INCLUSION OF WARM PRE-STRESS EFFECTS IN PROBABILISTIC FRACTURE MECHANICS CALCULATIONS PERFORMED TO ASSESS THE RISK OF RPV FAILURE PRODUCED BY PRESSURIZED THERMAL SHOCK EVENTS: AN OPINION

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Abstract: *The United States Nuclear Regulatory Commission and the commercial nuclear power industry in the United States (operating under the auspices of the Electric Power Research Institute) are in the process of re-evaluating the technical basis of current statutory requirements for the fracture toughness needed by a nuclear reactor pressure vessel to maintain its structural integrity during a pressurized thermal shock (PTS) event. These requirements, currently codified as 10CFR§50.61, state that the* RT_{NDT} *transition temperature must remain less than 270°F (132°C) for axial welds and plates, and 300°F (149°C) for circumferential welds for the plant to continue in routine licensed operation. These requirements are based on an analysis performed in the early 1980s that contained a number of conservatisms, conservatisms whose re-examination is now appropriate in light of the following factors: technical developments in the areas of probabilistic risk assessment, thermal hydraulics, and fracture mechanics; the current regulatory focus on minimizing overall plant risk; and the economic factors resulting from energy price deregulation in the United States. In this paper we assess the technical basis for including warm pre-stress (WPS) effects in the probabilistic fracture mechanics calculations being performed as part of the PTS rule re-evaluation. The information presented herein demonstrates that inclusion of WPS effects in these calculations is consistent with both theoretical expectations and available experimental evidence and is, therefore, appropriate.*

Keywords: Warm pre-stress, pressurized thermal shock, nuclear reactor, probabilistic fracture mechanics.

1. Background

Warm pre-stress (WPS) effects were first noted in the literature in 1963 [Brothers 63]. These investigators reported (as have many since them) that the apparent fracture

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[†] The views expressed herein represent those of the author and are not an official position of the USNRC.

toughness of a ferritic steel can be elevated in the fracture mode transition regime if the specimen is first "pre-stressed" at an elevated temperature. Once a specimen is subjected to a certain $K_{applied}$ and has not failed, the temperature can be reduced and the specimen will remain intact despite the fact that the process of reducing the temperature has also reduced the initiation fracture toughness (K_{Ic} or K_{Jc}) to values smaller than $K_{applied}$. In the past four decades, three mechanisms have been identified as producing (to different extents in different situations) the WPS phenomena [Nichols 68, Pickles 83, Chen 01]:

1. Pre-loading at an elevated temperature work hardens the material ahead of the crack tip. The increase of yield strength produced by decreasing the temperature "immobilizes" the dislocations in this plastic zone [Chell 79, Chell 80]. Consequently, additional applied load is needed for additional plastic flow (and, consequently, fracture) to occur at the lower temperature.
2. Pre-loading at an elevated temperature blunts the crack tip, reducing the geometric stress concentration and making subsequent fracture more difficult.
3. If un-loading occurs between the WPS temperature and the reduced temperature residual compressive stresses are generated ahead of the crack tip. The load applied at the lower temperature must first overcome these residual compressive stresses before the loading can produce additional material damage and, consequently, fracture.

A loss of coolant accident (LOCA) poses a potentially significant challenge to the structural integrity of a nuclear reactor pressure vessel (RPV). During a LOCA, operators must quickly replace the water lost through the breach in the primary system with much colder water held in external tanks to prevent exposure of the reactive materials in the core. The temperature differential between the nominally ambient temperature emergency coolant water and the operating temperature of a pressurized water reactor ($\Delta T = 290°F - 20°C = 270°C$) produces significant thermal stresses in the thick section steel wall of the RPV. These stresses would load cracks in the vessel wall, potentially generating $K_{applied}$ values that exceed the toughness of the RPV material. As illustrated in Figure 1.1, $K_{applied}$ first increases and then decreases as these transients progress, with the time of peak $K_{applied}$ varying depending on both the severity of the transient and the location of the crack in the vessel wall. It is the latter part of the transient when $K_{applied}$ decreases with time that is of interest within the context of WPS. If the $K_{applied}$ value generated by a LOCA were to enter the temperature dependent distribution of initiation fracture toughness values during the falling portion of the transient then the WPS phenomena suggests that crack initiation will not occur even though $K_{applied}$ exceeds the initiation fracture toughness of the material (see Figure 1.2).

