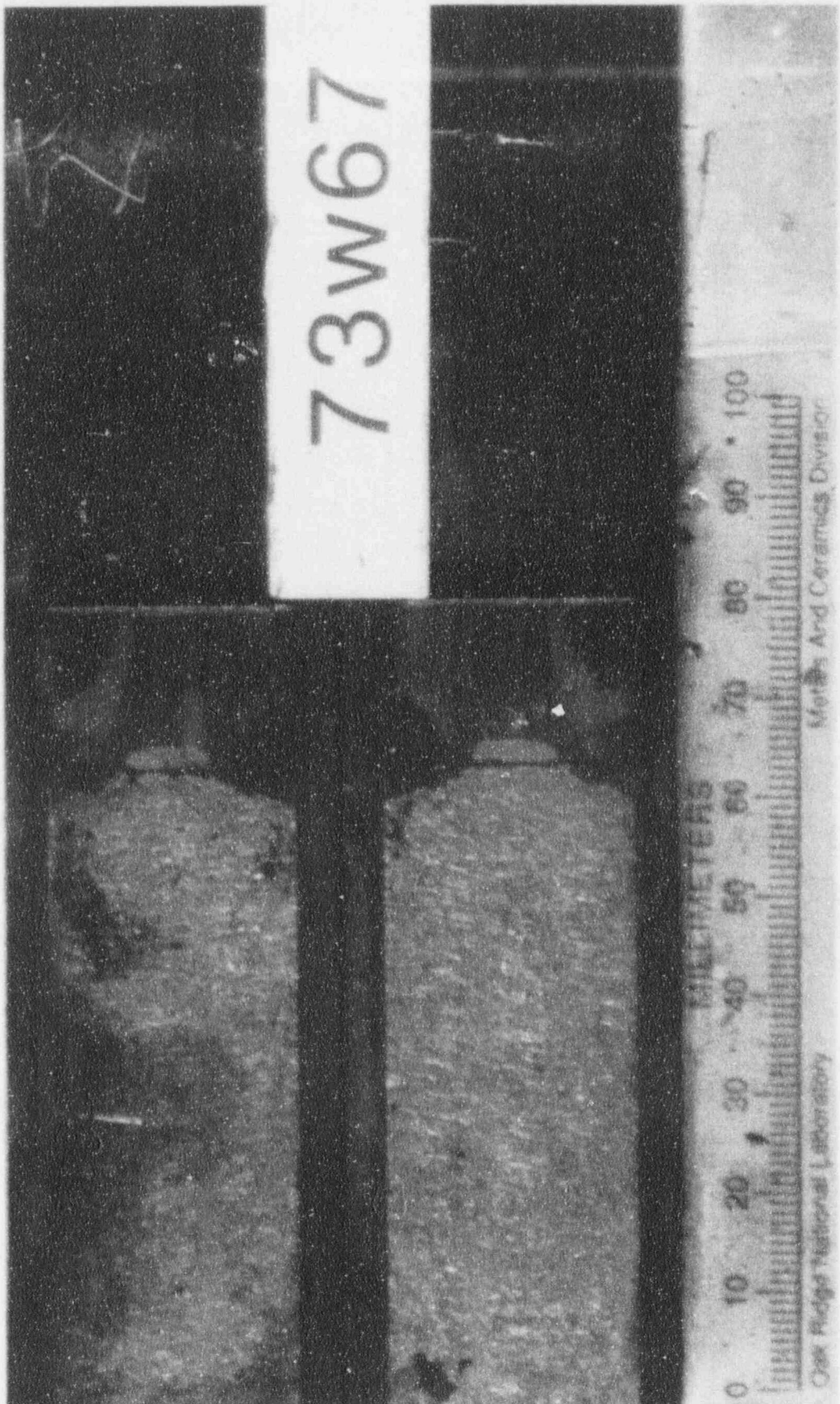
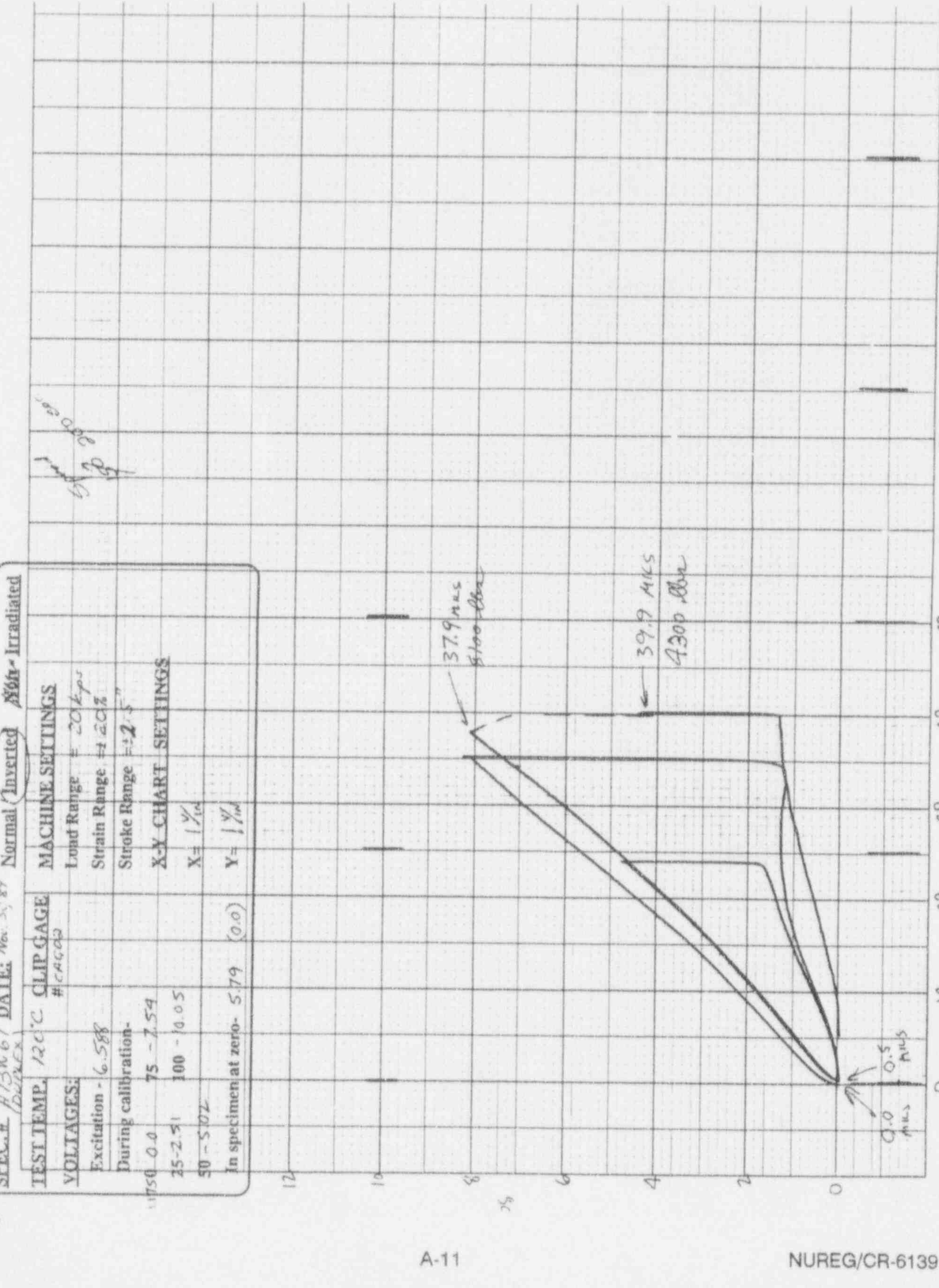
10
8
6
4
2
0
0
10
20
30
40
50
60
70
80
90
100


73w67
MILLIMETERS
Oak Ridge National Laboratory
Metals And Ceramics Division

b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CLIP GAGE
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VOLTAGES:
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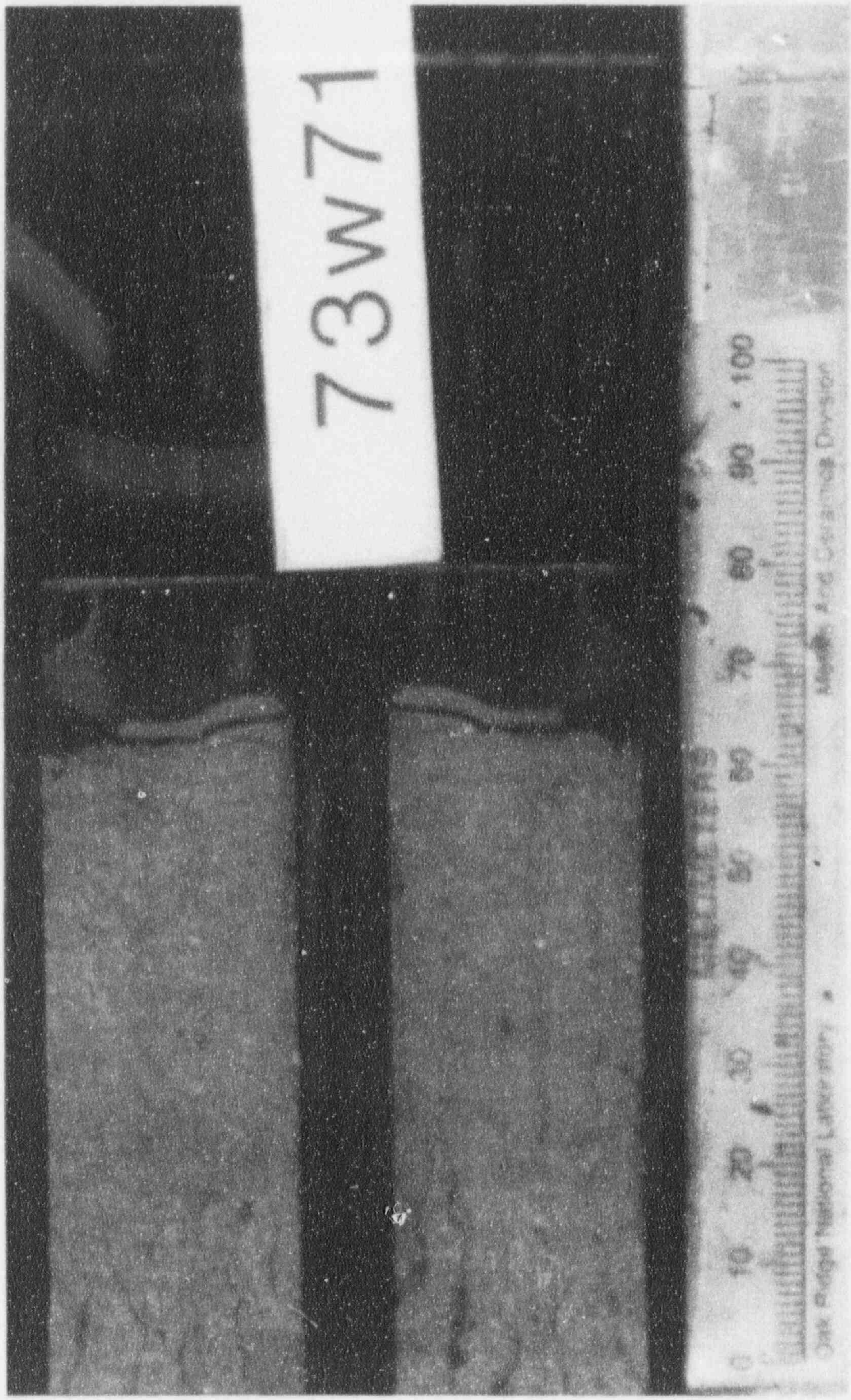
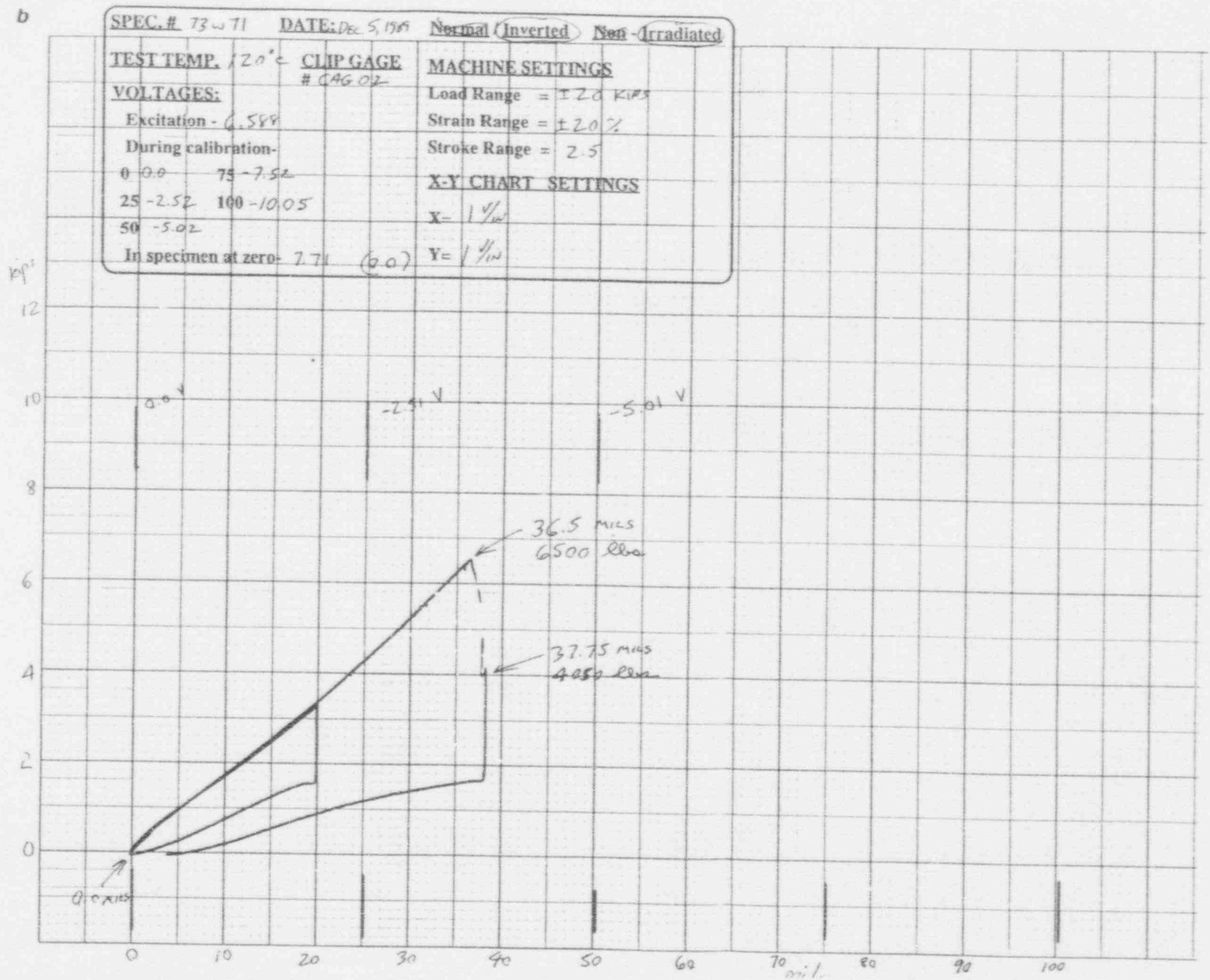
Load Range
Strain Range
Stroke Range
During calibration-
X-Y CHART SETTINGS
In specimen at zero- 5.79
37.9
39.9


73w71
Oak Ridge National Laboratory
Metals And Ceramics Division

a

b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Non - Irradiated
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CAG 02
VOLTAGES:
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During calibration-
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75 -7.52
25 -2.52
100 -10.05
50 -5.02
In specimen at zero- 7.71 (0.0)
MACHINE SETTINGS
Load Range = ±20 KIPS
Strain Range = ±20%
Stroke Range = 2.5
X-Y CHART SETTINGS
X= 1 V/in
Y= 1 V/in
kips
12
10
8
6
4
2
0
0.0 V
-2.51 V
-5.01 V
36.5 MILS
6500 lbs
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4050 lbs
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0
10
20
30
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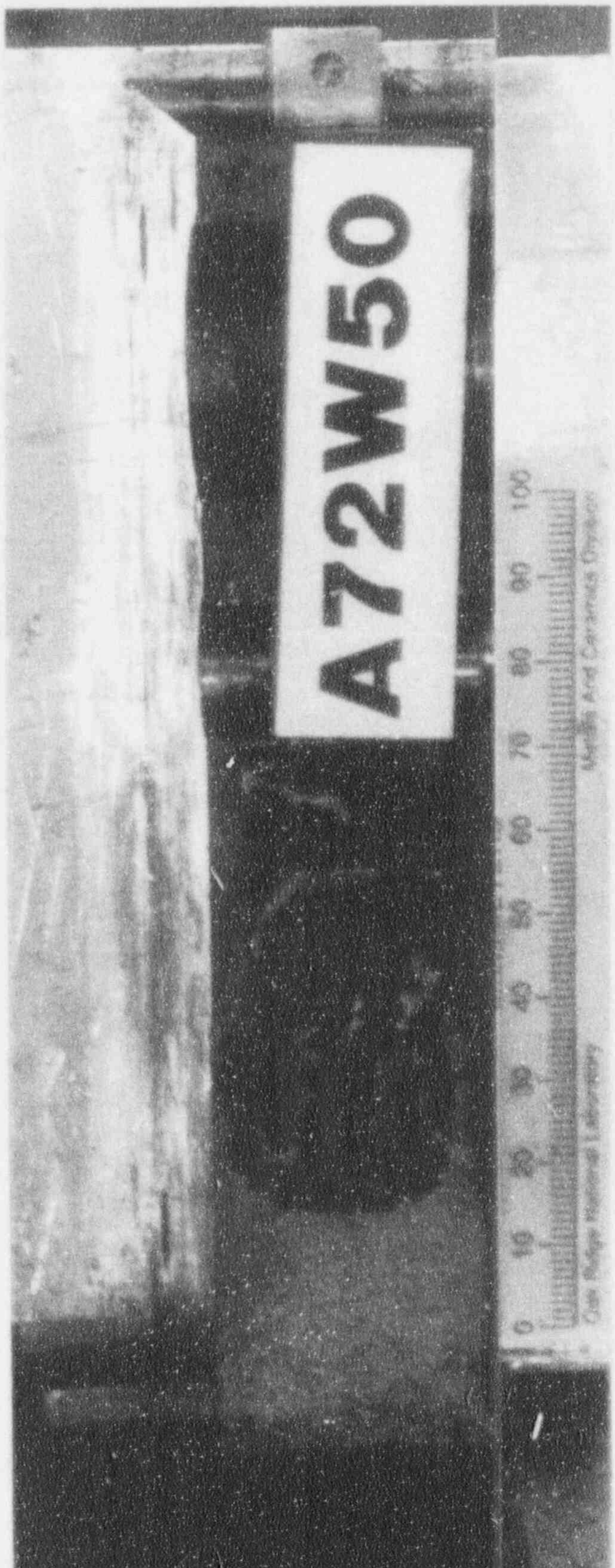
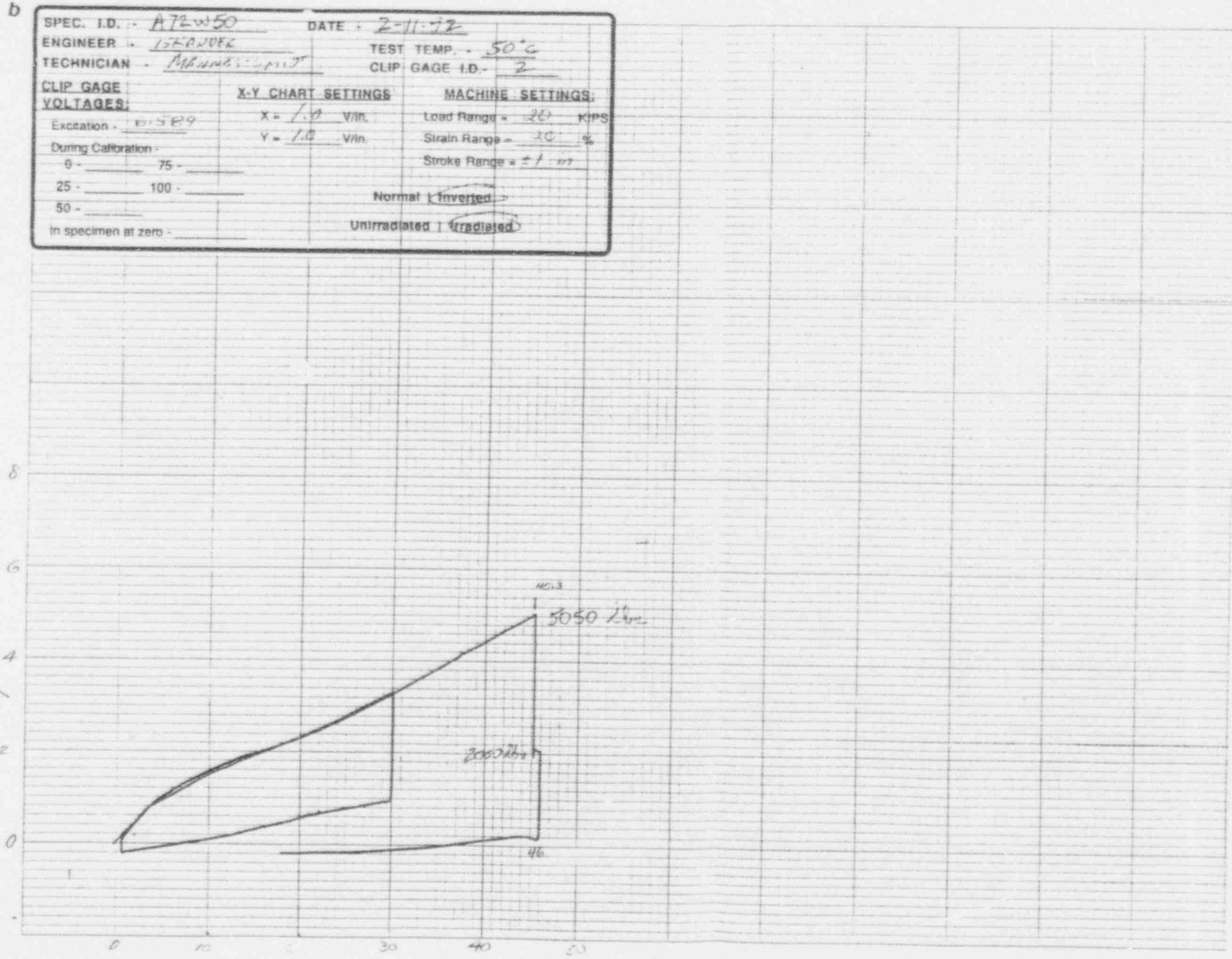
80
90
100
mil



a

b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TECHNICIAN -
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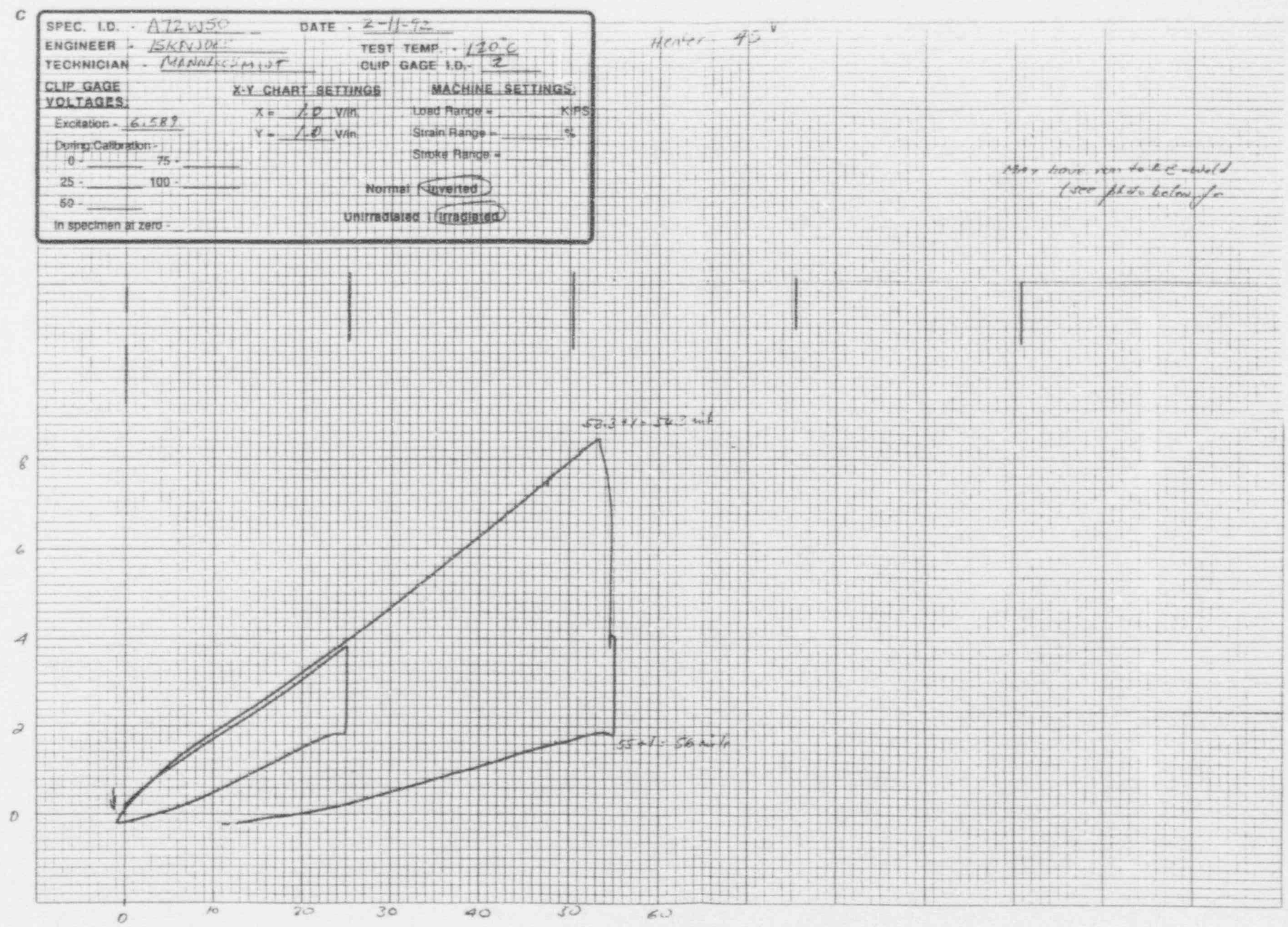
CLIP GAGE VOLTAGES:
Excitation - 0.589
During Calibration -
0 -
25 -
50 -
75 -
100 -
In specimen at zero -
X-Y CHART SETTINGS
X = 1.0 V/in.
Y = 1.0 V/in.
MACHINE SETTINGS:
Load Range = 20 KIPS
Strain Range = 20 %
Stroke Range = ±1 in
Normal | Inverted
Unirradiated | Irradiated
5050 lbs
46
8
6
4
2
0
0
30
40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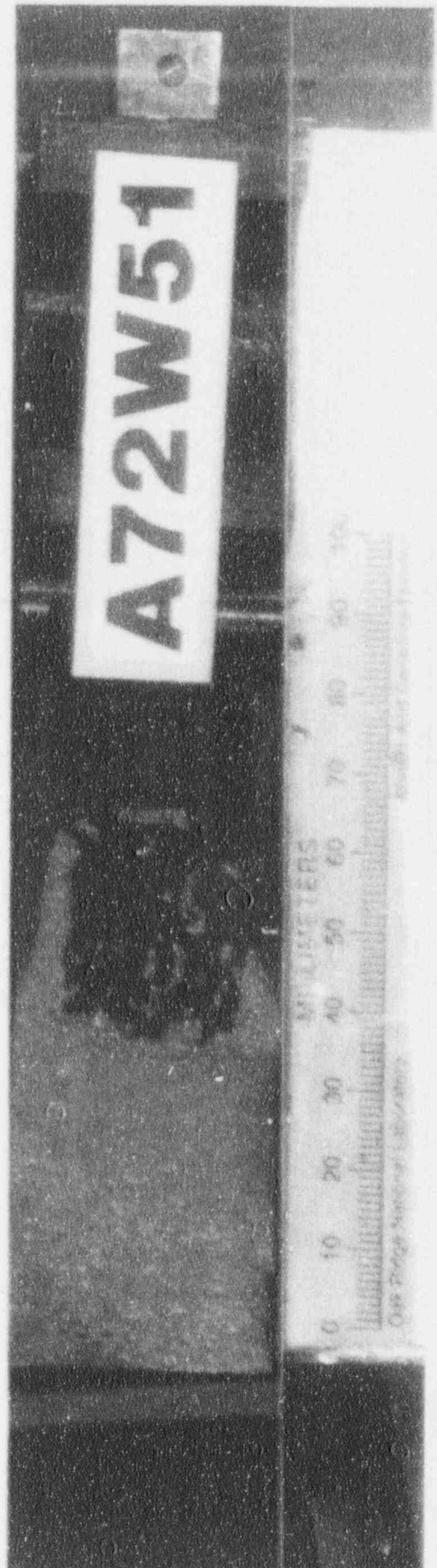
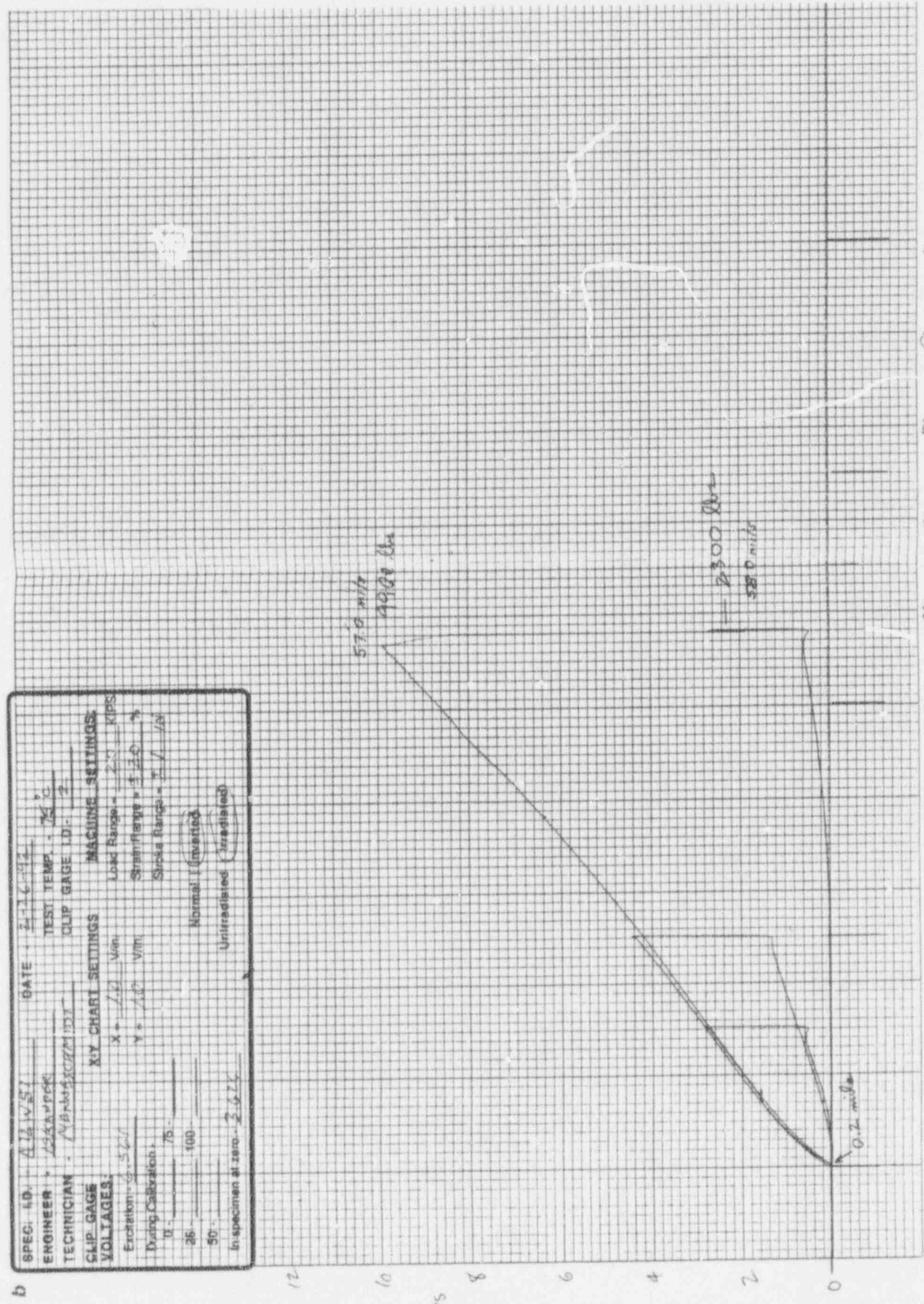
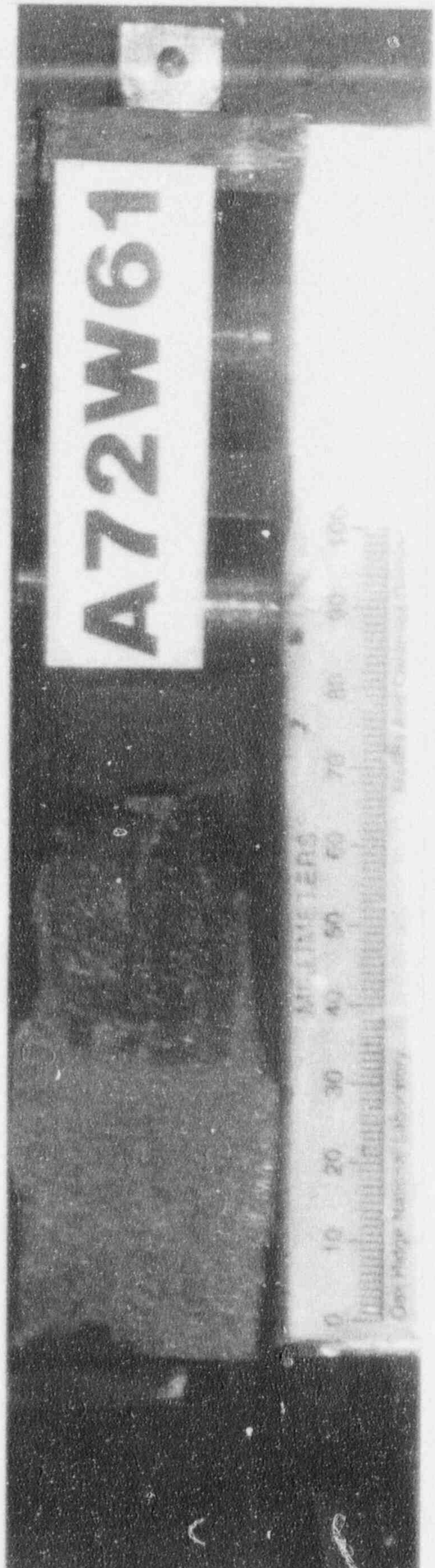
CLIP GAGE VOLTAGES:
Excitation - 6.589
During Calibration -
0 -
75 -
25 -
100 -
50 -
In specimen at zero -
X-Y CHART SETTINGS
X = 1.0 V/in.
Y = 1.0 V/in.
MACHINE SETTINGS
Load Range = KIPS
Strain Range = %
Stroke Range =
Normal / Inverted
Unirradiated / Irradiated
0
10
20
30
40
50
60
0
2
4
6
8

