SIGNIFICANCE OF WARM PRESTRESS TO CRACK INITIATION DURING THERMAL SHOCK

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SUMMARY

During a loss of coolant accident, LOCA, followed by operation of the emergency core cooling system, the inside wall of a nuclear pressure vessel is subjected to high thermal stresses that can cause extension of a preexisting flaw. During this event the crack-tip stress intensity factor, K_I, may achieve its maximum value early in the transient, but the critical level for crack initiation, K_{Ic}, may not be reached until minutes later at which time the loading has decreased from its peak. It is believed that this phenomenon, termed warm prestress, WPS, can preclude crack extension when K_I equals K_{Ic}.

NRL has conducted an experimental study, employing three-point bend specimens, to investigate the potential elevation in K_{Ic} by WPS, and to translate the significance of this behavior into structural terms in the sense of minimizing crack extension in a nuclear vessel during a LOCA. From the experiments it is concluded that the mechanisms associated with WPS act to elevate the K_{Ic} of the material at the crack tip and that this fact can greatly minimize crack extension that would have been predicted without consideration of WPS. The experiments demonstrated that failure never occurs during the unloading portion of the simulated LOCA path. This finding is of major significance to the integrity of a vessel. For example, with relatively deep cracks, initiation ordinarily would be predicted as K_{Ic} is reached along a decreasing K_I path. For this set of conditions the present research studies have shown that the WPS phenomenon will preclude all crack initiation.

In terms of margin of safety against fracture it is shown that the elevation in K_{Ic} caused by WPS is not universal and depends upon the WPS level, the degree of unloading, and the increment between the temperature of WPS and the failure temperature. In particular, it is concluded that WPS levels of 120 $MPa\sqrt{m}$ or less during a LOCA can result in an elevation of K_{Ic} to at least the WPS level, assuming of course that the material metallurgically is capable of exhibiting this level of toughness.

In terms of structural significance it is clear that WPS by itself cannot prevent the initiation of shallow cracks. For the specific case of a long, axial flaw it is shown that a shallow crack can extend to a relative depth of 0.34. However, cracks having initial depths greater than 0.2 are prevented, by WPS, from extending any amount. Finally, it was observed that an elastic analysis of crack extension during a LOCA has predicted complete penetration of the wall without consideration of WPS. Factoring this phenomenon into the analysis results in predicted crack extension of greatly reduced proportions such that complete penetration of the wall does not occur. Thus, WPS may form a key element upon which the assurance of vessel integrity during a LOCA can be based.

1. Background

One of the postulated events for a nuclear pressure vessel is a sudden loss of coolant accident (LOCA) followed by operation of the emergency core cooling system (ECCS). Introduction of the relatively cold ECCS water subjects the hot vessel wall to high thermal stresses, i.e., thermal shock. If the wall contains a crack-like defect at the inner surface, the stress intensity at the crack tip, K_I, increases with time to a maximum and then decays as the temperature gradient throughout the wall becomes smaller (Fig. 1). For highly irradiation sensitive materials, neutron bombardment causes a marked shift of the temperature dependence of the critical fracture toughness, K_{Ic}, to higher temperatures. With a sufficiently high fluence level, the K_I and K_{Ic} curves can intersect as illustrated in Fig. 1. At this point crack initiation would be predicted. Unfortunately, the magnitude of the ensuing crack extension cannot be easily computed. This fact has raised the possibility of complete crack penetration of the wall. However, the factors of decreasing fluence and increasing temperature toward the outside wall surface produce a steep gradient in toughness that provides a mechanism for arrest of the running crack.

During the accident, the stress intensity for a flaw of given depth can attain the critical value for initiation within the first few minutes of the transient. Since this K_{Ic} level changes with time in proportion to the changing temperature of the metal at the crack tip, the prediction of crack initiation does not necessarily correspond with the maximum K_I level. Under certain conditions when the critical stress intensity is achieved at a point where K_I is decreasing with time, as illustrated in Fig. 1, the crack-tip material has been subjected to "warm prestress". In other words, the crack-tip region was subjected to a preload, at a higher temperature, that exceeded the K_{Ic} value at the lower temperature. Previous studies of warm prestress (WPS) behavior [1, 2] suggest that this phenomenon elevates the fracture toughness of the crack-tip so that crack extension will not occur when the stress intensity reaches the K_{Ic} value of the virgin material at the lower temperature. Verification of this hypothesis for conditions associated with a LOCA is required to provide a meaningful basis with which to ensure the integrity of the vessel.

Experimental studies with fracture mechanics specimens are being conducted at the Naval Research Laboratory (NRL) to characterize WPS under simulated LOCA loading conditions. This research will permit one to quantify the benefits of WPS during thermal shock and to better define the margin of safety against rupture of the vessel. An experimental program on thermal shock is also being conducted by Oak Ridge National Laboratory (ORNL) to evolve a predictive capability for the extension of pre-existing flaws in small cylindrical sections of A508-2 steel subjected to a thermal shock [3]. In addition to providing an interpretation of the ORNL tests, the NRL studies will constitute a primary basis for the assessment of full-size vessel behavior in terms of WPS, that cannot be readily simulated by the ORNL tests.

2. APPROACH

The objectives of the experimental phase of the NRL program were: (a) to prove that WPS during a LOCA elevates the fracture toughness of the crack-tip region and (b) to define the important parameters and their role in achieving this K_{Ic} elevation The final objective was to translate the significance of a K_{Ic} elevation due to WPS into structural terms in the sense of minimizing crack extension in an actual vessel during a LOCA.

