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FRACTURE MECHANICS ASSESSMENT OF PWR VESSEL INTEGRITY INCORPORATING DYNAMIC CRACK ARREST DATA ABOVE 220 MPa√m

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ABSTRACT

The HSST Program at Oak Ridge National Laboratory has performed a series of large-scale fracture mechanics experiments to obtain crack arrest (K_{Ia}) data above 220 MPa$\sqrt{m}$, the implicit limit of the ASME Code and the limit used in the Integrated Pressurized Thermal Shock (IPTS) studies. Probabilistic fracture mechanics analyses were performed to examine the influence of the enhanced K_{Ia} data on the conditional probability of reactor pressure vessel failure.

1 INTRODUCTION

The present rules and criteria regarding the PTS issue, as established by the US Nuclear Regulatory Commission (NRC), are the PTS rule [Code of Federal Regulations, 1985] and Nuclear Regulatory Guide 1.154 [Regulatory Guide 1.154, 1987]. The PTS rule specifies screening criteria in the form of limiting values of reference nil ductility temperature (RT_{NDT}) of the reactor pressure vessel. Also, the PTS rule requires that a plant specific safety analysis must be performed for any plant that a utility seeks to operate beyond the screening criteria. Nuclear Regulatory Guide 1.154 provides guidance for utilities on how to perform the plant specific analysis. It references the IPTS study [Cheverton et al. 1985, 1986] as an acceptable methodology for performing the probabilistic fracture mechanics portion of the plant specific analysis and specifies that the frequency of vessel failure due to PTS shall not exceed 5 x 10^{-6} failures per reactor year.

Since the IPTS Program was completed, the Heavy Section Steel Technology (HSST) Program has conducted several large specimen fracture mechanics experiments [Cheverton et al. 1985; Bryan et al. 1987; Naus et al. 1989] which demonstrated that prototypical reactor pressure vessel steels are capable of arresting a crack propagating in the cleavage mode at fracture toughness values considerably above 220 MPa$\sqrt{m}$, the implicit limit of the American Society of Mechanical Engineers (ASME) Code [ASME Code, 1986] and the maximum value included in the IPTS studies. The purpose of this paper is to investigate the potential impact of the enhanced crack arrest data on the results of probabilistic fracture mechanics analyses.

2 PROBABILISTIC CONSIDERATIONS

A probabilistic approach to the PTS issue, as developed in the IPTS studies and as required for compliance with Regulatory Guide 1.154, includes (1) the postulation of PTS transients, (2) an estimation of their frequency of occurrence, (3) a systems analysis to determine the primary-system pressure, downcomer-coolant temperature and fluid-film heat-transfer coefficient on the inner surface of the vessel, and (4) a probabilistic fracture mechanics (PFM) analysis that uses the information from Item 3 as input. The PFM analysis provides an estimate of the conditional probability of failure, P(F|E), for each postulated transient. This is multiplied by the frequency of occurrence of the corresponding transient, $\phi(E)$, and the product summed over all postulated transients to obtain the total frequency of failure, $\phi(F)$, for a specific plant:

$$\phi(F) = \sum_n \phi_n(E)\, P_n(F|E)$$

where:

$\phi(F)$ = Total frequency of failure (failures per reactor year) for a specific plant
$\phi_n(E)$ = Frequency of occurrence of the nth postulated transient (transients per year)
$P_n(F|E)$ = Conditional probability of failure of the n^{th} postulated transient (failures per transient), i.e., the probability of failure assuming that the transient does occur.

The individual products of $\phi_n(E)\, P_n\, (F|E)$ define the order of dominance, i.e., they indicate the extent to which a particular transient contributes to the total frequency of failure for a specific plant. In the IPTS studies, it was determined that a distinguishing characteristic of the dominant transients was high pressure.

Thus for the enhanced crack arrest data to significantly impact the total frequency of failure, it must reduce the conditional probability of failure for high pressure transients. The Rancho Seco transient, (Fig. 1), which is a typical severe high-pressure transient, was chosen for evaluating the potential impact of the enhanced crack arrest data on the conditional probability of failure.

