**Pressure Vessel Fracture Studies
Pertaining to a PWR LOCA-ECC Thermal
Shock: Experiments TSE-1 and TSE-2**

R. D. Cheverton

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Engineering Technology Division

PRESSURE VESSEL FRACTURE STUDIES PERTAINING TO A PWR
LOCA-ECC THERMAL SHOCK: EXPERIMENTS TSE-1 AND TSE-2

R. D. Cheverton

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FOREWORD

The work reported here was performed at Oak Ridge National Laboratory (ORNL) under sponsorship of the U.S. Nuclear Regulatory Commission's (NRC) Heavy-Section Steel Technology (HSST) Program, which is directed by ORNL. The program is conducted as part of the ORNL Pressure Vessel Technology Program, of which G. D. Whitman is manager. The manager for the NRC is E. K. Lynn.

This report is designated Heavy-Section Steel Technology Program Technical Report No. 42. Prior reports in this series are listed below.

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Copies of these reports may be obtained from Laboratory Records Department, Oak Ridge National Laboratory, P.O. Box X, Oak Ridge, Tenn. 37830.

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**PRESSURE VESSEL FRACTURE STUDIES PERTAINING TO A PWR
LOCA-ECC THERMAL SHOCK: EXPERIMENTS TSE-1 AND TSE-2**

R. D. Cheverton

ABSTRACT

The LOCA-ECC Thermal Shock Program was established to investigate the potential for flaw propagation in pressurized-water reactor (PWR) vessels during injection of emergency core coolant following a loss-of-coolant accident. Studies thus far have included fracture mechanics analyses of typical PWRs, the design and construction of a thermal shock test facility, determination of material properties for test specimens, and two thermal shock experiments with 0.53-m-OD (21-in.) by 0.15-m-wall (6-in.) cylindrical test specimens.

The PWR calculations indicated that under some circumstances crack propagation could be expected and that experiments should be conducted for cracks that would have the potential for propagation at least halfway through the wall. The first step in the experimental program was to conduct relatively simple and considerably less expensive crack-initiation tests. In the first experiment initiation was not expected; and, although there are inconsistencies in the test results, it is tentatively concluded that unstable crack growth did not occur. Crack propagation definitely took place in the second experiment as expected. These results tend to validate the methods of analysis; however, additional experiments will be required before the validity can be determined with reasonable accuracy.

1. INTRODUCTION AND SUMMARY

In the event that a light-water reactor (LWR) system suffers a loss-of-coolant accident (LOCA), an emergency core-cooling system (ECCS) is activated that injects cold water into the reactor vessel to maintain coolant for the core. As shown schematically in Fig. 1, the coolant enters the vessel through the main coolant lines and passes over the inner surface of the vessel wall prior to reaching the core. Thus, a portion of the initially hot vessel is quenched by the emergency core coolant. This quenching action, or thermal shock, results in tensile stresses in the inner portion of the vessel wall and also reduces the fracture toughness of the material in that area. These two factors combined set the stage for the possible propagation of a hypothetical preexisting flaw on the inner surface of the vessel.

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Fig. 1. Schematic of typical PWR showing flow path for ECC.

Another factor that contributes to the possible extension of a crack, fast-neutron radiation damage, further reduces the fracture toughness. This effect is greater near the inner surface because of the attenuation of the fast-neutron flux through the wall. The net effect of higher fluence and lower temperature near the inner surface is a greater tendency for initiation of shallow rather than deep cracks and a possible means for

the arrest of an initially shallow propagating crack. The need to investigate crack propagation and arrest, specifically in connection with an ECC thermal shock, depends upon the probability of initiation and subsequent deep penetration. Preliminary calculations indicated that under some circumstances the probabilities of crack initiation and propagation are high in PWRs. Thus, both initiation of shallow flaws and the arrest of deep running cracks need to be considered in the study of the ECC thermal shock.

An initial step in the thermal shock studies at ORNL was to establish a calculational model for PWRs, considering both thermal and fracture mechanics aspects, and to explore the possibility of scaling from actual PWR conditions to practical experimental models. The results of this exploration indicated that direct scaling could not be achieved because of geometric and metallurgical problems. Therefore, the objective of the studies being performed at ORNL is to determine the accuracy of the calculational techniques for predicting crack initiation and arrest. PWR conditions are being simulated as closely as possible in order to minimize the degree of extrapolation required in applying the techniques to actual PWRs.

Results of calculations for the PWR reference calculational model (RCM) indicate that PWR vessels containing a low concentration of copper impurity will not experience significant crack propagation under ECC thermal shock conditions. However, near the end of its service life, a vessel with a high concentration of copper and either a long axial crack or a continuous circumferential crack may experience crack extension through at least half the vessel wall thickness, provided that the crack is not blunted by warm-prestressing effects during propagation. Thus, a small-scale experiment in which a crack, in the absence of warm prestressing, would run about halfway into the wall was proposed. Considering thermal shock and metallurgical capabilities, the test specimen required to achieve such penetration had to have an outside diameter of ≥ 1 m (40 in.) or larger. A 0.99 m OD (39 in.) was specified, but procurement time was longer than desired. It was decided that in the interim experiments would be conducted with two smaller specimens [0.53-m OD (21 in.)] that could be machined from existing forgings.

A test facility was designed for the 0.53- and 0.99-m-OD specimens that could apply a thermal shock severe enough to drive a crack quite deep

into the wall of a 0.99-m-OD specimen and fairly deep into the 0.53-m-OD cylinders. However, construction of this facility was terminated because of cost and scheduling considerations and uncertainty regarding the necessity for testing the larger cylinders. A relatively small loop with much less shock capability was constructed for the smaller test specimens. Because of the small diameter of the specimens and the limited testing capability, the initial tests fall in the category of initiation experiments, and under the most severe conditions only slight penetration in the radial direction is expected.

Thus far, two experiments with the 0.53-m-OD specimens have been conducted. The first is referred to as the noninitiation experiment because the calculated maximum K ratio (K_I/K_{IC}) was less than unity. The flaw was a long axial crack of optimum depth, and the specific K ratio selected was the same as that calculated for the PWR reference calculational model, assuming a low concentration of copper. Results of the experiment indicate a slight amount of crack extension which, based on the apparent time of occurrence, had to be of a stable nature but based on an examination of the fracture surface appears to be a frangible fracture. For the second experiment it was intended that some crack extension take place, and the full thermal shock capability of the test facility was used. The flaw was an axially oriented semicircular crack with a 38-mm diameter (1.5 in.) which, as a result of the thermal shock, extended axially to a total length of about 140 mm (5.6 in.). A summary of test conditions for these first two thermal shock experiments is presented in Table 1.

The study presented herein is a continuation of an earlier study conducted at ORNL by Robinson, Merkle, and Derby.¹

Table 1. Test conditions for TSE-1 and -2

Experiment	TSE-1	TSE-2
Test specimen	TSV-1	TSV-2
Test specimen dimensions, m (in.)		
OD	0.53 (21)	0.53 (21)
ID	0.24 (9.5)	0.24 (9.5)
Length	0.91 (36)	0.91 (36)
Test specimen material	A508 class 2	A508 class 2
Heat treatment	Quench only from 871°C (1600°F)	Quench only from 871°C (1600°F)
Flaw	Long axial crack, a = 11 mm (0.42 in.)	Semicircular, axial, a = 19 mm (0.75 in.)
Temperatures, °C (°F)		
Wall (initial)	288 (550)	289 (552)
Sink (initial)	4 (40)	-23 (-9.5)
Sink (final)	7 (45)	-15 (4.5)
Coolant	Water	40 wt % methyl alcohol, 60 wt % water
Coolant flow rate, m ³ /hr (gpm)	59 (260)	114 (500)
Coolant pressure in test section, kPa (psi)	1520 (220)	317 (133)
Back pressure orifice diam., mm (in.)	25.43 (1.001)	43.18 (1.700)
Heat transfer coefficient, W m ⁻² °C ⁻¹ (Btu hr ⁻¹ ft ⁻² °F ⁻¹)	~2800 (~500)	~5700 (~10 ³)
(K _I /K _{IC}) _{max}	0.74	1.33 (α = 75°)
Time of occurrence of (K _I /K _{IC}) _{max} , min	~8	~4
Duration of experiment, min	30	30

2. ANALYSIS OF PWRs

2.1 PWR Conditions

Typical temperature, thermal stress, and fluence distributions in a PWR vessel wall during an ECC transient are shown in Fig. 2, and fracture toughness (K_{IC}) vs temperature ($T - RT_{NDT}$) and ΔRT_{NDT} vs fluence and copper concentration are shown in Figs. 3 and 4 respectively. Combining the effects of temperature and fluence distributions in the wall with the tendency for K_{IC} to increase with increasing temperature and decreasing fluence produces a very steep positive gradient in toughness in the vessel wall at times of interest in the transient as shown in Fig. 5. This steep gradient in toughness tends to provide a mechanism for the arrest of

Fig. 2. Typical fast-neutron fluence attenuation and LOCA-ECC thermal shock temperature and stress distributions in a PWR.

Fig. 3. Static and arrest toughness vs $(T - RT_{NDT})$ for unirradiated ASTM A533, grade B, class 1 plate.

a running crack that initiates in the relatively low toughness region near the inner surface of the vessel wall.

In the analysis of PWRs, it is necessary to consider the upper and lower ranges of copper concentration indicated in Fig. 4. All recent and new PWR vessels have or will have the low copper content. However, many of the vessels in operation today contain high concentrations of copper.

The severity and specific nature of the thermal shock to a PWR vessel varies from one reactor design to another. In some cases forced-convection heat removal predominates, while in others the mechanism is primarily natural convection. Early in the shock there is a film blanketing condition that results in a very low heat transfer coefficient and thus a low

Fig. 4. Effect of fast-neutron fluence and copper content on shift of RT_{NDT} for reactor vessel irradiation at 550°F.

Fig. 5. K_{Ic} vs a/w for reference calculational model.

heat-removal rate. This is followed by nucleate boiling, which is characterized by a very high heat transfer coefficient. These two regimes last only seconds and are followed by single-phase (liquid) turbulent convective flow that results in an intermediate value of the coefficient. Calculations performed by ORNL and the PWR vendors indicate that the first two regimes are of such short durations that they have essentially no effect on vessel wall temperatures at times of interest. Results of the vendors' calculations also show that there is little difference in wall temperatures between the various reactor designs. Specific results are discussed in a following section.

Defects (flaws) on the inner surface of a PWR vessel wall presumably are more likely to occur in welds than in base material, and both circumferential welds (in vessels made from ring forgings) and axial welds (in vessels made from plate) are located in the region of intensive radiation damage. As will be discussed in a later section, the stress-intensity factor tends to be greater for long axial cracks than for continuous circumferential cracks (the difference increasing with increasing crack depth); however, the consequences of a continuous circumferential crack breaching the wall are much more serious than for an axial crack, because the former results in complete loss of coolant to the core while the latter presumably results only in a limited amount of coolant leakage from the vessel. In the unlikely event that a significant flaw did exist in a PWR vessel, it would be even more unlikely that the flaw would be "long." However, it is prudent to consider the possibility of a short crack, which has a relatively low probability of propagating radially, propagating in length to become a long crack.

2.2 PWR Reference Calculational Model

A PWR reference calculational model (RCM) was established for evaluating the appropriateness of experiments in terms of PWR conditions. Characteristics of this model, which simulates a present-generation PWR as nearly as possible at this time, are summarized in Table 2.

The fast-neutron dose of 4×10^{19} neutrons/cm² at the inner surface of the vessel corresponds to a 40-year irradiation period for a typical PWR. The attenuation of the dose through the wall, $\exp(-0.013a \text{ mm}^{-1})$, is typical also. Thermal shock conditions are based on transient temperature data provided by the PWR vendors. The vendor data are shown in Figs. 6 through 9 plotted as bands (temperature vs radial position in wall at various times in the transient). ORNL adopted the simple thermal model described in Table 2, and a comparison with the bands of vendor data is shown in the same figures.

The LOCA being considered at this time corresponds to a double-ended main pipe break in which the system pressure is essentially zero by the time appreciable thermal shock has taken place. Thus, pressure stresses are not included in the analysis.

Table 2. Reference calculational model for Thermal Shock Program studies

Outside diameter, m (in.)	4.8 (189)
Wall thickness, m (in.)	0.22 (8.5)
Neutron fluence ($E \geq 1$ MeV), neutrons/cm ²	$4 \times 10^{19} e^{-0.013a} \text{ cm}^{-1}$
Thermal shock (LOCA-ECC)	
Coolant temperature (not a function of time), °C (°F)	21 (70)
Total heat transfer coefficient (coolant film and cladding) (not a function of time), W m ⁻² °C ⁻¹ (Btu hr ⁻¹ ft ⁻² °F ⁻¹)	1140 (200)
Wall temperature (initial), °C (°F)	288 (550)
Pressure (gage)	0
Fracture toughness	
K_{Ic} source (unirradiated)	WCAP-7414 (Ref. 2)
K_{IR} source (unirradiated)	ASME Code, Section III, Subsection NA, App. G, and Ref. 3
$K_{Ia} = K_{IR}$	
RT_{NDT} (unirradiated), °C (°F)	4 (40)
ΔRT_{NDT} vs fluence and copper concentration (source)	Litton (October 1972) (Ref. 4)
Copper concentration extremes, %	
Low copper (ASTM Spec. A533-72a)	0.1
High copper (unrestricted residual)	20.25
Residual stresses	≤0, assumed zero

Fracture toughness data were taken from several sources, as indicated in Table 2. Curves for K_{Ic} (Ref. 2) and K_{IR} vs $T - RT_{NDT}$ (Ref. 3) for unirradiated material are those shown in Fig. 3. The value of RT_{NDT} (4°C) for unirradiated material was specified by the Thermal Shock Review Committee,* and ΔRT_{NDT} vs fluence and copper concentration (see Fig. 4) was

*The Thermal Shock Review Committee was established in connection with the LOCA-ECC Thermal Shock Program by NRC and is chaired by a member thereof. The committee assists in program planning and analysis of data.

Fig. 6. Temperature distributions in PWR vessel walls: comparison between ORNL reference calculational model and PWR vendors' models. Time = 5 min from ECC injection.

Fig. 7. Temperature distributions in PWR vessel walls: comparison between ORNL reference calculational model and PWR vendors' models. Time = 10 min from ECC injection.

Fig. 8. Temperature distributions in PWR vessel walls: comparison between ORNL reference calculational model and PWR vendors' models. Time = 25 min from ECC injection.

Fig. 9. Temperature distributions in PWR vessel walls: comparison between ORNL reference calculational model and PWR vendors' models. Time = 40 min from ECC injection.

obtained from a draft report by Litton.⁴ (Litton's curves are essentially the same as those specified in Regulatory Guide 1.99.)⁵ The effect of fluence and copper concentration on K_{IR} was assumed to be the same as that on K_{IC} .

Residual stresses presumably are present in PWR vessels and probably will affect crack propagation. However, such stresses are not included in the RCM at the present.

Flaw geometry and orientation for the RCM includes long and short cracks in the longitudinal and circumferential directions. The long axial crack is infinitely long in a two-dimensional ($r-\theta$) calculation, and the long circumferential crack is continuous. Short cracks in either direction are assumed to be semielliptical.

2.3 Methods for Calculating the Stress-Intensity Factor

2.3.1 Semielliptical cracks

These cracks were calculated by the following method, which was proposed by Merkle:⁶

$$K_I = \frac{M_1 M_2}{\phi} \sigma_s \sqrt{\pi a} F(\theta) , \quad (1)$$

where

$$M_1 = \psi_0(\theta) - \left(1 - \frac{\sigma_0}{\sigma_s}\right) \left(\frac{2a}{w}\right) \psi_1(\theta) , \quad (2)$$

$$M_2 = \left[\frac{\tan(\pi a/2w)}{\pi a/2w} \right]^{1/2} \left[1 + \left(\frac{a}{w}\right)^{5/2} \sin \theta \right] , \quad (3)$$

$$\psi_0(\theta) = 1.211 - 0.186 (\cos \theta)^{1/2} , \quad (4)$$

$$\psi_1(\theta) = 0.18 + 0.54 \left(\frac{a}{b}\right) \cos \theta , \quad (5)$$

$$F(\theta) = \left[1 - \left(\frac{b^2 - a^2}{b^2} \right) \left(\frac{r_c}{b} \right)^2 \sin^2 \theta \right]^{1/4}, \quad (6)$$

$$\phi^2 = 1 + 4.593 \left(\frac{a}{2b} \right)^{1.65}, \quad (7)$$

and a , b , r_c , t , w , σ_0 , σ_s , and θ are defined in Fig. 10. Equation (1) is strictly applicable for an unrestrained plate having a linear stress distribution through the wall and thus may tend to overestimate K_I for a small flaw in a cylindrical vessel wall. In applying this equation to the thermal shock problem, a least-squares fit of a straight line to the actual stress distribution over the crack depth is used, and the difference in bending restraint between vessel wall and unrestrained plate is ignored.

2.3.2 Long axial and continuous circumferential cracks

When an axial or circumferential crack is long and deep, the bending moment associated with the thermal stress tends to open the crack and thus increase the stress-intensity factor. This bending of the vessel wall is illustrated in Figs. 11 and 12 for the axial and circumferential cracks, respectively. The effect of bending on K_I is greater for a long axial crack than for a continuous circumferential crack because of circumferential restraint associated with the latter. This is depicted in Fig. 13, which shows comparisons of calculated K_I values with and without the bending effect for the two types of cracks.

The stress-intensity factors for long axial and circumferential cracks, neglecting the bending effect, were calculated with the Irwin equation,⁷ which is

$$K_I = 1.59 \left(w \tan \frac{\pi a}{2w} \right)^{1/2} \int_0^{a/w} \frac{\sigma \left(\frac{\lambda}{w} \right) \cos \frac{\pi \lambda}{2w} d \left(\frac{\lambda}{w} \right)}{\left(\sin^2 \frac{\pi a}{2w} - \sin^2 \frac{\pi \lambda}{2w} \right)^{1/2}}, \quad (8)$$

where λ is variable distance between the cylindrical surface and tip of the crack ($0 \leq \lambda \leq a$).

Fig. 10. Definition of terms associated with the analysis of a semielliptical surface crack.

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Fig. 11. Bending in a long cylinder containing a long axial crack and subjected to a thermal quench on the inner surface.

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Fig. 12. Cross section of long cylinder subjected to a uniform internal quench and containing a continuous deep circumferential flaw.

Fig. 13. $(K_I)_{max}$ (maximum with respect to time) vs a/w for long axial and continuous circumferential flaws in RCM considering (finite-element) and neglecting (Erwin) bending effects.

In order to include the bending effect, a two-dimensional finite-element analysis² was developed. For the axial crack the vessel was assumed to be infinitely long and a 360° cross section was considered, as shown in Fig. 11 (symmetry assumed about plane A). Figure 12 shows the cross section used for the continuous circumferential crack. Thus far, symmetry has been assumed about plane A, and the length of the cylinder has been considered to be effectively infinite.

The two-dimensional analysis of the long axial flaw in a PWR vessel tends to be conservative because in the actual three-dimensional case the vessel has restraints at the ends that limit the bending in the wall that tends to enhance opening of the crack. Furthermore, there are axial gradients in both temperature and fluence that result in a positive axial

gradient in fracture toughness. This gradient in toughness tends to limit longitudinal growth of the crack or, in the case of a hypothetical full-length crack, decreases radial growth with increasing distance from the core horizontal midplane. However, it is important to recognize that the continuous circumferential crack does not benefit from the conditions that tend to make the calculational model conservative for long axial cracks.

Another characteristic of the present calculational model that introduces uncertainty in some cases is the assumed strictly linear elastic behavior as opposed to a more realistic elastic-plastic behavior. When a long crack is more than halfway through the wall ($a/w > 0.5$), the size of the plastic zone becomes significant relative to the size of the remaining uncracked ligament ahead of the crack.

In spite of the above deficiencies in the RCM, it is believed that the model is adequate at this time for aiding in the development of the thermal shock experimental program.

2.4 Warm-Prestressing Considerations

Several investigators have found that the load required for unstable crack growth may be a function of preloading conditions. For instance,² if a preload is applied that is greater than the critical load corresponding to a temperature less than that at which the preload is applied, the critical load at the lower temperature may be greater than otherwise experienced. Or, if the specimen is loaded to a value just below the critical point and the temperature lowered while maintaining that load, a lower temperature than that corresponding to a constant-temperature test with single load applications may be required for fracture. The condition is referred to as warm prestressing and constitutes an effective increase in fracture toughness. With regard to its application to the thermal shock problem, if the K ratio (K_I/K_{Ic}) reaches unity after K_I begins to decrease, presumably the crack front will be warm prestressed and fracture may not be possible or, at least, a higher K ratio than that based on K_{Ic} would be required. To illustrate the application graphically, K_I is plotted in Fig. 14 for several different crack depths as a function

Fig. 14. Stress-intensity factor vs time for different values of a/w , showing locus of points for which $K_I/K_{IC} = 1$ (RCM, long axial crack, high-copper material).

of time and the locus of points for $(K_I/K_{IC}) = 1$ is superimposed. As indicated, for $0.03 < a/w < 0.2$, K_I is increasing when K_I/K_{IC} reaches unity. However, for $a/w > 0.2$, K_I is decreasing and one might conclude that flaws with fractional depths greater than 0.2 are warm prestressed.

It is possible that warm prestressing will be very beneficial with regard to limiting flaw propagation in PWR vessels. However, there is so little known about the phenomenon at this time that it was not considered in detail in the application of PWR conditions to the design of thermal shock experiments TSE-1 and TSE-2.

2.5 Results of Analysis

2.5.1 Long axial cracks

The calculated maximum stress-intensity factor (maximized with respect to time) as a function of crack depth (a/w) is shown in Fig. 13. As indicated, the maximum value with respect to a/w , $\sim 400 \text{ MN m}^{-3/2}$ ($\sim 365 \text{ ksi } \sqrt{\text{in.}}$), occurs at $a/w \approx 0.85$ and at about 10 min into the transient. For the low-copper case, a comparison of K_I and K_{Ic} vs a/w at various times in the transient shows that the K ratio (K_I/K_{Ic}) does not achieve unity, and thus propagation of the crack presumably would not take place. The maximum K ratio for this case was calculated to be 0.75 and corresponds to a crack depth (a/w) of 0.09 and a time of ~ 30 min.