To date, probabilistic calculations performed in the United States to assess the challenge to RPV integrity posed by pressurized thermal shock events have not included WPS as part of the PFM model [SECY-82-465, Selby 85a, Selby 85b, Burns 86] for two reasons:

1. TH transients were represented as smooth variations of both pressure and temperature with time. However, data taken from operating nuclear plants demonstrates that actual TH transients are not always so well behaved. This created the possibility that, due to short duration fluctuations of pressure and/or temperature with time, the criteria for WPS might be satisfied by the idealized transient, but not by the real transient it was intended to represent.
2. In the past, the probabilistic risk assessment (PRA) models of human reliability (HR) were not sufficiently sophisticated to capture the potential for plant operators to re-pressurize the primary system as part of their response to a reactor vessel integrity challenge. Since such a re-pressurization would largely nullify the benefit of WPS, it was viewed as non-conservative to account for the benefit produced by WPS within a model that may also ignore the potentially deleterious effects of operator actions.

Our current assessment of the PTS rule features both more realistic representations of the TH transients as well as more sophisticated PRA/HR models that consider explicitly both acts of omission and commission on the part of plant operators. These developments make it appropriate to revisit incorporation of WPS effects into the probabilistic fracture mechanics (PFM) computer code FAVOR (**F**racture **A**nalysis of **V**essels, **O**ak **R**idge; see [Williams 01]), which is used to estimate the effect of a PTS challenge on the RPV.

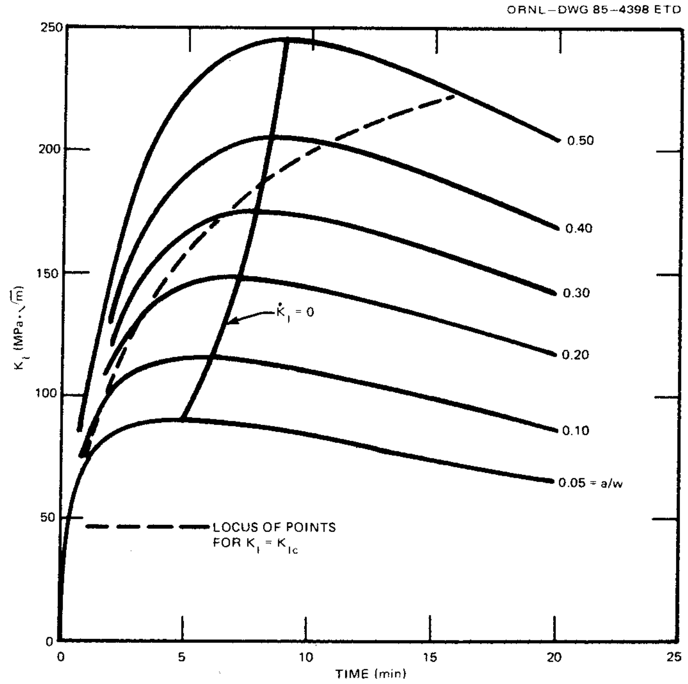

Figure 1.1. Illustration of the influence of crack depth on the variation of $K_{appplied}$ *vs*. time resulting from a large break LOCA [Cheverton 85].

The objective of this paper is to determine if sufficient evidence exists to propose a revision to the current FAVOR PFM model, which does not include WPS effects [Williams 01], that incorporates the "conservative WPS principal" first proposed by McGowan [McGowan 78]. This principal states that the criteria for cleavage crack initiation includes not just the commonly accepted requirement that $K_{applied}$ exceed K_{Ic}, but *also* the requirement that $K_{applied}$ must be increasing with time (i.e., $K_{applied}/dt > 0$) when $K_{applied}$ first enters the K_{Ic} distribution. The conservative WPS principal suggests that, even though $K_{applied}$ exceeds K_{Ic}, cleavage fracture cannot occur in the situation depicted by the rightmost diagram in Figure 1.2. Since a number of comprehensive review articles on WPS already exist [Nichols 68, Pickles 83] such a review is not repeated here. Rather, in Section 2 we summarize the results of large-scale structural experiments conducted by the NRC in the 1970s and 1980s to assess if the WPS effect is active in RPVs subjected to thermal shock and pressurized thermal shock conditions. On the basis of this summary and other supporting experimental and theoretical evidence we develop a recommended treatment of WPS effects to be incorporated in a future revision of the PFM code FAVOR (see Section 3).

