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**INCLUSION OF UNSTABLE DUCTILE TEARING AND EXTRAPOLATED
CRACK-ARREST TOUGHNESS DATA IN PWR VESSEL
INTEGRITY ASSESSMENT**

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INCLUSION OF UNSTABLE DUCTILE TEARING AND EXTRAPOLATED CRACK-ARREST TOUGHNESS DATA IN PWR VESSEL INTEGRITY ASSESSMENT¹

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ABSTRACT

Over the past several years, the Heavy-Section Steel Technology Program at Oak Ridge National Laboratory has performed a series of large-scale fracture-mechanics experiments. These experiments have demonstrated that prototypical nuclear reactor vessel steels can exhibit crack-arrest toughness values considerably above $220 \text{ MPa}\cdot\sqrt{\text{m}}$, although arrest can be followed immediately by unstable ductile tearing. This report evaluates the influence of the crack-arrest toughness above $220 \text{ MPa}\cdot\sqrt{\text{m}}$ on the integrity assessments of nuclear reactor pressure vessels for pressurized-thermal shock (PTS) loading conditions, taking into account the potential for unstable ductile tearing following arrest.

The influence of the high crack-arrest toughness data and unstable ductile tearing on pressurized-water reactor vessel integrity assessment is PTS transient dependent. However, it appears that the potential benefit from crack-arrest events corresponding to toughness values above $240 \text{ MPa}\cdot\sqrt{\text{m}}$ for low-upper-shelf weld (LUSW) material and above $370 \text{ MPa}\cdot\sqrt{\text{m}}$ for those vessels not containing LUSW material will usually be negated by unstable ductile tearing.

INTRODUCTION

Over the last several years, the Heavy-Section Steel Technology (HSST) Program has conducted several fracture-mechanics experiments on large specimens that produced crack-arrest fracture-toughness values above $220 \text{ MPa}\cdot\sqrt{\text{m}}$, which is the limit imposed by the *American Society of Mechanical Engineers (ASME) Code* and the limit included in the Integrated Pressurized Thermal Shock (IPTS) studies [1]. It is therefore appropriate and timely to investigate the influence that these high crack-arrest data have on the integrity assessment of nuclear reactor pressure vessels.

A review of the evolution of the pressurized-thermal-shock (PTS) issue and current methods of analy-

sis provides insight into the motivation for the HSST Program performing the large-specimen fracture-mechanics experiments. During the early 1970s, it was recognized that reactor pressure vessels could be subjected to severe thermal shock as the result of a large-break loss-of-coolant accident (LBLOCA). Analyses performed at that time indicated that thermal shock alone would not result in failure (through-wall cracking) of the vessel. However, a combination of pressure and a less severe thermal shock, the result of some postulated transients, could result in vessel failure. In March 1978, such a transient occurred at the Rancho Seco nuclear power plant. As a result of these events, parametric PTS studies were undertaken [2]. These studies indicated a rather high probability of vessel failure for PTS loading conditions occurring at the end of the licensing period; as a result, in May 1981, the Nuclear Regulatory Commission (NRC) established the IPTS Program. An objective of that program was to estimate the probability of vessel failure caused by through-wall cracking. The results of the IPTS Program [3,4,5], along with risk assessments and fracture analyses performed by the NRC and reactor system vendors, led to the establishment of the NRC PTS rule (10 CFR 50.61), which includes screening criteria in the form of limiting values of the reference nil-ductility transition temperature (RT_{NDT}) of the reactor vessel [6]. The PTS rule required that plant-specific analyses be performed for any plant that is intended to operate beyond the screening criteria. In addition, *Regulatory Guide 1.154* [7] provides guidance for utilities on how to perform the plant-specific safety analyses. It references the IPTS study as an acceptable methodology for performing the probabilistic fracture-mechanics portion of the plant-specific analysis.