For a high-copper vessel, the K ratio exceeds unity and over a wide range of crack depths, as indicated in Figs. 15 and 16, which show K_I , K_{Ic} , and K_{IR} vs a/w for times of 7.5 and 30 min. Thus, initiation of shallow cracks could be expected. The intercepts of the K curves in Figs. 15 and 16 and other similar ones were plotted as a function of the time at which the intercepts occurred. The results are shown in Fig. 17, which is a set of curves referred to as the critical crack depth curves. If K_{IR} is assumed to be an arrest toughness and if warm-prestressing effects are assumed to be negligible, crack propagation could proceed in a stepwise fashion as indicated. For the particular case under consideration, it is apparent that the crack would propagate well past $a/w = 0.5$ even if $K_{IR} < K_{Ia} \leq K_{Ic}$. One must keep in mind, however, that the calculational model tends to be conservative for fractional crack depths greater than 0.5.

2.5.2 Continuous circumferential cracks

The maximum stress-intensity factor as a function of a/w for the continuous circumferential crack is shown in Fig. 13. It is observed that there is a peak in the curve at $a/w \approx 0.5$ and the corresponding K_I value is $148 \text{ MN m}^{-3/2}$ ($135 \text{ ksi } \sqrt{\text{in.}}$). For the case of low copper, the potential for crack initiation is about the same as for the long axial crack; that is, $(K_I/K_{Ic})_{\text{max}} = 0.76$, and the corresponding time and depth are 30 min and 0.09, respectively. Thus, for the low-copper case, initiation would not be expected.

Fig. 15. Values of K_I , K_{IC} , and K_{IR} vs a/w for a long axial crack in RCM: high copper. Time = 7.5 min.

The maximum K ratio for the high-copper case is greater than unity, and the critical-crack-depth curve is that shown in Fig. 18. As indicated, initiation presumably will take place for fractional crack depths ranging from 0.01 to 0.5, and if $K_{Ia} = K_{IR}$ and warm prestressing is not a factor, a crack may penetrate to a fractional depth of 0.7.

2.5.3 Semicircular cracks

Calculated results for semicircular cracks of various depths are shown in Table 3 for both the low- and high-copper cases. For a semicircular crack the stress-intensity factor tends to be higher at the surface ($\theta = 90^\circ$) and decreases with decreasing θ , so that a minimum value occurs at the deepest part of the crack front ($\theta = 0^\circ$). This distribution

Fig. 16. Values of K_I , K_{IC} , and K_{IR} vs a/w for a long axial crack in RCM: high copper. Time = 30 min.

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Fig. 17. Critical crack depth for initiation and arrest in RCM assuming a long axial crack and high-copper material.

Fig. 18. Critical crack depth for initiation and arrest in RCM assuming a continuous circumferential crack and high-copper material.

of K_I , coupled with the positive gradient in K_{IC} , results in the decrease in the K ratio with decreasing θ as shown in Table 3. Although K_I is rather ill-defined right at the surface,¹⁰ the nominally negative gradient in the K ratio presumably results in a tendency for an initially semi-circular defect to grow long. This is discussed in greater detail in Section 2.5.4.

Table 3 shows that for the low-copper case the maximum K ratio is less than unity over most of the crack front. As already mentioned, the

Table 3. Calculated $(K_I/K_{IC})_{\max}$ values for
semicircular cracks; RCM

a [mm (in.)]	High copper			Low copper		
	θ			θ		
	90°	75°	0°	90°	75°	0°
19 (0.75)	1.57	1.34	0.97	0.90	0.70	0.41
25 (1.0)	1.78	1.50	0.98	1.02	0.76	0.38
51 (2.0)	2.36	1.80	0.74	1.37	0.84	0.25
102 (4.0)	2.89	1.80	0.20	1.72	0.71	0.06

maximum K ratio for the optimum-depth long crack is only 0.75. Thus, although the semicircular crack might extend in length a small amount, it will not become effectively long (see following discussion on semielliptical cracks), and even if it did, radial propagation presumably would not take place.

In the case of high copper the situation is different. As shown in Table 3, the maximum K ratio is greater than unity over most of the crack front. Furthermore, it has been shown that a long crack will penetrate radially. Thus, in the absence of warm prestressing, there is a high potential for the semicircular crack to become an effectively long crack.

2.5.4 Semielliptical cracks

Once a semicircular crack begins to extend along the length of the vessel, the geometry changes to an oblong shape. In an effort to determine how far a crack might run, calculations were made for semielliptical cracks with aspect ratios (major diameter/minor diameter) ranging upward from unity (semicircular crack). Results of this study are shown in Fig. 19, which shows the maximum K ratio for three points on the crack front ($\theta = 0, 75, \text{ and } 90^\circ$) as a function of crack depth and aspect ratio. Also shown are the approximate times at which the maximum ratios occur. As indicated by the curves, the K ratio at the intermediate point ($\theta = 75^\circ$) is nearly independent of the aspect ratio and increases with increasing crack depth. The K ratio at the bottom of the crack ($\theta = 0^\circ$) increases with increasing aspect ratio, although beyond $b/a = 10$ the ratio is nearly constant. Also, there is a maximum with respect to crack depth [$a \approx 25 \text{ mm}$ (1.0 in.)]. At the inner surface of the vessel ($\theta = 90^\circ$), the K ratio decreases with increasing aspect ratio but increases with increasing crack depth.

Based on the above information and in the absence of warm-prestressing effects, it appears that a shallow semicircular crack in a high-copper vessel would grow in length but at some point would tend to tunnel; that is, arrest would take place at the surface but not at points a short distance below the surface. On the other hand, the deviation from semielliptical geometry could result in higher K values at the surface that would allow surface cracking to continue. In either case there appears to be potential for a short crack to become long.

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Fig. 19. $(K_I/K_{Ic})_{max}$ vs b/a for semielliptical crack in RCM assuming high-copper material: (a) $a = 19 \text{ mm (0.75 in.)}$; (b) $a = 25 \text{ mm (1.0 in.)}$; (c) $a = 51 \text{ mm (2.0 in.)}$; (d) $a = 102 \text{ mm (4.0 in.)}$.

3. EXPERIMENTAL PROGRAM

3.1 Significance of PWR Analysis

Most of the present-generation PWR pressure vessels contain the low concentration of copper impurity and thus, based on calculations referred to herein, appear to be in little danger of experiencing significant flaw growth. However, there are a number of older vessels that presumably contain high concentrations of copper. Thus, in connection with these latter vessels it is desirable to study the propagation and arrest behavior of deep cracks ($a/w \geq 0.5$). Furthermore, the calculated margin of safety for the low-copper case is sufficiently small that experimental verification of the analytical technique is in order.

3.2 Simulation of PWR Conditions

3.2.1 Fracture toughness

The radial distribution of fracture toughness in the PWR vessel is a function of both temperature and fluence distributions. Since it is not practical to use an irradiated test specimen in the thermal shock experiments, the effect due to fluence must be achieved by other means if the radiation damage distribution is to be properly simulated. Two methods for obtaining the desired radial distribution in toughness were considered: (1) a sufficiently severe thermal shock to produce the desired toughness gradient in unirradiated pressure vessel steel (A508 class 2) and (2) a less severe thermal shock in combination with a non-uniform metallurgical degradation of the unirradiated material. The first method required cryogenic sink temperatures (liquid nitrogen) and appeared to be impractical because of coolant film blanketing problems. Radial gradients in toughness could be achieved by using a nonuniform tempering temperature distribution; however, the resulting residual stresses could not be coped with. Thus, for the time being, it was necessary to settle for an essentially uniform degradation in toughness; and the lowest toughness, in conjunction with acceptable strength and upper-shelf toughness, was obtained with a quench-only heat treatment [quenched from 871°C (1600°F) in water]. The fracture toughness curve (K_{Ic} vs

temperature) for this material is shown in Fig. 20, and the basis for the curve is discussed in Appendix A.

A comparison between the toughness curve in Fig. 20 and those for the RCM is illustrated in Fig. 21. As indicated, the test specimen material is tougher than the RCM material for the inner-surface fluence condition for both the high- and low-copper cases. This is an indication that the toughness is not low enough, if the severity of the thermal shock in the experiment were the same as that in the RCM. A better comparison in this

Fig. 20. Static fracture toughness curve used for analysis of 533-mm-OD (21-in.) thermal shock specimens TSV-1 and TSV-2. Curve based on data from A533, A508 (V-1 prolongation), and A508 (TSV-1 and TSV-5 prolongations), all in the as-quenched condition [quenched in water from $871^{\circ}C$ ($1600^{\circ}F$)].

Fig. 21. Comparison of toughness of quenched-only 871°C (1600°F) ASTM A533 material with reactor vessel (quenched [871°C (1600°F)] and tempered [677°C (1250°F)]) irradiated and unirradiated material.

regard is obtained by comparing K_{Ic} vs a/w curves at various times in the transient for the same thermal shock conditions. A comparison of this type is shown in Fig. 22. It is observed that the quench-only material is always considerably tougher than the RCM material. On the basis of these comparisons, it was concluded that the test specimens would have to be subjected to a more severe thermal shock than considered for the RCM.

Fracture toughness of a vessel wall presumably is a function of the ratio of uncracked ligament ($w - a$) to radius of the plastic zone (r_y) at the tip of the crack, if this ratio is too small. Corten¹¹ suggested

Fig. 22. K_{Ic} vs a/w for typical reactor temperature distributions for quenched [871°C (1600°F)] and tempered [677°C (1250°F)] A533 accounting for radiation damage, and for quenched-only [871°C (1600°F)] A533 neglecting radiation damage. RT_{NDT} (reactor material, unirradiated) = 4°C (40°F).

that the effect would be negligible if $(w - a)/r_y \geq 10$, and it was decided that this was a desirable condition for the test specimens. To use this criterion for the purpose of selecting w , it is necessary to specify a maximum value of a/w for which the criterion must be satisfied. For the RCM vessel this condition is satisfied for $a/w \leq 0.5$. Furthermore, at one time various members of the Thermal Shock Review Committee and NRC suggested that crack arrest within the inner half of the PWR vessel would be an acceptable condition. Thus, it seemed reasonable to select $0 \leq a/w \leq 0.5$ for the region in which the above criterion $[(w - a)/r_y \geq 10]$ should be satisfied.

3.2.2 Stress-intensity factor

The stress-intensity factor is a function of the severity of the thermal shock and, in the case of "deep" cracks, the flexibility of the vessel wall. As indicated above, the severity of the shock to the test specimen needs to be greater than that to the PWR vessel. Thus, in this regard K_I tends to be greater in the test specimen. However, since the ratio of wall thickness to diameter must be greater for the test specimen than for a PWR vessel (see Section 3.4), the test specimen is stiffer and thus K_I tends to be less for deep long cracks. This is illustrated in Fig. 23, which is a plot of $(K_I)_{\max}$ vs a/w for long axial cracks in the RCM and in several test specimens subjected to a variety of thermal shocks. It is observed that with the exception of the 102-mm-wall (4-in.) specimen, the K_I values for shallow cracks are greater in the test specimens than in the RCM. However, as the depth of the crack increases, there is an opposite trend that is more pronounced for the stiffer walls. It is noted that for the 0.533-m-OD (21-in.) $\times$ 0.152-m-wall (6-in.) specimen, K_I decreases with increasing a/w for $a/w > 0.15$, but for the 0.99-m-OD (39-in.) $\times$ 0.152-m-wall (6-in.) specimen, K_I continues to increase for $a/w < 0.55$. Decreasing the wall thickness makes the wall more flexible and thus increases K_I for deep cracks. However, the thinner wall results in a less severe thermal shock and thus a lower value of K_I for shallow cracks.

Fig. 23. Maximum stress-intensity factor for a long axially oriented crack for the reference calculational model and in various test vessels (1 in. = 25.4 mm).

3.2.3 The K ratio, K_I/K_{Ic}

The ratio of stress-intensity factor to fracture toughness is a measure of the potential for crack initiation and also provides a rough indication of how far a flaw might extend. To simulate a PWR noninitiation condition in an experiment, the maximum K ratio in the experiment should be the same as that calculated for the PWR. More generally, the range of maximum K ratio that should be included in the experimental determination of the validity of analytical techniques should be at least equal to the range calculated for the PWR.

3.2.4 Extent of crack propagation

The extent of crack propagation can be estimated from critical-crack-depth curves of the type discussed in Section 2.5. Calculations for the RCM, neglecting warm-prestressing effects, indicate that for the high-copper case a continuous circumferential crack and a long axial crack will penetrate more than half the thickness of the vessel wall. A similar situation should be considered in the experimental program.

3.2.5 Length of test specimens

With regard to fracture toughness for a long axial crack and bending restraint for a continuous circumferential crack, a PWR vessel is effectively infinitely long. However, the vessel heads provide end restraint that may have a significant effect on the degree of bending associated with a long axial crack. Nevertheless, it is intended that infinite-length conditions be attained for the first several experiments. To this end, no significant end restraints will be incorporated. Under these circumstances the length requirement for a continuous circumferential crack is greater than that for a long axial crack and is estimated from¹²

$$l \geq 2\pi \left[\frac{r_0^2 w^2}{3(1 - \nu^2)} \right]^{1/4}, \quad (9)$$

where

l = required length of test cylinder,

r_0 = inside radius of test cylinder,

w = wall thickness,

ν = Poisson's ratio.

For the RCM vessel, $l \geq 3.4$ m (11 ft) and the lengths of actual PWR vessels are at least twice this value.

3.3 Summary of Criteria for Selecting Test Specimen Dimensions, Material Properties, and Severity of Thermal Shock

Testing conditions should range from the noninitiation situation predicted for the low-copper PWR [$K_I/K_{Ic} \max \geq 0.75$] to the cases involving deep penetration ($a/w \geq 0.5$) as calculated for long circumferential and axial cracks in the high-copper vessels. The material for the test specimens should be A508 class 2 steel insofar as chemical composition is concerned and should have strengths comparable to those of actual PWR irradiated material (40-year reactor vessel life).

3.4 Selection of Test Specimen Dimensions, Heat Treatment for Specimen Material, and Severity of Thermal Shock

A test specimen similar in size to the intermediate test vessels (ITVs) was selected for preliminary analysis for the sake of maintaining continuity in the HSST vessel-testing program and because from a test-facility point of view a specimen about that size was practical. The outside diameter of the ITVs is 0.99 m (39 in.), and a 0.152-m wall (6 in.) and 1.27-m length (50 in.) appeared to satisfy the conditions stated in Section 3.2. The most severe thermal shock that could be administered in a practical sense consisted of a sink temperature of -73°C (-100°F) and a fluid film heat transfer coefficient of $\sim 5700 \text{ W m}^{-2} \text{ }^\circ\text{C}^{-1}$ ($10^3 \text{ Btu hr}^{-1} \text{ ft}^{-2} \text{ }^\circ\text{F}^{-1}$). As explained in Section 3.2.1, the lowest toughness achievable, while maintaining adequate strength, was specified and was

obtained with the quench-only heat treatment. The calculated maximum K_I value as a function of a/w for these conditions (long axial crack) and also for a sink temperature of -18°C (0°F) is shown in Fig. 23, where a comparison is made with similar data for the RCM. Important features to note in Fig. 23 are the higher K_I values for the 0.99-m-OD test specimen in the inner portion of the wall, the positive gradient in this same region of the wall, and at $a/w \approx 0.5$ the K_I values for the RCM and the 0.99-m-OD test specimen, with a sink temperature of -73°C (-100°F), are equal.

The calculated depth to which a crack would propagate in the test specimen, assuming $K_{Ia} = K_{Ic}$ and no warm-prestressing effects, is given in Table 4. As indicated, for a sink temperature of -73°C (-100°F), the crack presumably would go 70% of the way through the wall of the 0.99-m-OD test specimen. If $K_{Ia} < K_{Ic}$, the crack would go even deeper. All these characteristics are desirable and would be adequate for an initial series of thermal shock experiments.

Table 4. Calculated deepest point of penetration under various test conditions for long axial cracks in cylindrical thermal shock specimens, assuming $K_{Ia} = K_{Ic}$

Test vessel dimensions [m (in.)]		Thermal shock		Maximum crack depth (a/w)
OD	Wall thickness	T_s [$^\circ\text{C}$ ($^\circ\text{F}$)]	h [$\text{W m}^{-2} \text{ }^\circ\text{C}^{-1}$ ($\text{Btu hr}^{-1} \text{ ft}^{-2} \text{ }^\circ\text{F}^{-1}$)]	
0.53 (21)	0.152 (6)	-23 (-10)	5700 (10^3)	0.16
0.53 (21)	0.152 (6)	-73 (-100)	5700 (10^3)	0.35
0.99 (39)	0.152 (6)	-18 (0)	5700 (10^3)	0.30
0.99 (39)	0.152 (6)	-73 (-100)	5700 (10^3)	0.70

A proposal was submitted for conducting thermal shock experiments on 0.99-m-OD (39-in.) $\times$ 0.152-m-wall (6-in.) test specimens with sink temperatures down to -73°C (-100°F). However, the procurement time for the forgings was so long that interim measures were considered. Two forgings, which were the trepanned cores from two of the ITV vessels, were available

and could be machined into 0.53-m-OD (21-in.) test specimens. Maximum K_I values for 0.10-, 0.13-, and 0.15-m-wall (4-, 5-, and 6-in.) cylinders with this diameter and for sink temperatures of 4, -18, and -73°C (40, 0, and -100°F) are shown in Fig. 23, where they are compared with results for the 0.99-m-OD (39-in.) specimens and the RCM vessel. It is observed that for $a/w \geq 0.5$, the smaller diameter results in K_I values about half those for the larger diameter specimens. Also, the gradients for the 0.13- and 0.15-m-wall cases are negative rather than positive over a large range of wall thickness ($0.15 \leq a/w \leq 1$). Reducing the wall thickness tends to increase K_I and $dK_I/d(a/w)$ for $a/w > 0.3$. However, for smaller values of a/w , K_I tends to decrease with decreasing wall thickness. For shallow cracks and the same wall thickness and thermal shock, the K_I values are about the same for the 0.99- and the 0.53-m-OD test specimens.

The calculated maximum depths of crack propagation for the 0.53-m-OD specimen, assuming $K_{Ia} = K_{Ic}$, are shown in Table 4. For sink temperatures of -23°C (-10°F) and -73°C (-100°F), the fractional depths are 0.16 and 0.35, respectively.

In accordance with Eq. (9), the required minimum length for the 0.53-m-OD test specimens is about 0.91 m. The forgings were of sufficient size to yield a specimen of this length plus a prolongation for material property testing.

Characteristics for the 0.53-m-OD test specimen are not satisfactory for the study of deep cracks. However, the K_I values for a 0.15-m wall and $a/w < 0.15$ are large enough to permit useful shallow-crack experiments. Early in the thermal shock program, a decision was made to conduct preliminary experiments with two 0.53-m-OD specimens and eventually run tests on 0.99-m-OD test specimens, whereupon three forgings for 0.99-m-OD test specimens were purchased. However, more recently it was decided that the need for testing the larger specimens would be reevaluated following testing of the smaller specimens.

3.5 Thermal Shock Test Facility

The method for administering the thermal shock to the test specimens is shown schematically in Fig. 24. Prior to the shock the test specimen

Fig. 24. Schematic of thermal shock test facility.

is heated by an electric furnace to a specified initial temperature, and a large quantity of coolant contained in a storage tank is chilled to the desired sink temperature. To administer the thermal shock, the coolant is pumped through a narrow annulus formed by the inner surface of the test specimen and a cylindrical flow baffle. Heat given up by the system is absorbed and retained in the coolant for the duration of the test, which is about 30 min. The total quantity of coolant is specified on the basis of an acceptable increase in sink temperature. Variations in the severity of the thermal shock are achieved by varying the coolant velocity, and thus fluid film heat transfer coefficient, and the sink temperature. It also is possible to vary the initial temperature of the test specimen; however, it is not anticipated that a temperature other than the PWR vessel normal operating temperature [$\sim 288^{\circ}\text{C}$ (550°F)] will be used in the near future.

During the time that a test specimen is being heated and the coolant is being chilled, the test specimen is isolated from the coolant by the quick-opening valve, and the portion of the system from this valve to the level of the coolant in the storage tank is filled with low-pressure nitrogen gas. When the specimen and coolant are at their desired initial temperatures, the pump is energized and coolant is pumped through the bypass only. This ensures continuous operability of the pump and removes warm coolant from the area adjacent to the quick-opening valve. Moments later, room-temperature water is directed through the interior of the flow baffle to lower the temperature of the baffle and thus reduce steam formation in the adjacent coolant annulus during the thermal shock to the test specimen. Coolant to the baffle is applied for 30 sec and is then removed from the baffle in 30 sec with air. Immediately thereafter, the quick-opening valve is operated and the thermal shock to the test specimen is in progress. Most of the pump head is taken across an orifice near the outlet of the test specimen. The resultant pressurization in the test section reduces the duration of the vapor-film-blanket condition that occurs early in the transient and tends to insulate the test specimen from the thermal shock.

Two test facilities eventually were designed for the Thermal Shock Program. The first had the capability for testing the 0.99-m-OD as well

as the 0.53-m-00 test specimens with sink temperatures down to -73°C using methanol as the coolant. This rather elaborate facility was under construction when a decision was made to construct a less expensive facility for testing only the smaller specimens and for sink temperatures no lower than -23°C (-10°F). The larger facility, as conceived at that time, has been canceled. Photographs of the present facility are shown in Figs. 25 and 26. Figure 25 shows the basic components with the furnace removed from the test specimen, while Fig. 26 shows the facility with the furnace and all other equipment in place. The test section subassembly is shown in Fig. 27.

3.6 Data Retrieval from the Test Specimen During the Thermal Shock

Two types of data must be retrieved during the thermal shock: radial temperature distributions in the wall of the test specimen and indications of crack propagation or a lack thereof. Numerous thermocouples are located in the wall and on the surfaces of the test specimen to obtain the radial distributions, and complete sets of data are recorded on tape every 2.5 sec during the transient. Detailed locations and installation techniques for the thermocouples are described in Appendix B.

Two techniques are used for detecting crack propagation. One makes use of strain gages that are placed across and normal to the initial flaw or across the expected path of propagation. Output from the gages is recorded on tape periodically (every 2.5 sec) and also continuously on strip-chart recorders. Crack extension, whether in the form of a new crack appearing under the gages or as additional crack opening, appears as a step change in gage output on the chart and thus can be distinguished from gradual changes in output due to temperature and stress changes. The strain gages are the weldable type with gage and leads sheathed in stainless steel.

