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BEHAVIOR OF DEEP FLAWS IN A THICK-WALL CYLINDER UNDER THERMAL SHOCK LOADING*

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The behavior of inner-surface flaws in thick-wall vessels subjected to severe thermal-shock loadings has been under investigation at ORNL for several years. During this time five thermal shock experiments have been conducted. The first four[1-4] were conducted with 533-mm-OD x 152-mm-wall x 914-mm-length steel cylinders (A508, class 2, quench-only heat treatment). They demonstrated initiation and arrest of shallow flaws under severe thermal shock conditions and indicated that LEFM is valid for this particular situation.

Analysis of the PWR LOCA-ECC indicates that under some circumstances a pre-existing flaw on the inner surface of the vessel could propagate deep into the wall, and that the extent of propagation would be influenced by the vessel diameter-to-thickness ratio and also by warm prestressing (WPS).[1,2] Neither of these effects could be investigated in the first four experiments because the test specimen diameter-to-thickness ratio was too small and because the toughness was too low. Thus, additional experiments were in order.

The purpose of the fifth experiment (TSE-5), which has only recently been conducted,[5] was to demonstrate initiation, arrest, WPS and arrest in a rising K_I field during a severe thermal shock and under conditions that promote deep penetration prior to final arrest.

Appropriate design conditions for TSE-5 included a 991-mm-OD x 152-mm-wall x 1220-mm-length cylinder with toughness properties similar to those for HSST Plate 02, a test cylinder initial temperature of ~93°C and a thermal shock medium of liquid nitrogen (−197°C). To overcome film boiling associated with LN_2 quenching a special inner-surface coating was developed; and in an attempt to achieve the desired toughness characteristics for our existing A508 class-2-chemistry test cylinder, a toughness-vs-tempering-temperature study was conducted and subsequently a tempering temperature of 613°C specified. The initial flaw selected for TSE-5 was a sharp, 16-mm-deep, long (1220-mm) axial crack.

Data collected from the test specimen during TSE-5 included temperature distributions through the wall (180 thermocouples), indications of initiation

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and arrest events (COD, UT and AE instrumentation), crack depth (COD and UT), and crack velocity (COD).

As predicted, the long axial flaw experienced three initiation-arrest events during TSE-5, and selected data pertaining to these events are summarized in Table 1. As indicated, the final arrested fractional crack depth at mid-length of the cylinder was ∿0.8. UT measurements during the experiment indicate that as the crack progressed its depth became more and more nonuniform, being greater at mid-length than at the ends, as would be expected. The final fractional crack depth at the ends was ∿0.4.

The pretest analysis indicated that the maximum fractional crack jump for a single event would be ∿0.2, and yet the second crack jump during TSE-5 was ∿0.4, indicating a relatively higher effective toughness for the second initiation event. This event constituted a "long" crack jump, a condition that we were hoping to achieve by some means in a subsequent experiment for the purpose of studying dynamic effects of long crack jumps. During TSE-5 some of the COD gages were recorded on fast-phenomena digital equipment, and this provided a means for estimating crack velocity. For the second crack jump the velocity initially was ∿180 m/sec and decreased thereafter.

A post-test analysis of TSE-5 indicates that the toughness of the test cylinder above ∿0°C was less than had been expected, and also that the thermal shock was more severe than planned. This resulted in somewhat greater flaw penetration than expected (80% compared to a predicted range of 50 to 70%), and an inadequate demonstration, if any, of WPS. Furthermore, conditions were not favorable for demonstrating arrest in a rising K_I field. With regard to heat transfer, the symmetry in quenching was very good, thus preserving the desired two-dimensional aspects of the test.

There was additional cracking during TSE-5 that originated at a very small cross crack in the EB weld that was used to generate the long axial flaw. In addition to propagating radially, this cross crack extended (from one end only) initially in a circumferential direction and then branched many times forming longitudinal flaws, some of which extended to the ends of the cylinder and to a fractional crack depth of ∿0.4. This crack network continued around the inner surface, but as it approached the primary long axial flaw the longitudinal branching ceased; however, three circumferential branches continued until they terminated at or close to the primary axial flaw. At the present time it appears that the secondary cracking took place after the third initiation event associated with the long axial flaw and thus had no effect on the primary events. However, an accurate account of the time of occurrence awaits further analysis of the fractures.

It appears at this time that LEFM and the developing crack arrest methodology are valid for deep flaws as well as shallow flaws under severe thermal shock conditions. However, a firm conclusion awaits further characterization of the TSE-5 test-specimen material, additional post-test analysis and further study of the fractures.

Table 1. Summary of events for the long axial flaw (TSE-5)

Initiation-arrest event	1	2	3
Time (Sec)	105	177	205
Crack depth,* (a/w)			
Initiation	0.10	0.20	0.63
Arrest	0.20	0.63	0.80
Temperature, °C			
Initiation	−9	−3	79
Arrest	36	82	89
K_{Ic}, $MN \cdot m^{-3/2}$	79	111	115
K_{Ia}, $MN \cdot m^{-3/2}$	86	104	92
Duration of experiment, min	30		

*Maximum depth (mid-length of TSC-1).

References

1. R. D. Cheverton, *Pressure Vessel Fracture Studies Pertaining to a PWR LOCA-ECC Thermal Shock: Experiments TSE-1 and TSE-2*, ORNL/NUREG/TM-31 (September 1976).

2. R. D. Cheverton and S. E. Bolt, *Pressure Vessel Fracture Studies Pertaining to a PWR LOCA-ECC Thermal Shock: Experiments TSE-3 and TSE-4 and Update of TSE-1 and TSE-2 Analysis*, ORNL/NUREG-22 (December 1977).

3. R. D. Cheverton, S. K. Iskander, and S. E. Bolt, *Applicability of LEFM to the Analysis of PWR Vessels Under LOCA-ECC Thermal Shock Conditions*, ORNL/NUREG-40 (October 1978).

4. R. D. Cheverton and S. K. Iskander, *Application of Static and Dynamic Crack Arrest Theory to Thermal Shock Experiment TSE-4*, ORNL/NUREG-57 (June 1979).