Fracture-toughness criteria for protection against brittle fracture (cleavage) is contained in *ASME Code* Section XI, Appendix A [8], which includes an upper limit of $220 \text{ MPa}\cdot\sqrt{\text{m}}$ for the crack-arrest toughness. The ASME imposition of the $220\text{-MPa}\cdot\sqrt{\text{m}}$ limit for crack arrest is based partly on the fact that insufficient

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data existed above this level when these curves were derived [9]. However, in recent years there have been indications that higher values exist [10]. Because of the apparent need for and the existence of high-temperature crack-arrest capability, the NRC HSST Program and others [11,12] began to investigate the effect of higher crack-arrest values on the probability of failure and to determine if these values actually exist for prototypical reactor pressure vessel materials.

The NRC studies included experiments with unusually large specimens: pressurized thermal-shock experiments [13,14] (PTSE's) with thick-walled cylinders (0.15-m wall $\times$ 1.0-m diam $\times$ 1.2-m length) and wide-plate experiments [15] (WPE's) with specimens measuring 0.1 $\times$ 1.0 $\times$ 10 m. Results of the PTSE's and WPE's indicated that crack-arrest values above 220 MPa $\sqrt{m}$ do exist.

Probabilistic evaluations of vessel failure indicated that, depending upon the actual shape of the K_{Ia} toughness curve, the higher K_{Ia} data could reduce the probability of failure for PTS loading conditions [16]. The purpose of this paper is to evaluate the influence of the high crack-arrest values on integrity assessments of nuclear reactor pressure vessels. Sensitivity studies are performed to evaluate the influence of the shape and magnitude of the K_{Ia} curve on the predicted cleavage response of a reactor vessel. Also, limiting values of K_{Ia} are established to approximate the onset of unstable ductile tearing for an irradiated low-upper-shelf weld (LUSW) material and an irradiated A 533 grade B steel base material (assumed to be applicable for any non-LUSW material). Relative to the original IPTS studies, which define vessel failure as through-wall cracking, the extended K_{Ia} curve and higher K_I limits for unstable ductile tearing could result in a reduced probability of failure and thus in a greater life expectancy of reactor vessels.

HSST K_{Ia} DATA BASE

With contributions from the large-specimen tests the HSST K_{Ia} data base (Fig. 1) now includes data from compact specimens [HSST plate 02 (A 533 grade B material)], the WP series of wide-plate tests (A 533 grade B), thermal-shock experiments (TSE's) [17] (A 508 with

class-2 chemistry), and PTSE's (A 508 with class-2 chemistry and A-387 with grade 22 chemistry). It is apparent in Fig. 1 that much of the large-specimen data extend well above 220 MPa $\sqrt{m}$ and in an exponential manner. [The wide-plate data differ somewhat from those in Ref. 15 because the data in Fig. 1 have been corrected ("adjusted") for tunneling.] In all cases, the crack propagated by cleavage to the point of arrest. For the large specimens, most of the arrest events were followed by cleavage reinitiation or unstable tearing.

SENSITIVITY STUDY OF THE INFLUENCE OF K_{Ia} CURVE SHAPE ON REACTOR PRESSURE VESSEL CLEAVAGE FRACTURE RESPONSE

Analyses were performed to determine the influence of the steepness of the K_{Ia} toughness curve on the cleavage fracture response of a nuclear reactor vessel subjected to a PTS transient. The analyses were performed using OCA-P [18], a program developed at Oak Ridge National Laboratory (ORNL) specifically for simulating the cleavage fracture response of a reactor pressure vessel subjected to a PTS event. The program is based on linear elastic fracture-mechanics (LEFM) theory and is capable of performing both deterministic and probabilistic fracture-mechanics analyses.

The ASME lower-bound K_{Ia} curve (also known as the K_{IR} curve) and two steeper curves are shown in Fig. 2. The steeper K_{Ia} curves are generated by modifying the K_{IR} curve as follows:

$$K_{Ia} = 29.5 + 1.344 \times \exp [0.0261 \times \text{SAF} \times (T - RT_{NDT} + 89)] , \quad (1)$$

where SAF is slope amplification factor and T and RT_{NDT} are in $^{\circ}\text{C}$.

SAF = 1.1 represents a reasonable increase in the lower-bound K_{Ia} curve, for $K_{Ia} > 220 \text{ MPa}\sqrt{m}$, as indicated by the large-specimen high-temperature crack-arrest data. A value of 1.2 was added for the purpose of conducting the sensitivity study.