The other technique used for detecting crack extension is acoustic emission (AE). Four AE transducers with waveguides are used in appropriate positions on the outer surface of the test specimen to allow triangulation and thus location of a particular emission. There was concern that hydraulic noise would swamp the emission from crack propagation, but thus far this appears not to be the case.

Fig. 25. Photograph of thermal shock test facility during early stages of assembly, showing basic components of system.

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Fig. 26. Photograph of thermal shock test facility prepared for operation (test specimen enclosed by furnace).

Fig. 27. Drawing of test specimen subassembly.

Further details regarding the COD and AE instrumentation are provided in Appendix C.

3.7 Residual Stresses in Test Specimens

The quench-only heat treatment applied to the test specimens creates very high residual compressive stresses on the surfaces and considerably lower tensile stresses over a large portion of the interior of the wall. Following the quench and prior to machining of the inner and outer cylindrical surfaces, the radial distribution of the residual stresses is approximately as shown in Fig. 28. The high residual compressive stresses in the inner region of the wall must be removed; otherwise the desired K_I values could not be achieved during the thermal shock. Stress relieving by means of elevated temperatures cannot be used since this would cause some tempering of the material and thus an undesirable increase in fracture toughness. The problem was solved by starting with a wall thick enough so that the residual compressive stress could be machined away. Residual stress measurements obtained from the prolongations of the two 0.53-m-OD test specimen forgings provided the necessary information. Not enough material was available on the OD of the forgings, from which the test specimens were to be machined, to allow complete removal of the residual compressive stress in the outer region of the wall. Thus, in the final machined form, the test specimens had a residual tensile stress of about 55,000 kPa (8000 psi), extending from the inner surface to a fractional depth of about 0.75, and a residual compressive stress on the outer surface of about 550,000 kPa (80,000 psi). These stresses are added to the thermal stresses during a thermal shock and, in principle, must be considered in a determination of K_I . As yet, this has not been done for the analyses discussed herein. It is estimated that inclusion of the residual stresses in the analysis of the experiments conducted to date will increase the calculated K ratio by no more than 10%.

3.8 Flaw Generation

The flaws in the two 0.53-m-OD test specimens were generated by machining a slot 9.5 mm ($\frac{3}{8}$ in.) wide to within 6.4 mm ($\frac{1}{4}$ in.) of

Fig. 28. Approximate residual stress distribution in test specimen wall following quench-only heat treatment and prior to final machining.

the desired crack depth and then applying an electron-beam (EB) weld to the final crack depth. Residual stresses in the weld zone caused the weld to crack during cooling. The crack arrested just beyond the tip of the fusion zone, presumably in a region having a steep negative gradient in residual tensile stress and a positive gradient in toughness. Typical flaws prepared in this manner are shown in Figs. 29 and 30. Dimensional data for the flaws used in the 0.53-m-OD test specimens are included in Appendix B.

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Fig. 29. Crack contours for long and semicircular cracks in final checkout coupons.

Fig. 30. Photomicrograph of the tip region of an electron-beam weld that cracked immediately following welding operation.

3.9 Experiments with 0.53-m-OD (21-in.) Test Specimens

Two experiments have been conducted with the 0.53-mm-OD test specimens. They are referred to as TSE-1 and TSE-2, and the respective test specimens were TSV-1 and TSV-2. Test conditions are summarized in Table 1. The purpose of the first experiment (TSE-1) was to simulate fracture-oriented conditions pertaining to a PWR vessel with a long axial crack of optimum depth (maximum K ratio) and a low concentration of copper impurity.

The long axial crack was used because presumably it has the greatest potential for radial propagation. The calculated maximum K ratio for the low-copper PWR (RCM) vessel was 0.75, and an attempt was made to achieve the same maximum value in TSE-1. Since the maximum K ratio is substantially less than unity, it was not expected that the flaw would propagate for nominal stress and fracture toughness conditions.

The purpose of the second experiment (TSE-2) was to study the axial growth characteristics of a "short," axially oriented inside-surface flaw. Such a flaw tends to have high K ratios for points on the crack front near the surface and low values near the bottom of the flaw. It was postulated that a crack of this type might grow to become effectively a long crack and then propagate radially. A semicircular crack geometry was selected because it has a high ratio of K_I/K_{Ic} at the surface ($\theta = 90^\circ$) compared to that at the bottom ($\theta = 0^\circ$) and solutions for K_I are available. A parametric analysis indicated that a radius of ~ 19 mm (0.75 in.) for the semicircle would result in a maximum K ratio at $\theta = 0^\circ$ (maximum potential for radial growth), and this size flaw was selected. TSE-2 simulates the high-copper PWR case to the extent that at a specific reference point on the crack front ($\theta = 75^\circ$)* the maximum K ratios are very nearly the same (1.35) for the particular size flaw. To achieve this K ratio in TSE-2 required the maximum thermal shock capability of the test facility.

For TSE-2, the maximum K ratio for a long axial crack of depth 19 mm is ~ 1.2 . Therefore, if the semicircular crack did propagate axially to become effectively a long crack, the crack might grow in depth. However, the maximum K ratio at the bottom of the semicircular crack is less than unity, so that radial extension would not be expected unless the crack grew considerably in length. The maximum K ratio (maximum with respect to time) as a function of position on the semicircular crack front is shown in Fig. 31 ($b/a = 1$).

If one assumes that the initially semicircular crack retains a semi-elliptical shape, if and when the crack propagates axially, and if warm

* The 75° point was selected somewhat arbitrarily as being more indicative of the potential for axial extension of the flaw than points closer to the surface because of free surface effects.

Fig. 31. Maximum K ratio along semielliptical crack front for TSE-2 conditions.

prestressing is not a factor, a prediction can be made as to how far the flaw might extend. Calculations were made for semielliptical cracks with a depth of 19 mm (0.75 in.) and several aspect ratios, using the temperature distributions predicted for TSE-2. The maximum K ratios (maximum with respect to time) along the crack front are shown in Fig. 31. These results indicate that the crack would grow sufficiently in length that it

also could grow in depth, and this in turn would tend to increase the K ratio near the surface. Thus, the analysis indicates that there is a tendency for the crack to grow in length to become a long crack.

3.9.1 TSE-1 results

The maximum K ratio calculated from the measured temperature distributions for TSE-1, neglecting residual stresses and the effect of the flaw slot (weld groove) on heat transfer, was 0.74; it occurred at about 8 min into the transient. Output from the COD gages showed no step changes that would indicate crack extension except immediately upon application of the thermal shock, and this change could be due entirely to crack opening without extension and to thermal stress. According to Ying (see Appendix D), the AE output from TSE-1 was indicative of a maximum K ratio less than but close to unity (~ 0.8). Thus, it was tentatively concluded that unstable crack growth had not occurred.

Further examination of the test specimen (TSV-1) was conducted by trepanning from the specimen wall two 25-mm-diam (1-in.) cores that contained 25-mm lengths of the flaw. The cores were oriented radially, were removed by the electron discharge machining technique (EDM), and were located in the wall as shown in Fig. 32. The cracked portion of each trepanned core was partitioned as shown in Fig. 33 for metallographic examination, and the remaining portion containing the crack was chilled to liquid-nitrogen temperatures and split apart to expose the crack faces. Photomicrographs of the polished surfaces are shown in Figs. 34 and 35, and photographs of the exposed faces are shown in Fig. 36. A complete metallurgical examination (see Appendix G) of the available data indicate that crack extension up to 3 mm (0.1 in.) took place during the thermal shock. It is believed that the extension constitutes stable rather than unstable crack growth and that it took place at upper-shelf temperatures; however, all the data are not consistent in this regard. The nature of the crack extension is discussed below, and additional experimental and calculational data associated with TSE-1 are included in Appendix E.

Some recent experimental data indicate that during testing with compact-tension (CT) specimens subcritical crack growth takes place prior to

Fig. 32. Location of trepanned cores in TSV-1 following TSE-1.

the final drop in load on the load vs displacement diagram, provided that the testing temperature is in the upper-shelf-toughness range.^{13,14} These data indicate that for CT specimens larger than 0.5T, the load associated with the subcritical crack growth is about half the maximum. Based on this information, a stress-intensity factor of about $110 \text{ MN m}^{-3/2}$ (100 ksi $\sqrt{\text{in.}}$) would be required in the test specimen (TSV-1) to cause subcritical crack growth. Thermal stresses resulting from the nominal transient temperature distributions during TSE-1 were not high enough, particularly in the early moments of the transient, to produce a K value that high. However, residual stresses at the tip of the original crack, following formation of the crack during cooling of the EB weld deposit, could have contributed a large fraction of the necessary stress-intensity factor. During formation of the original crack, the greatest potential for crack extension is when the test specimen experiences some minimum temperature (maximum stress and minimum toughness), which in this case was room temperature. Since the original crack arrests at a point beyond the EB weld fusion zone (see Fig. 30), the toughness data in Fig. 20 are

Fig. 33. Sample of trepanned core for thermal shock vessel (TSV-1). Metallographic view along section A-A; scanning electron microscopy examination along section B-B.

Fig. 34. Posttest examination of the EB weld from trepanned core TSV-1-1 removed from TSV-1 following TSE-1. (a) EB weld showing crack and extension; EB fusion zone in this photomicrograph is 6.70 mm (0.264 in.) deep. (b) Region of crack tip extension. Crack has extended 0.91 mm (0.036 in.) at this location.

Fig. 35. Posttest examination of the EB weld from trepanned core TSV-1-2 removed from TSV-1 following TSE-1. (a) EB weld showing crack and extension; EB fusion zone in this photomicrograph is 7.31 mm (0.288 in.) deep. (b) Region of crack tip extension. Crack has extended 1.83 mm (0.072 in.) at this location.

Fig. 36. Photomacrographs of the fracture surfaces from two cores removed from TSV-1 by the electrodischarge machining process. The dark band located near the middle of the two specimens is the area of crack extension. The surface in this area exhibited a cleavage appearance, a crack mode indicative of frangible fracture.

probably applicable, assuming $K_{Ia} \approx K_{Ic}$. Thus, the residual stress-intensity factor for the original crack would be about $55 \text{ MN m}^{-3/2}$ (50 ksi $\sqrt{\text{in.}}$), which is half the value required to permit subcritical crack growth. The stress-intensity factor associated with the nominal thermal stress reaches a value of $55 \text{ MN m}^{-3/2}$ (50 ksi $\sqrt{\text{in.}}$) at about 20 sec into the transient. Thus, subcritical crack growth probably could occur within the first several seconds of the transient, and it is tentatively concluded that the short crack extension observed in TSE-1 was of this type.

On the other hand, SEM examination of the fracture surfaces available from the two trepanned cores indicates frangible fracture, contrary to the other findings. Presumably, a brittle fracture could not take place early in the transient, when temperatures are in the upper-shelf range; and there were no indications from the COD gages or acoustic-emission instrumentation that initiation occurred at a later time. However, it is of interest to note that in TSE-2 (see Section 3.9.3), a running crack penetrated a region having upper-shelf temperatures, and SEM examination of the corresponding surfaces indicates frangible fracture. These observations suggested that fracture of the quench-only material at upper-shelf temperatures might not result in a ductile-type fracture surface appearance. However, an examination of TSE-1 and -2 prolongation precracked Charpy specimen fracture surfaces shows a dimple (ductile) fracture surface for upper-shelf temperatures. The apparent discrepancies remain unresolved.

Although not verified by the COD gage and AE data from TSE-1, it is possible that the K ratio was considerably greater than the estimated nominal value of 0.74. This value was based on a model that neglected residual stresses resulting from the heat treatment (quench-only treatment), possible enhanced cooling associated with the existence of the open EB weld groove, and inaccuracies in the calculation of K_I . The estimated maximum effects of these three factors are 10, 7, and 10%, respectively. This could increase the calculated maximum K ratio to ≈ 0.96 , assuming nominal values for K_{Ic} . It is of interest to note that the uncertainty in K_{Ic} alone is large enough to increase the K ratio from 0.74 to nearly unity. Thus, it is possible from this point of view

that unstable crack growth took place. However, since there was no indication from the COD and AE output to indicate this happened, it is tentatively concluded that the observed extension resulted from subcritical crack growth.

3.9.2 TSE-2 results

The stress-intensity factor, fracture toughness, and K ratio calculated for the TSE-2 measured temperature distributions are shown in Figs. 37 to 39 for $\theta = 90, 75, \text{ and } 0^\circ$, respectively, as a function of time. As indicated, a K ratio of unity was achieved at 17 and 63 sec for $\theta = 90$ and 75° , respectively, assuming of course that no propagation took place. At $\theta = 0^\circ$, the maximum K ratio was less than unity. The maximum K ratio at $\theta = 75^\circ$, for the original semicircular geometry, was 1.33 and occurred at 34 min into the transient.

During the experiment, the COD and AE instrumentation indicated that the crack propagated at the upper end at 36 sec and at the lower end at 86 sec, with a possible second initiation of the upper end at 86 sec. Output from the COD gages is shown in Figs. 40 through 45, and the locations of the gages are shown in Figs. 46 and 47 (also see Appendix B). Also shown in these latter two figures is the apparent extent of crack extension on the surface as observed shortly after the experiment.

The COD traces in Figs. 43 and 45 show that there were two sets of blips from the upper end of the flaw (gages XE-33 and -34). This indicates that there was a second initiation at the upper end beyond the gages. However, these blips occurred at the same time as those at the lower end of the flaw. Thus, the second set of blips at the upper end could have resulted from crack opening associated with the crack extension at the lower end.

The AE instrumentation on TSE-2 indicated five significant events (see Appendix F), three of which (events 1, 3, and 5) took place along the crack line and the other two some distance from the crack. Events 3 and 5 coincided in time and position with the COD blips (36 and 86 sec, respectively) and had larger acoustic emissions associated with them than the others. The first event took place at about 8 sec, was located at

Fig. 37. Values of K_I , K_{IC} , and K_I/K_{IC} vs time for TSE-2, initial semicircular flaw, $\theta = 90^\circ$.

the upper end of the flaw, and was relatively low in amplitude. Other than this (in combination with event 5, which also was located at the upper end), there was no indication of a second initiation of the upper end. Based on this information, it is concluded that the first event probably was subcritical crack growth, and this was followed by a single propagation at the upper end (36 sec) and then a single propagation at

Fig. 38. Values of K_I , K_{IC} , and K_I/K_{IC} vs time for TSE-2, initial semicircular flaw, $\theta = 75^\circ$.

Fig. 39. Values of K_I , K_{IC} , and K_I/K_{IC} vs time for TSE-2, initial semicircular flaw, $\theta = 0^\circ$.

Fig. 40. COD trace during TSF-2. Gages XE-30 and -31, $t = 0$ to ~ 100 sec.

Fig. 41. COD trace during TSE-2. Gages XE-30 and -31, $t = \sim 60$ to ~ 100 sec.

Fig. 42. COD trace during TSE-2. Gages XE-32 and -33, $t = 0$ to ~ 60 sec.

Fig. 43. COD trace during TSE-2. Gages XE-32 and -33, $t = \sim 20$ to ~ 100 sec.

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Fig. 46. Flaw size and COD instrumentation data for TSE-2.

the lower end (86 sec). The source of events 2 and 4 is tentatively attributed to slag inclusions (see Appendix F).

The crack was further examined by trepanning a core that contained the entire crack (see Fig. 48). Several cross sections were cut through the core for metallography studies, and finally the pieces of the core were split at cryogenic temperatures to reveal the crack faces. The sectioned core is shown in Fig. 49, and typical photomicrographs of the cross sections are shown in Fig. 50. A photograph of the exposed fracture surface is shown in Fig. 51, and an outline of the entire final crack front showing the stages of development is depicted in Fig. 52. Additional photographs and a detailed discussion of the metallurgical aspects

Fig. 47. Photograph of flaw and crack extension in TSV-2 (TSE-2).

Fig. 48. Sketch of TSV-2 showing location and shape of core removed from the wall for further examination of the extended flaw.

of the crack extension are presented in Appendix G. It suffices to say here that there is no indication of a second initiation at the upper end; axial extension was ~ 66 mm (2.6 in.) at the upper end and ~ 41 mm (1.6 in.) at the lower end for a total final crack length of 142 mm (5.6 in.); there was a small amount of extension at the deepest point of the semicircular crack front ($\theta \approx 0^\circ$); and the fracture mode was predominantly brittle. There is some indication of subcritical crack growth along the original crack front (mixed mode fracture surface).

In an effort to explain why the flaw developed in the manner described above, the following information is provided: at 36 sec into the transient the calculated K ratio along the semicircular crack front ($b/a = 1$) was as shown in Fig. 53. It is observed that the K ratio is less than unity over most of the crack front [$a' > 2.5$ mm (0.1 in.)] and that for $a' > 8$ mm (0.3 in.) the toughness is on the upper shelf [temperature >

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Fig. 49. Photograph of partially reassembled core removed from TSV-2 following TSE-2 showing the crack face. The crack portion of the core was cut up for metallographic studies.

Fig. 50. Photomicrographs of crack extension in TSV-2 (TSE-2).
 (a) Typical new crack at axial location beyond end of original flaw;
 (b) cross section through original flaw showing machined slot, EB weld crack, and crack extension.

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Fig. 51. Photograph of reassembled pieces cut from the TSV-2 (TSF-2) trepanned core showing exposed faces of machined slot, EB weld flaw, and crack extension.

Fig. 52. Sketch of original semicircular flaw and flow extension in TSV-2 (TSE-2).

120°C (250°F)]. Even so, the upper end of the crack appears to have extended at this time to the shape shown in Fig. 52. This shape can be approximated with a semiellipse with an aspect ratio of ≈ 2.7 . The calculated K ratio along the front of this latter crack is shown for $t = 36$ sec in Fig. 53. As indicated, there is not much difference between the $b/a = 1$ and 2.7 curves. As the transient proceeds, the K ratio all along the crack front increases, achieving maximum values in excess of unity for $a' \leq 18$ mm (0.7 in.) (see Fig. 53) at times ranging from 3 to 8 min.

At 86 sec into the transient, the lower end of the flaw propagated. Just prior to this event the calculated K ratio along the assumed semielliptical crack front ($b/a \approx 2.7$) was as shown in Fig. 54. Here again, only a portion of the crack front [$a' \leq 8$ mm (0.3 in.)] has a K ratio greater than unity, and for $a' > 15$ mm (0.6 in.) the toughness is on the upper shelf. The final length of the crack on the surface was approximately 140 mm (5.6 in.), which corresponds to an aspect ratio of 3.7. Assuming semielliptical geometry with this aspect ratio, the K ratios at 86 sec are those shown in Fig. 54. Also shown in this figure are the

Fig. 53. K_I/K_{Ic} and temperature vs a' for $b/a = 1$ and 2.7 at $t = 36 \text{ sec}$ and t_{max} ; TSE-2.

maximum K ratios for $b/a = 3.7$ and the approximate times at which they occur. As before, the increase in aspect ratio (from 2.7 to 3.7 this time) decreased the K ratio some near the surface and increased it slightly elsewhere. The maximum K ratios occurred later (3 to 8 min) and were greater than unity along the entire crack front by about 25% .

A possible explanation for the crack behaving in the above described manner is as follows. Following initiation of the upper end of the flaw,

Fig. 54. K_I/K_{IC} and temperature vs a' for $b/a = 2.7$ and 3.7 at $t = 86$ sec and t_{max} ; TSE-2.

the crack was able to advance along much of the crack front because the dynamic toughness was sufficiently less than the static toughness to maintain a K ratio of unity. Arrest took place as the bottom portion of the new crack front ran into upper-shelf material, and the stress-intensity factor closer to and at the surface was reduced by the change in crack shape (smaller angle with inner surface). Once again under static conditions, the crack would not move until the static K ratio reached unity at

or near the surface. This occurred at 86 sec, initiation taking place at the lower end because the angle with the surface was steeper than at the upper end. Propagation and arrest took place as before. Initiation did not take place again because near the surface the K ratio was less than indicated in Fig. 54 due to lack of restraint and a shallower angle with the surface than assumed, and at deeper points the crack front was warm prestressed by the time the nominal K ratio passed through unity. In support of the above explanation, reference is made to K_I vs time data in Figs. 55 through 57 for aspect ratios of 1, 2.7, and 3.7, respectively.

Fig. 55. K_I vs time for TSE-2 showing locus of points for $(K_I/K_{Ic}) = 1$; semielliptical flaw with aspect ratio $(b/a) = 1$.

Fig. 56. K_I vs time for TSE-2 showing locus of points for $(K_I/K_{Ic}) = 1$; semielliptical flaw with aspect ratio $(b/a) = 2.7$.

Also plotted in these figures are the loci of points for $K_I/K_{Ic} = 1$. Presumably, warm-prestressing effects exist if a K ratio of unity is achieved after K_I reaches a maximum value. As indicated in Fig. 55, warm prestressing did not take place before the first crack propagation event ($t = 36$ sec). At $t = 36$ sec, the geometry changed such that $b/a = 2.7$, and Fig. 56 shows that prior to $t = 86$ sec (time of the second propagation event) warm-prestressing effects did not exist. At 86 sec, the aspect ratio changed from 2.7 to 3.7, and points on the crack front deeper than ~ 0.3 in. were warm prestressed (Fig. 57).

With regard to the postulate that the dynamic toughness was substantially less than the static toughness, toughness data reported by Shabbits¹⁵ and Crosley and Ripling¹⁶ for A533 quenched and tempered material indicate

Fig. 57. K_I vs time for TSE-2 showing locus of points for $(K_I/K_{Ic}) = 1$; semielliptical flaw with aspect ratio $(b/a) = 3.7$.

ratios of static to dynamic toughness in the transition region of about 2 to 3, with the ratios increasing with increasing temperature. Thus, in this regard the above explanation seems reasonable. However, a few dynamic data points obtained by ORNL¹⁷ for A533 in the quench-only condition indicate very little difference between static and dynamic toughness in the transition region and a higher dynamic toughness on the upper shelf. If the ORNL data are more appropriate, the above explanation for crack behavior in TSE-2 is not valid.

Additional experimental and associated data pertaining to TSE-2 are presented in Appendix F.