5. R. D. Cheverton, *Quick-Look Report for HSST Thermal Shock Experiment TSE-5*, TSP-1006, Aug. 14, 1979.

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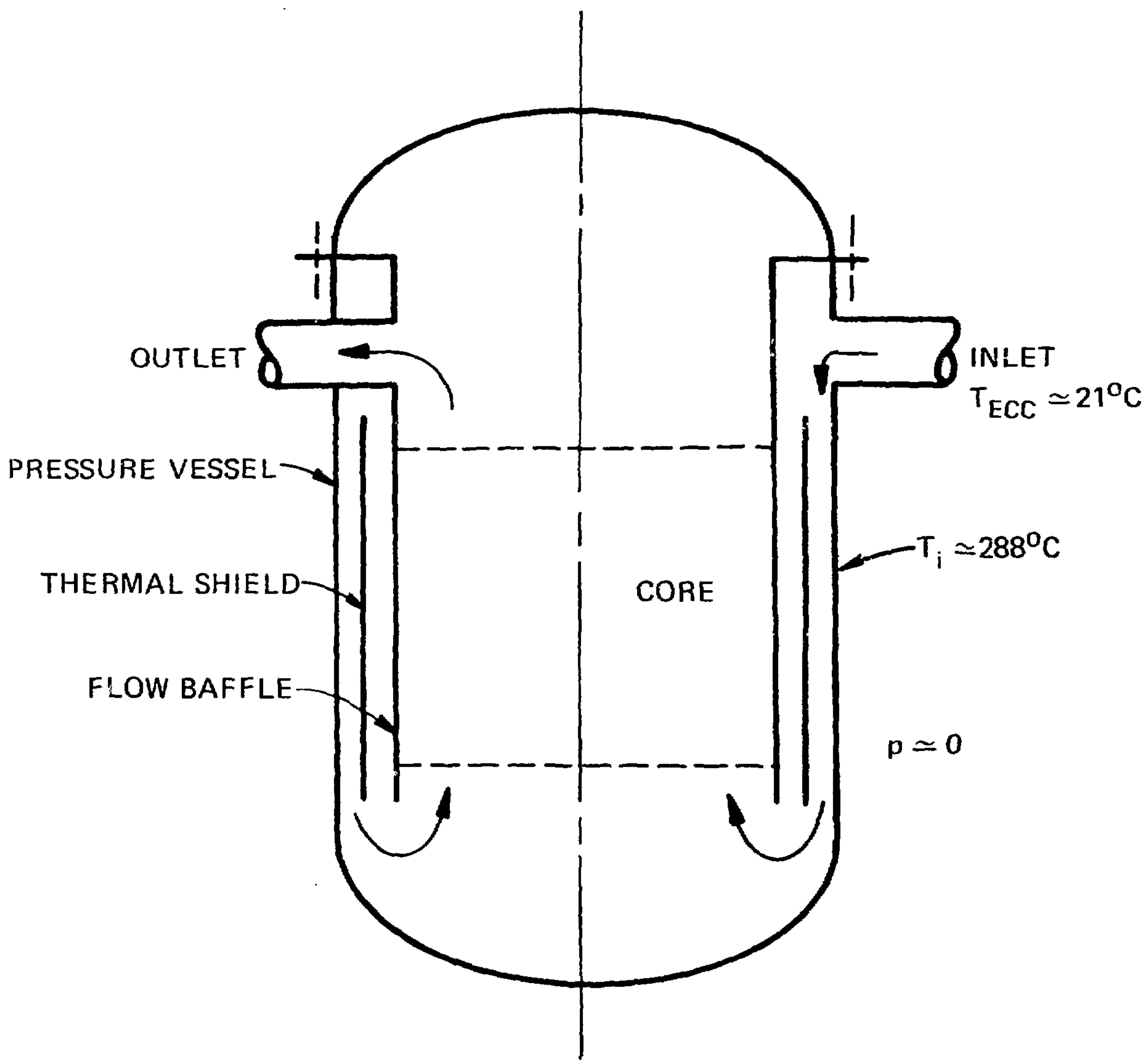
SCHEMATIC OF TYPICAL PWR SHOWING FLOW PATH FOR ECC



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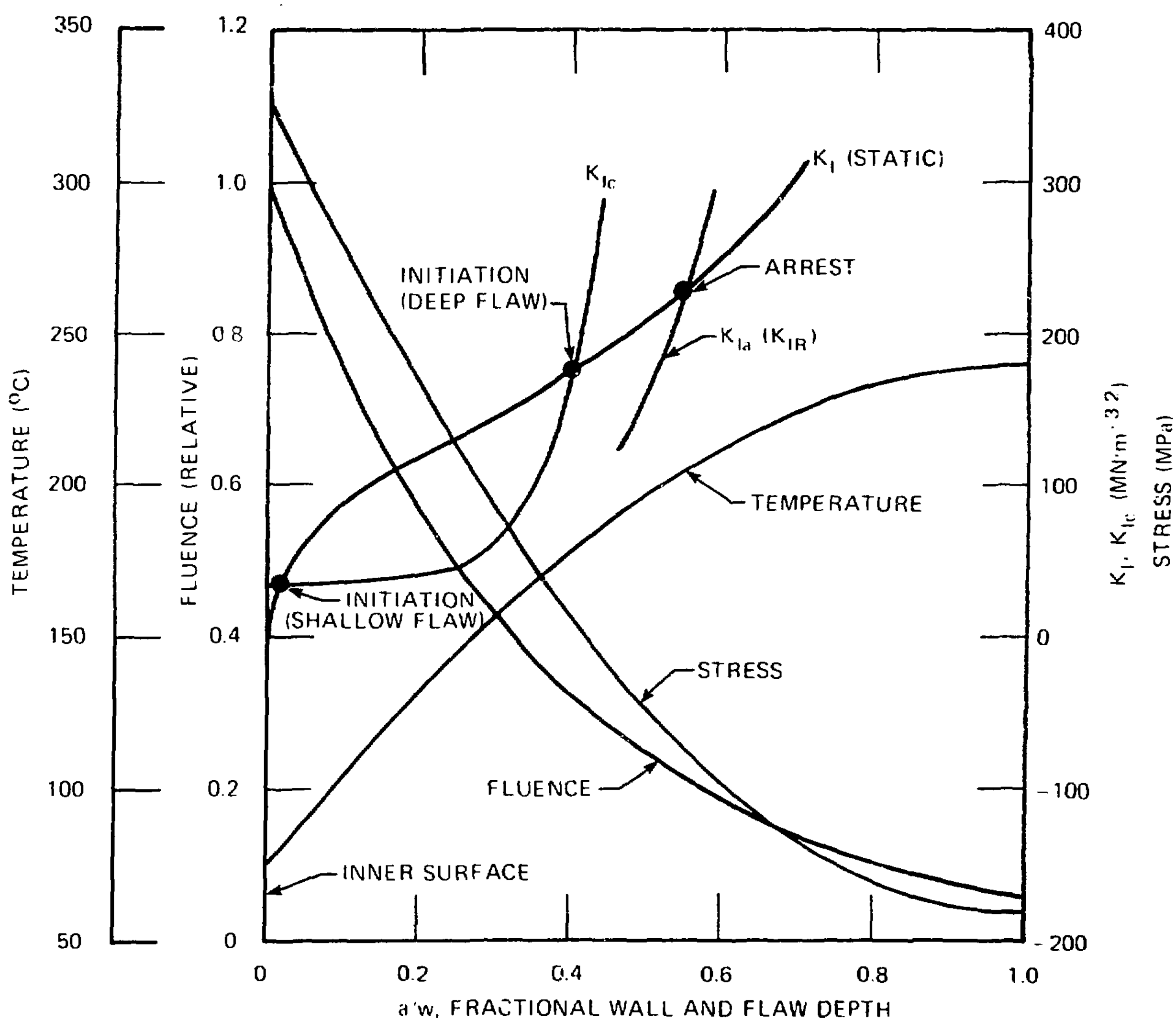
LOCA–ECC THERMAL SHOCK CHARACTERISTIC CURVES



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PURPOSE OF HSST THERMAL SHOCK PROGRAM

DETERMINE VALIDITY OF LEFM AND CRACK ARREST METHODOLOGY UNDER THERMAL SHOCK CONDITIONS SIMILAR TO LOCA-ECC

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SCOPE OF HSST THERMAL SHOCK PROGRAM

TSE-1, 2, 3, 4

- INITIATION AND ARREST OF SHALLOW FLAWS

TSE-5

- INITIATION AND ARREST OF DEEP FLAWS WITH SIGNIFICANT BENDING IN WALL
- ARREST IN RISING K_I FIELD
- DEMONSTRATE WPS

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TSE-5 TEST CONDITIONS

TEST SPECIMEN	TSC-1
TEST SPECIMEN DIMENSIONS (m)	
OD	0.991
ID	0.686
WALL THICKNESS	0.152
LENGTH	1.22
TEST SPECIMEN MATERIAL	A508, CLASS 2 CHEMISTRY
TEST SPECIMEN HEAT TREATMENT	TEMPERED AT 613°C FOR 4 HR
K_{Ic} VS TEMP CURVE SPECIFIED	HSST PLATE 02
K_{Ic} AND K_{Ia} CURVES USED IN TSE-5 DESIGN ANALYSES	ASME SECTION XI, APPENDIX A, $RT_{NDT} = -34°C$