In order to investigate the WPS phenomenon it was readily apparent that an experimental simulation was required because of the cost involved in the loading of an actual vessel. Even small cylinders of the type tested by ORNL (53 mm, 21 in. OD) do not have the thickness-to-diameter ratio required to exactly simulate the WPS that occurs in a prototype nuclear vessel. Fortunately, it is believed that the WPS effect encountered by the vessel can be simulated by the loading of three-point bend specimens that are notched and fatigue precracked. It is felt that mechanical loading of the specimens is a proper means of simulating the vessel thermal stress. A method of specimen loading was devised to achieve the following objectives:

(1) Limit the specimen crack-tip plastic zone to a size no larger than that which occurs in a thick vessel wall under plane strain constraint at the same applied K level.

(2) Fracture the specimens at a sufficiently low temperature so that the WPS level exceeds the K_{Ic} value at the fracture temperature.

(3) Permit investigation of the relative importance of unloading path.

It is important to restrict the plastic zone size in the specimens so that any benefit attributed to the WPS phenomenon is not subject to uncertainty that could arise if the simulated loading produced a plastic zone size larger than that in a vessel wall during a LOCA (objective 1). The specimens must be fractured at a sufficiently low temperature so that an elevation in K_{Ic} by WPS can be detected unambiguously (objective 2). For example, consider a specimen loaded to failure only slightly below the WPS temperature where the magnitude of K_{Ic} may equal or exceed the WPS level, K_{WPS}. If, as a consequence, the failure level, K_F, equals or exceeds K_{WPS}, the result may not constitute the elevation in K_{Ic}, but instead could reflect the expected K_{Ic} behavior of the virgin material. Finally, it was felt that the shape of the unloading path could contribute to the WPS effect. Since the particular unloading path that occurs during thermal shock had not previously been investigated, it was necessary to consider the relative importance of variations of this variable (objective 3).

3. Experimental Investigation

3.1 Material

The test specimens were fabricated from 300 mm (12 in.) thick A533-B1 steel plate obtained from the Heavy Section Steel Technology (HSST) program (HSST plate 02). This material was chosen because its static K_{Ic} trend as a function of temperature has been well characterized in thick sections [4, 5] . The limited amount of HSST plate available necessitated the electron beam welding of end extensions to the test sections to conserve material. During welding, the temperature of the test section was not significantly elevated due to the low heat input by the electron beam.

3.2 Specimens

Specimens of two different thicknesses, 38 and 76 mm (1-1/2 and 3 in.), were prepared in the TL orientation. Because of limited material, the 38 mm specimens were machined from several thickness positions so that the specimen mid thickness for different specimens ranged from the quarter thickness (1/4T) to 3/4T plate locations. The mid thickness of all the 76 mm specimens corresponded to either the 1/4T or 3/4T position.

The three-point bend specimens were machined to ASTM E399 proportions with a span to width (S/W), ratio of 4.0. A portion of the specimens was face-grooved* in order to maintain a straight crack front representative of a long crack in a vessel. The specimens were fatigue precracked at a maximum K_I level of 27 MPa√m (25 ksi √in.) to provide an overall crack depth to width ratio (a/W) of 0.42.

3.3 Experimental Apparatus

The specimens were loaded on a three-point bend fixture having roller supports at the outer edges. The fixture was surrounded by a cooling bath that was used to control the specimen temperature. The temperature was monitored by means of a thermocouple spot-welded to the specimen. Care was taken during cooling so that temperature differences throughout the specimen would be only a few degrees centrigrade . Thus, any thermal stresses during cooling did not significantly influence the crack-tip K level as computed from the mechanical loading.

Two linear variable displacement transducers (LVDT) one on either side of the specimen, were summed to monitor specimen deflections. Each LVDT was attached to the bend fixture and to the mid-span loading roller. Since both the deflection of the fixture and the indentation by the rollers were found to be small, the specimen deflections were directly measured by the LVDT.

3.4 Loading Sequence

The specimen loading sequence was designed to simulate a typical K_I vs temperature path of the crack-tip region as shown in Fig. 1. Warm prestressing was accomplished by slowly loading each specimen at room temperature to the desired K_{WPS} level. At that point the load and temperature were decreased simultaneously along one of the paths illustrated in Fig. 2. Then, at a predetermined temperature, the specimen was isothermally loaded to failure. The temperature difference (Δ T) between the temperature of WPS (T_{WPS}) and the failure temperature (T_F) was chosen to represent that which could occur during a LOCA.

From an analysis of a typical reactor vessel [3] it can be concluded that the actual Δ T is a function of the relative crack depth, a/W. For such a vessel, the Δ T at the first intersection in Fig. 1 can vary, for example, from a minimum of zero degree C at a relative crack depth of 0.2 to a value of approximately 90 degree C at a relative depth of 0.5. Hence, there exists no "typical" Δ T. In the present study, the Δ T values ranged from 100 to 220°C (Fig. 2). While the smaller value is representative of LOCA conditions, the larger values were chosen in order to investigate the importance of this parameter. Very small Δ T values (< 25°C), that also represents LOCA conditions, were not employed because the failure points would lie within the K_{Ic} data band for the material. In this event, assessment of the K_{Ic} elevation due to WPS would require a statistical approach and utilize more specimens than could be machined from the available material. A follow-on program with a different heat of A533-B steel is currently underway at NRL wherein small Δ T values are being investigated.

