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WARM PRESTRESS EFFECTS IN FRACTURE-MARGIN ASSESSMENT OF PWR-RPVs*

D.K.M. Shum

Heavy-Section Steel Technology Program, Oak Ridge National Laboratory, Oak Ridge, TN 37831-8056, USA

ABSTRACT

This paper examines various issues that would impact the incorporation of warm prestress (WPS) effects in the fracture-margin assessment of reactor pressure vessels (RPVs). By way of an example problem, possible beneficial effects of including type-I WPS in the assessment of an RPV subjected to a small break loss of coolant accident are described. In addition, the need to consider possible loss of constraint effects when interpreting available small specimen WPS-enhanced fracture toughness data is demonstrated through two- and three-dimensional local crack-tip field analyses of a compact tension specimen. Finally, a hybrid correlative-predictive model of WPS based on J-Q theory and the Ritchie-Knott-Rice model is applied to a small scale yielding boundary layer formulation to investigate near crack-tip fields under varying degrees of loading and unloading.

1 INTRODUCTION

The primary characteristics of warm prestress (WPS) are (1) crack initiation does not take place while the crack-tip is being unloaded, even if the crack-tip stress intensity factor (K) is decreasing such that the current value of K becomes greater than the fracture toughness (K_{Ic}) for monotonically increasing loads (type-I WPS); and (2) there is an apparent increase in fracture toughness upon reload as a result of prior loading (above K_{Ic} for the crack-initiation temperature) at a higher temperature (type-II and type-III WPS). To quantify the potentially beneficial effects of WPS on the fracture-margin assessment of pressurized-water reactor (PWR) reactor pressure vessels (RPVs) (Shum 1993), it is necessary to determine both the magnitude of the crack-driving force and the appropriate value of fracture toughness associated with a WPS scenario. In previous studies pertaining to the pressurized-thermal-shock (PTS) issue (Cheverton et al. 1985), the benefit of type-I WPS was evaluated using linear elastic fracture mechanics (LEFM). Since then, it has been demonstrated (Keeney-Walker et al. 1991 and Shum et al. 1993) that inclusion of plasticity in the cladding substantially decreases K_I (or J) for cases of special interest, and this indicates that the calculated benefit of type-I WPS might also be different for the more realistic model (elastic/plastic vs LEFM). With respect to fracture toughness, the question that needs to be addressed is to what extent can WPS history effects on the propensity for crack initiation be correlated with changes in crack-tip constraint? The pursuit of an answer requires inclusion of plasticity in the model because crack-tip constraint effects are dependent on the near-tip, elastic-plastic crack-tip fields. This paper

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summarizes some of the findings from an analytical investigation that seeks to address the crack-driving force and fracture-toughness issues under WPS loading conditions.

2 EXAMPLE OF TYPE-I WPS EFFECTS IN PWR-RPV APPLICATIONS

Currently, estimates of the conditional probability of vessel failure $[P(F|E)]$ due to PTS loading, as the vessel accumulates radiation damage over the operating life of the vessel, are performed using computer codes such as FAVOR and VISA-II (Dickson 1993 and Simonen et al. 1986). These codes assume that both the crack-driving force and fracture-toughness can be adequately characterized by K in the context of a linear-elastic fracture mechanics (LEFM) framework. In the application of these codes to the PTS issue, in accordance with Regulatory Guide 1.154 (U. S. Nuclear Regulatory Commission 1987), WPS is not accounted for. By way of an example problem, this paper illustrates the possible beneficial effect of type-I WPS and to what extent the effect is dependent on the type of model (LEFM or EPFM). The PTS transient used for this study pertains to a PWR small-break, loss-of-coolant accident without repressurization. The vessel had typical dimensions and an axially oriented inner-surface flaw with a depth of 10 mm [see Shum (1993) for further details]. Because of the complex interactions among analysis variables such as vessel and flaw geometries, material properties and transient conditions, the results to be presented are necessarily specific to the conditions examined. Nevertheless, it is believed that these results do reveal a conservative element in the current RPV fracture-margin assessment methodologies that can be quantified in a straightforward manner for other vessel and transient combinations.

