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OF TWO HIGH-COPPER WELDS\*

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## EFFECTS OF IRRADIATION ON CRACK-ARREST TOUGHNESS OF TWO HIGH-COPPER WELDS

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

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

KEY WORDS: ASME Boiler and Pressure Vessel Code - Section III, Charpy V-notch impact toughness, copper content, crack arrest, crack-arrest toughness, drop-weight, embrittlement, fracture toughness, irradiation, K<sub>Ia</sub>, light-water reactors, neutron fluence,

nil-ductility transition temperature, radiation damage, reactor pressure vessels, reference nil-ductility-transition temperature,  $RT_{NDT}$ , regulatory guide, submerged-arc welds, surveillance, transition temperature shift,  $\Delta RT_{NDT}$ .

## NOMENCLATURE

### ACRONYMS

CMOD	Crack-mouth opening displacement
CVN	Charpy V-notch
dpa	displacements per atom
EPRI	Electric Power Research Institute
HSSI	Heavy-Section Steel Irradiation
ORNL	Oak Ridge National Laboratory, Oak Ridge, Tennessee, U.S.A.
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 <sub>NDT</sub>	Reference nil-ductility-transition temperature, determined in accordance with Subarticle NB-2330 of the ASME Boiler and Pressure Vessel Code, Section III.

### SYMBOLS

$a_a$	Arrested crack-length
$\Delta T_{41-J}$	Shift in the 41-J CVN-impact energy level
E	Young's modulus
$\Phi$	Fluence, neutrons/cm <sup>2</sup> , (>1 MeV)

K <sub>a</sub>	The value of the stress intensity factor shortly after arrest <sup>1</sup>
K <sub>Ia</sub>	The value of the crack-arrest fracture toughness K <sub>a</sub> for a crack that arrests under conditions of crack front plane-strain <sup>1</sup>
K <sub>Ic</sub>	Plane-strain fracture toughness
K <sub>Jc</sub>	A measure of fracture toughness calculated from the J-integral J <sub>c</sub> at the point of cleavage using the relationship $(K_{Jc})^2 = EJ_c$
T	Test temperature
W	Nominal width of a crack-arrest specimen

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<sup>1</sup> Excerpted from ASTM E 1221-88.

## 1. INTRODUCTION

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

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

Two of these programs are the Fifth and Sixth Irradiation Series. The objective of the Fifth Series is to determine the effect of neutron irradiation on the shift and shape of the  $K_{Ic}$  vs  $(T - RT_{NDT})$  curve, where  $K_{Ic}$  is the plane-strain fracture toughness,  $T$  is the temperature, and  $RT_{NDT}$  is the reference nil-

ductility transition temperature. The objective of the Sixth Series is similar, but investigates the effect on K<sub>Ia</sub>, the plane-strain crack-arrest fracture toughness. Both programs investigate the effects of irradiation on the fracture toughness of welds, since some pressure vessels in operation have welds with copper contents and end-of-life fluences which make them susceptible to severe degradation in toughness. It is noted that the amount of experimental data on the effects of irradiation on crack-arrest fracture toughness is rather meager, [1], [2].

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

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

## 2. DESCRIPTION OF MATERIALS AND PROCEDURES

The weld wire for both programs was produced commercially in one melt. The melt was split to allow for copper additions and resulted in two weld wires that

were comparable in chemical composition except for copper. Several meters of weldment were commercially fabricated from each weld wire and were designated 72W (0.23 wt % Cu) and 73W (0.31 wt % Cu). The welds were commercially fabricated in A533 grade B class 2 plate of 220-mm (8 5/8-in) thickness using the submerged-arc weld process with one lot of Linde 0124 flux. A macrograph of weld 72W is shown in Fig. 1 and the chemical compositions of both welds are given in Table 1. The welds were given a postweld heat treatment of 607°C for 40 h, typical of that given commercial RPVs.

Two capsules, each containing 30 compact crack-arrest specimens of the two weldments, have been irradiated at a nominal temperature of 288°C to a fluence of approximately  $1.9 \times 10^{19}$  neutrons/cm<sup>2</sup> (>1 MeV) in the Oak Ridge Research Reactor located at the Oak Ridge National Laboratory (ORNL). The total irradiation time was 96 days, thus the average flux is approximately  $2.3 \times 10^{12}$  neutrons·cm<sup>-2</sup>·s<sup>-1</sup>. The irradiated specimen complement is given in Table 2, which gives the overall nominal specimen dimensions. For administrative purposes, the program was conducted in two phases. This paper presents results of Phase 1 which consists of crack-arrest tests on the 36 weld-embrittled type specimens. In Phase 2, the remaining 24 duplex type crack-arrest specimens will be tested.

### *Testing Procedures*

Testing was performed according to the ASTM Test for Determining Plane-Strain Crack-Arrest Fracture Toughness,  $K_{Ia}$ , of Ferritic Steels (E 1221-88). Crack-arrest testing of the irradiated specimens was performed in a hot cell using a servo-hydraulic machine and the test chamber shown schematically in Fig. 2. It allows specimens to be tested with the split pins in either the so-called



"normal" or "inverted" configuration at test temperatures ranging from -100 to 260°C. In the "normal" configuration, the lateral surfaces of the specimen are in contact with the test-machine platten and the friction decreases the crack-driving force somewhat compared to the "inverted" configuration in which the specimen sits on narrow shoulders of the split pin. The "inverted" configuration is used at testing temperatures above the NDT temperature. For further information on the "normal" and "inverted" test configuration in crack-arrest testing, see Note 5 of ASTM E 1221-88.

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

A considerable effort was made to ensure the uniformity of temperature in the crack-arrest specimen as well as its accuracy. Specimens of A533B steel and of the same three sizes as those to be tested were instrumented with thermocouples and thermally conditioned in the fixture over the relevant temperature range in both normal and inverted configurations. The uniformity and accuracy of the temperature throughout the specimen were within  $\pm 1^\circ\text{C}$  when compared to the values measured by the contact thermocouple used during testing.

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

#### *Analysis Procedures*

The arrested crack front was marked by heat-tinting the specimen after testing. The specimen was then cooled with liquid nitrogen and broken open. The length of the remaining ligament for each specimen was obtained by measuring the position of the arrested crack front using the averaging procedure prescribed in ASTM E 1221-88. In the case of irradiated specimens, a digitizing tablet is used to measure the length of the remaining ligament on a photograph taken through a Kollmorgan periscope of the broken specimen half. Typical fracture surfaces for two 25 x 152-mm specimens are shown in Fig. 3. Numerous unbroken ligaments, typical for pressure vessel steels at these test temperatures, can be observed on the fracture surface of the specimens. The known dimensions of the specimen serve as the scale for these measurements. In the case of unirradiated specimens, the length of the remaining ligament is directly measured by a digital

measuring microscope. The errors due to the *measurement method* are probably less than those due to the *shape* of the crack front.

As previously mentioned, the measurement of the final crack length  $a_a$  is performed according to ASTM E 1221-88 by an averaging procedure. Since it is rare that the arrested crack front is square or straight, see Fig. 3, it is difficult to estimate the error in such a determination. Using the expression for  $K_a$  given in ASTM E 1221-88, estimates of the error were made using the maximum valid value of an arrested crack length  $a_a$  in a small specimen to obtain an upper bound on the error. A value of  $a_a = 54$  mm is the maximum valid length allowed by E 1221-88 for the small  $25 \times 76 \times 76$  mm specimen. Errors of  $\pm 1$  or  $\pm 2$  mm in  $a_a$  for this case results in errors of  $\pm 6.5\%$  or  $\pm 13\%$  respectively in  $K_a$ . The total maximum error in  $K_a$  from all sources is estimated to be approximately  $\pm 10\%$  for the small specimens, and  $\pm 5\%$  for the large ones.

### 3. RESULTS AND DISCUSSION.

The temperature control for the two irradiation capsules, each containing 30 specimens, was excellent. The temperature of the majority of both weld-embrittled and duplex-type specimens (22 in one capsule and 23 in the other) ranged from 286 to 290°C, while the few remaining specimens were irradiated at temperatures ranging from 280 to 286°C. The average irradiation temperature of all 60 crack-arrest specimens is approximately 287°C. For both the 72W and 73W specimens, the fluences to which the weld-embrittled type crack-arrest specimens were irradiated ranged from approximately  $1.4$  to  $2.4 \times 10^{19}$  n/cm<sup>2</sup> ( $>1$  MeV). For

both the 72W and 73W weld-embrittled type specimens, the average fluence and standard deviation is approximately  $1.9$  and  $0.3 \times 10^{19}$  n/cm<sup>2</sup> (>1 MeV), respectively. A bar chart showing the distribution of fluence of the 18 specimens from the 72W Series weldment is given in Fig. 4, (that for the specimens from the 73W weldment is similar). The average irradiation temperature and the exposure values of each specimen are given later in this paper with the results of the crack-arrest testing. A detailed report on the dosimetry of the two capsules has been published [5] and another report on their operating history is in preparation.