The specimen loading path in the subject study differs from that of a vessel material in two respects. First, the WPS was applied isothermally at room temperature; whereas the WPS in the vessel occurs with decreasing temperature. It is believed that this difference will not change the resultant fracture behavior of the specimens, vis-a-vis the vessel. Second,

*The face grooves were machined to a depth of 5% of the thickness of each face. The grooves had a 45° included angle with 0.25 mm (0.010 in.) root radius.

the temperature increment, Δ T, in the experimental investigation was imposed at lower absolute temperatures than occur in the vessel. Since the program employs unirradiated material, the K_{Ic} vs temperature trend increases sharply at relatively low temperatures (Fig. 3). Thus, an intersection between the K_I and K_{Ic} curves is possibly only at temperatures lower than those which would occur in a vessel during a LOCA. In the vessel the intersection of the two curves occurs at higher absolute temperatures because of the elevation of the K_{Ic} curve by irradiation as previously described.

In order to restrict the specimen plastic zone to a size no larger than that in a thick (plane strain) vessel wall at the same K level, the maximum K_I during WPS was limited to the plane strain measurement capacity of the specimen as defined by ASTM E399, i.e., 59 MPa $\sqrt{m}$ (54 ksi $\sqrt{}$ in.) for the 38 mm specimen and 84 MPa $\sqrt{m}$. (77 ksi $\sqrt{in.}$) for the 76 mm specimen. For a deep crack, however, the maximum computed K level during a LOCA can exceed 200 MPa $\sqrt{m}$. For this reason some specimens were subjected to a K_{WPS} in excess of the ASTM E399 limit. Nevertheless, the specimen thicknesses used in the program are considered to be sufficiently large to demonstrate and to quantify the WPS phenomenon.

4. K_{Ic} Trends

It is essential that the K_{Ic} trends for the test material be fully characterized so that the apparent elevation in K_{Ic}, attributable to WPS, can be assessed. The temperature dependence of K_{Ic} for the program material has been well defined by Westinghouse investigators [4, 5]. A few additional verification tests were required since the specimens were not from exactly the same plate thickness position as the Westinghouse specimens. With respect to plate location, some of the NRL K_{Ic} and WPS specimens were machined from the broken halves of the Westinghouse K_Ic specimens. Other NRL K_{Ic} specimens were taken from a location adjacent to the plate section used for the Westinghouse tests. All of the Westinghouse specimens straddled the 1/2T plane. Due to the limited material, the NRL K_{Ic} specimens straddled the 1/4T and 3/4T planes. This sampling was considered acceptable in that prior investigations of the plate [6, 7] did not show a gradient in toughness through the thickness beyond a shallow (25 mm) layer at the surfaces.

Comparison of K_{Ic} data from both laboratories is presented in Fig. 3. Some of the NRL data unexpectedly fell outside of the Westinghouse data band. Although the scatter was not unreasonable, the cause of this behavior has not been ascertained. The differences may be attributable to the different thickness positions used for the specimens from the two laboratories. The higher K_{Ic} values for the NRL specimens from the 1/4T and 3/4T locations, as opposed to the 1/2T location, would be consistent with higher toughness properties often observed at these locations in quenched and tempered materials. In analyzing the elevation of K_{Ic} by WPS, the "invalid" data by Fig. 3 were not considered.

5. WARM PRESTRESS TRENDS

Results from the 38 mm and 76 mm (1.5 and 3.0 in.) thick bend specimens are summarized in Figs. 4 and 5, respectively. In both figures, specimens were loaded to a predetermined K_I level at room temperature (i.e., warm prestressed) and then simultaneously unloaded and cooled to the temperatures shown. This was followed by an isothermal loading to failure. The figures illustrate the behavior of two specimen loading patterns. The filled symbols denote a partial unloading (e. g., 30-60%) over the increment, Δ T, between the temperature of WPS (T_{WPS}) and the temperature of isothermal loading to failure, T_F. The open symbols denote loading to K_{WPS}, unloading completely at T_{WPS}, cooling to T_F and failure by subsequent isothermal loading (LUCF). It must be emphasized that only the partial unloading path is representative of LOCA conditions in that complete unloading will not occur during the accident. The LUCF path, however, provided a means to characterize the significance of the degree of unloading.

In order to understand the data trends it is important to note first that no specimens failed during the simultaneous unloading and cooling even though the critical K_{Ic} for the virgin material was attained. This fact is of major importance to the vessel integrity as explained later. Next, note that all specimens that were partially unloaded following the WPS, with one exception discussed later, exhibit a value of K_I at failure (K_F) exceeding the K_{Ic} value at the specific failure temperature. It is therefore concluded that WPS during a LOCA artificially elevates the K_{Ic} of the material. The specimens that were completely unloaded also exhibited an elevation of K_{Ic} but to a lesser degree than was the case for the partial unloading. In fact, no elevation in K_{Ic} was exhibited by specimens that were completely unloaded and then fractured at a very low temperature (-196°C, -320°F). Thus, the data suggest that the extent of the unloading (partial unloading vs complete unloading) does influence the specimen behavior. It appears, however, that the specific partial unloading path (paths 1, 2, 3, 1A, and 2A in Fig. 2) had no discernable influence on the results. This topic is considered in greater detail later.

The following observations were also made. First, no trend attributable to the face grooves was displayed by the data. This was not unexpected considering the crack-front curvature of the fatigue precrack in both specimen types. Specifically, the crack front of the face-grooved specimens was generally straight; the ungrooved specimens did exhibit precrack tunneling but this tunneling was not large. Approximately, one-half of the specimens in Figs. 4 and 5 were face grooved. Second, the linear nature of the load vs deflection records for the specimens suggested an absence of plastic bending and stable crack extension during WPS and during the path leading to fracture. This deduction was reinforced by the fracture appearance of all specimens. The crack extended from the fatigue precrack entirely in the cleavage (brittle) mode. This appearance is observed with fracture representing plane strain behavior. Third, no firm conclusions regarding the benefits of WPS can be drawn from the group of data at -73°C in Fig. 4 for the lower prestress. Comparing these data with the NRL K_{Ic} data of Fig. 3 at the same temperature, it can be observed that the K_F levels exceed only marginally the upper boundary of the K_{Ic} scatterband as it could be drawn to encompass the valid NRL K_{Ic} data. Consequently, the benefits of WPS cannot be readily ascertained. This problem results from the choice of too small a ΔT (i.e., $T_{WPS} - T_F$) as discussed earlier. On the other hand, it should be noted that the values of K_F in this case consistently exceeded K_{WPS}. If there were no benefit of WPS, one would have expected some of the K_F values to be within the adjusted K_{Ic} band.

