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PRESSURIZED-THERMAL-SHOCK EXPERIMENTS: PTSE-1 RESULTS AND PTSE-2 PLANS*

R. H. Bryan J. G. Merkle
R. K. Nanstad G. C. Robinson
R. Wannert† G. D. Whitman

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Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831

ABSTRACT

The first pressurized-thermal-shock experiment (PTSE-1) was performed with a vessel with a 1-m-long flaw in a plug of specially tempered steel having the composition of SA-508 forging steel. The second experiment (PTSE-2) will have a similar arrangement, but the material in which the flaw will be implanted is being prepared to have low tearing resistance. Special tempering of a 2 1/4 Cr — 1 Mo steel plate has been shown to induce a low Charpy impact energy in the upper-shelf temperature range. The purpose of PTSE-2 is to investigate the fracture behavior of low-upper-shelf material in a vessel under the combined loading of concurrent pressure and thermal shock. The primary objective of the experimental plan is to induce a rapidly propagating cleavage fracture under conditions that are likely to induce a ductile tearing instability at the time of arrest of the cleavage fracture. The secondary objective of the test is to extend the range of the investigation of warm prestressing.

INTRODUCTION

The pressurized-thermal-shock experiments in the Heavy-Section Steel Technology (HSST) Program are part of a series of fracture-mechanics experiments in pressure vessels on a scale large enough to produce restraint at the crack tip similar to that of full-scale pressure vessels. The combined loading of pressure and thermal shock makes it feasible to investigate fracture phenomena of particular concern to the evaluators of overcooling accidents in pressurized-water reactors.

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†Swiss Federal Institute of Reactor Research, Wurenlingen, Switzerland.

Results of the first pressurized-thermal-shock experiment, PTSE-1, have now been evaluated, and the second experiment, PTSE-2, is planned for mid-1986. Preliminary conclusions from PTSE-1 were reported at last year's information meeting.[1] Now all the data recorded during the test and fractographic evidence of the behavior of the flaw have been thoroughly evaluated and described in a topical report.[2] These experimental results are important because fracture phenomena were observed under conditions that were as representative of plane strain as are likely to be studied experimentally at temperatures and stresses representative of real reactor pressure vessels.

The series of pressurized-thermal-shock experiments was motivated by a concern for the behavior of flaws in reactor pressure vessels having welds or shells exhibiting low upper-shelf Charpy impact energies, ~68 J or less. Evaluations of overcooling accidents, however, involved consideration of other complexities that had not been explored under particularly realistic conditions. Issues that have an important impact on accident evaluation and are also amenable to investigation in pressurized-thermal-shock experiments are: effects of sequences of warm-prestressing and anti-warm-prestressing episodes on crack initiation; behavior of cleavage fractures propagating into ductile regions; transient crack stabilization in ductile regions; and crack shape changes in bimetallic zones of clad vessels.

The experiments are performed with nominally 150-mm-thick intermediate test vessels of the HSST program in a facility designed to impose coordinated pressure and thermal-shock loads. Figure 1 shows a typical arrangement of a flawed test vessel inside a shroud (outer vessel). During the pretransient phase of an experiment, the shroud serves as an oven for heating the test vessel to nearly isothermal conditions. The thermal transient is produced by circulating a chilled mixture of water and methanol through the shroud. The annulus between the cylindrical sections of the shroud and test vessel is designed to permit a suitable range of convective heat transfer to be attained. Transient internal pressurization of the test vessel to ~100 MPa is feasible. Figure 2 shows a test vessel being lowered into the shroud.

The intermediate test vessels are geometrically suitable for fracture experiments that can be directly related to fracture phenomena in reactor pressure vessels. The vessels are sufficiently long and thick for testing the validity of methods of linear elastic fracture mechanics for cracks extending less than halfway through the wall.[3,4]

The first two experiments, PTSE-1 and PTSE-2, are concerned with crack behavior near to and on the ductile upper shelf and with warm prestressing. The flawed material in PTSE-1 had good upper-shelf toughness, while PTSE-2 is being planned to have low tearing resistance.