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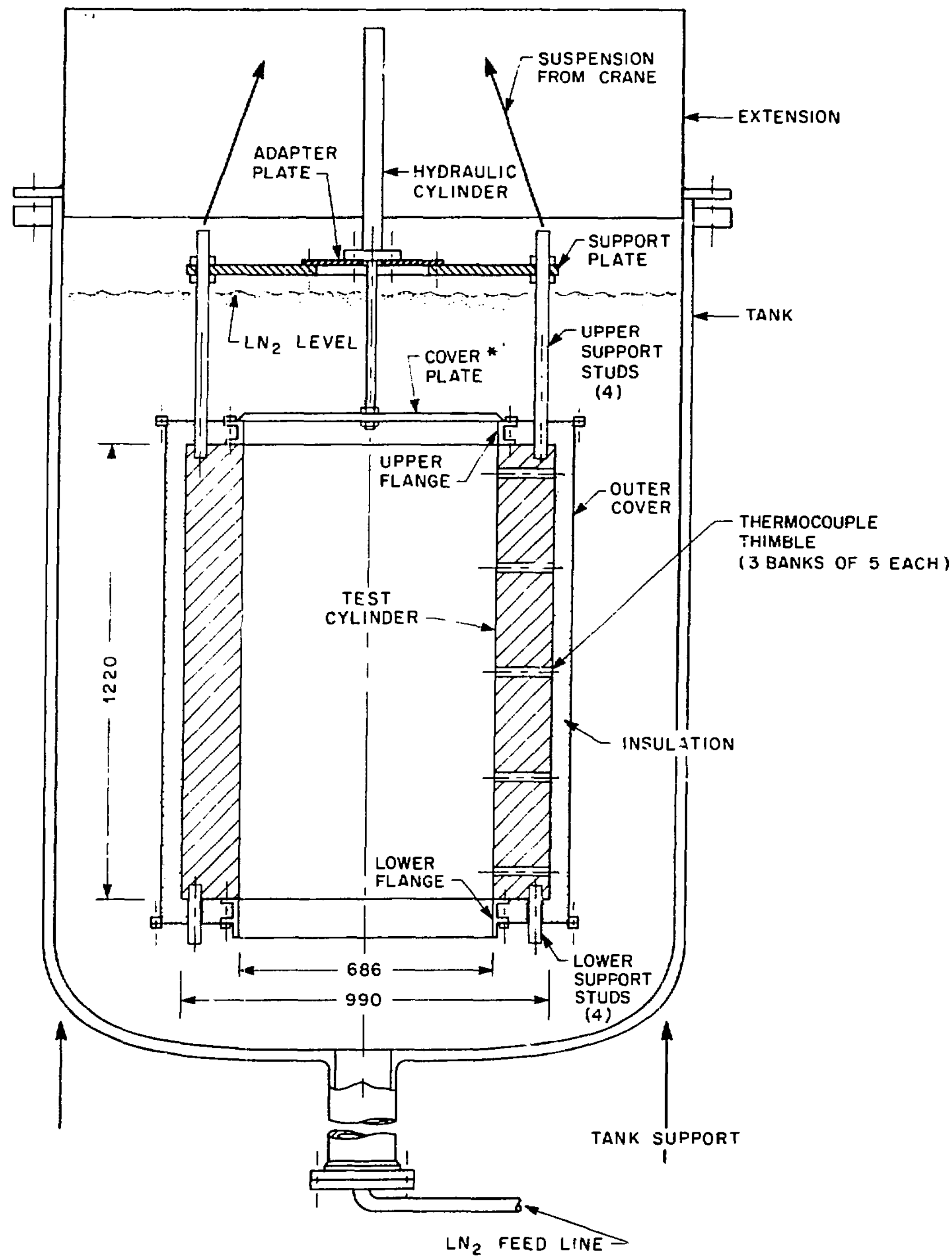
LN_2 – THERMAL SHOCK TEST FACILITY



* POSITION DURING SUBMERGENCE, RAISED TO INITIATE FLOODING

DIMENSIONS IN mm

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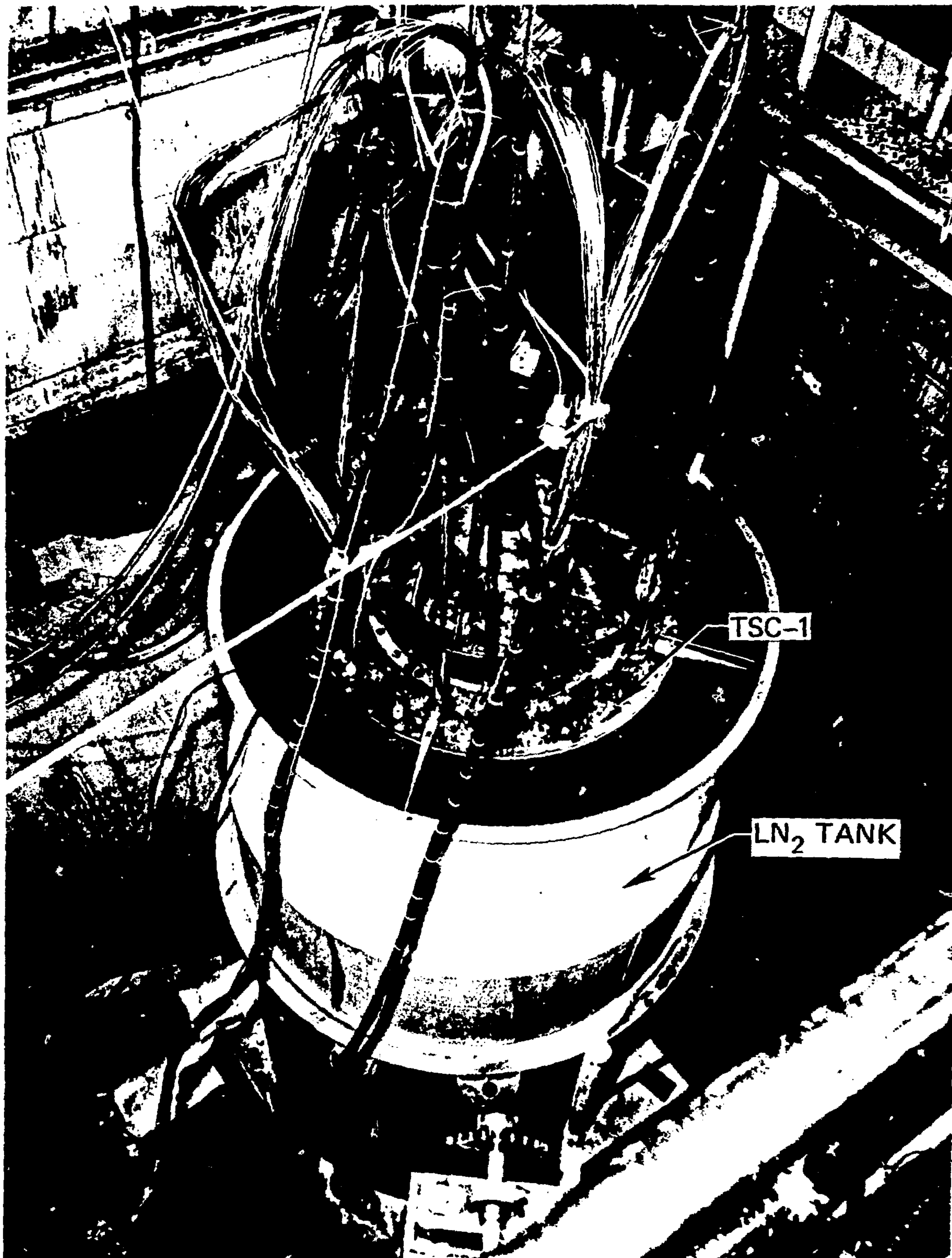
TSC–1 BEING LOWERED INTO LN_2