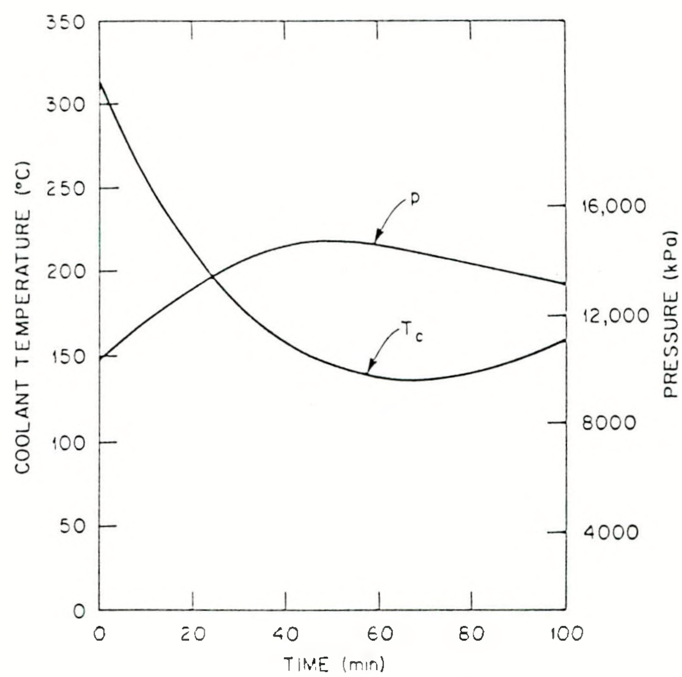

Fig.1 Pressure and temperature histories based on idealization of Rancho Seco transient.

3 EFFECT OF ENHANCED K_{Ia} DATA ON PROBABILISTIC FRACTURE MECHANICS (PFM) ANALYSES

To evaluate the effect of the enhanced crack arrest toughness data on P(F|E), PFM analyses were performed for the Rancho Seco transient using OCA-P [Cheverton et al. 1984], applying the three mean K_{Ia} curves illustrated in Fig. 2.

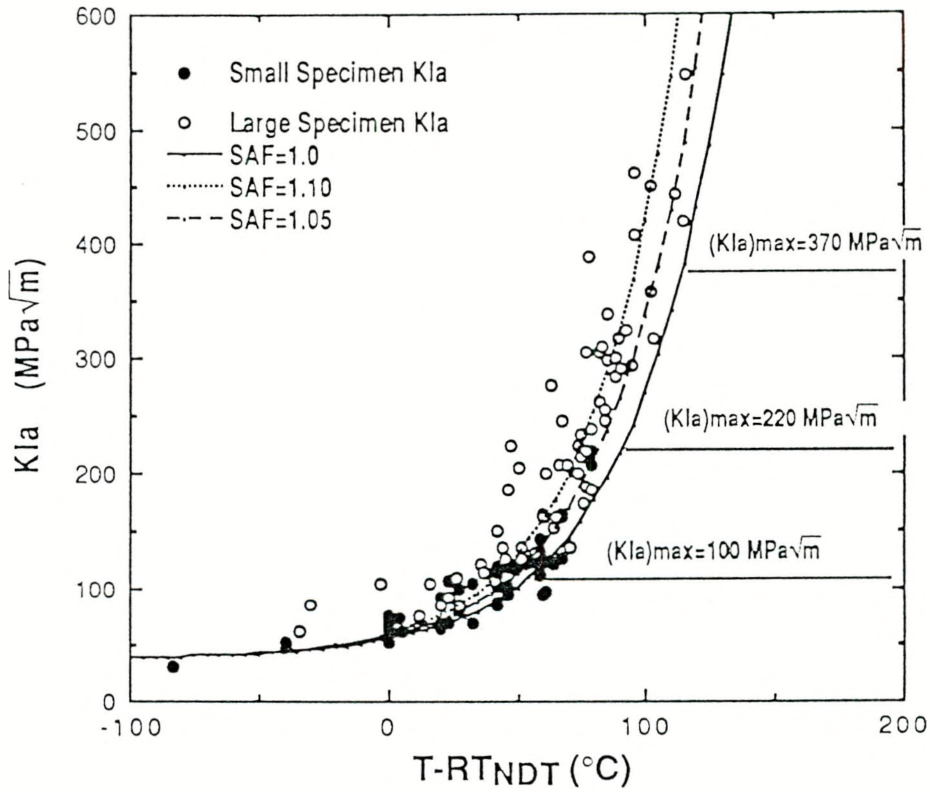

Fig.2 Combined HSST large and small specimen K_{Ia} database.

These K_{Ia} curves are represented by the following relationship:

$$(K_{Ia})\ mean = 1.25*\{29.5 + 1.344*\exp\ [SAF*\ 0.0261*\ (T\text{-}RT_{NDT} + 89)]\}$$

where

T = Temperature (C)
K_{Ia} = Crack arrest toughness (MPa√m)
SAF = Slope Amplication Factor

A value of SAF = 1.0 corresponds to the same curve which was utilized in the IPTS studies, i.e., a factor of 1.25 times the ASME lower bound K_{Ia} curve. The K_{Ia} mean curve corresponding to SAF = 1.05 is a more appropriate curve for the combined HSST large and small-specimen K_{Ia} database; the K_{Ia} mean curve corresponding to SAF = 1.10 was included for sensitivity purposes.