OCA-P was used to perform deterministic fracture-mechanics analyses of the Rancho Seco PTS transient,

Fig. 1. Combined large- and small-specimen HSST crack-arrest data base.

using each of the three K_{Ia} curves illustrated in Fig. 2. The Rancho Seco transient was chosen because it is reasonably typical of postulated PTS transients. The results are presented in the form of critical-crack-depth plots, the concept of which is described briefly below.

Fig. 2. $K_{Ia} = 29.5 + 1.344 \times \exp [0.261 \times \text{SAF} \times (T - RT_{NDT} + 89)]$.

The temperature, resultant circumferential stress, mode I stress-intensity factor, fracture-toughness, and fluence distribution through the wall of the vessel at a particular time during a transient are shown in Fig. 3. The intersection(s) of the K_I and K_{Ic} curves ($K_I = K_{Ic}$) define the critical crack depth(s) for initiation. Similarly, the intersection of the K_I and K_{Ia} curves ($K_I = K_{Ia}$) define critical-crack depth for arrest of a running crack. A critical-crack-depth initiation curve is the locus of all such points through time for $K_I = K_{Ic}$ (Fig. 4). Similarly, a critical-crack-depth arrest curve is the locus of all such points through time for $K_I = K_{Ia}$. As indicated by the dashed line in Fig. 4, the flaw would propagate in a series of initiation-arrest events; but for times greater than those corresponding to the incipient warm-prestress (WPS) curve ($K_I = 0$), reinitiation would not take place because $K_I < 0$ [13, 14, 17, 19]. Thus, a set of critical-crack-depth curves predicts the cleavage fracture response of a flaw during the entire transient.

The pressure and thermal transients for Rancho Seco² are shown in Fig. 5 [from Ref. 18], and the corresponding critical-crack-depth curves are shown in Fig. 6. These critical-crack-depth curves were generated using the ASME lower-bound-toughness curves for both K_{Ia} and K_{Ic} ; a fast neutron fluence ($E > 1.0$ MeV) of 1.5×10^{19} neutrons/cm², which corresponds to 32 EFPY, and copper and nickel concentrations of 0.35 and 0.65%, respectively [18]; and two-dimensional, axially oriented surface flaws. The K_{Ia} curve was not terminated at the 220 MPa√m cutoff but was extrapolated using the ASME equation. The definition of "cleavage initiation window" is illustrated in Fig. 6 to be the

²The pressure transient is reasonably accurate, but the thermal transient is an approximation of the fluid temperature in the downcomer for the actual Rancho Seco transient.

Fig. 3. Fracture-related parameters in RPV wall at given time during PTS transient.

Fig. 4. Critical-crack-depth curves defined by plotting locus of crack-initiation and crack-arrest values as function of time during PTS transient.

time period and the range of crack depths for which a cleavage crack initiation can occur. The cleavage initiation window is a function of the WPS line (transient dependent), the K_{Ic} curve, and the value of RT_{NDT} (the greater RT_{NDT} , the larger the window). For this particular case, no part of the initiation window is "covered" by the critical-crack-depth arrest curve; therefore, any crack initiation occurring in the "initiation window" would propagate through the wall

Fig. 5. Pressure and temperature time histories based on idealization of Rancho Seco transient.

Fig. 6. Cleavage initiation window with range of times and corresponding flaw depths in which cleavage initiation can occur.

(as indicated by the vertical dashed line), resulting in vessel failure caused by cleavage followed by plastic instability.

The critical-crack-depth arrest curves corresponding to the steeper K_{Ia} curves (Fig. 2) are illustrated in Fig. 7. As indicated, the critical-crack-depth arrest curves corresponding to the steeper K_{Ia} curves are shifted to a later time on the transient-time axis. The result of the shift is to "cover" the initiation window. For the particular cases shown ($SAF = 1.1$ and 1.2), the cleavage initiation window has been completely covered; therefore, any cleavage propagation would be arrested below the ligament-instability curve. As illustrated in Fig. 7, for $SAF = 1.1$, a propagating crack would be arrested between $a/w = 0.37$ and 0.56 ; for $SAF = 1.2$, a propagating crack would be arrested between $a/w = 0.23$ and 0.34 . The ligament-instability curve represents the crack depth at which the remaining ligament is insufficient to prevent tensile failure;

therefore, crack arrest must occur below this depth to be stable.