3.9.3 Discussion of results and recommendations for additional studies

Results from TSE-1 and TSE-2 tend to validate the methods of analysis; that is, in TSE-1 presumably unstable crack growth did not take place, and in TSE-2 it did. However, for TSE-1, the calculated maximum K ratio was rather small (~ 0.74) compared to unity and the uncertainty in fracture toughness was fairly large (at least $\pm 25\%$). In TSE-2, crack propagation took place where the K ratio based on static fracture toughness was well below unity (< 0.5) and in regions where the temperature corresponded to upper-shelf toughness. Furthermore, following arrest of the crack, reinitiation did not take place even though calculations that ignored warm-prestressing effects predicted reinitiation. Thus, it is not possible to conclude that the analysis procedures used for TSE-1 and TSE-2 are complete at this time.

Another point of interest with regard to our knowledge of crack performance under thermal shock loading at this time is that the crack surfaces exposed by subcritical crack growth (TSE-1 and TSE-2) and by fracture at upper-shelf temperatures (TSE-2) show more evidence of brittle fracture (cleavage) than ductile fracture (dimpling). An examination of the laboratory specimens indicates that these characteristics are not typical for the quench-only material, which has an upper-shelf Charpy V-notch impact energy of only 41 J (30 ft-lb).

With regard to material properties, it should be mentioned again that the forgings from which TSV-1 and TSV-2 were machined were the cores trepanned from the central portion of larger forgings (intermediate test vessels associated with the HSST program) and therefore, as could be expected, appear to contain unusually high concentrations of impurities and to have a high degree of inhomogeneity. This situation results in a spread in material property data that may exceed that to be expected for reactor-grade material and that is undesirable for an experimental program that includes accuracy determinations for analytical techniques. Thus, there is a need to conduct additional thermal shock experiments with higher grade material. There is also a need to obtain more extensive material

property data, particularly dynamic (K_{ID}) and arrest toughness, for the existing test specimens. In order to accomplish this, TSV-1 and TSV-2 will have to be used as a source of test material since most of the prolongation material has been consumed.

With regard to recommendations for future experiments, it is apparent that, in the case of the long axial crack, K ratios closer to and greater than unity need to be achieved in order to determine more closely the accuracy of the analytical techniques. The study of finite-length flaws should be continued also using different size flaws, perhaps more than one flaw in the same test specimen, to see if there is a significant difference in axial growth due to initial flaw size and shape. Some or all of these experiments (long and short flaws) can be conducted with specimens TSV-1 and TSV-2 using multiple flaws. One additional experiment that has already been approved consists of applying a more severe thermal shock to TSV-1 with the existing long axial crack such that the maximum K ratio will be ~ 1.2 .

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APPENDIX A
FRACTURE TOUGHNESS AND STRENGTH DATA USED
IN THE DESIGN AND ANALYSIS OF THE
THERMAL SHOCK EXPERIMENTS

During the early part of the thermal shock program, a decision was made to use A508 class 2 material in the as-quenched condition for the initial thermal shock experiments. To expedite the acquisition of appropriate material property data, we used A533 grade B, 152-mm (6-in.) plate, which was on hand, for obtaining preliminary fracture toughness and strength data. Shortly thereafter, data for quench-only A508 class 2 material were obtained from prolongations from intermediate test vessels V-1 and V-5. Over the temperature range of interest $[-18$ to 288°C (0 to 550°F)], the yield strengths for the two materials were 690 to 830 kPa (100 to 120 ksi). The static fracture toughness data are plotted in Fig. A-1, which shows the K_{IC} curve that was used in the design of the experiments.

Materials property data eventually were obtained for prolongations from the TSV-1 and TSV-2 test specimens. Since the test specimens were to be heated slowly to 288°C (550°F) in preparation for a thermal shock test, material property specimens were soaked at 288°C (550°F) for 24 hr following the quench-only heat treatment. Tensile data are shown in Table A-1, and static fracture toughness data are given in Tables A-2 and A-3. Static fracture toughness data are also plotted in Figs. A-2 to A-5 to show a comparison between these data and the curve that was used in the design calculations.

Fig. A-1. Static fracture toughness data for A533 grade B and A508 class 2 (V-1 and V-5) in the as-quenched condition [871°C (1600°F) austenitizing temperature].

Table A-1. Tensile^a values from C-oriented specimens from
TSV-1 and TSV-2 prolongations: aged 24 hr at 550°F
and furnace cooled

Depth ^b	Test temperature (°F)	Strength		Elongation ^c		Reduction of area (%)
		Yield (ksi)	Ultimate (ksi)	Uniform (%)	Total (%)	
TSV-1						
0.05T	-100	158	195	4.2	7.0	21
	77	155	183	2.7	7.5	42
	250	153	184	2.5	5.0	24
	500	150	193	4.3	8.3	27
0.34T	-100	128	161	4.9	10.4	38
	77	123	148	3.5	9.2	50
	250	115	146	3.1	6.0	34
	500	123	160	5.6	9.2	27
0.86T	-100	140	175	4.0	7.0	24
	77	130	160	2.7	5.5	25
	250	130	159	2.7	5.8	30
	500	121	171	5.1	7.7	23
TSV-2						
0.05T	-100	156	177	3.6	7.7	34
	71	138	165	2.9	7.5	45
	250	133	161	2.5	5.9	36
	500	135	171	5.4	10.5	33
0.35T	-100	130	163	4.3	9.3	41
	71	122	153	3.5	7.4	36
	250	123	154	2.8	5.8	35
	500	129	165	4.8	9.5	40
0.66T	-100	165	196	2.3	3.6	14
	71	159	184	1.5	2.2	14
	250	160	183	1.2	1.3	5
	500	151	191	3.8	5.2	16
0.96T	-100	124	158	4.9	8.8	30
	71	120	148	3.3	7.8	44
	250	117	146	2.9	5.8	29
	500	123	157	4.5	8.6	33

^a $\dot{\epsilon} = 0.016 \text{ min}^{-1}$.

^bDepth from outer surface : wall thickness (OD = 0T).

^cGage length/gage diameter ratio = 7.

Table A-2. Charpy-V impact and static fracture toughness values
from CA-oriented specimens from thermal shock vessel TSV-1
prolongation after aging for 24 hr at 550°F
and cooling in air

Depth ^a	Test temperature (°F)	Charpy-V impact		Static fracture toughness		
		Energy (ft-lb)	Lateral expansion ($\times 10^{-3}$ in.)	Precracked Charpy (ksi $\sqrt{\text{in.}}$)	Compact	cension Toughness (ksi $\sqrt{\text{in.}}$)
0.15T	200				1.000	138
	300				0.394	155
0.33T	74			75		
	150			116	1.000	95
	200			128	2.000	104
	300			138		
0.58T	74			63		
	150	9.5	3	89		
	175				0.394	111
	200	20	10	135		
	300	31.5	24	120		
	400	35	24			
0.69T	100				2.000	66
	150			95		
	200			124	1.000	111
	300			126		
0.77T	74			91		
	150	7.5	2	109	0.394	82
	200	16	12	136		
	300	36	25	136		
	400	43.5	34			
0.86T	74			75		
	150	11	1	114		
	200	18.5	8	118		
	300	28	20	123		
	400	31.5	24			

^aDepth from outer surface : wall thickness (6 in.).

Table A-3. Charpy-V impact and static fracture toughness values
from CA-oriented specimens from thermal shock vessel TSV-2
prolongation after aging for 24 hr at 550°F
and cooling in air

Depth ^a	Test temperature (°F)	Charpy-V impact		Static fracture toughness	
		Energy (ft-lb)	Lateral expansion ($\times 10^{-3}$ in.)	Precracked Charpy ^b (ksi $\sqrt{\text{in.}}$)	Compact tension Size (in.) Toughness (ksi $\sqrt{\text{in.}}$)
0.05T	72			111	
	150			126	
	150			147	
	175			129	
	175			132	
	200			131	
	200			141	
	300			125	
	400			122	
0.30T	175				1.000 101
0.32T	150				2.000 95
0.35T	72			28	
	150			135	
	150			114	
	175			158	
	175			99	
	200			146	
	200			138	
	300			129	
	400			133	
0.50T	200				1.000 126
0.57T	-50	6	0		
	0	10	0		
	50	6.5	3		
	100	8	5		
	150	17	7		
	200	17	12		
	250	28	17		
	350	34.5	26		
	450	30.5	19		
0.66T	72			78	
	150			102	
	150			90	
	175			100	
	175			93	

Table A-3 (continued)

Depth ^a	Test temperature (°F)	Charpy-V impact		Static fracture toughness	
		Energy (ft-lb)	Lateral expansion (× 10 ⁻³ in.)	Precracked Charpy ^b (ksi √in.)	Compact tension Size (in.) Toughness (ksi √in.)
0.66T	200			117	
	200			105	
	300			103	
	400			112	
0.68T	175				2.000 100
0.70T	175				1.000 114
0.76T	-50	8.5	0		
	0	10.5	0		
	50	8	5		
	100	13	7		
	150	11	6		
	177				C.394 96
	200	16	10		
	250	29	24		
	350	31.5	23		
	450	32.5	24		
0.86T	150			148	
	150			114	
	150			117	
	175			149	
	175			132	
	175			113	
	200			153	
	200			145	
	200			134	
0.91T	153				1.000 92
0.96T	72			77	
	150			141	
	150			163	
	150			124	
	175			126	
	175			170	
	176				0.395 99
	200			154	
	200			141	
	300			142	

^aDepth from outer surface : wall thickness (6 in.).^bDeflection rate 0.100 in./min.; $f\left(\frac{a}{w}\right) = \frac{1}{\left(1 - \frac{a}{w}\right)^{1.5}}$.

Fig. A-2. Toughness data for TSV-1 prolongations aged at 288°C (556°F) for 24 hr; compact-tension data.

Fig. A-3. Toughness data for TSV-1 prolongations aged at 288°C (550°F) for 24 hr; precracked Charpy data.

Fig. A-4. Toughness data for TSV-2 prolongations aged at 288°C (550°F) for 24 hr; compact-tension data.

Fig. A-5. Toughness data for TSV-2 prolongations aged at 288°C (550°F) for 24 hr; precracked Charpy data.

APPENDIX B

TEST SPECIMEN DIMENSIONS AND THERMOCOUPLE AND COD
GAGE DETAILS AND LOCATIONS FOR TSE-1 AND -2

Figures B-1 through B-6 and Table B-1 present dimensional, design, and installation information for the test specimens and their thermocouple and COD gage instrumentation. The figures are reasonably self-explanatory with the exception that thermocouples 10-A, 11-A, 12-A, 16-B, and 17-B (additional inner-surface thermocouple used in TSE-2) were surface mounted as shown in Fig. B-6 (detail E-1) except that the leads came through the instrument ring at the upper end of the test specimen rather than through the wall.

For thermocouples terminating in the wall, the end of the sheath was fused with the thermocouple wire, leaving a nearly hemispherical tip. This tip was gold plated to achieve a better thermal bond with the conical tip of the well while under spring loading. Transient tests were conducted with a typical in-wall installation (Fig. B-6) in a test bar to confirm that the thermocouple response time with the gold plated tip was adequate for TSE-1 and -2.

Prior to installation of the thermocouples in the test specimen, they were conditioned by heating at $\sim 320^{\circ}\text{C}$ (600°F) in a furnace for three days.

Fig. B-1. Test specimen dimensions and instrumentation.

Fig. B-2. Detail A - dimensional details for long axial flaw and COD gages for TSE-1.

ORNL-DWG 75-1000

Fig. B-3. Detail B - dimensional details for semicircular flaw and COD gages in TSE-2.

Fig. B-4. Detail C - thermocouple locations in test specimens for TSE-1 and -2: (a) plane A; (b) plane B; (c) plane C.

Fig. B-5. Detail D - thermocouple-well design (TSE-1 and -2).

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Fig. B-6. Detail E - installation details for in-wall and through-the-wall thermocouples (TSE-1 and -2).

Table B-1. Specified locations^a for thermocouples (TSE-1 and -2)

Section A			Section B			Section C		
Thermocouple No.	Angle	Depth (in.)	Thermocouple No.	Angle	Depth (in.)	Thermocouple No.	Angle	Depth (in.)
1-A	0°	0.0	1-B	0°	0.0	1-C	0°	0.0
3-A	22.5°	2.15	2-B	11.25°	1.25	3-C	22.5°	2.15
5-A	45°	3.65	3-B	22.5°	2.15	5-C	45°	3.65
7-A	67.5°	4.75	4-B	33.75°	2.95	7-C	67.5°	4.75
9-A	90°	5.75	5-B	45°	3.65	9-C	90°	5.75
10-A	96°	5.75	6-B	56.25°	4.25			
11-A	186°	5.75	7-B	67.5°	4.75			
12-A	0°	5.75	8-B	78.75°	5.15			
			9-B	90°	5.75			
			10-B	101.25°	5.65			
			11-B	112.5°	5.45			
			12-B	270°	5.75			
			13-B	292.5°	4.75			
			14-B	315°	3.65			
			15-B	337.5°	2.15			
			16-B	186°	5.75			
			17-B	0°	5.75			

^aRefer to Figs. B-4 and B-5.

APPENDIX C

INSTRUMENTATION FOR DETECTING CRACK PROPAGATION

While planning the instrumentation for detection of flaw propagation, consideration was given to ultrasonics (UT), acoustic-emission (AE), and mechanical devices (COD) that would measure directly crack opening and thus crack extension. Experiments conducted with the UT equipment indicated that with no loading on the test specimen, the flaw was too tight to be detected, but with a typical thermal stress imposed, detection was possible. Another factor that had to be considered was that the temperature of the UT crystal had to be kept below 66°C (150°F). Since the temperature of the test specimen wall would be as high as 288°C (550°F), a thermal insulator had to be placed between the wall and the crystal. Even without the insulator the transmitted signal was somewhat marginal, and thus the insulator had to have high UT transmission efficiency; a low-carbon steel cylinder 76 mm (3 in.) in diameter by 203 mm (8 in.) long was found to be satisfactory. The next task was to find a high-temperature couplant to acoustically couple the steel insulator to the test specimen. Greases out-gassed excessively and liquid metals would not properly wet the surfaces. Finally, soldering was resorted to, but even with copper plating of both components and the trial of a wide assortment of fluxes, the effort was unsuccessful because of gas pockets. It is possible that a satisfactory couplant eventually will be found, but the search was deferred until after the first thermal shock experiments.

Several inquiries were made regarding the application of AE, and most expressed real concern over the relative magnitude of the hydraulic noise. However, Shuh-Pan Ying of Southwest Research Institute recorded the hydraulic noise during a flow test and concluded that there was sufficient difference in spectrum to allow detection of crack propagation. The problem of high temperature was overcome with the attachment of 3.2-mm-diam (0.125-in.) waveguides to the outer surface of the test specimen, using a high-temperature grease as a couplant.* Four detectors were used so that the

* This grease was provided by Ying quite some time after the UT effort was terminated. It is possible that this grease would be satisfactory for the UT thermal insulator.

location of an emission could be determined by triangulation. The locations of the detectors (waveguides) are shown in Fig. C-1.

The device used for direct measurement of crack opening displacement (COD) was an electrical-resistance strain gage of the weldable type (Ailtech), which is encased in a stainless steel sheath, including the leads. For TSE-1, five of these gages were placed in transverse slots along the length of the flaw. The transverse slots were machined to a depth slightly greater than the EB weld groove so that there would be no discontinuity in the attachment of the gage where the gage spanned the EB weld and crack. This detail and the location of the gages are shown in Figs. B-1 and B-2 of Appendix B. For TSE-2, the gages were placed on the inner surface at

Fig. C-1. Developed view of outer surface of test specimen showing locations of contact points for acoustic-emission waveguides for TSE-1 and -2.

the two ends of the semicircular EB weld groove directly across the expected path of crack extension. As shown in Figs. B-1 and B-3 of Appendix B, three gages, 13 mm (0.5 in.) apart, were placed at the upper end and two at the lower end.

Prior to acceptance of the weldable strain gages for the intended task, various thermal shock tests were conducted in the laboratory with gages mounted and unmounted to determine their response to such treatment. Finally, a gage was mounted in a flow-test specimen (TSV-F) and subjected to thermal shock conditions similar to those that would be encountered in the thermal shock experiments TSE-1 and -2. Performance of the gages was quite satisfactory. As expected, there would be a change in gage output associated with the thermally induced strain and the change in temperature of the gage, but crack propagation would appear as a step change in the otherwise smooth curve. Output was recorded on tape every 2.5 sec as well as on strip charts.

APPENDIX D

ACOUSTIC-EMISSION DATA ACQUISITION AND ANALYSIS

Shuh-Pan Ying of Southwest Research Institute, San Antonio, Tex., was contracted to provide and operate the acoustic-emission instrumentation for the thermal shock experiments and to gather and analyze the data. Enclosed are reports submitted by Ying for TSE-1 and TSE-2.

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HEAVY SECTION STEEL TECHNOLOGY PROGRAM

ACOUSTIC EMISSION MONITORING OF
THE FIRST THERMAL SHOCK TEST SPECIMEN

to

Oak Ridge National Laboratory
Post Office Box Y
Oak Ridge, Tennessee 37830

ORNL Order No. 11Y-7333V

October 10, 1975

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ACOUSTIC EMISSION MONITORING OF THE FIRST THERMAL SHOCK TEST SPECIMEN*

S. P. Ying†

1. Introduction

A solid under thermal stress during a thermal shock can generate acoustic emission. The source of emission may be directly related to either plastic deformation or growth of a crack. It is important to define the characteristics of these acoustic emissions resulting from deformations or cracking in nuclear power reactor vessels undergoing thermal shocks. It is also desirable that the growth of a crack during thermal shock be evaluated by observing various parameters of acoustic emission. In an effort to investigate acoustic emission to obtain these goals, acoustic emission experiments are being conducted at Oak Ridge National Laboratory with a series of thermal shock tests of two flawed 6-inch-thick cylindrical steel specimens. The first is classified as a no-crack propagation experiment, and the second is a crack propagation and arrest experiment.¹

The thermal shock is introduced by a quenching technique. Hydraulic flow noise and cavitation noise are generated during quenching. These acoustic emission background noises are analyzed for a proper selection of monitoring frequency-range before each thermal shock test.

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†Southwest Research Institute.

This report describes the work on acoustic emission for the period ending at the completion of the first thermal shock experiment. The results of acoustic emission monitoring, including the background noise analysis, are presented and discussed.

2. Background Noise Analysis

Acoustic background noise generated in an unflawed specimen was monitored during quenching from a temperature of 550°F toward room temperature. The same test was also conducted at room temperature (without any preheating), and the background noise was checked in the same manner as during the first quenching process, that is the cooling liquid and the procedures were identical. It was found that the background noise in the two tests was quite similar. Therefore, since the unflawed test specimen had the same dimensions and shape as those of the flawed specimens to be used for the thermal shock tests and since the background noise was relatively unaffected by temperature change, this background noise analysis was used when monitoring acoustic emission in the first thermal shock test.

The noise background for the unflawed specimen tests was monitored by a transducer through a 1/8-inch-diameter, 18-inch-long carbon steel waveguide. High temperature grease was used as acoustic coupling at the interface of the waveguide and the vessel wall heated to 550°F. The noise signal detected by the transducer was fed into a preamplifier which provided 60 dB gain in a frequency range from 120 kHz to 1 MHz. (This frequency range was

adequate for acoustic emission monitoring.) The output signal of the preamplifier was analyzed by a Hewlett-Packard frequency spectrum analyzer (Model 141T with 8553B, R.F. section and 8552B, I.F. section) which transformed the noise from a time domain to a frequency domain. The noise signal from the preamplifier was recorded in a wideband (0 to 2 MHz) video tape recorder for off-line data analyses. When the tape was played back, the noise was analyzed again by the spectrum analyzer through a wideband analog gate.

The original frequency spectrum obtained directly from the spectrum analyzer depends on the frequency response of the monitoring system and is a superposition of the acoustic noise and a relatively low electronic noise of the monitoring system. In comparison with acoustic noise, the electronic noise is relatively low when it is near 100 kHz, and is negligibly small when it is above 150 kHz. Figure 1 shows a typical calibrated acoustic background noise spectrum of the thermal shock test vessel. In this frequency spectrum the electronic noise has been subtracted, and the spectrum has been calibrated with the frequency response of the monitoring system. Thus, the frequency spectrum in Figure 1 represents the true acoustic background noise spectrum in the thermal shock test vessel during quenching.

As shown in Figure 1, the noise frequency spectrum indicates that the frequency components of noise in the frequency range from 0.4 to 0.6 MHz are relatively low; therefore, this frequency range will be used for acoustic emission detection.

3. Acoustic Emission Monitoring

Four acoustic emission monitoring channels with an on-line mini-computer were used in the first thermal shock test of the flawed specimen. A 1/8-inch-diameter and 15-inch-long carbon steel waveguide was installed on the test vessel with a 30 lb. spring load and a high temperature grease coupling. Figure 2(b) shows a plane view of the waveguide locations on the test specimen. A 120 kHz high-pass filter was used in each preamplifier, and a bandpass filter from 300 to 600 kHz was used in each signal conditioner (Figure 3). The total gain of each channel was set at about 75-80 dB. The computer cathode ray tube (CRT) screen graphically displayed the number of acoustic emission events at individual locations on the vessel in cylindrical coordinates. The monitored signals were recorded in a multi-channel wideband tape recorder. The details of the monitoring system are described in a previous paper.² Instead of a counter shown in Figure 3, a linear coincident gate circuitry was used for channels 1 and 3. Only the emission from the crack vicinity passed through the gate, and individual amplitudes of the emission pulses were recorded on a paper strip chart through a video detector and a video amplifier.

Figure 2(a) shows an on-line computer CRT display of the locations of the acoustic emission sources. The numbers of maximum two digits on the screen represent cumulations of events at the particular locations. The screen is a plane view of the cylindrical coordinates of the test vessel as shown in Figure 2(a). This photograph was taken at a time approximately two

minutes after the start of quenching. There are nineteen events near the edge of crack. The cumulative acoustic emission events $n_e(t)$ from the crack region was plotted as a function of time, t , during the thermal shock in Figure 4. The experiment results fit to an empirical equation,

$$n_e(t) = \alpha (1 - e^{-t/\beta}) \quad (1)$$

where the constants $\alpha \cong 35$ events
 $\beta \cong 8.2$ min.

for this experiment. The constant α is the total number of events as $t \rightarrow \infty$ and depends on the acoustic emission character of the crack during thermal shock and the detection ability of the monitoring system in a high temperature noisy environment. The time constant β depends on the quenching speed and related thermal shock parameters. From Equation (1), the time rate of change of events can be calculated, which gives

$$\begin{aligned} \frac{d}{dt} n_e(t) &= \frac{\alpha}{\beta} e^{-t/\beta} \\ &\cong 4.27 e^{-t/8.2} \end{aligned} \quad (2)$$

This exponential decay curve is also presented in Figure 4. The acoustic emission data obtained from the computer screen are consistent with that detected by the coincident technique. Equation (2) is not adequate when $t \rightarrow 0$.