2.1 Deterministic Analysis Results

The first step in the study was a set of deterministic analyses that considered both linear-elastic and elastic-plastic material response. The vessel was assumed to be made of either base-material only (cladding assigned A533B properties) or both stainless steel (SS) and A533B. The four combinations of analysis conditions examined are as follows: (1) el,base = LEFM, A533B only; (2) ep,base = EPFM, A533B only; (3) el,bi = LEFM, SS, and A533B; (4) ep,bi = EPFM, SS, and A533B.

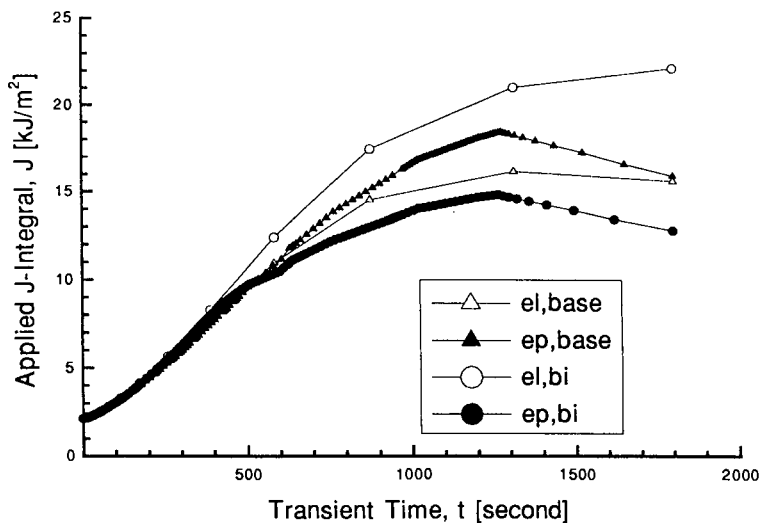


Fig. 1. Effects of analysis assumptions on J as a function of transient time.

Evolution of the crack-driving force (J) as a function of transient time is indicated for the four sets of analysis conditions in Fig. 1. As indicated, the type of analysis currently employed by FAVOR and VISA-II (namely [el, bi]) evidently results in the most conservative (largest) prediction of J among the four cases examined, whereas the more physically accurate (namely [ep, bi]) analysis method results in the lowest J values. Specifically, for all times during the postulated transient, $J_{el,bi} \geq J_{ep,bi}$. These results indicate, as mentioned earlier (Cheverton et al. 1985), that inclusion

of plasticity in the model will decrease the calculated value of $P(FIE)$, and they also indicate that the calculated benefit of type-I WPS may be dependent on which model is used (LEFM or EPFM). To explore the latter possibility in a quantitative manner, values of $P(FIE)$ were calculated using both models.

2.2 Probabilistic Analysis Results

These analyses were carried out by incorporating the J-reduction observed in the deterministic analyses (Fig. 1) into FAVOR. The outcome from these analyses are indicated in Fig. 2 in the form of predicted value of $P(FIE)$ as a function of inside-surface fluence. Results indicate that (1) invoking type-I WPS using either LEFM or EPFM models can significantly reduce $P(FIE)$; (2) the calculated benefit of type-I WPS in terms of percent reduction in $P(FIE)$ is about the same for both models (LEFM and EPFM); (3) inclusion of clad yielding effects on J *without* further invoking type-I WPS reduces $P(FIE)$ by roughly the same amount; and (4) the beneficial effects of including clad yielding and type-I WPS are additive.

