

# Radiation-Induced Temperature Shift of the ASME $K_{Ic}$ Curve

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## ABSTRACT

The objective of this study was to determine the effects of neutron irradiation on the temperature shift and shape of the  $K_{Ic}$  curve described in Sect. XI of the *ASME Boiler and Pressure Vessel Code*.

Two submerged-arc welds with copper contents of 0.23 and 0.31 wt % were commercially fabricated in 215-mm-thick plate. Charpy impact, tensile, drop-weight, and compact specimens up to 203.2 mm thick were fabricated and tested to provide a large data base for unirradiated material. Similar specimens with compacts up to 101.6 mm thick, irradiated at about 288°C to a mean fluence of about  $1.6 \times 10^{19}$  neutrons/cm<sup>2</sup> in the Oak Ridge Research Reactor, were tested to provide a similarly large data base with which to evaluate the temperature shift and shape of the ASME  $K_{Ic}$  curve. Testing was performed by both Oak Ridge National Laboratory and Materials Engineering Associates. Both linear-elastic and elastic-plastic fracture mechanics techniques were used to analyze test results.

Both the unirradiated and irradiated fracture toughness results exhibited large scatter which amplified the need for statistical analyses. The shift of the drop-weight nil-ductility transition and Charpy 41-J temperatures were about the same for both materials and were substantially less than the guidelines of *Regulatory Guide 1.99* (Rev. 2). The 125-MPa $\sqrt{m}$  fracture toughness shift for the higher copper weld was about 20°C greater than that of the 41-J Charpy shift. A decrease in the slope of the  $K_{Ic}$  curve similar to that of the Charpy curve was observed. For the irradiated tests, evaluation of cleavage pop-ins was very important in the analyses.

## INTRODUCTION

Operating procedures for commercial light-water reactors (LWRs) include provisions for consideration of fracture toughness of the reactor pressure vessel (RPV). The basic fracture toughness requirements are contained in Title 10, *Code of Federal Regulations*, Part 50 (10CFR50). Appendix G of 10CFR50 requires determination of a reference nil-ductility temperature,  $RT_{NDT}$ , and refers to Sect. III of the *ASME Boiler and Pressure Vessel Code* (American Society of Mechanical Engineers, 1986) which delineates the use of drop-weight (DWT) specimens and Charpy V-notch (CVN) impact specimens to determine both the nil-ductility transition (NDT) temperature and the  $RT_{NDT}$ .

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Furthermore, Appendix A of Sect. XI of the ASME Code contains fracture toughness ( $K_{Ic}$ ) and crack arrest toughness ( $K_{Ia}$ ) curves as a function of temperature (T) normalized to the  $RT_{NDT}$ , i.e.,  $T - RT_{NDT}$ . Using surveillance test results, the irradiated  $RT_{NDT}$  [ $RT_{NDT}(I)$ ] is determined by adding the temperature shift between the unirradiated and irradiated CVN curves at the 30 ft-lb level ( $\Delta TT_{30}$ ) to the unirradiated  $RT_{NDT}$  [ $RT_{NDT}(U)$ ].

The  $K_{Ic}$  and  $K_{Ia}$  curves are shifted upward in temperature by virtue of the change in the  $RT_{NDT}$ . The implicit assumptions with the procedures are (1) the CVN  $\Delta TT_{30}$  represents the shift in the  $RT_{NDT}$ , (2) the fracture toughness shifts are the same as the CVN shift, and (3) the shape of the fracture toughness curves do not change as a consequence of irradiation. The specific objectives of the Heavy-Section Steel Technology (HSST) Program Irradiation Series 5 is to evaluate the accuracy and conservatism of those assumptions relative to the  $K_{Ic}$  curve and, where necessary, recommend changes.

## DESCRIPTION OF MATERIALS AND PROCEDURES

Weld wire was specially produced commercially for the program in one melt and the melt was split to allow for copper additions to one-half. The chemical compositions of the two welds are as comparable as possible except for copper, with 0.60 wt % Ni and 0.006 wt % P. About 14.6 m of each weld were commercially fabricated in A533 grade B class 2 plate of 220-mm (8.6-in.) thickness using the submerged-arc process with one lot of Linde 0124 flux. The welds are designated HSST 72W (0.23 wt % Cu) and 73W (0.31 wt % Cu). All welds were postweld heat treated at 607°C (1125°F) for 40 n, typical of that given commercial reactor vessels. The specimen complement is quite large and was selected to allow for practicable statistical analyses of the results. Specimens used were tensile, CVN, DWT, and compact specimens from 25.4- to 203.3-mm thick (1TCS to 8TCS). The testing of specimens was a cooperative venture between ORNL and Materials Engineering Associates (MEA). The irradiations were performed in the poolside facility of the Oak Ridge Research Reactor (ORR). A more comprehensive presentation of the program procedures and results can be found elsewhere (Nanstad, 1989).