REVIEW OF PTSE-1 RESULTS

The first experiment was performed with an unclad vessel with a 1-m-long, 12.2-mm-deep surface crack in a welded-in plug of specially tempered steel. The plug was made of a forging that, with normal heat treatment, would meet the specifications for SA-508 class 2 steel, a material with extensively studied properties. The objectives were to induce cleavage propagation and arrest of the initial crack, warm prestress the arrested crack, and reinitiate propagation under conditions that would drive the crack well beyond the onset of the Charpy upper shelf.

The course of the actual experiment, which consisted of three separate transients, is presented in Fig. 3. The first transient (A) was too conservatively designed; consequently the crack did not propagate. The A transient, however, provided a strong demonstration of the inhibiting effect of warm prestressing. During this transient the crack experienced two long periods of simple anti-warm prestressing ($\dot{K}_I > 0$) while the stress intensity factor K_I was greater than K_{Ic}. In the B transient the crack propagated, arrested slightly above the onset of the Charpy upper shelf (ductile threshold in Fig. 3), and again became warm prestressed without propagation. The C transient produced a crack propagation and arrest.

The fracture surfaces, of which a small segment is shown in Fig. 4, were examined extensively by scanning electron microscopy. This disclosed that both crack extensions were predominantly cleavage with 0 to 15% of the surface appearing as dispersed ductile tearing. There was no evidence of ductile tearing at either of the two arrest sites, although ~10 mm of tearing was implied by a J-integral-tearing resistance analysis of the C transient.

Analysis by linear elastic fracture mechanics with a plastic-zone-size adjustment of K_I represented initiation and arrest events well. Figure 5 shows K_{Ic} and K_{Ia} values inferred from the transient data in comparison with K_{Ic} and K_{Ia} curves premised on small specimen data for the PTSE-1 material. The figure also shows that ASME Section XI curves for the measured RT_{NDT} of 91°C are conservative relative to the experiment. The K_{Ia} point at 300 $MPa \cdot \sqrt{m}$ is particularly significant because the PTSE-1 stress state was nearly a plane strain condition.

PLANS FOR PTSE-2

The primary objective of the second pressurized-thermal-shock experiment, PTSE-2, is to investigate the influence of low-tearing resistance on crack propagation and growth. Vulnerability of reactor pressure vessels to damage in overcooling accidents is a potential problem only in instances of vessel materials that coincidentally have low Charpy impact energies at upper-shelf temperatures. While conclusions of overcooling accident analysis are principally determined by transition temperature and its effect on crack initiation, in some hypothetical transients crack arrest is the controlling phenomenon. In a fracture evaluation it may be found that the arrested cleavage crack is unstable relative to ductile tearing. PTSE-2 is being designed to produce and investigate a cleavage arrest followed by unstable tearing. Ductile tearing prior to crack propagation by cleavage may also be observed. In addition to modeling an important fracture condition, the experiment is expected to elucidate the transition from a rapidly propagating crack in a cleavage mode to a slowly propagating ductile fracture.

The PTSE-2 experiment is also being designed to continue the investigation of warm prestressing started in PTSE-1. The first experiment clearly demonstrated the inhibiting effect of warm prestressing for both positive and negative values of $\dot{K}_I$ when K_I is less than a previous relative maximum. Initiation and reinitiation of crack propagation after periods of warm prestressing were also experienced in PTSE-1, but only after intervening periods of complete unloading. The first phase of the PTSE-2 experiment will be designed to (1) induce simple warm prestressing ($\dot{K}_I < 0$) prior to the time $K_I = K_{Ic}$, (2) induce simple anti-warm prestressing ($\dot{K}_I > 0$) while $K_I > K_{Ic}$, and (3) during anti-warm prestressing increase K_I to levels substantially above the prior maximum value.