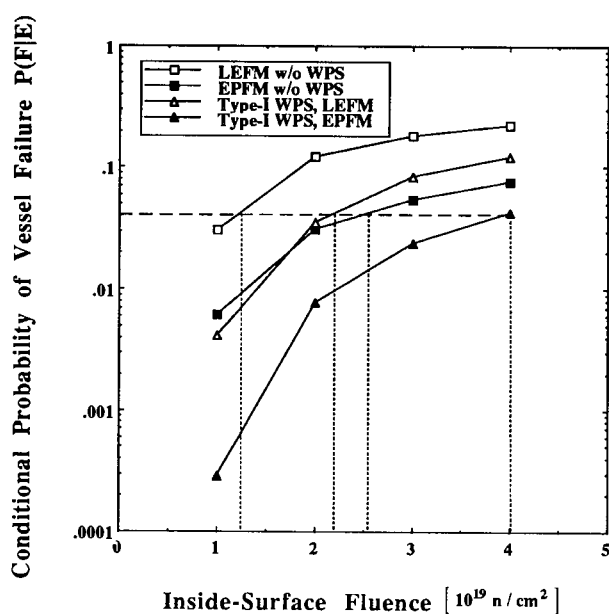


Fig. 2. Effects of clad yielding and type-I WPS on $P(FIE)$.

When compared with limits of acceptable vessel-failure probabilities, results in Fig. 2 provide an estimation of the residual life of an RPV. As an *illustrative* example, consider the "high" fluence range of 2 to $4 \times 10^{19} \text{ n/cm}^2$, which is representative of the embrittlement conditions of some PWR-RPVs at the end of original license period (32 EFPYs). For definiteness, an increment in fluence of 10^{19} n/cm^2 is identified with an increment of ~ 10 effective-full-power-years (EFPYs). It is further assumed that the acceptable value of $P(FIE)$ corresponding to the event frequency of the SBLOCA is ~ 0.04 . The predicted *increase* in permissible fluence or EFPY due to considering clad yielding effects and type-I WPS separately and together is indicated in Fig. 2 by the vertical dotted lines. Specifically, (1) invoking type-I WPS within a LEFM framework would permit ~ 10 additional EFPYs, (2) inclusion of clad yielding effects on J *without* further invoking type-I WPS would permit ~ 13 additional EFPYs, (3) inclusion of clad yielding effects on J *and* invoking type-I WPS would permit ~ 28 additional EFPYs. Results in Fig. 2 also indicate that, over the fluence range $> 1.7 \times 10^{19} \text{ n/cm}^2$, incorporation of clad yielding effects (with or without invoking type-I WPS) provides a greater increase in fracture-margin than a LEFM framework that invokes type-I WPS effects.

3 INTERPRETATION OF SMALL-SPECIMEN WPS-ENHANCED TOUGHNESS

A framework for interpreting available small-specimen WPS-enhanced fracture-toughness data is needed to provide a basis for determining the limits of transferability of small-specimen data to vessel applications. The conventional approach assumes that both the crack-driving force and the WPS-enhanced fracture toughness in small-scale specimens can be adequately characterized by single-parameter (K- or J-only) methods. In the context of J-Q theory, the assumption of single-parameter dominance of crack-tip fields is associated with a crack-tip constraint state $Q \approx 0$ (O'Dowd et al. 1991).

The initial focus of this part of the investigation is to quantify the "capacity" of the 4T-planform compact-tension (CT) specimen geometry with respect to the determination of values of the crack-driving force and fracture toughness that are consistent with the $Q \approx 0$ crack-tip constraint state. Motivation for focusing on the 4T-planform CT geometry is that WPS-enhanced fracture-toughness data for unirradiated A533B steel have been obtained with this geometry. Specifically, the data involve 2-in.-thick 4T-planform CT specimens with the nominal flaw-depth to width ratio $a/W = 0.5$ (Stonesifer et al. 1989). The WPS cycle corresponds to load-unload-cool-fracture (type-II WPS). The preload was carried out at 177°C with $K_{\text{WPS}} \sim 200 \text{ MPa}\sqrt{\text{m}}$. Fracture occurred at -95°C with $K_{\text{c}} \sim 170 \text{ MPa}\sqrt{\text{m}}$. In the absence of prior WPS the toughness at -95°C is $K_{\text{IC}} \sim 70 \text{ MPa}\sqrt{\text{m}}$. In this investigation attention is focused on the evaluation of the crack-tip fields under isothermal, monotonic loading conditions. These analysis conditions can alternately be associated with "conventional" isothermal fracture mechanics tests that involve no prior WPS, or with the preload and final-fracture phases of a WPS load cycle. See Shum (1993) for analysis details.