The yield strength and Young's modulus of the test material are required in crack-arrest testing. The unirradiated and irradiated tensile strengths have been reproduced from Ref. [3] in Figs. 5 and 6 for welds 72W and 73W respectively. The average fluence of the tensile samples, approximately  $1.6 \times 10^{19}$  neutrons/cm<sup>2</sup>, (>1 MeV), is about 15% less than that for the crack-arrest specimens. This will not effect the values of the crack-arrest toughnesses  $K_{IC}$  but may have a small effect on the validity of each specimen as it is prescribed in ASTM E 1221-88. As mentioned elsewhere in this paper, the observations reached in this report are preliminary. Young's modulus is calculated from the following expression, [6]:  $E = 207.2 - 0.0571T$ , where  $E$  = Young's modulus in GPa, and  $T$  = temperature in °C.

The  $RT_{NDT}$  values for both weldments in the unirradiated and irradiated conditions are given in Table 3, (Refs. [3] and [4]). The initial  $RT_{NDT}$  values were determined in accordance with Subarticle NB-2330 of the ASME Boiler and Pressure Vessel Code, Section III, and are the same as the drop weight NDT

values. The "adjusted"  $RT_{NDT}$  values were determined according to paragraph 10.2.2 of ASTM E 185-82 by adding the CVN  $\Delta TT_{41-J}$  values to the initial  $RT_{NDT}$  values. The CVN  $\Delta TT_{41-J}$  shifts have been determined from a relatively large number of specimens as shown in Fig. 7 (also from Refs. [3] and [4]). Approximately 84 and 56 unirradiated and irradiated CVN specimens were tested from each of the 72W and 73W welds, respectively. The fluence of CVN-impact energy specimens from the 72W and 73W weldments is  $1.51 \times 10^{19}$  neutrons/cm<sup>2</sup>, while that for the crack-arrest specimens is approximately  $1.9 \times 10^{19}$  neutrons/cm<sup>2</sup>. In order to normalize the  $RT_{NDT}$  shift, an average trend curve applicable to the behavior of test reactor data and having a slope of 0.5 was used, [7]. It is of the form:

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

where  $\Phi'$  and  $\Phi$  are the average fluences for the crack-arrest and the CVN-impact specimens respectively, in neutrons/cm<sup>2</sup> (>1 MeV). Both shifts for each weldment are given in Table 3. The normalized  $RT_{NDT}$  values were used to shift the ASME  $K_{Ia}$  curves shown later in this paper.

Tables 4 and 5 give the results of testing the unirradiated crack-arrest specimens of the 72W and 73W Series respectively, and Tables 6 and 7 give data for the irradiated specimens of these two Series. The latter two tables also give the irradiation temperatures and the exposure values, (fluence for energies greater than 1 MeV and greater than 0.1 MeV, as well as the displacements per atom - dpa). The crack-arrest toughnesses  $K_a$  are plotted as a function of the test temperature for the 72W and 73W weldments in Figs. 8 and 9 respectively. In Tables 4 - 7, the results of the crack-arrest tests that were "invalid" relative to the requirements of ASTM E 1221-88 are indicated by one or more

letters, a blank implying a valid result.

It should be mentioned that the irradiated K<sub>a</sub>-values have not been normalized to a single average fluence to account for the variation of fluence from one specimen to another. Thus, the question arises as to whether the scatter in the K<sub>a</sub>-values could be attributed to the variation in fluence between the specimens. An examination of Tables 6 and 7 reveal that the fluence does not seem to be a contributing factor in the scatter, since the variation in fluence between specimens tested at the same temperature is relatively small. For example, if data for the 4 specimens tested at 75°C from the 73W weld are examined, the K<sub>a</sub> values range from 88 to 150 MPa√m with an average value of 119 MPa√m. Thus, the maximum and minimum values of K<sub>a</sub> at that temperature are approximately ±25% smaller or greater than the average value. The corresponding range of fluence for the specimens exhibiting the maximum and minimum K<sub>a</sub>-value is less than ±5%. Moreover, the scatter of the unirradiated K<sub>a</sub>-values is approximately the same as that of the irradiated K<sub>a</sub>-values. Nonetheless, statistical analysis of the data will be performed and normalization of the K<sub>a</sub>-values to a single fluence could then be considered.

One specimen in Table 7, A73W17, the crack failed to initiate in a cleavage mode, and exhibited tearing. It was retested at 30°C, but the crack did not arrest, and the specimen broke. The K<sub>a</sub> value from specimen A73W37 (tested at -25°C), is recognized as too low because the arrested crack length a<sub>a</sub> is 96% of the nominal specimen width W. The expression in ASTM E 1221-88 used to calculate K<sub>a</sub> is limited to  $a_a/W \leq 0.85$ . While other specimens may be slightly invalid and hence may or may not necessarily represent plane-strain behavior, the authors

believe this specimen to be so far beyond the validity limits as to be clearly non-representative of plane-strain crack-arrest toughness of the weld. Hence its position is below the ASME  $K_{Ia}$  curve in the figures given later in this paper is of no significance. In general, even though some of the other individual specimens may not strictly meet all of the ASTM validity criteria, the authors believe the data to be representative of the arrest toughness which would exist within a thick-walled RPV.

The task group responsible for the ASTM crack-arrest test procedure E 1221 recognized the need for the data to be under plain-strain conditions. Conservative validity criteria were selected, based on existing analytical and experimental results, [8] to assure that specimens which met those criteria would indeed be representative of plane-strain conditions. Even at that time, however, it was recognized that those criteria might be overly restrictive, but they were nonetheless chosen to be utilized until more evidence justifying their relaxation could be amassed. More data are now available; for example, Ref. [9] shows crack arrest test results, clearly violating the size criteria of ASTM E 1221-88, which still accurately predict the arrest behavior of a thick-walled pressure vessel under simulated pressurized-thermal loading. Based on these and other considerations, the ASTM task group will be asked to reconsider the relaxation of the validity criteria.

The crack-arrest toughness  $K_a$  of the 72W and 73W weldments presented in Figs. 8 and 9 also show the unirradiated and irradiated ASME  $K_{Ia}$  curves for each weldment indexed to their respective  $RT_{NDT}$  values. Lower-bound curves to the test results have also been plotted as dotted curves. The dotted curves are the

ASME curves shifted to the left towards a lower temperature (or downwards in temperature) until the first data point is encountered. The amount of the shift for each material is given in Figures 8 and 9 as a temperature difference in Kelvin (K) between the solid and dotted curves. The downward shifts in temperature for weld 72W are 28 and 36 K for the irradiated and unirradiated data respectively, and the corresponding temperature shifts for weld 73W are 39 and 28 K respectively. Thus, in case of 72W, the shift downward in temperature from the normalized curve for the irradiated specimens is smaller than for unirradiated ones by 8 K. For the 73W specimens, however, the opposite is obtained; the shift for the irradiated condition is 11 K greater than that for the unirradiated. With all the uncertainties involved, the differences between the downward shifts are not deemed to be significant. Thus, the preliminary observation is that the shift in  $K_a$  due to irradiation is about the same as the shift of the CVN impact energy at the 41-J energy level as may be judged by the dotted curves in Figs. 8 and 9.

The ASME curve when shifted by the normalized CVN  $\Delta TT_{41-J}$  is a conservative estimate of the irradiated crack-arrest toughness of the 72W and 73W weldments in the transition region to approximately 40 K above the  $RT_{NDT}$ . At temperatures below the  $RT_{NDT}$ , there is a smaller  $K_{Ia}$  margin between the lower-bound curves and the ASME  $K_{Ia}$  curves. For example, the lower-bound values are approx. 70, 35, and 10% higher than the ASME  $K_{Ia}$  values at temperatures with respect to  $RT_{NDT}$  of +50, 0, and -50 K.