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INSTRUMENTATION FOR TSE-5

- THERMOCOUPLES: GRADIENT IN WALL (180)
- COD GAGES: EVENTS, a/w, $\dot{a}$ (9)
- UT: CRACK DEPTH (3)
- AE: EVENTS (3)

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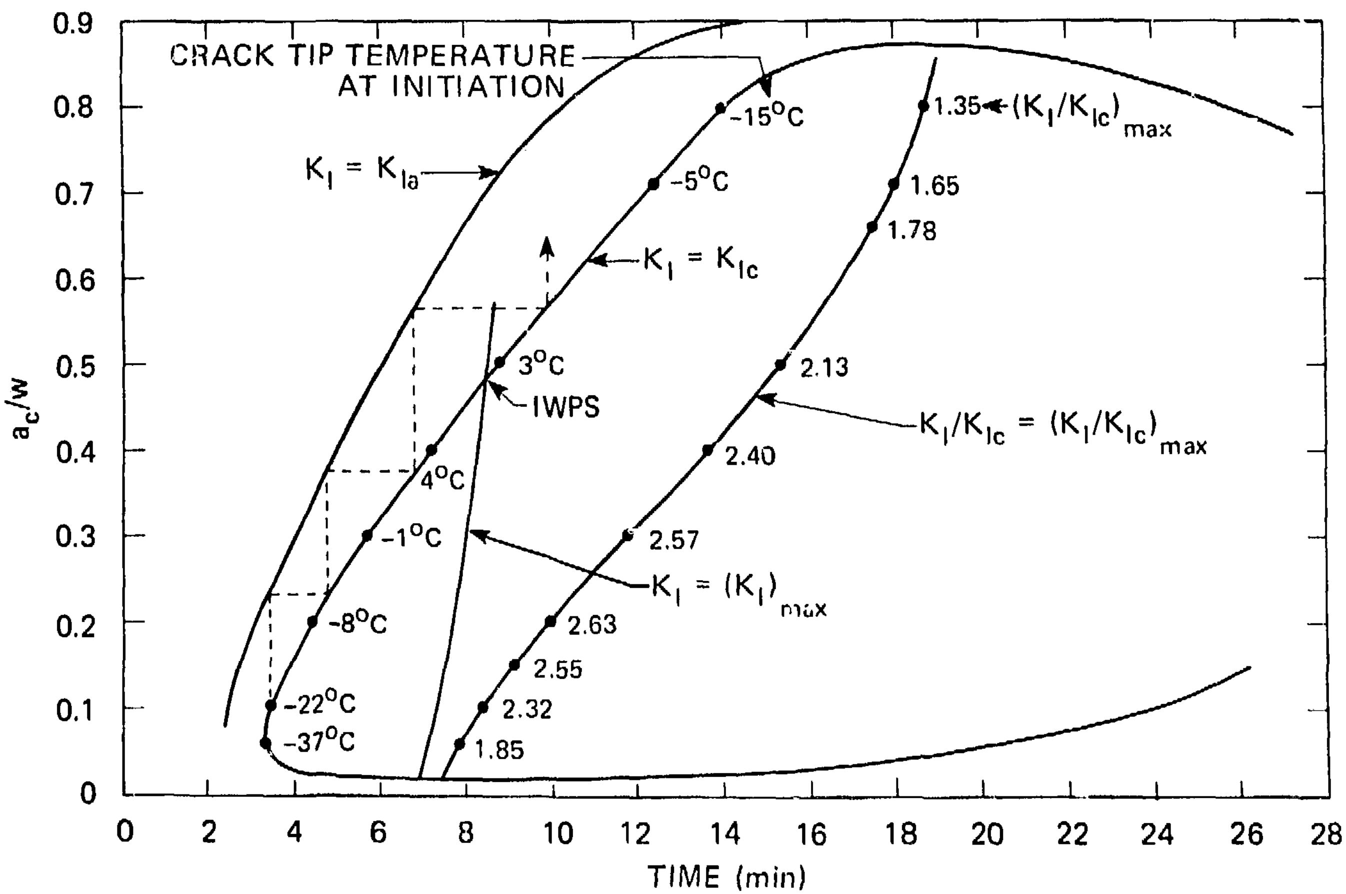
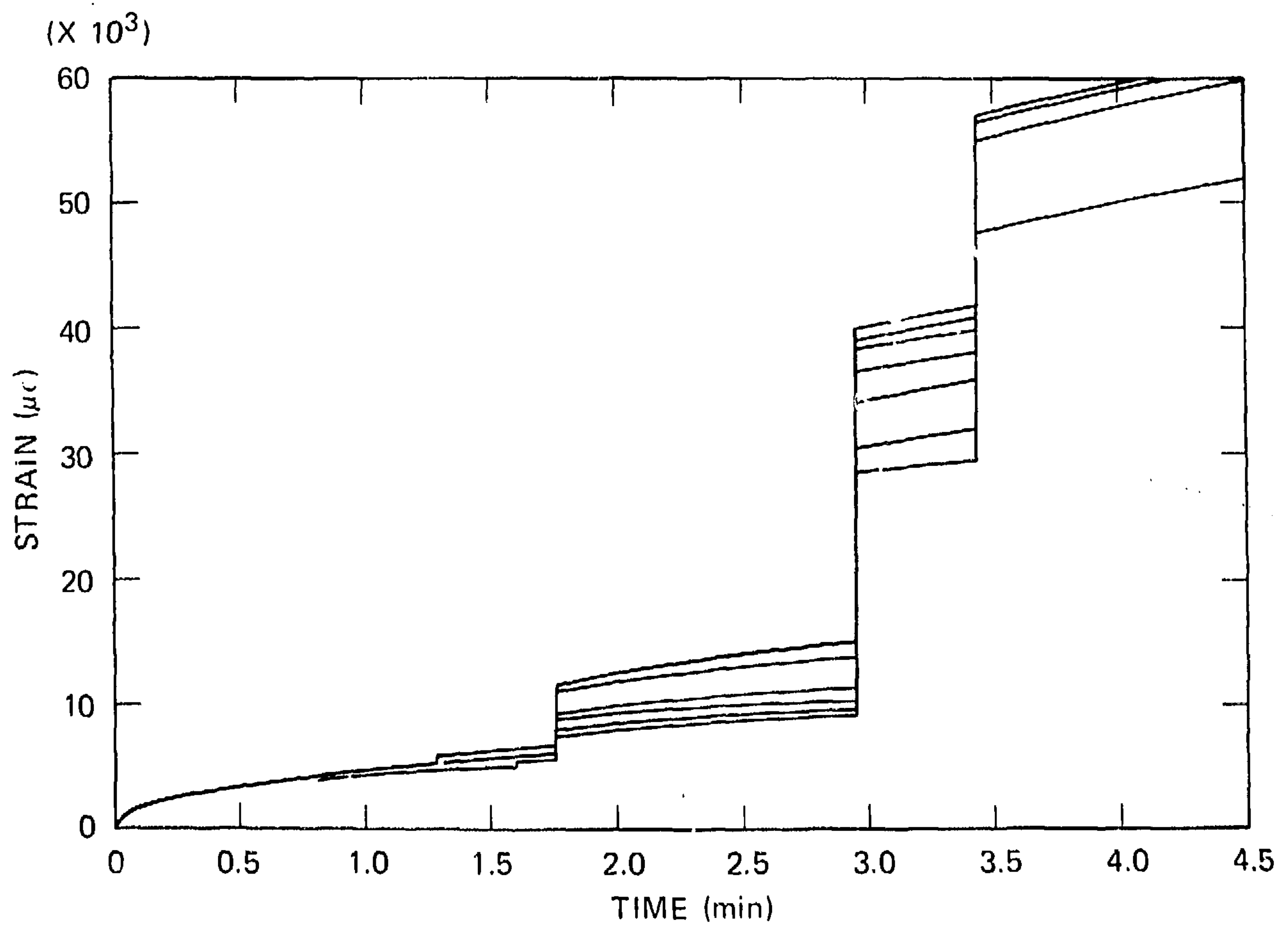
PRETEST CRITICAL-CRACK-DEPTH CURVES FOR TSE-5



