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(To Cynthia)

PERFORMANCE OF LOW UPPER-SHELF MATERIAL UNDER
PRESSURIZED-THERMAL-SHOCK LOADING (PTSE-2)*

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ABSTRACT

The second pressurized-thermal-shock experiment (PTSE-2) of the Heavy-Section Steel Technology Program was conceived to investigate fracture behavior of steel with low ductile-tearing resistance. PTSE-2 was designed primarily to reveal the interaction of ductile and brittle modes of fracture and secondarily to investigate the effects of warm prestressing. A test vessel was prepared by inserting a crack-like flaw of well-defined geometry on the outside surface of the vessel. The flaw was 1 m long by ~15 mm deep. The instrumented vessel was placed in a test facility in which it was initially heated to a uniform temperature and was then concurrently cooled on the outside and pressurized on the inside. These actions produced an evolution of temperature, toughness, and stress gradients relative to the prepared flaw that was appropriate to the planned objectives. The experiment was conducted in two separate transients, each one starting with the vessel nearly isothermal. The first transient induced a warm prestressed state, during which K_I first exceeded K_{Ic} . This was followed by repressurization until a cleavage fracture propagated and arrested. The final transient was designed to produce and investigate a cleavage crack propagation followed by unstable tearing. During this transient the fracture events occurred as had been planned.

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INTRODUCTION

The pressurized-thermal-shock experiments in the Heavy-Section Steel Technology Program are part of a series of fracture mechanics experiments in pressure vessels on a scale large enough to produced 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. The pressurized-thermal-shock experiments provide a basis for evaluating theoretical models of fracture behavior for possible application to fracture analysis of nuclear plants.

The first two experiments in this series (PTSE-1 and PTSE-2) were performed with flawed vessels of identical geometry, shown in Fig. 1. In PTSE-1 (Ref. 1), the surface crack was embedded in a welded-in plug of specially tempered steel. The plug was made of a forging that, with normal heat treatment, would have met 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.

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. However, the loading in the anti-warm-prestressing phase of this experiment was insufficient to

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cause crack initiation. Consequently, one of the objectives of the second experiment was to pursue the warm prestressing to the point of successful crack initiation.

The principal impetus for PTSE-2 was to investigate the influence of low-tearing resistance on crack propagation and growth.² 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. If tearing resistance is low, a crack may tear prior to cleavage initiation during a pressurized-thermal-shock transient, thereby exacerbating the outcome. Furthermore, an arrested cleavage crack may be unstable with respect to ductile tearing. PTSE-2 was designed to produce a cleavage arrest followed immediately by unstable tearing.

In PTSE-2 the flaw was in an insert of special material welded into the 147.6-mm-thick wall of the vessel. The insert and a piece of material used for characterizing the properties of the insert were cut from a 2 1/4 Cr-1 Mo plate meeting SA-387 grade 22 specifications. These two pieces were exposed to the same heat treatment after the insert was welded into the vessel. The heat treatment was intended to provide tensile and toughness characteristics favorable for the experimental requisites. The tensile strengths were undesirably low, but other properties, although somewhat uncertain, were satisfactory. The properties determined prior to the experiment are summarized in Table 1.

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The tearing resistance of the characterization piece (PTC1) is represented in Fig. 2, which shows tearing resistance (J_R) vs incremental crack depth (Δa) for the specimens from PTC1 that exhibited the highest and lowest resistance. These are compared in this figure with similar tearing resistances of irradiated high-copper welds.^{3,4} The PTSE-2 material was evidently representative with respect to tearing resistance of the type of material that is of greatest concern in evaluation of overcooling accidents.

The design of the thermal and pressure transients for the PTSE-2 experiment required reliable estimates of crack initiation and arrest toughnesses. The fact that these toughnesses are difficult or impossible to measure with conventional fracture mechanics specimens contributes to the importance of a large-scale test, as PTSE-2. Values of K_{IC} and K_{Ia} were estimated from specimen tests of PTC1 material for use in extensive pretest fracture analyses. Pretest crack arrest (K_{Ia}) and fracture toughness (K_{IC} and K_J) data are shown in Figs. 3 and 4, respectively. The K_{Ia} data were obtained from tests of 33 and 51-mm-thick specimens. K_{IC} and K_J data are from tests of 25-mm-thick compact specimens. From PTSE-1 experience,¹ it was expected that the K_{Ia} data would provide the most reliable indication of fracture toughness at high transitional temperatures. Therefore, the K_{Ia} data were evaluated first, and the upper and lower toughness curves shown in Fig. 3 were determined by least-squares fits to the raw K_{Ia} data and to β -adjusted⁵ data, respectively. The curves representing K_{IC} at high transitional temperatures were presumed, in the absence of reliable data, to be ~ 30 K from the respective K_{Ia} curves. It

transpired that a curve determined by the low-temperature K_{Ic} points and fitting β and rate-adjusted^{1,5} K_J data in the transition was suitably related to the upper K_{Ia} curve. This fitted K_{Ic} curve and a lower toughness K_{Ic} curve, displaced by 30 K from the former (Fig. 4), were adopted for planning the PTSE-2 experiment.

Experimental Procedure

The experiment was planned to consist of two transients, of which the first would induce warm prestressing ($\dot{K}_I < 0$) followed by reloading ($\dot{K}_I > 0$) until the crack propagated by cleavage. The second transient was planned to produce a deep cleavage crack jump with an arrest or mode conversion occurring only after conditions conducive to unstable tearing were attained. The second transient was also necessary to provide a measurement of K_{Ic} that was not strongly affected by warm prestressing so that the effects of warm prestressing in the first transient could be evaluated.

The initial crack in PTSE-2 was formed by hydrogen charging a shallow electron beam weld in the insert. The crack was 1 m long by 14.5 mm deep. The vessel was instrumented to measure temperature profiles through the cylindrical wall and opening displacements of the crack mouth. The latter instrumentation is shown in the photograph of the vessel in Fig. 5.

The pressure and temperature transients are shown in Figs. 6 and 7, respectively. The fracture behavior throughout the experiment was resolved into

events that were evident in the recordings of crack-mouth-opening displacements versus time and in the distinct stages of fracture visible on the fracture surfaces. Figure 8 shows the response of the crack during the entire first transient, PTSE-2A. Ductile tearing occurred in three separate phases of PTSE-2A: (1) prior to warm prestressing (before A, $t < 184.6$ s), (2) during reloading (B to C, 341.8 s $< t < 361.4$ s), and (3) after the cleavage arrest (C' to D, $t > 361.4$ s). The crack propagated both axially and radially by cleavage at 361.4 s. In the second transient, PTSE-2B, K_I increased monotonically while the crack tore stably, propagated radially in cleavage, and tore unstably. The phases of fracture in both transients are shown by the photograph of the fracture surface in Fig. 9. The final tearing ruptured the vessel over a distance of ~730 mm. The important events and conditions are summarized in Table 2.