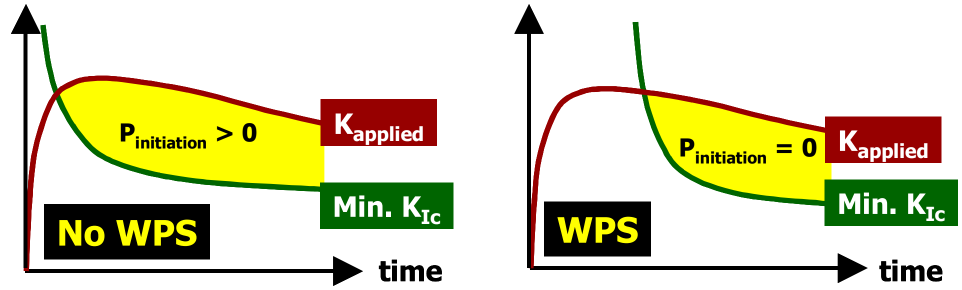

Figure 1.2. Schematic diagram illustrating how the WPS effect could be active during a LOCA depending upon the combination of the transient and the position of the crack within the vessel wall.

2. Evidence of WPS in Large Scale RPV Experiments

In the late 1970s and early 1980s the USNRC Office of Nuclear Regulatory Research sponsored two series of structural-scale RPV experiments at the Oak Ridge National Laboratory under the auspices of the Heavy Section Steel Technology HSST program. The first series of experiments, conducted between 1976 and 1985, focused on the experimental quantification and prediction of the effects of LOCA-type thermal transients on a reactor pressure vessel. The threat of interest during this time was the so-called "large break LOCA." In this transient the postulated break is sufficiently large to rapidly de-pressurize the vessel, so pressure was not a variable modeled in the experiments. On March 20, 1978 Rancho Seco experienced an excessive feedwater transient. Loss of power to control room instrumentation caused operators to maintain reactor coolant system pressure while the vessel was cooled from the operating temperature to 140°C (285°F) in approximately one hour [SECY-82-465]. This event focused attention on the challenges to vessel integrity posed by LOCAs that have less severe thermal stresses (due to smaller break sizes) but during which total depressurization cannot be assumed (also due to smaller break sizes) Rancho-Seco was one factor that motivated the conduct of a second series of structural-scale experiments between 1983 and 1989, this time focused on *pressurized* thermal shock events.

Aspects of both the early thermal shock experiments (TSEs) and later pressurized thermal shock experiments (PTSEs) focused on investigating and quantifying the existence of WPS effects. In the following two sections we summarize the experiments that provided evidence of the WPS effect under both TS and PTS conditions. It is also worthwhile to note that none of the experiments conducted in either test series (eight thermal shock experiments and three pressurized thermal shock experiments) provided any evidence that WPS does not occur (i.e., no experiment experienced crack initiation when $K_{applied}$ was falling with increasing time in the transient).

2.1 WPS in Thermal Shock Experiments

In the thermal shock experiments, a thick walled cylinder (nominally 0.9m OD, 1.2m long, having either a 76 mm or 152 mm thick wall) containing either semi-elliptic or uniform depth axial cracks was first heated uniformly, and then chilled rapidly on the inner diameter to initiate cracking. Depending on the particular test conditions a series of initiation / run / arrest / re-initiation (and so on) events ensued. TSE-5 and TSE-5a both exhibited evidence of WPS. Data from these experiments are provided in Figure 2.1 and in Figure 2.2, respectively. In both figures the complete range of K_{Ic} values is superimposed over the part of the transient where WPS may have been responsible for preventing crack initiation, and the portion of this K_{Ic} range that fell below the applied K_I value is cross-hatched.

2.2 WPS in Pressurized Thermal Shock Experiments

In the pressurized thermal shock experiments, a thick walled cylinder (nominally 0.98m OD, 1.3m long, having a 148 mm thick wall) containing a 1m long axial crack of uniform depth was first heated uniformly and then chilled rapidly on the inner diameter to initiate cracking. During this thermal transient pressure also varied, as illustrated in Figure 2.3. In both PTSE-1 and PTSE-2, WPS may have been responsible for the absence of crack initiation during the first of several PTS transients that were applied to each vessel. Data from these experiments are provided in Figure 2.4 and in Figure 2.5, respectively. In both figures the complete range of K_{Ic} values is superimposed over the part of the transient where WPS may have been responsible for preventing crack initiation, and the portion of this K_{Ic} range that fell below the applied K_I value is cross-hatched.