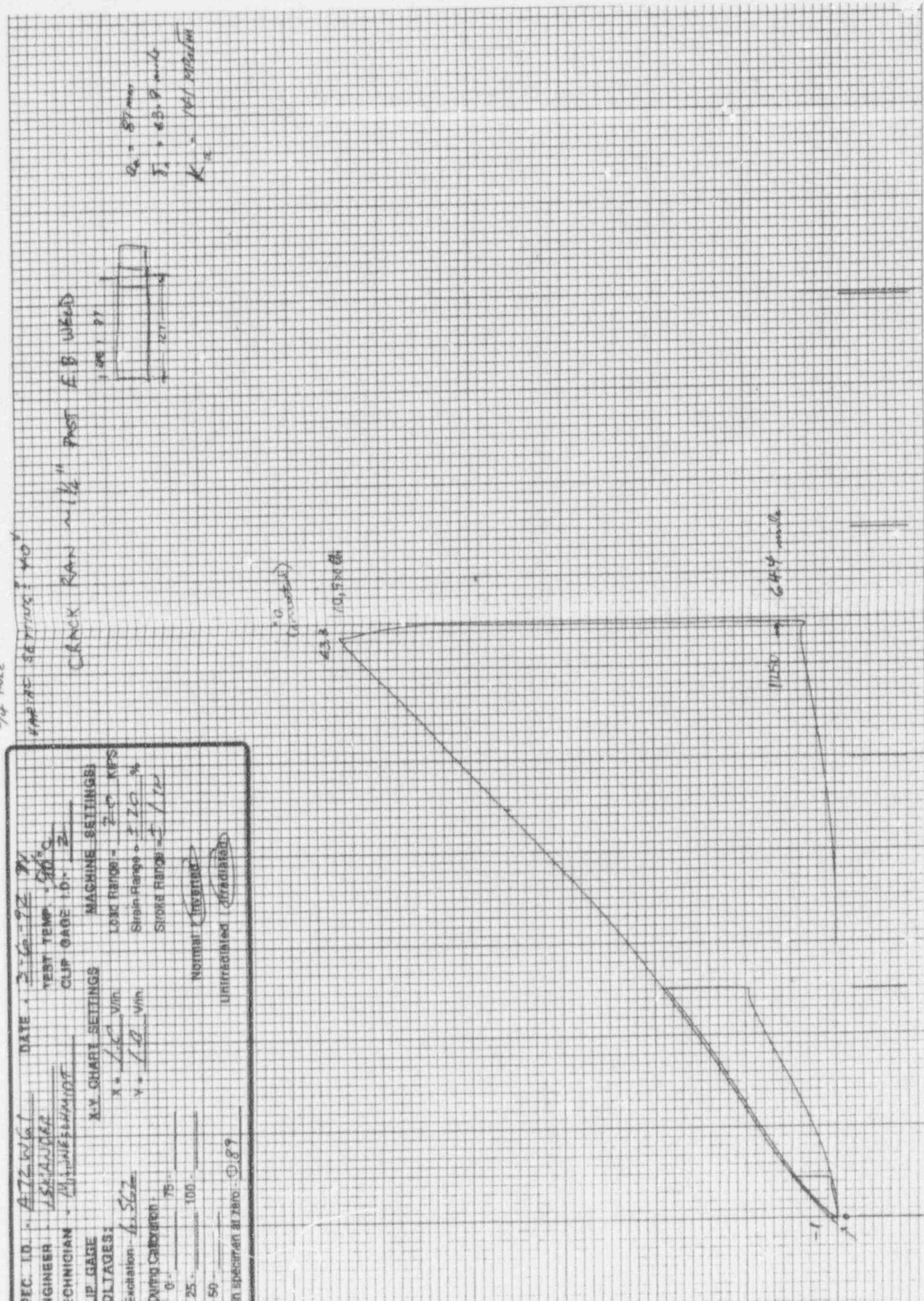


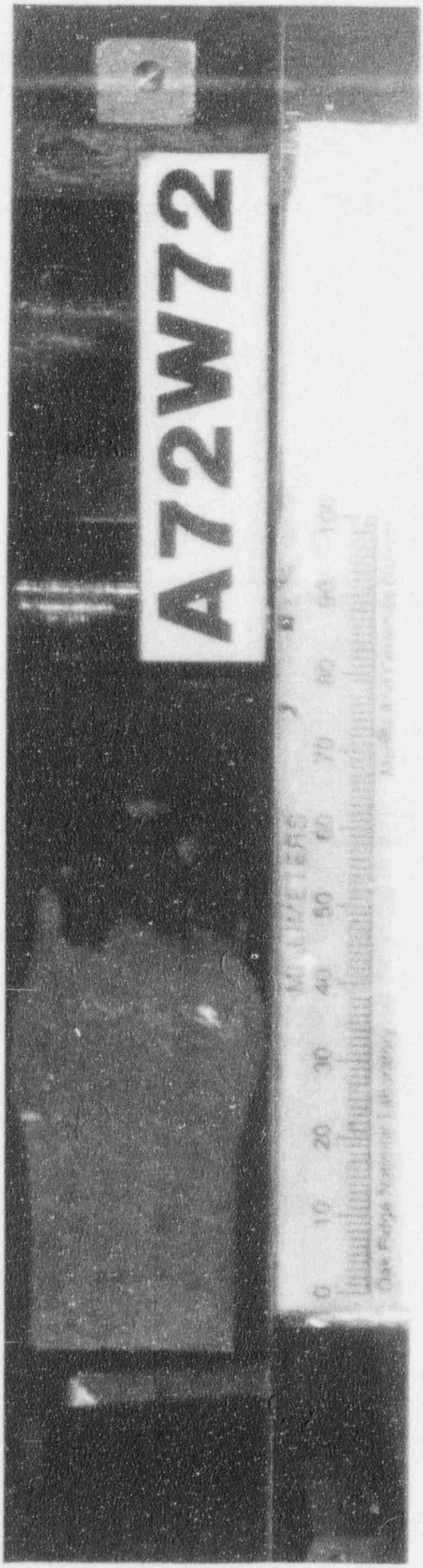
a

b


SPEC. I.D.
DATE
ENGINEER
TEST TEMP.
TECHNICIAN
CLIP GAGE I.D.
CLIP GAGE VOLTAGES:
X-Y CHART SETTINGS
MACHINE SETTINGS
Excitation
During Calibration
Load Range
Strain Range
Stroke Range
Normal / Inverted
Unirradiated / Irradiated
In specimen at zero
Kips

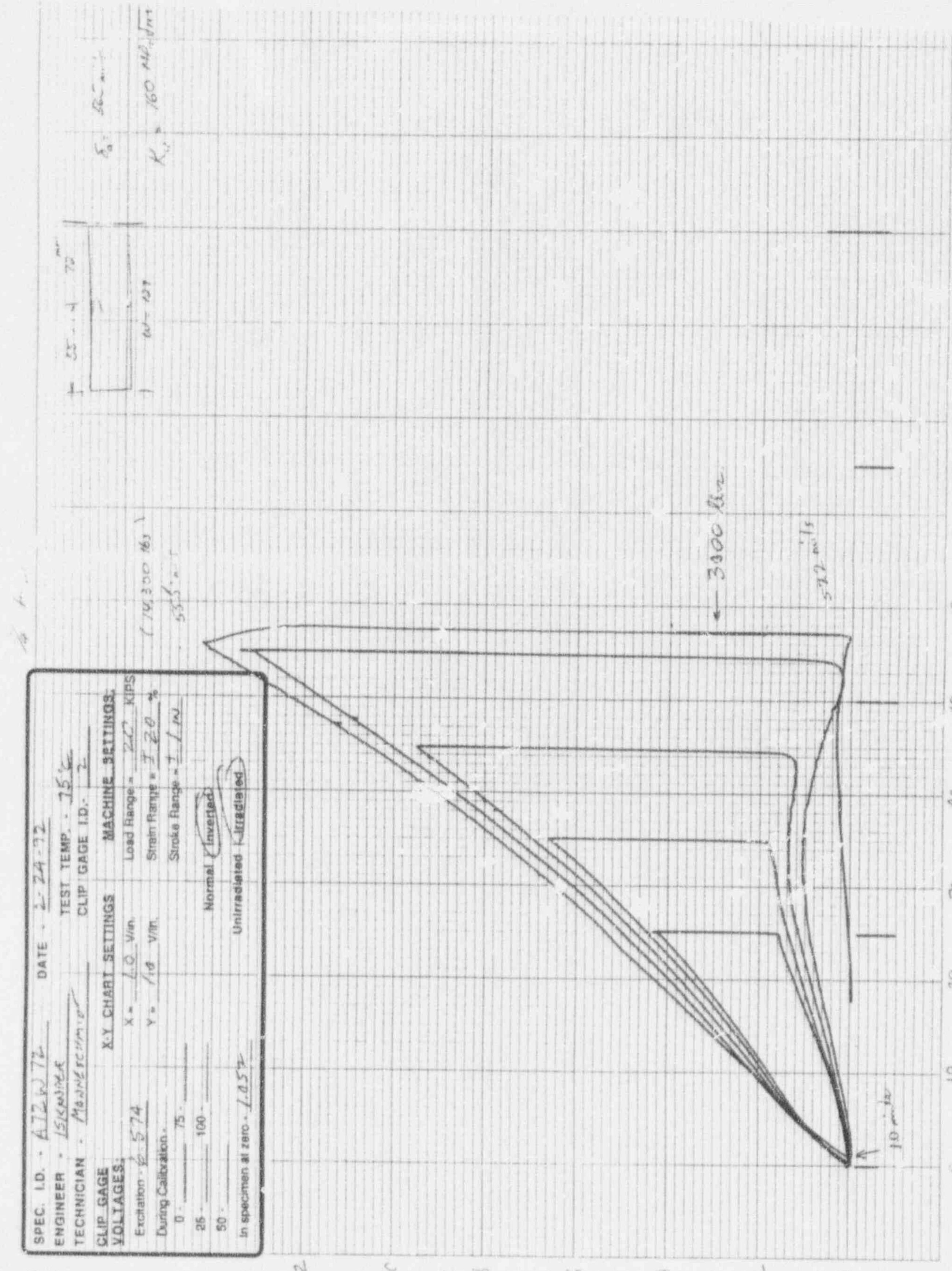

A72W61

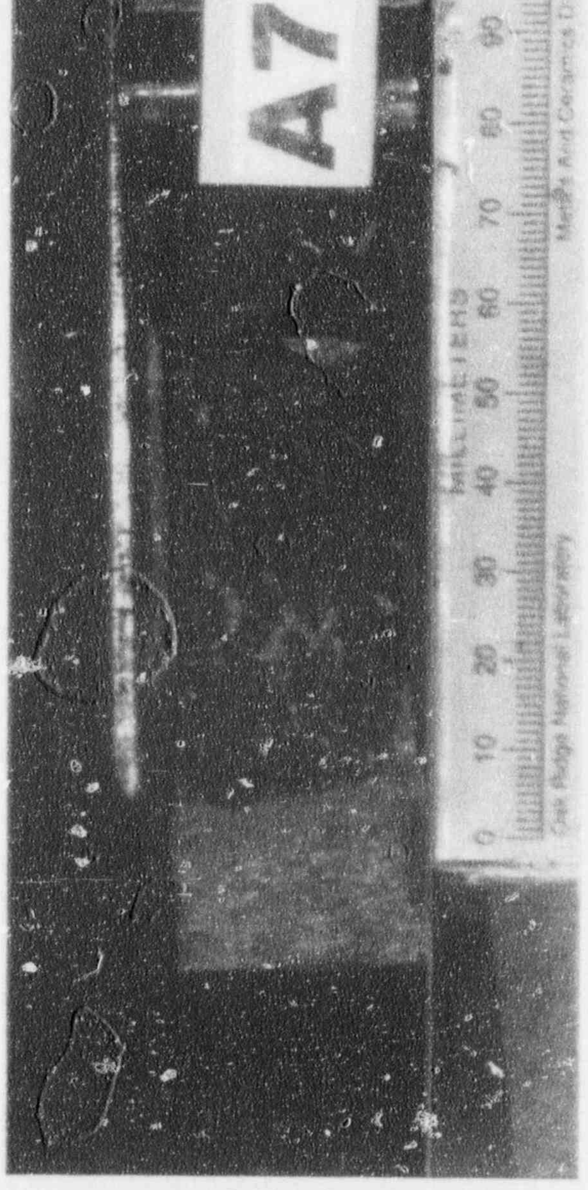

b
SPEC. I.D. - A72WG1
DATE - 3-6-92
ENGINEER - ISKANDER
TEST TEMP. - 90°C
TECHNICIAN - M. J. WEBSHMIDT
CLIP GAGE I.D. - 2
CLIP GAGE VOLTAGES:
Excitation - 6.562
During Calibration:
0 -
25 -
50 -
75 -
100 -
In specimen at zero - Θ.89
X-Y CHART SETTINGS
X = 1.0 V/in.
Y = 1.0 V/in.
MACHINE SETTINGS:
Load Range = 20 KIPS
Strain Range = ± 20 %
Stroke Range = ± 1 in
Normal / Inverted
Unirradiated / Irradiated
3/4" HOLE
CRACK RAN ~1 1/4" PAST E B WELD
63.8
10,580 lb
1150
64.4 mils
KIPS
MILS



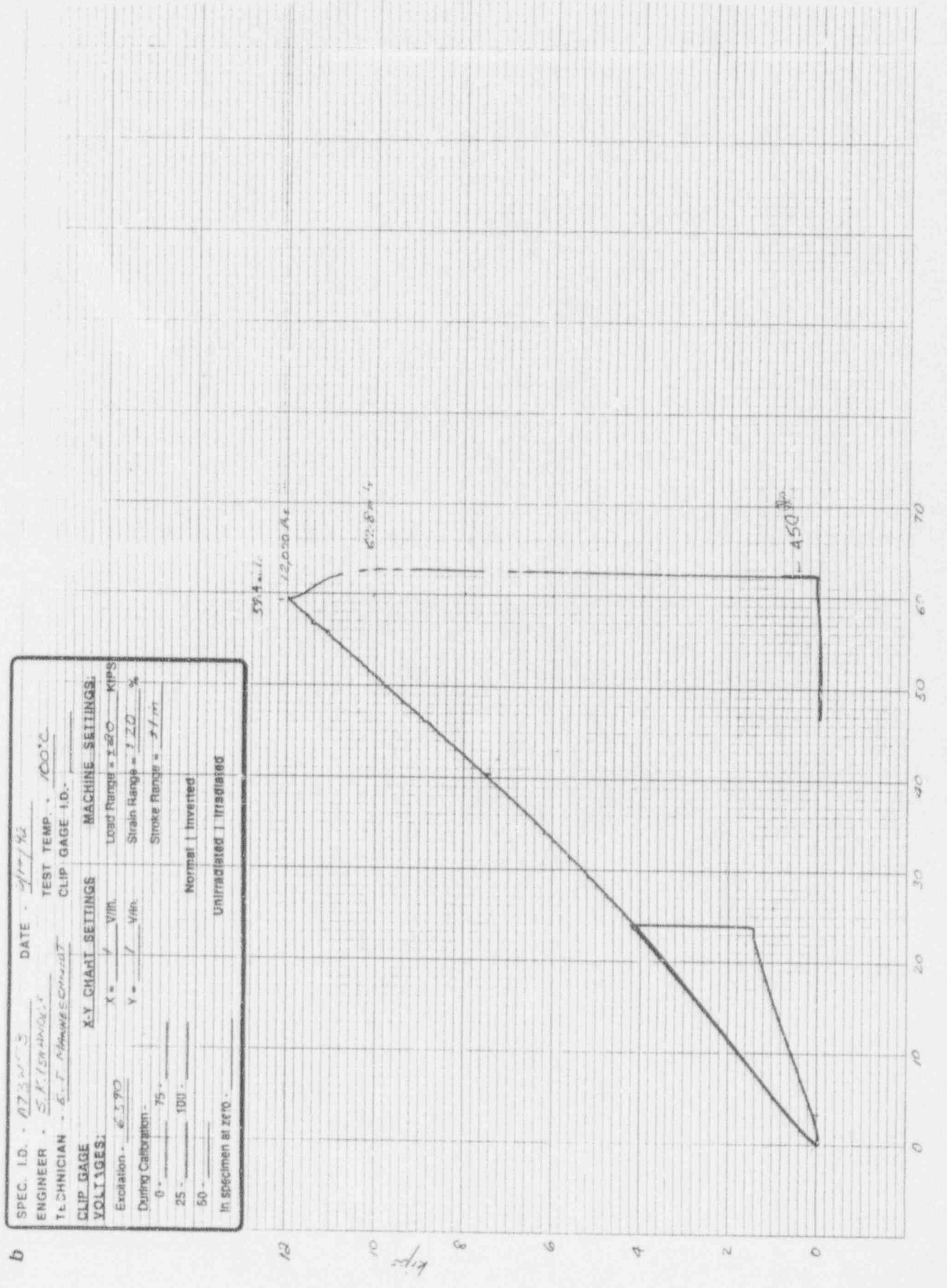
a

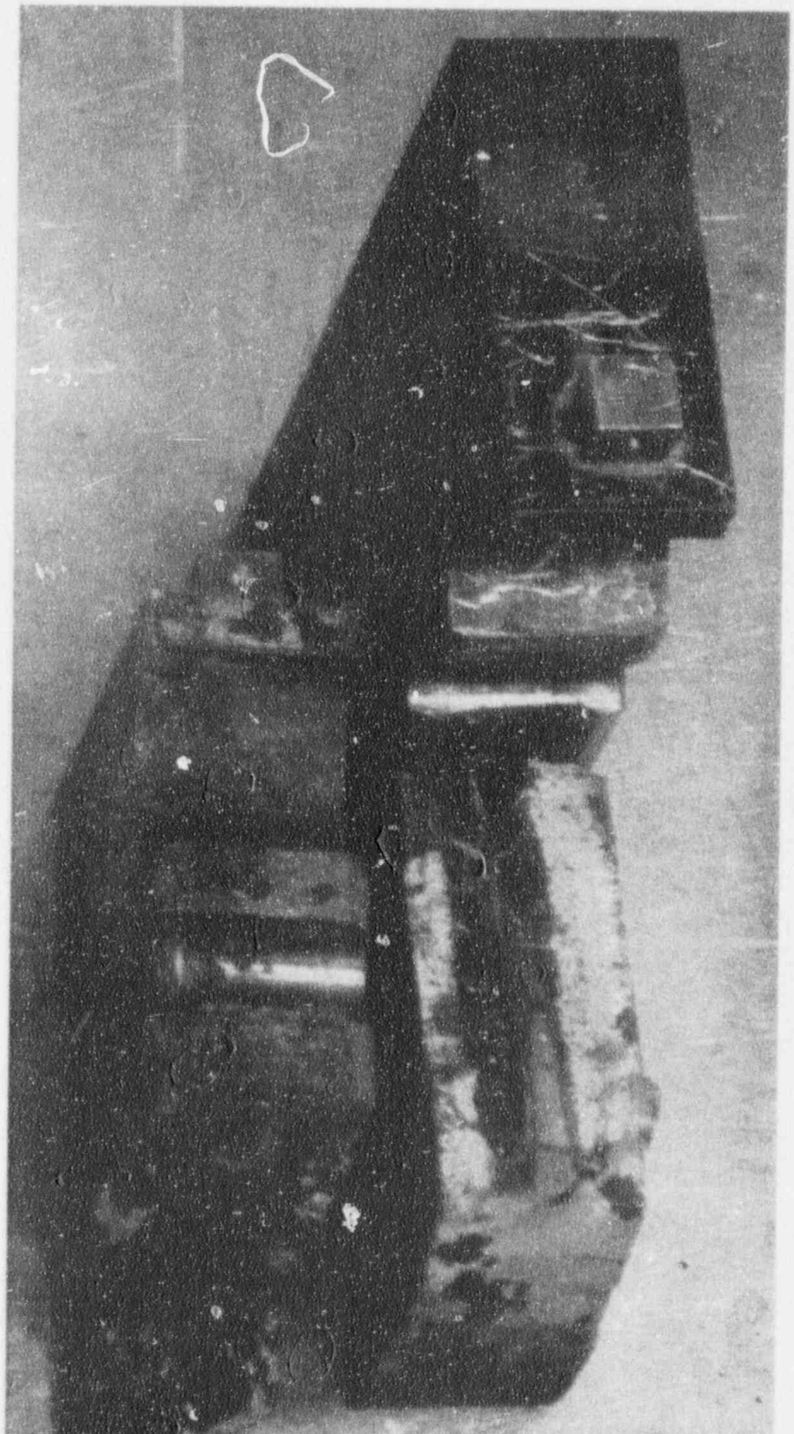
b


SPEC. I.D.
DATE
ENGINEER
TEST TEMP.
TECHNICIAN
CLIP GAGE I.D.
CLIP GAGE VOLTAGES:
X-Y CHART SETTINGS
MACHINE SETTINGS
Excitation
During Calibration
In specimen at zero
Load Range
KIPS
Strain Range
Stroke Range
Normal
Inverted
Unirradiated
Irradiated
MILS
3300 lbs

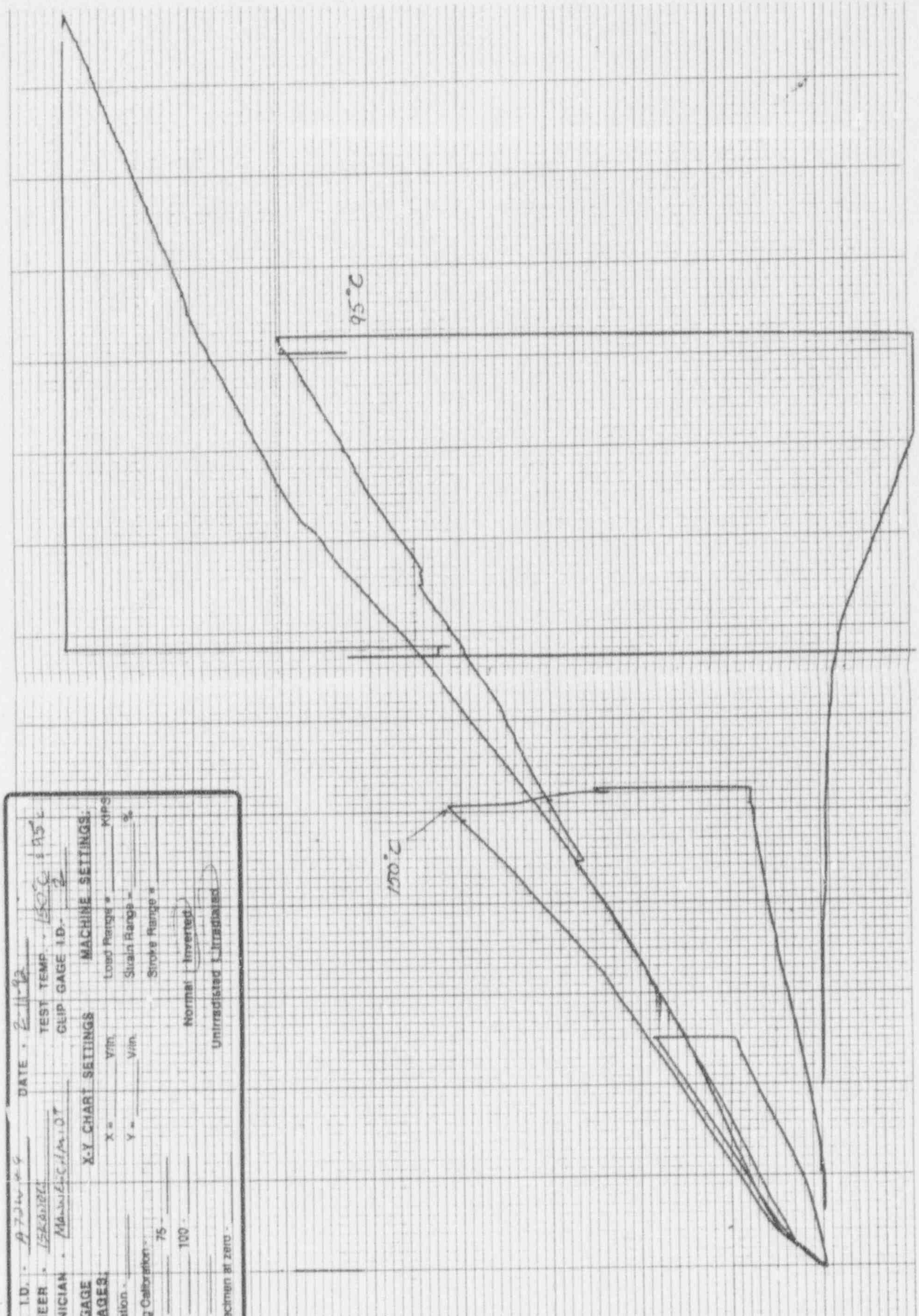

A73W53
MILLIMETERS
Oak Ridge National Laboratory
Metals And Ceramics Division

a


b
SPEC. I.D. -
DATE -
ENGINEER -
TEST TEMP. -
TECHNICIAN -
CLIP GAGE I.D.-
CLIP GAGE VOLTAGES:
X-Y CHART SETTINGS
MACHINE SETTINGS:
Excitation -
During Calibration -
0 -
25 -
50 -
75 -
100 -
X = V/in.
Y = V/in.
Load Range =
KIPS
Strain Range =
%
Stroke Range =
Normal | Inverted
Unirradiated | Irradiated
In specimen at zero -
0
10
20
30
40
50
60
70
0
2
4
6
8
10
12