The time shift in the critical-crack-depth arrest curve associated with increased values of SAF occurs because more time is required for K_{Ia} to decrease, as a result of decreasing temperature, to the value of K_I . Also, as is apparent in Fig. 7, the slope of the critical-crack-depth arrest curve is less for larger values of SAF because, for deeper crack depths, more time is required to reduce the temperature.

It can be concluded that the steeper K_{Ia} curves defined in Fig. 2 increase the probability of crack arrest and therefore decrease the probability of vessel failure caused by cleavage for some PTS transients. The above analysis indicates that arrest can take place at high values of K_I . However, as will be examined later, it is possible that unstable ductile tearing could lead to failure immediately following the cleavage arrest event.

Fig. 7. Steeper K_{Ia} curves showing enhanced ability of critical-crack-depth arrest curve to "cover" cleavage initiation window.

EXTENSION OF THE K_{Ia} CURVE ABOVE 220 MPa $\sqrt{m}$

In Fig. 8, the HSST K_{Ia} data base is compared with the ASME lower-bound K_{Ia} (K_{IR}) curve and two extrapolations thereof above 220 MPa $\sqrt{m}$. One extrapolation was obtained using the ASME K_{Ia} vs $(T - RT_{NDT})$ equation and the other using a straight line that represents a more appropriate lower bound of the data. To evaluate the effect of the steeper lower-bound K_{Ia} curve on the cleavage fracture behavior (relative to the use of the K_{Ia} curve with SAF = 1.0, Fig. 2), a deterministic fracture-mechanics analysis, similar to those described

previously, was performed using the following criteria:

$$K_{Ia} = K_{IR} \text{ (ASME equation)}$$

$$\text{for } K_{Ia} < 220 \text{ MPa}\sqrt{m},$$

$$= 15.0 \times (T - RT_{NDT}) - 1300.0$$

$$\text{for } K_{Ia} > 220 \text{ MPa}\sqrt{m}. \quad (2)$$

The corresponding critical-crack-depth curves are shown in Fig. 9. As indicated, use of the linear extension increases the chances of crack arrest (reduces the range of flaw depths that can result in

Fig. 8. HSST K_{Ia} data base, suggesting a linear extension of the K_{IR} curve.

Fig. 9. K_{Ia} linear extrapolation showing reduction of range of flaw depths that can result in failure.

failure) and therefore decreases the probability of vessel failure. The extent to which it decreases the probability of failure depends on the flaw-size distribution function because in this case only a portion of the cleavage initiation window is covered.

DUCTILE TEARING CONSIDERATIONS

As discussed earlier, another possible mode of vessel failure is unstable ductile tearing, and it must be considered before making the generalization that enhanced cleavage crack-arrest potential decreases the probability of failure. It is possible that the onset of unstable ductile tearing could negate the benefit of the enhanced crack-arrest potential. The large-specimen K_{Ia} tests demonstrates that a crack can run and arrest in a cleavage mode at K_I values that are greater than those corresponding to the onset of ductile tearing under static conditions. However, immediately following arrest, unstable ductile tearing leads to failure. As a specific example, during PTSE-2B, arrest took place at $K_I = 419 \text{ MPa}\cdot\sqrt{\text{m}}$ and was followed immediately by unstable ductile tearing [14].

To determine if unstable ductile tearing negates the enhanced crack-arrest potential, a curve was generated on the critical-crack-depth plot that approximates the onset of unstable ductile tearing, that is, the crack depth beyond which ductile tearing becomes unstable. The associated critical-crack depths correspond to the point of tangency between the tearing-resistance (J_R) and applied-load (J_{applied}) curves, in which case the point of tangency represents the initial flaw-depth value plus extension due to tearing up to the point of instability [20].