If the crack arrest K_I value is high enough, there is the possibility of unstable ductile tearing to failure immediately following the cleavage arrest event. Because the tearing resistance will be different for different vessels (high and low upper shelf weld material, for instance) the sensitivity study included (K_{Ia}) max values corresponding to the onset of unstable ductile tearing of 100, 220, 370, and 1000 MPa√m, i.e., no crack arrest was allowed to occur above these values. The value of 370 MPa√m was derived in an earlier HSST study [Dickson et al. 1990] as an approximation for the onset of unstable ductile tearing for a vessel that did not contain low-upper-shelf weld material. The value of 1000 is certainly not considered realistic; however, it was included in the analyses for sensitivity purposes.

Each of the PFM analyses was performed for 210,000 vessels assuming a mean-value fast neutron fluence of 1.5 x 10^{19} neutrons/cm^2 (E > 1.0 MeV) and mean-value copper and nickel concentrations of 0.35% and 0.65%, respectively; two-dimensional, axially oriented surface flaws were also assumed. The probabilistic distribution parameters were identical to those used in the IPTS studies and are the default values recommended in OCA-P.

The results of these PFM analyses are illustrated in Fig. 3–5. A stable crack arrest is defined as a crack arrest that (1) occurs at a K_I value less than that corresponding to the onset of unstable ductile tearing and (2) is not followed by a cleavage reinitiation, i.e., it is a terminating event. Figure 3 illustrates that the total number of crack arrests varies with the increasing values of

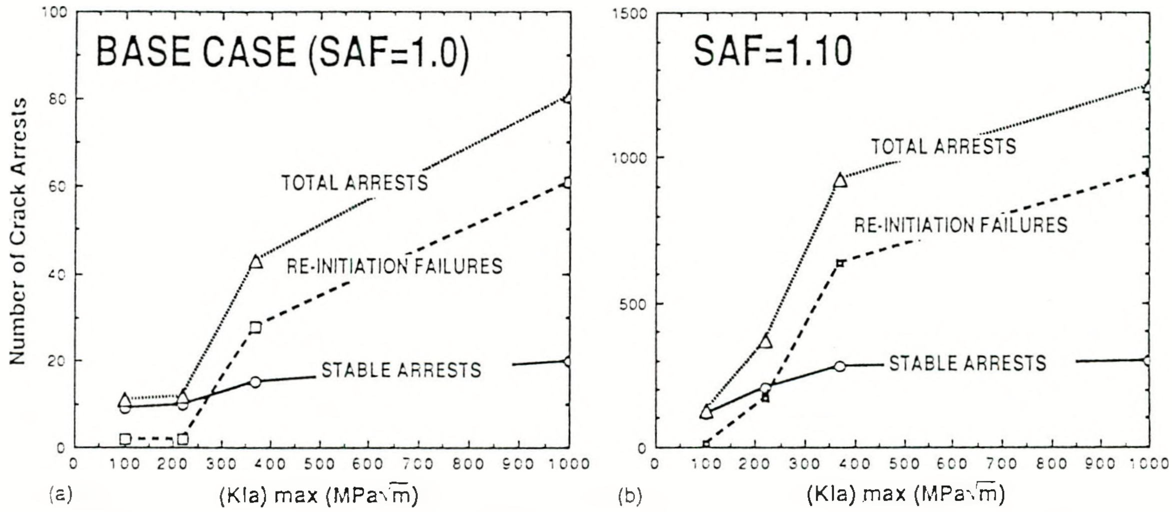

Fig. 3 Number of crack arrests as a function of (K_{Ia}) max: (a) SAF = 1.0; (b) SAF = 1.1.

steepness (SAF) and onset of tearing instability (K_{Ia}) max. The total number of crack arrests increases more than the number of stable crack arrests. This is due to the fact that a large percentage of total crack arrests are followed by cleavage reinitiation(s) leading to failure.

Figure 4 shows that the steeper K_{Ia} curves and higher upper-shelf limits do decrease P(F|E), although the decrease is essentially insignificant. Even for the most extreme case of enhancement (SAF = 1.10 and (K_{Ia}) max = 1000), the P(F|E) is reduced by less than 0.2% relative to the IPTS base case (SAF = 1.0 and (K_{Ia}) max = 220 MPa$\sqrt{m}$).