COD OUTPUT DURING TSE-5 INDICATES THREE INITIATION–ARREST EVENTS



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SUMMARY OF EVENTS FOR LONG AXIAL FLAW (TSE-5)

INITIATION-ARREST EVENTS	1	2	3
TIME (sec)	105	177	205
CRACK DEPTH,* (a/w)			
INITIATION	0.10	0.20	0.63
ARREST	0.20	0.63	0.80
TEMPERATURE (^{o}C)			
INITIATION	−9	−3	79
ARREST	36	82	89
K_{Ic}, $MN \cdot m^{-3/2}$	79	111	115
K_{Ia}, $MN \cdot m^{-3/2}$	85	104	92
DURATION OF EXPERIMENT (min)	30		

*MAXIMUM DEPTH (MID-LENGTH OF TSC-1)

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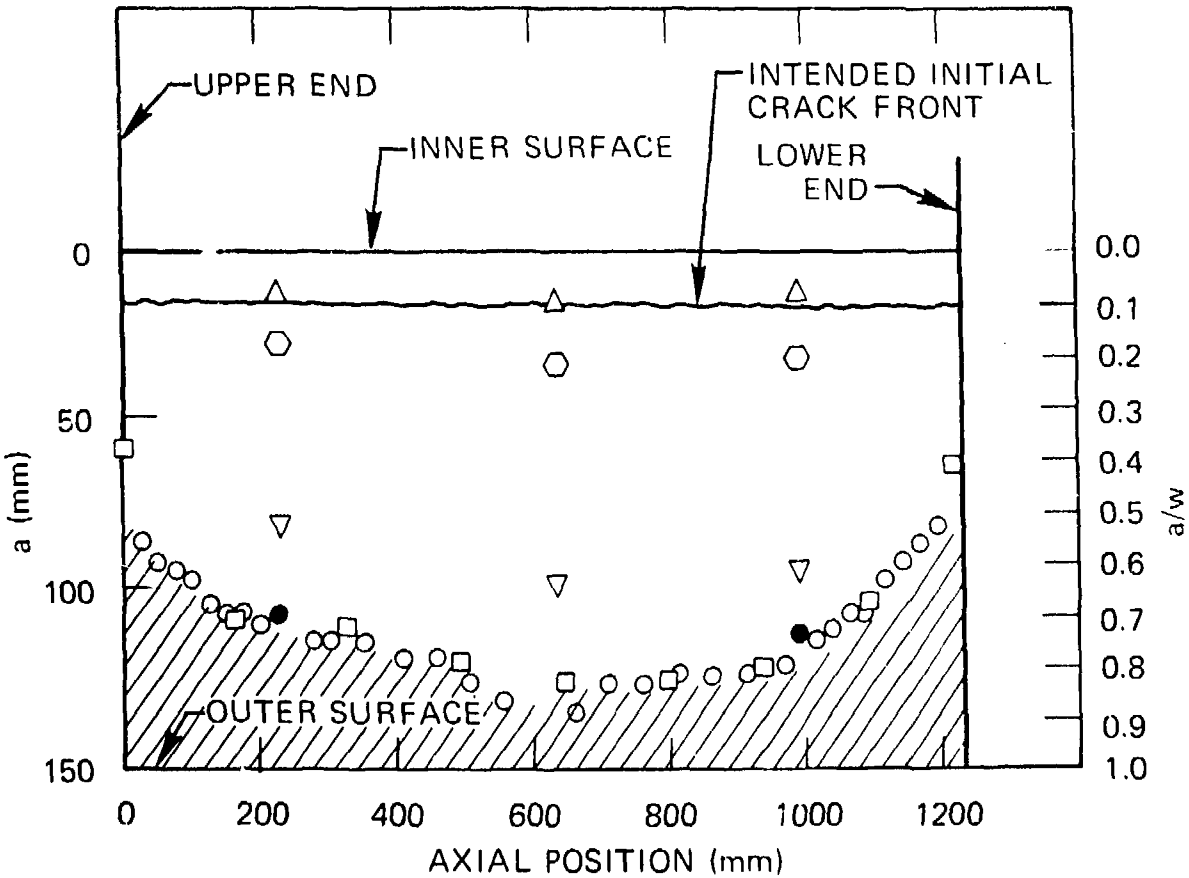
CRACK–DEPTH MEASUREMENTS DURING AND AFTER TSE–5



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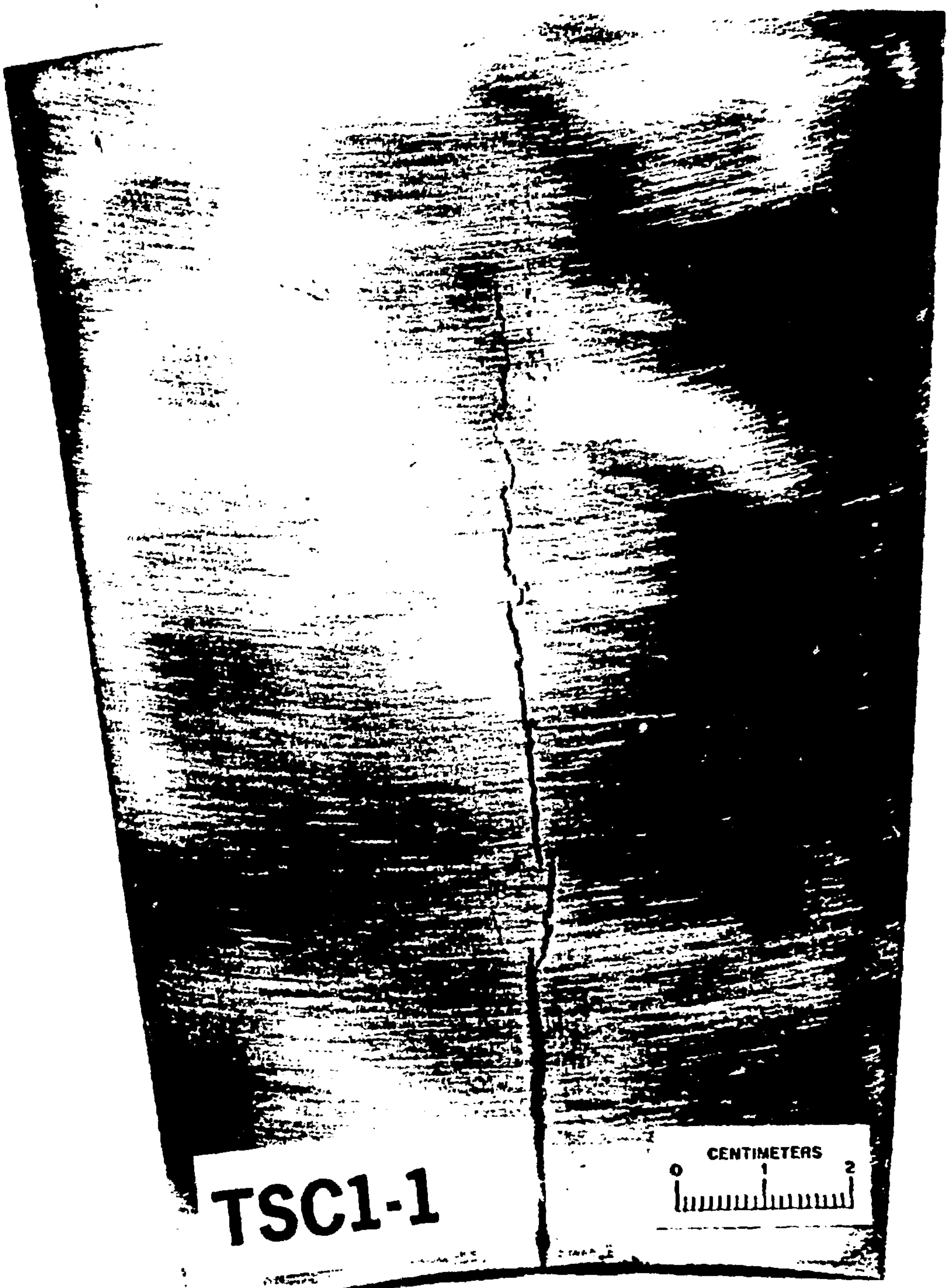
CROSS SECTION OF TSE-5 FLAW