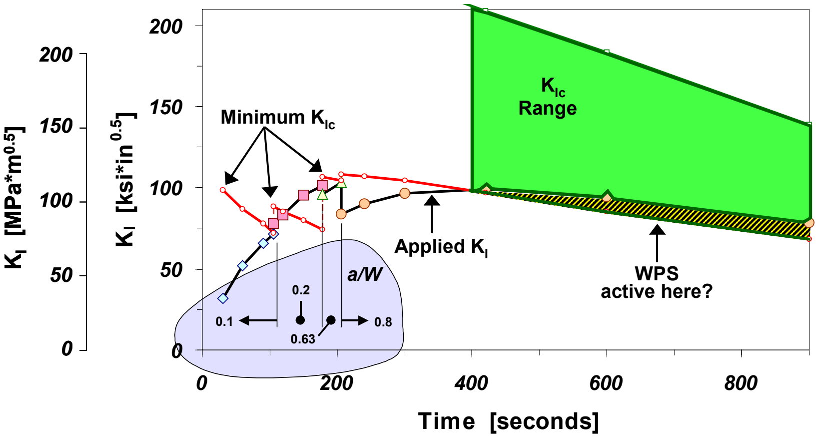

Figure 2.1. Variation of $K_{applied}$ and K_{Ic} with time in TSE-5 showing evidence of a potential WPS effect beginning at ≈400 seconds [Cheverton 85].

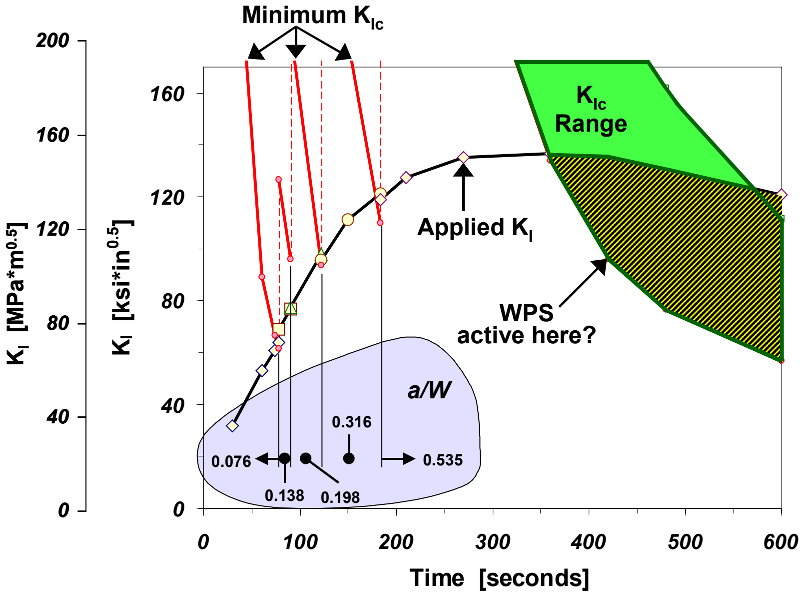

Figure 2.2. Variation of $K_{applied}$ and K_{Ic} with time in TSE-5A showing evidence of a potential WPS effect beginning at ≈360 seconds [Cheverton 85].

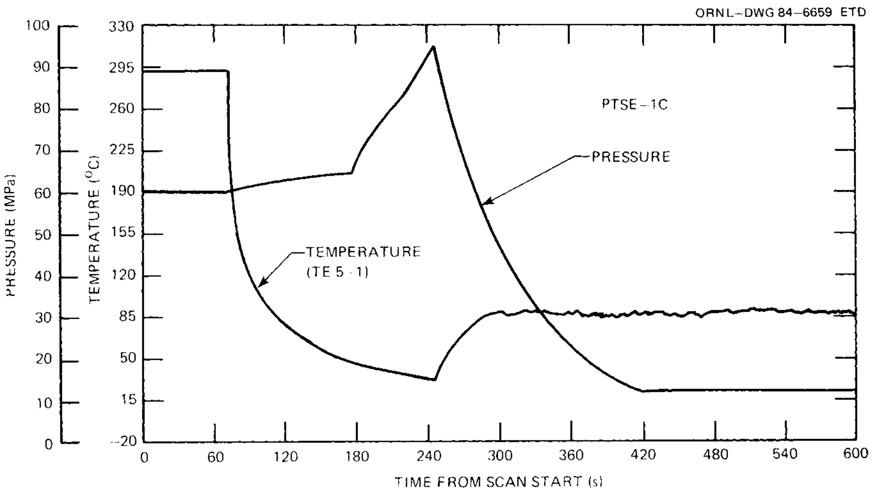

Figure 2.3. Schematic of the pressure / temperature *vs*. time transients applied during the pressurized thermal shock experiments [Bryan 85].