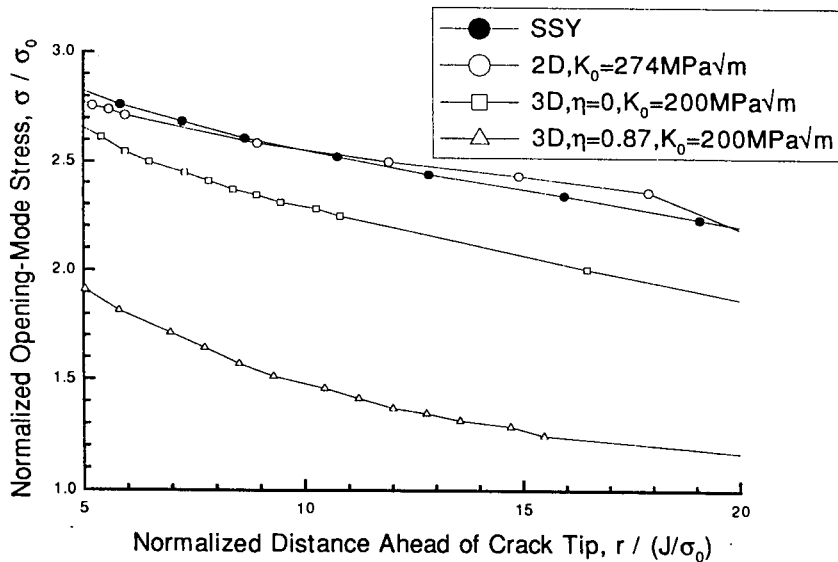


Fig. 3. Finite-element results for 2-D and 3-D model of 2-in.-thick 4T-planform CT specimen.

In Fig. 3, distributions of the opening-mode stress component (σ) along the crack plane directly ahead of the crack front are indicated for a 2-D plane strain and a 3-D model of a plane-sided 2-in.-thick 4T-planform CT specimen. The nominal flaw-depth to width ratio is $a/W = 0.56$. Analysis results for the 2-D model are indicated for $K \sim 274 \text{ MPa}\sqrt{\text{m}}$, and are representative of distributions up to that load level. The 3-D results are indicated at a stage of loading characterized by $K_0 \sim 200 \text{ MPa}\sqrt{\text{m}}$, where K_0 is the value of K at the symmetry-plane crack-front location. The distributions are presented for two crack-front locations in terms of the normalized crack-front coordinate (η), where ($\eta = 0$) corresponds to the symmetry-plane location and ($\eta = 1$) corresponds

to the specimen's free-surface. The opening-mode stress is normalized with respect to the yield stress (σ_0). Distances ahead of the crack tip in terms of undeformed original coordinates are normalized with respect to J/σ_0 where J is the value of the J-integral. Also indicated in Fig. 3 is the distribution associated with the so-called K-dominant small-scale-yielding (SSY) conditions. Briefly, plane strain fracture toughness is identified with the magnitude of K at the onset of crack initiation under SSY conditions.

It has often been assumed that the in-plane crack-tip fields along much of the crack front in "thick-section," "high-constraint" specimens such as the 2-in.-thick 4T-planform CT specimen with $a/W \sim 0.5$ are of the K-dominant type and can be well approximated using 2-D plane strain assumptions. Indeed, one would have arrived at this conclusion based on the similarity of the 2-D plane strain and SSY results. However, the 3-D results clearly indicate the presence of 3-D effects on crack-tip constraint. Furthermore, the loss of SSY-constraint occurs even at the symmetry plane of the 2-in.-thick geometry. Significantly, no indication of possible 3-D effects on crack-tip fields of the type indicated in Fig. 3 is manifested in a 2-D plane strain analysis in the form of Q-stress-like in-plane effects. However, analysis results indicate that, along the crack front, deviation of the 3-D in-plane crack-tip fields from the reference SSY distribution can be characterized in a Q-like (opening-mode stress) or Q_m -like (mean or hydrostatic stress) manner as appropriate to considerations of cleavage or ductile crack initiation (Shum 1993). A 3-D J-Q methodology thus appears necessary to provide a more accurate basis for interpreting small-specimen crack-tip fields and fracture toughness values, including those resulting from WPS load histories.