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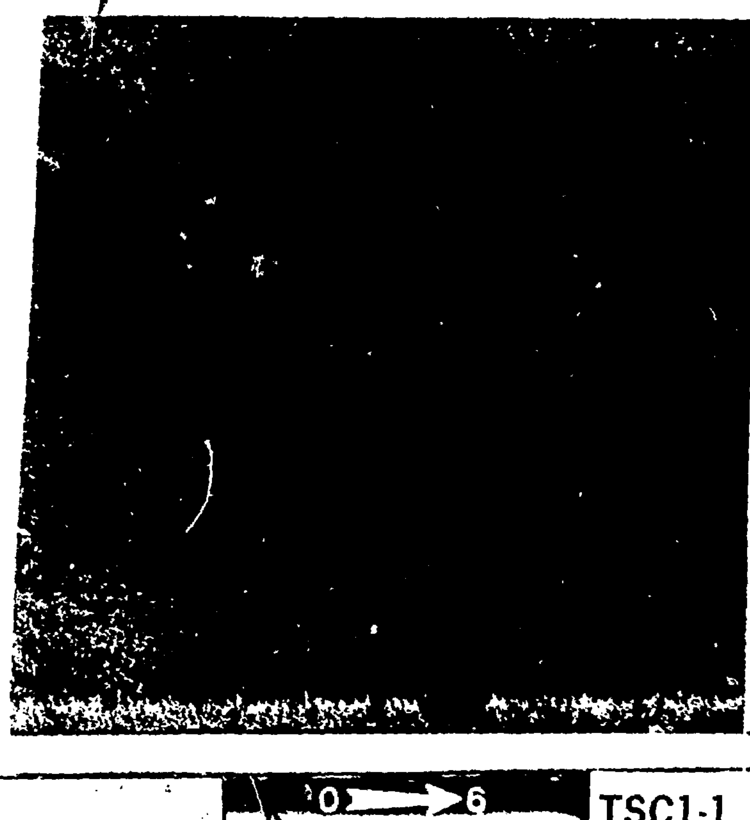
TSE-5 FRACTURE SURFACE NEAR MID LENGTH



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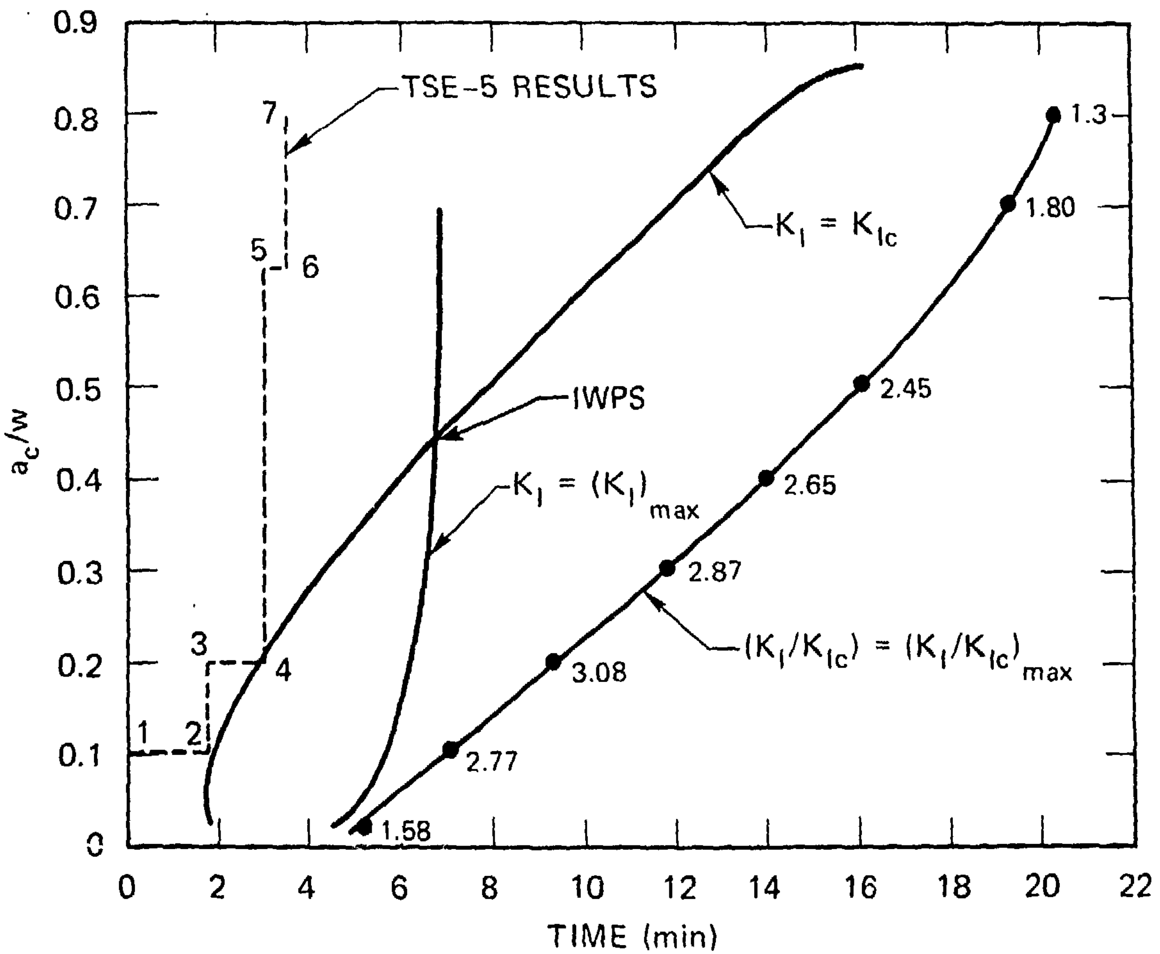
POSTTEST CRITICAL-CRACK-DEPTH CURVES FOR TSE-5 WITH SPECIFIED TOUGHNESS