When the magnetic tape was played back and the emission events were displayed on the computer screen, the corresponding waveforms of the emission pulses were observed in an oscilloscope. It was found that the main frequency of the emission from the crack region is near 150 kHz.

4. Discussion

Examining the acoustic emission experiment described in the preceding section, the overall gain of each monitoring channel was set at a level less than 80 dB, which is relatively low in comparison with that for a condition without significant background noise. The main frequency of burst type emission detected in the crack region was near 150 kHz; therefore, the emission signals of frequency components near and above 150 kHz were amplified by the 40 dB preamplifier with a 120 kHz highpass filter. The frequency components below 300 kHz did not gain amplifications in the signal conditioner with a band-pass from 300 to 600 kHz. The signal conditioner only amplifies frequency components of the emission between 300 and 600 kHz. In other words, acoustic emission from the crack region detected by the system set at such gain level must have high amplitudes.

Before discussing these high amplitude acoustic emissions, an understanding of the relationship between the amplitude of acoustic emission and the applied stress is necessary. When a flawed reactor grade steel specimen is subject to tension at a temperature above the transition temperature of the material, high amplitude emission may appear at the stress level such

that the ratio of the stress intensity factors between the applied stress and the stress at failure $K_I/K_{Ic} = 0.5$. As the stress increases to a level, $K_I/K_{Ic} = 0.8$, almost 50% of the acoustic emission events attain high amplitudes. This percentage becomes approximately 100 when $K_I/K_{Ic} = 0.9$ prior to the failure. These phenomena were observed previously at Oak Ridge National Laboratory during two of the Intermediate Vessel Tests under the Heavy Section Steel Technology program, i.e., Vessel V_1 , with an outer surface flaw in base metal, tested at 130°F, and Vessel V_5 , with a flaw at the inner corner of the nozzle, tested at 190°F.

The so-called high amplitude acoustic emission is distinguishably different in amplitude; it is approximately 10 dB higher than the amplitude of weak acoustic emission. The weak acoustic emission is usually directly related to plastic deformation, and the strong emission is related to the mechanisms of formation of cracks. Since high amplitude emission was detected without extremely high emission rate during the thermal shock test, the maximum thermal stress probably reached a level such that $K_I/K_{Ic} = 0.8$, but did not reach the value at failure as predicted. Furthermore, low frequency acoustic emission in the frequency range of 100-200 kHz was observed in unflawed A533-B steel specimen prior to the failure during tensile tests, which implies that low frequency emission relates to the mechanisms of crack formation. The low frequency emission detected from the crack region during thermal shock does not contradict the previous discussion on the amplitude of the emission.

At the present time the acoustic mission data could not give a precise conclusion. However, hopefully a more definite conclusion will be made after the comparison of data between this experiment and the next experiment.

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Fig. 1. Acoustic background noise of thermal shock tests.

Fig. 2. (a) A typical computer CRT screen display. (The photograph was taken approximately 2 min after the start of quenching.) (b) A plane view of waveguide distribution in cylindrical coordinates. Same coordinates are used in (a).

Fig. 3. Functional diagram of three typical channels of the acoustic-emission monitoring system.

Fig. 4. Acoustic-emission events in the crack region and the rate of acoustic emission as functions of time during thermal shock.

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ACOUSTIC EMISSION MONITORING OF THE SECOND THERMAL SHOCK TEST SPECIMEN*

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The second thermal shock experiment was conducted at Oak Ridge National Laboratory (ORNL) on December 12, 1975. A semicircular surface flaw with a surface length of 1-1/2 inches and a maximum depth of 3/4 inches was created in the inner surface of a cylindrical specimen. The specimen, with a 21-inch outer diameter and a 5.75-inch wall thickness, was preheated uniformly to 552°F and quenched by -9.5°F liquid at a flow rate of 500 gal/min in the cylinder. Under such a procedure of thermal shock, acoustic background noise was relatively high in comparison with that of the first thermal shock test. The frequency spectra of the noise for both tests are presented in Figure 1 for a comparison.

Acoustic emission was monitored by four sensors with an on-line mini-computer such as that used for the first thermal shock test. The monitored signals were recorded on a multichannel wideband tape recorder through a 40 dB preamplifier with a 120 kHz high-pass filter for each channel.

Figure 2 shows a strip chart record of acoustic emissions during the first 2 minutes of the thermal shock. No significant amount of acoustic emission with an amplitude greater than hydraulic noise was detected after 2 minutes. The numbered signals on the chart simultaneously appeared on the computer cathode-ray tube screen which showed the locations of the acoustic sources in the vessel wall. The signals in the strip chart, except the No. 2 and No. 4 signals, were all emitted from the crack in the inner surface of the cylindrical wall. The generation of No. 1 acoustic emission event from the crack under a sufficient high thermal stress occurred at about 8 seconds after the start of thermal shock. The No. 3 and No. 5 events were generated near the upper end, and the lower end of the crack, respectively. The No. 5 event was detected at about 36 sec after the start of thermal shock. The time separation between the No. 3 event and the No. 5 event was about 50 sec, as shown in Figure 2. These were consistent with the indication of crack propagations by the strain gages mounted at those locations. Figure 3 shows the approximate locations of the numbered acoustic emission events near the crack. The numbers shown in Figure 3 correspond to the numbers on the strip chart in Figure 2.

The relative amplitudes of larger signals, Nos. 3, 4, and 5 shown in the strip chart, are not precise because of the limited range of amplitude measurement. However, correct amplitude measurements were performed directly by an oscilloscope. Table 1 shows the relative peak values of emission

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†Southwest Research Institute

pulses in a dB unit compared to the hydraulic noise level during the generation of the No. 3 event, as shown in Figure 2. The peak amplitudes of No. 3 and No. 5 events are relatively large in comparison with the others.

The crack was examined after the thermal shock test. It was found that the crack was extended about 1.5 inches at the lower end and about 2.5 inches at the upper end. Therefore, the No. 3 and No. 5 events with large amplitudes, at least, were acoustic emission resulting from crack propagation. Since the acoustic emission was detected through a 40 dB preamplifier only, the emission must be relatively strong in comparison with the emission related to plastic deformation and approaching to crack initiation detected in the first thermal shock test.

After an examination of the crack in the first thermal shock test specimen, it was found that the crack was also propagated slightly on the order of $1/32$ to $1/16$ inches. A small amount of acoustic emission events detected in the first thermal shock experiment must be due to the small crack extension.

Table 1. Relative Amplitudes of Acoustic Events

Event	Relative Amplitude, [*] dB
No. 1	4.68
No. 2	8.20
No. 3	20.00
No. 4	16.72
No. 5	21.69

^{*}Referred to the background noise when
No. 3 event was generated.

Fig. 1. Acoustic background noise of the first thermal shock test.

Fig. 2. Strip-chart record of acoustic emission during thermal shock.

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Fig. 3. Approximate locations of acoustic-emission events projected to the inner surface.

APPENDIX E
EXPERIMENTAL DATA AND RESULTS OF CALCULATIONS
PERTAINING TO TSE-1

1. RESULTS IGNORING EFFECT OF WELD
GROOVES ON HEAT REMOVAL

Table E-1 lists test specimen wall temperatures measured during the TSE-1 thermal shock transient. The specified locations of the thermocouples are shown in Appendix B. There were some small deviations in radial positions of the in-wall couples; measured positions are listed in Table E-1.

Temperature distributions at times of interest for making fracture mechanics calculations are presented in Figs. E-1 to E-5. It is observed that upper- and lower-bound curves are plotted; this reflects the uncertainty in the measurement of surface temperatures and the need to know the uncertainty in the calculated stress-intensity factor. The upper-bound curve, which results in a relatively low stress-intensity factor, is probably more realistic. The range in $(K_I/K_{Ic})_{\max}$ corresponding to the two temperature curves is 0.68 to 0.80, using the fracture toughness curve shown in Fig. 20. Of course there is uncertainty associated with the fracture toughness also. There are so few data points for the quench-only material that a determination of the actual variation is not possible. Based on data for quenched and tempered material, the variation in K_{Ic} in the temperature range of interest [38-93°C (100-200°F)] is estimated at $\pm 25\%$.

Tabulated results for the fracture mechanics calculations, showing temperatures, stresses (in the absence of the flaw), K_I , and K_{Ic} all as a function of a/w and time in the transient are enclosed at the end of this appendix. Typical plots of fracture mechanics parameters are shown in Figs. E-6 to E-8.

2. EFFECT OF WELD GROOVE

The existence of the open weld groove directly above the EB weld alters the heat transfer and thus K_I and K_{Ic} to some extent compared to

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Table E-1. Temperatures in TSV-1 during TSE-1

Test specimen: TSV-1
 Wall temp. (initial): -550°F
 Sink temp. (initial): -540°F
 Time zero: 20:05:41

TIME	20:06:13	20:06:43	20:07:13	20:07:43	20:08:13	20:08:43	20:09:13	20:10:43	20:12:13	20:14:13	20:16:13	20:18:13	20:20:13	20:21:13
T/C	a/w								Temperature					
9A	0	196	168	153	144	132	125	120	114	111	108	104	99	94
7A	0.176	477	419	381	354	320	294	278	266	256	237	221	207	187
5A	0.360	514	513	489	468	432	406	385	359	345	333	311	288	268
3A	0.616	540	538	535	528	512	493	476	451	435	420	391	365	330
1A	1.00	537	537	537	536	532	524	513	493	476	461	431	402	367
9B	0	197	169	156	147	136	128	123	117	114	113	107	105	98
10B	0.0104	301	252	218	202	182	169	159	150	145	140	133	127	119
11B	0.0504	352	293	268	240	214	198	186	174	168	162	153	145	132
8B	0.0874	395	331	295	276	254	227	213	199	192	186	175	166	153
7B	0.174	486	425	386	359	325	299	281	268	262	253	226	213	195
6B	0.256	529	487	452	425	386	359	339	318	303	292	275	265	233
5B	0.362	552	534	511	490	455	428	406	380	365	353	331	310	280
4B	0.483	554	550	539	526	500	477	457	430	415	400	374	350	320
3B	0.616	554	554	550	553	526	509	491	466	451	436	408	382	346
2B	0.781	554	554	554	552	544	533	520	497	482	467	438	409	371
1B	1.00	555	555	555	555	551	543	532	511	496	481	451	423	383
12B	0	216	177	163	153	140	132	127	120	117	114	109	104	99
13B	0.172	492	431	392	364	329	304	285	271	264	253	230	216	197
14B	0.365	553	532	508	485	449	422	401	375	361	348	327	305	278
15B	0.624	557	557	553	547	530	512	495	469	455	439	410	385	349
9C	0	186	159	145	139	129	122	118	115	113	110	108	105	100
7C	0.169	495	432	391	363	329	303	284	270	263	248	227	213	195
5C	0.362	559	537	511	488	451	423	401	374	359	345	324	301	275
3C	0.619	564	563	560	552	535	517	498	471	456	430	410	387	349
1C	1.00	565	565	565	565	560	552	540	518	502	485	454	423	380

Fig. E-1. Temperature distributions in TSV-1 during TSE-1: (a) $t = 2$ min, (b) $t = 3$ min.

Fig. E-2. Temperature distributions in TSV-1 during TSE-1: (a) $t = 4$ min, (b) $t = 5$ min.

Fig. E-3. Temperature distributions in TSV-1 during TSE-1: (a) $t = 6.5$ min, (b) $t = 7.5$ min.

Fig. E-4. Temperature distributions in TSV-1 during TSE-1: (a) $t = 8.5$ min, (b) $t = 10.5$ min.

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Fig. E-5. Temperature distributions in TSV-1 during TSE-1: (a) $t = 12.5$ min, (b) $t = 15.5$ min.

Fig. E-6. K_I , K_{IC} , and K_I/K_{IC} vs a/w for TSE-1: $t = 2$ min.

 Fig. E-7. K_I , K_{Ic} , and K_I/K_{Ic} vs a/w for TSE-1: $t = 7.5$ min.

Fig. E-8. K_I , K_{Ic} , and K_I/K_{Ic} vs a/w for TSE-1: $t = 15.5$ min.

a case in which the groove does not exist. The increased surface area for heat removal tends to result in a more severe thermal shock locally; however, the smaller hydraulic diameter within the groove tends to reduce the fluid film heat transfer coefficient and thus decrease the severity of the shock. The net effect is not known but probably is an increase in K_I/K_{Ic} . To determine an upper limit it was assumed that the heat transfer coefficient in the groove was equal to that on the inner surface of the test specimen. Near the tip of the flaw the calculated temperatures are about 8°C (15°F) less than those calculated ignoring the weld groove. A comparison of calculated temperatures and K_I , K_{Ic} , and K_I/K_{Ic} values for a long axial crack with $a/w = 0.074$ for the cases of no weld groove and a weld groove with maximum heat transfer coefficient is summarized in Table E-2. As indicated, the K_I values are about the same, but the K_{Ic} values for the weld-groove case are about 7% less and thus the K ratios about 7% higher.

Table E-2. Comparison of calculated results for TSE-1^a considering and ignoring the existence of the weld groove; all parameters evaluated at $a/w = 0.074$ (tip of flaw)

t (min)	Temperature (°C)		K_I (MN m ^{-3/2})		K_{Ic} (MN m ^{-3/2})		K_I/K_{Ic}	
	b	c	b	c	b	c	b	c
5	90	80	82.4	82.2	126	112	0.65	0.73
7.5	78	69	73.5	73.2	107	99	0.69	0.74
10	69	61	65.2	64.7	98	90	0.67	0.72

^aK values are based on calculated rather than measured temperatures and thus are somewhat different than reported elsewhere in this report for the case of no weld groove.

^bIgnoring weld groove.

^cConsidering weld groove.

W/S TEMPS. L20 9/26/75 TSE-1 0340A.SK100000.TEMP0026 UPPER 004000

```

0000 METHOD OF CALCULATING RI ... PERM
CYCLE.  MP.  MPM.  MPT.  ISIP.  INEAT.  RICTIV.  NOLCT.  RIPLT.  RINSTPT
00      0      0      1      0      1      2      0      0

```

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      (VOLUME)
      SUMMER RAINFALL IN =          4.750
      WINTER RAINFALL IN =          10.500
      SIMILAR TEMPERATURE SIMILAR =          0.0
      POSITIVE TEMPERATURE DIFFERENCE =          555.0
      INTERNAL PRESSURE IN PSI =          0.0

```

MATERIAL PROPERTIES	
MODULUS OF ELASTICITY	E = 20.000E+06
POISSON'S RATIO	MU = 0.300
COEFFICIENT OF EXPANSION	ALFA = 0.5000E-06
SPECIFIC HEAT	CP = 1.070E-01
DENSITY LBS/CU. IN	GMA = 0.280

```
INTERNAL PRESSURE LOADING CONDITION: MPa
  = 0 MPa INTERNAL PRESSURE
  = 1 INT.PRESS. UPPER ENDS
  = 2 INT.PRESS. LOWER ENDS      MPa = 0
```

SELECTED TIME INTERVAL NUMBERS FOR ALL CALCULATIONS