Analysis and Interpretations

Fracture analyses were performed by methods of linear elastic fracture mechanics and by two- and three-dimensional elastic-plastic finite element analysis. Pretest analysis was based on calculated temperature distributions and prospective pressure transients attainable with the test facility. Post-test analysis was based on measured pressures and temperatures. Results reported here are all based on two dimensional elastic-plastic finite element analysis.

The course of transient PTSE-2A is shown in Fig. 10, a plot of K_I and K_{IC} vs time. Prior to initial warm prestressing (points A to B) the K_I is shown for the initial (14.5 mm) and intermediate (19.6 mm) crack depths, the latter depth determined by measured displacements and analysis and confirmed by the appearance of the fracture surface. The crack was at its intermediate depth from points B to C, and during the time from C to D it grew by tearing from a depth of 19.6 to 22.5 mm. The crack propagated by cleavage (D to E) and subsequently tore. The K_{IC} vs time curves shown in Fig. 10 were calculated from the measured temperatures for two crack depths on the basis of the upper toughness K_{IC} curve of Fig. 4 shifted temperature-wise by ~ 20 K so as to agree with the cleavage initiation event in PTSE-2B. Figure 10 shows that the crack attained the $K_I = K_{IC}$ condition during the warm prestressing phase, B to C, as had been planned.

The conditions of the cleavage fracture in PTSE-2B are shown in Fig. 11. The K_I curve is for the precleavage crack depth, 46.1 mm. The momentary arrest at 69.2 mm was evident only by the long narrow band of ductile tearing visible on the fracture surface (Fig. 9).

The toughness values K_{IC} and K_{Ia} inferred from the experimental data are shown in Fig. 12 in comparison with the pretest upper-toughness K_{Ia} curve and the upper K_{IC} curve shifted to agree with PTSE-2B. The apparent elevation of the PTSE-2A initiation point as a consequence of warm prestressing is $\sim 50 \text{ MPa}\cdot\sqrt{\text{m}}$.

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The crack initiation after warm prestressing in PTSE-2A was interpreted on the basis of a theoretical procedure developed by Chell.⁶ For application to PTSE-2, Chell's theory was modified to account for tearing during the final loading step. The modification is similar to that described by Chell in Ref. 7. The analysis described here involves simplification of the physical states of the real structure: the strip yield model of plastic zones is used; the temperature and flow stresses at the crack tip are attributed to the entire plastic zones; the loading states are expressed in terms of K_I values calculated by a deformation theory plasticity model; and tearing is assumed to take place in a short time interval immediately preceding cleavage.

The significant effects of warm prestressing with and without ductile tearing are illustrated in Fig. 13. The solid curves in parts a and b of the figure represent the theoretical predictions of K_I at fracture for a fix crack and a tearing crack, respectively. The experimental point in Fig. 13(a) would be the perceived initiation condition if one did not know that the crack tore immediately prior to cleavage. For both the tearing and the fixed cracks, the theoretical and experimental fracture points exceed K_{Ic} substantially, namely, more than $40 \text{ MPa}\cdot\sqrt{\text{m}}$. The calculations for the tearing crack predicted that fracture would have occurred at a $K_I = 7 \text{ MPa}\cdot\sqrt{\text{m}}$ lower than the experimental point, as shown in Fig. 13(b). When tearing is involved the predicted fracture conditions are very sensitive to the extent of tearing and the tensile strength of the material.

The low tearing resistance of the PTSE-2 material promoted ductile tearing in both transients. The tearing occurred while material at the crack tip was at or below the onset of the Charpy upper shelf. The tearing behavior in PTSE-2 was remarkably different from that of PTSE-1, in which there was no contiguous region of ductile tearing. The extent of tearing was estimated for both experiments on the assumption that stable tearing is controlled by the condition $J_I = J_R$, where J_I and J_R are the applied J integral and the tearing resistance, respectively. Although J_R was much higher for PTSE-1 than PTSE-2, measurable tearing was predicted from J_R data for that experiment. Within the scatter of J_R - Δa data presented in Fig. 2, calculated values of Δa that agree with the PTSE-2 experiment can be found. However, no single J_R - Δa curve can predict all of the stable crack extensions in PTSE-2.

Conclusions

This experiment produced, for the first time with stress and toughness states representative of reactor pressure vessels, (1) the arrest of a brittle fracture with an immediate tearing instability and (2) brittle fracture following warm prestressing. Principal conclusions are that: (1) low-upper-shelf material can exhibit very high arrest toughness; (2) ductile tearing promotes more severe fractures in low-upper-shelf material; (3) warm prestressing inhibits brittle fracture to some degree even when crack driving forces are increasing with time; (4) benefits of warm prestressing are diminished by ductile tearing; (5) a simple theoretical analysis of warm prestressing represented fracture conditions reasonably well; and (6) calculations of ductile

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tearing based on resistance curve test data did not consistently predict the observed tearing.

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Table 1. PTSE-2 characterization material (PTCl) properties

Property	Value
Yield strength (MPa)	255
Ultimate strength (MPa)	518
NDT temperature (°C)	49
Onset of Charpy upper shelf (100% shear fracture appearance) (°C)	150
Charpy upper shelf energy (J)	~50-75 ^a
Charpy transition temperature:	
At 50% shear fracture appearance	90
At 0.89 mm lateral expansion	98

^aRange for all depths in plate.
The average at 1/4 depth is ~68 J.

Table 2. Events and conditions during the PTSE-2 transients

Event	Time (s)	Crack depth, a (mm)	Crack-tip temperature (°C)	K_I (MPa·√m)
<u>PTSE-2A</u>				
Initiation of thermal shock	~112	14.5	302.8	
First maximum K_I	184.6	19.6	128.0	195.7
Minimum K_I	341.8	19.6	77.0	171.0
Onset of secondary precleavage tearing	341.8	19.6	77.0	171.0
Initiation of cleavage	361.4	22.5	80.7	198.9
Cleavage arrest	361.4	39.3	130.6	261.4
Termination of tearing (by unloading)	365.6	42.4	138.0	278.7
<u>PTSE-2B</u>				
Initiation of thermal shock	~155	42.4	274.9	
Onset of precleavage tearing	<575.8	42.4	a	a
Initiation of cleavage	575.82	46.1	102.4	248.1
Interruption of cleavage by ductile tearing and reinitiation		69.2	146.8	361.6
Final cleavage arrest	575.82	78.8	162.9	419.3
Onset of ductile tearing	576.2	78.8	162.9	406.5
Vessel rupture (and complete unloading)	576.7	147.6	216.4	

^aAt $t = 575.82$ s, $T = 94.8^\circ\text{C}$ and $K_I = 233.8$ MPa·√m at this depth.