The PTSE-1 vessel is being repaired for use in PTSE-2. As in PTSE-1, the flaw will be in a plug of special material welded into the wall of the vessel. The properties specified for the plug are given in Table 1. The steel purchased for PTSE-2 is a 2 1/4 Cr — 1 Mo plate meeting SA-387 grade 22 specifications. Preliminary investigations of various heat treatments indicate that acceptable values of the Charpy-V upper-shelf energy can be obtained. However, the preferred heat treatment will probably not produce yield strengths and transition temperatures within the specified ranges. Yield strength may be as low as 220 MPa. The transition temperature, as defined in Table 1, may be in the range 90 to 110°C. These deviations from the specified properties have been evaluated by fracture analyses and appear to be acceptable and consistent with the objectives of the experiment.

PRELIMINARY ANALYSIS

The experiment may be conducted by a single thermal and pressure transient or it may require, as in the case of PTSE-1, multiple transients. The optimal conditions for attaining the objectives of the upper-shelf aspects of the experiment are not the optimum for an investigation of warm prestressing. Since the first phase of the experiment will be concerned with warm prestressing, a single transient is convenient for exploring and illustrating a prospective experiment.

A transient of interest is illustrated by Fig. 6, which shows crack tip temperature for a crack of feasible initial depth, the concurrent pressure transient, and the induced K_I and K_{Ic} variations with time. This transient induces simple warm prestressing between points A and B and simple anti-warm prestressing between B and D. K_I becomes greater than K_{Ic} in the period A-B. K_I is substantially greater than K_{Ic} during much of the anti-warm prestressing phase. From point C to D, K_I is greater than its previous relative maximum value (point A). It is in this phase of the experiment (C-D) that crack initiation is expected to take place.

Figure 7 shows the importance of uncertainty in K_{Ic} on the success of the warm-prestressing phase of the experiment. In addition to a nominal K_{Ic} curve (for RT_{NDT} = 100°C), the figure shows curves for values of RT_{NDT} 10 K higher and lower. It is imperative that the intersection of the K_{Ic} and K_I curves be in the warm-prestressing phase A-B. An uncertainty of ±10 K would probably preclude conclusive experimental results. However, it is evident that a modified depressurization transient would expand the admissible uncertainty in RT_{NDT} to ±10 K without degrading other aspects of the transient significantly. The window for the K_{Ic} intersection is also quite sensitive to the uncertainty in initial crack depth. Unlike crack depth, which will be measured precisely after the experiment, the location of the K_{Ic} curve will not be revealed by this transient experiment, unless subsequent transients are run without warm prestressing.

The conditions prevailing at the time of the crack-arrest event following the warm-prestressing phase of the experiment are essential to the primary objective of determining upper-shelf behavior following a cleavage arrest. The processes that control the rapid propagation of a crack in transitional material is not well understood (see Fig. 8). The PTSE-1 fractures, which were predominantly cleavage, exhibited a tendency toward a greater proportion of tearing at higher temperatures in the transitional region. However, the qualitative features of the PTSE-2 fracture in the upper transition will be uncertain until after the experiment. Consequently, the strategy of the test will be to avoid initiation and arrest at low K_I values. In particular, K_I at the time of arrest must be at least high enough to precipitate an unstable tear on a quasistatic basis.

Figure 9 illustrates the course of a marginally acceptable transient with respect to arrest and instability. If crack initiation is inhibited by warm prestressing until K_I becomes slightly greater than the previous maximum (point I), the crack jump induces a K_I of ~250 $MPa \cdot \sqrt{m}$ at the time of arrest (at point A). This value of K_I is equivalent to a J_I value of ~0.28 MJ/m^2, which, for low toughness material, may be high enough to generate a tearing instability. A detailed evaluation of this point must be made after tearing resistance data become available. In the experiment the vessel will be depressurized rapidly when a tearing instability is detected.