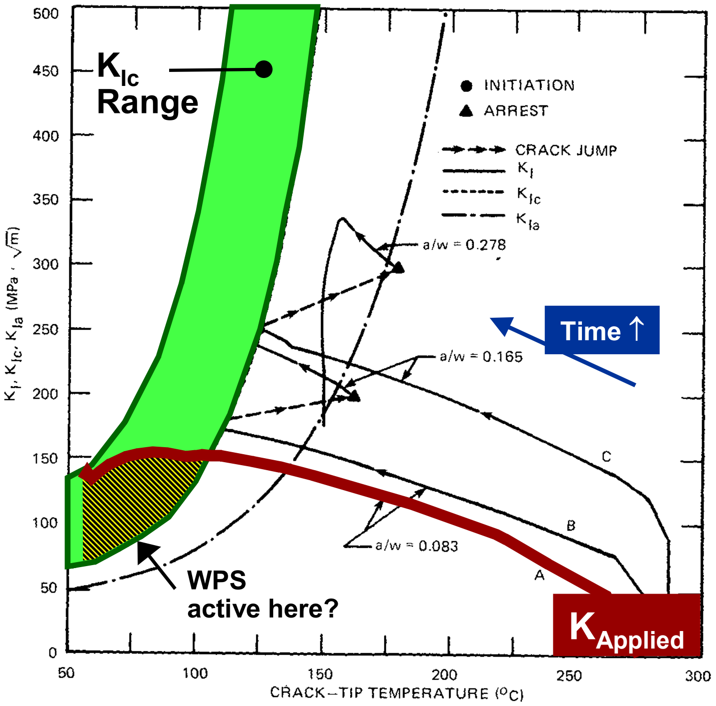

Figure 2.4. Variation of $K_{applied}$ and K_{Ic} with time in PTSE-1 showing evidence of a potential WPS effect in Transient A below a crack tip temperature of ≈110°C [Bryan 87].

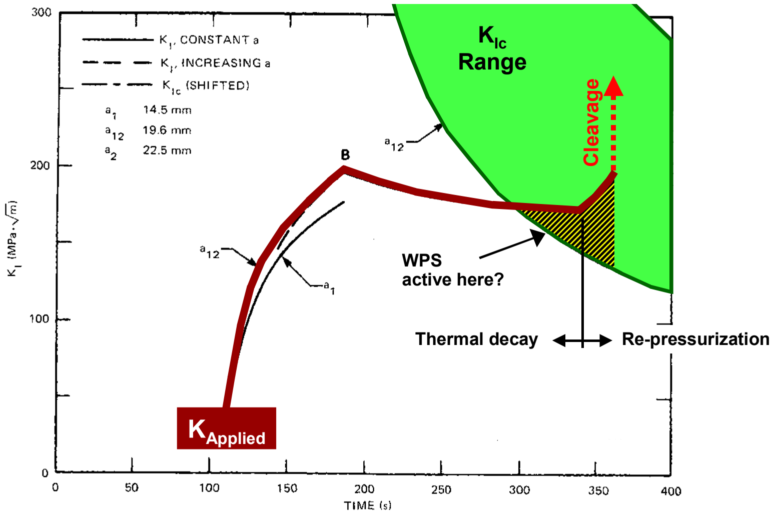

Figure 2.5. Variation of $K_{applied}$ and K_{Ic} with time in PTSE-2 showing evidence of a potential WPS effect beginning at ≈300 seconds.

3. Existence of WPS in RPVs Subjected to Thermal Shock and Pressurized Thermal Shock Conditions

3.1 Summary of Evidence from Vessel Experiments

The data summarized in Section 2 demonstrates that in four fracture experiments conducted on prototypic reactor pressure vessels subjected to loadings characteristic of thermal shock and pressurized thermal shock conditions the value of $K_{applied}$ exceeded the minimum value of K_{Ic}, and yet cleavage crack initiation did not occurr. In each experiment $K_{applied}$ first exceeded K_{Ic} at a time in the transient when $dK_{applied}/dt$ was either zero or negative, suggesting WPS as one potential explanation for the absence of cleavage crack initiation. However, since the existence of WPS can only be implied based on what does *not* happen (i.e., a cleavage crack does not initiate even though $K_{applied}$ exceeds K_{Ic}), it is prudent to examine other factors that could also explain these observations (see Sections 3.1.1 and 3.1.2).