Figure Captions

Fig. 1. PTSE-2 test vessel geometry.

Fig. 2. Tearing resistance J_R vs crack extension Δa for PTCl, the characterization material for the low upper-shelf insert in the PTSE-2 vessel. The PTCl data are compared with data from tests of irradiated high-copper welds. The points plotted are for the highest and lowest J_R curves for each of the two materials.

Fig. 3. Crack-arrest toughness data for characterization piece PTCl. The upper-toughness curve is a least-squares fit to the data shown. The lower-toughness curve is a similar fit to β -adjusted data (points not shown).

Fig. 4. Fracture toughness data for characterization piece PTCl. The two lowest points are the only valid K_{IC} data. The upper-toughness curve is a least-squares fit to the lower bound β -adjusted and the rate-adjusted points.

Fig. 5. Photograph of PTSE-2 vessel showing crack-mouth-opening-displacement gage installation.

Fig. 6. Pressure vs time measured in the PTSE-2 transients. Dashed lines show the planned continuation for pressurization if the crack had not jumped at the times indicated. (a) PTSE-2A. (b) PTSE-2B.

Fig. 7. Temperature vs time at the radii of the initial crack depths in the PTSE-2A and 2B transients.

Fig. 8. CMOD vs time at the center of the flaw for the PTSE-2A transient.

Fig. 9. Photograph of a central segment of the PTSE-2 fracture surfaces.

Fig. 10. K_I and K_{IC} vs time from posttest elastic-plastic finite element analyses based on actual pressure and temperatures measured in PTSE-2A for precleavage crack depths.

Fig. 11. Crack-tip conditions for the precleavage crack depth from post-test elastic-plastic finite element analysis using experimental pressure and temperature data from transient PTSE-2B: K_I , K_{IC} , and K_{Ia} vs crack-tip temperature.

Fig. 12. Crack initiation (K_{IC}) and arrest (K_{Ia}) toughness values observed in PTSE-2 compared with the shifted pretest K_{IC} curve and the upper toughness K_{Ia} curve.

Fig. 13. Theoretical prediction of post-warm-prestressing fracture conditions K_I vs K_{IC} for the PTSE-2A transient compared with actual fracture. Predictions are based on K_I values from posttest elastic-plastic finite element analysis using measured pressure and temperatures. Plastic zones in the warm-prestressing analysis are based on measured flow stresses for characterization material PTCl. (a) Crack without tearing. (b) Tearing crack.

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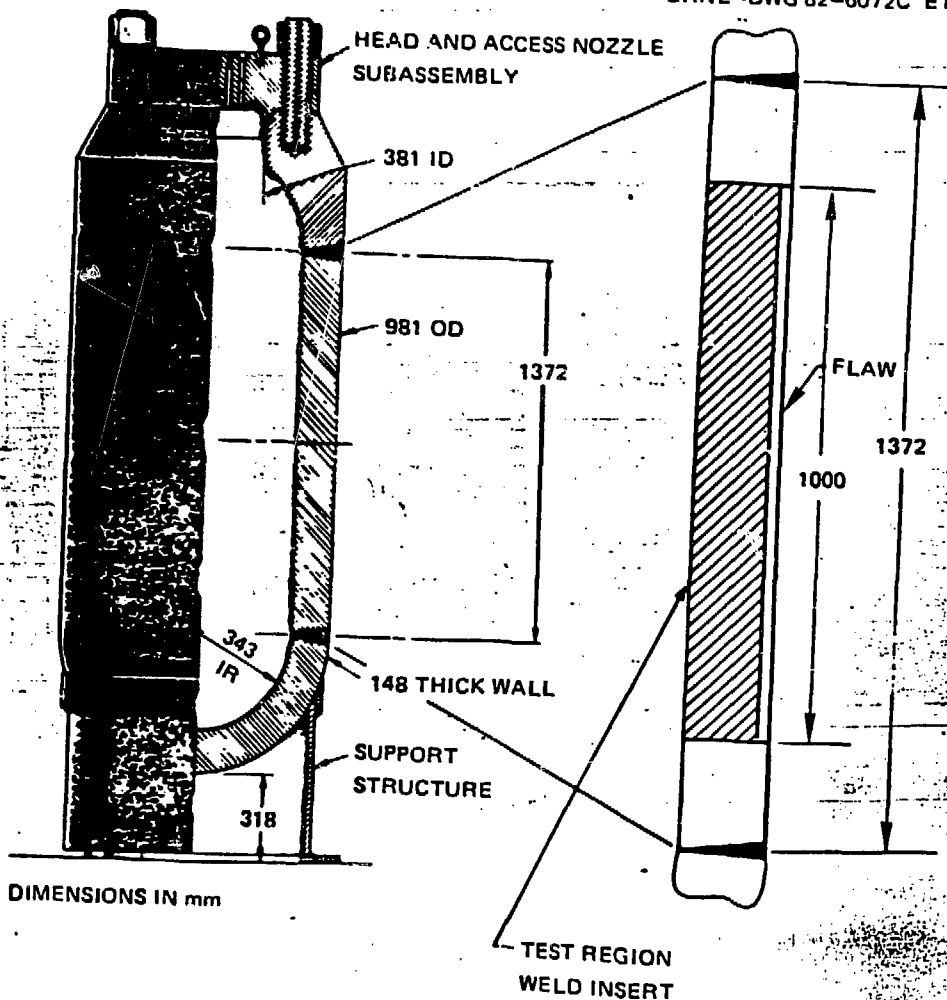