If crack initiation were delayed beyond point I (Fig. 9) the crack jump would be deeper, the K_I and J_I at arrest higher, and the likelihood of a tearing instability greater. This would be a more desirable situation, because the prediction of a marginally unstable crack is uncertain. If the crack were to initiate earlier than point I, the crack jump would be small and an instability condition would be doubtful. In this case a second pressurized-thermal-shock transient would be run to complete the experiment. This turn of events could be advantageous, since the second initiation would provide a valid measurement of K_{Ic} at a value high enough to resolve the ambiguity mentioned earlier relative to the warm-prestressing phase of the experiment.

The crack-tip conditions for the single-transient experiment are summarized by Fig. 10. This figure shows the K_I-temperature trajectory of the initial crack, the crack jump, and the arrested crack. The extension of the K_I trajectory of the initial crack indicates that this transient would provide a good margin for crack initiation during the anti-warm-prestressing phase.

Critical conditions for all crack depths in this transient are presented in Fig. 11. The points I and A correspond to the respective points I and A in Figs. 9 and 10. An initiation at I′, or from a deeper crack at the same time, would result in an arrest at A′, at which $K_I \approx 350$ MPa·$\sqrt{m}$ which is more favorable for an instability. Ligament instability would not occur for cracks less than 55% of the thickness of the wall even for the low tensile strength material.

CONCLUSIONS

Experiment PTSE-1 demonstrated the strongly inhibiting effects of simple warm prestressing and also showed that simple anti-warm prestressing is not a sufficient condition to alleviate prior warm prestressing. One of the objectives of PTSE-2 is to induce an initiation following warm prestressing and to provide experimental data for comparison with theoretical predictions. PTSE-1 also demonstrated a cleavage crack arrest at a high K_I value without consequential ductile tearing. Similar conditions will be produced in PTSE-2 with material having lower tearing resistance, in which a tearing instability is expected.

REFERENCES

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Table 1. Impact and tensile property requirements

Property	Desired value	Acceptable values	
		Minimum	Maximum
Yield strength (MPa)	517.1	448.2	620.5
Charpy-V upper-shelf energy[a] (Joules)	61.0	54.2	67.8
Temperature at which Charpy-V energy is at the midpoint of the transition (°C)[b]	65.5	51.7	90.6
Maximum temperature at which 100% shear first occurs (°C)	121.1	–	176.7

[a]To be determined at a temperature where the specimen exhibits 100% shear.

[b]Midpoint energy shall be determined by adding 6.8 J to the average of the values obtained with 100% shear and dividing the result by 2.

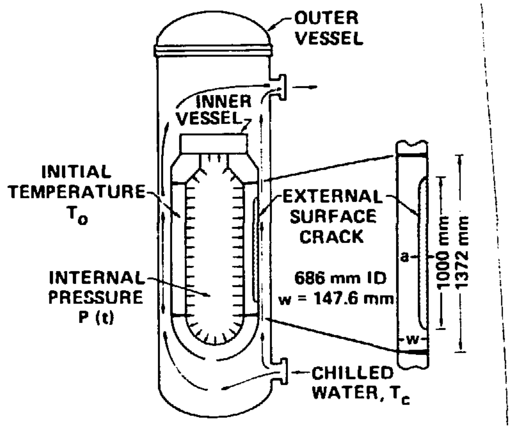

Fig. 1. Schematic view of pressurized-thermal-shock vessel inside shroud. Dimensions shown are for the PTSE-1 vessel.