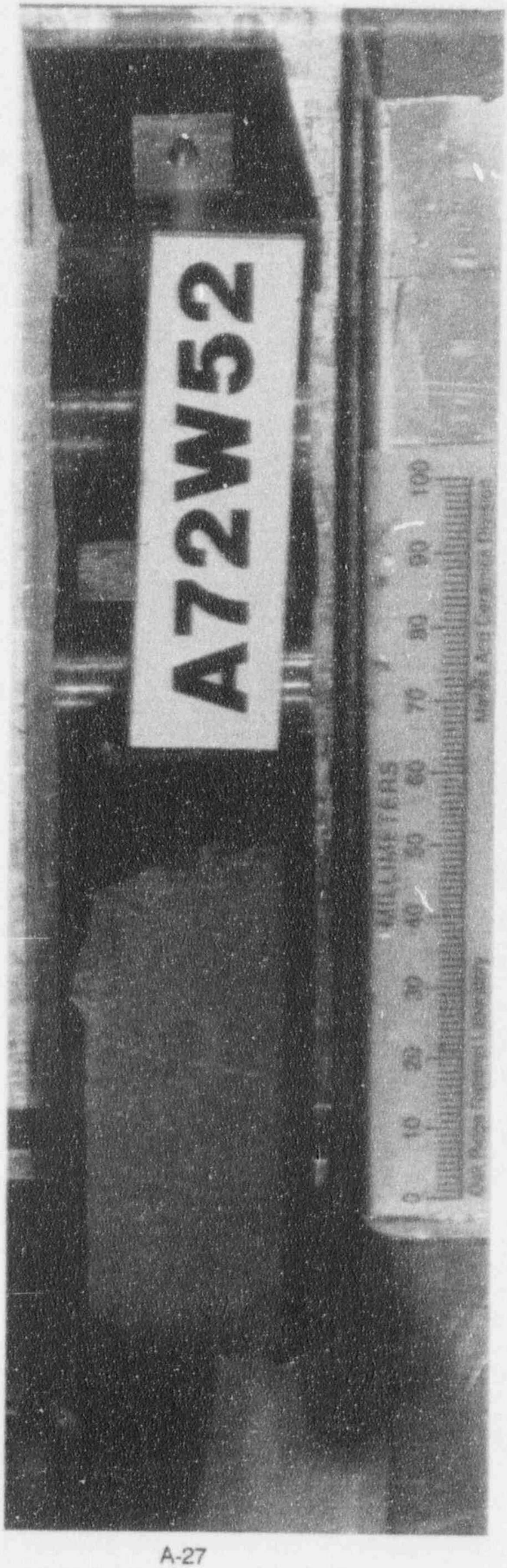


a

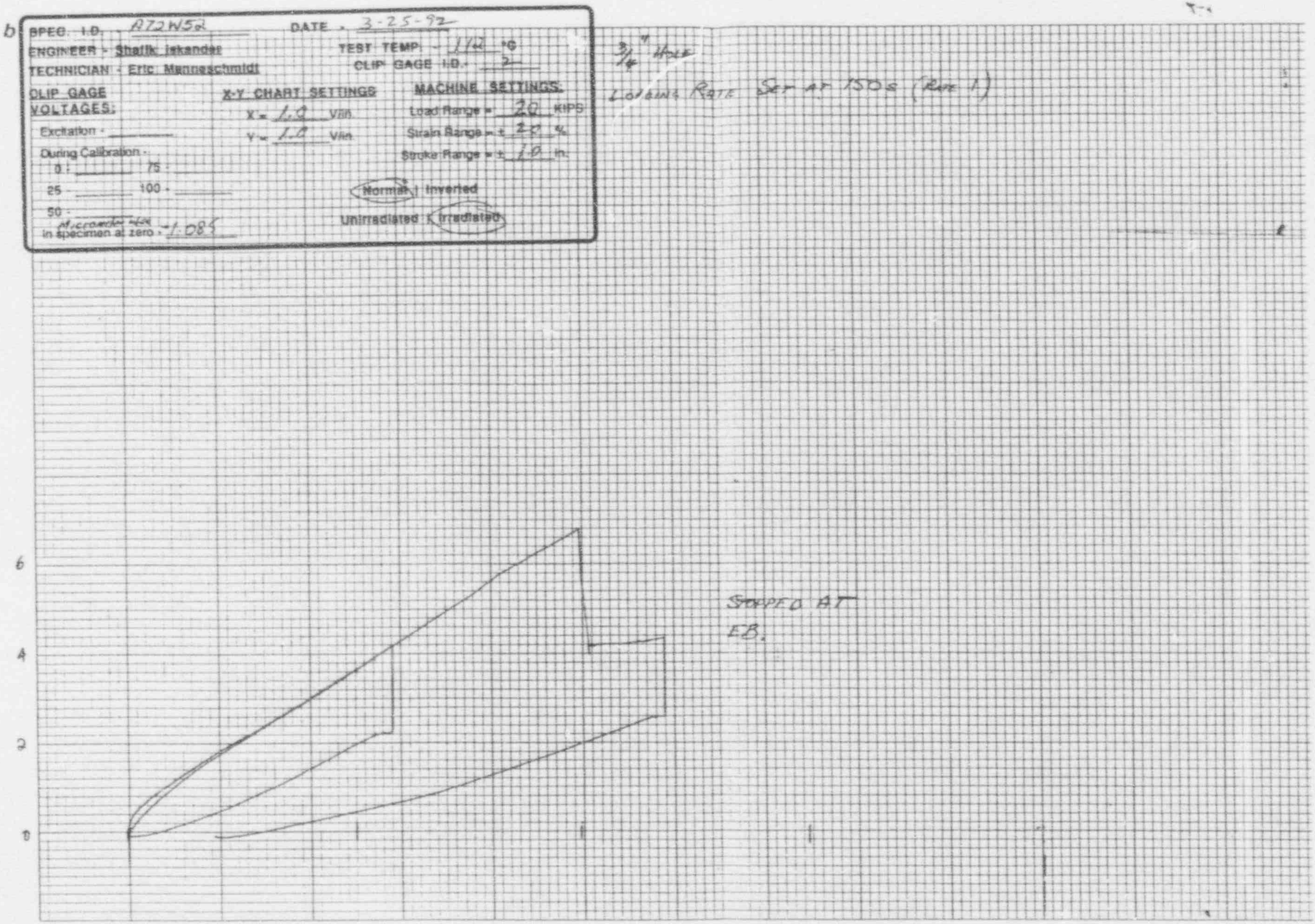


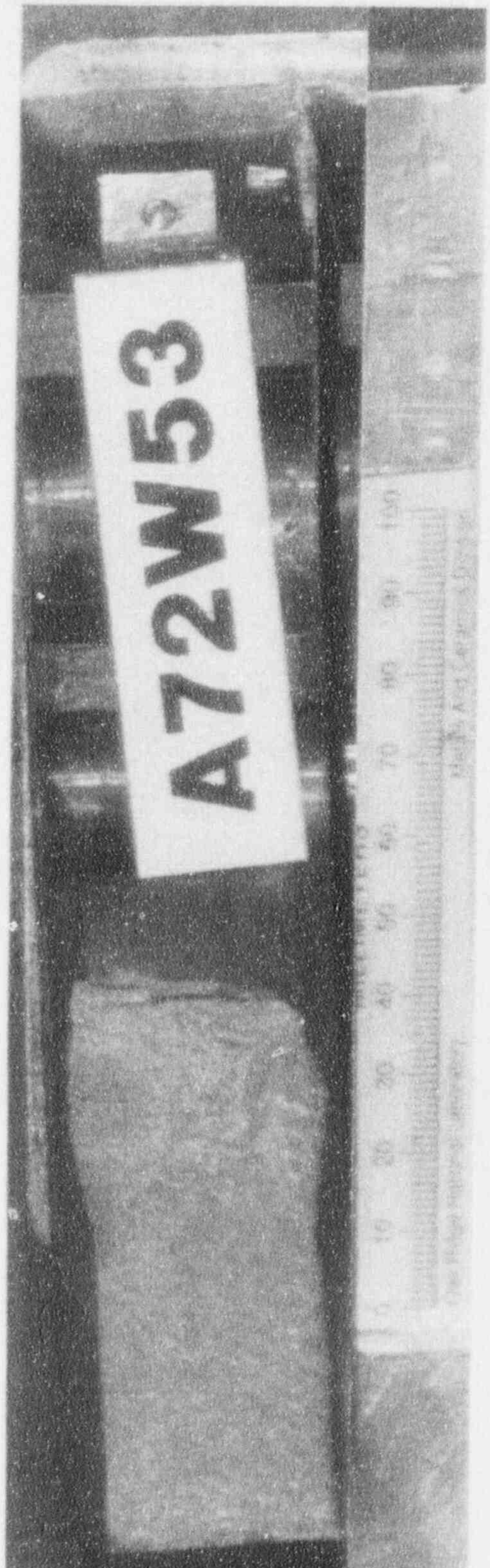
SPEC. I.D.
ENGINEER
TECHNICIAN
DATE
TEST TEMP
CLIP GAGE I.D.
CLIP GAGE VOLTAGES:
Excitation
During Calibration
0
25
50
75
100
In specimen at zero
X-Y CHART SETTINGS
X =
V/in.
Y =
V/in.
MACHINE SETTINGS:
Load Range =
KIPS
Strain Range =
%
Stroke Range =
Normal | Inverted
Unirradiated | Irradiated
95°C
150°C

b



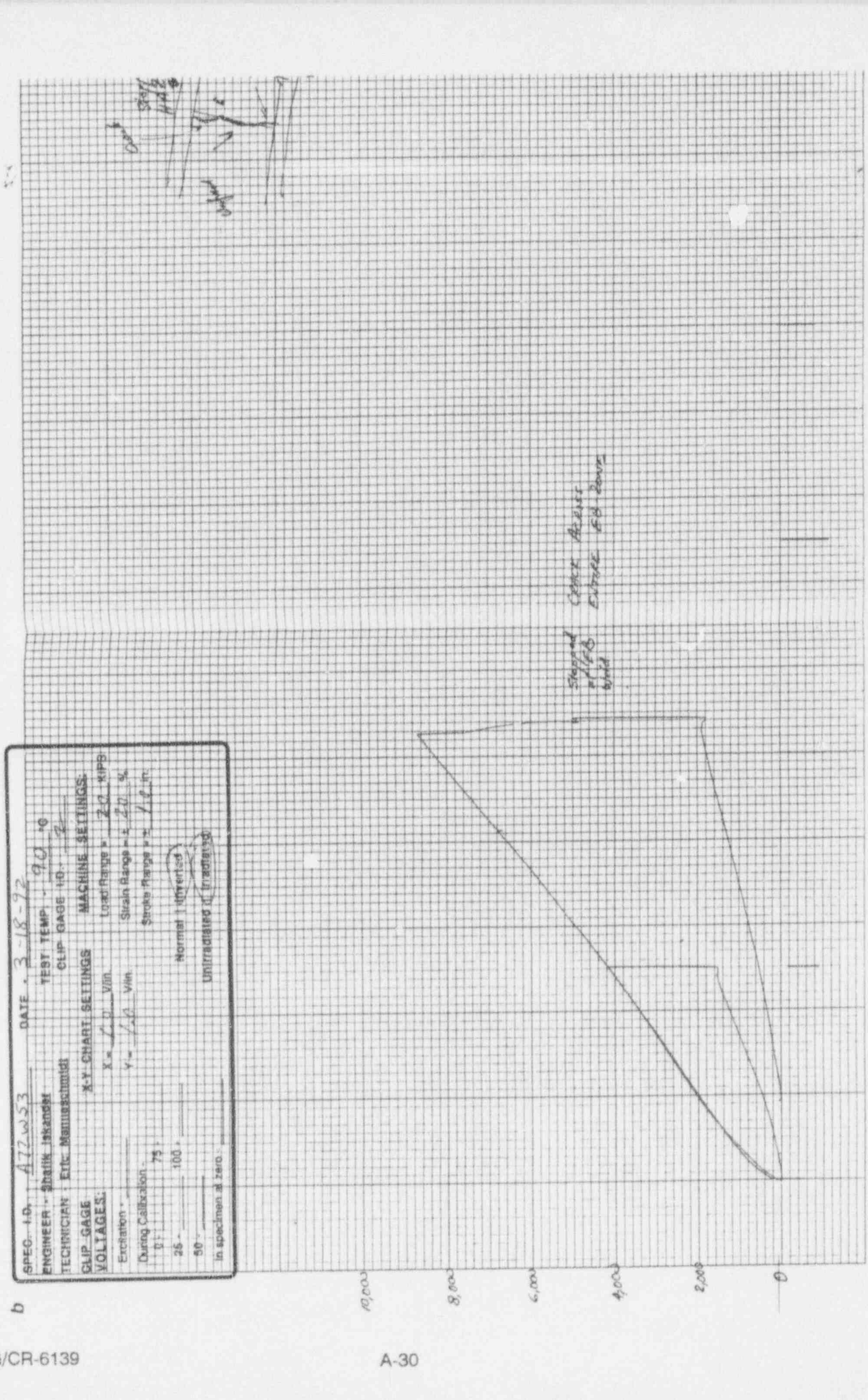
a


b
SPEC. I.D. - A72W52
DATE - 3-25-92
ENGINEER - Shafik Iskander
TEST TEMP. - 112 °C
TECHNICIAN - Eric Manneschmidt
CLIP GAGE I.D. - 2
CLIP GAGE VOLTAGES:
Excitation -
During Calibration -
0 -
75 -
25 -
100 -
50 -
Micrometer Hdt in specimen at zero - -1.085
X-Y CHART SETTINGS
X = 1.0 V/in
Y = 1.0 V/in
MACHINE SETTINGS:
Load Range = 20 KIPS
Strain Range = ± 20 %
Stroke Range = ± 1.0 in.
Normal
Inverted
Unirradiated
Irradiated
3/4" Hole
Loading Rate Set at 150s (Rate 1)
Stopped at EB.
6
4
2
0

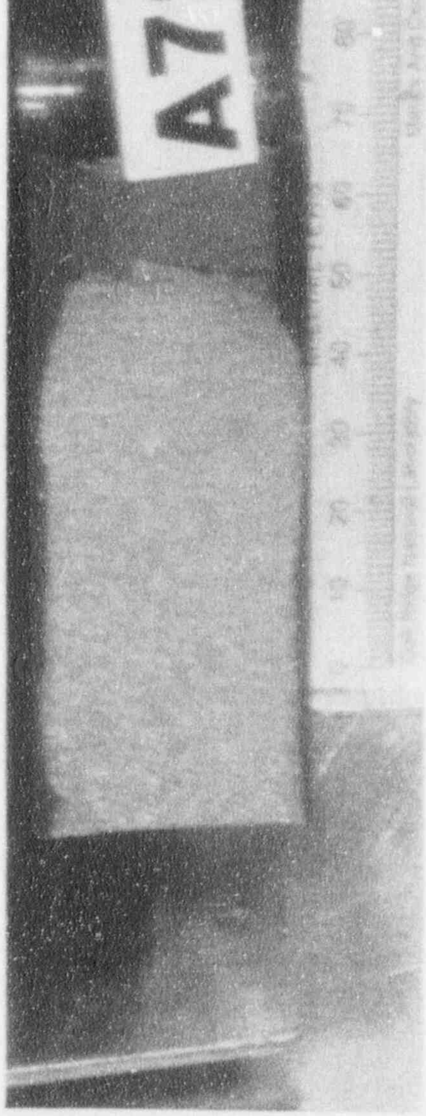


a

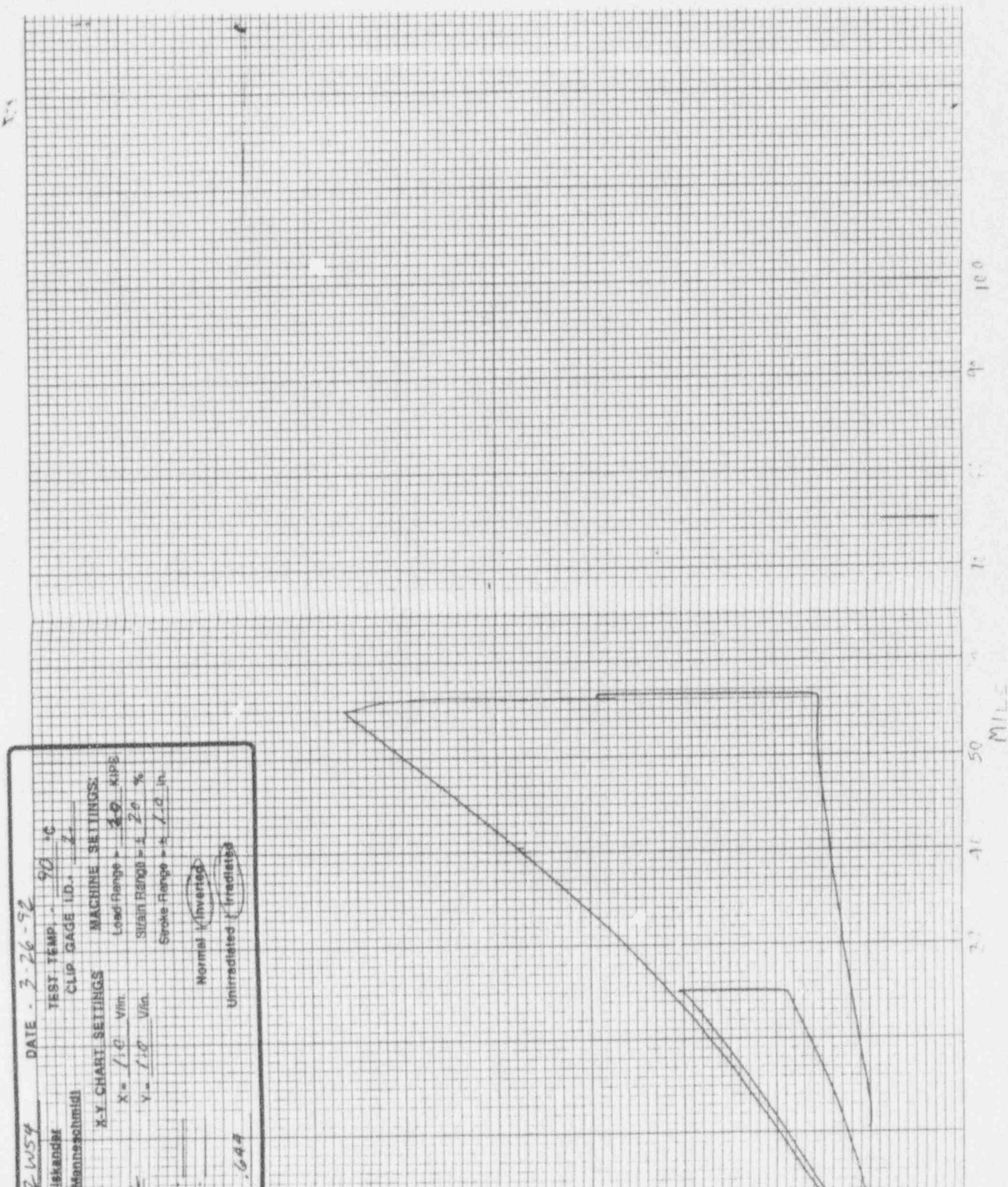
b

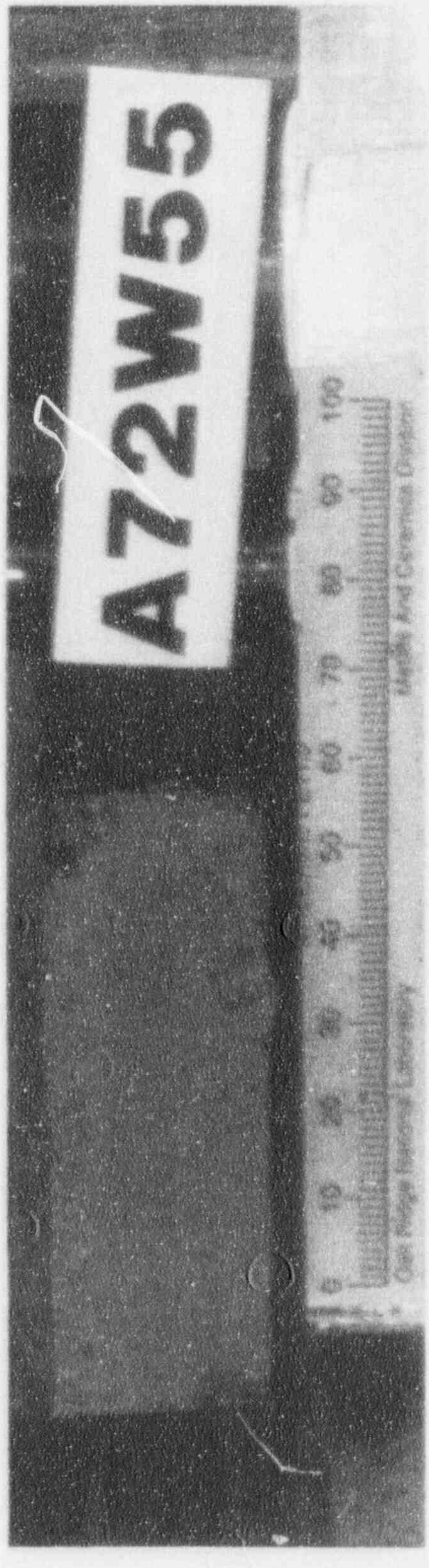


SPEC. I.D. A77W53
DATE 3-18-92
ENGINEER : Shafik Iskander
TEST TEMP. 90 °C
TECHNICIAN : Eric Manneschmidt
CLIP GAGE I.D.
CLIP GAGE VOLTAGES:
X-Y CHART SETTINGS
MACHINE SETTINGS:
Excitation
X = 1.0 V/in.
Load Range = 20 KIPS
Y = 1.0 V/in.
Strain Range = ± 20 %
Stroke Range = ± 1.0 in.
During Calibration
0
25
50
75
100
Normal | Inverted
Unirradiated | Irradiated
In specimen at zero
10,000
8,000
6,000
4,000
2,000
0
Stopped at FB weld
CRACK ACROSS ENTIRE FB ZONE



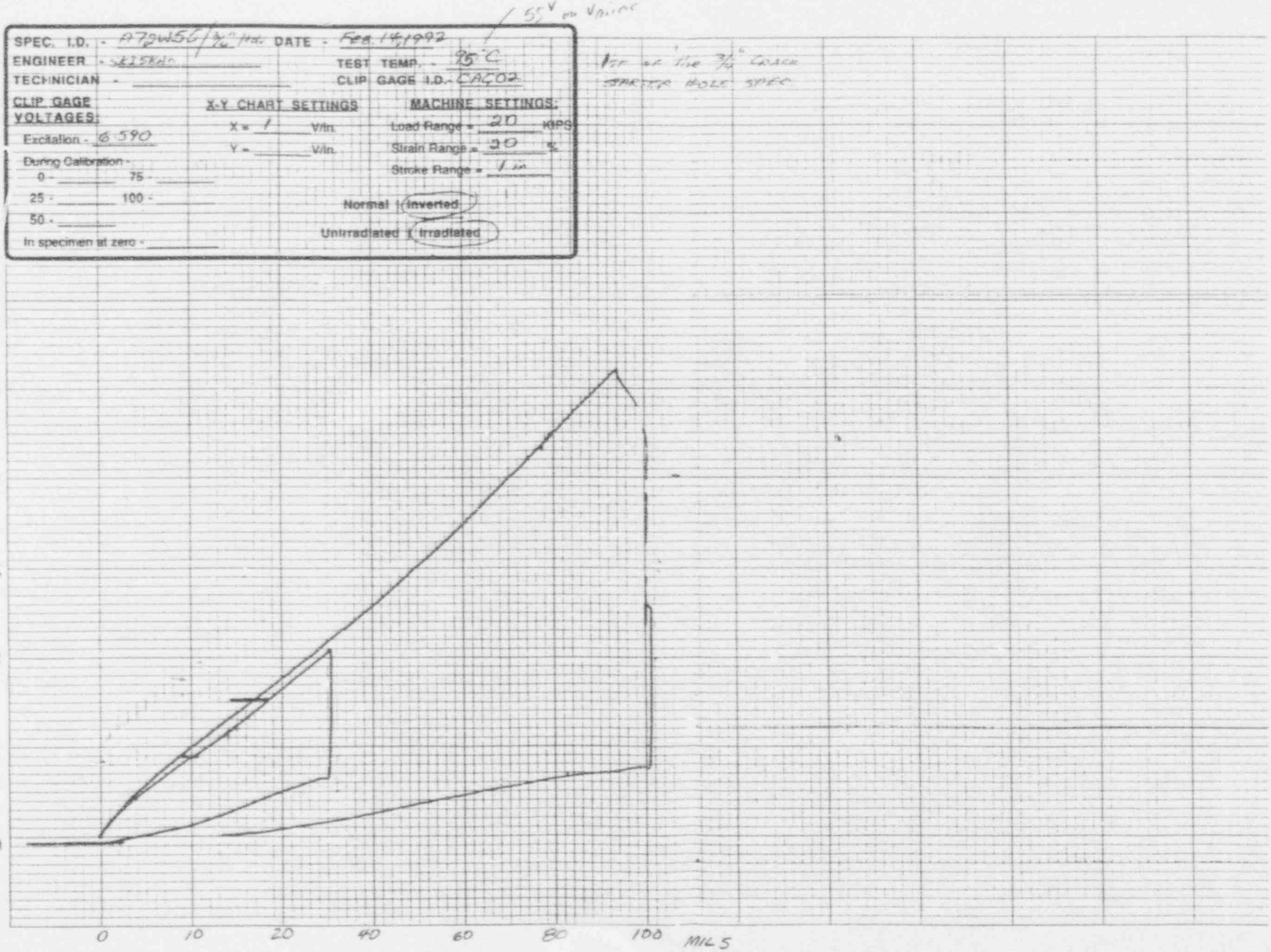
a

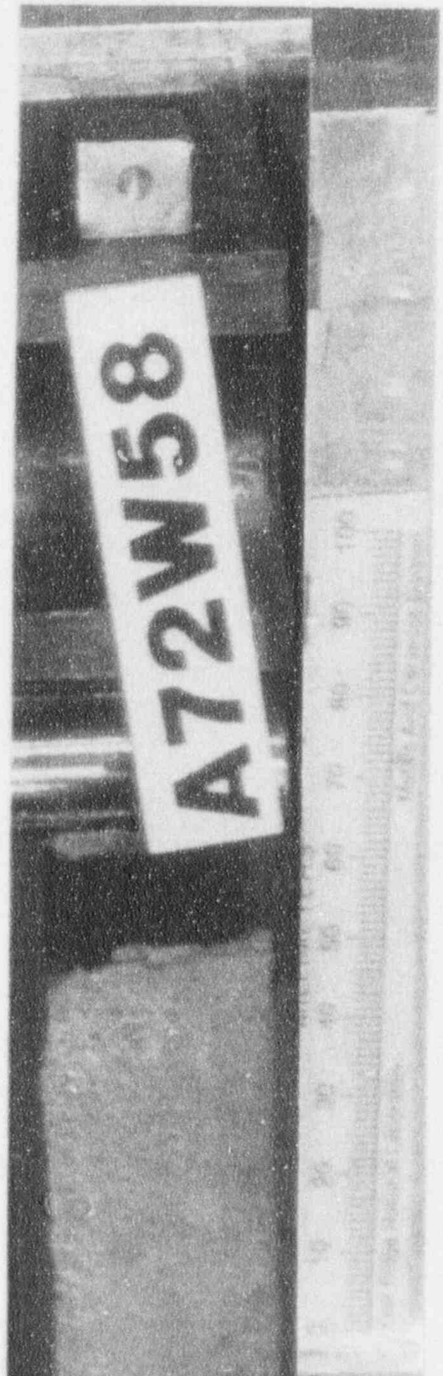

SPEC. I.D. - A72W54
DATE - 3-26-92
ENGINEER - Shafik Iskander
TEST TEMP. - 90 °C
TECHNICIAN - Eric Manneschmidt
CLIP GAGE I.D. - 2
CLIP GAGE VOLTAGES:
X-Y CHART SETTINGS
MACHINE SETTINGS:
X= 1.0 V/in.
Load Range - 10 KIPS
Excitation - 6.592
Y= 1.0 V/in.
Strain Range - ± 20 %
Stroke Range - ± 1.0 in.
During Calibration:
0 -
75 -
25 -
100 -
50 -
Normal / Inverted
Unirradiated / Irradiated
In specimen at zero - .644
0
2
4
6
8
10
0
50
100
MILS



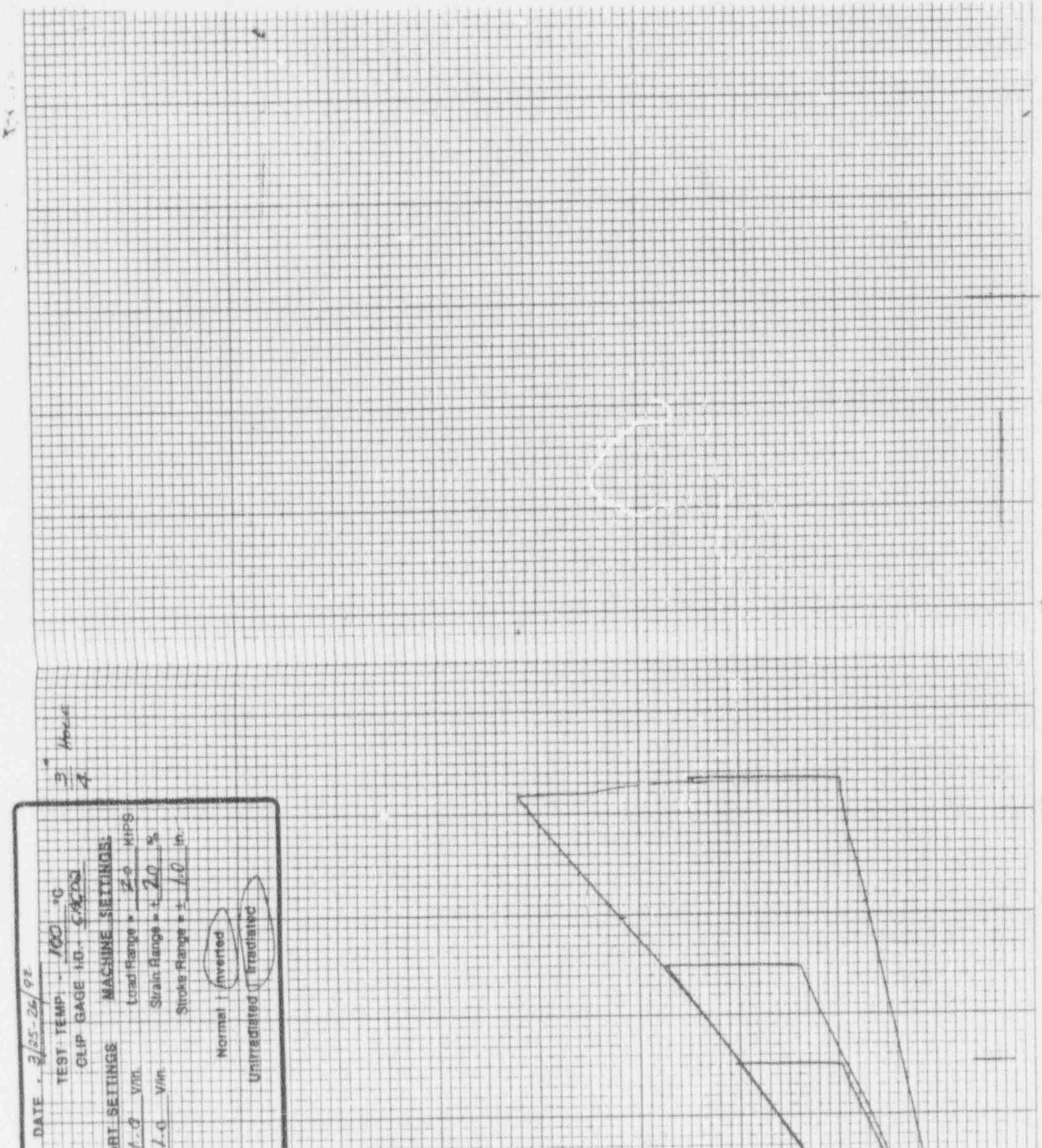
a

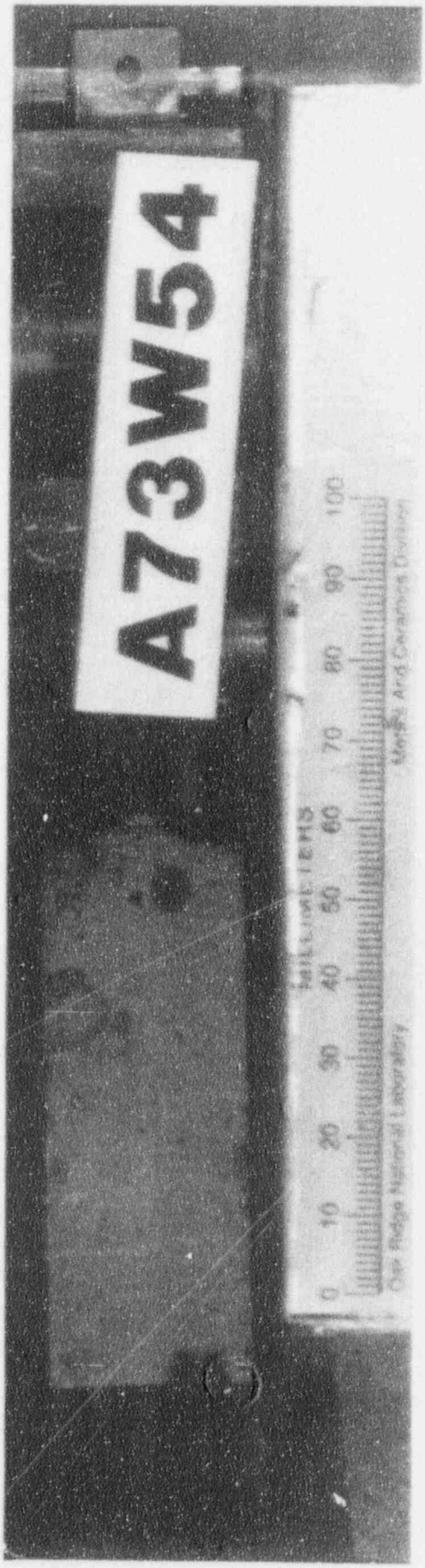
b


SPEC. I.D.
DATE - Feb 14 1992
ENGINEER
TECHNICIAN
TEST TEMP. - 95°C
CLIP GAGE I.D. - CAC02
CLIP GAGE VOLTAGES:
Excitation - 6.590
During Calibration -
0 -
75 -
25 -
100 -
50 -
In specimen at zero -
X-Y CHART SETTINGS
X = 1 V/in.
Y = V/in.
MACHINE SETTINGS:
Load Range = 20 KIPS
Strain Range = 20 %
Stroke Range = 1 in
Normal / Inverted
Unirradiated / Irradiated
0
2
4
6
8
10
0
10
20
40
60
80
100
MILS