The shape of the lower-bound curves for the data obtained in Phase 1 of the



6th Irradiation Series does not seem to have been altered by irradiation. Moreover, the lower-bound crack-arrest curves have about the same shape as that of the ASME K<sub>Ia</sub> curve. The CVN-impact energy curve for the 72W weld, and more so for the 73W weld, changed shape when irradiated to a fluence level of  $1.51 \times 10^{19}$  neutrons/cm<sup>2</sup> (>1 MeV), (see Ref. [3] and Fig. 7). There are many empirical correlations between the CVN-impact energy and fracture toughness of unirradiated ferritic steels [10]. Assuming that such a relationship also exists for irradiated ferritic steels, if the irradiated CVN curve changes shape, then the irradiated fracture toughness curve may also change shape correspondingly. One of the objectives of the 5th and 6th Irradiation Series research programs is to investigate whether irradiation induces such a shape change in the toughness curves. Indeed, such a change has been observed in the lower-bound curve to the irradiated initiation toughness K<sub>Jc</sub> data for the 73W weldment; similarly, a change in shape of the CVN impact energy curve was observed [3]. Although no such change in shape has been observed in the K<sub>Ia</sub> data obtained in tests to approx. 40 K above RT<sub>NDT</sub>, further tests at higher temperatures are needed to ascertain whether a similar change in shape occurs in the arrest toughness curve.

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

the brittle weld crack starter material allows for a higher crack driving force enabling testing at higher temperatures.

#### *Comparison with Other Data*

Almost all the published data on the effect of irradiation on crack-arrest toughness is contained in the Electric Power Research Institute (EPRI) report by Mager and Marschall [2]. Four steels were tested in the EPRI project: two welds and two plate materials. Both the plates and the welds included a low-copper as well as a high-copper steel. Six to 12 specimens were tested from each of the four materials for a total of 36 and 34 specimens in the unirradiated and irradiated condition, respectively. The results of the irradiated crack-arrest toughness were compared to the unirradiated data by shifting the irradiated data downwards in temperature to achieve an approximate data coincidence. The EPRI downward shift is approximately comparable to the lower-bound one used in the present paper (obtained by shifting the ASME  $K_{Ia}$  curve downwards in temperature until the first data point is encountered). The EPRI shift in  $K_{Ia}$  due to irradiation for high-copper materials is less than the  $\Delta T_{41-J}$ , whereas for the low-copper materials, the shift in  $K_{Ia}$  is slightly greater or equal to  $\Delta T_{41-J}$ , (in the EPRI program, the CVN shifts were also evaluated in several other ways). In this study a similar trend is obtained, although the range of copper contents is quite different. In the EPRI program, the copper contents ranged from approximately 0.03 to 0.23 % by weight. In the present study, the copper contents for the two materials are 0.23 and 0.31% and the normalized  $\Delta T_{41-J}$  are 80 and 93 K for the 72W and 73W welds, respectively, while the shifts of the lower-bound  $K_a$  curves were 88 and 82 K for the 72W and 73W welds, respectively. This study also increased the maximum values of irradiated crack-arrest toughness

obtained when compared to those of the EPRI program from approximately 130 to 185 MPa $\cdot\sqrt{m}$ . Irradiated crack-arrest toughness data for both welds in this study were also obtained at higher temperatures with respect to the normalized  $RT_{NDT}$  (up to 40 K above the  $RT_{NDT}$ ) than the EPRI data for the high-copper weld (EPRI data were obtained up to approximately the adjusted  $RT_{NDT}$ ).

## 5. SUMMARY

Crack-arrest testing of high copper submerged-arc welds has been performed on unirradiated and irradiated weld embrittled type specimens 25 and 33-mm thick. Most of the crack-arrest test results are either valid or only marginally invalid according to ASTM E 1221-88. The 34 data points obtained by testing the irradiated crack-arrest specimens have approximately doubled the known data base of irradiated crack-arrest toughness and extended it 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 K above the irradiated  $RT_{NDT}$  of the welds. This is significant because a temperature of 20 K above the  $RT_{NDT}$  is generally considered to be the limit for obtaining useful results with the unirradiated weld-embrittled type of crack-arrest specimen.
2. The shifts of the lower-bound  $K_a$  curves for the 72W and 73W welds are approximately the same as the corresponding 41-J CVN-impact energy level

shifts.

3. The ASME K<sub>Ia</sub> curve, when shifted by  $\Delta T_{41-J}$  is a conservative estimate of the irradiated crack-arrest toughness for welds 72W and 73W in the transition region about 40 K above the RT<sub>NDT</sub>. At temperatures below the RT<sub>NDT</sub>, there seems to be a smaller margin of toughness between the lower-bound curves and the ASME K<sub>Ia</sub> curves.
4. The shape of the lower-bound curves compared to those of the ASME K<sub>Ia</sub>-curve did not seem to have been altered by irradiation for the test temperature range covered by the tests.

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Table 1. Chemical composition of the two submerged-arc welds in the HSSI Fifth and Sixth Irradiation Series<sup>1</sup>

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

<sup>1</sup> Ref: R. K. Nanstad et al., "Effects of Irradiation on  $K_{Ic}$  curves for High-Copper Welds," *Effects of Radiation on Materials, 14th International Symposium, ASTM STP 1046, Vol. II*, N. H. Packan, R. E. Stoller, and A. S. Kumar, Eds., American Society for Testing and Materials, Philadelphia, 1990, pp. 214-233.

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

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

Table 3. Initial, adjusted, and normalized reference temperatures ( $RT_{NDT}$ ) for welds 72W and 73W

Weld	Initial $RT_{NDT}$ (°C)	Charpy impact <sup>a</sup> observed results		Adjusted <sup>b</sup> $RT_{NDT}$ (°C)	Charpy impact normalized <sup>c</sup> to crack-arrest fluences		Normalized $RT_{NDT}$ (°C)
		Fluence, $\Phi$ ( $10^{19}$ n/cm <sup>2</sup> ) (>1 MeV)	$\Delta TT_{41-J}$ (K)		Fluence, $\Phi'$ ( $10^{19}$ n/cm <sup>2</sup> ) (>1 MeV)	$\Delta TT_{41-J}$ (K)	
72W	-23	1.51	72	49	1.88	80	57
73W	-34	1.51	82	48	1.93	93	59

<sup>a</sup>Source: R. K. Nanstad et al., "Effects of Radiation of  $K_{IC}$  Curves for High-Copper Welds," pp. 214-33 in *Effects of Radiation on Materials: 14th International Symposium, Vol. II*, ASTM STP 1046, N. H. Packan, R. E. Stoller, and A. S. Kumar, Eds., American Society for Testing and Materials, Philadelphia, 1990.

<sup>b</sup>Adjusted  $RT_{NDT}$  = initial  $RT_{NDT}$  +  $\Delta TT_{41-J}$  (according to ASTM 185-82).

<sup>c</sup>Normalization:  $(\Delta TT_{41-J})(\Phi'/\Phi)^{0.5}$ . Source: 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, L. E. Steele, Ed., American Society for Testing and Materials, Philadelphia, 1986.

NOTE:

$\Phi$  = fluence for Charpy V-notch impact specimens.

$\Phi'$  = fluence for crack-arrest specimens.

n = neutrons.

$\Delta TT_{41-J}$  = shift in 41-J Charpy V-notch impact energy level.

Table 4. Unirradiated crack arrest toughness data obtained from testing weldment 72W ( $RT_{NDT} = -23^{\circ}C$ ).

Specimen ID	Test Temperature ( $^{\circ}C$ )	$K_a$ MPa $\cdot\sqrt{m}$	Validity <sup>1</sup>
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Weld-embrittled 25 x 76 x 76 mm specimens

A72W37	-61	66	
A72W35	-60	53	
A72W38	-59	57	
A72W36	-47	71	
A72W34	-45	73	
A72W24	-30	61	
A72W28	-30	60	
A72W25	-30	79	B
A72W31	-15	108	B, E

Weld-embrittled 25 x 152 x 152 mm specimens

A72W44	-60	76	
A72W39	-60	45	A
A72W20	-47	67	
A72W41	-45	74	
A72W46	-45	92	
A72W43	-32	92	
A72W08	-30	104	
A72W05	-30	107	
A72W48	-30	98	
A72W01	-16	97	
A72W03	-14	128	C

Weld-embrittled 33 x 152 x 152 mm specimens

A72W45	-45	76	
A72W47	-30	91	
A72W07	-15	103	
A72W04	-15	94	
A72W19	-15	94	
A72W02	0	93	
A72W12	0	114	
A72W40	0	114	B

Duplex 33 x 152 x 152 mm specimens

A72W71	-14	91	
A72W66	-2	103	
A72W63	-1	125	
A72W64	1	108	
A72W65	4	125	
A72W68	5	115	
A72W73	5	142	C, D
A72W62	10	136	B, C
A72W57	21	146	C, D

Weld-embrittled 51 x 203 x 203 mm specimens

A72W83	-30	85
A72W85	-15	95
A72W84	0	107

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<sup>1</sup>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 the ones in Table 2 of ASTM E 1221-88 which can be paraphrased as:

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

Table 5. Unirradiated crack arrest toughness data obtained from testing weldment 73W ( $RT_{NDT} = -34^{\circ}C$ ).