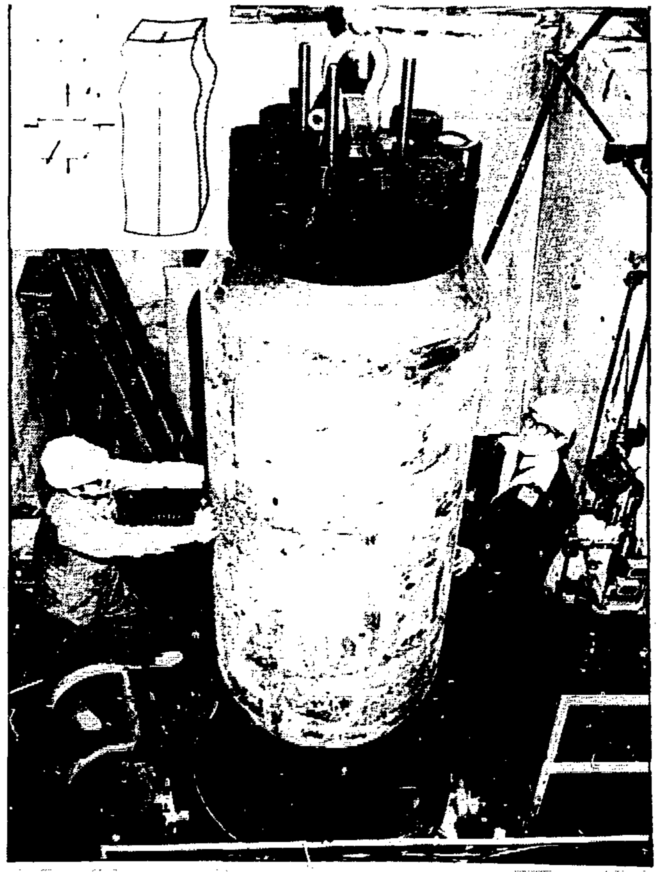

Fig. 2. Test vessel used for preliminary thermal hydraulic tests (PTSE-0) being lowered into shroud.

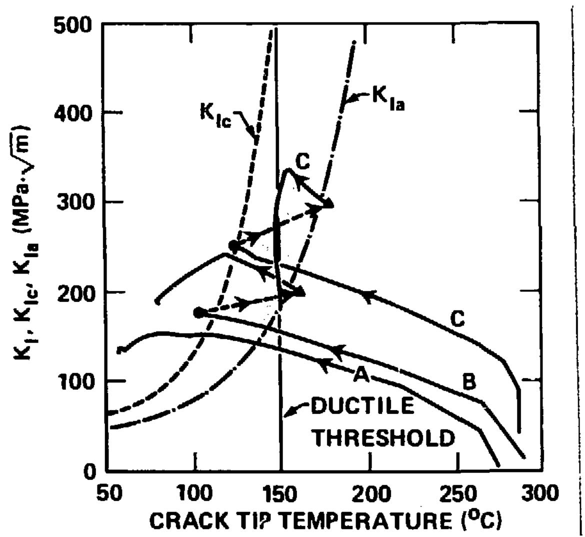

Fig. 3. K_I-temperature trajectory of the crack tip in the three PTSE-1 transients.