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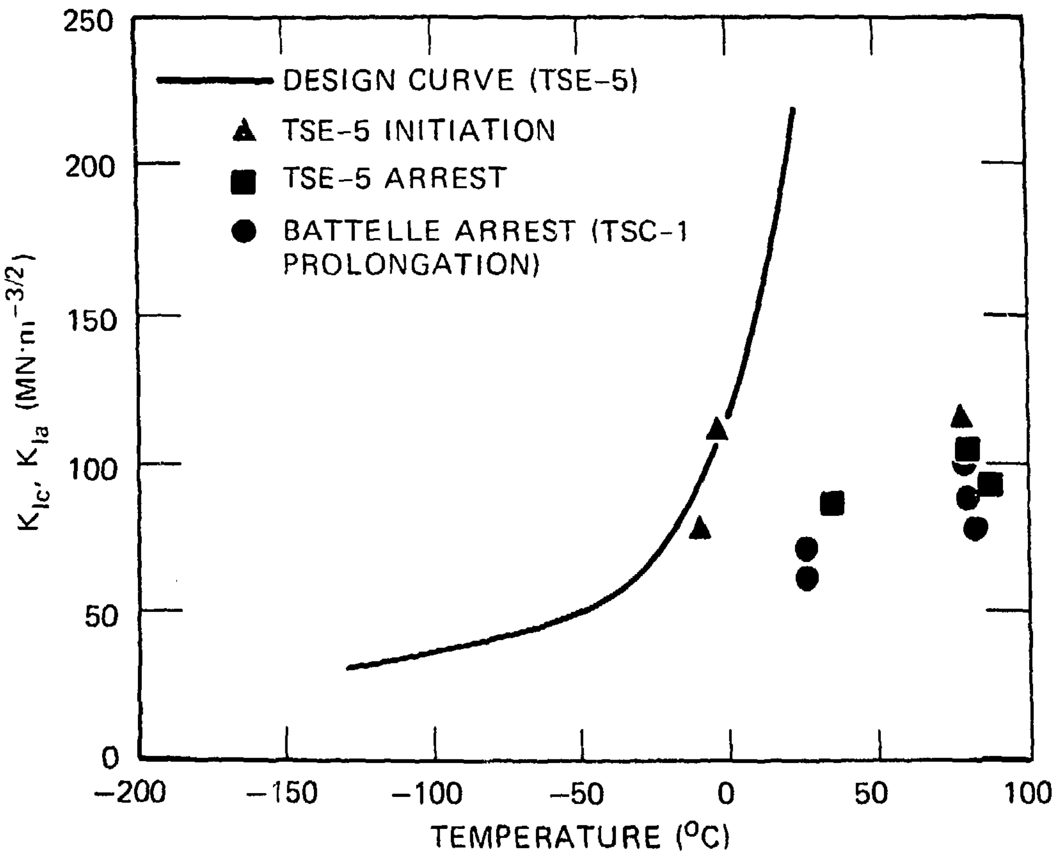
K_{Ic} VS TEMPERATURE: DESIGN CURVE, K_{Ic} AND K_{Ia} DATA FROM TSE-5, K_{Ia} DATA FROM TSC-1 PROLONGATION



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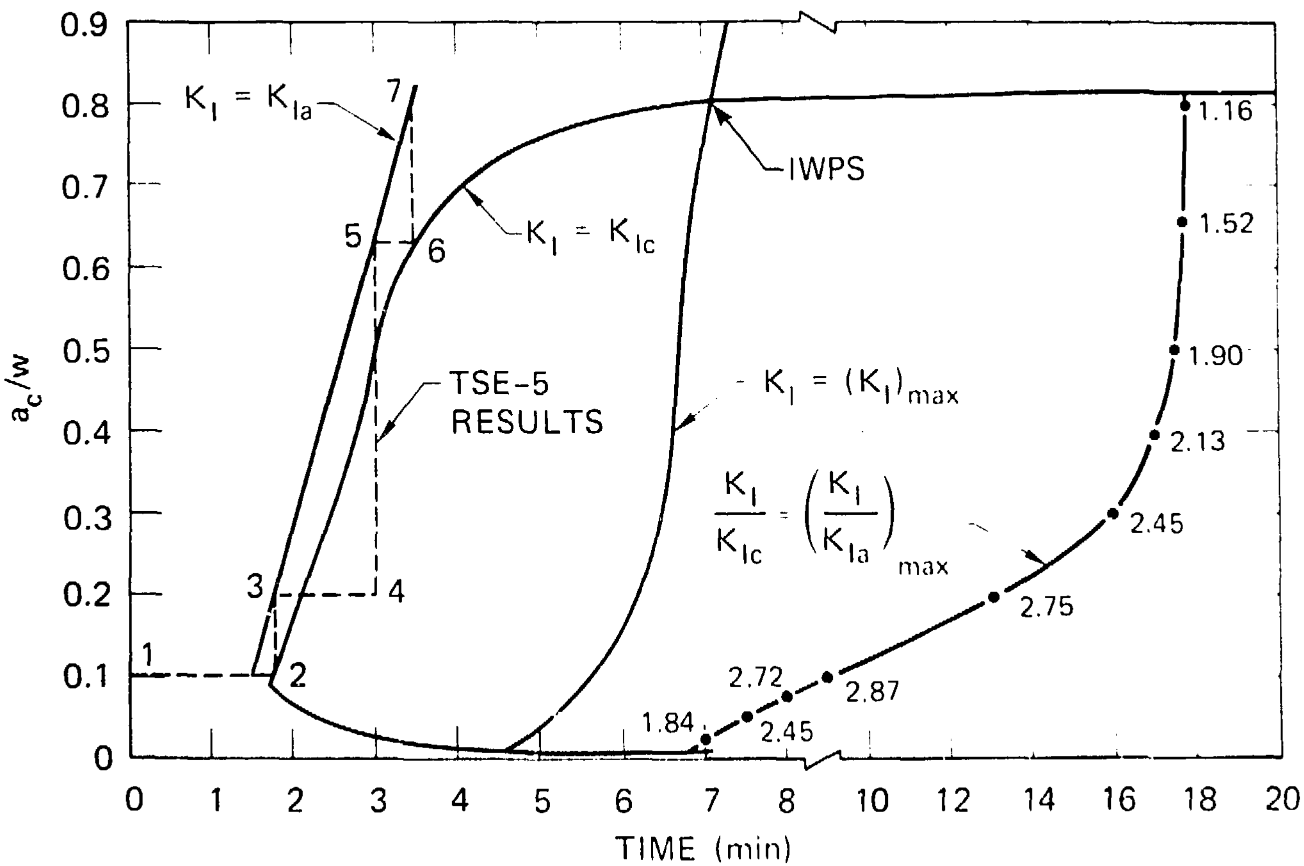
POSTTEST CRITICAL-CRACK-DEPTH CURVES FOR TSE-5 WITH TSE-5 IMPLIED TOUGHNESS