3.1.1 $K_{applied}$ Is Less Than We Think It Is

As illustrated by the diagram of the crack front for TSE-5 and TSE-5A provided in Figure 3.1 and Figure 3.2 (respectively), the cracks in these experiments took on a decidedly three-dimensional shape because of the reduction in crack driving force near the cylinder's free end. However, the $K_{applied}$ values reported in Figure 2.1 and Figure 2.2 assume a crack of uniform depth equal to the maximum extent of crack penetration into the vessel wall. Relative to this approximation, the correct $K_{applied}$ for the non-uniform depth crack front is lower, suggesting that the crack may not have initiated in these experiments simply because $K_{applied}$ never exceeded K_{Ic}. The impact of this uncertainty on conclusions regarding the existence of WPS in the four structural experiments is as follows:

- <u>TSE-5</u>: Because of the small degree by which $K_{applied}$ exceeded K_{Ic} (see Figure 2.1), it is possible that the Kapplied for the actual (non-uniform depth) crack (shown in Figure 3.1) may not have exceeded K_{Ic}. Thus, some doubt regarding the demonstration of WPS during TSE-5 exists.
- <u>TSE-5A</u>: Uncertainties in $K_{applied}$ are not believed to alter the conclusion that WPS was responsible for the lack of crack initiation in TSE-5A after 360 seconds for two reasons. First, after 180 seconds the crack penetrated to its maximum depth over a length of nearly 0.5m, suggesting that deviations between the $K_{applied}$ values for the crack as it existed in the vessel and the approximate $K_{applied}$ values (estimated by assuming a uniform depth crack of infinite extent) should be small. Furthermore, $K_{applied}$ exceeded the maximum of the K_{Ic} distribution before the end of the transient, suggesting that (were it not for WPS) cleavage crack initiation should have certainly occurred, yet it did not.
- <u>PTSE-1&2</u>: In both of the pressurized thermal shock experiments WPS may have occurred during the first transient. The crack depth during this transient was the pre-test crack depth, making the uniform depth / infinite extent assumptions made in the calculation of $K_{applied}$ appropriate.

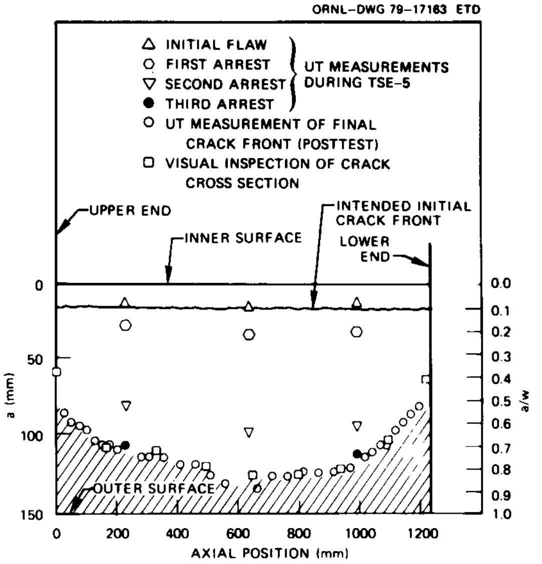

Figure 3.1. Crack profile from TSE-5 [Cheverton 85].

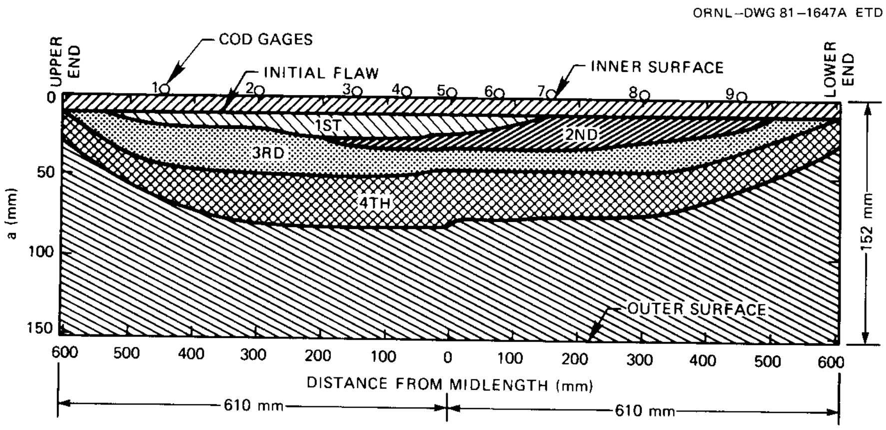

Figure 3.2. Crack profile from TSE-5A[Cheverton 85].