Currently, there is a lack of consensus on which tearing-resistance parameter (J_D or J_M) more accurately characterizes material crack extension [21-23]. The value of the J-integral, originally developed for a deformation plasticity material [24], is identified with the subscript D to emphasize its relation to deformation plasticity. The J_D formulation is used in ASTM E1152-87. A modified J-integral parameter, J_M , was introduced by Ernst [25] in an attempt to eliminate size effects and/or negative slopes that develop in some J_D -based tearing-resistance curves.

In addition to the choice of tearing-resistance parameter, the methodology for extending laboratory-

obtained tearing-resistance data (based on either J_M or J_D) to crack extension on the order of tens of millimeters is still an open issue. Because this study is concerned with the relative influence of unstable ductile tearing on enhanced crack-arrest prediction, these crack extension issues will not be pursued here. The J_R curves employed in this study are based on J_M and are assumed to be a material property. Extrapolation of crack growth data is accomplished via a power-law fit of laboratory data as outlined below.

An unstable-tearing curve was generated for a high-copper LUSW material irradiated to a fluence of 1.5×10^{19} neutrons/cm² [Ref. 26]. The J_R curve (Fig. 10) is very flat, and the assumption is made that the point of tangency between the J_R curve and any J_{applied} curve is constant and equal to 275 KJ/m^2 . This is equivalent to $K = 242 \text{ MPa}\cdot\sqrt{\text{m}}$ (assuming a value of 191.3 GPa for Young's modulus and 0.3 for Poisson's ratio); therefore, the approximate onset of unstable tearing in this LUSW material is considered to occur at $K_I = 240 \text{ MPa}\cdot\sqrt{\text{m}}$. Graphically, this can be considered as the $K = 240 \text{ MPa}\cdot\sqrt{\text{m}}$ isocline in the critical-crack-depth plot.

J_R curves for irradiated (average fluence = 1.77×10^{19} neutrons/cm²) A 533 grade B steel are shown in Figs. 11 and 12 [Ref. 27]. Three J_R curves and

Fig. 10. J_R curve showing the asymptotic J_M value used to estimate onset of unstable ductile tearing for LUSW material.

their average are shown in Figs. 11 and 12, corresponding to temperatures of 288 and 121°C, respectively. Each curve is a power-law curve fit of experimental data of the form

$$J_R = C \times \Delta^n, \quad (3)$$

where C and n are the coefficient and exponent, respectively, derived from the curve fit.

The J_{Applied} values for this study were obtained by converting K_I to J using the plane-strain transformation

$$J_{\text{Applied}} = (K_I^2) (1 - \nu^2)/E. \quad (4)$$

The K_I values were calculated making a correction for the plastic zone size.

A graphical solution was used to find the point of tangency between the J_{Applied} and J_R curves. An example in Fig. 13 shows the point of tangency between

Fig. 11. J_R curves for irradiated A 533 grade B class 1 steel at temperature of 288°C.

Fig. 12. J_R curves for irradiated A 533 grade B class 1 steel at temperature of 121°C.

Fig. 13. Point of tangency defining initial crack depth and crack extension that approximates onset of unstable ductile tearing.

the J_{Applied} curve at time = 3000 s for the Rancho Seco PTS event and the average J_R curve for a temperature of 288°C. The point of tangency defines the initial crack depth ($a_0 = 88$ mm) and the crack extension ($\Delta = 15$ mm) that approximates the onset of unstable ductile tearing. Points of tangency are obtained for various times throughout the transient to obtain a locus of points on the critical-crack-depth plot corresponding to the onset of unstable ductile tearing.

For each time examined for the average J_R curve, corresponding to a temperature of 288°C, the value of a_0 (initial crack depth) varied while the value of Δ (crack extension) and J remained approximately constant at 15 mm and 633 KJ/m², respectively. For each time examined for the average J_R curve corresponding to a temperature of 121°C, the value of a_0 varied, while crack extension and J remained approximately constant at 12 mm and 750 KJ/m².