Specimen ID	Test Temperature ( $^{\circ}C$ )	$K_a$ MPa $\cdot\sqrt{m}$	Validity <sup>1</sup>
Weld-embrittled 25 x 76 x 76 mm specimens			
A73W38	-62	50	A
A73W42	-60	58	
A73W32	-59	56	A
A73W36	-59	72	
A73W01	-45	52	
A73W02	-45	75	
A73W03	-45	64	A, B
A73W06	-35	83	B
A73W04	-30	67	
A73W05	-30	70	A, B
Weld-embrittled 25 x 152 x 152 mm specimens			
A73W28	-61	69	
A73W43	-45	73	
A73W47	-45	85	
A73W30	-44	71	
A73W11	-32	85	
A73W48	-31	75	
A73W50	-30	80	
A73W16	-29	89	
A73W52	-29	77	
A73W20	-16	126	C
A73W25	-15	141	B, C
Weld-embrittled 33 x 152 x 152 mm specimens			
A73W29	-30	100	
A73W10	-16	77	A
A73W22	-16	110	
A73W46	-15	124	
A73W44	-15	123	
A73W49	-15	117	
A73W24	-13	89	A, B
A73W27	-12	111	

Duplex 33 x 152 x 152 mm specimens

A73W86	-5	101	
A73W07	5	129	B
A73W08	5	119	
A73W09	5	112	
A73W85	5	137	C,D
A73W87	5	113	
A73W88	15	132	

Duplex 51 x 203 x 203 mm specimen

A73W75	5	107
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<sup>1</sup>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 the ones in Table 2 of ASTM E 1221-88 which can be paraphrased as:

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

Table 6. Irradiated crack arrest toughness data for the weld-embrittled type specimens from weldment 72W, (RT<sub>NDT</sub> = 57°C). The average fluence and irradiation temperatures were  $1.88 \times 10^{19}$  neutrons/cm<sup>2</sup> (>1 MeV) and 286°C respectively.

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

<sup>1</sup>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 the ones in Table 2 of ASTM E 1221-88 which can be paraphrased as:

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



Table 7. Irradiated crack arrest toughness data for the weld-embrittled type specimens from weldment 73W, (RT<sub>NDT</sub> = 59°C). The average fluence and irradiation temperatures were  $1.93 \times 10^{19}$  neutrons/cm<sup>2</sup> (>1 MeV) and 285°C respectively.

Specimen ID	Test temperature (°C)	K <sub>a</sub> (MPa·√m)	Irradiation temperature (°C)	Exposure values			Validity <sup>1</sup>
				$\Phi$ (>1 MeV) (neutrons/cm <sup>2</sup> )	$\Phi$ (>0.1 MeV) (neutrons/cm <sup>2</sup> )	dpa	
A73W37 <sup>2</sup>	-25	29	25 x 76 x 76 mm specimens.	2.38E+19	1.44E+20	0.0548	A
A73W39	-25	41	280	2.13E+19	1.31E+20	0.0497	
A73W31	29	57	282	2.10E+19	1.29E+20	0.0490	D
A73W34	29	60	283	2.08E+19	1.28E+20	0.0484	D
A73W35	29	67	283	2.37E+19	1.42E+20	0.0544	D
A73W33	60	74	282	2.39E+19	1.44E+20	0.0550	D
A73W40	60	81	280	2.26E+19	1.42E+20	0.0542	D
A73W41	60	79	284	2.11E+19	1.30E+20	0.0492	D
A73W15	60	81	25 x 152 x 152 mm specimens.	1.68E+19	1.15E+20	0.0421	
A73W13	75	150	289	1.69E+19	1.16E+20	0.0424	C, D
A73W18	75	131	287	1.56E+19	1.04E+20	0.0385	
A73W21	75	107	289	1.73E+19	1.14E+20	0.0426	
A73W26	75	88	288	1.58E+19	1.05E+20	0.0387	
A73W23	90	180	288	1.58E+19	1.05E+20	0.0389	B, C
A73W45	90	114	287	1.46E+19	9.45E+19	0.0354	
A73W14	90	159	33 x 152 x 152 mm specimens.	1.71E+19	1.17E+20	0.0429	B, C
A73W17 <sup>3</sup>	100		289	1.90E+19	1.29E+20	0.0474	
A73W51	100	184	289	1.90E+19	1.30E+20	0.0475	B, C

<sup>1</sup>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 the ones in Table 2 of ASTM E 1221-88 which can be paraphrased as:

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

<sup>2</sup>Value of K<sub>a</sub> is unrealistically low because remaining ligament is too small.

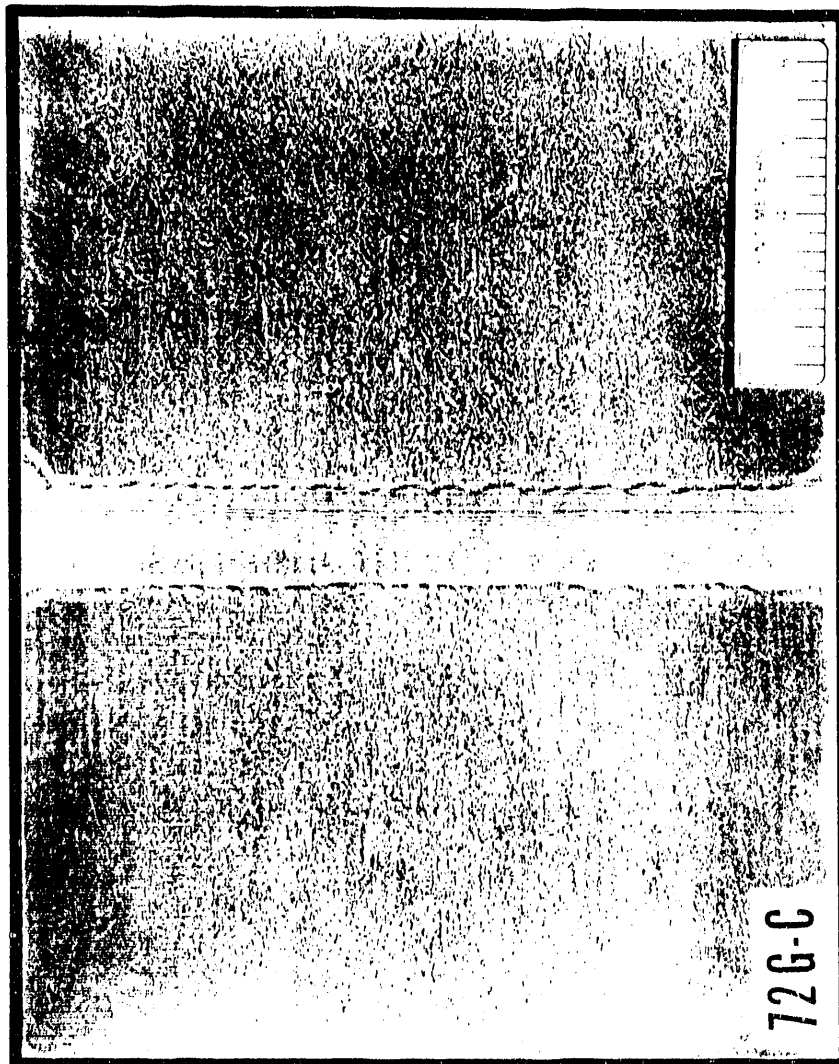
<sup>3</sup>Specimen exhibited tearing behaviour when tested at this temperature, then broke without arresting when retested at 30° C.