3.1.2 K_{Ic} Exceeds What We Think It Is

Were the K_{Ic} distributions illustrated in Figure 2.1, Figure 2.2, Figure 2.4, and Figure 2.5 for some reason lower than the K_{Ic} for the material at the crack tips in the structural tests this could explain the lack of crack initiation because, in that case, $K_{applied}$ would not have exceeded K_{Ic}. Specifically, the well-documented through-thickness variability in toughness that is expected in rolled plate and extruded forgings could be a confounding factor in this regard [Viehrig 02]. This uncertainty is not believed to influence the conclusions drawn about the existence of WPS in any of the structural experiments discussed in Section 2 for the following reasons:

- The K_{Ic} distributions drawn in these figures is based on fracture experiments conducted using specimens removed from the TSEs and PTSEs themselves, making these material properties the most relevant to understanding the results of the structural test.
- In the TSEs at the time of potential WPS, the crack had advanced well into the portion of the vessel wall thickness where uniform toughness properties are normally observed.
- In the PTSEs the 150 mm thick test vessel was machined from a thicker (203 mm) forging. This forging thickness was reduced to the 150 mm thickness of the PTSEs by machining 38mm from the outer diameter and 13mm from the inner diameter. Thus, even though the crack depth at the time of WPS was shallow ($a/W \approx 0.1$) in both experiments, the crack-tip was actually located at deeper into the thickness of the original forging, a region that typically exhibits uniform fracture toughness properties.

3.1.3 Summary

Even taking into account the various factors described in this Section, there is little doubt that WPS was responsible for the non-initiation of a cleavage crack in both TSE-5a and in PSTE-1 owing to the considerable degree to which $K_{applied}$ exceeded K_{Ic} in each experiment. While TSE-5 and PTSE-2 both suggest the possibility of WPS, the conclusion that WPS was *the* factor responsible for lack of cleavage crack initiation must, with all factors considered (see Sections 3.1.1 and 3.1.2), be made somewhat more equivocally.

While these results are heartening, they do not by themselves provide an adequate technical basis to justify inclusion of WPS in the FAVOR code. Evidence supporting WPS therefore needs to be drawn from other sources (e.g., experimental evidence obtained from specimen tests, and from the theoretical understanding of the WPS phenomena itself: see Section 3.2). Additionally, it is important to recognize that none of these experiments (nor any other experiments conducted to date on either vessels or fracture specimens) have been performed using irradiated materials. Since the aim of this paper is identification of a WPS model that can be applied to irradiated materials, this will be discussed in Section 3.2 as well.

3.2 Summary of Other Evidence

3.2.1 Experimental

Since experiments on fracture toughness specimens can be conducted more economically than prototypic vessel experiments, such results more comprehensively quantify all of the factors relevant to WPS than has been possible using the vessel experiments reported in Section 2. Quoting from a review of warm pre-stressing studies reported by Pickles and Cowan in the *International Journal of Pressure Vessels and Piping* [Pickles 83],

> *Many experiments have been made on simple fracture toughness specimens to demonstrate that the {WPS} phenomenon exists and, almost without exception, beneficial effects have been found. For cases where no unloading is involved, no reported instance has been found of a specimen failing at low temperature following warm pre-stress without addition of further load above the warm pre-stress load; this is the case despite the fact that the warm pre-stress load could be well above the load to achieve the low temperature {minimum}* K_{Ic}.

Since the no-unloading case represents the upper-bound to $dK_{applied}/dt < 0$ (i.e., $dK_{applied}/dt = 0$), the experimental evidence provides strong testament to the appropriateness of the "conservative warm-prestressing" principal expressed by McGowan that is being considered here for inclusions in a future version of FAVOR [McGowan 78]. However, since no WPS experiments have been conducted on irradiated materials, the appropriateness of WPS in this situation must be justified on a basis that includes more than just experimental evidence (see Section 3.2.2).