As illustrated in Figs. 4 and 5 the specimens were subjected to different levels of WPS. The lower level in each case corresponds to the ASTM E399 allowable for the specific thickness. In the case of the 38 mm specimen (Fig. 4) the higher WPS level corresponds to that which is permitted for a specimen of 76 mm or greater thickness. For the 76 mm specimens the higher WPS level corresponds to the allowable value for a 152 mm (6 in.) or greater thickness specimen. No differences are apparent between the trends for the 38 mm specimens prestressed to 80 MPa$\sqrt{m}$ (the ASTM allowable for a 76 mm specimen) in Fig. 4 and those in Fig. 5 for the 76 mm specimen prestressed to the same level. Also, a similar fracture surface appearance was observed for both specimen thicknesses. This correspondence suggests that the larger plastic zone size resulting from the "overload," to 80 MPa$\sqrt{m}$, of the 38 mm specimens is not a deterrent factor in assessing the effects of WPS. On this basis, it is concluded that the geometrically similar overload of the 76 mm specimens, to approximately 120 MPa $\sqrt{m}$ (Fig. 5) would also represent the behavior of 152 mm thick specimens, had they been available for test. This conclusion is significant in that it permits a more general interpretation of the benefits of WPS to the higher K levels that may be experienced by a vessel during a LOCA.

6. ANALYSIS OF DATA

The magnitude of the K_{Ic} elevation by WPS is best observed from Figs. 4 and 5. It is not possible to assign a quantitative value to this elevation in terms of say, K_F/K_{Ic}, since K_F depends upon: (a) WPS level, (b) failure temperature, and (c) degree of unloading. However, it should be noted that for a given failure temperature and unloading path, K_{Ic} is elevated in proportion to the magnitude of K_{WPS}. Thus, it appears that a high value of K_{Ic} could be obtained at a very low temperature simply through the application of a high level of K_{WPS}.

The preceding is a simplistic analysis of the WPS phenomenon. Therefore, it is of benefit to consider the interaction of the three major independent parameters listed above and depicted in Fig. 6. From this figure it can be concluded that the maximum benefit of WPS, in terms of the highest K_F/K_{WPS} ratio, is obtained for the case of partial unloading for which ΔT is small and the K_{WPS} is low. Fortunately, during a LOCA, two of the above three conditions are met. First, the metal at the crack tip is always partially unloaded and this unloading is not expected to exceed the 30 to 60% to which the specimens were subjected. Second, the ΔT is expected to be small between the temperature of peak applied K_I during a LOCA and the temperature at which K_I attains the K_{Ic} level. That is to say, a ΔT of 100°C, corresponding to a T_F of -73°C, may represent the largest value that could occur during a LOCA. Consequently, the partial unloading data at -73°C in Fig. 6 would be most applicable to a LOCA. From this, it can be concluded that for K_{WPS} less than 120 MPa $\sqrt{m}$ (109 ksi $\sqrt{in.}$), the WPS phenomenon will: (a) provide an artificial elevation of K_{Ic}, and (b) assure that the failure level will equal or exceed the level of WPS.

An alternate way to interpret the interaction of WPS level, failure temperature, and degree of unloading is presented in Fig. 7. This figure clearly illustrates that the elevation in K_{Ic}, as reflected by K_F, increases with WPS level. The magnitude of the K_{Ic} elevation can be observed by comparing K_F with the mean K_{Ic} values for the appropriate failure temperature. For example, a K_{Ic} elevation in excess of 200% is exhibited by the extreme of the partial unloading data at -73°C; whereas, essentially no elevation in K_{Ic} is exhibited by the LUCF data at -196°C.

An extrapolation of the trend illustrated in Fig. 7 suggests that even higher elevations in K_{Ic} could be obtained with the higher imposed values of K_{WPS}. Unfortunately, the data deviate from the one-to-one relationship between K_F and K_{WPS} as K_{WPS} is increased. The reason for this deviation is believed to be related to the interaction of: (a) the compressive residual stresses that can cause reverse yielding upon unloading of the crack tip, and (b) the temperature elevation of the yield stress that results when a large ΔT is employed.

When ΔT is zero there can be no yield stress elevation. In this case, one would expect K_F to equal or slightly exceed K_{WPS} in that no mechanism exists to prevent the specimen from again supporting the load it had withstood a short time previously at the same temperature. The detrimental effect of reverse yielding upon unloading results from the increased yield stress associated with a low value of T_F. If one assumes that the K_I level and local strain are proportional, then an attempt to apply K_{WPS} at the low value of T_F will subject the crack-tip region to the same strain as during the WPS loading. In attempting to reach this strain, the metal may first achieve the critical cleavage stress, which in turn, precipitates fracture. Consequently, one would predict a deviation from the one-to-one line as illustrated in Fig. 7 for a large K_{WPS} in combination with a large ΔT.