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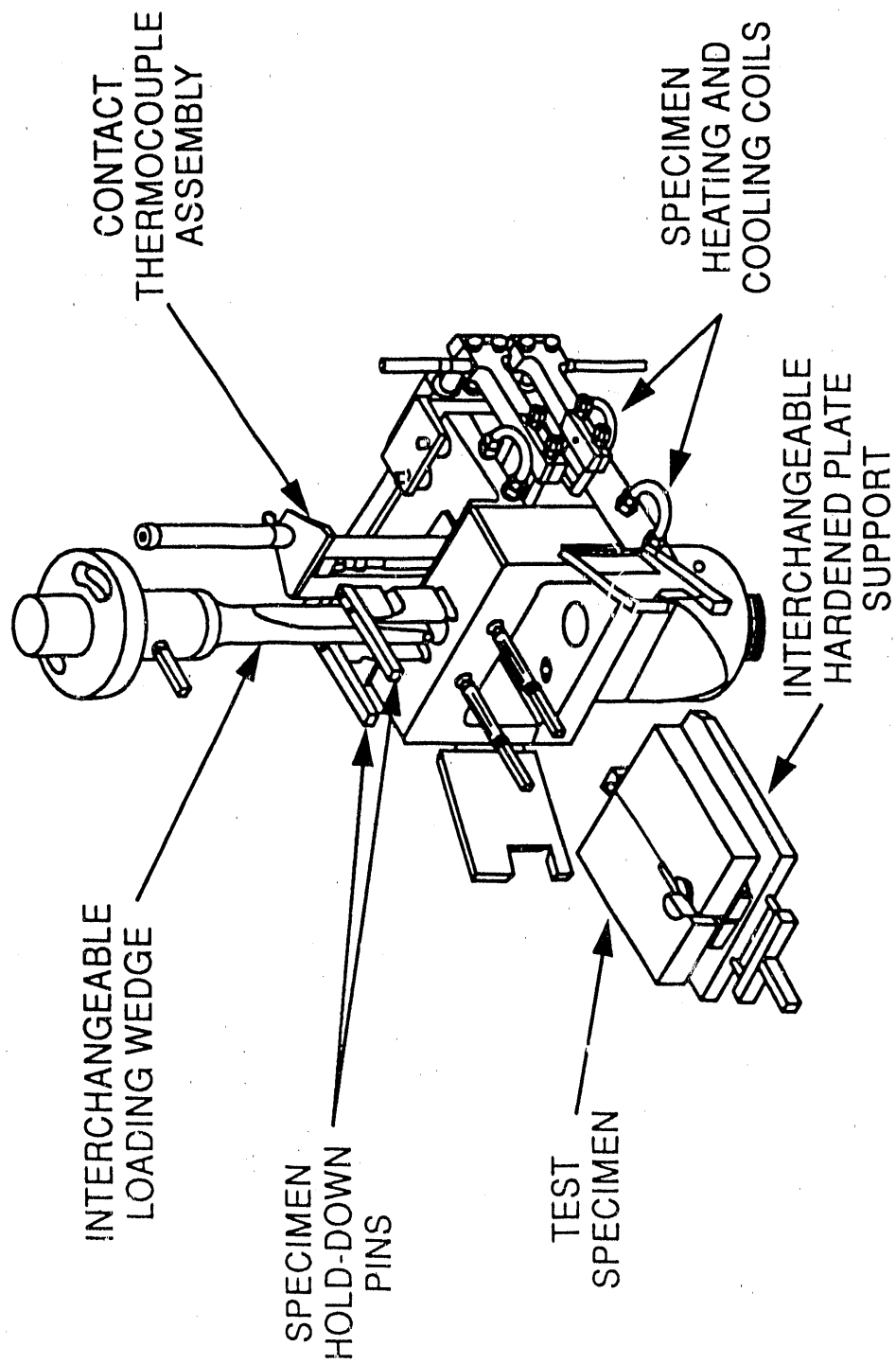
Figure  
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1. Cross section of typical submerged-arc weld used in the 72W and 73W welds of the Fifth and Sixth Irradiation Series. The welds were made with specially produced wire (with copper added to the melt) and fabricated in 220-mm-thick plate.
2. Schematic drawing of equipment used to perform crack-arrest testing of irradiated specimens before it was set up in the hot-cell 500-kN testing machine.
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8. Unirradiated and irradiated crack arrest toughness  $K_a$  vs test temperature for the 72W weldment. The dotted curves are lower bounds to the data obtained by shifting the ASME curves to a lower temperature by the amounts shown.
9. Unirradiated and irradiated crack arrest toughness  $K_a$  vs test temperature for the 73W weldment. The dotted curves are lower bounds to the data obtained by shifting the ASME curves to a lower temperature by the amounts shown.