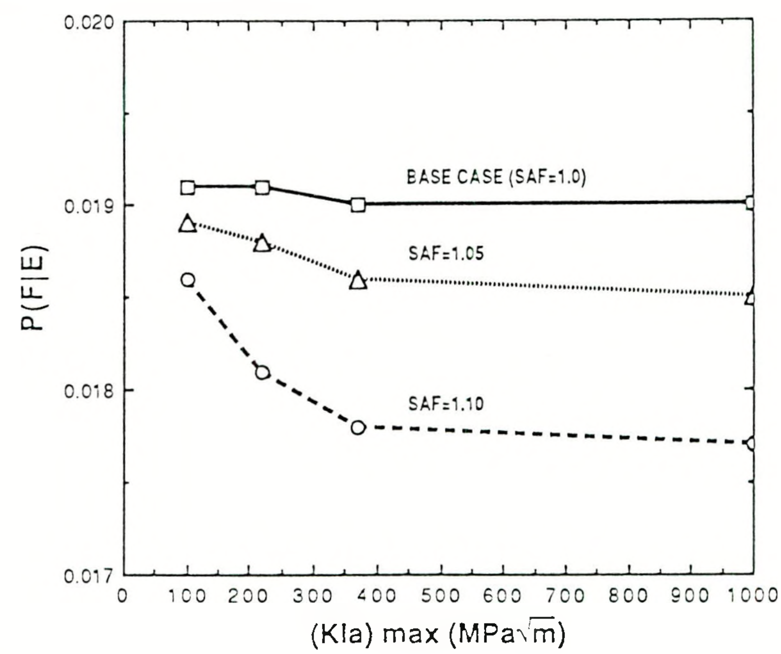

Fig.4 Conditional probability of failure as a function of (K_{Ia}) max and SAF.

The inhibiting effect of Type I warm-prestressing (WPS) i.e., cleavage fracture cannot initiate (or reintiate) when $\dot{K}_I < 0$, was not included in the above analyses. Figure 5 shows that the impact of the enhanced crack arrest data would have a more pronounced effect on P(F|E) if the inhibiting effect of Type I WPS was included in the model, since many of the reinitiation failures were predicted to occur after WPS became effective (~42 min into the transient).

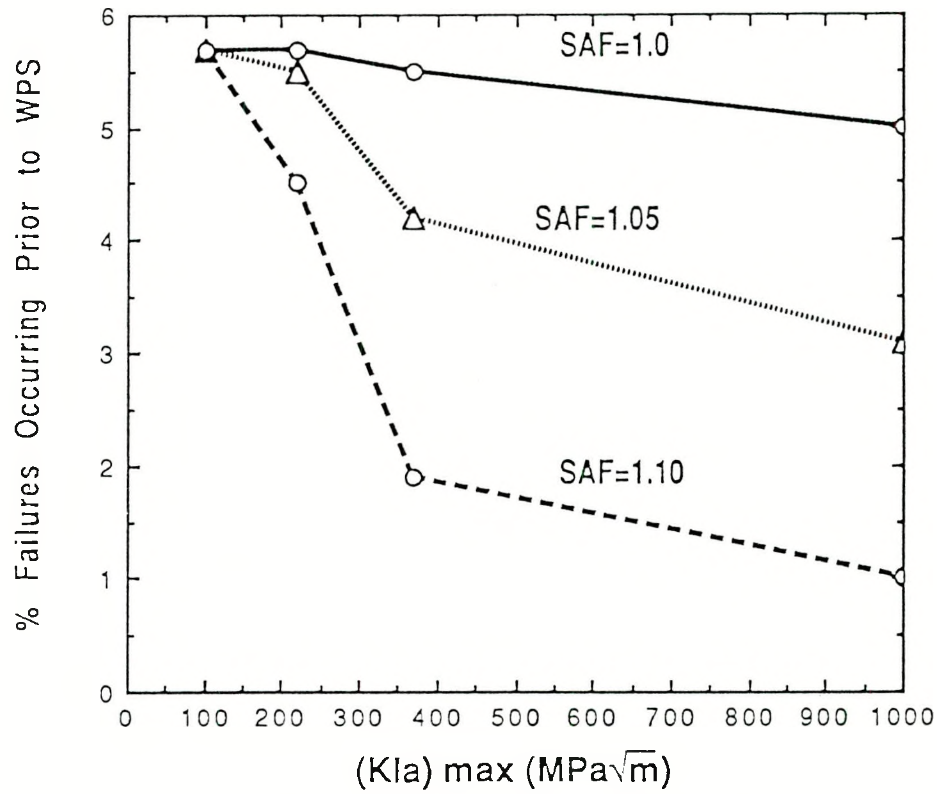

Fig. 5 Percentage of failures occurring prior to warm-prestressing (WPS) as a function of (K_{Ia}) max and SAF.

4 CONCLUSIONS

Probabilistic fracture mechanics analyses have demonstrated that the inclusion of the K_{Ia} values above the ASME limit of 220 MPa√m reduces the calculated conditional probability of failure P(F|E), but not by a significant margin for high-pressure (dominant) transients. The benefit of the enhanced K_{Ia} data is more significant when the inhibiting effect of Type I WPS is included in the model.

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