Fig. 1

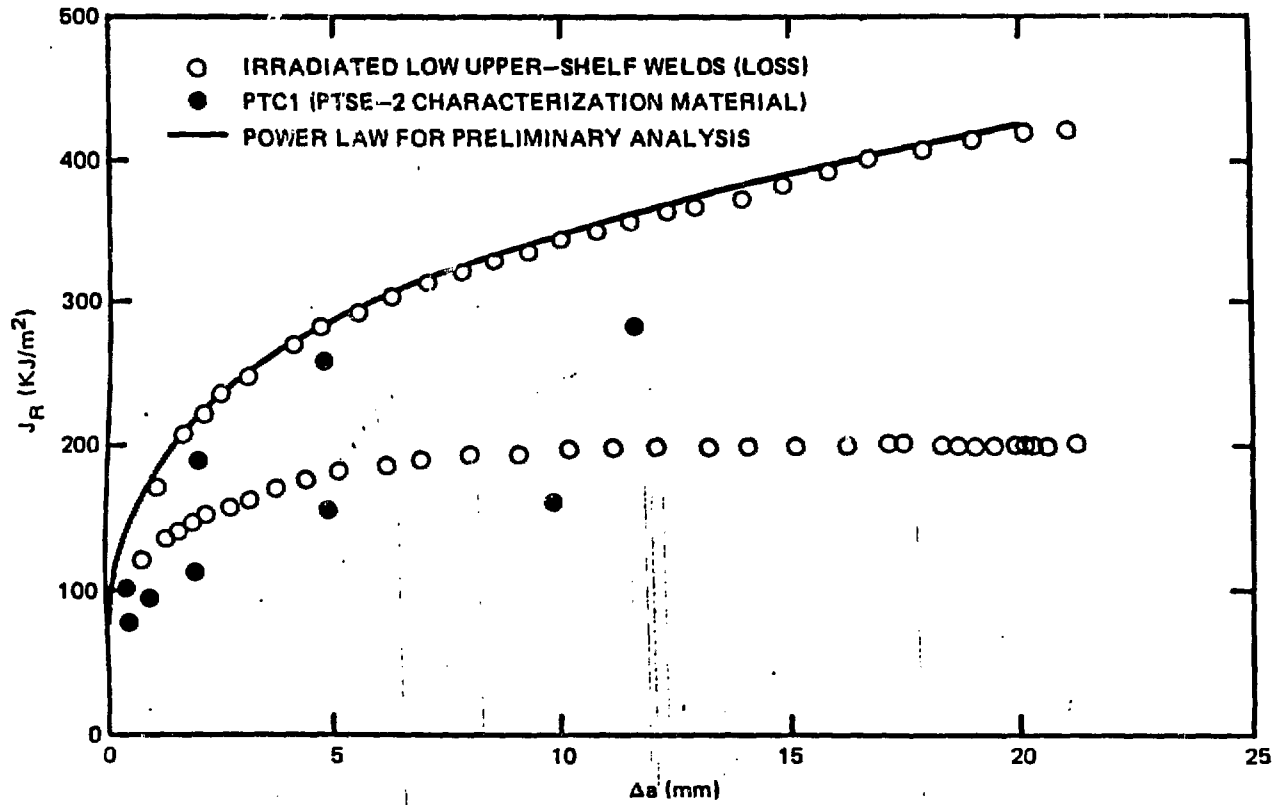


Fig. 2

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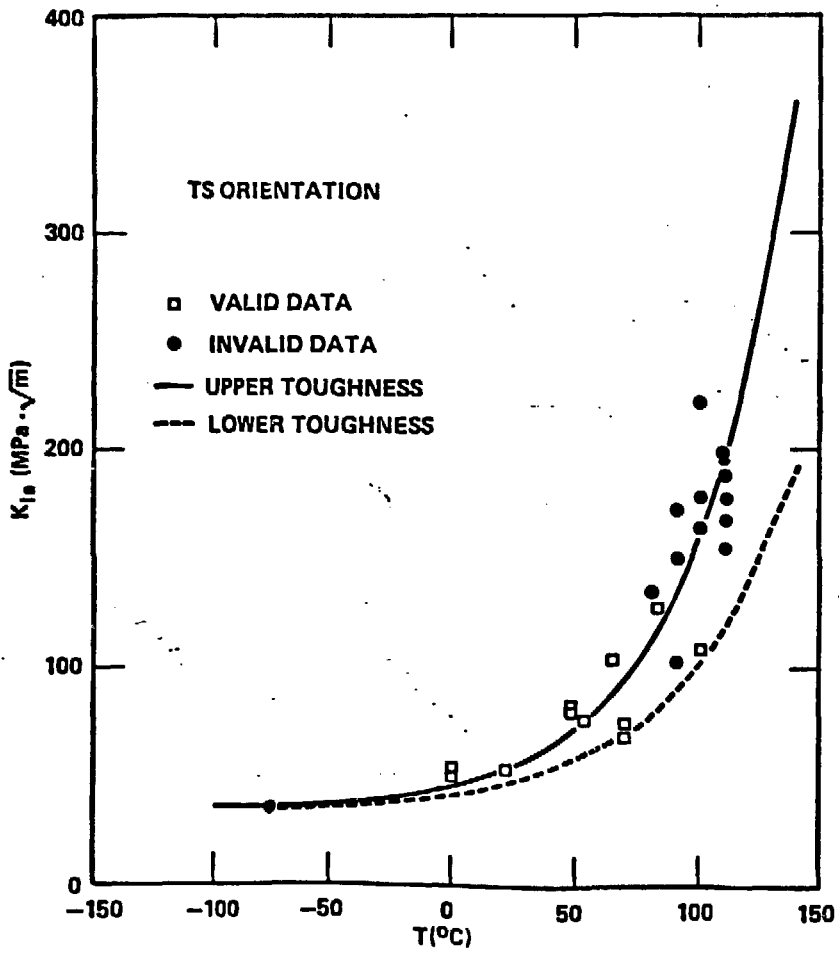
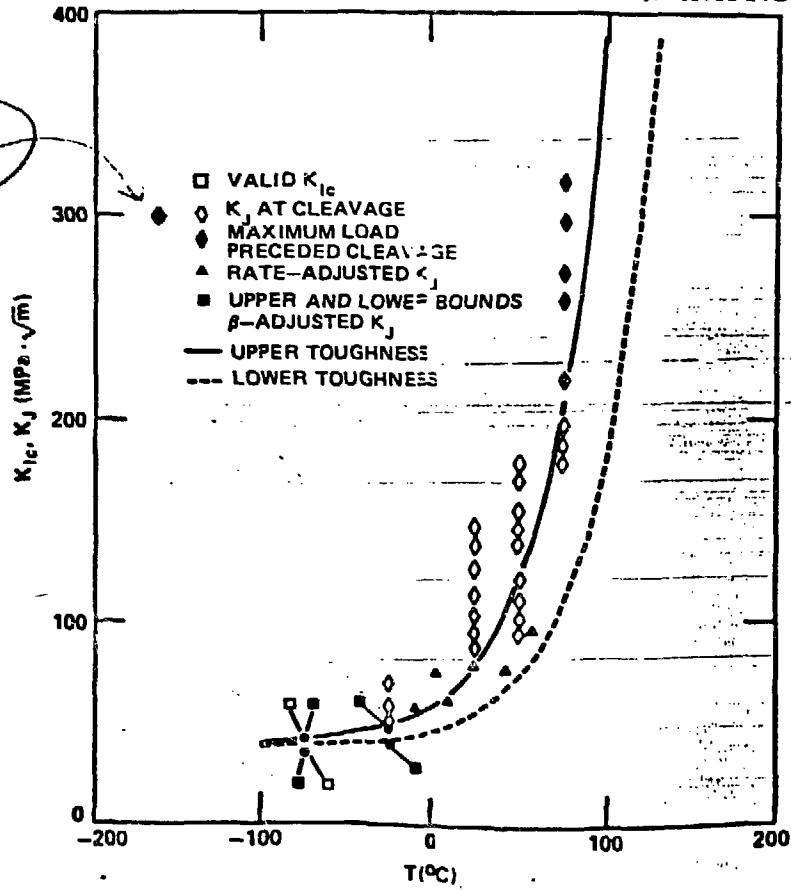