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73W26

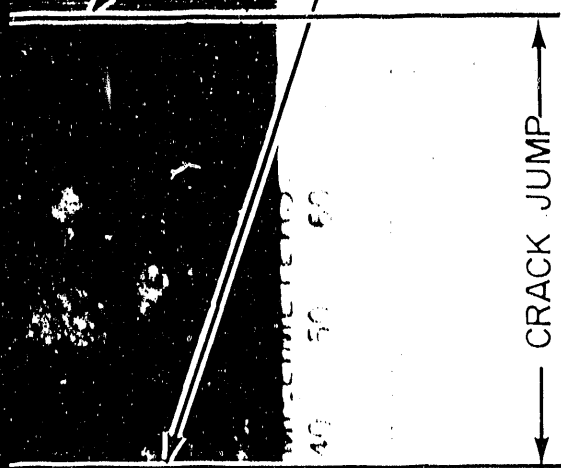
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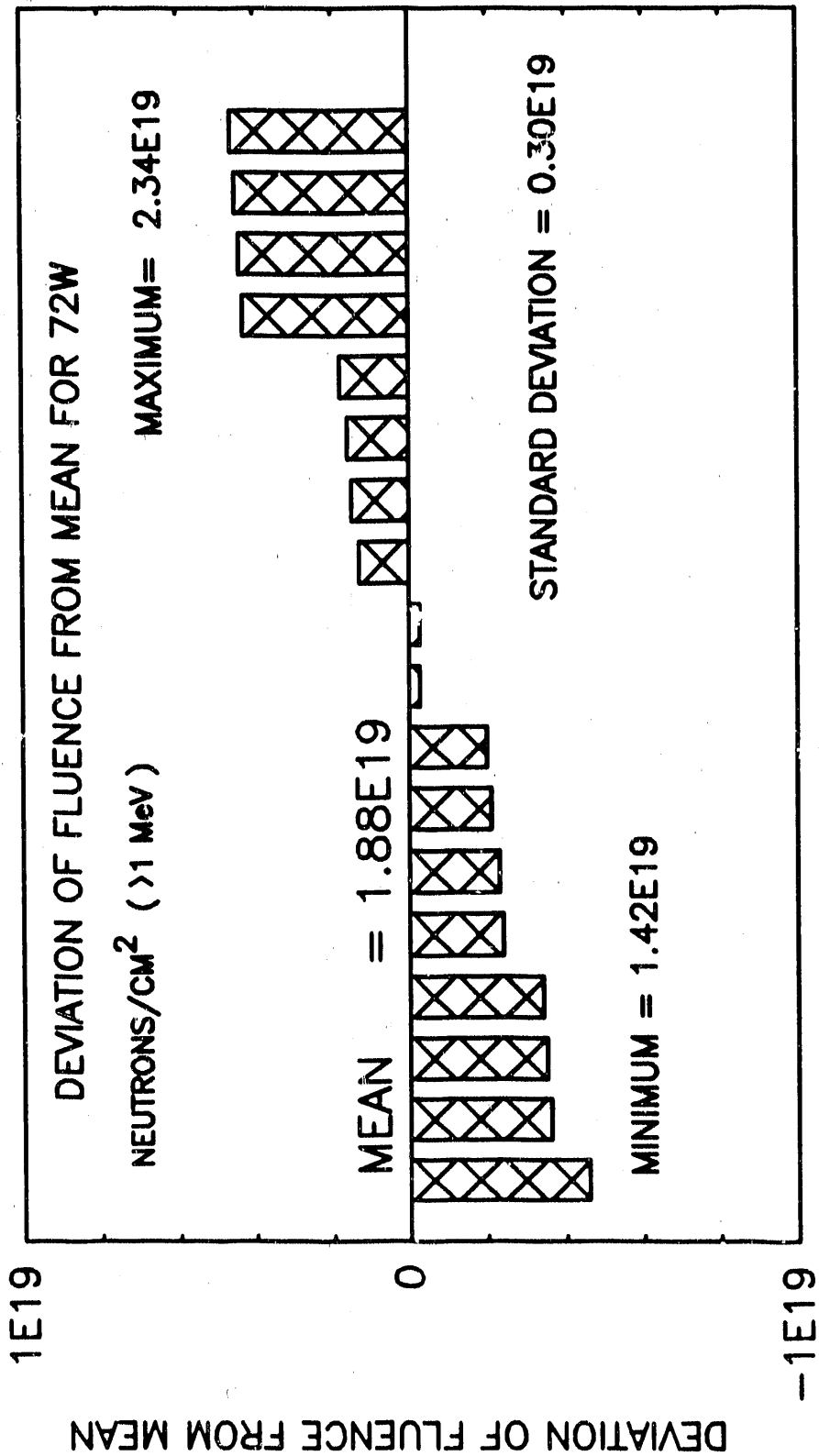
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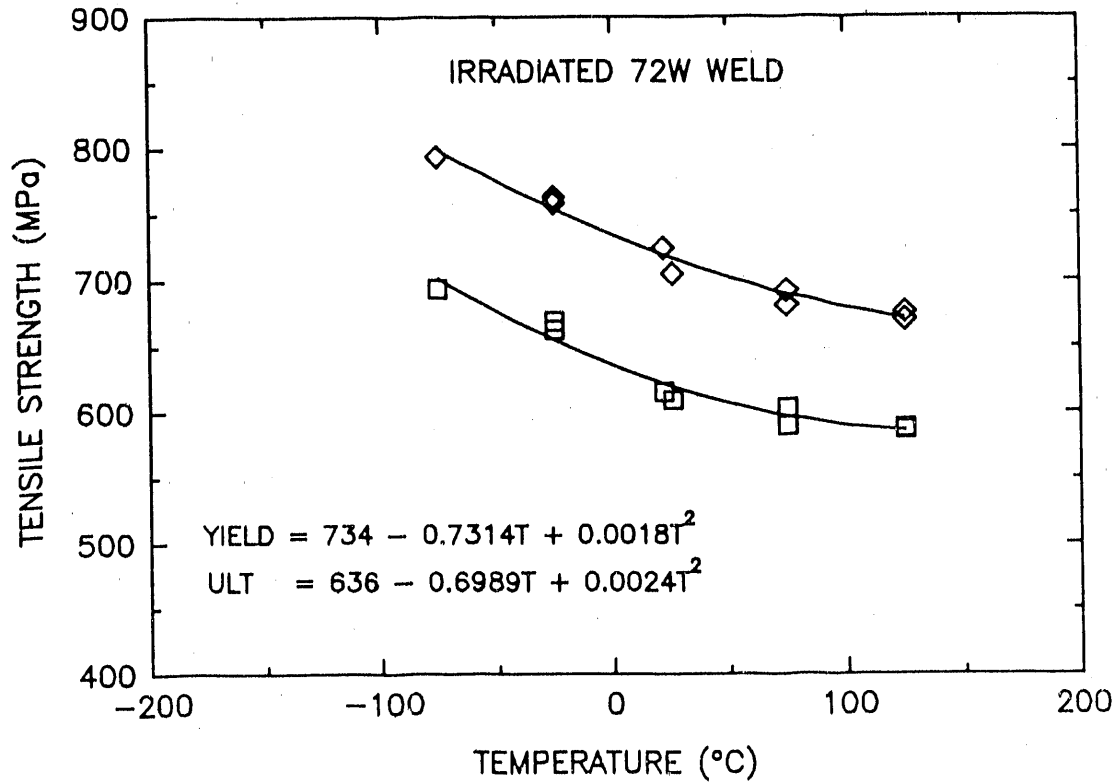