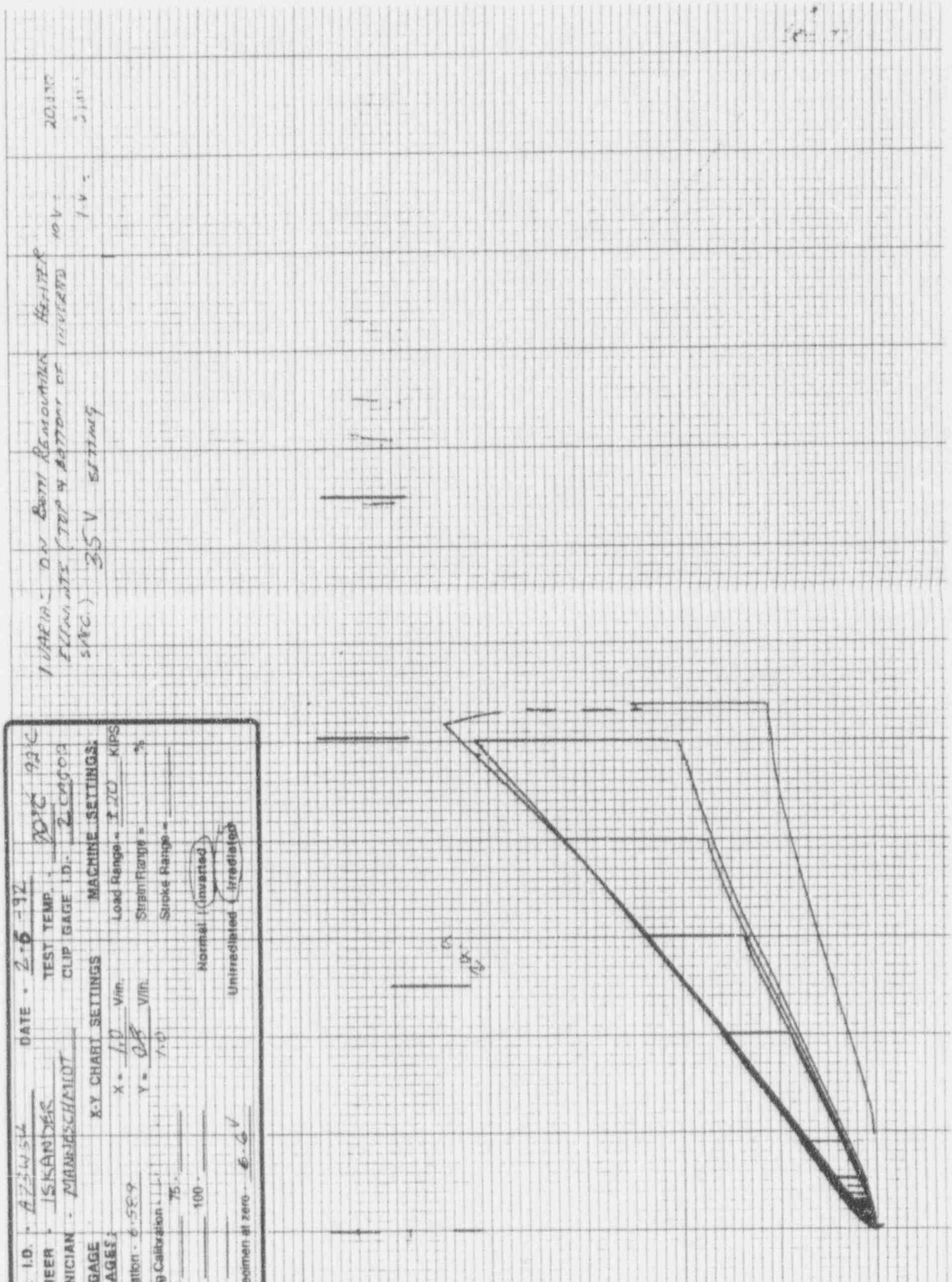
a

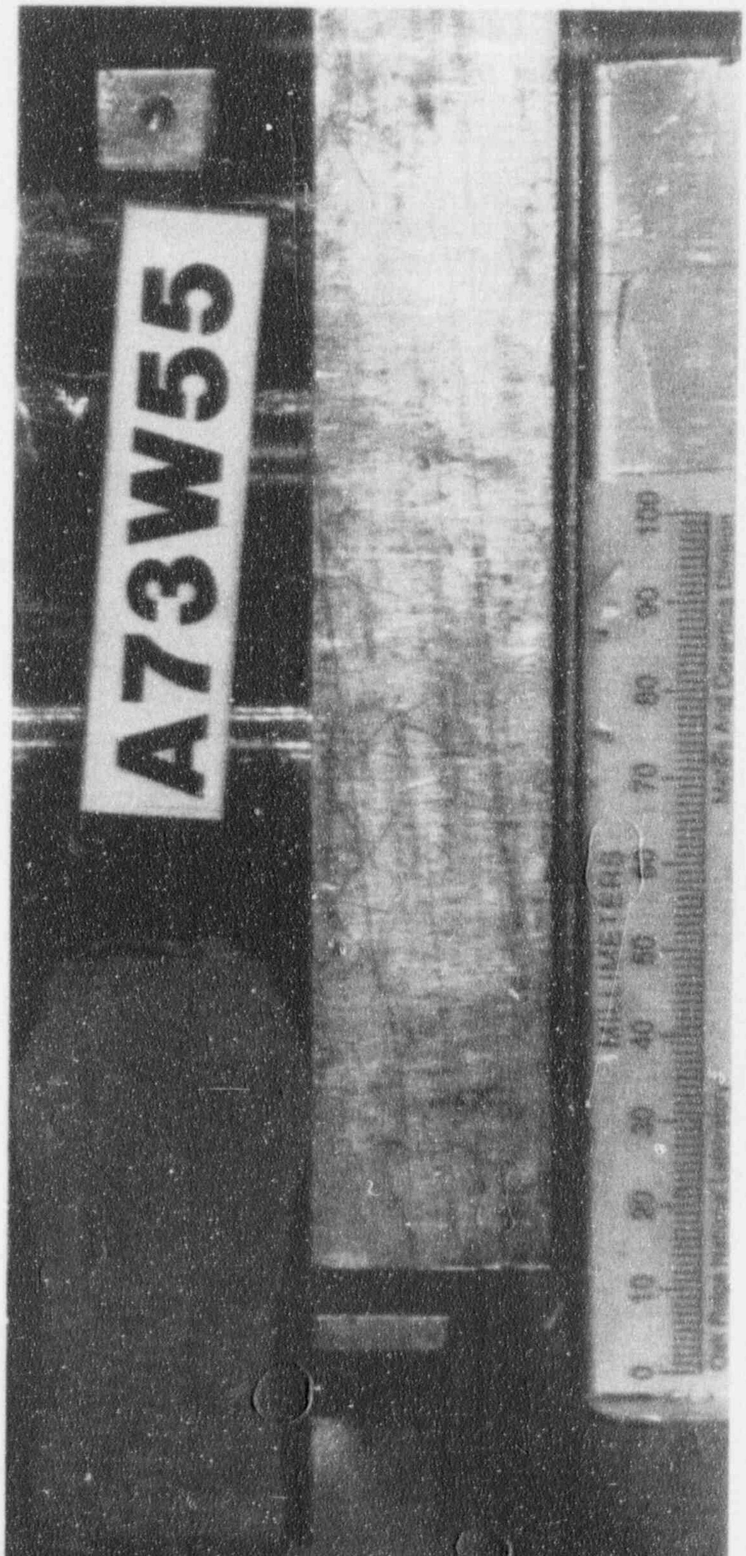

SPEC. I.D. 872W58
DATE 3/25-26/92
ENGINEER Shafik Iskander
TEST TEMP: 100 °C
TECHNICIAN Eric Manneschmidt
CLIP GAGE I.D. CMCOD
CLIP GAGE VOLTAGES:
X-Y CHART SETTINGS
MACHINE SETTINGS:
Excitation 6.542
X = 1.0 V/in.
Y = 1.0 V/in.
Load Range = 20 KIPS
Strain Range = ± 20 %
Stroke Range = ± 1.0 in.
During Calibration:
0
25
50
75
100
Normal / Inverted
Unirradiated / Irradiated
In specimen at zero: 0.201
0
2
4
6
8
10
0
10
20
30
40
50
60
70



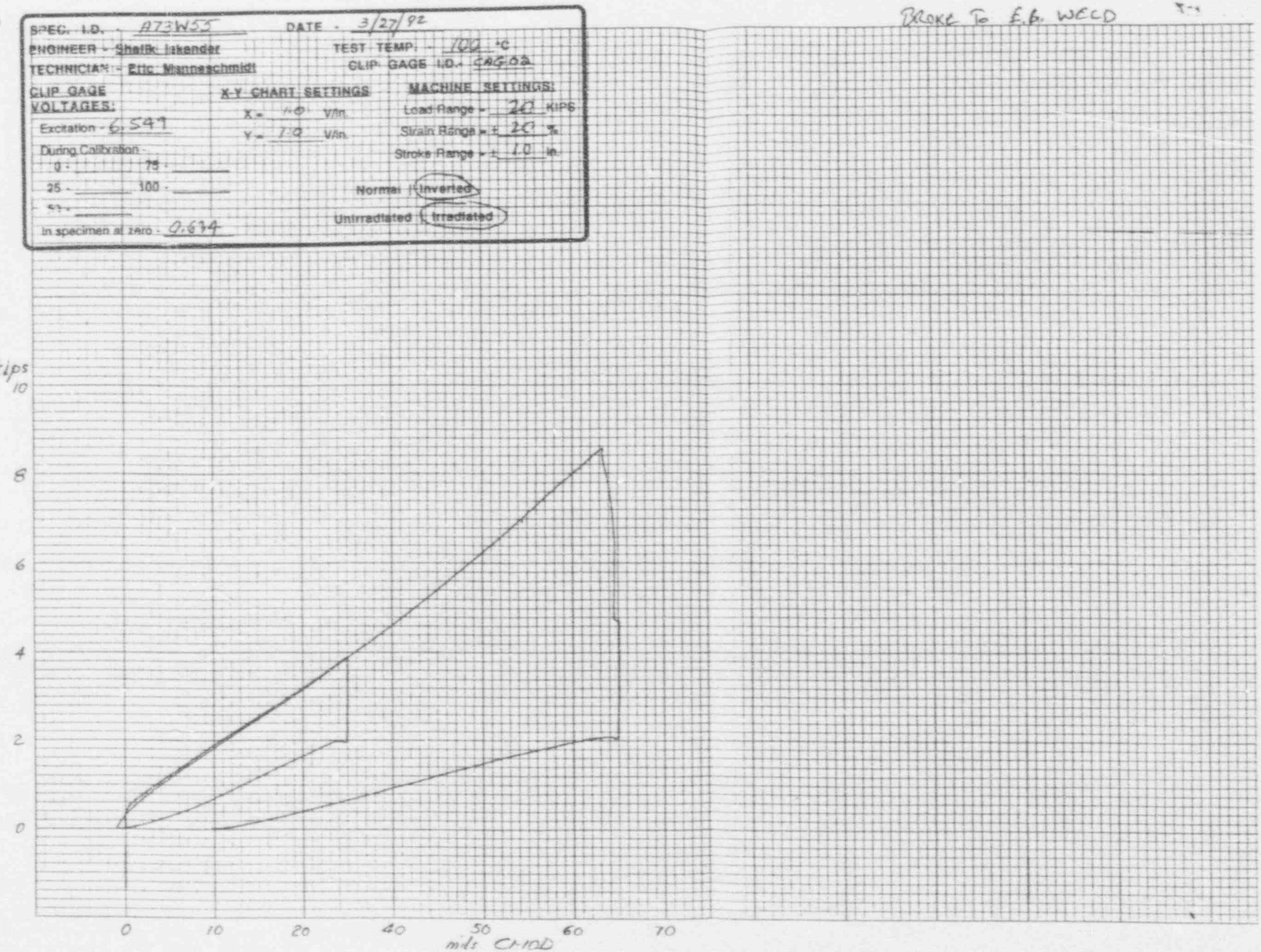
a

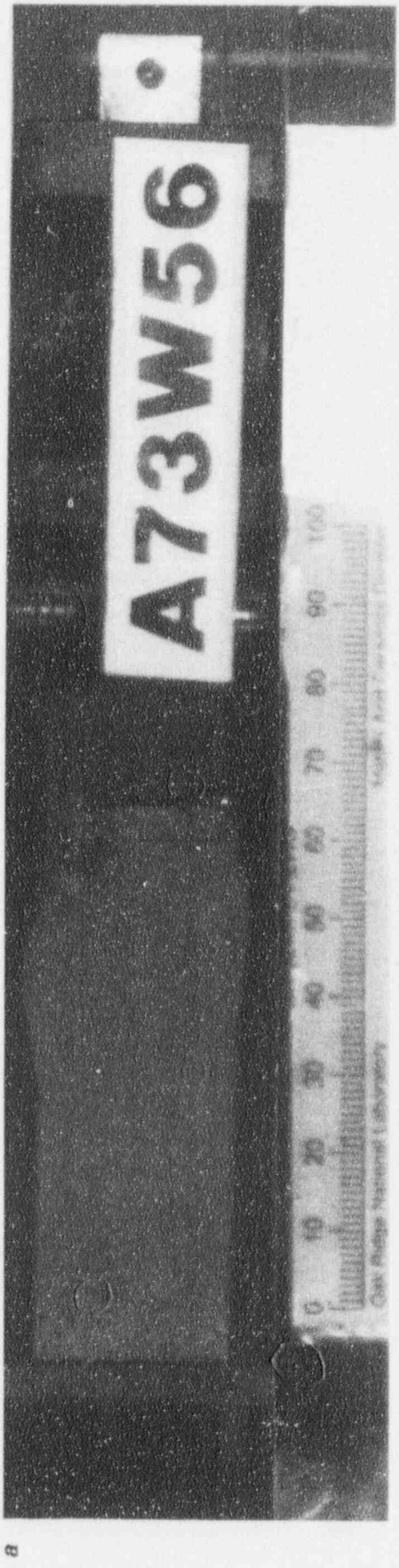
b


SPEC. I.D. - A73W5H
DATE - 2-6-92
ENGINEER - ISKANDER
TEST TEMP. - 90°C 93°C
TECHNICIAN - MANNESCHMIDT
CLIP GAGE I.D. - 2CAGOP
CLIP GAGE VOLTAGES:
X-Y CHART SETTINGS
MACHINE SETTINGS:
X = 1.0 V/in.
Y = 0.8 V/in.
Load Range = 120 KIPS
Excitation - 6.589
Strain Range = %
Stroke Range =
During Calibration -
0 -
75 -
25 -
100 -
50 -
Normal / Inverted
Unirradiated / Irradiated
In specimen at zero - 6.6V
35V SETTING
10
8
6
4
2
0
Kips


A73W55
MILLIMETERS

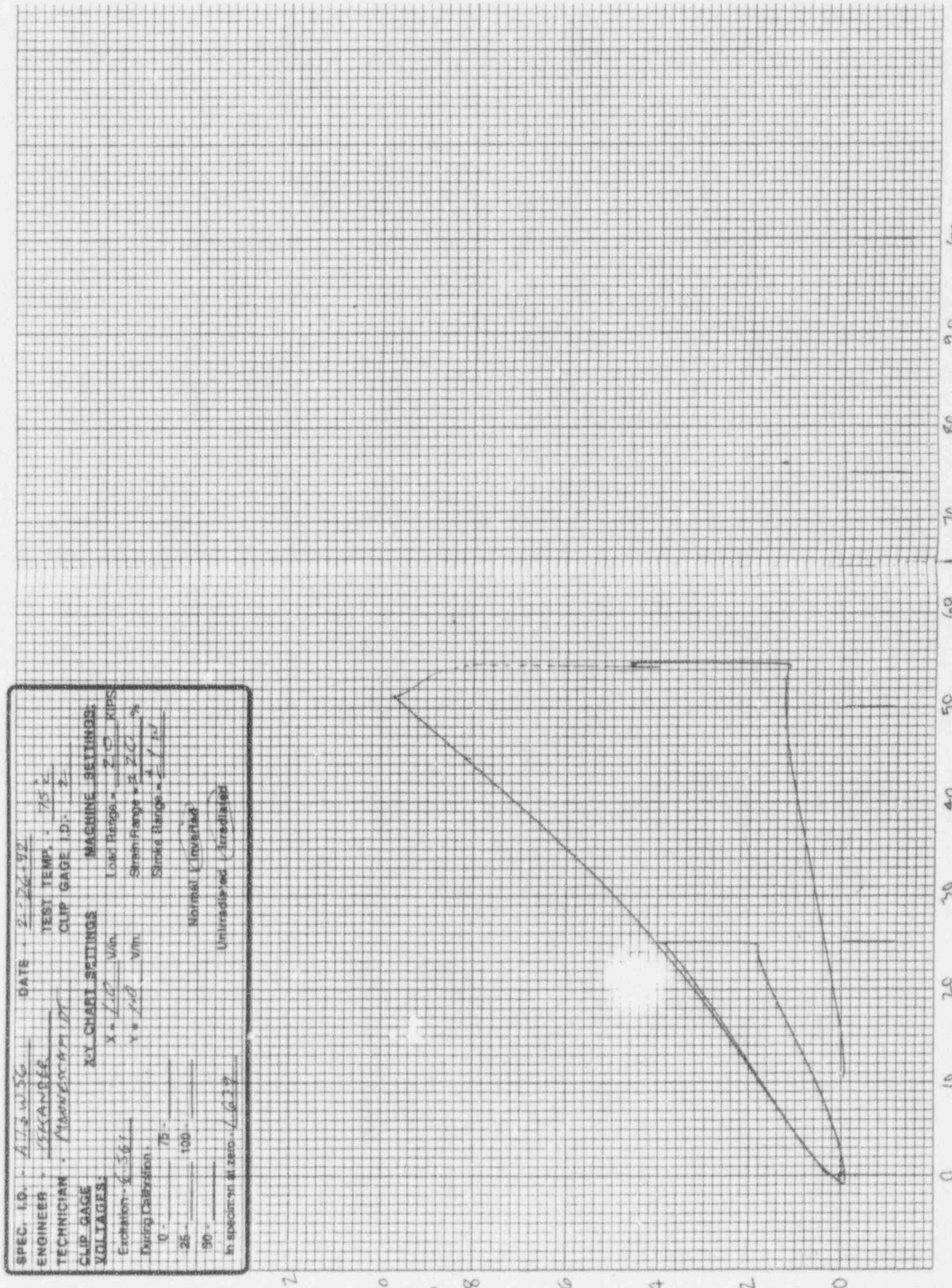
b

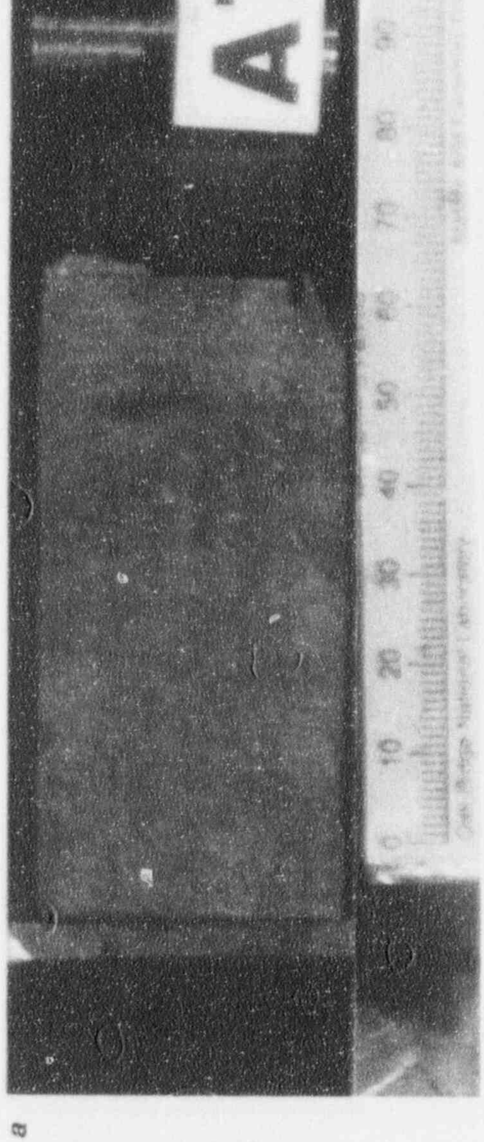

SPEC. I.D. - A73W55
DATE - 3/27/92
ENGINEER - Shafik Iskander
TEST TEMP. - 100 °C
TECHNICIAN - Eric Mannaschmidt
CLIP GAGE I.D. - CAG 02
CLIP GAGE VOLTAGES:
Excitation - 6.549
During Calibration -
0 -
25 -
50 -
75 -
100 -
In specimen at zero - 0.634
X-Y CHART SETTINGS
X = 4.0 V/in.
Y = 1.0 V/in.
MACHINE SETTINGS:
Load Range - 20 KIPS
Strain Range = ± 20 %
Stroke Range = ± 1.0 in.
Normal | Inverted
Unirradiated | Irradiated
BROKE TO E.B. WELD
kips
10
8
6
4
2
0
0
10
20
40
50
60
70
mils CMOD



a

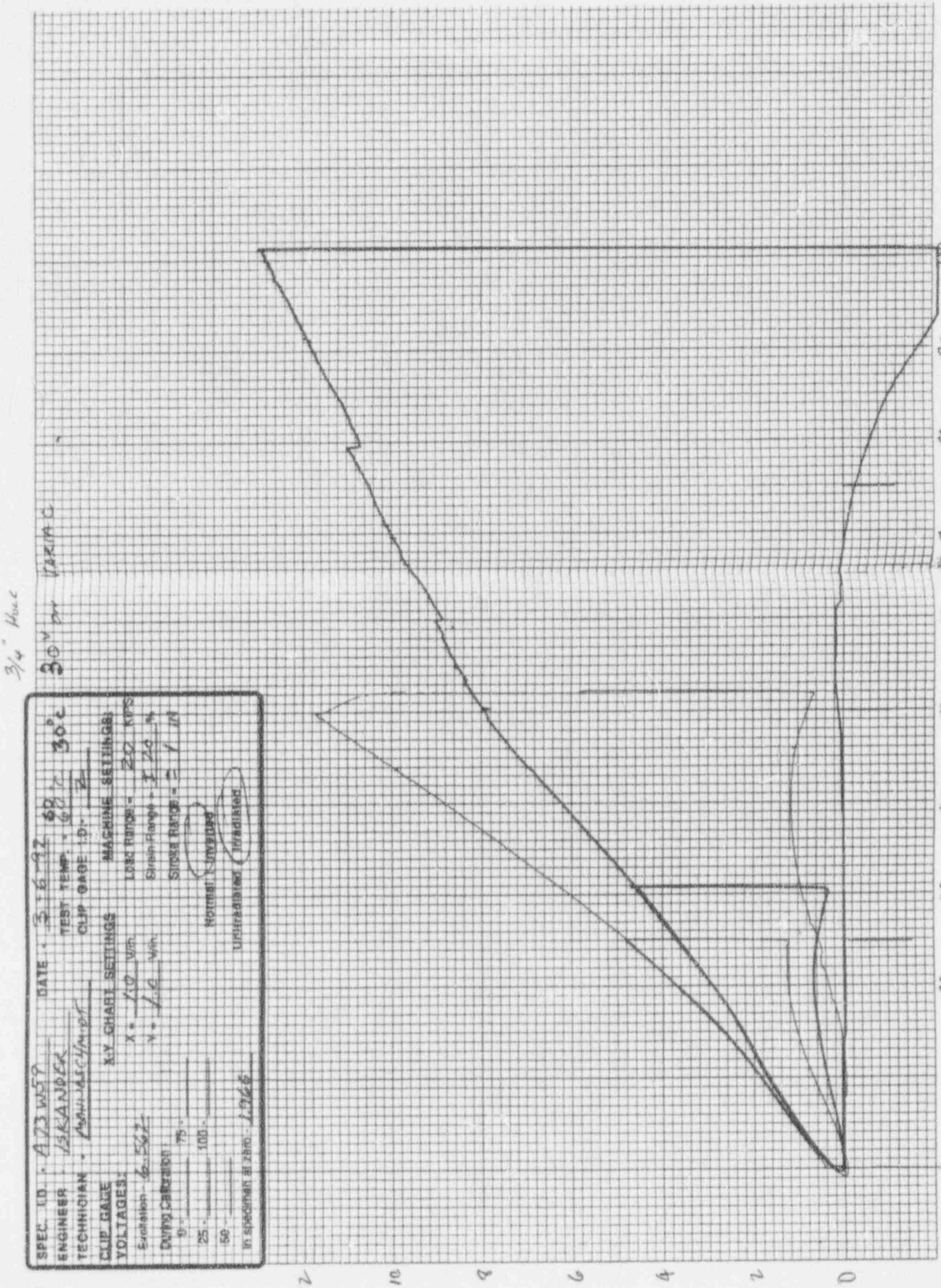
b

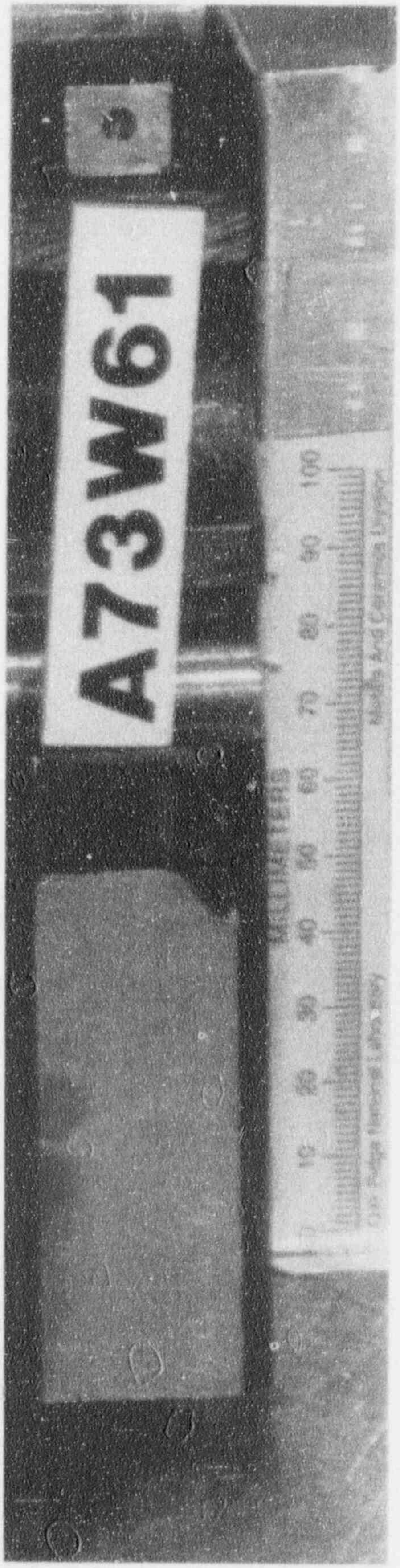

SPEC. I.D.
DATE
ENGINEER
TEST TEMP.
TECHNICIAN
CLIP GAGE I.D.
CLIP GAGE VOLTAGES:
X-Y CHART SETTINGS
MACHINE SETTINGS
Load Range
KIPS
Strain Range
Stroke Range
Excitation
During Calibration
Normal
Inverted
Unirradiated
Irradiated
In specimen at zero



a

b


SPEC. I.D.
DATE
ENGINEER
TECHNICIAN
TEST TEMP.
CLIP GAGE
CLIP GAGE I.D.
VOLTAGES:
X-Y CHART SETTINGS
MACHINE SETTINGS
Excitation
Load Range
Strain Range
Stroke Range
During Calibration:
In specimen at zero
Normal
Invalid
Unirradiated
Irradiated
0
2
4
6
8
10
12
0
10
20
30
40
50
60
70
80
90
100