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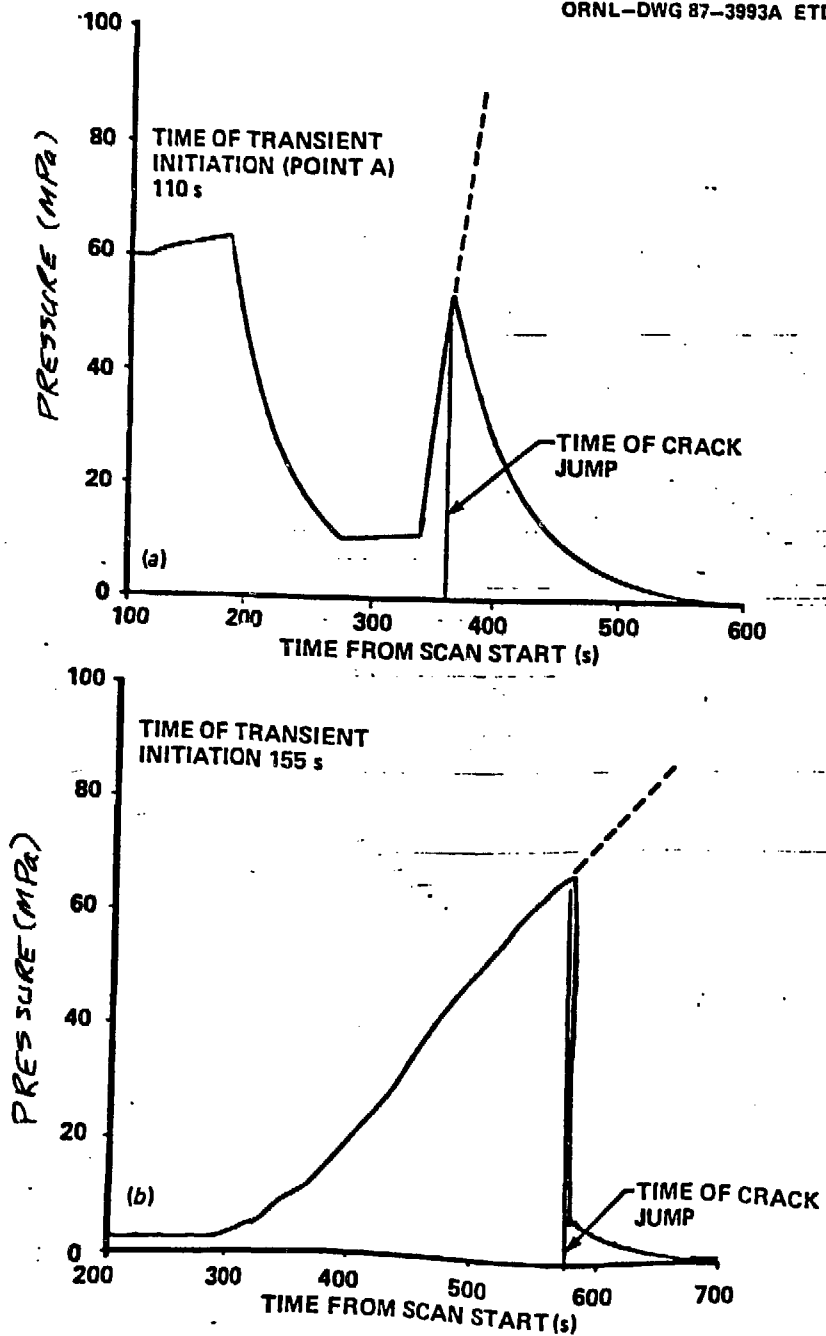
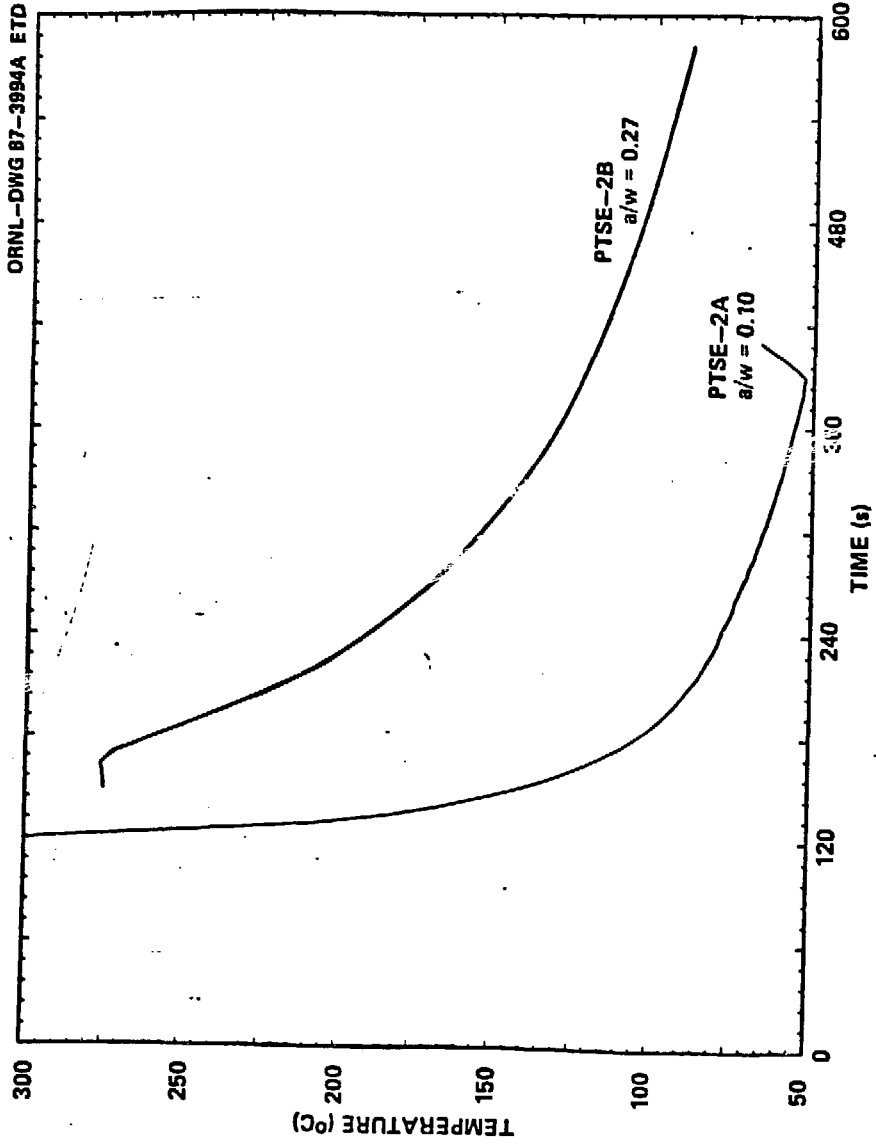