Fortunately, the reverse yielding that tends to prevent the attainment of the K_{WPS} level upon reloading at a lower temperature has a minimal effect under LOCA conditions. First, only partial unloading is experienced and therefore little, if any, reverse yielding at the crack tip is expected. Second, the ΔT is expected to be small so there can be little elevation in yield strength. Thus, the critical cleavage stress will be achieved at a K_F level that is not significantly below the original value of K_{WPS}.

The above model appears to offer a satisfactory explanation for the observed trends in Fig. 7. Specifically, the large elevations in yield strength in the experimental program that resulted from the relatively large ΔT values (95 to 220°C) are not expected to occur during a LOCA. Consequently, that portion of the data in Fig. 7 most directly applicable to the LOCA conditions (i.e., partial unloading and failure temperature of -73°C) supports the conclusion that WPS can be effective in preventing crack extension during a LOCA. The structural implications of WPS to a LOCA are considered next.

7. STRUCTURAL INTERPRETATION OF WPS DURING A LOCA

A theoretical analysis of the potential for crack extension during a LOCA has been performed by Cheverton [3] for a typical pressurized water reactor vessel. His results are interpreted here to characterize the maximum depth of crack extension when considering the influence of WPS. The time-dependent stress intensities computed from Cheverton's analysis for a long, axial crack are presented in Figs. 8-10. The following assumptions were made in modeling the vessel:

- Wall thickness = 216 mm (8.5 in.)
- Inner wall fluence = 4×10^{19} n/cm^2 >1 MeV (Corresponding to a 40-year irradiation period)
- High impurity copper level (>0.25%)
- Preirradiation K_{Ic} vs temperature as defined by Westinghouse Corporation [4,5] for A533-B steel.
- Vessel not pressurized during the LOCA

As previously described, the factors of decreasing fluence and increasing temperature toward the outside wall surface provide the mechanism for the arrest of a running crack that may initiate in the material of relatively low toughness near the inner wall surface. Arrest is assumed to occur when the K_{IR}* value exceeds the K_I value at the crack tip. Furthermore,

*The K_{IR} vs temperature behavior for unirradiated material is defined in Section III of the ASME Boiler and Pressure Vessel Code. The mechanics of crack arrest is a topic of current research and presently one cannot guarantee that crack arrest will occur exactly when K_{Ic} = K_{IR}.

the degradation in K_{IR} caused by neutron bombardment through the wall has been characterized in the subject analysis according to the procedures of Regulatory Guide 1.99 [8]. The latter defines the K_{IR} vs temperature trend for irradiated material by a simple temperature translation of the preirradiation trend, based on the fluence level and residual impurity content of the steel. The K_{Ic} vs temperature trend for the irradiated material has been similarly projected. The validity of the latter assumption, however, is subject to additional verification.

Figure 8 illustrates the maximum K_I level for a long axial flaw 7.5 minutes after the LOCA initiation. From the first intersection of K_I and K_{Ic} it is concluded that an axial crack having a depth-to-wall-thickness ratio (a/W) of 0.03 will initiate at this time. The flaw will propagate to a relative depth of a/W = 0.36 before it is assumed to arrest. It should be noted that different size flaws can initiate at different times. In other words, Fig. 8 represents crack initiation conditions only at 7.5 minutes.

A cross plot of the intersections of K_I with K_{Ic} and K_{IR} at various times is shown in Fig. 9. The dashed line illustrates the progressive initiation-arrest-reinitiation behavior of a shallow crack. This description suggests that the crack could completely penetrate the wall. However, Cheverton [3] has pointed out that the assumptions of his model are conservative and that complete wall penetration may not actually take place. Specifically, the K_{Ic} calculations were based on linear elastic behavior. For large crack penetrations (a/W >0.5) the remaining ligament is subjected to plastic deformation and the assumption of linear elastic behavior is not valid. The presence of plasticity will result in K_I levels less than those computed elastically and therefore will decrease the propensity to penetrate the wall[9].

Figure 10 depicts the behavior of K_I with time for a family of long, axial flaws. It is important to note the relationship between these curves and the locus of points for which K_I/K_{Ic} is unity. With flaws of relative depth greater than 0.2, it is clear that the intersection of K_I and K_{Ic} occurs with decreasing K_I. This points out that all cracks greater than a relative depth of 0.2 have been warm prestressed. On the basis of the NRL investigations, it is therefore expected that cracks greater than this depth will not initiate. Given the above, it is possible, nevertheless, to predict crack extension to relative depths greater than 0.2 Consider a flaw of relative depth of 0.1 in the framework of Fig. 9. Since this flaw is not subject to WPS, it will begin to extend at a time of 3 minutes and penetrate to a relative depth of 0.2 Because only cracks of relative depth greater than 0.2 are subject to WPS, the crack will reinitiate at a time of 7 minutes and extend to a relative depth of 0.34. Further extension is not likely because of WPS during the time periods up to 18 minutes when the next initiation would be predicted in the absence of WPS.

The preceding description illustrates that while crack initiation from shallow cracks cannot be prevented by WPS, the magnitude of the crack extension can be limited by this phenomenon so as to preclude complete penetration of the wall. The benefit of WPS is such that a potentially severe accident, that of complete wall penetration, is reduced to one of lesser severity in which the vessel integrity is maintained.

8. SUMMARY CONCLUSIONS

The present research investigations have considered the phenomenon of warm prestress and its potential benefit for the minimization of crack extension during a LOCA. It is concluded that the mechanisms associated with WPS act to elevate the critical fracture toughness, K_{Ic}, of the material at the crack tip. During a LOCA, an elevation of K_{Ic} results when the peak value of WPS, K_{WPS}, is applied at a sufficiently high temperature so that the K_{Ic} of the material exceeds K_{WPS}. After this peak loading to K_{WPS} the K_I level in the vessel decreases and achieves the critical K_{Ic} value at lower temperature (because of the temperature dependence of K_{Ic}). This study has demonstrated that failure never occurs during unloading. This observation is of major significance to the integrity of a prototype vessel. From this behavior it is concluded that crack initiation will not take place in a vessel once the crack tip has been subjected to WPS. This conclusion is valid irrespective of either the degree to which K_I at the crack tip falls below K_{Ic} or the nature of the unloading path. In other words, crack extension after WPS can take place only with increasing K_I; since K_I does not increase after the peak K_{WPS}, no mechanism exists upon which to postulate crack extension.