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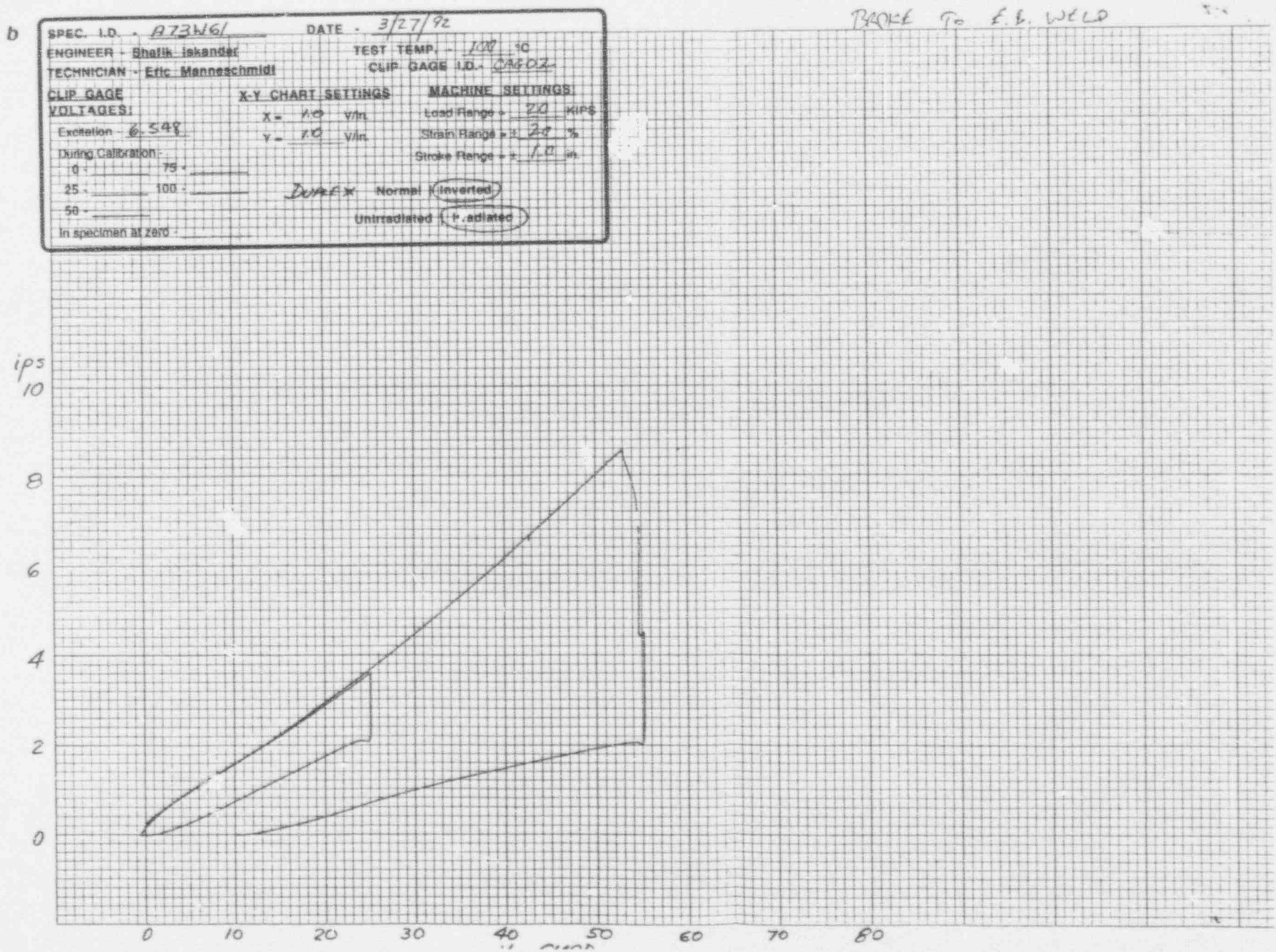
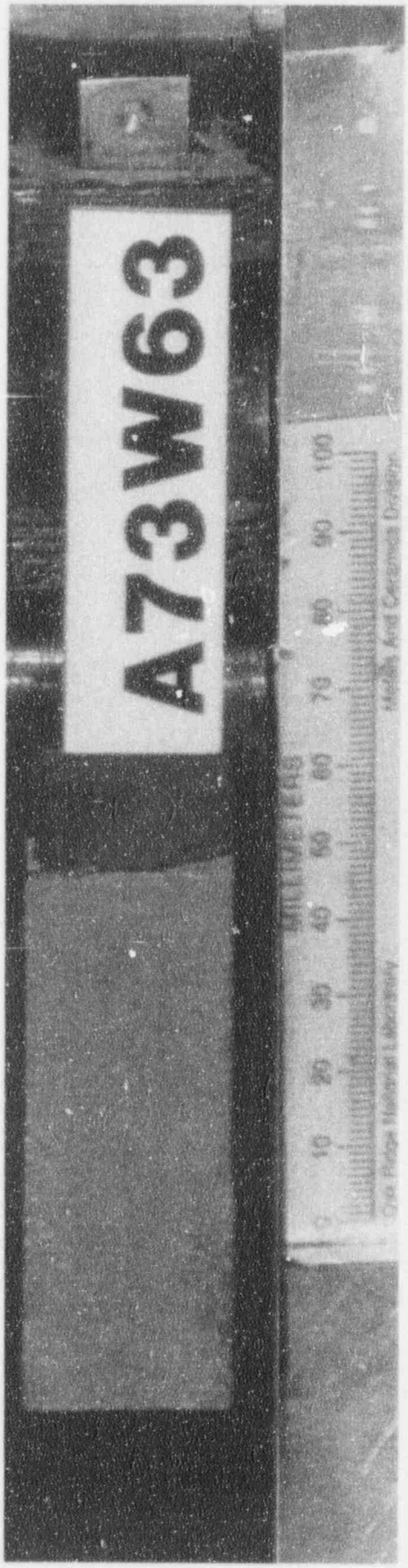

b
SPEC. I.D. - A73W61
DATE - 3/27/92
ENGINEER - Shafik Iskander
TEST TEMP. - 100 °C
TECHNICIAN - Eric Manneschmidt
CLIP GAGE I.D. - CAG02
CLIP GAGE VOLTAGES:
Excitation - 6.548
During Calibration -
0 -
25 -
50 -
75 -
100 -
In specimen at zero -
X-Y CHART SETTINGS
X = 1.0 V/in.
Y = 1.0 V/in.
MACHINE SETTINGS:
Load Range = 20 KIPS
Strain Range = ± 20 %
Stroke Range = ± 1.0 in.
Normal
Inverted
Unirradiated
Irradiated
BROKE TO E.B. WELD
ips
10
8
6
4
2
0
0
10
20
30
40
50
60
70
80



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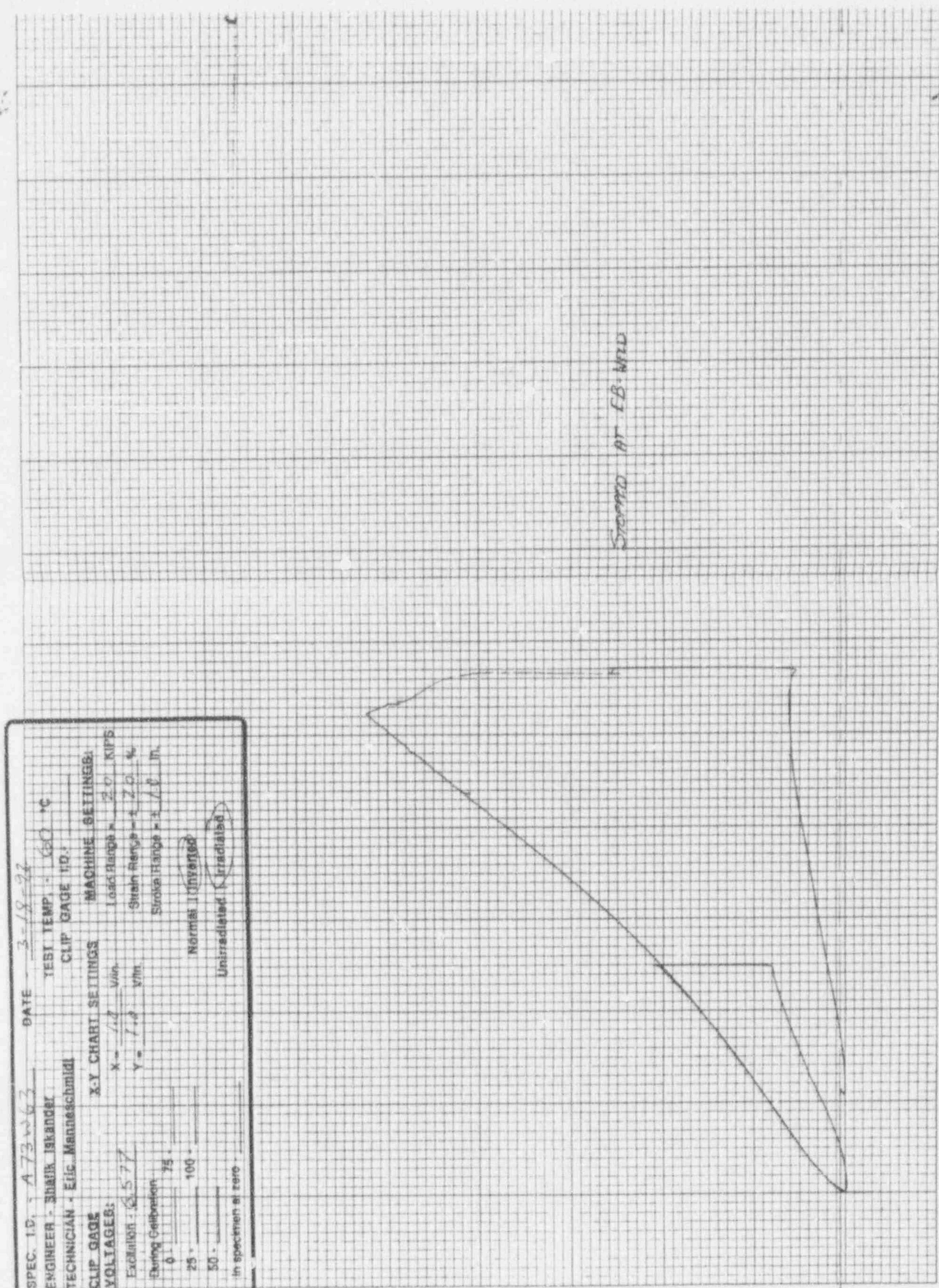
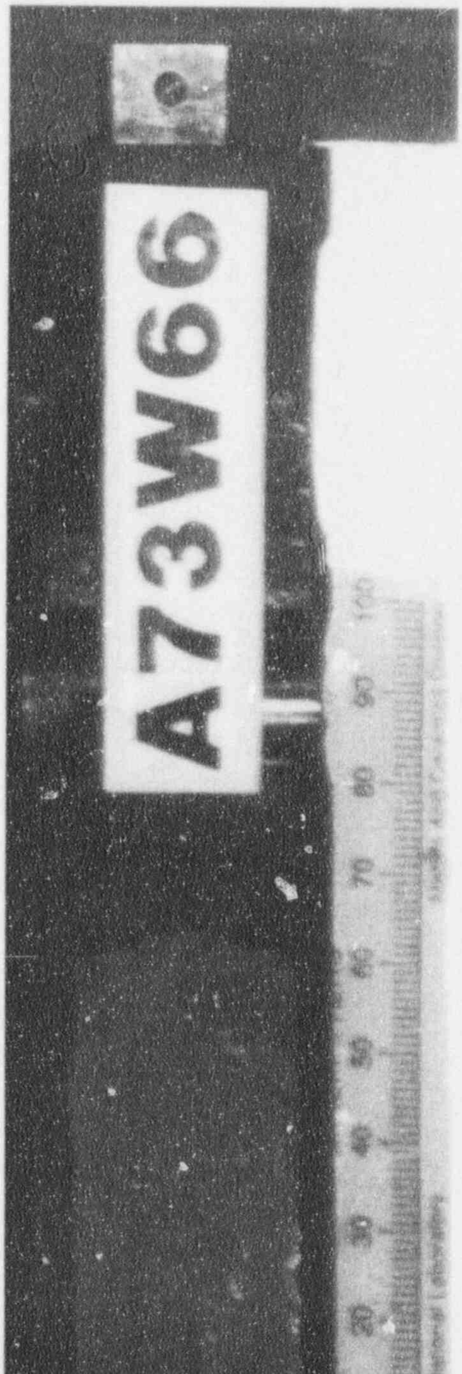
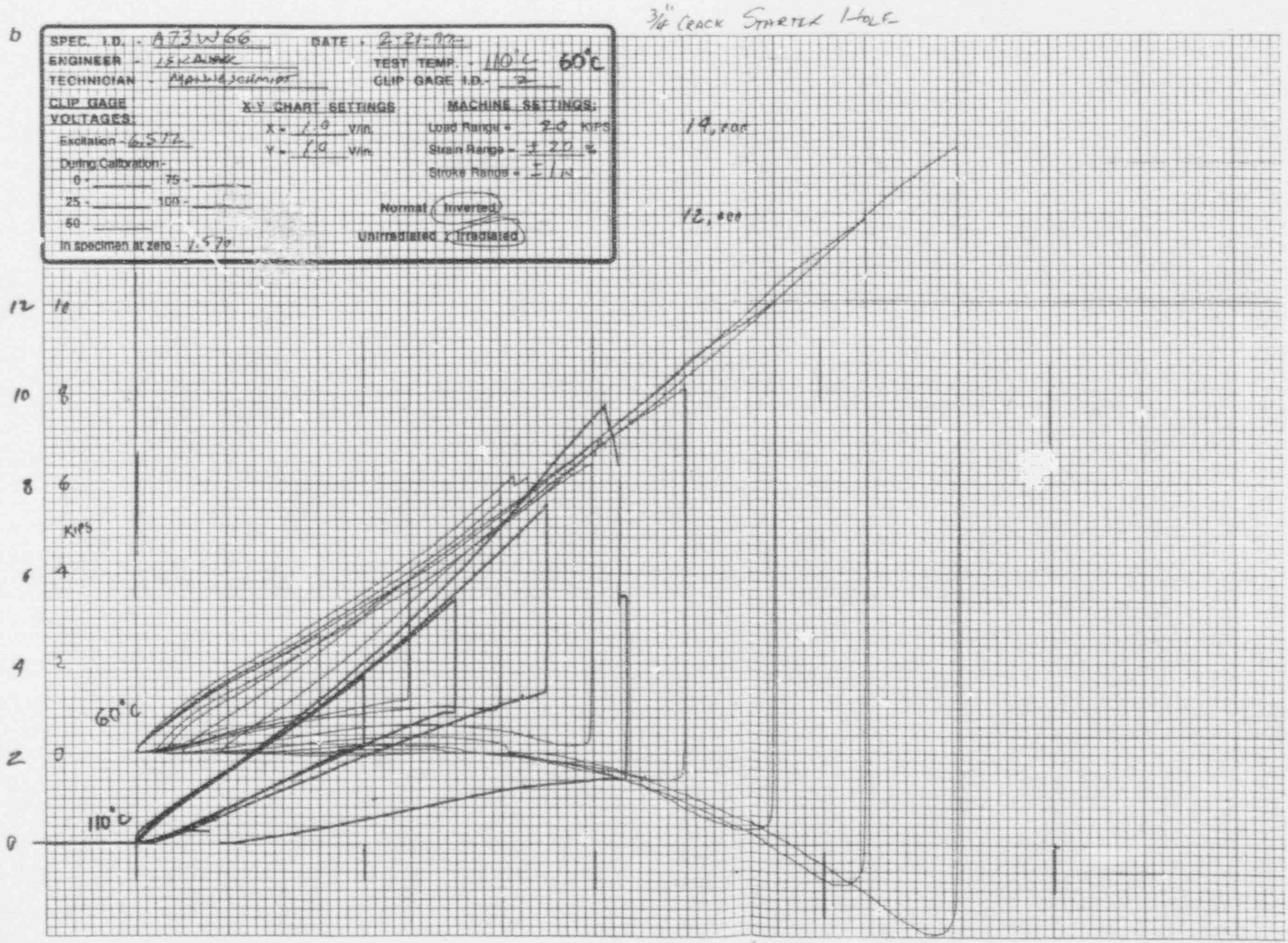
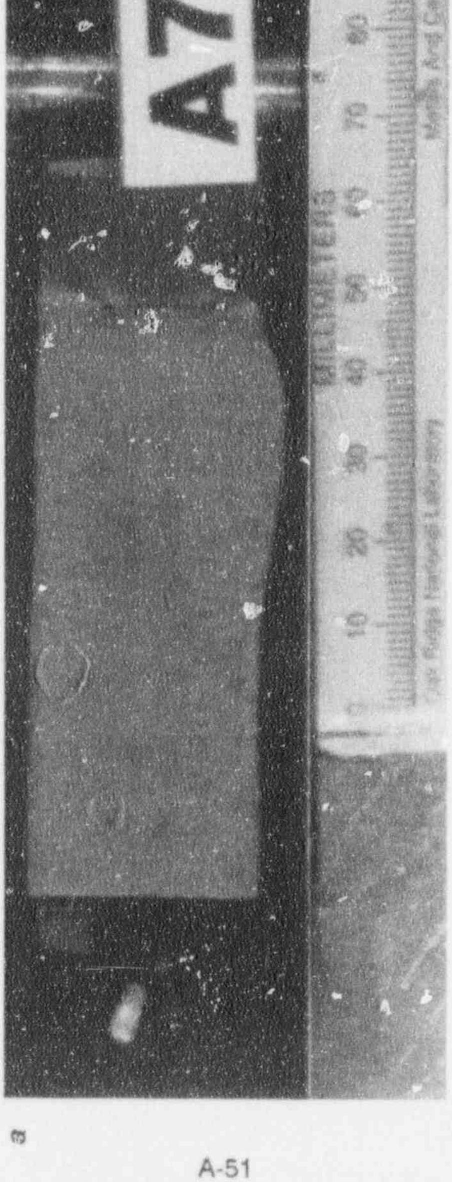

SPEC. I.D. - A73W63
DATE - 3-18-92
ENGINEER - Shafik Iskander
TEST TEMP. - 60 °C
TECHNICIAN - Eric Manneschmidt
CLIP GAGE I.D. -
CLIP GAGE VOLTAGES:
Excitation - 8.577
During Calibration
0 -
25 -
50 -
75 -
100 -
In specimen at zero -
X-Y CHART SETTINGS
X = 1.0 V/in.
Y = 1.0 V/in.
MACHINE SETTINGS:
Load Range = 20 KIPS
Strain Range = ± 20 %
Stroke Range = ± 1.0 in.
Normal | Inverted
Unirradiated | Irradiated
STOPPED AT EB-WELD
0
2
4
6
8
10
12
0
10
20
30
40
50
60
70
80
90
100
b

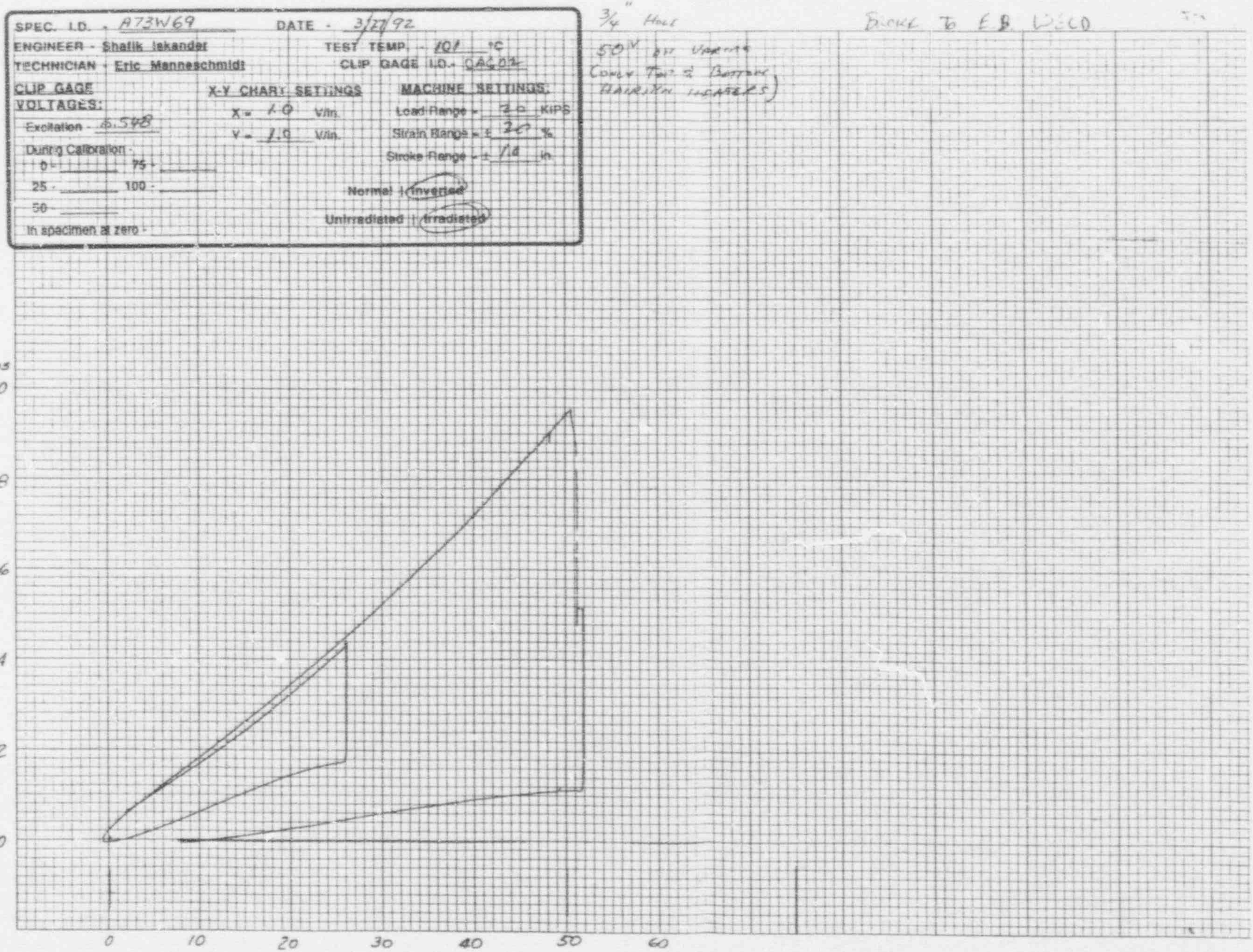


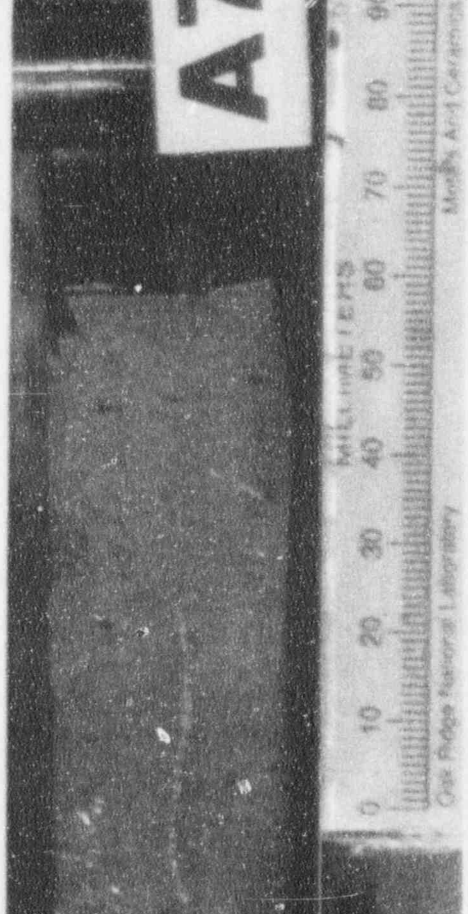
a


3/4" CRACK STARTER HOLE
SPEC. I.D. - A73W66
DATE - 2-21-93
ENGINEER - ISKANDER
TEST TEMP. - 110°C 60°C
TECHNICIAN - MANNESCHMIDT
CLIP GAGE I.D. - 2
CLIP GAGE VOLTAGES:
X-Y CHART SETTINGS
MACHINE SETTINGS:
Excitation - 6.572
X - 1.0 V/in.
Y - 1.0 V/in.
Load Range = 20 KIPS
Strain Range = ±20 %
Stroke Range = ±1 in
During Calibration -
0 -
75 -
25 -
100 -
50 -
In specimen at zero - 1.570
Normal / Inverted
Unirradiated / Irradiated
14,700
12,000
KIPS
60°C
110°C
12
10
8
6
4
2
0

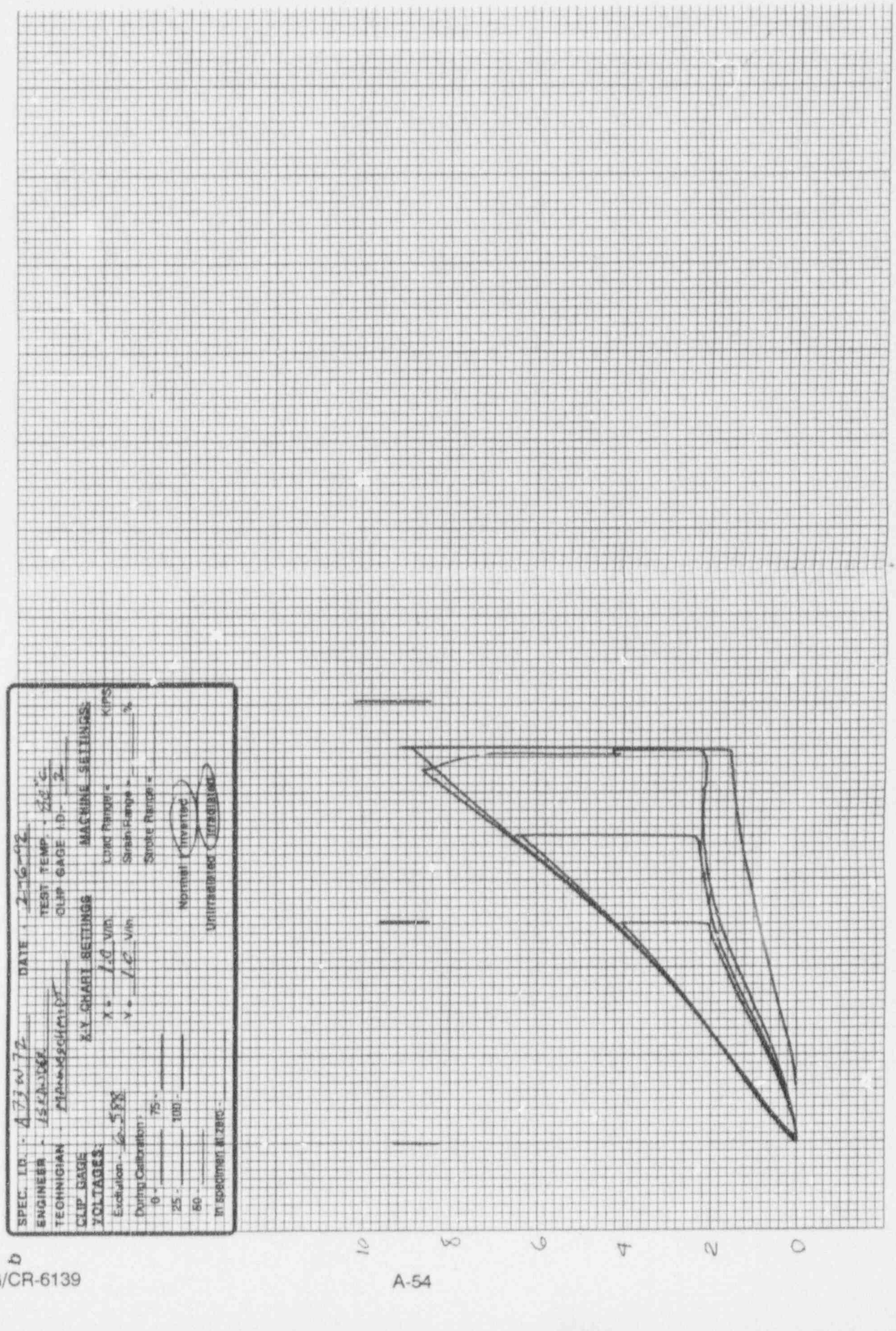

A73W69

b


SPEC. I.D. - A73W69
DATE - 3/27/92
ENGINEER - Shafik Iskander
TEST TEMP. - 101 °C
TECHNICIAN - Eric Manneschmidt
CLIP GAGE I.D. - CAG02
CLIP GAGE VOLTAGES:
Excitation - 6.598
During Calibration -
0 -
75 -
25 -
100 -
50 -
In specimen at zero -
X-Y CHART SETTINGS
X = 1.0 V/in.
Y = 1.0 V/in.
MACHINE SETTINGS:
Load Range - 20 KIPS
Strain Range - ± 20 %
Stroke Range - ± 1.4 in.
Normal | Inverted
Unirradiated | Irradiated
3/4" Hole
Broke to E.B. Weld
kips
10
8
6
4
2
0
0
10
20
30
40
50
60


A73W72
MILLIMETERS
0 10 20 30 40 50 60 70 80 90 100
Oak Ridge National Laboratory
Metals And Ceramics Division

a


SPEC. I.D. -
DATE -
ENGINEER -
TEST TEMP. -
TECHNICIAN -
CLIP GAGE I.D. -
CLIP GAGE
VOLTAGES:
X-Y CHART SETTINGS
MACHINE SETTINGS:
Excitation -
X = 1.0 V/in.
Y = 1.0 V/in.
Load Range =
KIPS
Strain Range =
%
Stroke Range =
During Calibration:
0 -
25 -
50 -
75 -
100 -
In specimen at zero -
Normal
Inverted
Unirradiated
Irradiated
10
8
6
4
2
0

Appendix B

Trial Tests on Duplex-Type Crack-Arrest Specimens With Intentionally Unfused Electron-Beam Weld Mid-Region

Appendix B

Trial Tests on Duplex-Type Crack-Arrest Specimens With Intentionally Unfused Electron-Beam Weld Mid-Region

The first four irradiated duplex-type crack-arrest specimens tested, two each from the 72W and 73W welds, were unsuccessful. In all four specimens, the flaw arrested in the fusion zone between the 4340 crack-starter material and the weld metal test section. There was significant lack of fusion, which was probably the major reason for the crack arresting in that region (the heat-affected zone in unirradiated duplex specimens sometimes arrests the flaw). It was judged at the time, and this was justified later, that this lack of fusion probably existed in the remaining 20 specimens. That would preclude successful testing in their present form at temperatures higher than those chosen for Phase I. The specimens could have been tested at temperatures that are low with respect to RT_{NDT}, but that would not have yielded very useful information. In order to utilize these specimens, various modifications to the duplex specimens have been considered and were described in the main body of the text. This appendix describes the tests made on unirradiated specimens to verify that increasing the crack-starter hole diameter, if made to the remaining 20 irradiated specimens, would increase the chances of obtaining useful data.

Increasing the diameter of the crack-starter hole also increases the crack-driving force. Originally, the diameter of the hole in the 24 irradiated duplex specimens was approximately 4 mm. The idea behind this modification is that a sufficiently large crack-driving force may cause the propagating flaw to jump across the unfused zone. About ten unirradiated duplex crack-arrest specimens with 16- and 19-mm (5/8- and 3/4 in.) crack-starter holes were manufactured to determine the optimum hole diameter.* An attempt was made to fabricate duplex crack-arrest specimens with approximately the middle one-third of the net remaining specimen thickness unfused. The electron-beam (EB) weld was purposely made "defective" to simulate the condition found in the irradiated specimens. This is not an easy proposition, but as the photos of the fracture surfaces show later, this was partially successful. The test section of these "trial" specimens was machined from A 533 grade B plate whose crack-arrest behavior is already known. This material was used in the Clad Plate Program [1] and is a specially heat-treated A 533 grade B plate with a nil-ductility transition temperature (NDT) of 36°C.