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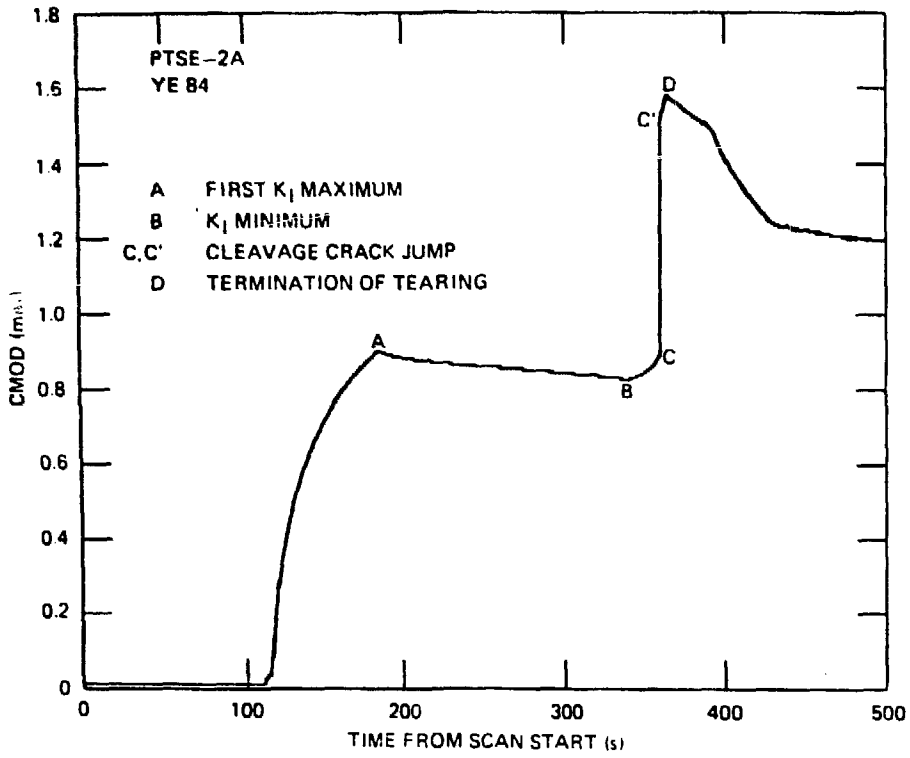


Fig 8

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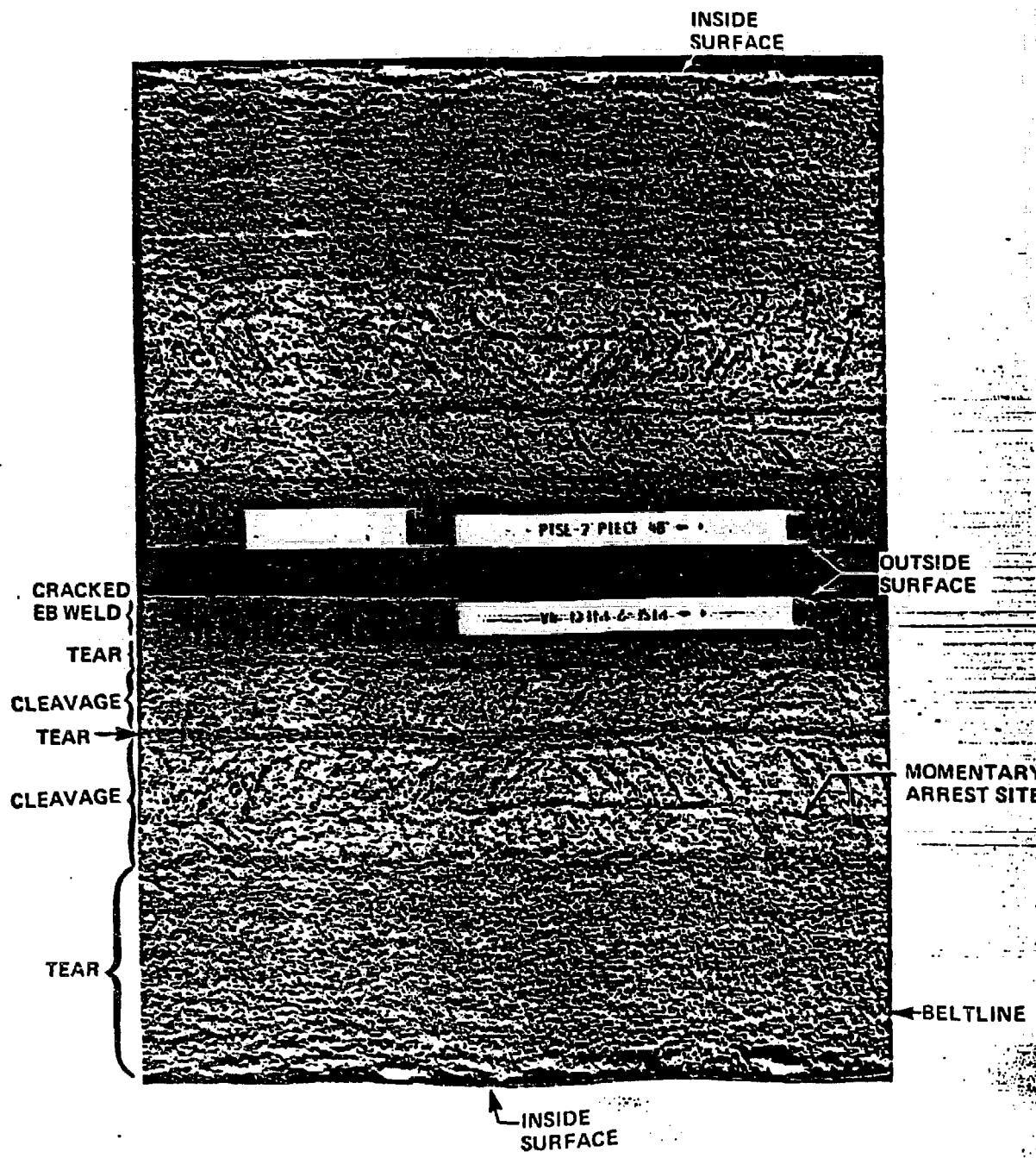