In terms of margin of safety against fracture, this study has shown that the elevation in K_{Ic} caused by WPS is not uniform and depends upon: (a) the WPS level, (b) the ΔT between the failure temperature and the temperature of WPS, and (c) the degree of unloading. Specifically, the beneficial elevation of K_{Ic} appears to be greatest when both the ΔT and the degree of unlaoding are small. Fortunately, both of these conditions are met during a LOCA and an elevation of K_{Ic} should be assured by the WPS phenomenon. In particular, it is concluded that WPS levels of 120 $MPa\sqrt{m}$ or less can result in an elevation of K_{Ic} for the vessel material to at least the WPS level during a LOCA transient, assuming of course, that the material is metallurgically capable of exhibiting this level of toughness.

In these experiments, a relatively large ΔT was necessitated in order to unambiguously demonstrate the elevation of K_{Ic} by WPS. During the LOCA however, the ΔT can be much smaller than the values investigated. It is felt that a small ΔT will result in even greater benefit of WPS than demonstrated by this study. Nevertheless, experimental investigations are continuing at NRL to characterize the WPS phenomenon in the case of a small ΔT.

It has been suggested that the use of uniaxially-stressed bend specimens in the present investigation does not permit simulation of the biaxial loading that occurs in the vessel during a LOCA. However, the influence of biaxial loading in the linear elastic regime is not considered to be significant and should not alter the conclusions of the present investigation. A partial verification of this hypothesis results from a comparison of the data from the uniform specimens vs specimens having face grooves. Although not exactly similar, face grooves increase the crack-tip constraint as does the biaxial loading. However, the data have shown that no trend was effected by the face-grooving.

An interpretation of the structural significance of WPS has been made for a typical reactor pressure vessel containing a long-axial flaw and whose wall has been severely embrittled. Based upon an interpretation of K_I trends for this vessel computed by ORNL [3], it is concluded that WPS by itself cannot prevent the extension of shallow cracks. However, for the reference vessel containing a long-axial flaw, it is concluded that: (a) a shallow crack (a/W >0.2) can initiate and extend to a relative depth of 0.34, and (b) a crack of initial relative depth greater than 0.2 is prevented from extending any amount by the WPS phenomenon. While the preceding interpretation of WPS to a reactor pressure vessel was meant to consider the worst case, a general conclusion regarding the significance of WPS to the mitigation of crack extension during a LOCA requires a parametric analysis to be made that considers different initial flaw geometrics as well as differences in K_{Ic} trends, fluence and material sensitivity to irradiation.

Finally, it was observed that an elastic analysis of crack extension during a LOCA has predicted complete penetration of the wall without consideration of WPS. Due to the conservatism in the elastic analysis, complete penetration of the wall may not actually occur. Nevertheless, the crack extension computed more exactly by means of a refined elastic-plastic model cannot be easily verified by full-scale experiments. Thus, the WPS phenomenon may eliminate the need for further elastic plastic computations and, more importantly, may provide the key element upon which to predicate the integrity of the vessel during a LOCA.

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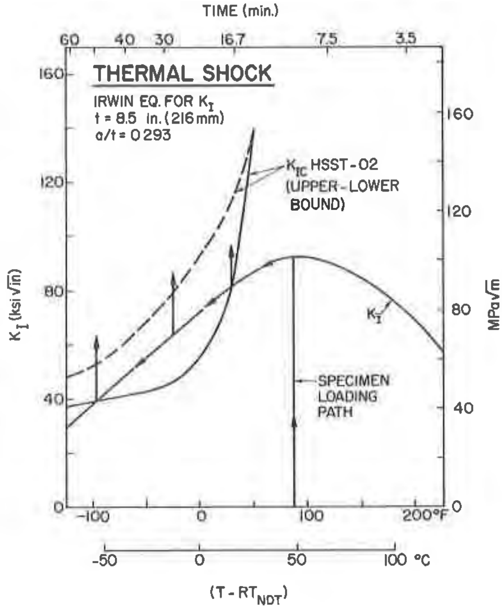

Fig. 1 - Representation of the K levels experienced by the material at the tip of a flaw in the nuclear pressure vessel undergoing thermal shock. The time scale orginates with the LOCA; RT_{NDT} is the reference temperature as defined by Sec III, ASME Boiler and Pressure Vessel Code.

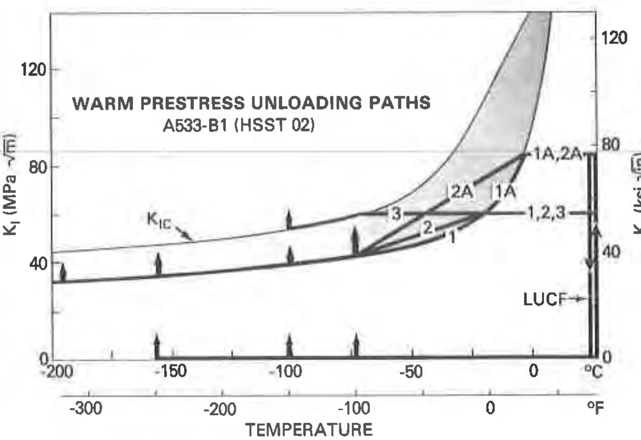

Fig. 2 - Unloading paths for warm prestress specimens. The vertical arrows, after the initial loading, designate isothermal loading to failure. The data for the K_{Ic} trend are given in Ref 4 and 5.