Five of these ten specimens tested were successful, and a fast-running crack propagated beyond the unfused EB weld region and into the test section. The crack-arrest toughness values from these successful tests are shown as filled points in Figure B.1. The values of the crack-arrest toughness are given in Table B-1. The open points are from previous tests on weld-embrittled crack-arrest specimens, [1] (at the end of this appendix). This is another illustration that duplex specimens can give crack-arrest toughness values at temperatures as much as 65°C above the NDT temperature.

These results show that, by increasing the crack-starter hole, the crack-driving force could be increased sufficiently for the crack to jump across a partially unfused EB zone provided that the size of the unfused region is not greater than one-third the net section. Although the test sections of the dummy duplex crack-arrest specimens were base metal, the results were encouraging enough that it was believed that the same modification could be used successfully with the remaining 20 irradiated 72W and 73W weld metal duplex crack-arrest specimens. It should be noted that all the successful trial tests were with specimens that had 16-mm-diam crack-starter holes. Because the extent of the unfused region is difficult to control, it varied from specimen to specimen.

The remaining five specimens were unsuccessful because of various defects in the EB weld. It is difficult to make a successful duplex crack-arrest specimen. To intentionally make a defective one to specifications is even more difficult. The fracture surfaces of the successful and unsuccessful specimens are shown in Figures B.2 and B.3, respectively. It may be seen that in some

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*Theoretically, increasing the hole diameter fourfold increases the force required for crack-initiation by approximately twofold.

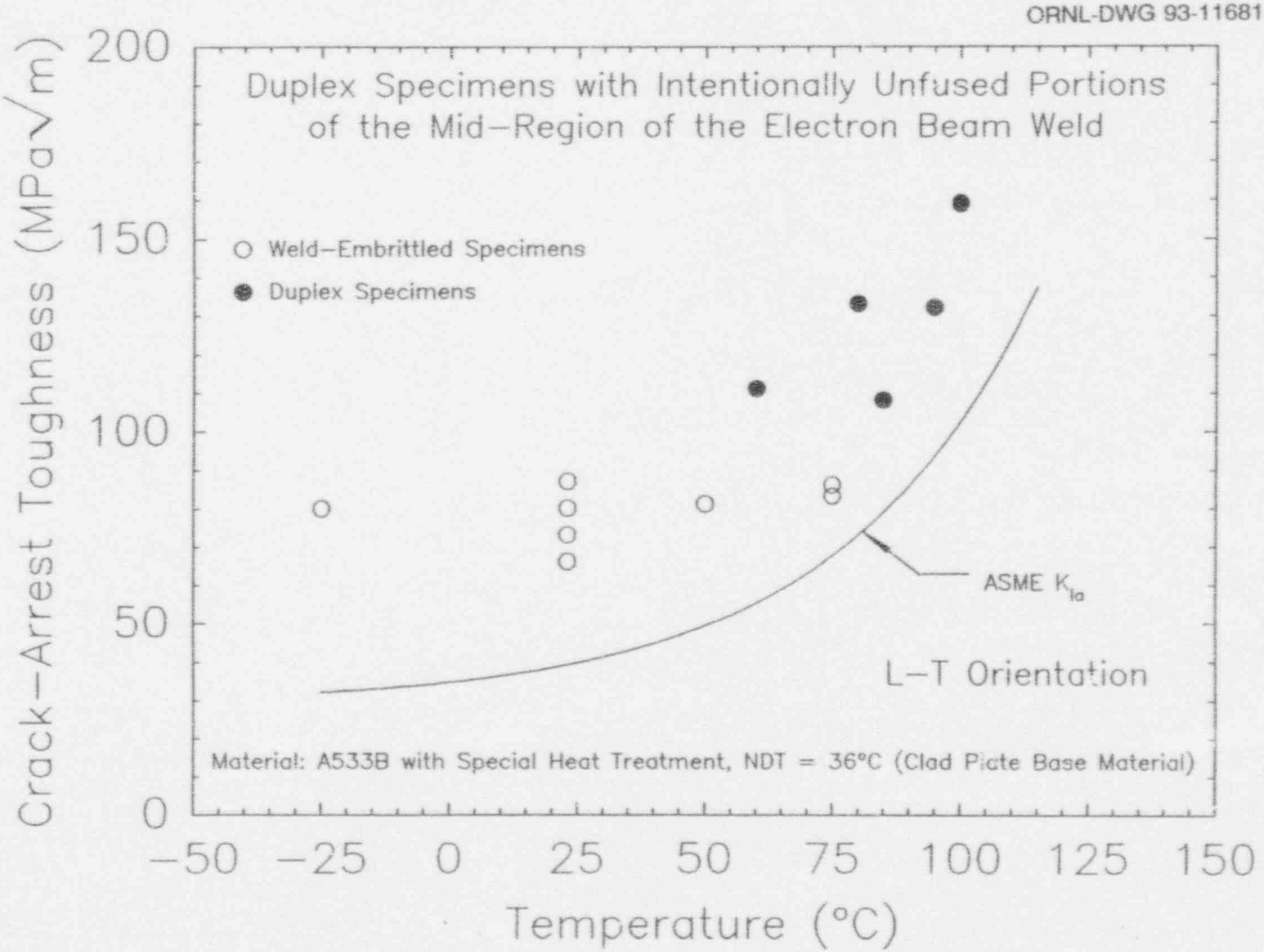


Figure B.1. Comparison of crack-arrest toughness values obtained from duplex specimens (with 16-mm crack-starter holes) with those from weld-embrittled type specimens. The duplex specimens had "unfused" electron-beam weld regions of varying extent.

Table B-1. Crack-arrest toughness values obtained from testing A 533 grade B material with a nil-ductility transition temperature of 36°C. The crack-starter hole diameter is 16 mm, and the specimens were fabricated with intentionally defective electron-beam weld regions

Specimen	Test temperature (°C)	Crack-arrest toughness, K_a (MPa√m)
CP33	60	111
CP36	80	133
D10	85	108
D9	95	132
CP43	100	159

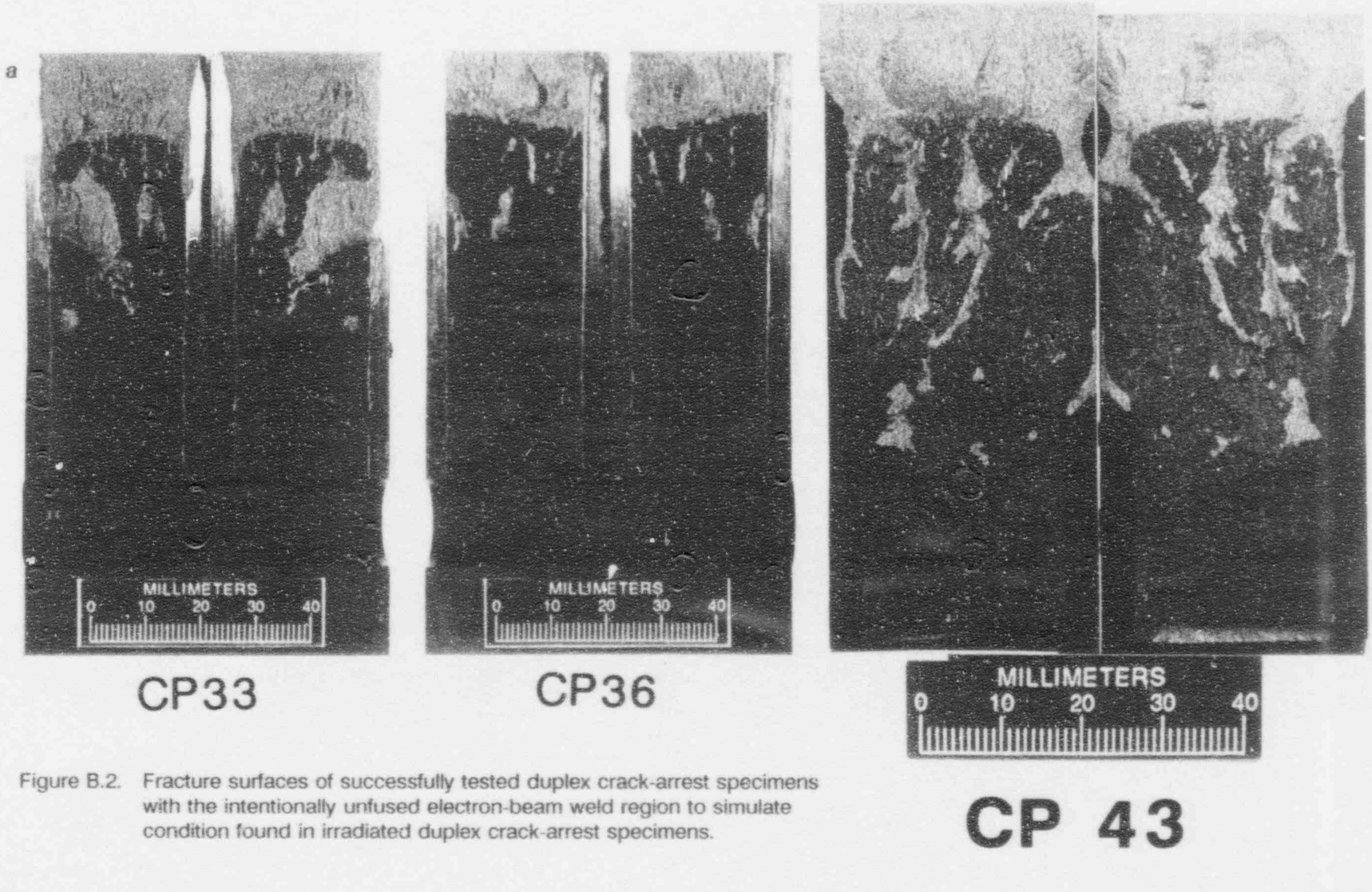


Figure B.2. Fracture surfaces of successfully tested duplex crack-arrest specimens with the intentionally unfused electron-beam weld region to simulate condition found in irradiated duplex crack-arrest specimens.

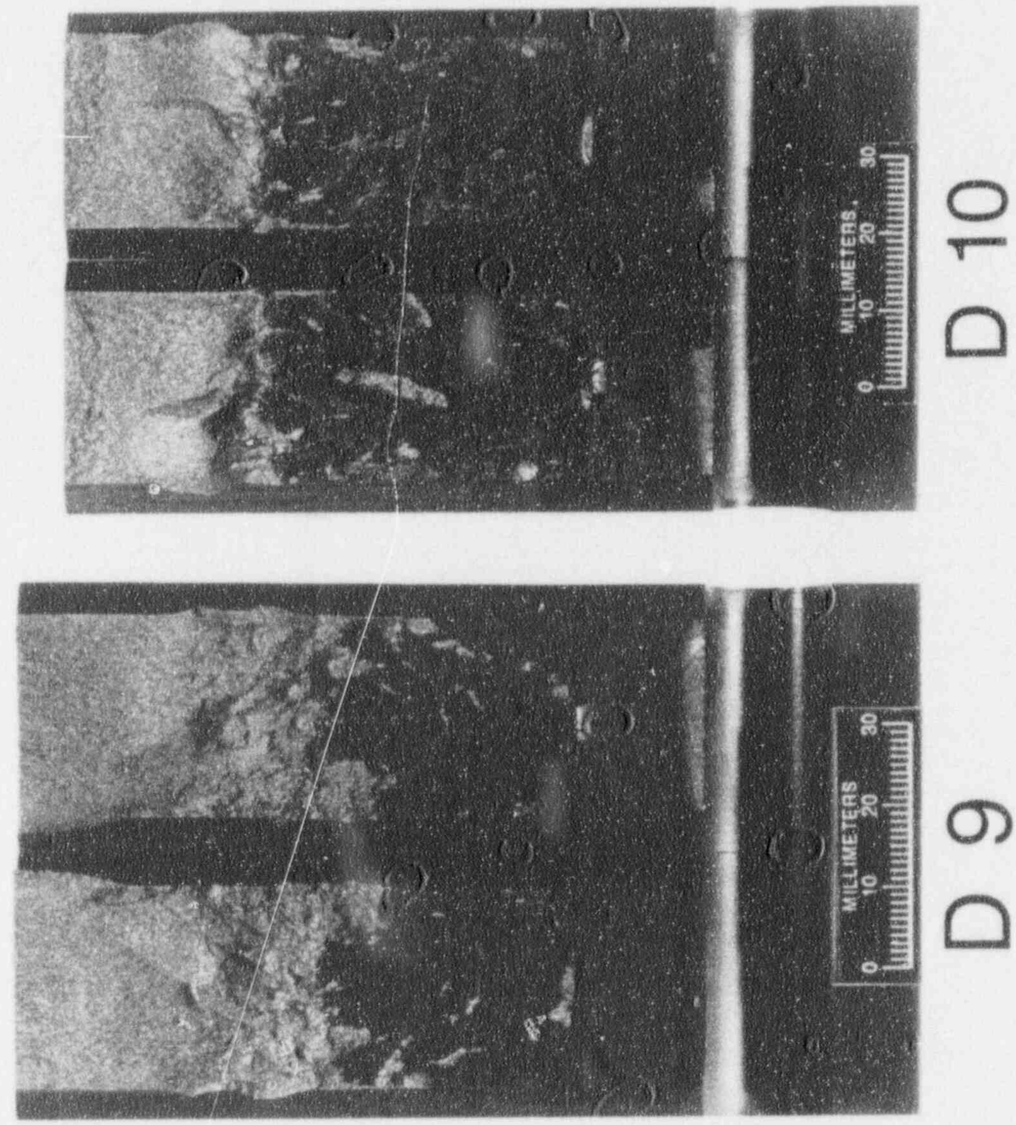


Figure B.2 (continued)

a

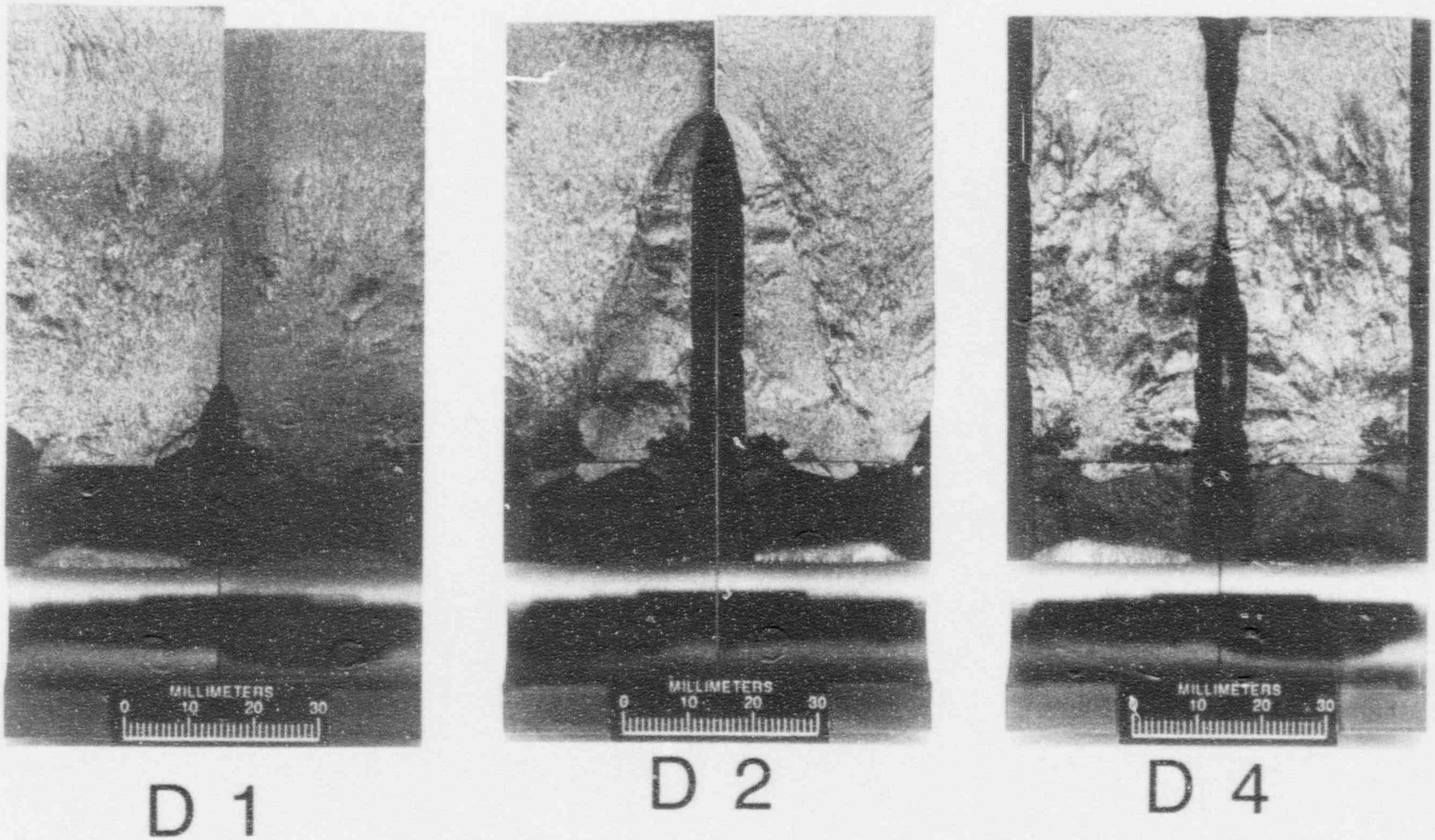
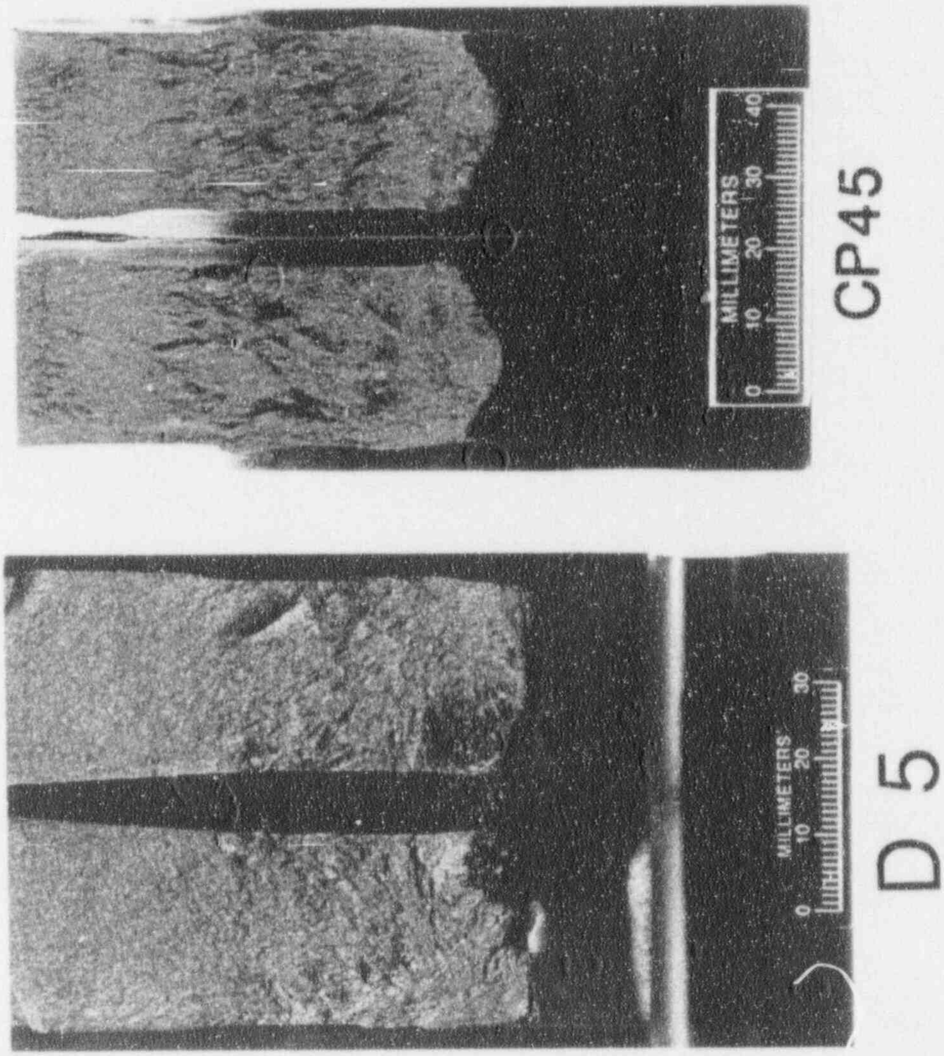


Figure B.3. Fracture surface of the unsuccessful duplex crack-arrest specimens. The extent of the intentionally defective electron-beam weld region was difficult to control.



b

Figure B.3 (continued)

of these specimens, the unfused region extended over almost two-thirds of the net section, and presumably this arrested the flaw in the weld fusion zone. The crack did propagate, however, some distance across the fused portion into the test section.

It is of interest to note that various ultrasonic (UT) examinations of the duplex crack-arrest specimens have revealed the presence of an unfused zone but failed to accurately determine its size. The anisotropy of the materials in the EB weld fusion zone seems to scatter the UT signal so that this type of test cannot be used to screen duplex-type crack-arrest specimens as a quality control technique. A new UT examination method, the B-scan method, is being evaluated at this time.

There were several unirradiated duplex crack-arrest specimens made from the 73W weld that were previously rejected because the lack of fusion between the 4340 and the test section was readily discernable on the sides of the specimen. They were remachined with 16- and 19-mm holes, but none of these specimens were tested successfully, probably because the size of the unfused region was too large.

Experimental values of the yield strengths of the material at the temperatures needed for the crack-arrest testing were not known but were estimated using an expression developed by Irwin.[2] For loading rates approximately equal to those customarily used in "static" tensile testing, the following equation gives the yield strength at any temperature (t) if the yield strength is known at another temperature (which can be room temperature for convenience):

$$\sigma_{yt} = \sigma_{yt'} - A + \frac{55,000}{t + 273} , \qquad (1)$$

where

σ_{yt} = yield strength at temperature, t, in MPa,
t = temperature in °C,
$\sigma_{yt'}$ = the known yield strength at the temperature, t',
A = a calibration constant equal to the value of the term $55,000/(t + 273)$ at the temperature at which the yield strength is known.

When the value of the yield strength at room temperature is substituted, the equation becomes:

$$\sigma_{yt} = 395 + \frac{55,000}{t + 273} . \qquad (2)$$

However, in cases such as this one in which the yield strength is known at various temperatures,* it may be preferable to fit an equation of the form:

$$\sigma_{yt} = A + \frac{B}{t + 273} . \qquad (3)$$

This gives the following equation:

$$\sigma_{yt} = 442 + \frac{42,400}{t + 273} . \qquad (4)$$

Equation (4) was used in the analysis of the crack-arrest data.

It was of interest to determine the degree of approximation in cases were the yield strength of this class material is known only at one temperature. Figure B.4 shows Equations (2) and (4) plotted together with the available data at various temperatures, which shows that the agreement is reasonable. Thus, expressions of the form of Equation (1) give reasonable estimates if the yield strength is required as a function of temperature and the yield strength is only known at one temperature. On the other hand, if the yield strength is already known at various temperatures, the two-parameter Equation (3) may fit the data more effectively than a three or more parameter polynomial.

References

1. S. K. Iskander, G. C. Robinson, W. R. Corwin, B. C. Oland, D. J. Alexander, and K. V. Cook, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., *Experimental Results of Tests to Investigate Flaw Behavior in Mechanically Loaded Stainless Steel Clad Plates,* USNRC Report NUREG/CR-5785 (ORNL/TM-11950), April 1992, p. 57.†

*See Tables 3.3 and 3.11 of Ref. [1] in this Appendix.

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

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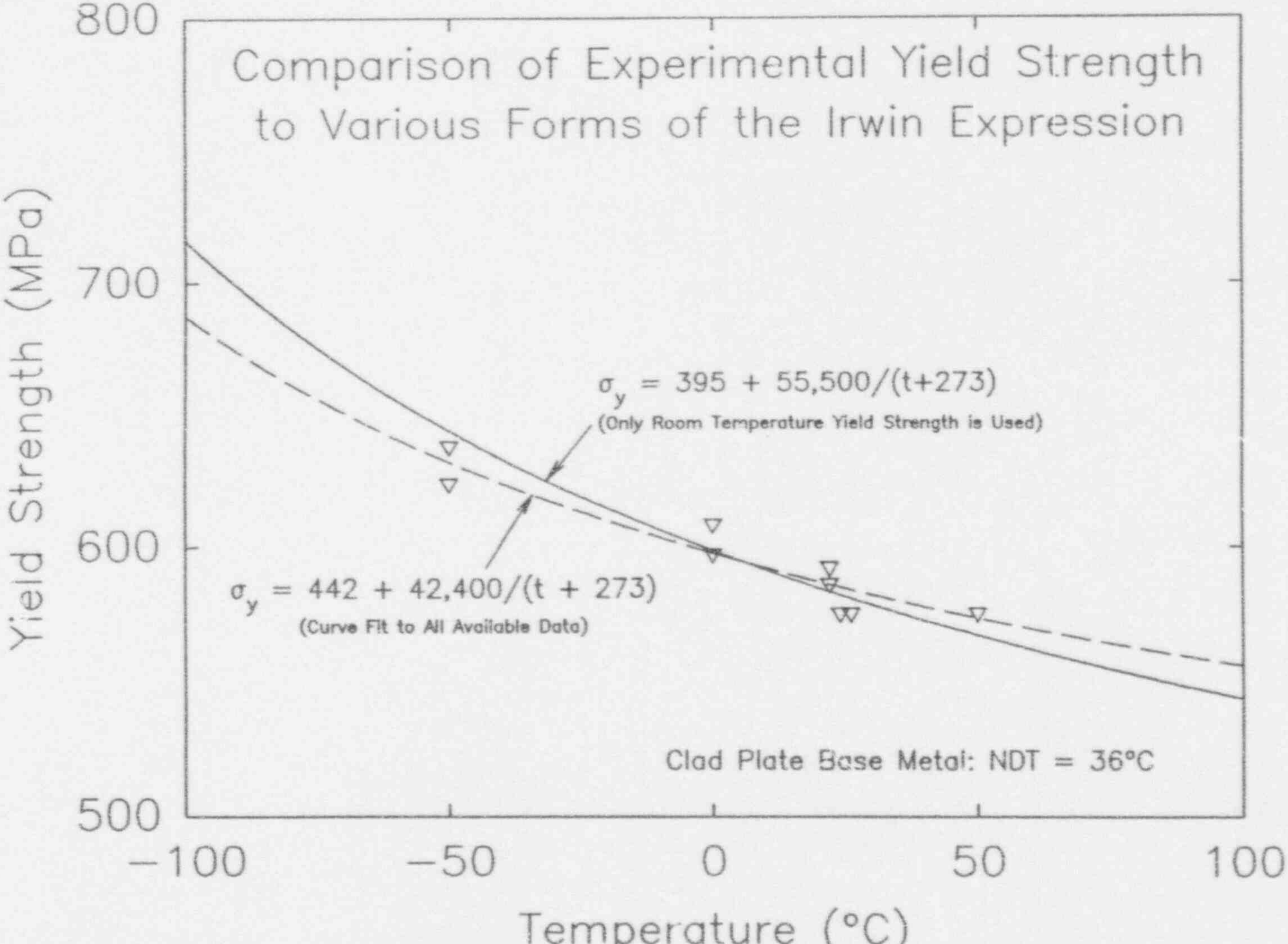

Figure B.4. Curve fitting used to extrapolate yield strength of the À 533 grade B base metal used in the test section of the "unfused" duplex crack-arrest specimens.

2. G. R. Irwin, "Linear Fracture Mechanics, Fracture Transition, and Fracture Control," *Engineering Fracture Mechanics*, Vol. 1, 1968, pp. 241-57.*

*Available in public technical libraries.

Appendix C

Equipment for Modifying the Irradiated Duplex Crack-Arrest Specimens

Appendix C

Equipment for Modifying the Irradiated Duplex Crack-Arrest Specimens

The end mill used to modify the irradiated duplex crack-arrest specimens is commercially known as a "Hawg Cutter." It is primarily used with portable equipment* to cut holes in steel structures in the field. The carbide-tipped end mill is actually a trepanning cutter that minimizes the amount of metal removed and, thus, is a very efficient means of machining holes (see Figure C.1). Both the cutter and a conical chuck to hold it in a lathe had to be modified by electrodischarge machining for use in a lathe. A small hole was electrodischarge-machined in the cutter and a roll pin inserted. The conical chuck had two diametrically opposite, semicircular grooves electrodischarge machined to act as a "key" to prevent the cutter from slipping inside the chuck. The cutter was also designed for materials less than 25 mm thick (1 in.), and the length of the flutes of the cutter was increased by machining the larger diameter of the cutter to move back the shoulder fillet. The inside hole was drilled the entire length of the cutter.

It should be recalled that the entire machining operation had to be performed remotely in a hot cell with manipulators. A remotely operable lathe was converted into a horizontal milling machine to modify the specimens. The cutter was gripped in a horizontal position by the rotating lathe head. On the lathe bed, a quick-acting vise was secured in place of the tool-cutter post. The quick-acting vise contained a suitable jig so that all the operator needed to do was drop the specimen into the jig, and the specimen would be at the proper position for the modification.

Provisions were made for machining either of two crack-starter hole diameters: 16 or 19 mm (5/8 or 3/4 in.). It was not known beforehand how much of a crack-driving force would be required to drive the crack across the unfused region. On one hand, it was desired to limit the necessary hole diameter to the smallest possible in order to minimize plastic deformation. On the other hand, it was believed that as large a crack-driving force as possible was desirable.

Lubrication and cooling of the cutter inside the hot cell is also a problem because of the severe restrictions on the amount of liquid wastes that could be generated. A plastic squirt bottle with TRIM™SOL worked well if the flow of coolant could be aimed at the proper location. Coolant was critical and, until the operator had sufficient experience in directing it on the tool by observing the area using a Kollmorgen periscope, the carbide tips of the cutter would quickly become dull and would no longer advance into the hardened material. The heat resulting from this dull tool rubbing against the 4340 steel hardened the area to the extent that it was very difficult for a new tool to restart the operation. Of course, the greatest of care was exercised to prevent this from happening. Until the coolant problem was overcome, it took two or more cutters to complete one hole. Once sufficient experience was gained, one cutter was sufficient to machine the remaining dozen or so specimens!

Cutting speed and feed were also important. In trepanning out the hole section in the hardened 4340, there was a tendency for the cutter to just rub on the surface. It was necessary for the feed to be sufficiently large that a chip be produced; otherwise, the rubbing would locally harden the hole bottom, as mentioned above. If the feed was too large, the lathe would stall. Considerable trial and error were necessary on the irradiated material. None of the parameters that were developed on an unirradiated trial specimen of specially heat-treated 4340 were of use. The trial specimen was hardened to about HRC 50, rather than the customary 42 to 45 HRC, to account for the hardening due to irradiation.

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*Both the cutter and the boring equipment, known as the MILWAUKEE 4240 STEEL HAWG™ Metal Boring System, are manufactured by the Milwaukee Electric Tool Corporation, Brookfield, WI 53005.