Fig 9

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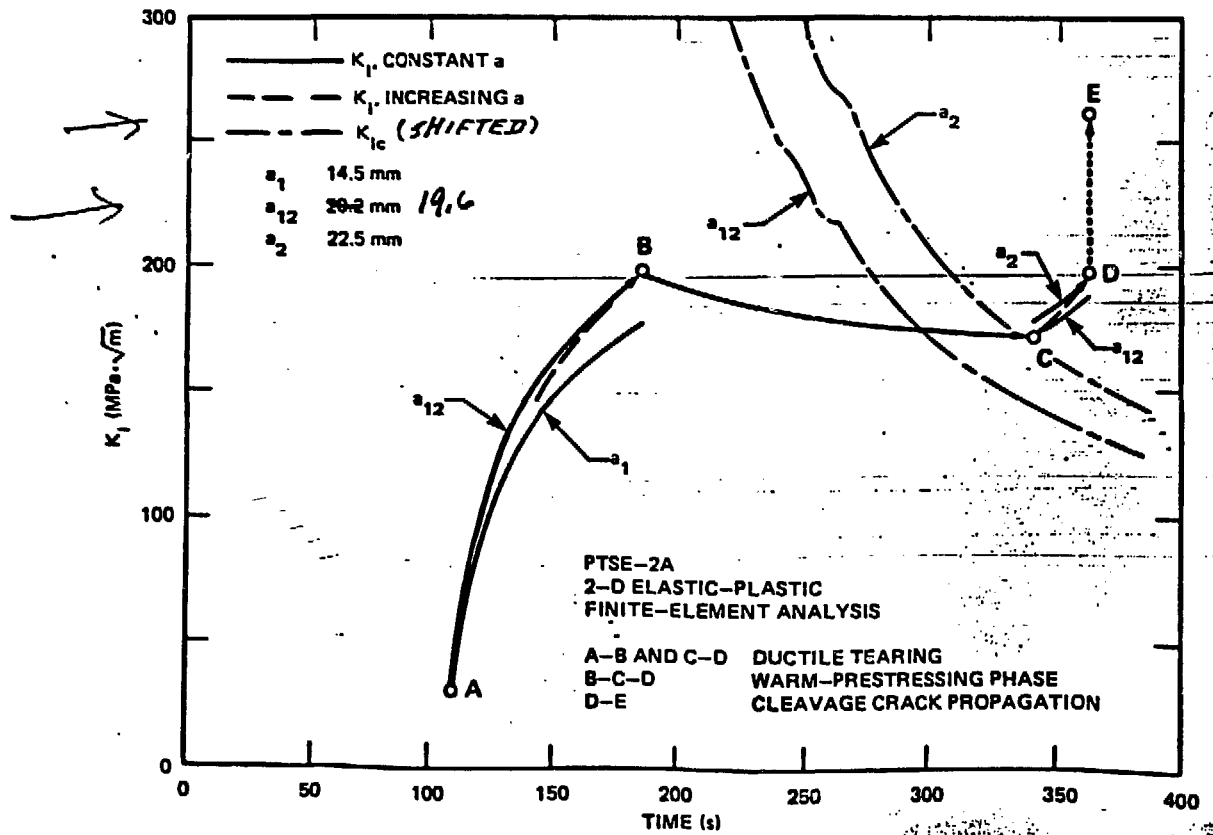
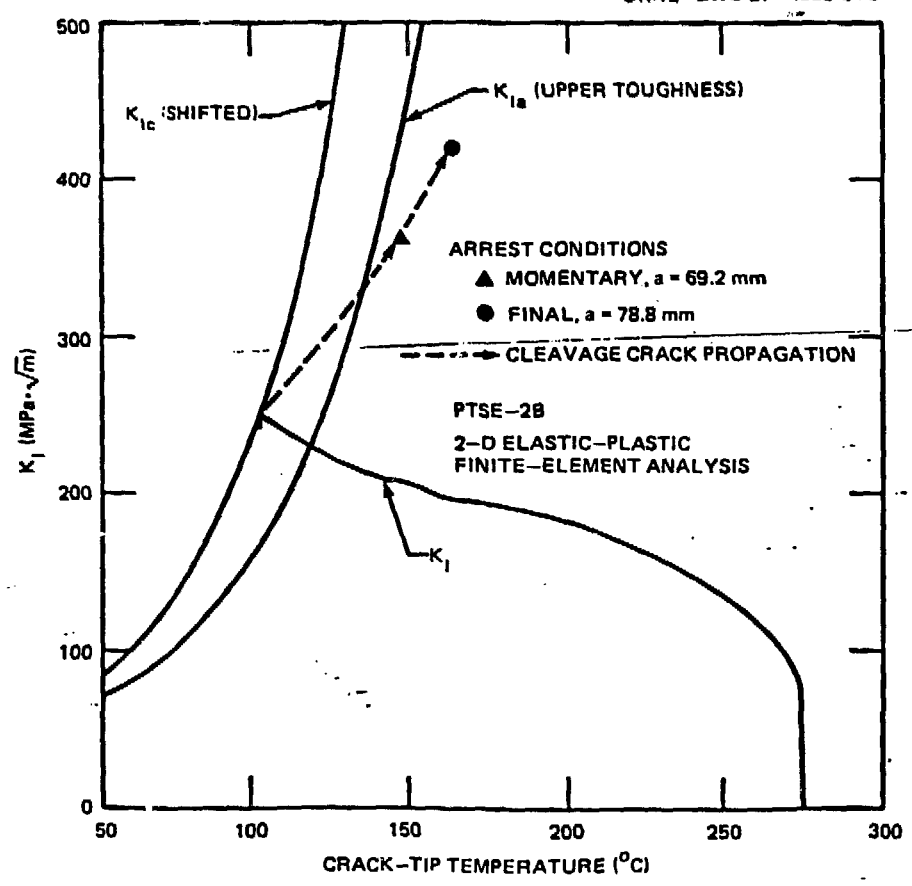