4 DEVELOPMENT OF WPS MODEL

A validated WPS model provides an additional avenue for establishing the limits of transferability of available WPS-enhanced toughness data to vessel applications. The phenomenon of WPS-enhanced fracture toughness necessarily involves the combined influences of load-path and temperature-dependent material properties on the micromechanics of fracture. In this part of the investigation, the emphasis is on examining the influence of load-path on the propensity for crack initiation. A hybrid correlative-predictive model of WPS based on J-Q theory and the Ritchie-Knott-Rice (RKR) cleavage-fracture model is adopted. Near-tip crack-tip fields under isothermal, K-dominant far-field conditions and varying degrees of unloading and reloading have been obtained. A finite-element based SSY, boundary-layer (BL) formulation based on isotropic hardening is employed. Details of the analysis conditions can be found in Shum (1993). Within the context of a SSY-BL framework with the requisite remote elastic region, the value of the "remotely" applied K , and hence J , remains uniquely defined throughout a given load-cycle. Consequently, characterization of crack-tip deformation in terms of J remains possible. The crack-tip fields, however, are understood to be potentially load-path dependent.

In Fig. 4, results are indicated at various stages of reload from full unloading for an isothermal single-cycle load-unload-reload (LUR) load-path (type-II WPS). The value of K upon completion of the reload is identical to the value of K at initial loading. Crack-tip constraint is quantified based on deviations in the opening-mode stress (σ) of the reloading results from the reference SSY distribution. The nomenclature K_{WPS} is adopted to facilitate identification of the magnitude of the initial preload with the preload load-cycle associated with WPS loading. Subsequent load-paths are expressed *relative* to this initial value. It is emphasized that the results presented herein are not dependent on the specific value of K_{WPS} or the specific values of K during unloading or reloading, but are dependent only on the value of K *relative* to K_{WPS} due to the nature of a SSY-BL formulation. From Fig. 4, it is observed that the crack-tip fields under reload exhibit higher crack-tip constraint relative to the SSY distribution over a limited extent of the near-tip region. The increase in crack-tip constraint decreases with increasing reload. At the same time, evolution of the crack-tip fields with reload is in a manner indicative of progressive conformance toward a J-Q-annulus description of the near-crack-tip fields. Indeed, a J-Q description appears viable for reloading $>73\%$ K_{WPS} . As discussed in Shum (1993), the isothermal SSY-BL results, when interpreted in light of the RKR model, appear to provide a partial explanation for the experimentally

observed decrease in WPS-enhanced fracture toughness with increase in the amount of prior unloading during a WPS cycle.

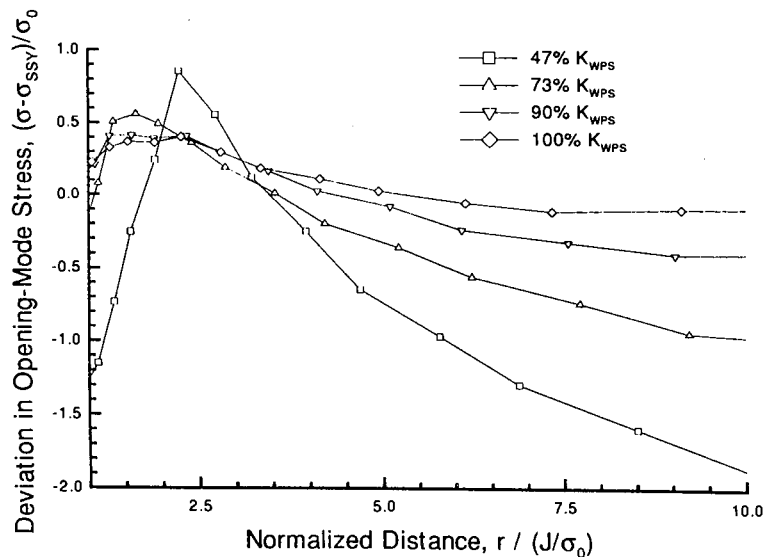


Fig. 4. SSY-BL crack-tip fields at various stages of reload from full unloading.

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