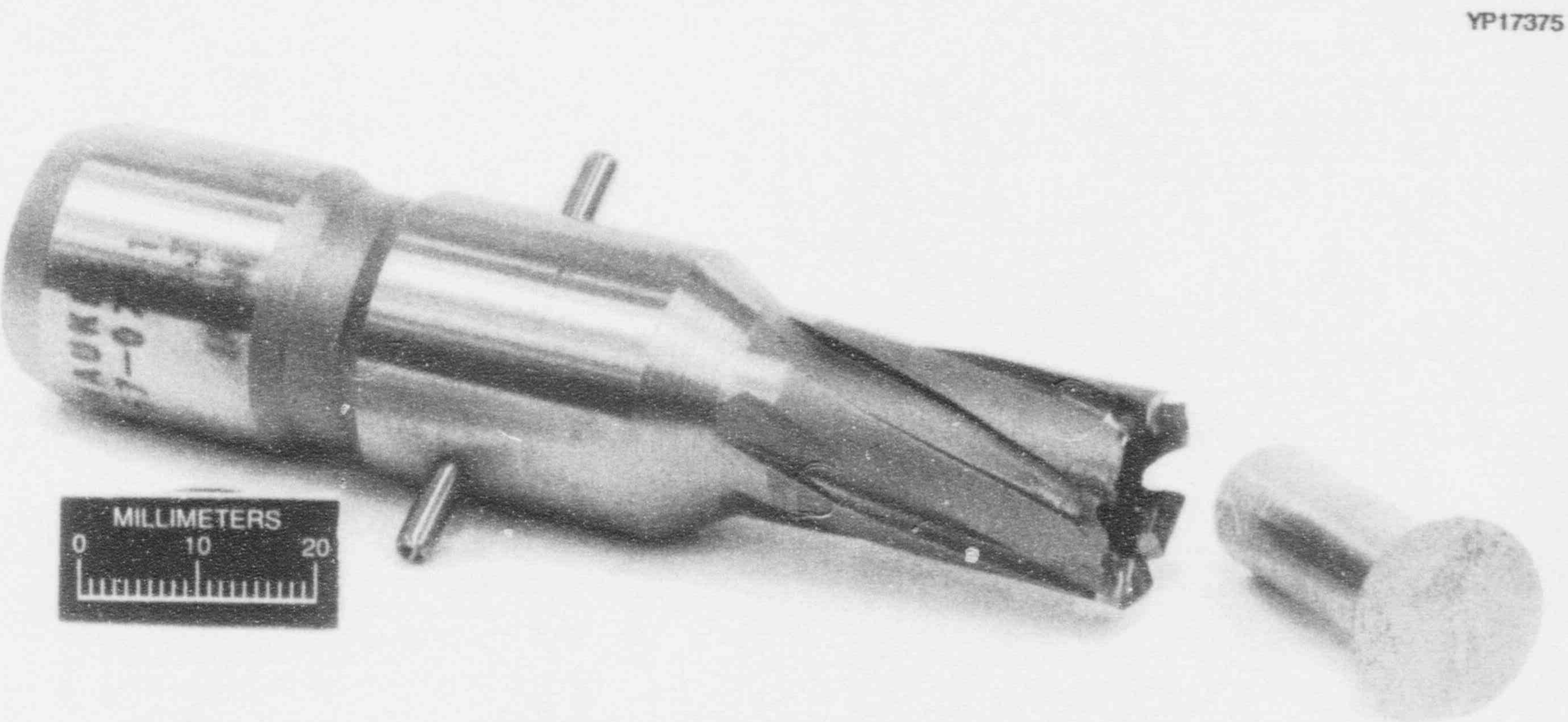

Figure C.1. Modified trepanning cutter used to increase hole diameter of the irradiated duplex crack-arrest specimens.

Appendix D

Detailed Output from Excel™ Showing Method of Calculations According to ASTM E 1221-88

Appendix D

Detailed Output from Excel™ Showing Method of Calculations According to ASTM E 1221-88

The specimen dimensions, the intermediate calculations of crack-mouth opening displacement at initiation and arrest, the outcome of calculations of the validity criteria according to American Society for Testing and Materials (ASTM) E 1221-88, K_o, and K_a, etc., are shown in this appendix in Table D-1 in the form of output from Excel™. The nomenclature used in the column headings for the specimen dimensions is explained in Figure D.1. The macrosheet for the formulae for calculating the yield strength, Young's modulus, the specimen compliance calibration function, and the maximum crack-mouth opening displacement during loading is shown in Table D-2. The validity criteria used in Table D-1 and excerpted from ASTM E 1221-88 are summarized in Table D-3.

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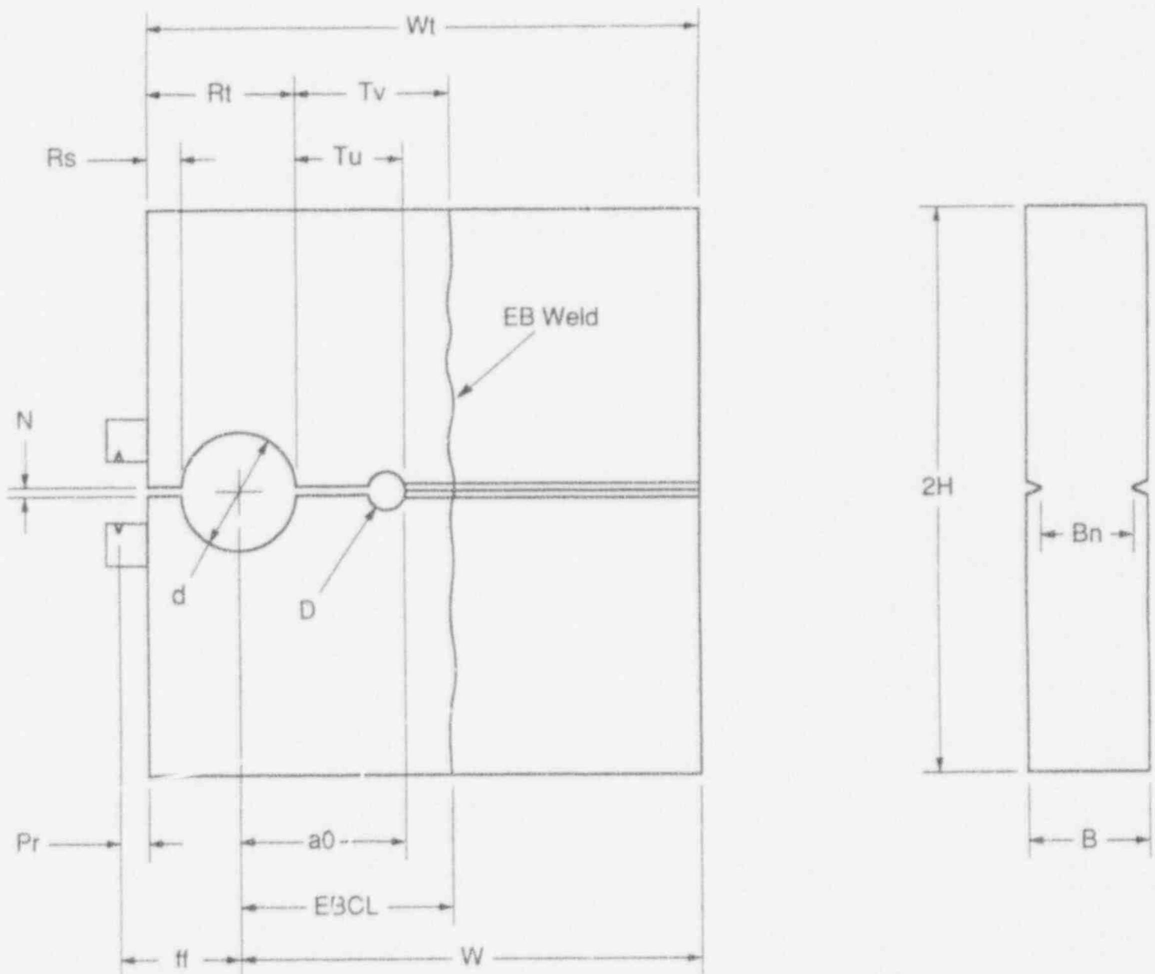

Figure D.1. Nomenclature used for the specimen dimensions and for column headings in Table D-1.

Table D-1. Detailed data on the duplex specimens, test results, and validity criteria

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	*Basic data on specimen*										*Duplex only*		
2	Spec Id	Specimen Type	B (In)	Bn (In)	2H (In)	Wt (In)	Pr (mm)	Rs (mm)	Rt (mm)	Tu (mm)	Tv (mm)	D (In)	N (mm)
3	A72W50	DX	1.300	0.975	6.000	6.000	6.350	9.597	41.313	27.034	41.910	0.625	1.067
4	A72W51	DX	1.300	0.975	6.000	6.000	6.350	9.389	41.089	26.767	45.212	0.750	1.067
5	A72W61	DX	1.300	0.976	6.000	6.000	6.350	9.468	41.175	26.702	45.085	0.750	1.067
6	A72W72	DX	1.300	0.975	6.000	5.999	6.350	9.444	41.166	27.048	45.085	0.750	1.067
7	*Test conditions & results*					Length of Remaining Ligament							
8	Spec	Test	Temperature		Position	(in)				CODs (mils)			
9	Id	Date	(°F)	(°C)	(I/U)	+Bn/4	Mid	-Bn/4	Average	R1	R3	P4	P5
10	A72W50	11-Feb-92	122	50	I	1.161	1.138	1.142	1.147	0	0	45.3	46.0
11	A72W51	12-Feb-92	167	75	I	1.614	1.654	1.772	1.680	0	0	57.0	58.0
12	A72W61	13-Feb-92	196	91	I	1.457	1.535	1.535	1.509	0	-1	63.3	64.4
13	A72W72	14-Feb-92	167	75	I	2.094	2.098	2.047	2.080	0	1	55.5	57.2
14	*Preliminary Calculations*												
15	Spec	Dist to CL	Hole rad	W	a0	aa	ff	ff/W	a0/W	aa/W	f(a0/W)	f(aa/W)	EBCL
16	Id	(in)	(in)	(in)	(in)	(in)	(in)						(in)
17	A72W50	1.002	0.624	4.998	1.689	3.851	1.252	0.251	0.338	0.771	0.2524	0.1070	2.274
18	A72W51	0.994	0.624	5.006	1.678	3.326	1.244	0.248	0.335	0.664	0.2535	0.1390	2.404
19	A72W61	0.997	0.624	5.003	1.675	3.494	1.247	0.249	0.335	0.698	0.2536	0.1287	2.399
20	A72W72	0.996	0.624	5.003	1.689	2.923	1.246	0.249	0.338	0.584	0.2525	0.1642	2.399
21	*Results of Calculations*												
22		Yield							Stress Intensity Factors				
23	Spec	Static		Dynamic		E	d0	da	K0		Ka		Tempera
24	Id	MPa	(ksi)	MPa	(ksi)	ksi	(mils)	(mils)	(ksi|in)	(MPa|m)	(ksi|in)	(MPa|m)	(°C)
25	A72W50	607	88.0	814	118.0	29639	45.3	45.7	175.1	192.4	74.8	82.2	50
26	A72W51	586	85.0	793	115.0	29432	57.0	57.5	219.0	240.7	121.0	133.0	75
27	A72W61	591	85.7	798	115.7	29299	64.3	64.4	247.0	271.5	125.0	137.4	91
28	A72W72	586	85.0	793	115.0	29432	54.5	55.9	209.0	229.7	139.0	152.8	75
29	*Validity Criteria*												
30		Unbroken Ligament						Thickness					
31	Spec	(a)			(b)			(c)					
32	Id	W-aa	0.15W		W-aa	1.25(Ka/sigyd)^2		B	1.0(Ka/sigyd)^2				
33	A72W50	1.15	0.75	OK	1.15	0.50	OK	1.30	0.40	OK			
34	A72W51	1.68	0.75	OK	1.68	1.38	OK	1.30	1.11	OK			
35	A72W61	1.51	0.75	OK	1.51	1.46	OK	1.30	1.17	OK			
36	A72W72	2.08	0.75	OK	2.08	1.83	OK	1.30	1.46	Fail			
37		Crack-jump length								Fracture Forces			
38	Spec	(d)			(e)					Pmax	Pmin	Pmin/Pmax	
39	Id	aa-a0	2N or 2D		aa-a0	(K0/sigys)^2 / (2*PI)				(lbs)			
40	A72W50	2.162	1.250	OK	2.162	0.630	OK			5050	2000	0.40	
41	A72W51	1.649	1.500	OK	1.649	1.056	OK			9900	2300	0.23	
42	A72W61	1.819	1.500	OK	1.819	1.321	OK			10900	1250	0.11	
43	A72W72	1.234	1.500	Fail	1.234	0.962	OK			14300	3000	0.21	

Table D-2. Excel macrosheet used for calculating yield strength, Young's modulus, compliance, crack-mouth opening displacement, conversion from °C to °F, and the stress-intensity factor

	A	B
1	*All values returned in US Customary units*	
2		
3	yield	Yield strength of irradiated 72W weld material
4	=RESULT(1)	
5	=ARGUMENT("temp",1)	Temperature in °C
6	=636-0.6989*temp+0.0024*temp^2	
7	=RETURN(A6)	
8		
9	Youngs_mod	Young's modulus using the EPRI formula
10	=RESULT(1)	
11	=ARGUMENT("temp",1)	
12	=(30.2-0.0046*temp)*1000	EPRI expression in US Customary units
13	=RETURN(A12)	Value returned in ksi
14		
15		
16	calib_func	Crack-arrest specimen compliance calibration function
17	=RESULT(1)	
18	=ARGUMENT("x",1)	
19	=(2.24*(1.72-0.9*x+x^2)*SQRT(1-x))/(9.85-0.17*x+11*x^2)	
20	=RETURN(A19)	
21		
22	K	Stress intensity factor K
23	=RESULT(1)	
24	=ARGUMENT("E",1)	Young's Modulus is in ksi
25	=ARGUMENT("d",1)	CMOD is in mils
26	=ARGUMENT("x",1)	
27	=ARGUMENT("B",1)	
28	=ARGUMENT("Bn",1)	
29	=ARGUMENT("W",1)	
30	=E*d*0.001*calib_func(x)*SQRT(B/(Bn*W))	
31	=RETURN(A30)	
32		
33	DegC_F	Converts °C to °F
34	=RESULT(1)	
35	=ARGUMENT("T",1)	
36	=T*1.8+32	
37	=RETURN(A36)	
38		
39	cod_max	Function to calculate crack mouth opening displacement
40	=RESULT(1)	used during loading and unloading
41	=ARGUMENT("yield_str",1)	Yield strength in MPa
42	=ARGUMENT("W",1)	
43	=ARGUMENT("Bn",1)	
44	=ARGUMENT("B",1)	
45	=ARGUMENT("E",1)	Young's Modulus is in ksi
46	=ARGUMENT("x",1)	
47	=1000*0.69*yield_str*W*SQRT(Bn/B)/(E*calib_func(x))	Returns max CMOD in mils
48	=RETURN(A47)	

Table D-3. Summary of validity criteria (excerpted from ASTM E 1221-88) that are used to ensure that K_a is a linear elastic, plane-strain value. The symbols and nomenclature of E 1221-88 have also been adopted.

Feature	Criterion
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) $a_a - a_o \geq 2N$
Crack-jump length	(E) $a_a - a_o \geq (K_o/\sigma_{Yd})^2/2\pi$

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 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.

Appendix E

Results of Testing Charpy V-Notch Specimens of Welds 72W and 73W Irradiated in the Sixth HSSI Series Capsules

Appendix E

Results of Testing Charpy V-Notch Specimens of Welds 72W and 73W Irradiated in the Sixth HSSI Series Capsule

Introduction

The preliminary analysis [1] of the irradiated weld-embrittled crack-arrest specimens that were previously tested in Phase I of this program was performed using an adjusted shift at the Charpy V-notch (CVN) 41-J energy level ($\Delta TT_{41\text{-}J}$). This adjusted shift was calculated from tests performed for the Fifth Irradiation Series [2] on CVN specimens whose average fluence was 1.51×10^{19} neutrons/cm^2. The average fluence of the crack-arrest specimens is 1.88×10^{19} neutrons/cm^2 and 1.93×10^{19} neutrons/cm^2 for the 72W and 73W weld-embrittled crack-arrest specimens, respectively. For purposes of adjusting the $\Delta TT_{41\text{-}J}$ to the higher fluence, the following expression was used: [3]

$$Adjusted\ \Delta TT_{41-J} = \Delta TT_{41-J} \left(\frac{\Phi'}{\Phi}\right)^{0.5}, \qquad (1)$$

where

Φ = fluence for the CVN specimens,

Φ' = fluence for the adjusted $\Delta TT_{41\text{-}J}$.

Twenty-two CVN specimens made from the 72W and 73W welds were irradiated in each of the two Sixth Series capsules together with the crack-arrest specimens. Seven CVN specimens from each of these two welds have exposure levels comparable to that of the crack-arrest specimens. These seven CVN specimens, from each of the two welds, were tested in order to provide a better estimate of the adjusted reference temperature of the irradiated crack-arrest specimens. The remaining 15 specimens were tested in order to provide data at a lower fluence level.

Specimen Complement

The 72W and 73W weld metal used for the CVN specimens was used for both the Fifth and Sixth HSSI Irradiation Series. The irradiation temperatures and exposure values for these specimens, which were irradiated in the notches of the Sixth Series crack-arrest specimens, are given in Tables E-1 and E-2 for the 72W and 73W welds, respectively, and are from ref. [4]. The average, minimum, maximum, and standard deviations of the irradiation temperatures and fluences (>1 MeV) for the top, middle, and bottom banks of specimens are shown in Table E-3. It may be noted that the average fluences of the top and bottom banks of specimens are 70 and 60%, respectively, less than that of the middle set of specimens. The middle set of specimens has average fluences that are close to those of the crack-arrest specimens.

As mentioned above, for purposes of testing, the CVN specimens from each of the two welds were grouped into two sets. The range of fluence of the group of seven specimens is 1.8 to 1.9×10^{19} neutrons/cm^2 and for the group of 15 specimens is 1.2 to 1.3×10^{19} neutrons/cm^2. The average, minimum, maximum, and standard deviations of the irradiation temperatures and fluences (>1 MeV) for the two groups of specimens are shown in Table E-4.

Test Results

The test results for the CVN specimens are given in Tables E-1 and E-2 for welds 72W and 73W, respectively. The CVN impact energy values of the 56 irradiated specimens of the Fifth Series and the 15 specimens were fitted with a three-parameter hyperbolic tangent curve. The lower-shelf energy was prescribed at 2.7 J based on five specimens from the submerged-arc weld of the Midland reactor pressure vessel (RPV) tested at the liquid nitrogen temperature of −196°C. The results have been summarized in Table 3 of Chapter 3 and are all shown graphically in Figures E.1 and E.2 for welds 72W and 73W, respectively.

The particular form of the hyperbolic tangent curve selected has been used by many authors because the parameters are easily related to physical characteristics of the test, as illustrated in Figure E.3. There were insufficient specimens to

Table E-1. Irradiation exposures values and results of testing Charpy V-notch specimens of HSSI weld 72W irradiated in the Sixth Series Capsule 6-1

Specimen	Irradiation temperature (°C)	Fluence, n/cm^2 (>1 MeV)	Fluence, n/cm^2 (>0.1 MeV)	dpa[a]	Test temperature (°C)	Energy (J)	Fracture appearance (%)
Average Fluence = 1.84 n/cm^2 (>1 MeV)							
72W373	289	1.88E+19	1.29E+20	0.0472	38	15	10
72W399	289	1.88E+19	1.29E+20	0.0473	38	17	15
72W401	289	1.88E+19	1.28E+20	0.0471	38	25	10
72W369	287	1.75E+19	1.17E+20	0.0436	38	32	20
72W391	289	1.89E+19	1.30E+20	0.0475	63	35	20
72W368	286	1.72E+19	1.15E+20	0.0427	63	54	50
72W383	289	1.89E+19	1.29E+20	0.0474	63	59	50
Average Fluence = 1.22 n/cm^2 (>1 MeV)							
72W402	289	1.16E+19	7.53E+19	0.0280	23	13	5
72W351	289	1.33E+19	9.03E+19	0.0330	23	14	5
72W314	289	1.32E+19	9.01E+19	0.0330	23	17	5
72W422	287	1.06E+19	6.69E+19	0.0252	23	29	5
72W353	289	1.32E+19	8.97E+19	0.0329	50	22	10
72W403	289	1.17E+19	7.58E+19	0.0281	50	25	10
72W313	289	1.32E+19	8.95E+19	0.0328	50	28	15
72W410	289	1.15E+19	7.44E+19	0.0277	50	37	25
72W346	289	1.33E+19	9.07E+19	0.0332	71	49	70
72W428	286	1.04E+19	6.51E+19	0.0247	71	57	45
72W366	287	1.20E+19	7.95E+19	0.0296	71	57	70
72W416	289	1.14E+19	7.35E+19	0.0274	71	59	55
72W367	286	1.18E+19	7.74E+19	0.0289	200	88	100
72W365	289	1.29E+19	8.74E+19	0.0321	200	89	100
72W363	289	1.30E+19	8.84E+19	0.0324	200	97	100

[a]dpa = displacements per atom.

Table E-2. Irradiation exposures values and results of testing Charpy V-notch specimens of HSSI weld 73W irradiated in the Sixth Series Capsule 6-2

Specimen	Irradiation temperature (°C)	Fluence, n/cm² (>1 MeV)	Fluence, n/cm² (>0.1 MeV)	dpa[a]	Test temperature (°C)	Energy (J)	Fracture appearance (%)
Average Fluence = 1.89 n/cm² (>1 MeV)							
73W540	289	1.94E+19	1.33E+20	0.0486	35	17	10
73W537	289	1.81E+19	1.21E+20	0.0450	35	24	15
73W542	289	1.94E+19	1.33E+20	0.0487	35	31	10
73W543	289	1.94E+19	1.33E+20	0.0487	68	38	10
73W700	289	1.93E+19	1.32E+20	0.0484	68	43	20
73W461	288	1.78E+19	1.19E+20	0.0442	68	46	25
73W703	289	1.92E+19	1.31E+20	0.0481	68	50	40
Average Fluence = 1.25 n/cm² (>1 MeV)							
73W415	289	1.33E+19	8.96E+19	0.0330	50	34	35
73W428	286	1.21E+19	7.94E+19	0.0297	50	37	20
73W317	289	1.35E+19	9.19E+19	0.0337	50	38	40
73W319	289	1.36E+19	9.25E+19	0.0339	50	50	55
73W713	288	1.17E+19	7.54E+19	0.0281	90	45	45
73W711	288	1.18E+19	7.63E+19	0.0284	90	49	45
73W719	286	1.07E+19	6.68E+19	0.0253	90	62	75
73W708	288	1.20E+19	7.78E+19	0.0289	90	66	75
73W425	287	1.24E+19	8.16E+19	0.0304	125	68	90
73W335	289	1.36E+19	9.26E+19	0.0339	125	82	90
73W347	289	1.35E+19	9.20E+19	0.0337	125	88	95
73W706	288	1.20E+19	7.73E+19	0.0287	125	90	95
73W333	289	1.37E+19	9.31E+19	0.0340	200	90	100
73W405	289	1.34E+19	9.07E+19	0.0333	200	91	100
73W717	287	1.09E+19	6.86E+19	0.0259	200	97	100

[a]dpa = displacements per atom.

Table E-3. The average, minimum, maximum, and standard deviation of the irradiation temperatures and fluences (>1 MeV) for the top, middle, and bottom banks of specimens of the Sixth Series capsules 6-1 and 6-2

	Capsule top (9 specimens)		Capsule middle (7 specimens)		Capsule bottom (6 specimens)		Entire capsule (22 specimens)	
	Irradiation temperature (°C)	Fluence (>1 MeV)	Irradiation temperature (°C)	Fluence (>1 MeV)	Irradiation temperature (°C)	Fluence (>1 MeV)	Irradiation temperature (°C)	Fluence (>1 MeV)
Capsule 6-1 with HSSI weld 72W								
Average	288.4	1.29E+19	288.3	1.84E+19	288.2	1.12E+19	288.3	1.42E+19
Minimum	286	1.18E+19	286	1.72E+19	286	1.04E+19	286	1.04E+19
Maximum	289	1.33E+19	289	1.89E+19	289	1.17E+19	289	1.89E+19
Standard deviation	1.1	5.39E+17	1.2	6.79E+17	1.2	5.07E+17	1.1	3.03E+18
Capsule 6-2 with HSSI weld 72W								
Average	288.4	1.32E+19	288.9	1.89E+19	287.5	1.15E+19	288.3	1.46E+19
Minimum	286	1.21E+19	288	1.78E+19	286	1.07E+19	286	1.07E+19
Maximum	289	1.37E+19	289	1.94E+19	288	1.20E+19	289	1.94E+19
Standard deviation	1.1	5.42E+17	0.3	6.37E+17	0.8	5.21E+17	1.0	3.11E+18

Table E-4. The average, minimum, maximum, and standard deviation of the irradiation temperatures and exposure values for the two groups of Charpy V-notch specimens tested from the Sixth Series capsules 6-1 and 6-2.

	Group of 7 specimens				Group of 15 specimens			
		Fluence (neutrons/cm²)				Fluence (neutrons/cm²)		
	Irradiation temperature (°C)	(>1 MeV)	(>0.1 MeV)	dpa	Irradiation temperature (°C)	(>1 MeV)	(>0.1 MeV)	dpa
HSSI weld 72W								
Average	288.3	1.84E+19	1.25E+20	0.0461	288.3	1.22E+19	8.09E+19	0.0299
Minimum	286.0	1.72E+19	1.15E+20	0.0427	286.0	1.04E+19	6.51E+19	0.0247
Maximum	289.0	1.89E+19	1.30E+20	0.0475	289.0	1.33E+19	9.07E+19	0.0332
Standard deviation	1.3	7.34E+17	6.40E+18	0.0020	1.2	1.01E+17	9.00E+18	0.0030
HSSI weld 73W								
Average	288.9	1.89E+19	1.29E+20	0.0474	288.1	1.25E+19	8.30E+19	0.0307
Minimum	288.0	1.78E+19	1.19E+20	0.0442	286.0	1.07E+19	6.68E+19	0.0253
Maximum	289.0	1.94E+19	1.33E+20	0.0487	289.0	1.37E+19	9.31E+19	0.0340
Standard deviation	0.4	6.88E+17	6.12E+18	0.0019	1.1	1.03E+17	9.24E+18	0.0031

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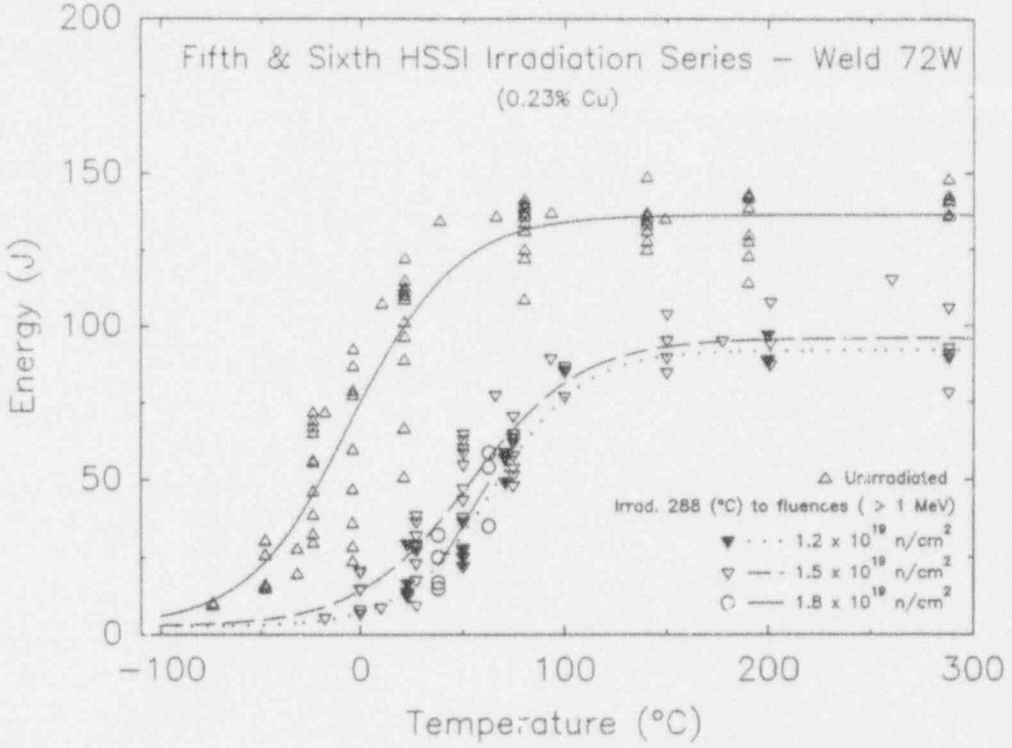

Figure E.1 Charpy V-notch impact energy of irradiated specimens from the Fifth and Sixth Irradiation Series for weld 72W.

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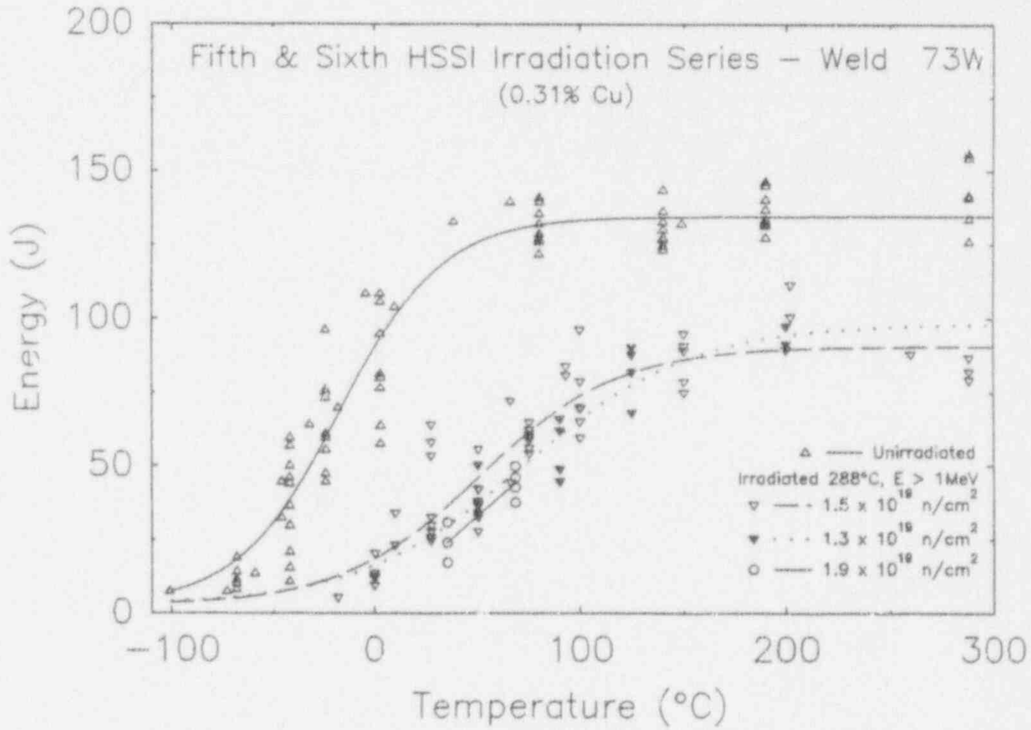

Figure E.2 Charpy V-notch impact energy of irradiated specimens from the Fifth and Sixth Irradiation Series for weld 73W.