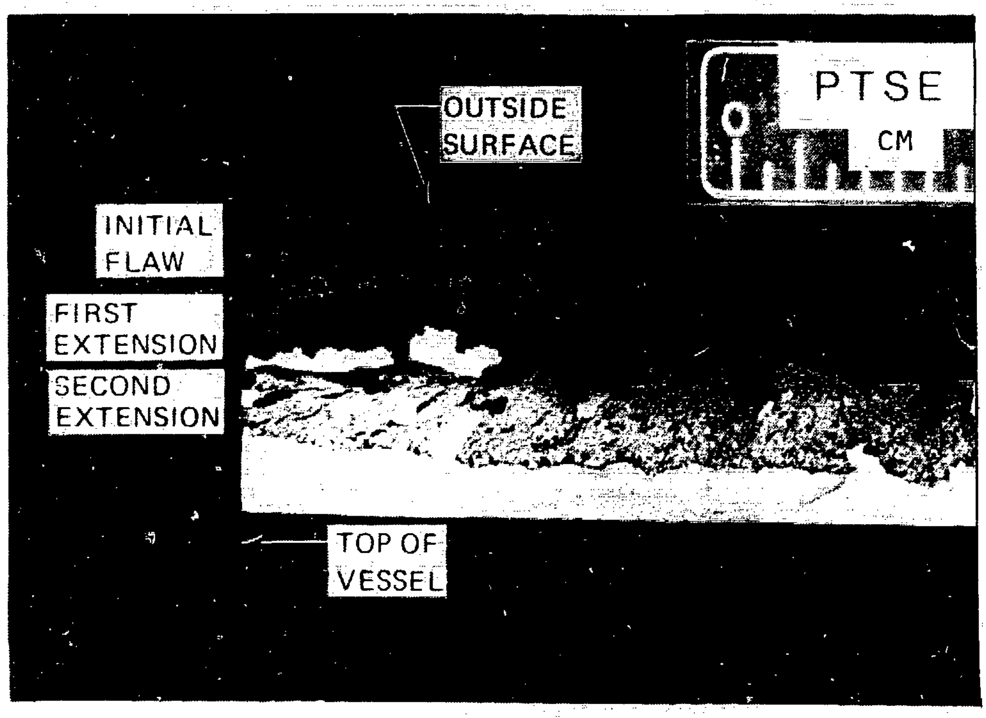

Fig. 4. One segment (3B) of the fracture surfaces of the PTSE-1 vessel.

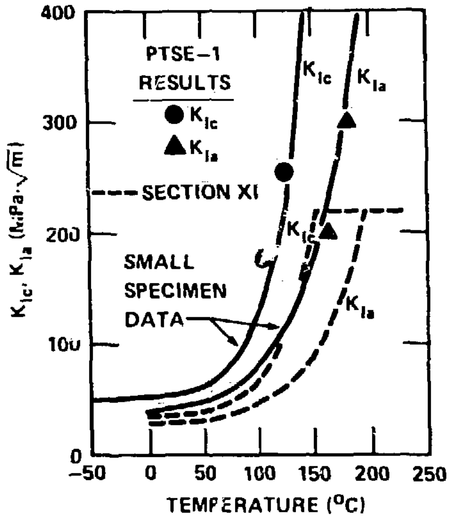

Fig. 5. Fracture toughness values derived from PTSE-1 data compared with pretest expectations and values prescribed by Section XI of the ASME Boiler and Pressure Vessel Code.

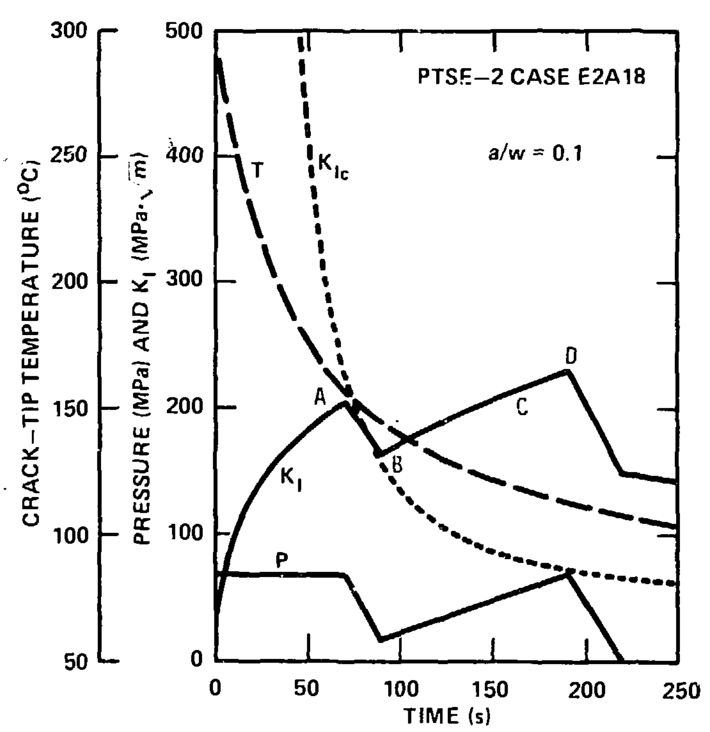

Fig. 6. Pressure, crack-tip temperature, K_I, and K_{Ic} transients for a/w = 0.1 from a preliminary analysis of PTSE-2 based on speculative properties.