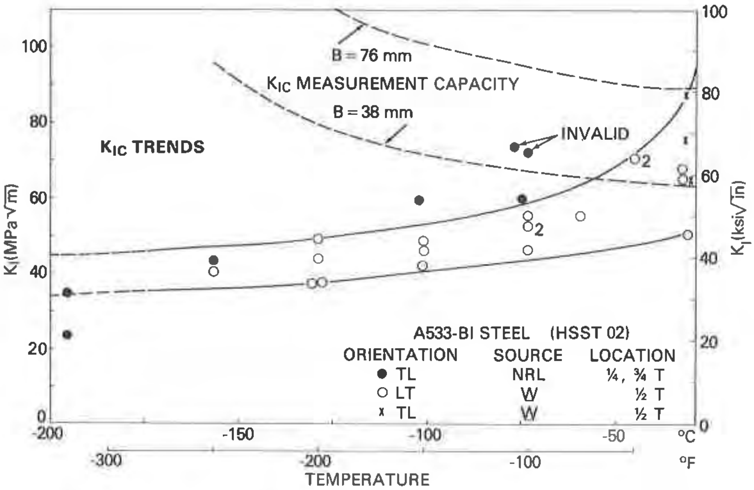

Fig. 3 - K_{Ic} trends for the program material (Ref 4,5). NRL verification tests with 38 mm thick specimens suggest a somewhat larger scatterband. The K_{Ic} measurement capacity is defined by ASTM E-399.

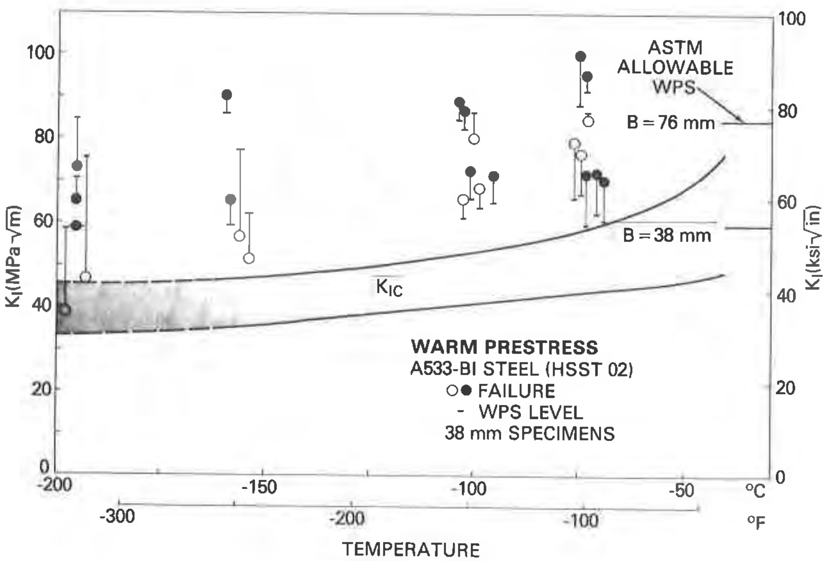

Fig. 4 - Warm prestress trends for 38 mm thick specimens. The open circles represent the LUCF unloading path while the filled circles represent partial unloading paths illustrated in Fig. 2. The K_{Ic} band is taken from Fig. 3.

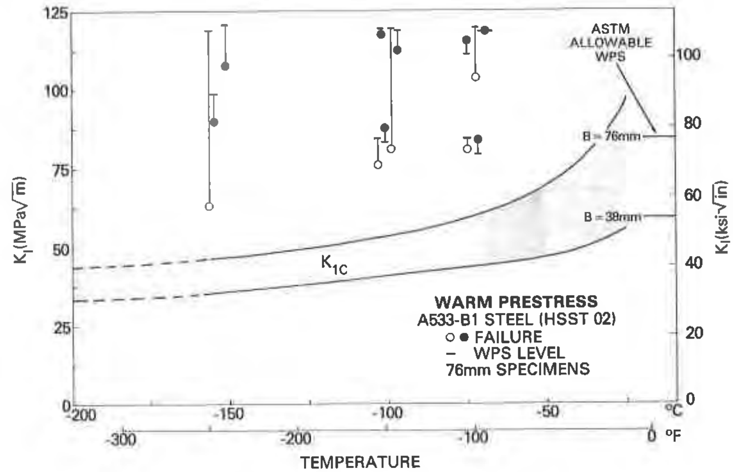

Fig. 5 - Warm prestress trends for the 76 mm thick specimens. The open circle represent the LUCF unloading path while the filled circles represent partial unloading path 2A in Fig. 2.