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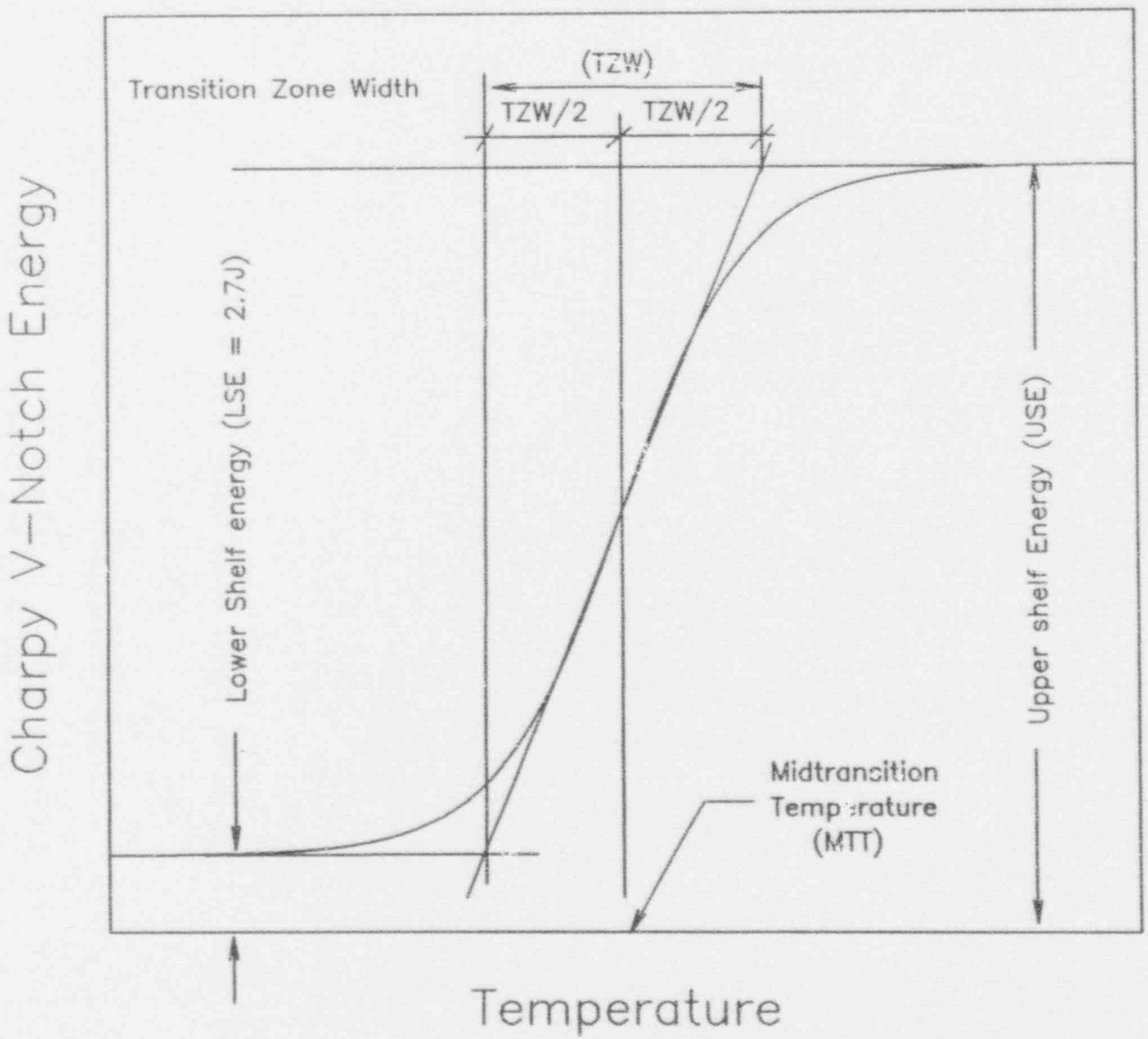

Figure E.3 Nomenclature used for the hyperbolic tangent expression that is regression fit to Charpy V-notch energy data.

generate a complete CVN curve for the high fluence data, and the specimens were all tested at two temperatures that were estimated to bracket the 41-J energy level. The $TT_{41\text{-}J}$ was estimated from a straight-line fit between the data at the two temperatures. The 68-J energy level was extrapolated from the straight-line fit and should be treated as a rough estimate only. The 95% confidence and prediction intervals on the mean and on the data were also generated. The resulting fits are shown in Figures E.4 through E.9, and the width of the confidence bands is summarized in Table 3 of Chapter 3.

References

1. S. K. Iskander, W. R. Corwin, and R. K. Nanstad, "Effects of Irradiation on Crack-Arrest Toughness of Two High-Copper Welds," pp. 251-69 in *Effects of Radiation on Materials: 15th International Symposium, ASTM STP 1125*, ed. R. E. Stoller, A. S. Kumar, and D. S. Gelles, American Society for Testing and Materials, Philadelphia, 1992.*

2. R. K. Nanstad, F. M. Haggag, D. E. McCabe, S. K. Iskander, K. O. Bowman, and B. H. Menke, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., *Irradiation Effects on Fracture Toughness of Two High-Copper Submerged-Arc Welds, HSSI Series 5*, USNRC Report NUREG/CR-5913, Vol. I (ORNL/TM-12156/V1), August 1992.†

3. G. R. Odette and G. E. Lucas, "Irradiation Embrittlement of Reactor Pressure Vessel Steels: Mechanisms, Models, and Data Correlations," pp. 206-41 in *Radiation Embrittlement of Nuclear Pressure Vessel Steels: An International Review (Second Volume), ASTM STP 909*, ed. L. E. Steele, American Society for Testing and Materials, Philadelphia, 1986.*

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

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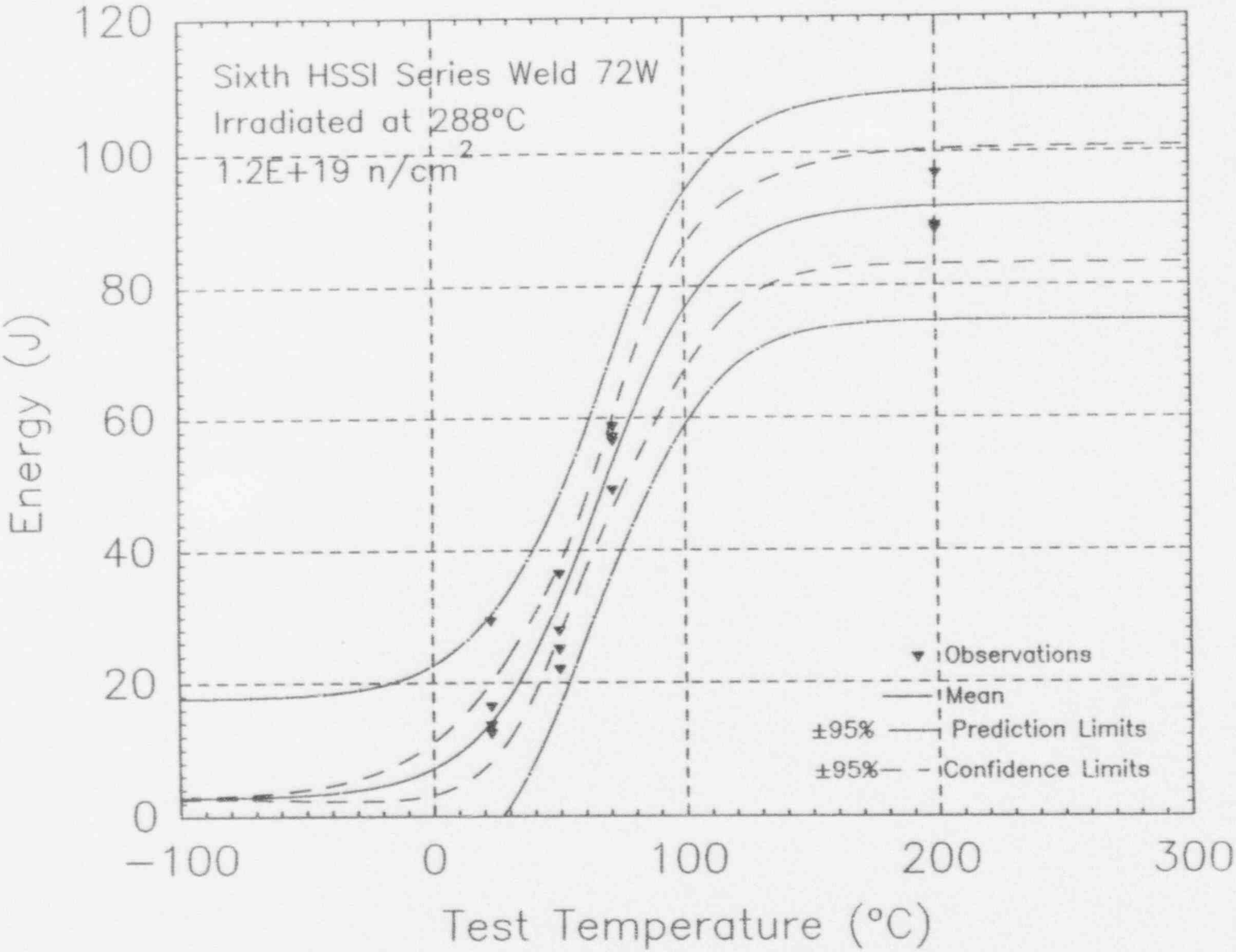

Figure E.4 Mean, ±95% confidence, and prediction limits for weld 72W and Charpy V-notch impact energy test results for the 15 specimens irradiated in the Sixth Series capsules.

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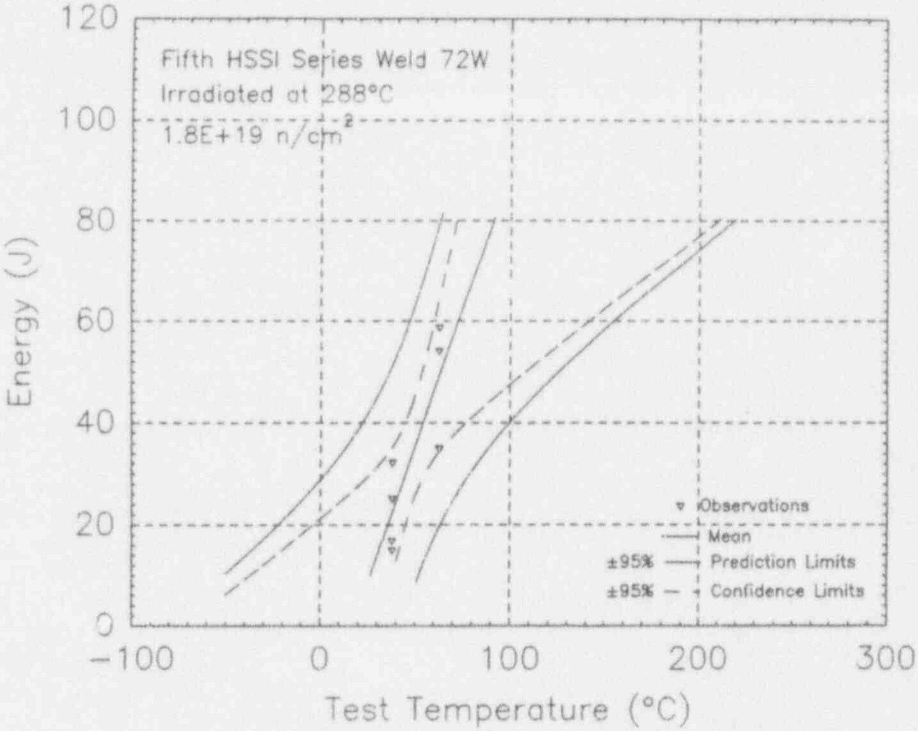

Figure E.5 Mean, ±95% confidence, and prediction limits for weld 72W Charpy V-notch impact energy test results for the seven specimens irradiated in the Sixth Series capsules.

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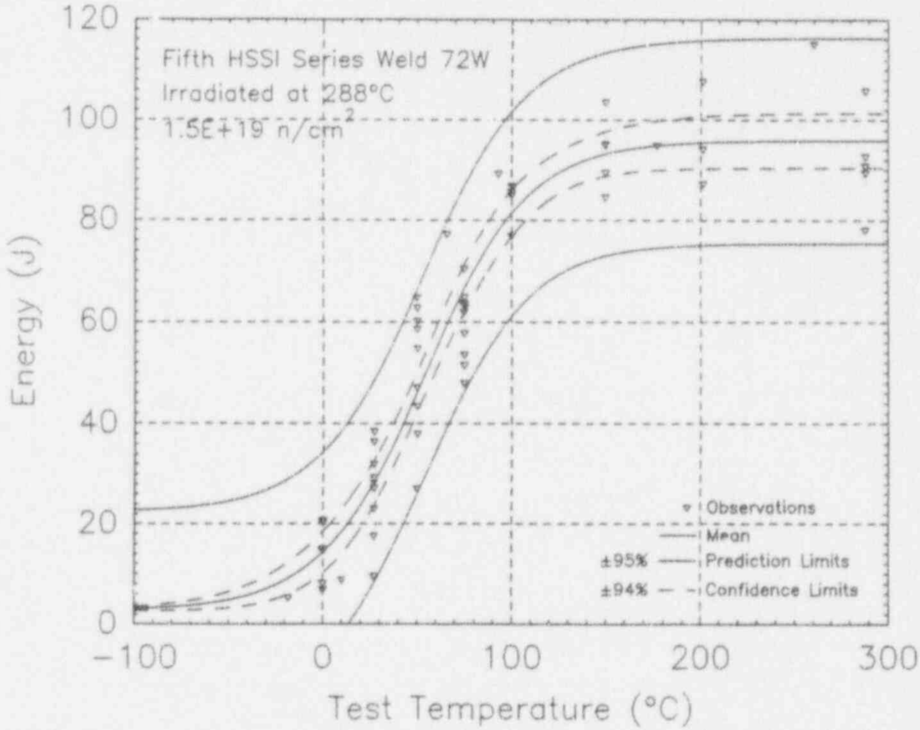

Figure E.6 Mean, ±95% confidence, and prediction limits for weld 72W Charpy V-notch impact energy test results for the 56 specimens irradiated in the Fifth Series capsules.

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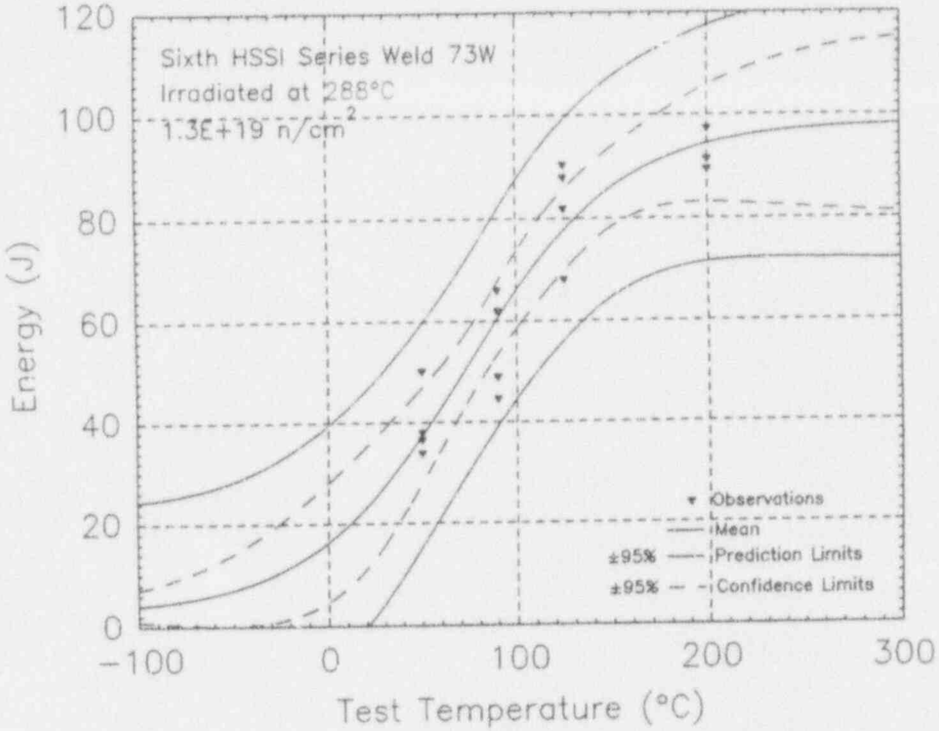

Figure E.7 Mean, ±95% confidence, and prediction limits for weld 73W Charpy V-notch impact energy test results for the 15 specimens irradiated in the Sixth Series capsules.

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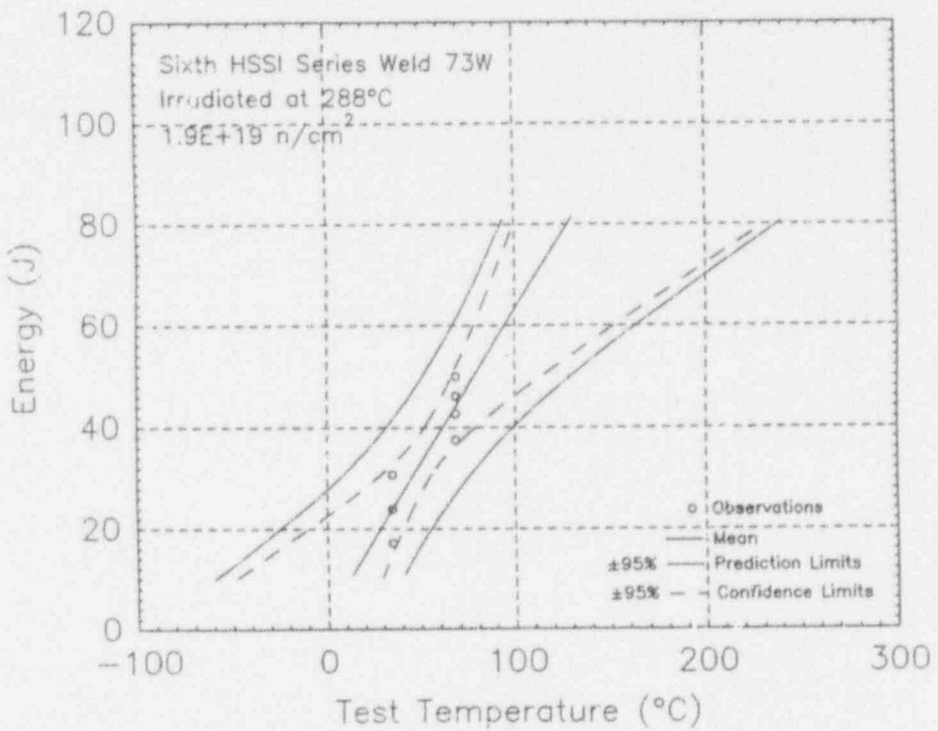

Figure E.8 Mean, ±95% confidence, and prediction limits for weld 73W Charpy V-notch impact energy test results for the seven specimens irradiated in the Sixth Series capsules.

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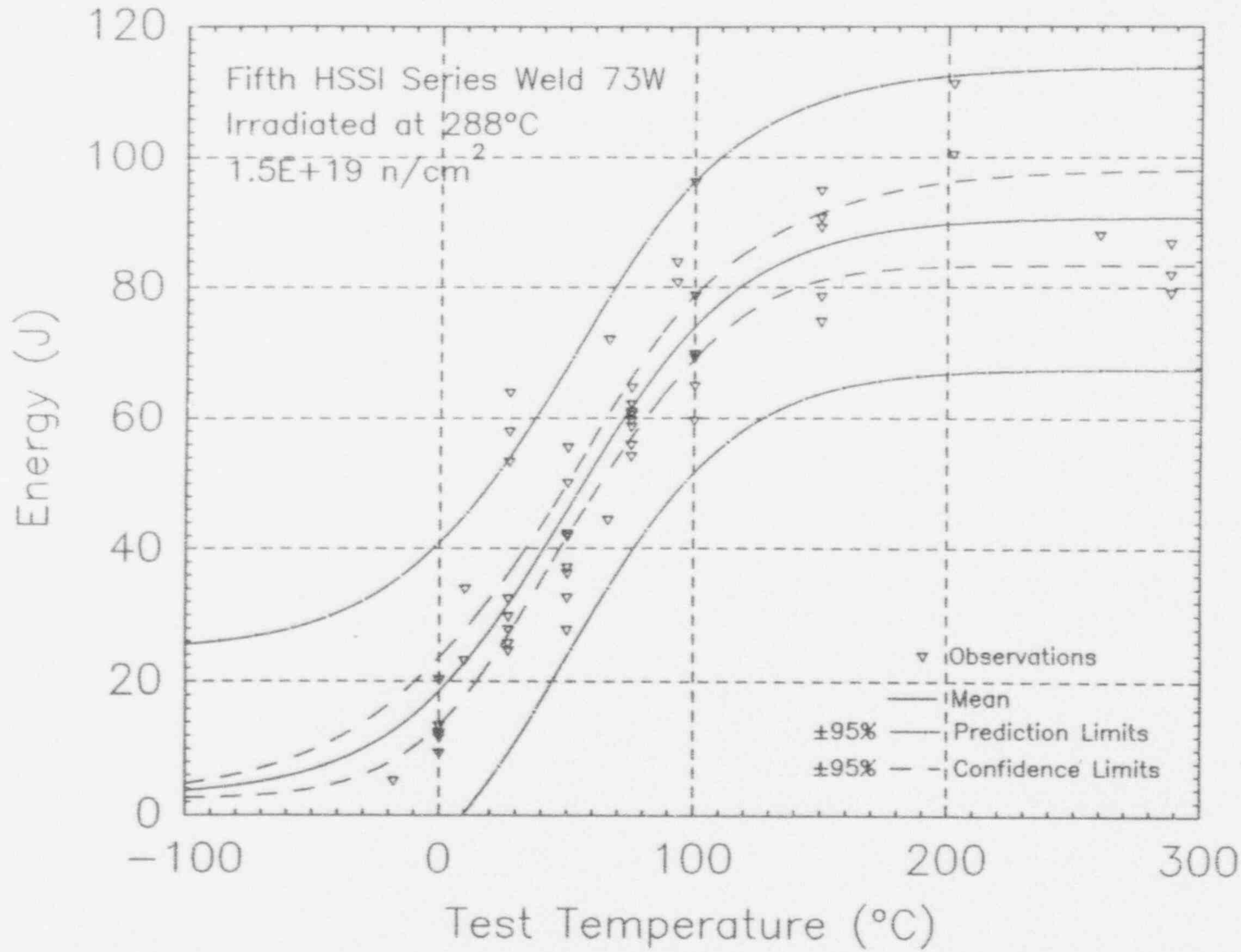

Figure E.9 Mean, ±95% confidence, and prediction limits for weld 73W Charpy V-notch impact energy test results for the 56 specimens irradiated in the Fifth Series capsules.

Appendix F

Variation of Crack-Driving Force With Hole Diameter

Appendix F

Variation of Crack-Driving Force With Hole Diameter

The maximum stresses near the crack-starter hole of duplex crack-arrest specimens just before crack-initiation may be estimated by assuming that the specimen is a curved flexural member subjected to in-plane bending and tensile loads. Such stresses may be estimated using e.g., the Winkler-Bach formula [1]. An expression relating the crack-initiation force to some critical stress may then be derived. Such an expression would indicate that the crack-initiation force increases with crack-starter hole diameter in a non-linear manner. It may also be shown that this force is sensitive to the friction between the various components that are in contact with crack-arrest specimen during the loading.

It is of interest to determine the variation of measured fracture loads (which include friction), as a function of the crack-starter hole diameter. The experimentally indicated loads at the instant of crack initiation for various crack-starter hole diameters are given in Table F.1 and plotted in Fig. 1. The variation of friction from one experiment to another may have contributed significantly to the scatter shown. It should be recalled that neglecting the effects of friction, the wedge* generates two equal and opposite loads, acting through the "split pin," on the specimen each approximately 10 times the experimentally indicated load. The data were fitted with approximately 3250 different "trial" equations using TableCurve [2], and the one with the smallest "residual" chosen. It's form is:

$$Force = a + bD^{n} \tag{1}$$

where a, b, and n are parameters to be determined. The best fit was obtained with a value of n=3 but, because of scatter, n could have been taken to equal 1 with no significant increase in error.

References

1. F.B. Seely, and J.O. Smith, "Advanced Mechanics of Materials," 2nd. ed. John Wiley & Sons, Inc., New York, pp. 139, August 1967.*

2. *User's Manual for TableCurve for Windows*, Version 1.0, Jandel Scientific, San Rafael, California, 1992.†

*The included angle of the wedge is 5°.

*Available in public technical libraries.
†Available from the publisher.

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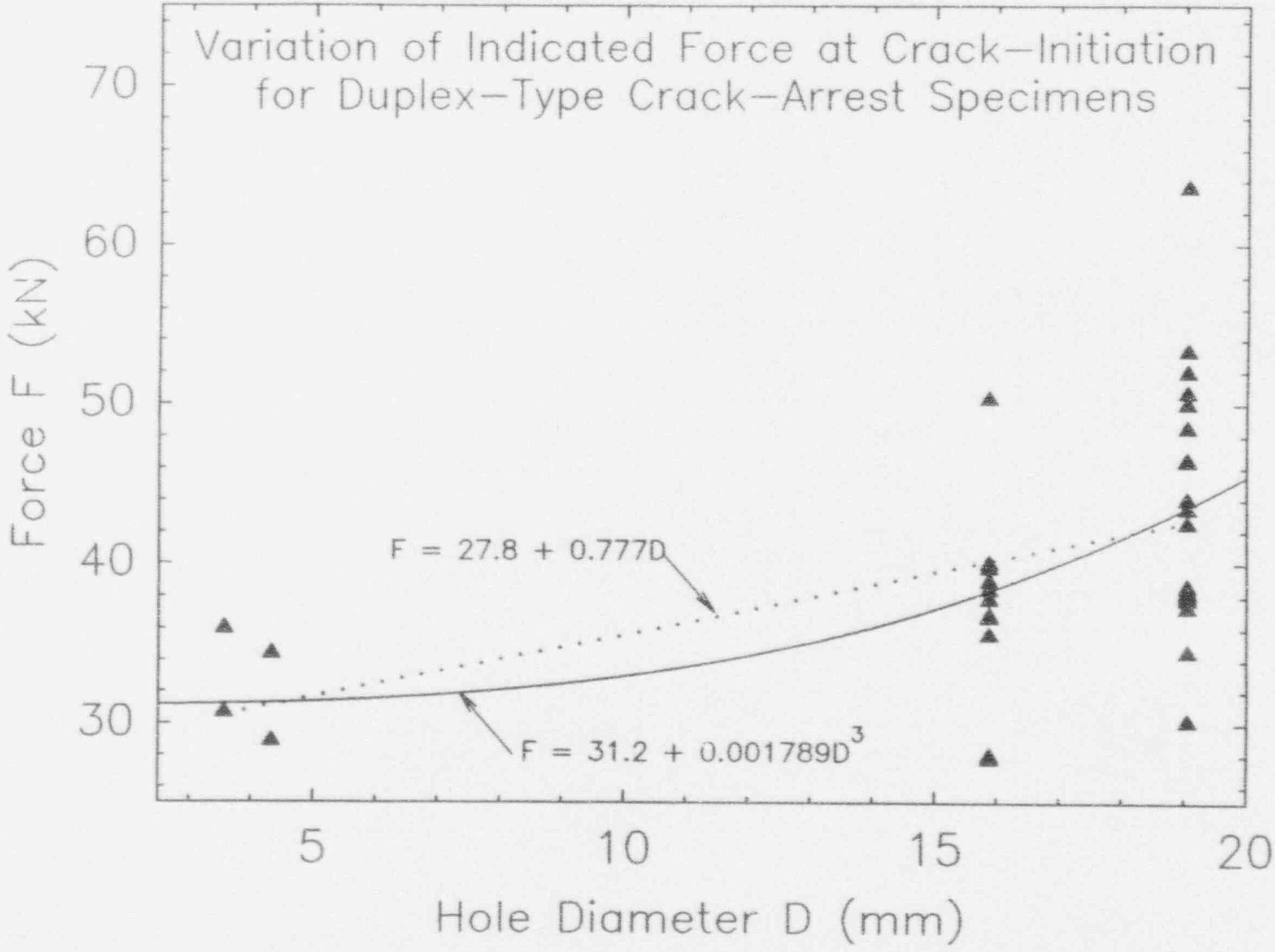

Figure F.1 Variation of experimentally indicated loads at crack initiation with crack-starting hold diameter.

Table F-1. Experimentally indicated loads at crack initiation for the various specimens tested for this report

Specimen	Crack-starter hole diameter (mm)	Force at crack initiation (kN)
A72W59	3.6	30.7
A73W67	3.6	36.0
A73W71	4.3	28.9
A72W67	4.3	34.4
CP45	15.9	27.8
CP43	15.9	28.0
D5	15.9	35.6
D9	15.9	36.7
A72W49	15.9	36.8
A72W50	15.9	37.8
A73W72	15.9	38.4
CP33	15.9	38.9
A73W54	15.9	39.7
D10	15.9	40.0
CP36	15.9	50.3
A72W52	19.1	30.2
D4	19.1	34.5
A72W58	19.1	37.3
D1	19.1	37.8
A73W55	19.1	38.0
A73W61	19.1	38.2
D2	19.1	38.3
A72W53	19.1	38.6
A73W69	19.1	42.5
A73W56	19.1	43.4
A73W66	19.1	43.4
A72W51	19.1	44.0
A72W55	19.1	46.4
A73W63	19.1	46.5
A72W61	19.1	48.5
A72W54	19.1	50.0
A73W60	19.1	50.7
A73W59	19.1	52.0
A73W53	19.1	53.3
A72W72	19.1	63.6

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11. ABSTRACT (200 words or less)

The objective of the Heavy-Section Steel Irradiation Program Sixth Irradiation Series is to determine the effect of neutron irradiation on the shift and shape of the lower-bound curve to crack-arrest toughness data. Two submerged-arc welds with copper contents of 0.23 and 0.31 wt % were commercially fabricated in 200-mm-thick plate. Crack-arrest specimens fabricated from these welds were irradiated at a nominal temperature of 288°C to an average fluence of 1.9×10^{19} neutrons/cm^2 (>1 MeV). This is the second report giving the results of the tests on irradiated duplex-type crack-arrest specimens. Charpy V-notch specimens irradiated in the same capsules as the crack-arrest specimens were also tested, and a 41-J transition temperature shift was determined from these specimens. "Mean" curves of the same form as the ASME K_{Ia} curve were fit to all the data with only the reference temperature as a parameter. The shift between the mean curves agrees well with the 41-J transition temperature shift obtained from the Charpy V-notch specimen tests.

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