The onset of unstable ductile tearing using the above methodology was found to be ~ 370 MPa $\cdot\sqrt{m}$, using the average J_R curve for 288°C, and 400 MPa $\cdot\sqrt{m}$, using the average J_R curve for 121°C. This range of temperatures is consistent with those encountered in the Rancho Seco PTS transient; therefore, the $K_{Ic} = 370$ MPa $\cdot\sqrt{m}$ isocline is a reasonable lower-bound curve to approximate the onset of unstable ductile tearing for the vessel assumed in the Rancho Seco transient, that is, A 533 grade B steel irradiated to a fluence of 1.5×10^{19} neutrons/cm² with a chemistry of 0.35% copper and 0.65% nickel.

The analysis could be refined by including the effects of temperature dependence on J_R . This would effectively increase the range of crack depths for the case in which the enhanced crack-arrest potential decreases the probability of failure.

THE INFLUENCE OF THE INCLUSION OF UNSTABLE DUCTILE TEARING CURVES ON THE BENEFIT OF THE ENHANCED CRACK-ARREST TOUGHNESS DATA

By way of illustration, the onset of unstable ductile tearing curves is included (Fig. 14) for the Rancho Seco transient evaluation described previously. In this case, the enhanced crack-arrest potential is negated by unstable ductile tearing. It is apparent

Fig. 14. Negation of enhanced crack-arrest potential by onset of unstable ductile tearing.

that crack arrest for some range of crack depths will take place, but in each case the arrest will be followed immediately by unstable ductile tearing to failure. For another range of flaw depths, no crack arrest takes place, resulting in failure by cleavage.

In general, the relative position of the critical-crack-depth arrest curve and the unstable ductile tearing curve are transient dependent. For instance, for a lower-pressure transient, the critical-crack-depth arrest curve could cover the cleavage initiation window at flaw depths less than those corresponding to the onset of the unstable ductile tearing curve.

APPLICATION OF HIGH-TOUGHNESS CRACK-ARREST DATA TO IPTS

In the IPTS study, a mean K_{Ia} curve of $1.25 \times K_{IR}$ was used, and the onset of unstable ductile tearing was considered to be $220 \text{ MPa}\sqrt{m}$ [1]. The mean curve deduced from the combined large- and small-specimen HSST data base (Fig. 15) is $1.25 \times K_{IR}$ with $\text{SAF} = 1.05$;

thus, in general, there would be a greater chance of crack arrest using the high K_{Ia} data. However, as illustrated by the Rancho Seco analysis discussed previously, inclusion of unstable ductile tearing, even for the A 533 grade B steel (non-LUSW material), can result in failure following arrest for high-pressure transients. Thus, there may not be a significant advantage associated with the higher crack-arrest toughness data for high-pressure transients.

SUMMARY

Application of the high crack-arrest toughness data (above the ASME $220\text{-MPa}\sqrt{m}$ cutoff) and the unstable ductile tearing data for reactor pressure vessel steels to the IPTS-type studies has the potential for decreasing the calculated probability of vessel failure relative to values calculated in the original IPTS study. The benefit is more likely to exist for low-pressure transients than for high-pressure transients,

Fig. 15. Similarity between statistical mean curve for combined HSST large- and small-specimen data base and that for IPTS mean with $\text{SAF} = 1.05$.

and the benefit will be dependent on the flaw-size distribution function. It is apparent that sufficient large-specimen crack-arrest data presently exist to conduct this evaluation; therefore, it does not seem appropriate at this time to conduct additional large-specimen crack-arrest tests.

The influence of the high crack-arrest-toughness data and unstable ductile tearing on pressurized-water reactor vessel integrity assessment is PTS transient dependent. However, it appears that the potential benefit from crack-arrest events corresponding to toughness values above $240 \text{ MPa}\cdot\sqrt{\text{m}}$ for LUSW material and above $370 \text{ MPa}\cdot\sqrt{\text{m}}$ for those vessels not containing LUSW material will usually be negated by unstable ductile tearing.

It is difficult to draw final conclusions regarding the effect of the high crack-arrest toughness data ($K_{Ia} > 220 \text{ MPa}\cdot\sqrt{\text{m}}$) on the conditional probability of failure until probabilistic fracture mechanics analyses have been performed that will consider a variety of postulated transients.

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