Testing of CVN, round tensile and P-3 DWT specimens was conducted in accordance with ASTM E 23, E 8, and E 208, respectively. The P-3 DWT specimen (with a one-pass weld bead) was used to determine NDT temperatures. All compact specimens were tested with a single-specimen unloading compliance procedure as generally described in ASTM E 813. Calculations were performed according to E 399 where applicable, but, if the requirements for a valid  $K_{Ic}$  were violated, a J-integral at the point of cleavage fracture,  $J_c$ , was determined and a critical value of stress intensity,  $K_{Jc}$ , was calculated from the relation  $K_{Jc}^2 = EJ_c$ , where  $E$  [=] Young's modulus. Of particular importance to the analysis procedures is the treatment of specimens that exhibit small cleavage instabilities, pop-ins, prior to the final cleavage instability that leads to specimen fracture. For the preliminary analyses of this study, all cleavage pop-ins have been considered significant and  $K_{Jc}$  values calculated therefrom are specifically noted. Statistical analyses of the test results are currently under way.

## RESULTS

Tensile tests were conducted over the temperature range anticipated for fracture toughness testing of both unirradiated and irradiated materials. The tensile properties of the two welds are quite similar in the unirradiated condition, with yield and ultimate strengths about 496 and 606 MPa, respectively. Their responses to irradiation show the high-copper weld 73W (0.31 wt % Cu) to be more sensitive to irradiation than the lower-copper weld 72W (0.23 wt % Cu), with room temperature yield strength increases of about 32 and 25%, respectively. The unirradiated Charpy 41-J transition temperatures are -28 and -39°C while the drop-weight NDTs are -23 and -34°C for welds 72W and 73W, respectively. The Charpy upper-shelf energy for both welds is about 135 J and the  $RT_{NDT}$  of each weld is equal to its NDT. Figures 1 and 2 show the unirradiated and irradiated

CVN results at an average fluence of about  $1.75 \times 10^{19}$  neutrons/cm<sup>2</sup> (>1 MeV). Based on computer curve fits, the 41-J shifts are 72 and 82°C while the upper-shelf energy decreases are 30 and 33% for welds 72W and 73W, respectively. The irradiation-induced changes are greater for the higher-copper weld 73W.

Table 1 gives the radiation-induced shifts of the DWT NDTs and the CVN 41-J shifts with the corresponding fast fluences. A comparison of the 41- and 68-J shifts substantiates the observation from Figs. 1 and 2 that the slope of the Charpy curve for weld 73W has decreased due to irradiation more than that for weld 72W. For both welds, the shifts are substantially less than predicted by *Regulatory Guide 1.99* (Rev. 2) (U.S. Nuclear Regulatory Commission, 1988). To facilitate a more direct comparison, NDT shifts were adjusted, as described in the table, to provide an estimate of the shifts at the fluence of the CVN specimens. Using the adjusted values, the CVN 41-J and DWT NDT shifts compare very well for the primary specimens. The higher adjusted NDT shifts for the scoping groups are likely due to their lower irradiation temperatures.

The results of fracture toughness tests show that all the unirradiated data are above the  $K_{Ic}$  curves, although the lower data for weld 72W are closer to the curve than those for 73W. The 6TCS and 8TCS specimen results scatter well above the  $K_{Ic}$  limits. The only valid result indicated was the result of a pop-in in a 6TCS of 72W at 10°C and none of the 6TCS or 8TCS experienced in-plane stable ductile tearing prior to onset of cleavage even at  $K_{Jc}$  values over 300 MPa $\sqrt{m}$ .

Figures 3 and 4 show the results of irradiated fracture toughness tests for welds 72W and 73W, respectively. The unirradiated results are represented by the scatter bands. The ASME  $K_{Ic}$  curve is shifted upward in temperature equal to the CVN 41-J shift as specified by ASTM E 185. For weld 72W, the procedure is quite representative of the data obtained, except for one  $K_{Jc}$  value from a 2TCS and one from a 4TCS specimen at 95°C that fall below the curve. For weld 73W, however, five data points fall below the shifted curve. A lower-bound curve based on the actual data is also shown and indicates a change in the shape of the fracture toughness curve, similar to that shown by the CVN curve. Final determination of curve shape changes will depend on more detailed analyses.