```

*****
** SCALLANECUS PARAMETERS USED IN THIS VERSION **
BASE FLUENCE      IF10 = 4219
UNRADIATED INTYD0 = 40 DEGR-FAMN.
DATE ON CURVES FOR (DELTA)INT ... 10-28-74
DATE ON EXPRESSIONS FOR MIC (REACTION VESSEL) ... 0-12-74
DATE ON EXPRESSION FOR AID ( " " ) ... 12-2-74
NUMBER OF D/A RATIOS TO BE PROCESSED NDA = 1
D/A VALUES = 1.000
NUMBER OF CRACK DEPTHS TO BE PROCESSED NCD = 0
CRACK DEPTH VALUES = 0.0 0.152 0.321 0.639 0.561 0.882 1.156 1.731

```

GRID GEOMETRY OVER CYLINDERS

SEQ.NO.	CASE NO.	RADIUS	INCREMENT
.....			

1	1	4.7500	0.0
2	2	5.3250	572.00-03
3	3	5.9000	572.00-03
4	4	6.4750	573.00-03
5	5	7.0500	573.00-03
6	6	7.6250	572.00-03
7	7	8.2000	573.00-03
8	8	8.7750	572.00-03
9	9	9.3500	573.00-03
10	10	9.9250	572.00-03
11	11	10.5000	572.00-03

AS QUENCHED RIC VALUES FOR RICVP=2 (11-10-74)/ 17 CTS DATA

1	-300.	27.
2	-250.	20.
3	-200.	10.
4	-150.	32.
5	-100.	30.
6	-50.	41.
7	0.	48.
8	50.	57.
9	100.	60.
10	150.	01.
11	200.	123.
12	250.	225.

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N/S TEMP. END 9/26/78 152-1 05MMA-51104995-TEMP0020 UPPER BOUND

TEMPERATURE INTERVAL NUMBER = 2. TIME = 3.0000 00 MINUTES

GRID NO.	RADIUS INCHES	DELTA R	DELTA R/ INCH	TEMPERATURE DEGR.FAHR.	AS QUENCHED MIC
1	0.2500	0.0	0.0	172.0	90430.
2	0.3750	0.0750	0.1000	368.0	225000.
3	0.5000	1.1000	0.2000	363.0	225000.
4	0.6250	1.7250	0.3000	410.0	225000.
5	0.7500	2.3000	0.4000	473.0	225000.
6	0.8750	2.9250	0.5000	506.0	225000.
7	1.0000	3.4000	0.6000	524.0	225000.
8	1.1250	4.0250	0.7000	537.0	225000.
9	1.2500	4.6000	0.8000	540.0	225000.
10	1.3750	5.1750	0.9000	540.0	225000.
11	1.5000	5.7500	1.0000	551.0	225000.

000 NO. OF POINTS OF CONSTANT TEMP. POINTS = 0

NUMBER OF TEMPERATURES USED = 11

NUMBER OF LAST GRID POINT USED = 11

TOTAL HEAT LOSS UP TO 1 INCLUDING THIS TIME INTERVAL = 0.775320 02 BTU PER ARIAL INCH OF CYLINDER

P-6. VALUES READ IN FOR TIME INTERVAL NO. = 2

0.0	02.00	73.00	01.20	03.00	03.00	00.02	00.04	0.0	0.0	0.0	0.0
-----	-------	-------	-------	-------	-------	-------	-------	-----	-----	-----	-----

N/S TEMP. END 9/26/78 152-1 05MMA-51104995-TEMP0020 UPPER BOUND

TEMPERATURE INTERVAL NUMBER = 2. TIME = 3.0000 00 MINUTES

STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSES AT SURFACE = 70035.
 MAX RADIUS DEPTH A/B TEMPER. TANGENT. AS QUENCHED
 NO. IN. IN. DEGR.FAHR. STRESS PSI MI MIC MI/MIC

1	4.750	0.0	0.0	172.0	70030.	0.	90430.	0.0
2	4.007	0.157	0.000	190.2	69930.	0.	110031.	0.001
3	3.071	0.321	0.000	222.0	69990.	0.	163010.	0.000
4	2.100	0.439	0.070	241.3	69993.	0.1200.	203000.	0.307
5	1.333	0.503	0.101	263.2	67900.	0.7000.	225000.	0.300
6	0.812	0.502	0.100	263.0	31000.	0.3200.	225000.	0.010
7	0.500	1.150	0.301	300.1	24153.	0.0020.	225000.	0.000
8	0.001	1.731	0.301	410.7	00000.	0.0000.	225000.	0.300

M/S TEMPS. EXP 9/26/75 TSE-1 DSN=A.SK104999.TEMP0926 UPPER BOUND

TEMPERATURE INTERVAL NUMBER = 3. TIME = 4.0000 00 MINUTES

GRID NO.	RADIUS INCHES	DELTA R	DELTA R/R	TEMPERATURE DEGR.FAHN.	AS QUENCHED KIC
----------	------------------	---------	-----------	---------------------------	--------------------

1	4.7500	0.0	0.0	150.0	80327.
2	5.3250	0.5750	0.1000	247.0	217913.
3	5.9000	1.1500	0.2000	324.0	225000.
4	6.4750	1.7250	0.3000	389.0	225000.
5	7.0500	2.3000	0.4000	441.0	225000.
6	7.6250	2.8750	0.5000	489.0	225000.
7	8.2000	3.4500	0.6000	545.0	225000.
8	8.7750	4.0250	0.7000	523.0	225000.
9	9.3500	4.6000	0.8000	535.0	225000.
10	9.9250	5.1750	0.9000	541.0	225000.
11	10.5000	5.7500	1.0000	545.0	225000.

*** NO. OF POINTS OF CONSTANT TEMP. FOUND = 0

NUMBER OF TEMPERATURES USED = 11
NUMBER OF LAST GRID POINT USED = 11

TOTAL HEAT LOST UP TO 6 INCLUDING THIS TIME INTERVAL = 0.100200 02 BTU PER AXIAL INCH OF CYLINDER

F.E. VALUES READ IN FOR TIME INTERVAL NO. = 3
0.0 51.54 72.77 86.46 88.77 92.50 98.75 88.27 0.0 0.0 0.0 0.0 0.0

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M/S TEMPS. EXP 9/26/75 TSE-1 DSN=A.SK104999.TEMP0926 UPPER BOUND

TEMPERATURE INTERVAL NUMBER = 3. TIME = 4.0000 00 MINUTES

STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSES AT SURFACE = 77812.
S/R RADIUS DEPTH A/R TEMPER. TANGENT. AS QUENCHED
NO. IN. IN. S-FAHN. STRESS PSI KI KIC KI/KIC

1	4.750	0.0	0.0	150.0	77812.	0.	80330.	0.3
2	4.902	0.152	0.026	162.2	80253.	21540.	103610.	0.497
3	5.071	0.321	0.054	205.7	66370.	72770.	136450.	0.523
4	5.169	0.439	0.076	226.0	64370.	66460.	171714.	0.669
5	5.333	0.583	0.101	246.2	47800.	88770.	220670.	0.393
6	5.612	0.862	0.150	287.1	35741.	92500.	225000.	0.611
7	5.900	1.150	0.201	320.0	24797.	98700.	225000.	0.403
8	6.481	1.731	0.301	389.6	7452.	88270.	225000.	0.392

M/S TEMPS. EXP 9/26/78 TSE-1 DSN=A.SKID4999.TEMP0026 UPPER BOUND

TEMPERATURE INTERVAL NUMBER = 4. TIME = 5.0000 00 MINUTES

GRID NO.	RADIUS INCHES	DELTA R	DELTA R/B	TEMPERATURE DEGR.FAHN.	AS QUENCHED KIC
1	4.7500	0.0	0.0	148.0	85191.
2	5.3250	0.5750	0.1000	230.0	178764.
3	5.9000	1.1500	0.2000	301.0	225000.
4	6.4750	1.7250	0.3000	367.0	225000.
5	7.0500	2.3000	0.4000	420.0	225000.
6	7.6250	2.8750	0.5000	461.0	225000.
7	8.2000	3.4500	0.6000	489.0	225000.
8	8.7750	4.0250	0.7000	509.0	225000.
9	9.3500	4.6000	0.8000	522.0	225000.
10	9.9250	5.1750	0.9000	529.0	225000.
11	10.5000	5.7500	1.0000	531.0	225000.

*** NO. OF POINTS OF CONSTANT TEMP. FOUND = 0

NUMBER OF TEMPERATURES USED = 11
NUMBER OF LAST GRID POINT USED = 11

TOTAL HEAT LOST UP TO & INCLUDING THIS TIME INTERVAL = 9.547470 02 BTU PER AXIAL INCH OF CYLINDER

P.E. VALUES READ IN FOR TIME INTERVAL NO. = 4
0.0 50.61 71.68 79.51 86.88 92.74 91.90 98.58 0.0 0.0 0.0 0.0 0.0

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M/S TEMPS. EXP 9/26/78 TSE-1 DSN=A.SKID4999.TEMP0026 UPPER BOUND

TEMPERATURE INTERVAL NUMBER = 4. TIME = 5.0000 00 MINUTES

STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSES AT SURFACE = 76165.
SEQ RADIUS DEPTH A/B TEMPER. TANGENT. AS QUENCHED
NO. IN. IN. O.FAHN. STRESS PSI KI KIC KI/KIC

SEQ	RADIUS IN.	DEPTH IN.	A/B	TEMPER. O.FAHN.	TANGENT. STRESS PSI	KI	AS QUENCHED KIC	KI/KIC
1	4.750	0.0	0.0	148.0	76165.	0.	85194.	0.0
2	4.902	0.152	0.028	176.4	88115.	50610.	95467.	0.530
3	5.071	0.321	0.056	194.9	99095.	71680.	116332.	0.614
4	5.189	0.439	0.076	211.9	10171.	79910.	141388.	0.562
5	5.333	0.583	0.101	231.1	47855.	88880.	101120.	0.475
6	5.612	0.862	0.150	266.4	36905.	92740.	225000.	0.412
7	5.900	1.150	0.201	302.0	26497.	91907.	225000.	0.400
8	6.481	1.731	0.301	367.6	8745.	98600.	225000.	0.403

N/S TEMPS. EXP 9/20/78 TSE-1 DSM-A.SKD0999.TEMP0926 UPPER ROUND

TEMPERATURE INTERVAL NUMBER = 5. TIME = 0.5000 00 MINUTES

GRID NO.	RADIUS INCHES	DELTA R	DELTA R/ INCH	TEMPERATURE DEGR.FAH.	AS QUENCHED MIC
1	4.7500	0.0	0.0	141.0	02390.
2	5.3250	0.5750	0.1600	215.0	107224.
3	5.9000	1.1500	0.3200	201.0	225000.
4	6.4750	1.7250	0.4800	343.0	225000.
5	7.0500	2.3000	0.6400	307.0	225000.
6	7.6250	2.8750	0.8000	430.0	225000.
7	8.2000	3.4500	0.9600	404.0	225000.
8	8.7750	4.0250	0.7600	404.0	225000.
9	9.3500	4.6000	0.8000	400.0	225000.
10	9.9250	5.1750	0.9000	507.0	225000.
11	10.5000	5.7500	1.0000	512.0	225000.

000 NO. OF POINTS OF CONSTANT TEMP. FOUND = 6

NUMBER OF TEMPERATURES USED = 11

NUMBER OF LAST GRID POINT USED = 11

TOTAL HEAT LOSS UP TO 6 INCLUDING THIS TIME INTERVAL = 1.141770 93 BTU PER AXIAL INCH OF CYLINDER

P.E. VALUES READ IN FOR TIME INTERVAL NO. = 5

0.0 40.10 60.32 75.97 82.47 89.28 96.00 98.62 0.0 0.0 0.0 0.0 0.0 0.0

N/S TEMPS. EXP 9/20/78 TSE-1 DSM-A.SKD0999.TEMP0926 UPPER ROUND

TEMPERATURE INTERVAL NUMBER = 5. TIME = 0.5000 00 MINUTES

STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSES AT SURFACE = 72177.

310 RADIUS DEPTH A/R TEMPER. TANGENT AS QUENCHED

NO. IN. IN. STRESS PSI MI MIC MI/MIC

.....

1	4.750	0.0	0.2	141.0	72177.	0.	02392.	0.0
2	5.325	0.102	0.026	161.0	4043.	0.	90407.	0.530
3	5.901	0.321	0.056	183.1	57150.	0.320.	104302.	0.638
4	6.476	0.439	0.076	199.1	52094.	75070.	120012.	0.631
5	7.051	0.503	0.101	210.0	40268.	02470.	140000.	0.581
6	7.626	0.602	0.130	240.0	31021.	00200.	222000.	0.402
7	8.201	0.701	0.201	201.0	24259.	00000.	225000.	0.399
8	8.776	0.731	0.201	343.0	4470.	00000.	220000.	0.390

N/S TEMPS. EXP 9/26/75 TSE-1 DSN=A.S104999.TEMP0926 UPPER BOUNC

TEMPERATURE INTERVAL NUMBER = 6. TIME = 7-5000 00 MINUTES

GRID NO. RADIUS DELTA R DELTA R/W TEMPERATURE AS QUENCHED
INCHES DEGR.FAHR. KIC

1	4.7500	0.0	0.0	136.0	80427.
2	5.3250	0.3750	0.1000	200.0	135319.
3	5.9000	1.1500	0.2000	274.0	227000.
4	6.4750	1.7250	0.3000	333.0	225000.
5	7.0500	2.3000	0.4000	381.0	225000.
6	7.6250	2.8750	0.5000	421.0	225000.
7	8.2000	3.4500	0.6000	450.0	225000.
8	8.7750	4.0250	0.7000	472.0	225000.
9	9.3500	4.6000	0.8000	485.0	225000.
10	9.9250	5.1750	0.9000	492.0	225000.
11	10.5000	5.7500	1.0000	497.0	225000.

000 ML. OF POINTS OF CONSTANT TEMP. FOUND = 0

NUMBER OF TEMPERATURES USED = 11

NUMBER OF LAST GRID POINT USED = 11

TOTAL HEAT LOST UP TO 6 INCLUDING THIS TIME INTERVAL = 1.240300 03 BTU PER ARIAL INCH OF CYLINDER

P.E. VALUES READ IN FOR TIME INTERVAL NO. = 6
0.0 46.02 66.31 73.98 80.22 86.77 88.13 88.69 0.0 0.0 0.0 0.0

N/S TEMPS. EXP 9/26/75 TSE-1 DSN=A.S104999.TEMP0926 UPPER BOUNC

TEMPERATURE INTERVAL NUMBER = 6. TIME = 7-5000 00 MINUTES

STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSES AT SURFACE = 70220.

SEQ RADIUS DEPTH A/W TEMPER. TANGENT. AS QUENCHED
NO. IN. IN. O.FAHR. STRESS PSI KI KIC KI/KIC

1	4.750	0.0	0.0	136.0	70220.	0.	80429.	0.0
2	4.902	0.182	0.426	155.4	63131.	40020.	88190.	0.531
3	5.071	0.321	0.656	176.7	55473.	40510.	95475.	0.669
4	5.189	0.439	0.876	191.4	50734.	73920.	112361.	0.658
5	5.333	0.583	0.101	205.0	45068.	66290.	136903.	0.586
6	5.512	0.862	0.150	241.7	34817.	66776.	205507.	0.423
7	5.908	1.156	0.201	274.9	28102.	66130.	225000.	0.303
8	6.461	1.731	0.301	333.6	9186.	65696.	225000.	0.301

M/S TEMPS. EXP 9/26/75 TSE-1 OSM=A.SKID4999.TEMP0026 UPPER BOUND
 TEMPERATURE INTERVAL NUMBER = 7. TIME = 8.5000 00 MINUTES

GRID NO.	RADIUS INCHES	DELTA R	DELTA R/B	TEMPERATURE DEGR.FAHR.	AS QUENCHED KIC
1	4.7500	0.0	0.0	131.0	70504.
2	5.3250	0.5750	0.1000	200.0	123000.
3	5.9000	1.1500	0.2000	263.0	225000.
4	6.4750	1.7250	0.3000	319.0	225000.
5	7.0500	2.3000	0.4000	366.0	225000.
6	7.6250	2.8750	0.5000	405.0	225000.
7	8.2000	3.4500	0.6000	436.0	225000.
8	8.7750	4.0250	0.7000	455.0	225000.
9	9.3500	4.6000	0.8000	468.0	225000.
10	9.9250	5.1750	0.9000	477.0	225000.
11	10.5000	5.7500	1.0000	481.0	225000.

000 NO. OF POINTS OF CONSTANT TEMP. FOUND = 0

NUMBER OF TEMPERATURES USED = 11
 NUMBER OF LAST GRID POINT USED = 11

TOTAL HEAT LOST UP TO & INCLUDING THIS TIME INTERVAL = 1.360110 03 BTU PER AXIAL INCH OF CYLINDER

P.E. VALUES READ IN FOR TIME INTERVAL NO. = 7
 0.0 45.10 64.21 71.63 77.56 83.90 83.40 83.40 0.0 0.0 0.0 0.0 0.0

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M/S TEMPS. EXP 9/26/75 TSE-1 OSM=A.SKID4999.TEMP0026 UPPER BOUND
 TEMPERATURE INTERVAL NUMBER = 7. TIME = 8.5000 00 MINUTES

STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSES AT SURFACE = 67747.
 SEQ RADIUS DEPTH A/B TEMPER. TANGENT. AS QUENCHED
 NO. IN. IN. O.FAHR. STRESS PSI KI KIC KI/KIC

1	4.750	0.0	0.0	131.0	67747.	0.	70500.	0.0
2	5.325	0.152	0.026	149.0	60931.	45100.	85010.	0.520
3	5.971	0.321	0.056	170.0	53769.	64210.	95257.	0.676
4	6.189	0.430	0.076	184.1	49020.	71430.	105236.	0.679
5	6.333	0.503	0.101	200.0	43532.	77560.	120311.	0.620
6	6.612	0.662	0.160	232.3	33760.	83900.	163071.	0.450
7	6.900	1.150	0.201	263.0	24000.	83400.	220000.	0.371
8	6.401	1.731	0.301	319.5	4300.	83400.	220000.	0.371

M/S TEMPS. EXP 9/26/78 TSE-1 DSWA.SKIDA999.TEMP0026 UPPER BOUND

TEMPERATURE INTERVAL NUMBER = 0. TIME = 1.0800 0: MINUTES

GRID NO.	RADIUS INCHES	DELTA R	DELTA T/ΔR	TEMPERATURE DEGR.FAHN.	AS QUENCHED KIC
1	4.7500	0.0	0.0	129.0	76262.
2	5.3250	0.5750	0.1500	191.0	111954.
3	5.9000	1.1500	0.2800	250.0	228000.
4	6.4750	1.7250	0.3800	301.0	228000.
5	7.0500	2.3000	0.4800	348.0	228000.
6	7.6250	2.8750	0.5500	378.0	228000.
7	8.2000	3.4500	0.6000	404.0	228000.
8	8.7750	4.0250	0.7000	428.0	228000.
9	9.3500	4.6000	0.8000	439.0	228000.
10	9.9250	5.1750	0.9000	448.0	228000.
11	10.5000	5.7500	1.0000	452.0	228000.

000 NO. OF POINTS OF CONSTANT TEMP. FOUND = 0

NUMBER OF TEMPERATURES USED = 11
NUMBER OF LAST GRID POINT USED = 11

TOTAL HEAT LOST UP TO & INCLUDING THIS TIME INTERVAL = 1.500010 03 BTU PER ARIAL INCH OF CYLINDER

P.E. VALUES READ IN FOR TIME INTERVAL NO. = 0

0.0 41.00 50.50 66.21 71.76 77.43 76.60 76.76 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0

M/S TEMPS. EXP 9/26/78 TSE-1 DSWA.SKIDA999.TEMP0026 UPPER BOUND

TEMPERATURE INTERVAL NUMBER = 0. TIME = 1.0800 0: MINUTES

GRID NO.	RADIUS IN.	DELTA R	DELTA T/ΔR	TEMPERATURE DEGR.FAHN.	AS QUENCHED KIC
1	4.7500	0.0	0.0	129.0	76262.
2	5.3250	0.5750	0.1500	191.0	111954.
3	5.9000	1.1500	0.2800	250.0	228000.
4	6.4750	1.7250	0.3800	301.0	228000.
5	7.0500	2.3000	0.4800	348.0	228000.
6	7.6250	2.8750	0.5500	378.0	228000.
7	8.2000	3.4500	0.6000	404.0	228000.
8	8.7750	4.0250	0.7000	428.0	228000.
9	9.3500	4.6000	0.8000	439.0	228000.
10	9.9250	5.1750	0.9000	448.0	228000.
11	10.5000	5.7500	1.0000	452.0	228000.

STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSES AT SURFACE = 63067.

GRID NO. RADIUS DEPTH A/B TEMPER. TANGENT. AS QUENCHED
IN. IN. O.FAHN. STRESS PSI K1 KIC K1/KIC

1	4.7500	0.0	0.0	129.0	63067.	0.	76262.	0.0
2	5.3250	0.5750	0.1500	191.0	63067.	0.	76262.	0.0
3	5.9000	1.1500	0.2800	250.0	63067.	0.	76262.	0.0
4	6.4750	1.7250	0.3800	301.0	63067.	0.	76262.	0.0
5	7.0500	2.3000	0.4800	348.0	63067.	0.	76262.	0.0
6	7.6250	2.8750	0.5500	378.0	63067.	0.	76262.	0.0
7	8.2000	3.4500	0.6000	404.0	63067.	0.	76262.	0.0
8	8.7750	4.0250	0.7000	428.0	63067.	0.	76262.	0.0
9	9.3500	4.6000	0.8000	439.0	63067.	0.	76262.	0.0
10	9.9250	5.1750	0.9000	448.0	63067.	0.	76262.	0.0
11	10.5000	5.7500	1.0000	452.0	63067.	0.	76262.	0.0

W/S TEMP. EXP 0/20/78 VS8-1 05N0A.5N1004900.TEMP0026 UPPER BOUND

TEMPERATURE INTERVAL NUMBER = 0. TIME = 1.2500 01 MINUTES

GRID NO.	RADIUS INCHES	DELTA R	DELTA R/ D.F.A.M.	TEMPERATURE DEGR.FAH.	AS QUENCHED K1/C
1	4.7000	0.0	0.0	110.0	73700.
2	5.3250	0.6250	0.1300	170.0	100400.
3	5.9500	1.1500	0.2400	230.0	107713.
4	6.5750	1.7250	0.3600	262.0	205000.
5	7.2000	2.3000	0.4800	322.0	205000.
6	7.8250	2.8750	0.6000	384.0	205000.
7	8.4500	3.4500	0.7200	370.0	205000.
8	9.0750	4.0250	0.8400	390.0	22000.
9	9.7000	4.6000	0.9600	400.0	22000.
10	10.3250	5.1750	1.0800	410.0	22000.
11	10.9500	5.7500	1.2000	423.0	22000.

000 NO. OF POINTS OF CONSTANT TEMP. FOUND = 0

NUMBER OF TEMPERATURES USED = 11
NUMBER OF LAST GRID POINT USED = 11

TOTAL HEAT LOSS UP TO 6 INCLUDING THIS TIME INTERVAL = 1.773030 03 BTU PER AXIAL INCH OF CYLINDER

P.E. VALUES READ IN PER TIME INTERVAL NO. = 0
30.00 00.00 01.72 00.00 22.29 71.01 71.31 0.0 0.0 0.0 0.0

W/S TEMP. EXP 0/20/78 VS8-1 05N0A.5N1004900.TEMP0026 UPPER BOUND

TEMPERATURE INTERVAL NUMBER = 0. TIME = 1.2500 01 MINUTES

STRESS INTENSITY CALCULATIONS FOR A LENGTH, CRACK, STRESSES AT SURFACE = 00001.
NO. RADIUS DEPTH A/D TEMPER. TANGENT. AS QUENCHED
NO. IN. IN. D.F.A.M. STRESS PSI K1 K1/C K1/NIC

NO.	RADIUS IN.	DEPTH IN.	A/D	TEMPER.	TANGENT.	AS QUENCHED K1/C	K1/NIC
1	4.700	0.0	110.0	00001.	0.	73700.	0.0
2	5.325	0.625	170.0	30000.	70450.	0.103	0.103
3	5.950	1.250	230.0	10400.	00700.	0.000	0.000
4	6.575	1.875	262.0	01700.	00001.	0.070	0.070
5	7.200	2.500	322.0	00000.	101002.	0.003	0.003
6	7.825	3.125	384.0	20070.	133000.	0.000	0.000
7	8.450	3.750	370.0	20000.	100371.	0.070	0.070
8	9.075	4.375	390.0	71310.	220000.	0.317	0.317

N/S TEMPS. EXP 9/26/78 TSE-1 DSM=A.5K104999.TEMP0026 UPPER BOUND

TEMPERATURE INTERVAL NUMBER = 10. TIME = 1.5500 01 MINUTES

GRID NO.	RADIUS INCHES	DELTA R	DELTA R/S	TEMPERATURE DEGR.FAHR.	AS QUENCHED KIC
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1	4.7500	0.0	0.0	111.0	71300.
2	5.3250	0.5750	0.1000	103.0	91003.