Fig. 10

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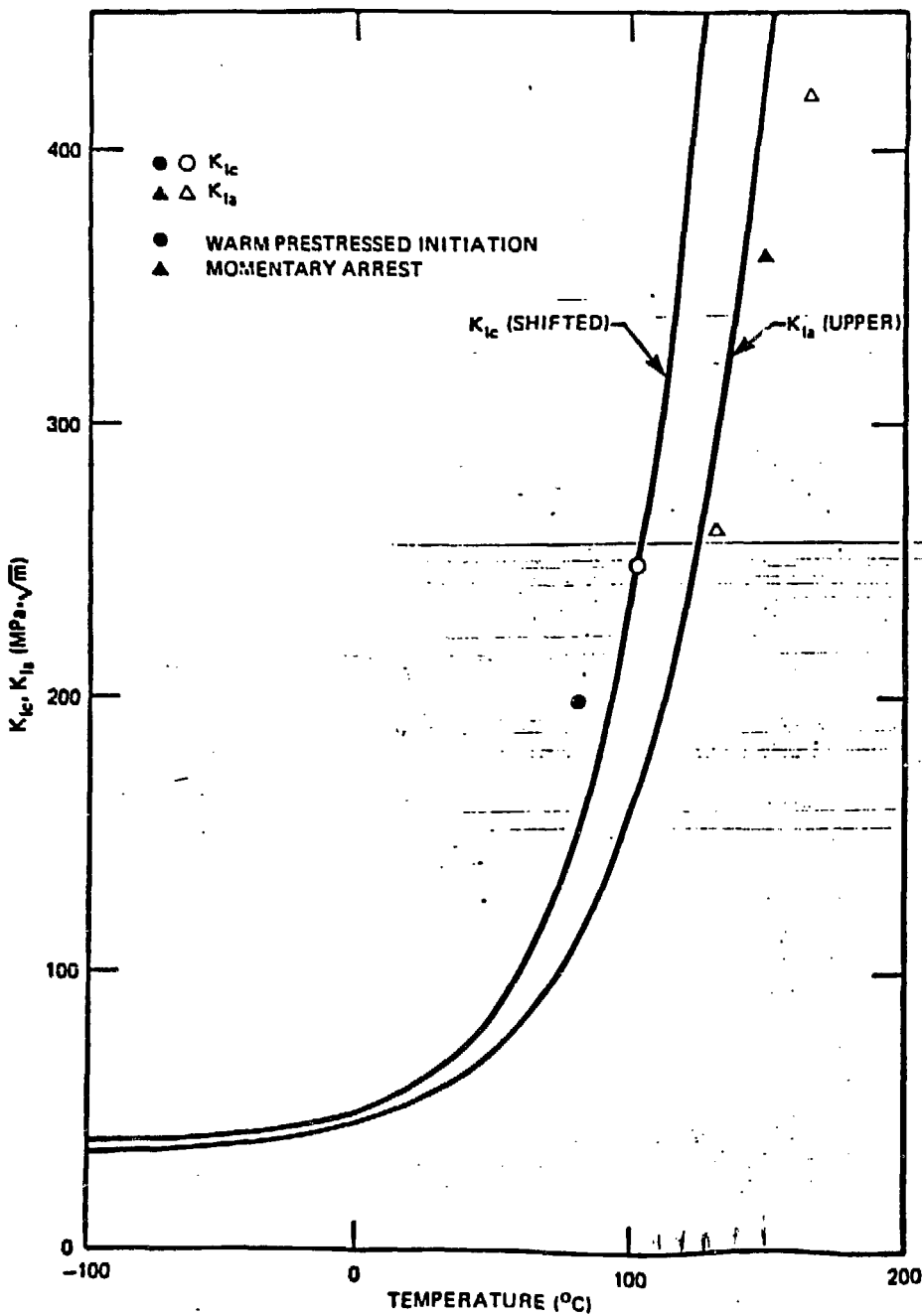
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Fig. 11

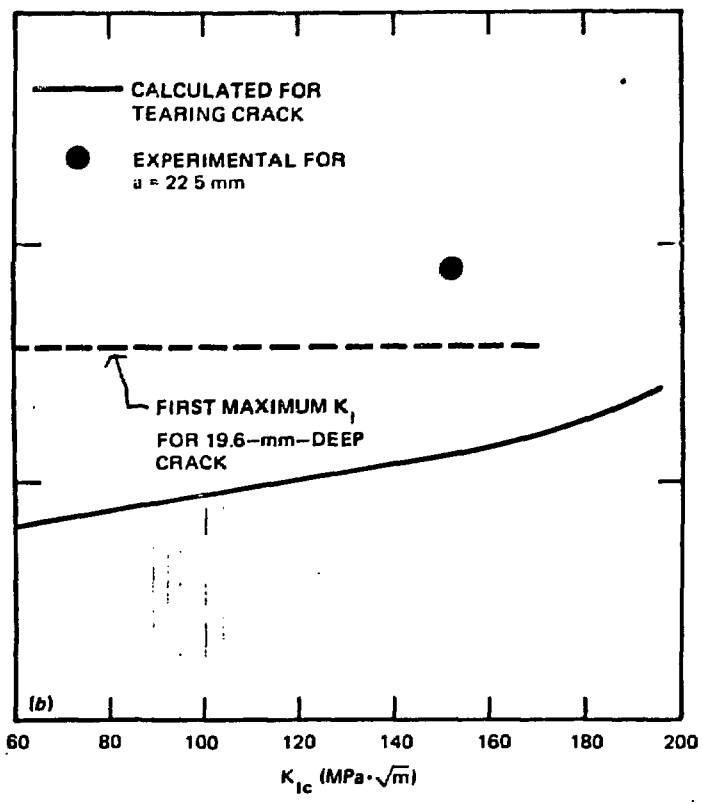
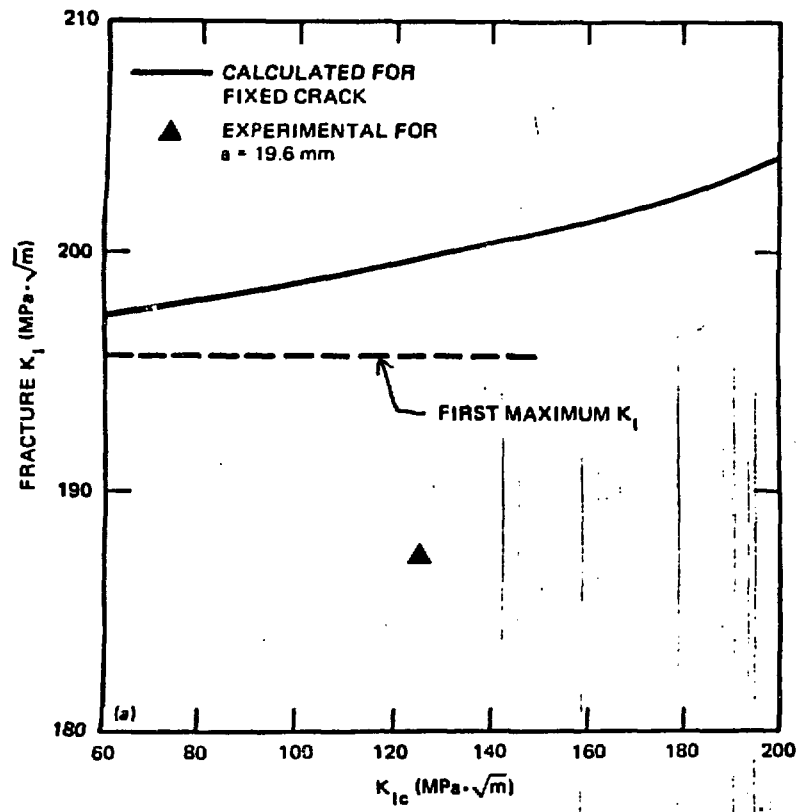
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Fig. 13

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