3.2.2 Theoretical

Returning to the three mechanisms of WPS identified in Section 1 we see that the first WPS mechanism involves the effect that pre-loading at an elevated temperature has on work hardening the material ahead of the crack tip. The increase of yield strength produced by decreasing the temperature "immobilizes" the dislocations in this plastic zone [Chell 79, Chell 80]. Consequently, additional applied load is needed for additional plastic flow (and, consequently, fracture) to occur at the lower temperature. Combining this WPS mechanism with a dislocation-mechanics based understanding of the combined effects of temperature and irradiation on flow properties provides assurance that the "conservative WPS principal" can be *expected* to apply to irradiated steels, even in the absence of direct experimental evidence. Natishan, et al. point out that irradiation influences only the long-range barriers to dislocation motion in ferritic steels, it has no effect on the short-range barriers (provided by the lattice spacing) that control the temperature dependency of the flow behavior [Natishan 99]. This understanding, combined with an experimentally validated dislocation mechanics based flow model [Zerilli 87] (see Figure 3.3) demonstrates that the increase of yield strength with decreasing temperature needed to ensure the existence of WPS in irradiated materials can be expected on firm theoretical grounds.

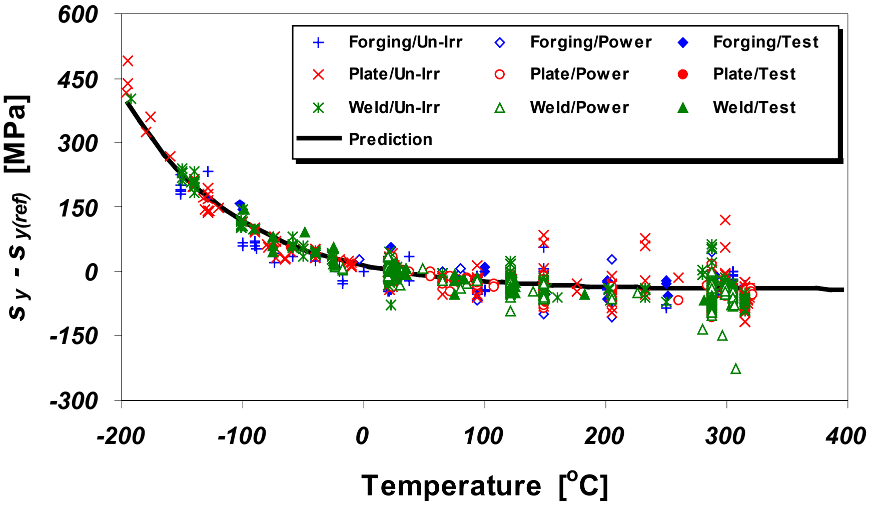

Figure 3.3. Agreement of the thermal component of yield strength in irradiated and un-irradiated RPV steels (irradiations conducted in both test and commercial power reactors) with the dislocation mechanics model (curve labeled "prediction") of Zerilli and Armstrong [Zerilli 87] reported by Kirk, et al. [Kirk 01].

3.3 Recommendations for FAVOR Calculations

Based on the information provided herein, it is justified to include the "conservative WPS principal" in the probabilistic fracture mechanics code FAVOR. Specifically, the conditional probability of crack initiation (CPI) can be non-zero only if **both** of the following conditions are met:

Condition 1. $K_{applied} \geq K_{Ic(min)}$. The time when this condition is first satisfied is designated t_{WPS}
Condition 2. $\mathrm{d}K_{applied}/\mathrm{d}t > 0$ when Condition 1 is first satisfied (i.e., at t_{WPS}).

If Conditions 1 and 2 are never both satisfied during the course of a transient then either the crack driving force has never exceeded the minimum value of fracture toughness or, even though it has, WPS has occurred. In either case the CPI is, by definition, zero. However, should the following two conditions also **both** be met at some time after t_{WPS}:

Condition A. $K_{applied}$ at the current temperature/time exceeds the $K_{Ic(min)}$ value at t_{WPS}, and
Condition B. $\mathrm{d}K_{applied}/\mathrm{d}t > 0$ at this same temperature/time.

then CPI can exceed zero because a significant re-pressurization has occurred. In this case all benefits of WPS are lost, and CPI is calculated accordingly.

These checks for WPS will be made during both calculations made to assess if a crack will initiate from a pre-existing defect, and during calculations made to assess if an arrested crack will re-initiate at some later time in the transient. Because the flaw distributions used in these calculations contain mostly small flaws that are placed close to the inner radius of the RPV [Simonen 02] we expect that the influence of WPS on preventing first initiations to be minimal. However, a considerably greater effect of WPS is anticipated in preventing re-initiations from cracks that have arrested at depths deeper into the vessel wall.

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