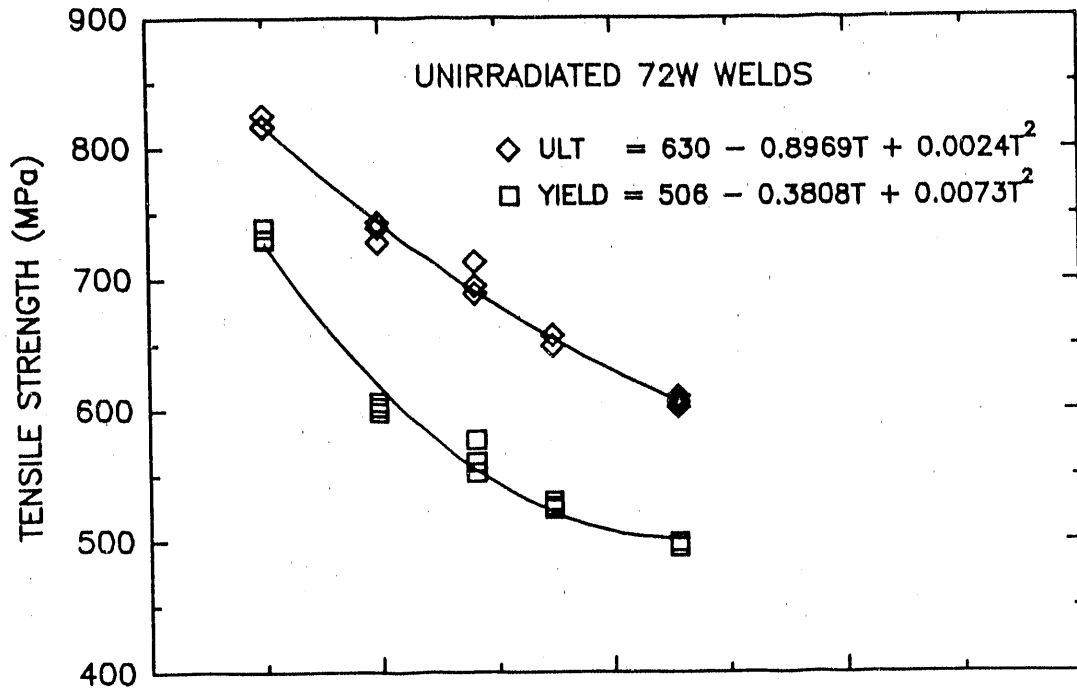
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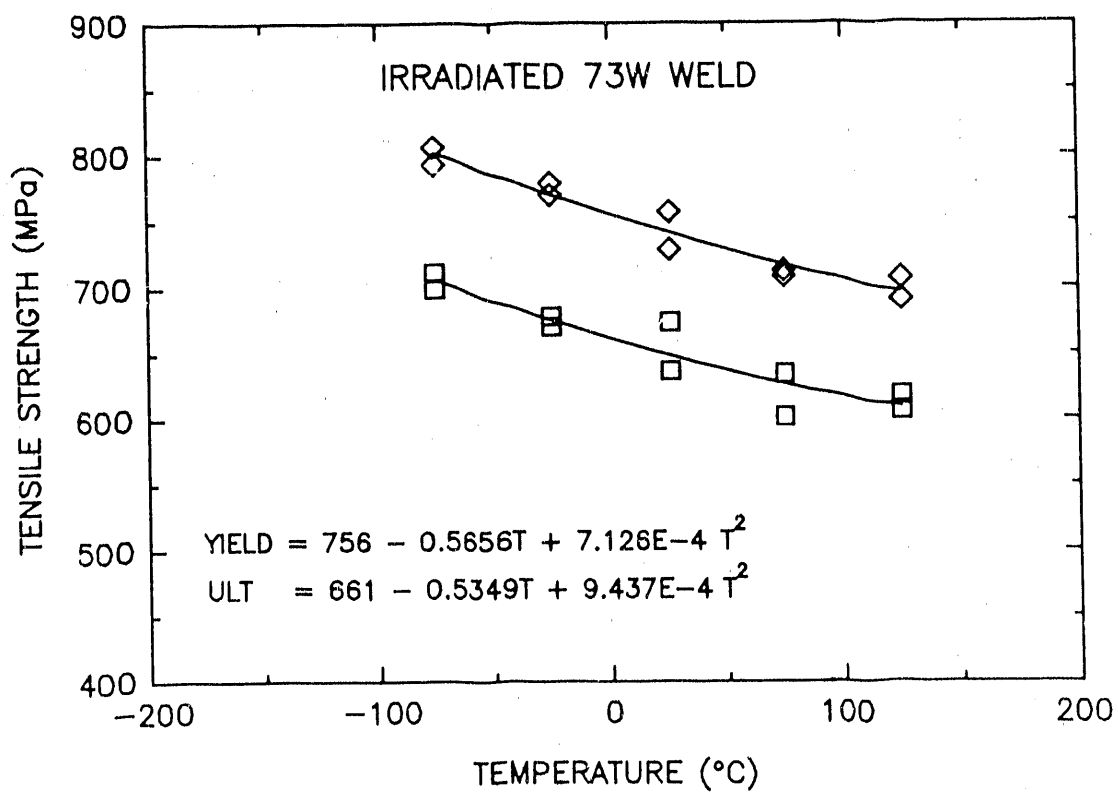
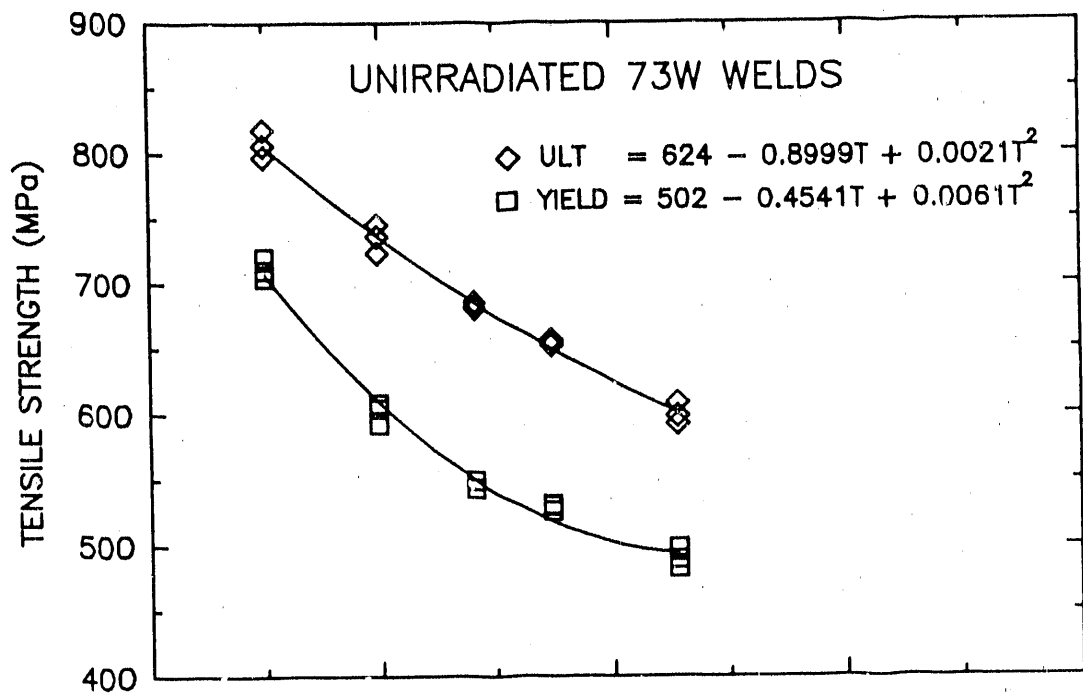
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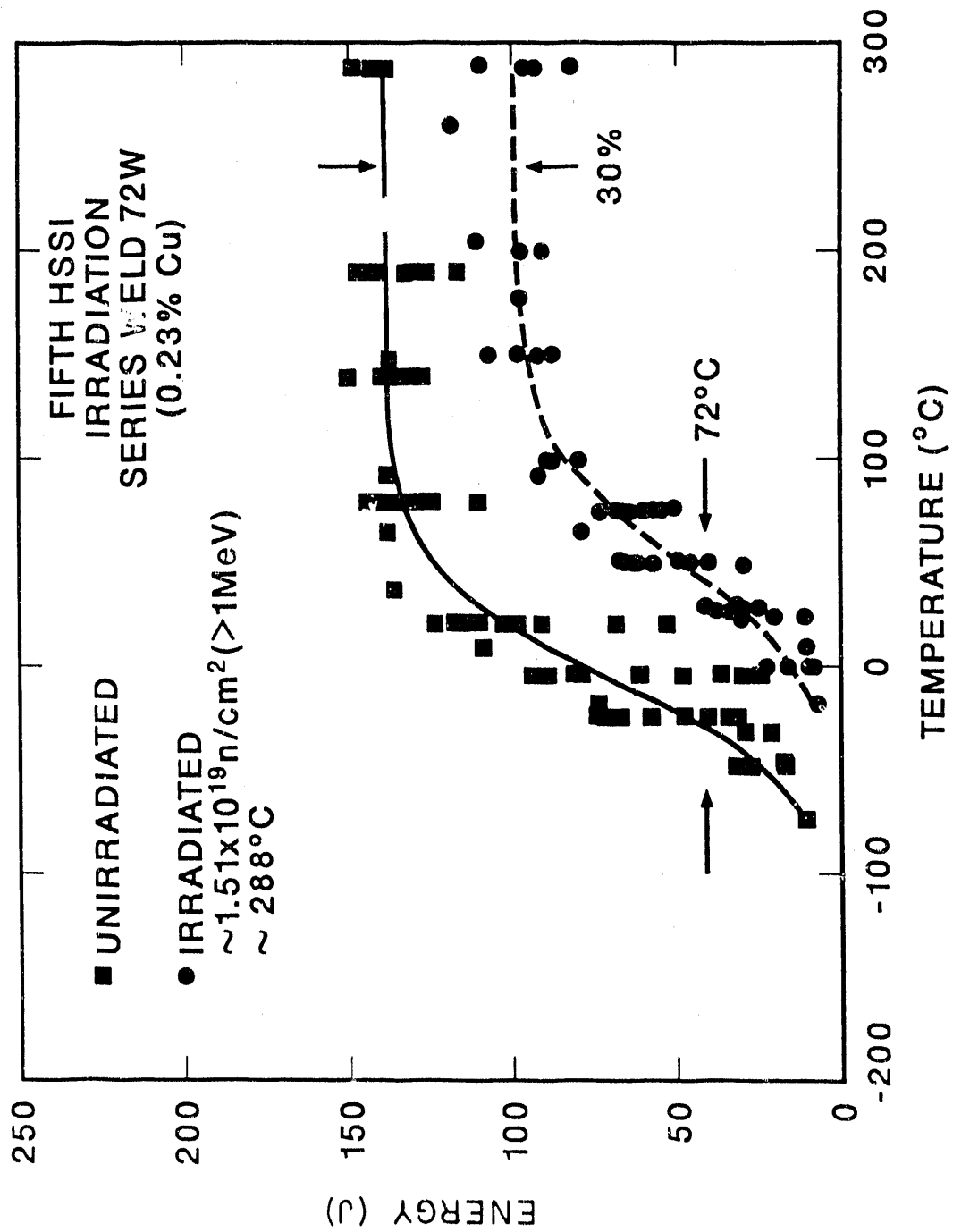