3	5.9000	1.1500	0.2000	112.0	142200.
4	6.4750	1.7250	0.3000	253.0	225000.
5	7.0500	2.3000	0.4000	200.0	225000.
6	7.6250	2.8750	0.5000	310.0	225000.
7	8.2000	3.4500	0.6000	343.0	225000.
8	8.7750	4.0250	0.7000	360.0	225000.
9	9.3500	4.6000	0.8000	372.0	225000.
10	9.9250	5.1750	0.9000	379.0	225000.
11	10.5000	5.7500	1.0000	383.0	225000.

*** NO. OF POINTS OF CONSTANT TEMP. FOUND = 0

NUMBER OF TEMPERATURES USED = 11
NUMBER OF LAST GRID POINT USED = 11

TOTAL HEAT LOSS UP TO & INCLUDING THIS TIME INTERVAL = 2.04143D 03 BTU PER AXIAL INCH OF CYLINDER

P.E. VALUES READ IN FOR TIME INTERVAL NO. = 10
0.7 34.75 49.45 55.00 59.65 64.74 64.33 64.81 6.0 0.0 0.0 0.0 0.0

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N/S TEMPS. EXP 9/26/78 TSE-1 DSM=A.5K104999.TEMP0026 UPPER BOUND

TEMPERATURE INTERVAL NUMBER = 10. TIME = 1.5500 01 MINUTES

STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSES AT SURFACE = 52035.
SAS RADIUS DEPTH A/B TEMPER. TANGENT. AS QUENCHED
IN. IN. IN. O.FAHR. STRESS PSI KI KIC KI/KIC

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1	4.750	0.0	0.0	111.0	52035.	0.	71307.	0.0
2	4.902	0.152	0.020	124.0	44011.	34750.	70104.	0.456
3	5.071	0.321	0.056	140.1	41000.	49430.	62049.	0.603
4	5.259	0.509	0.076	150.8	37003.	55500.	56320.	0.630
5	5.433	0.683	0.101	163.7	33678.	59850.	61050.	0.651
6	5.612	0.862	0.150	180.3	28030.	64740.	109140.	0.693
7	5.800	1.150	0.201	212.0	18003.	64330.	143422.	0.449
8	6.001	1.731	0.301	253.0	7710.	64610.	225000.	0.260

***TOTAL NUMBER OF TEMPERATURE INTERVALS PROCESSED = 10

INC0021 STOP 0

W/S TEMPS. EMP 9/28/75 15E-1 DSMA-SR104990.TEMP0026 LOWER BOUND

0000 METHOD OF CALCULATING KI ... PERA
 NCVLE. NP. NPB. NPT7. ISKIP. INEAT. NICTYP. NPLCT. KIPLT. NSTPT
 00 0 0 1 0 1 2 C 0 0

CYLINDER
 INNER RADIUS RI = 4.750
 OUTER RADIUS RO = 10.500
 SINK TEMPERATURE TSINK = 40.0

INITIAL TEMPERATURE TZERO = 555.0

INTERNAL PRESSURE IN PSI = 0.0

MATERIAL PROPERTIES
 MODULUS OF ELASTICITY E = 20.000E 06
 POISSONS RATIO MU = 0.300
 COEFFICIENT OF EXPANSION ALFA = 6.500E-06
 SPECIFIC HEAT CP = 1.070E-01
 DENSITY LBS/CL-IN DEN = 0.200

INTERNAL PRESSURE LOADING CONDITION NPB
 = 0 NO INTERNAL PRESSURE
 = 1 INT. PRESS. OPEN ENDS
 = 2 INT. PRESS. CLOSED ENDS NPB = 0

SELECTED TIME INTERVAL NUMBERS FOR KI CALCULATIONS
 0
 0

MISCELLANEOUS PARAMETERS USED IN THIS VERSION
 BASE FLUENCE (F10) = 4E19
 UNRADIATED INTENSITY = 40 DEGR.FAH.
 DATE ON CURVES FOR (DELTIME) ... 10-20-74
 DATE ON EXPRESSIONS FOR KIC (REACTION VESSEL) ... 0-12-74
 DATE ON EXPRESSION FOR KIR (" ") ... 12-2-74
 NUMBER OF E/A RATIOS TO BE PROCESSED NBA = 1
 B/A VALUES = 1.000
 NUMBER OF CRACK DEPTHS TO BE PROCESSED NCC = 0
 CRACK DEPTH VALUES = 0.0 0.152 0.321 0.439 0.503 0.662 1.150 1.731

GRID GEOMETRY OVER CYLINDER BALL

SEQ.NO. GRID NO. RADIUS INCREMENT

SEQ.NO.	GRID NO.	RADIUS	INCREMENT
1	1	4.7500	0.0
2	2	5.3250	575.00-03
3	3	5.9000	575.00-03
4	4	6.4750	575.00-03
5	5	7.0500	575.00-03
6	6	7.6250	575.00-03
7	7	8.2000	575.00-03
8	8	8.7750	575.00-03
9	9	9.3500	575.00-03
10	10	9.9250	575.00-03
11	11	10.5000	575.00-03

AS QUENCHED KIC VALUES FOR NICTYP=2 (11-10-74)/ AT CTS DATA

1	-300.	27.
2	-250.	28.
3	-200.	30.
4	-150.	32.
5	-100.	36.
6	-50.	41.
7	0.	48.
8	50.	57.
9	100.	68.
10	150.	86.
11	200.	123.
12	250.	225.

N/S TEMPS. EXP 9/26/75 15E-1 DSMMA-SKID4999-TEMP0926 LOWER BOUND

TEMPERATURE INTERVAL NUMBER = 1. TIME = 2.0000 00 MINUTES

GAID NO. RADIUS DELTA R DELTA R/M TEMPERATURE AS QUENCHED
INCHES O-F.A.M. R/C

1	4.7500	0.0	0.0	145.0	03504.
2	5.3250	0.0750	0.1500	270.0	22000.
3	5.9000	1.1500	0.3000	302.0	220030.
4	4.4750	1.7250	0.3000	455.0	220000.
5	7.0300	2.3000	0.4000	502.0	220000.
6	7.0250	2.8750	0.5000	520.0	220000.
7	6.2000	3.4500	0.6000	541.0	220000.
8	6.7750	4.0250	0.7000	545.0	220000.
9	6.3500	4.6000	0.8000	504.0	220000.
10	4.0250	5.1750	0.9000	525.0	220000.
11	10.5000	6.7500	1.0000	555.0	220000.

000 NO. OF POINTS OF CONSTANT TEMP. FOUND = 2

NUMBER OF TEMPERATURES USED = 11

NUMBER OF LAST GAID POINT USED = 11

TOTAL HEAT LOST UP TO 6 INCLUDING THIS TIME INTERVAL = 9.300370 02 BTU PER AXIAL INCH OF CYLINDER

P-C. VALUES READ IN FOR TIME INTERVAL NO. = 1

0.0 50.50 01.20 00.22 03.33 05.35 07.37 79.29 0.0 0.0 0.0 0.0

N/S TEMPS. EXP 9/26/75 15E-1 DSMMA-SKID4999-TEMP0926 LOWER BOUND

TEMPERATURE INTERVAL NUMBER = 1. TIME = 2.0000 00 MINUTES

STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSES AT SURFACE = 90147.
540 RADIUS OPEN A/R TEMPER. TANGENT.
NO. IN. IN. O-F.A.M. STRESS PSI KI R/C KI/SEC

1	4.750	0.0	0.0	145.0	90147.	0.	03500.	0.0
2	4.902	0.152	0.020	180.0	77030.	0.	102029.	0.071
3	5.071	0.321	0.054	221.2	61103.	0.	189903.	0.000
4	5.149	0.439	0.070	240.3	54003.	0.	220024.	0.300
5	5.333	0.503	0.101	270.7	47053.	0.	220000.	0.414
6	5.612	0.602	0.150	334.2	31050.	0.	220000.	0.483
7	5.909	1.130	0.301	303.2	15100.	0.	220000.	0.300
8	6.401	1.731	0.301	455.0	-915.	0.	220000.	0.350

W/S TEMPS. SEP 9/84/75 TSE-1 05MVA-34104000.TEMP0020 LOWER SOUND

TEMPERATURE INTERVAL NUMBER = 2. TIME = 3.0000 00 MINUTES

GRID NO.	RADIUS INCHES	DELTA R	DELTA R/R	TEMPERATURE DEGR.FAHR.	AS QUENCHED KIC
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1	4.7500	0.0	0.0	135.0	00070.
2	5.3250	0.5750	0.1000	255.0	22040.
3	5.9000	1.1500	0.2000	343.0	22050.
4	6.4750	1.7250	0.3000	414.0	22060.
5	7.0500	2.3000	0.4000	473.0	22080.
6	7.6250	2.8750	0.5000	500.0	22090.
7	8.2000	3.4500	0.6000	525.0	22090.
8	8.7750	4.0250	0.7000	537.0	22090.
9	9.3500	4.6000	0.8000	545.0	22090.
10	9.9250	5.1750	0.9000	549.0	22090.
11	10.5000	5.7500	1.0000	551.0	22090.

000 NO. OF POINTS OF CONSTANT TEMP. FOUND = 0

NUMBER OF TEMPERATURES USED = 11
NUMBER OF LAST GRID POINT USED = 11

TOTAL HEAT LEFT UP TO & INCLUDING THIS TIME INTERVAL = 0.00010 02 BTU PER ANIAL INCH OF CYLINDER

P-E. VALUES READ IN FOR TIME INTERVAL NO. = 2
0.0 37.30 56.00 57.00 63.30 67.00 72.07 80.77 86.0 8.0 8.0 8.0 8.0

W/S TEMPS. SEP 9/84/75 TSE-1 05MVA-34104000.TEMP0020 LOWER SOUND

TEMPERATURE INTERVAL NUMBER = 2. TIME = 3.0000 00 MINUTES

STRESS INTENSITY CALCULATIONS FOR A LENGTH. CRACK. STRESSES AT SURFACE = 27780.
SEE RADIUS DEPTH A/D TEMPER. TANGENT. AS QUENCHED

NO.	IN.	IN.	DELTA R	STRESS PSI	KI	KIC	SI/KIC
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1	4.750	0.0	0.0	135.0	07750.	0.	00045. 0.0
2	5.325	0.152	0.028	160.2	74007.	0.	00225. 0.009
3	5.901	0.321	0.054	204.1	04071.	00000.	120000. 0.021
4	6.476	0.435	0.076	228.0	07601.	07500.	174470. 0.052
5	7.052	0.503	0.091	255.0	09000.	03300.	220000. 0.115
6	7.627	0.612	0.100	282.0	10503.	07000.	270000. 0.122
7	8.202	1.102	0.201	340.1	23303.	03000.	280000. 0.110
8	8.781	1.731	0.301	414.7	00710.	00710.	280000. 0.308

M/S TEMPS. EXP 9/26/75 15E-1 DSMMA-SH104000-TEMP0026 LOWER BOUND

TEMPERATURE INTERVAL NUMBER = 3. TIME = 4.0000 00 MINUTES

GRID NO.	RADIUS INCHES	DELTA R	DELTA R/ INCH	TEMPERATURE USGA-FAMR.	AS QUENCHED K1C
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1	4.7500	0.0	0.0	120.0	77373.
2	5.2750	0.5250	0.1000	229.0	170163.
3	5.8000	1.1500	0.2000	317.0	220000.
4	6.3250	1.7250	0.3000	387.0	220000.
5	7.0000	2.3000	0.4000	461.0	220000.
6	7.6250	2.8250	0.5000	480.0	220000.
7	8.2000	3.4000	0.6000	505.0	220000.
8	8.7750	4.0250	0.7000	523.0	220000.
9	9.3500	4.6000	0.8000	535.0	220000.
10	9.9250	5.1750	0.9000	561.0	220000.
11	10.5000	5.7500	1.0000	645.0	220000.

000 NO. OF POINTS OF CONSTANT TEMP. FOUND = 0

NUMBER OF TEMPERATURES USED = 11
NUMBER OF LAST GRID POINT USED = 11

TOTAL HEAT LOSS UP TO 6 INCLUDING THIS TIME INTERVAL = 0.010030 02 BTU PER ARIAL INCH OF CYLINDER

P.O. VALUES READ IN FOR TIME INTERVAL NO. = 3
50.00 70.00 87.19 93.77 99.33 95.50 92.50 0.0 0.0 0.0 0.0 0.0

M/S TEMPS. EXP 9/26/75 15E-1 DSMMA-SH104000-TEMP0026 LOWER BOUND

TEMPERATURE INTERVAL NUMBER = 3. TIME = 4.0000 00 MINUTES

STRESS INTENSITY CALCULATIONS FOR A LENGTH. CRACK. STRESSES AT SURFACE = 00000.
SEQ RADIUS DEPTH A/B TEMPER. TANGENT. AS QUENCHED
NO. IN. IN. IN. STRESS PSI K1 K1/K1C

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1	4.750	0.0	0.0	120.0	00000.	0.	77370.	0.0
2	4.902	0.152	0.026	155.3	78205.	0.0000.	00170.	0.620
3	5.071	0.321	0.056	185.3	43224.	70040.	100342.	0.743
4	5.189	0.439	0.076	205.9	50575.	07190.	131850.	0.461
5	5.323	0.583	0.101	230.3	50909.	03770.	170521.	0.422
6	5.412	0.662	0.180	278.1	37081.	00330.	220000.	0.401
7	5.508	1.150	0.201	318.1	28167.	00500.	220000.	0.429
8	6.481	1.731	0.301	307.0	00331.	02500.	220000.	0.411

M/S TEMPS. EXP 9/26/75 TSE-1 DSN=A.SKID4999.TEMP0026 LOWER BOUND

TEMPERATURE INTERVAL NUMBER = 4. TIME = 5.0000 00 MINUTES

GRID NO.	RADIUS INCHES	DELTA R	DELTA R/R	TEMPERATURE DEGR.FAHN.	AS QUENCHED KIC
1	4.7500	0.0	0.0	122.0	75172.
2	5.3250	0.5750	0.1000	219.0	155585.
3	5.9000	1.1500	0.2000	300.0	225000.
4	6.4750	1.7250	0.3000	367.0	225000.
5	7.0500	2.3000	0.4000	420.0	225000.
6	7.6250	2.8750	0.5000	461.0	225000.
7	8.2000	3.4500	0.6000	489.0	225000.
8	8.7750	4.0250	0.7000	509.0	225000.
9	9.3500	4.6000	0.8000	527.0	225000.
10	9.9250	5.1750	0.9000	549.0	225000.
11	10.5000	5.7500	1.0000	533.0	225000.

NO. NO. OF POINTS OF CONSTANT TEMP. FOUND = 0

NUMBER OF TEMPERATURES USED = 11
NUMBER OF LAST GRID POINT USED = 11

TOTAL HEAT LOSS UP TO & INCLUDING THIS TIME INTERVAL = 9.600590 02 BTU PER AXIAL INCH OF CYLINDER

P.E. VALUES READ IN FOR TIME INTERVAL NO. = 4
0.0 24.54 76.07 84.04 91.35 97.24 98.23 92.77 0.0 0.0 0.0 0.0 0.0

147

M/S TEMPS. EXP 9/26/75 TSE-1 DSN=A.SKID4999.TEMP0026 LOWER BOUND

TEMPERATURE INTERVAL NUMBER = 4. TIME = 5.0000 00 MINUTES

STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSES AT SURFACE = 82511.
SEE RADIUS DEPTH A/R TEMPER. TANGENT. AS QUENCHED
NO. IN. IN. O.FAHN. STRESS PSI KI KIC KI/KIC

NO.	RADIUS IN.	DEPTH IN.	A/R	TEMPER. O.FAHN.	TANGENT. STRESS PSI	KI	AS QUENCHED KIC	KI/KIC
1	4.750	0.0	0.0	122.0	82511.	0.	75174.	0.0
2	4.902	0.152	0.026	140.5	73208.	54840.	85397.	0.639
3	5.071	0.321	0.064	177.5	63674.	76870.	100045.	0.760
4	5.109	0.439	0.076	197.2	57093.	84840.	119224.	0.712
5	5.333	0.583	0.101	220.3	49810.	91380.	150104.	0.578
6	5.612	0.802	0.150	261.5	37207.	97240.	225000.	0.432
7	5.900	1.150	0.201	301.0	28072.	95230.	225000.	0.423
8	6.401	6.731	0.301	367.0	7990.	92770.	225000.	0.412

TEMPERATURE INTERVAL NUMBER • 5. TIME = 6.000 00 MINUTES

CARD NO.	RADIUS INCHES	DELTA R	DELTAR'S	TEMPERATURE DEGR.FAHN.	AS QUENCHED MIC
1	4.7500	0.0	0.0	115.0	72721.
2	5.2500	0.750	0.100	201.0	126612.
3	5.7500	1.1500	0.2000	277.0	220000.
4	6.2500	1.7250	0.3000	345.0	220000.
5	7.2500	2.3000	0.4000	397.0	220000.
6	7.2750	2.2750	0.5000	430.0	220000.
7	6.7500	3.4500	0.6000	465.0	220000.
8	6.7500	4.0250	0.7000	495.0	220000.
9	5.2500	4.6000	0.8000	495.0	220000.
10	5.2500	5.1750	0.9000	507.0	220000.
11	10.5000	9.7500	1.0000	515.0	220000.

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NUMBER OF TEMPERATURES USED	NUMBER OF LOGS AND POINTS USED
11	11
11	11

TOTAL HEAT LOSS UP TO 6 INCLUDING THIS TIME INTERVAL = 1.16890 OJ STU PER AXIAL INCH OF CYLINDER

[illegible]

NY 78403. EMP 9/30/73 132-1 OSMMA-SMID0003-YZMP0026 LOWER BOUND

TEMPERATURE INTERVAL NUMBER = 3. TIME = 6.000 00 MINUTES

STRESS INTENSITY CALCULATIONS FOR A LONG CYCLE STRESS AT SURFACE = 7800 PSI

[illegible]

W/S TEMPS. EXP 9/26/75 TSE-1 DSN=A.5K1D4999.TEMP0926 LOWER BOUND

TEMPERATURE INTERVAL NUMBER = 6. TIME = 7.5000 00 MINUTES

GRID NO.	RADIUS INCHES	DELTA R	DELTA R/R	TEMPERATURE DEGR.FAHR.	AS QUENCHED RIC
1	0.7500	0.0	0.0	111.0	71300.
2	0.3250	0.4250	0.1000	105.0	11000.
3	0.9000	1.1500	0.2800	86.0	22500.
4	0.4750	1.7250	0.3600	33.0	22500.
5	7.0000	2.3000	0.4000	301.0	22500.
6	7.6250	2.6750	0.3500	421.0	22500.
7	0.3000	3.4000	0.0000	400.0	22500.
8	0.7750	4.0250	0.7000	472.0	22500.
9	0.3500	4.6000	0.0000	405.0	22500.
10	0.9200	5.1750	0.9000	492.0	22500.
11	10.5000	5.7500	1.0000	497.0	22500.

999 NO. OF POINTS OF CONSTANT TEMP. FOUND = 0

NUMBER OF TEMPERATURES USED = 11
NUMBER OF LAST GRID POINT USED = 11

TOTAL HEAT LOST UP TO & INCLUDING THIS TIME INTERVAL = 1.263910 03 BTU PER LINEAL INCH OF CYLINDER

P.E. VALUES READ IN FOR TIME INTERVAL NO. = 9
0.0 30.25 71.32 79.23 85.66 91.94 98.60 100.02 0.0 0.0 0.0 0.0 0.0

W/S TEMPS. EXP 9/26/75 TSE-1 DSN=A.5K1D4999.TEMP0926 LOWER BOUND

TEMPERATURE INTERVAL NUMBER = 6. TIME = 7.5000 00 MINUTES

STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSES AT SURFACE = 76103.

NO.	DEPTH IN.	RADIUS IN.	A/R	TEMPER. DEGR.FAHR.	YAMINAT. STRESS PSI	KI	AS QUENCHED RIC	KI/KIC
1	4.750	0.0	0.0	111.0	76103.	0.	71300.	0.0
2	4.002	0.152	0.026	133.0	68004.	00550.	70001.	0.635
3	5.071	0.321	0.056	160.0	59442.	71520.	69733.	0.797
4	5.109	0.430	0.076	176.0	53016.	70230.	60000.	0.400
5	5.333	0.503	0.101	190.0	47370.	85000.	117053.	0.727
6	5.612	0.602	0.150	212.0	36102.	01000.	104468.	0.498
7	5.900	1.150	0.201	269.0	28005.	00000.	225000.	0.403
8	6.401	2.731	0.301	333.0	8194.	00020.	225000.	0.395

N/S TEMPS. EXP 9/26/78 TSE-1 OSMMA-SHID4999.TEMP0026 LOWER SOUND

TEMPERATURE INTERVAL NUMBER = 7. TIME = 3.0000 00 MINUTES

GRID NO.	RADIUS INCHES	DELTA H	DELTA T/V	TEMPERATURE DEGR.FAH.	AS QUENCHED MIC
1	4.7500	0.0	0.0	110.0	71000.
2	5.3250	0.0750	0.1000	100.0	110000.
3	5.9000	1.1500	0.2000	250.0	220000.
4	6.4750	1.7250	0.3000	310.0	220000.
5	7.0500	2.3000	0.4000	360.0	220000.
6	7.6250	2.8750	0.5000	400.0	220000.
7	8.2000	3.4500	0.6000	420.0	220000.
8	8.7750	4.0250	0.7000	430.0	220000.
9	9.3500	4.6000	0.8000	440.0	220000.
10	9.9250	5.1750	0.9000	477.0	220000.
11	10.5000	5.7500	1.0000	481.0	220000.

000 NO. OF POINTS OF CONSTANT TEMP. FOUND = 0

NUMBER OF TEMPERATURES USED = 11
NUMBER OF LAST GRID POINT USED = 11

TOTAL HEAT LOST UP TO & INCLUDING THIS TIME INTERVAL = 1.201000 03 BTU PER ARIAL INCH OF CYLINDER

P.C. VALUES READ IN FOR TIME INTERVAL NO. = 7
0.0 00.31 00.34 75.70 01.00 07.95 00.07 00.77 0.0 0.0 0.0 0.0

N/S TEMPS. EXP 9/26/78 TSE-1 OSMMA-SHID4999.TEMP0026 LOWER SOUND

TEMPERATURE INTERVAL NUMBER = 7. TIME = 3.0000 00 MINUTES

STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSES AT SURFACE = 72700.
STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSES AT SURFACE = 72700.
STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSES AT SURFACE = 72700.

NO.	IN.	DEPTH IN.	AVG D.FAH.	STRESS PSI	MI	AS QUENCHED MIC
1	4.750	0.0	110.0	72700.	0.	71002. 0.0
2	5.325	0.075	100.0	64993.	0.0310.	70700. 0.013
3	5.900	0.150	250.0	56323.	0.0310.	60310. 0.774
4	6.475	0.225	310.0	51000.	0.0310.	60310. 0.774
5	7.050	0.300	360.0	46323.	0.0310.	60310. 0.774
6	7.625	0.375	400.0	42000.	0.0310.	60310. 0.774
7	8.200	0.450	420.0	38000.	0.0310.	60310. 0.774
8	8.775	0.525	430.0	34000.	0.0310.	60310. 0.774
9	9.350	0.600	440.0	30000.	0.0310.	60310. 0.774
10	9.925	0.675	477.0	26000.	0.0310.	60310. 0.774
11	10.500	0.750	481.0	22000.	0.0310.	60310. 0.774

M/S TEMPS. EXP 9/26/75 TSE-1 OSMMA:KID4999.TEMPO026 LOSEN BOUND

TEMPERATURE INTERVAL NUMBER = 0. TIME = 1.0500 01 MINUTES

GRID NO. RADIUS INCHES DELTA R DELTA R/b TEMPERATURE DEGR.C/AMP. AS QUENCHED K/KIC

.....

1	4.7800	0.0	0.0	105.0	69484.
2	5.3250	0.3750	0.1600	177.0	90888.
3	5.9000	1.1100	0.2000	243.0	208499.
4	6.4750	1.7250	0.3000	298.0	225000.
5	7.0500	2.3000	0.4000	345.0	225000.
6	7.6250	2.8250	0.5000	378.0	225000.
7	8.2000	3.4500	0.6000	404.0	225000.
8	8.7750	4.0250	0.7000	425.0	225000.
9	9.3500	4.6000	0.8000	439.0	225000.
10	9.9250	5.1750	0.9000	448.0	225000.
11	10.5000	5.7500	1.0000	452.0	225000.

000 NO. OF POINTS OF CONSTANT TEMP. FOUND = 0

NUMBER OF TEMPERATURES USED
NUMBER OF LAST GRID POINT USED = 11

TOTAL HEAT LOST UP TO & INCLUDING THIS TIME INTERVAL = 1.580940 03 BTU PER AXIAL INCH OF CYLINDER

F.E. VALUES READ IN FOR TIME INTERVAL NO. = 4

45.02 63.86 70.89 76.76 82.47 81.33 80.49 0.0 0.0 0.0 0.0 0.0

M/S TEMPS. EXP 9/26/75 TSE-1 OSMMA:KID4999.TEMPO026 LOSEN BOUND