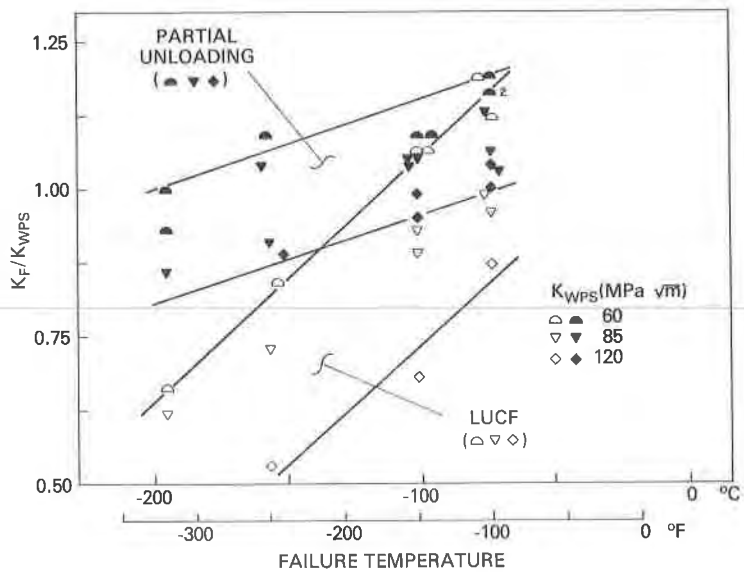

Fig. 6 - Relationship between the failure level (K_F) for three-point bend specimens and (a) warm prestress level (K_{WPS}), (b) failure temperature, and (c) degree of unloading. The term LUCF is defined in Fig. 2.

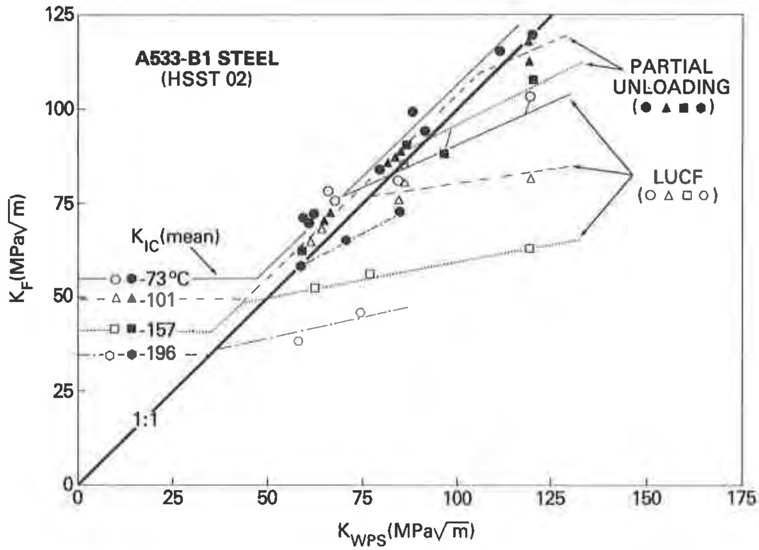

Fig. 7 - Comparison of the fracture level (K_F), with the warm prestress level (K_{WPS}). The mean K_{Ic} values are taken from Fig. 3; the term LUCF is defined in Fig. 2.

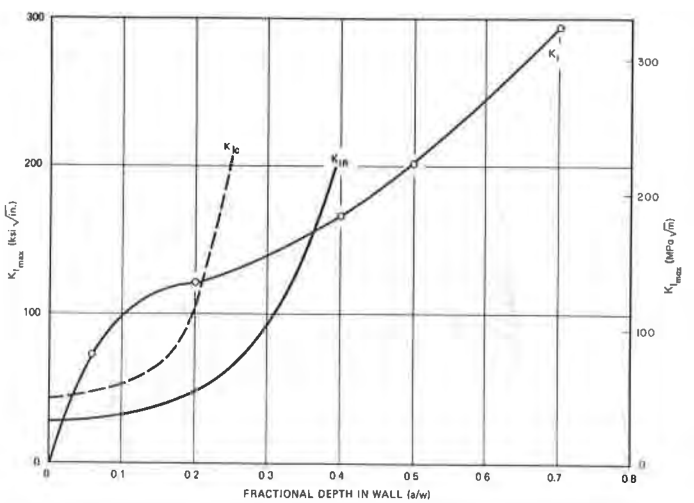

Fig. 8 - Illustration of the critical levels for initiation (K_{Ic}) and arrest (K_{IR}) as defined by the intersection of these curves with the maximum K_I level for a long-axial flaw 7.5 minutes after the LOCA initiation.

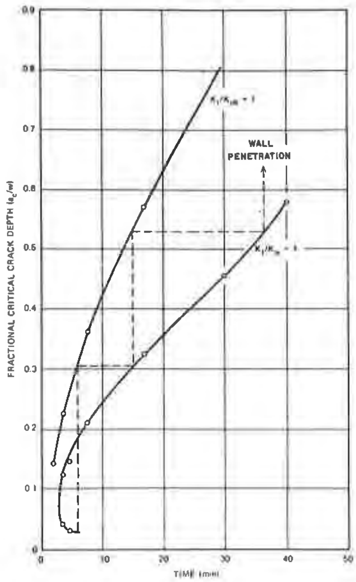

Fig. 9 - Crossplot of the intersections of K_I with K_{Ic} (e.g., Fig. 8) at various times.

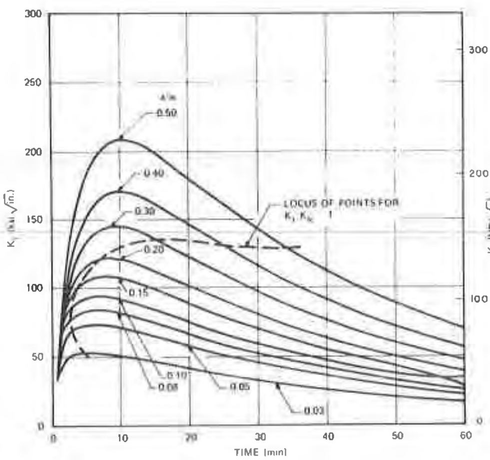

Fig. 10 - Stress intensity factor (K_I) vs time for different relative crack depths (a/W), showing the locus of points at which the critical level for initiation (K_{Ic}) would be attained in the absence of warm prestress.