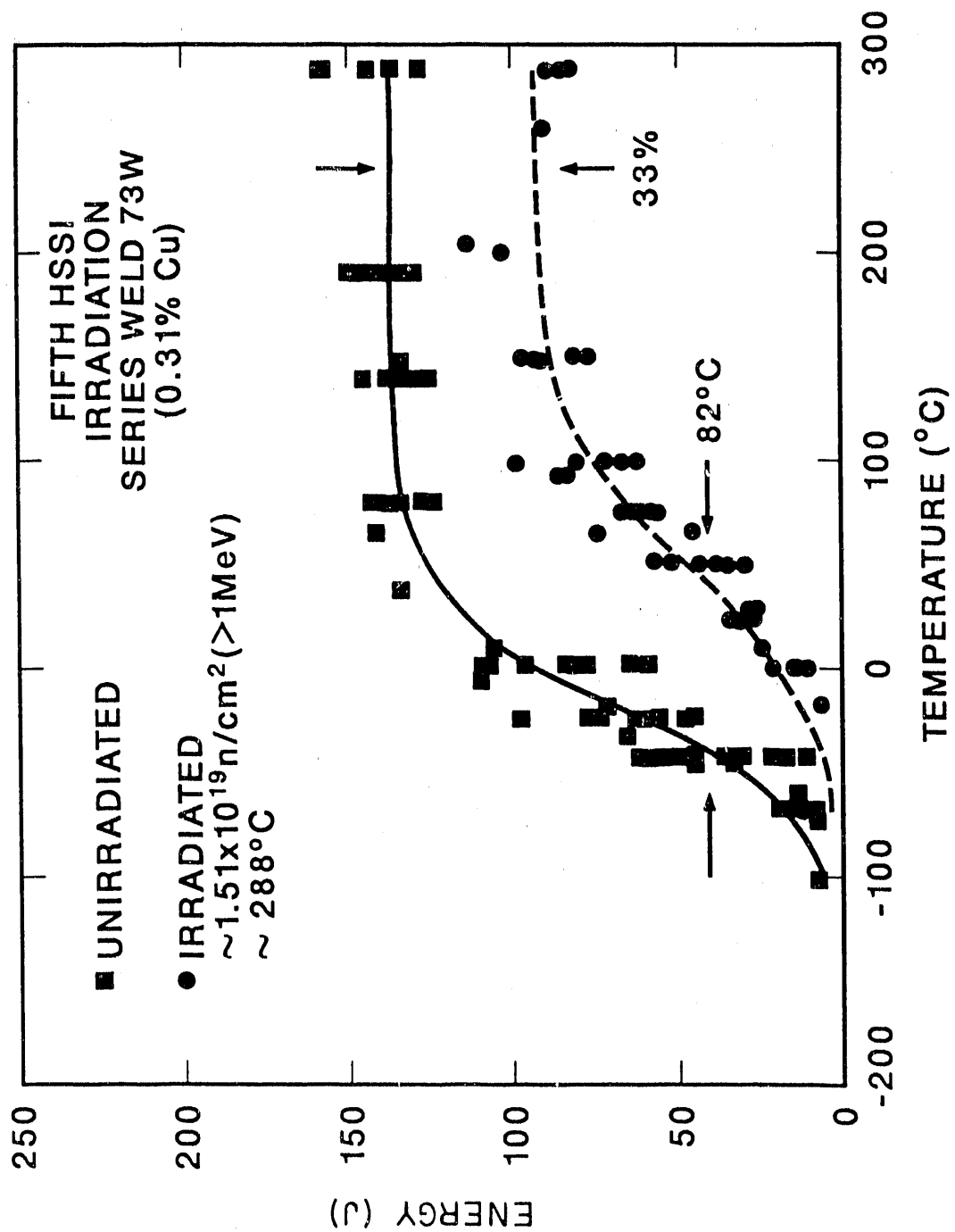


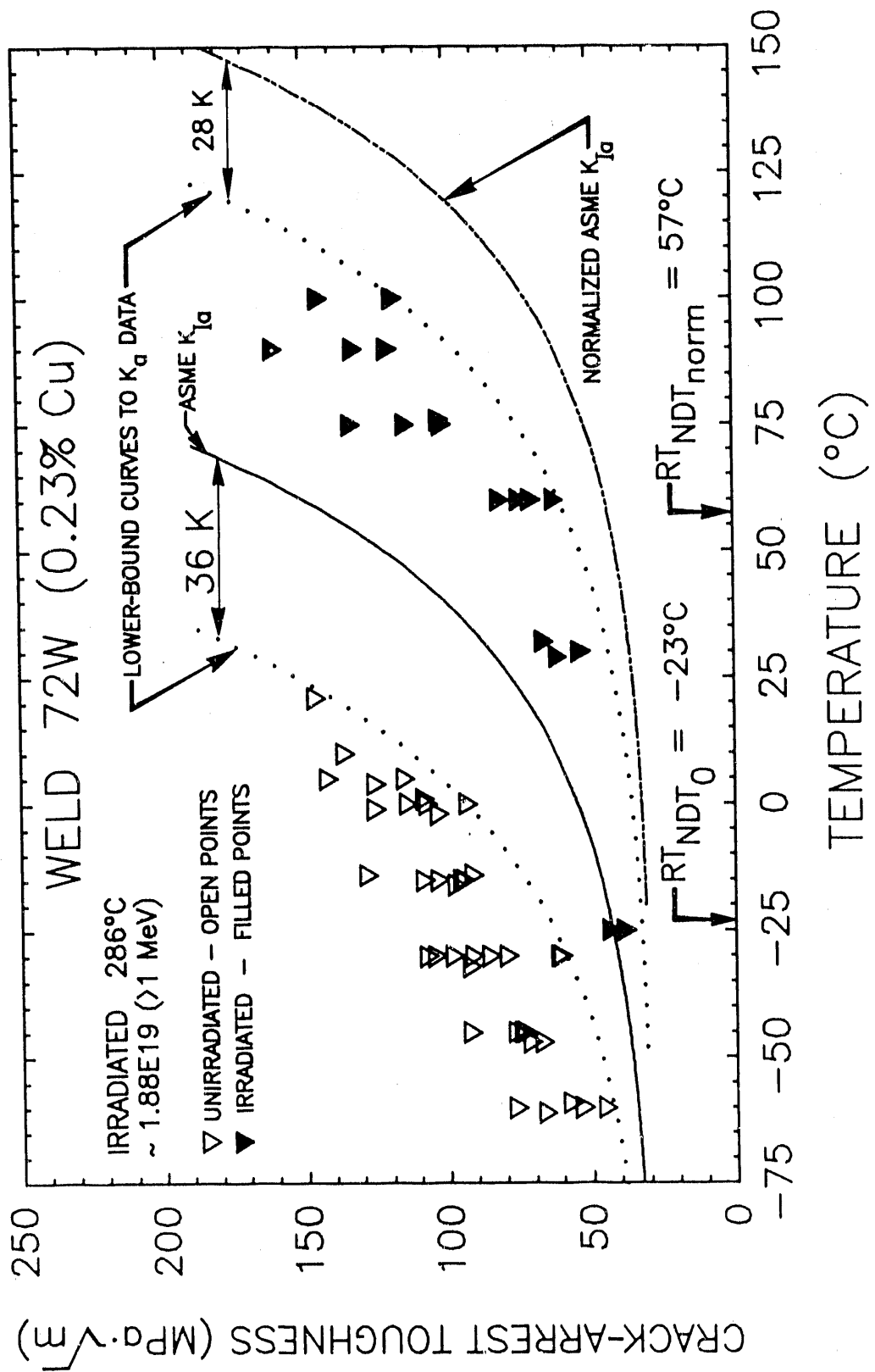


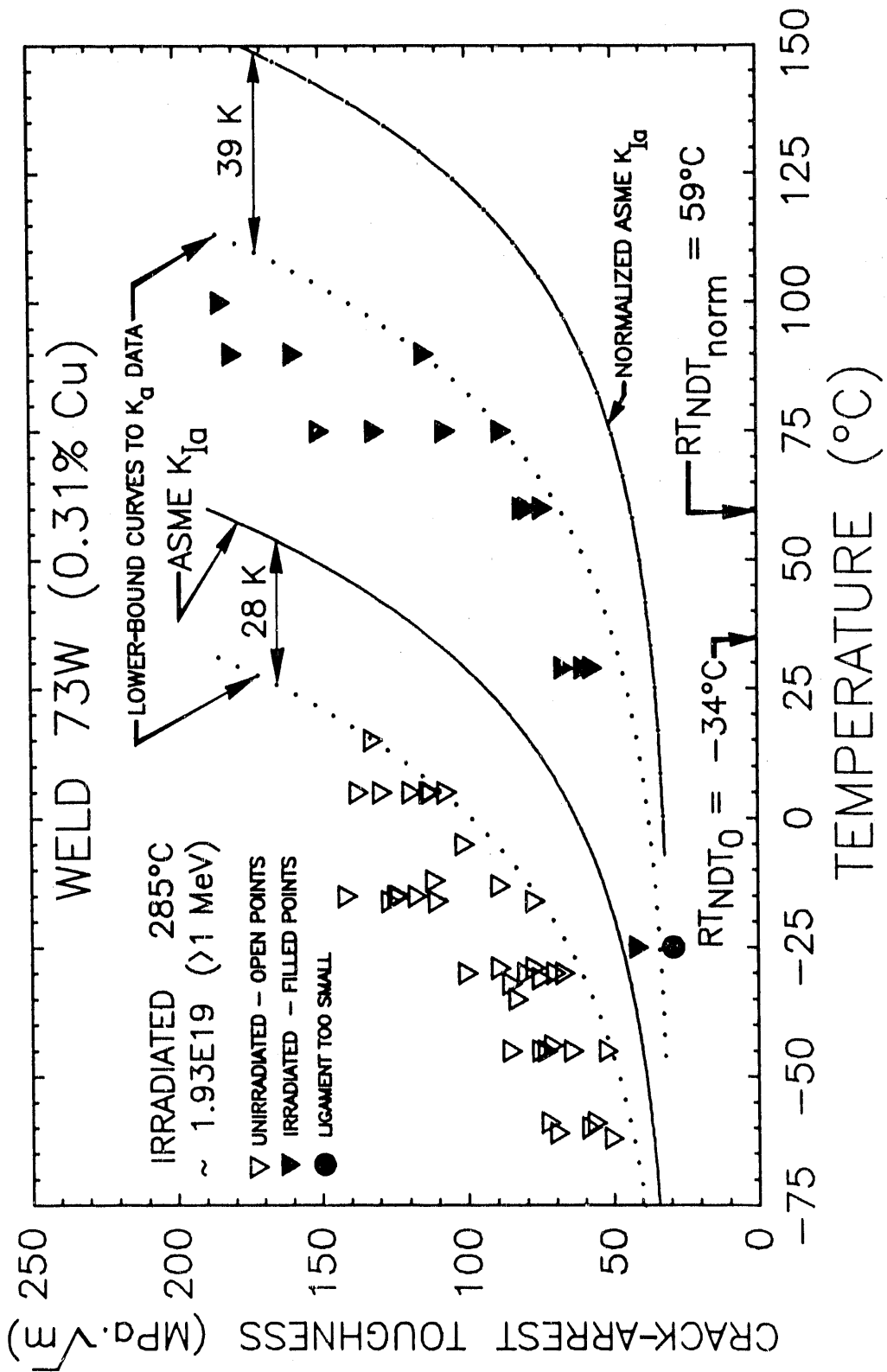












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