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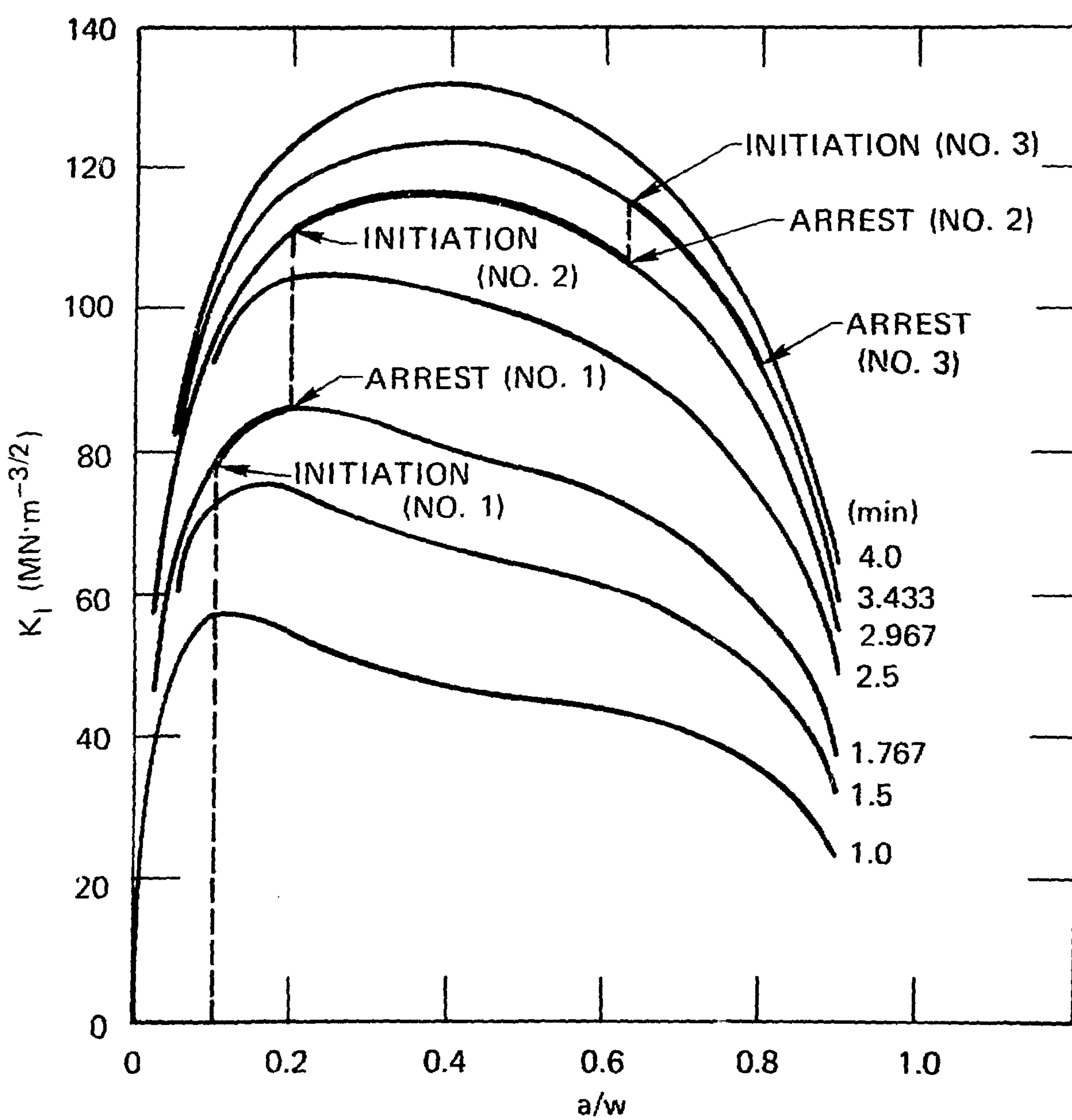
K_I VS a/w FOR TSE-5



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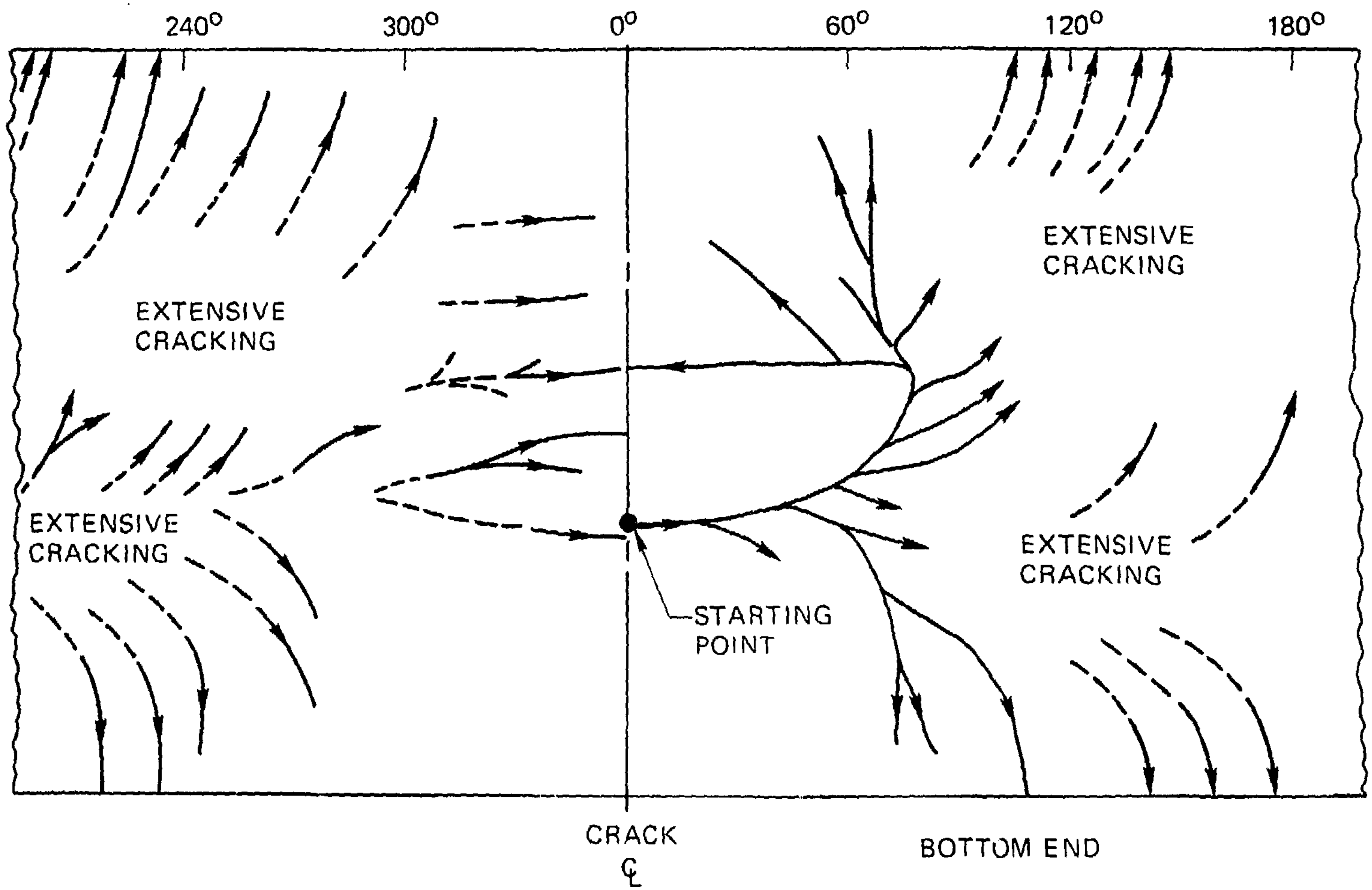
SECONDARY CRACKING DURING TSE-5 (LAYOUT OF INNER SURFACE OF TSC-1)



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SUMMARY

- TOUGHNESS LESS THAN EXPECTED
- CONDITIONS FOR ARREST IN RISING K_I FIELD NOT ATTAINED
- WPS NOT DEMONSTRATED CONCLUSIVELY
- QUENCHING SYMMETRY GOOD
- MULTIPLE INITIATION–ARREST EVENTS
- INITIATION AND ARREST OF DEEP FLAWS
- LONG CRACK JUMP
- LEFM APPEARS VALID