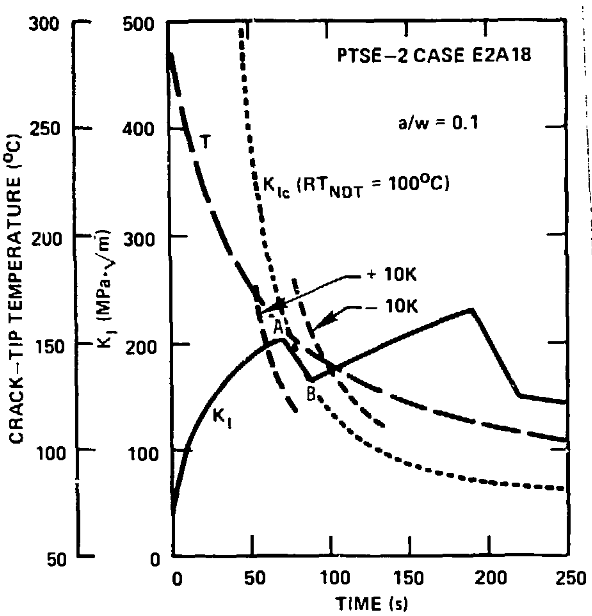

Fig. 7. Effect of uncertainty in K_{Ic} on the timing of a warm-prestressing phase. Curve segments marked ±10K are the K_{Ic} loci for RT_{NDT} 10K higher and lower, respectively, than the nominal value 100°C.

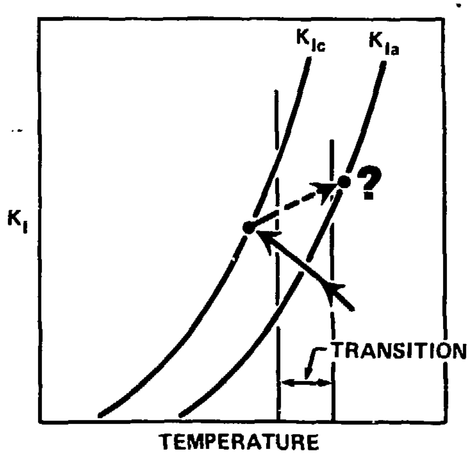

Fig. 8. Illustration of the temperature range in which the mode of fracture in a well-restrained structure is unknown.

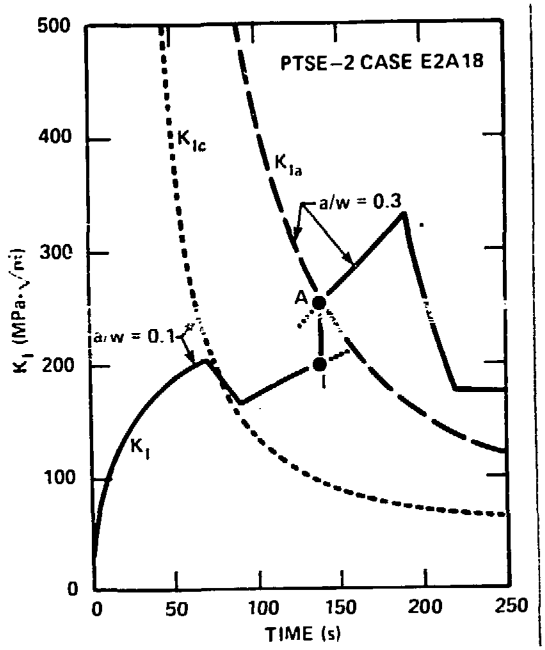

Fig. 9. K_I, K_{Ic}, and K_{Ia} vs time for illustrative PTSE-2 transient in which it is presumed that the crack will propagate at point I during simple anti-warm prestressing. In this case the crack arrests at point A.