The fracture toughness shifts (adjusted for small fluence differences) were determined at a  $K_{Jc}$  value of 125 MPa $\sqrt{m}$ , which is about the  $K_{Ic}$  measuring capacity for the irradiated 4TCS. For 72W, the  $K_{Jc}$  shift is slightly greater than the CVN 41-J shift. For 73W, however, the 125-MPa $\sqrt{m}$  shift relative to the unirradiated ASME curve is substantially greater than the CVN 41-J shift, 103 vs 82°C, respectively. Although the  $K_{Jc}$  shift is still well within the predicted 41-J shift (127°C) of *Regulatory Guide 1.99*, it demonstrates that the CVN 41-J shift may provide a nonconservative basis for predicting the  $K_{Ic}$  curve shift. The CVN 68-J shift of 104°C corresponds very well with the  $K_{Jc}$  125-MPa $\sqrt{m}$  shift of 103°C, however. The same observation applies to weld 72W. This amplifies the changes in the shapes of both the CVN and  $K_{Ic}$  curves. Although the CVN 41-J shift may not represent the shift of the fracture toughness curve, it is significant that the CVN and  $K_{Jc}$  curves appear to change shape in a similar fashion. Various statistical and empirical adjustment schemes are being investigated, all aimed toward the development of a rational scheme for constructing irradiated  $K_{Ic}$  curves.

## SUMMARY

Using two submerged-arc welds with different copper contents, compact specimens up to 200 mm thick (unirradiated) and 100 mm thick (irradiated) have been tested, as have Charpy impact, tensile, and drop-weight specimens. The following observations summarize the results.

1. The scatter for unirradiated and irradiated fracture toughness results is large; statistical analyses of elastic-plastic fracture mechanics data will be required to adequately assess the relationship between fracture toughness and Charpy shifts.

2. The irradiated Charpy impact shifts are about the same as the drop-weight nil-ductility transition temperature shifts.

3. For weld 73W (0.31% Cu), the lower-bound  $K_{Ic}$  curve shift at 125 MPa $\sqrt{m}$  is about 103°C, while the Charpy 41-J shift is about 82°C.

4. For weld 73W, the lower-bound  $K_{Ic}$  curve shape changes, but in a manner similar to the change in the Charpy impact curve.

5. The evaluation of cleavage pop-ins in irradiated fracture toughness tests will be a significant aspect in the conclusions regarding  $K_{Ic}$  curve shift and shape change.

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Table 1. Comparison of radiation-induced Charpy impact and drop-weight NDT temperature shifts for 72W and 73W

Charpy impact			Drop-weight				
Fluence (n/cm <sup>2</sup> )	$\Delta T_{T30}$ (°C)	Draft RG 1.99 Rev. 2 (°C)	Actual fluence (n/cm <sup>2</sup> )	Actual $\Delta NDT$ (°C)	Draft RG 1.99 Rev. 2 (°C)	Adjusted fluence (n/cm <sup>2</sup> )	Adjusted $\Delta NDT$ (°C)
<b><u>Weld 72W, 0.23 wt % Cu, 0.60 wt % Ni</u></b>							
1.75 × 10 <sup>19</sup>	72	Primary group (291°C irradiation)					
		107	1.0 × 10 <sup>19</sup>	61	93	1.75 × 10 <sup>19</sup>	70
		Scoping group (277°C irradiation)					
			1.5 × 10 <sup>19</sup>	72	104	1.75 × 10 <sup>19</sup>	74
<b><u>Weld 73W, 0.31 wt % Cu, 0.60 wt % Ni</u></b>							
1.75 × 10 <sup>19</sup>	82	Primary group (291°C irradiation)					
		127	1.0 × 10 <sup>19</sup>	72	110	1.75 × 10 <sup>19</sup>	83 <sup>a</sup>
		Scoping group (277°C irradiation)					
			1.5 × 10 <sup>19</sup>	94	122	1.75 × 10 <sup>19</sup>	98

<sup>a</sup>Weld 73W adjustment:  $\Delta RG 1.99 (1.75 - 1.0) = 17^\circ C$   
 $(72/110) * 17 = 11^\circ C$   
 $72 + 11 = 83^\circ C$   
adjusted  $\Delta NDT = 83^\circ C$