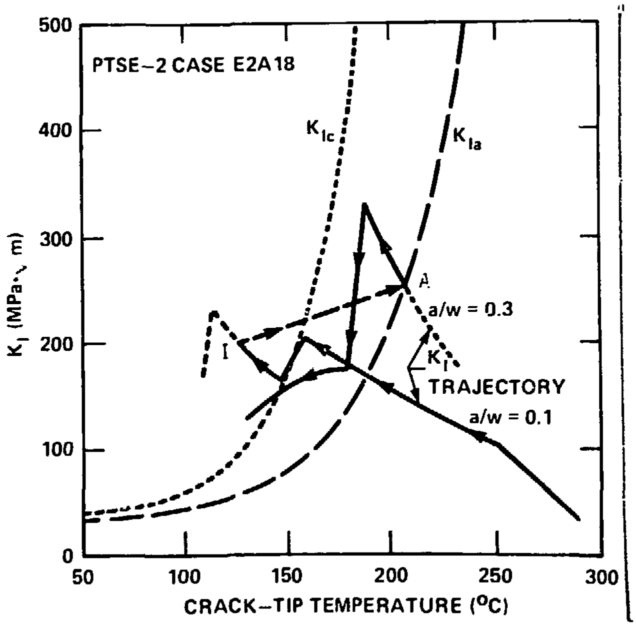

Fig. 10. K_I-temperature trajectory for the transient of Figs. 6, 7, and 9. This shows that, if the initial crack does not propagate, K_I will eventually become ~3 times K_{Ic}.

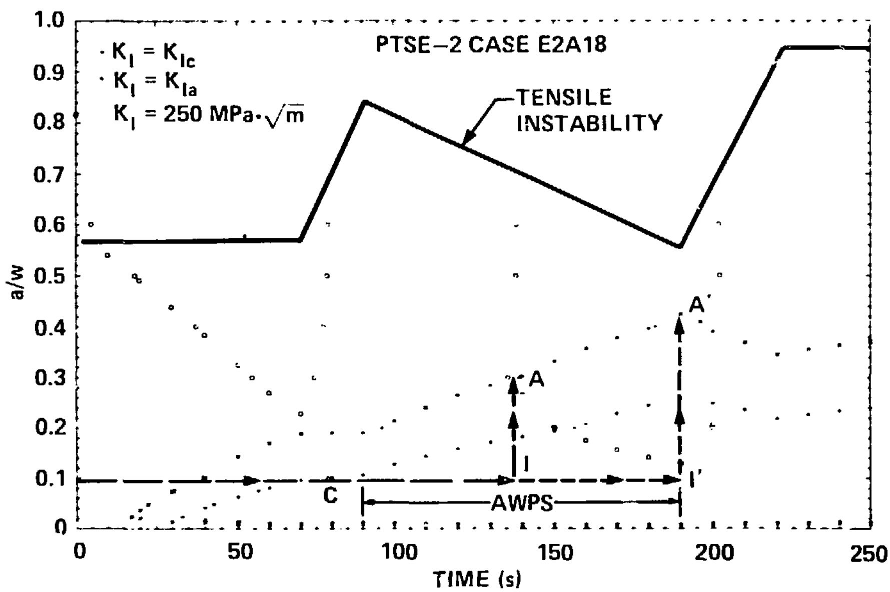

Fig. 11. Critical crack depth curves for crack initiation, arrest, and tensile instability. A crack initiating at point I would arrest when K_I is ~250 MPa·$\sqrt{m}$. This K_I value may be necessary to induce a tearing instability. a/w = ratio of crack depth to wall thickness.

DISCLAIMER