TEMPERATURE INTERVAL NUMBER = 0. TIME = 1.0500 01 MINUTES

STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSES AT SURFACE = 67448.

SEO RADIUS DEPTH A/R TEMPER. TANGENT. AS QUENCHED K/KIC

NO. IN. IN. C/AMP. STRESS PSI KI KI/KIC

1	4.780	0.0	105.0	67448.	0.	69485.	0.0
2	4.902	0.152	124.1	60493.	45020.	75991.	0.592
3	5.021	0.321	143.5	53207.	43450.	84205.	0.758
4	5.189	0.439	160.3	48392.	70850.	90331.	0.788
5	5.322	0.503	178.0	42887.	76760.	100386.	0.788
6	5.412	0.562	211.2	32492.	82470.	140809.	0.546
7	5.908	1.158	243.8	22993.	81330.	210477.	0.386
8	6.481	1.731	298.5	8178.	80490.	225080.	0.158

M/S TEMPS. EXP 9/26/75 TSE-1 DSNWA-SKID4999.TEMP0826 LOWER BOUND

TEMPERATURE INTERVAL NUMBER = 9. TIME = 1.2500 01 MINUTES

GRID NO.	RADIUS INCHES	DELTA R	DELTA R/B	TEMPERATURE DEGR.FAHN.	AS QUENCHED NIC
1	4.7500	0.0	0.0	103.0	66679.
2	5.3750	0.6250	0.1300	167.0	93609.
3	5.9000	1.1500	0.2400	227.0	172212.
4	6.4250	1.7250	0.3900	277.0	228000.
5	7.0500	2.3000	0.4600	321.0	238000.
6	7.6250	2.8750	0.5800	354.0	228000.
7	8.2000	3.4500	0.6000	378.0	228000.
8	8.7750	4.0250	0.7000	396.0	228000.
9	9.3500	4.6000	0.8000	408.0	228000.
10	9.9250	5.1750	0.9000	418.0	228000.
11	10.5000	5.7500	1.0000	423.0	228000.

000 NO. OF POINTS OF CONSTANT TEMP. FOUND = 0

NUMBER OF TEMPERATURES USED = 11
NUMBER OF LAST GRID POINT USED = 11

TOTAL HEAT LOST UP TO & INCLUDING THIS TIME INTERVAL = 1.792140 03 BTU PER AXIAL INCH OF CYLINDER

F.E. VALUES READ IN FOR TIME INTERVAL NO. = 5
0.0 41.24 58.58 65.14 70.84 76.00 78.21 74.83 0.0 0.0 0.0 0.0

M/S TEMPS. EXP 9/26/75 TSE-1 DSNWA-SKID4999.TEMP0826 LOWER BOUND

TEMPERATURE INTERVAL NUMBER = 9. TIME = 1.2500 01 MINUTES

STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSES AT SURFACE = 61857.

SEQ	RADIUS IN.	DEPTH IN.	A/R	TEMPER. DEGR.FAHN.	TANGENT STRESS PSI	MI	AS QUENCHED NIC	MI/KIC
1	4.750	0.0	0.0	103.0	61857.	0.	66680.	0.0
2	4.902	0.15	0.026	120.0	5811.	41240.	74467.	0.354
3	5.071	0.32	0.056	138.0	49023.	58580.	81540.	0.718
4	5.189	0.439	0.076	152.0	44631.	45140.	86813.	0.780
5	5.333	0.503	0.101	167.0	39489.	70840.	94080.	0.791
6	5.612	0.662	0.150	198.0	30208.	76090.	120259.	0.433
7	5.908	1.158	0.201	227.0	21521.	75210.	173873.	0.433
8	6.481	1.731	0.301	277.5	8010.	74830.	275000.	0.333

N/S TEMPS. EXP 9/26/75 TSE-1 DSN=A,SKID4999,TEMP0926 LOWER BOUND

TEMPERATURE INTERVAL NUMBER = 10. TIME = 1.5500 01 MINUTES

GRID NO.	RADIUS INCHES	DELTA R	DELTA R/B	TEMPERATURE DEGR.FAHN.	AS QUENCHED KIC
1	4.7500	0.0	0.0	94.0	66348.
2	5.3250	0.5750	0.1000	154.0	87634.
3	5.9000	1.1500	0.2000	207.0	133657.
4	6.4750	1.7250	0.3000	252.0	225000.
5	7.0500	2.3000	0.4000	290.0	225000.
6	7.6250	2.8750	0.5000	319.0	225000.
7	8.2000	3.4500	0.6000	343.0	225000.
8	8.7750	4.0250	0.7000	360.0	225000.
9	9.3500	4.6000	0.8000	372.0	225000.
10	9.9250	5.1750	0.9000	379.0	225000.
11	10.5000	5.7500	1.0000	383.0	225000.

*** NO. OF POINTS OF CONSTANT TEMP. FOUND = 0

NUMBER OF TEMPERATURES USED = 11
NUMBER OF LAST GRID POINT USED = 11

TOTAL HEAT LOST UP TO 6 INCLUDING THIS TIME INTERVAL = 2.054750 C3 BTU PER AXIAL INCH OF CYLINDER

P.E. VALUES READ IN FOR TIME INTERVAL NO. = 10
0.0 37.26 52.82 58.61 63.46 68.28 67.55 67.27 0.0 0.0 0.0 0.0 0.0

N/S TEMPS. EXP 9/26/75 TSE-1 DSN=A,SKID4999,TEMP0926 LOWER BOUND

TEMPERATURE INTERVAL NUMBER = 10. TIME = 1.5500 01 MINUTES

STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSES AT SURFACE = 56041.
SEE RADIUS DEPTH A/B TEMPER. TANGENT. AS QUENCHED
NO. IN. IN. D.FAHN. STRESS PSI KI KIC KI/KIC

NO.	RADIUS IN.	DEPTH IN.	A/B	TEMPER. D.FAHN.	TANGENT. STRESS PSI	KI	AS QUENCHED KIC	KI/KIC
1	4.750	0.0	0.0	94.0	56041.	0.	66349.	0.0
2	4.962	0.152	0.026	118.2	50182.	37260.	71120.	0.524
3	5.071	0.321	0.056	128.0	44033.	52820.	77386.	0.463
4	5.180	0.439	0.076	140.3	39972.	54610.	82096.	0.474
5	5.333	0.583	0.101	154.0	38288.	63460.	87966.	0.721
6	5.612	0.862	0.150	181.5	27040.	88280.	103043.	0.862
7	5.908	1.158	0.201	207.7	19391.	87550.	134786.	0.501
8	6.481	1.731	0.301	252.4	7227.	67270.	225000.	0.299

***TOTAL NUMBER OF TEMPERATURE INTERVALS PROCESSED = 10

APPENDIX F
EXPERIMENTAL DATA AND RESULTS OF CALCULATIONS
PERTAINING TO TSE-2

Table F-1 lists test specimen wall temperatures measured during the TSE-2 thermal shock transient. The specified locations of the thermocouples are shown in Appendix B. There were some small deviations in radial positions of the in-wall couples; measured positions are listed in Table F-1.

Temperature distributions at times of interest for making fracture mechanics calculations are presented in Figs. F-1 through F-5. Because of a higher susceptibility to asymmetrical quenching (higher coolant velocity and narrower coolant channel), TSV-2 was equipped with more inner-surface thermocouples than TSV-1. As indicated in Figs. F-1 through F-5, there is a rather wide variation in measured surface temperature. The variation is tentatively attributed to the usual difficulties in measuring surface temperatures during a fast thermal transient, and the "actual" surface temperature was obtained by extrapolation of the in-wall data points. As indicated, the extrapolated value is a reasonable average of the measured values.

As discussed in the text of this report, the semicircular flaw appears to have propagated in two steps, the second crack shape being similar to a semiellipse with $b/a = 2.7$ and the third with $b/a = 3.7$. Results of calculations for the semicircular and these two semielliptical flaws with $a = 19 \text{ mm}$ (0.75 in.) and based on the measured temperature distributions are enclosed.

Table F-1. Temperatures in TSV-2 during TSE-2

Test specimen: TSV-2
 Wall temp. (initial): 550°F
 Sink temp. (initial): 10°F
 Time zero: 17:02:35

TIME		17:02:45	17:02:55	17:03:05	17:03:35	17:04:05	17:04:35	17:05:35	17:07:35	17:10:35	17:17:35	17:27:35
T/C	a/w	Temperature										
9A	0	284	223	197	155	140	128	109	101	75	65	45
7A	0.174	531	494	461	391	348	322	279	236	193	148	101
5A	0.366	544	543	540	517	489	465	426	372	321	237	157
3A	0.618	542	542	542	541	535	528	509	468	414	311	204
1A	1.00	531	531	531	531	531	531	526	504	455	353	226
10A	0	331	270	230	174	152	138	118	104	77	64	45
11A	0	182	154	140	107	99	91	62	60	46	39	26
12A	0	274	225	200	154	140	128	103	92	73	52	41
9B	0	193	149	128	99	86	80	69	60	54	42	33
10B	0.010	263	200	172	127	108	99	78	67	60	41	29
11B	0.050	375	310	274	208	177	158	130	110	95	67	46
8B	0.100	478	406	358	279	241	218	187	156	134	99	68
7B	0.170	539	498	460	382	336	306	270	223	188	140	94
6B	0.262	553	543	524	466	422	390	345	295	261	186	123
5B	0.366	554	553	548	520	488	461	418	363	315	233	154
4B	0.483	554	554	554	546	530	512	479	427	371	280	184
3B	0.618	553	553	553	551	546	538	517	474	419	318	208
2B	0.782	552	552	552	552	551	549	540	510	457	345	228
1B	1.00	546	546	546	546	546	546	541	518	468	356	234
12B	0	152	121	107	83	74	68	62	52	46	39	29
13B	0.175	540	502	467	393	347	318	277	230	192	144	96
14B	0.361	553	552	547	521	490	464	422	366	317	234	154
15B	0.623	553	552	553	551	547	539	519	478	423	321	210
16B	0	179	153	138	104	94	86	72	65	53	41	29
17B	0	270	220	195	145	135	123	100	88	72	49	40
9C	0	162	129	113	90	78	72	64	56	51	40	29
7C	0.170	535	494	457	360	334	304	273	224	189	139	88
5C	0.366	552	551	547	520	489	462	420	363	312	225	144
3C	0.627	552	552	552	551	546	539	518	476	418	309	196
1C	1.00	552	551	550	550	550	550	545	520	467	347	222

Fig. F-1. Temperature distributions in TSV-2 during TSE-2: (a) $t = 10$ sec, (b) $t = 20$ sec.

Fig. F-2. Temperature distributions in TSV-2 during TSE-2: (a) $t = 30$ sec, (b) $t = 1$ min.

Fig. F-3. Temperature distributions in TSV-2 during TSE-2: (a) $t = 1.5$ min, (b) $t = 2$ min.

Fig. F-4. Temperature distributions in TSV-2 during TSE-2: (a) $t = 3$ min, (b) $t = 5$ min.

Fig. F-5. Temperature distributions in TSV-2 during TSE-2: (a) $t = 8$ min, (b) $t = 15$ min, (c) $t = 25$ min.

N/S TEMPS. EXP 12/12/75 TSE-2

DSN=A.5K104999.TEMPS(TSE2)

0000 METHOD OF CALCULATING K1 ... ELPS
 MEYCLL. NP. NPR. NPT. ISHIP. INEAT. KICTYP. NPLCT. KIPLT. NSTOPT
 00 0 0 0 1 0 1 2 C 0 0

CYLINDER
 INNER RADIUS RI = 4.750
 OUTER RADIUS RO = 10.500
 SINK TEMPERATURE TSINK = -10.0

INITIAL TEMPERATURE TZERO = 555.0

INTERNAL PRESSURE IN PSI = 3.0

MATERIAL PROPERTIES
 MODULUS OF ELASTICITY E = 28.000E 06
 POISSONS RATIO MU = 0.300
 COEFFICIENT OF EXPANSION ALFA = 6.500E-06
 SPECIFIC HEAT CP = 1.070E-01
 DENSITY LBS/CU.IN DEN = 0.284

INTERNAL PRESSURE LOADING CONDITION NPR
 = 0 NO INTERNAL PRESSURE
 = 1 INT.PRESS. OPEN ENDS
 = 2 INT.PRESS. CLOSED ENDS NPR = 0

SELECTED TIME INTERVAL NUMBERS FOR K1 CALCULATIONS

0
 0

MISCELLANEOUS PARAMETERS USED IN THIS VERSION

BASE FLUENCE (F10) = 4E19
 UNRADIATED (RTNOT10) = 90 DEGR.FAHR.
 DATE ON CURVES FOR (DELRT)NOT ... 10-20-74
 DATE ON EXPRESSIONS FOR KIC (INACTOR VESSEL) ... 0-12-74
 DATE ON EXPRESSION FOR KIR (' ') ... 12-2-74
 NUMBER OF B/A RATIOS TO BE PROCESSED MBA = 3
 B/A VALUES = 1.000 2.700 3.700
 NUMBER OF CRACK DEPTHS TO BE PROCESSED MCC = 1
 CRACK DEPTH VALUES = 0.750

GRID GEOMETRY OVER CYLINDER WALL

SEQ.NO. GRID NO. RADIUS INCREMENT

.....

1	1	4.7500	0.0
2	2	5.0375	287.50-03
3	3	5.3250	287.50-03
4	4	5.6125	287.50-03
5	5	5.9000	287.50-03
6	6	6.4750	575.00-03
7	7	7.0500	575.00-03
8	8	7.6250	575.00-03
9	9	8.2000	575.00-03
10	10	8.7750	575.00-03
11	11	9.3500	575.00-03
12	12	10.5000	115.00-02

AS QUENCHED KIC VALUES FOR KICTYP=2 (11-10-74)/ IT CTS DATA

1	-300.	27.
2	-250.	20.
3	-200.	30.
4	-150.	32.
5	-100.	36.
6	-50.	41.
7	0.	46.
8	50.	57.
9	100.	68.
10	150.	86.
11	200.	123.
12	250.	225.

DSNMA-SKID4999-TEMPS(TEMP)

1/5 TEMPS. EXP 12/12/75 158-2

TEMPERATURE INTERVAL NUMBER = 1. TIME = 1.667D-01 MINUTES

GRID NO.	RADIUS INCHES	DELTA R	DELTA R/V	TEMPERATURE DEGR.FAHR.	AS QUENCHED	STRESS PSI
1	4.750	0.0	0.0	193.0	114188.	
2	5.0375	0.2875	0.000	370.0	225000.	
3	5.3250	0.2875	0.1000	470.0	225000.	
4	5.6125	0.2875	0.1500	520.0	225000.	
5	5.9000	0.2875	0.2000	542.0	225000.	
6	6.1875	0.2875	0.2500	552.0	225000.	
7	6.4750	0.2875	0.3000	553.0	225000.	
8	6.7625	0.2875	0.3500	554.0	225000.	
9	7.0500	0.2875	0.4000	554.0	225000.	
10	7.3375	0.2875	0.4500	553.0	225000.	
11	7.6250	0.2875	0.5000	552.0	225000.	
12	7.9125	0.2875	0.5500	546.0	225000.	

000 NO. OF POINTS OF CONSTANT TEMP. FOUND = 2

NUMBER OF TEMPERATURES USED = 13

NUMBER OF LAST GRID POINT USED = 12

TOTAL HEAT LOST UP TO & INCLUDING THIS TIME INTERVAL = 1.46603D 02 BTU PER AXIAL INCH OF CYLINDER

1/5 TEMPS. EXP 12/12/75 158-2 DSNMA-SKID4999-TEMPS(TEMP)

TEMPERATURE INTERVAL NUMBER = 1. TIME = 1.667D-01 MINUTES R/A RATIO = 1.000 CRACK GLETH = 0.750

SEQ NO.	RADIUS IN.	DEPTH IN.	TEMPERATURE DEGR.FAHR.	STRESS PSI	MI	STRESS PSI	MI	STRESS AT SURFACE =	STRESS AT ROOT =
1	4.750	0.0	193.0	09240.	78748.	114188.	0.000		
2	5.0375	0.000	370.0	71302.	68049.	225000.	0.302		
3	5.3250	0.100	470.0	54810.	60333.	225000.	0.268		
4	5.6125	0.200	520.0	40487.	53108.	225000.	0.230		
5	5.9000	0.300	542.0	29047.	46137.	225000.	0.205		
6	6.1875	0.400	552.0	20219.	39328.	225000.	0.175		
7	6.4750	0.500	553.0	13221.	32636.	225000.	0.145		
8	6.7625	0.600	554.0	7812.	26027.	225000.	0.116		
9	7.0500	0.700	554.0	3430.	19490.	225000.	0.087		

STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSES AT SURFACE = 79116. STRESSES AT ROOT = -8236.

W/S TEMPS. EXP 12/12/75 TSE-2 DSMMA-SKID4000-TEMP5(15E2)

TEMPERATURE INTERVAL NUMBER = 1. TIME = 1.0070-01 MINUTES B/A RATIO = 2.700 CRACK DEPTH = 0.750

STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSES AT SURFACE = 70116. STRESSES AT ROOT = -5830.

SE0 RADIUS DEPTH A/V TEMPER. TANGENT. AS QUENCHED

NO. IN. IN. D-FAHR. STRESS PSI KI KIC KI/KIC

1	4.750	0.0	0.0	193.0	69248.	66374.	114189.	0.501
2	4.044	0.094	0.016	255.8	71342.	61596.	225000.	0.207
3	4.038	0.100	0.023	318.0	84810.	46595.	225000.	0.294
4	5.031	0.201	0.049	346.9	40487.	40803.	225000.	0.311
5	5.125	0.378	0.068	408.7	28007.	73328.	225000.	0.324
6	5.219	0.469	0.082	441.3	20219.	74254.	225000.	0.338
7	5.313	0.563	0.093	487.0	13321.	77644.	225000.	0.348
8	5.406	0.656	0.116	487.8	7812.	76929.	225000.	0.367
9	5.500	0.750	0.130	504.6	3438.	66117.	225000.	0.294

W/S TEMPS. EXP 12/12/75 TSE-2 DSMMA-SKID4000-TEMP5(15E2)

TEMPERATURE INTERVAL NUMBER = 1. TIME = 1.0070-01 MINUTES B/A RATIO = 3.700 CRACK DEPTH = 0.750

STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSES AT SURFACE = 70116. STRESSES AT ROOT = -5830.

SE0 RADIUS DEPTH A/V TEMPER. TANGENT. AS QUENCHED

NO. IN. IN. D-FAHR. STRESS PSI KI KIC KI/KIC

1	4.750	0.0	0.0	193.0	59248.	56428.	114189.	0.520
2	4.044	0.094	0.016	255.8	71342.	60755.	225000.	0.268
3	4.038	0.100	0.023	318.0	84810.	64716.	225000.	0.298
4	5.031	0.201	0.049	346.9	40487.	70800.	225000.	0.318
5	5.125	0.378	0.068	408.7	28007.	76825.	225000.	0.301
6	5.219	0.469	0.082	441.3	20219.	82016.	225000.	0.305
7	5.313	0.563	0.098	487.0	13321.	85916.	225000.	0.382
8	5.406	0.656	0.116	487.8	7812.	87237.	225000.	0.308
9	5.500	0.750	0.130	504.6	3438.	75819.	225000.	0.337

DSM=A-SKID0009-TEMP-115721

M/S TEMPS. EXP 12/12/75 TSE-2

TEMPERATURE INTERVAL NUMBER = 2. TIME = 3.3330-01 MINUTES

GRID NO.	RADIUS INCHES	DELTA R	DELTA T/M	TEMPERATURE DEGR.FAHM.	AS QUENCHED MIC
1	4.7500	0.0	0.0	148.0	28191.
2	5.0375	0.2875	0.0000	305.0	225000.
3	5.3250	0.2875	0.1000	415.0	228000.
4	5.6125	0.2875	0.1000	475.0	228000.
5	5.9000	0.2875	0.2000	511.0	228000.
6	6.1875	0.2875	0.2000	548.0	228000.
7	6.4750	0.2875	0.2000	585.0	228000.
8	6.7625	0.2875	0.3000	585.0	228000.
9	7.0500	0.2875	0.3000	585.0	228000.
10	7.3375	0.2875	0.3000	585.0	228000.
11	7.6250	0.2875	0.3000	585.0	228000.
12	7.9125	0.2875	0.3000	585.0	228000.

NO. OF POINTS OF CONSTANT TEMP. FOUND = 2

 NUMBER OF TEMPERATURES USED = 12
 NUMBER OF LAST GRID POINT USED = 12

TOTAL HEAT LOST UP TO 6 INCLUDING THIS TIME INTERVAL = 2.276600 OR BTU PER AREA INCH OF CYLINDER

M/S TEMPS. EXP 12/12/75 TSE-2 DSM=A-SKID0009-TEMP-115721

TEMPERATURE INTERVAL NUMBER = 2. TIME = 3.3330-01 MINUTES B/A RATIO = 1.000 CRACK DEPTH = 0.750

 STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSES AT SURFACE = 91808. STRESSES AT ROOT = 4727.
 SEC RADIUS DEPTH A/V TEMPER. Y-ANGENT. AS QUENCHED
 IN. IN. O.FAHM. STRESS PSI KI MIC KI/KIC

1	4.750	0.0	0.0	148.0	0.0737.	0.3100.	0.0201.	1.004
2	4.844	0.094	0.014	302.0	0.2955.	0.1504.	1.25506.	0.608
3	4.938	0.188	0.023	415.0	0.8047.	0.3390.	2.50000.	0.326
4	5.031	0.281	0.040	475.0	0.4467.	0.6703.	2.24000.	0.292
5	5.125	0.375	0.068	511.0	0.2421.	0.8470.	2.24000.	0.260
6	5.219	0.469	0.082	548.0	0.3560.	0.1346.	2.24000.	0.228
7	5.313	0.563	0.098	585.0	0.2433.	0.4351.	2.24000.	0.197
8	5.406	0.656	0.114	585.0	0.1765.	0.3762.	2.24000.	0.166
9	5.500	0.750	0.130	585.0	0.1276.	0.0651.	2.24000.	0.136

M/S TEMPS. EXP 12/12/75 YSE-2 DSM-A-SKID4000-TEMP5(15621)
 TEMPERATURE INTERVAL NUMBER = 2. TIME = 3.330-01 MINUTES B/A RATIO = 3.700 CRACK DEPTH = 0.750
 STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSES AT SURFACE = 91500. STRESSES AT ROOT = 9727.
 SE0 RADIUS DEPTH A/B TEMPER. TANGENT. AS QUENCHED
 NO. IN. IN. D.P.A.M.R. STRESS PSI KI KIC KI/KIC

1	4.750	0.0	0.0	148.0	98737.	76550.	85201.	0.922
2	4.844	0.094	0.016	202.0	87654.	74825.	128808.	0.609
3	4.938	0.188	0.033	253.9	68043.	70149.	235000.	0.352
4	5.031	0.281	0.049	302.0	54467.	63113.	235000.	0.370
5	5.125	0.375	0.065	344.5	42621.	47533.	235000.	0.389
6	5.219	0.469	0.082	380.9	32850.	31345.	235000.	0.408
7	5.313	0.563	0.098	411.4	24231.	23708.	235000.	0.417
8	5.406	0.656	0.114	436.1	17569.	93364.	235000.	0.418
9	5.500	0.750	0.130	458.9	12774.	87460.	235000.	0.366

M/S TEMPS. EXP 12/12/75 YSE-2 DSM-A-SKID4000-TEMP5(15621)
 TEMPERATURE INTERVAL NUMBER = 2. TIME = 3.330-01 MINUTES B/A RATIO = 3.700 CRACK DEPTH = 0.750
 STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSES AT SURFACE = 91500. STRESSES AT ROOT = 9727.
 SE0 RADIUS DEPTH A/B TEMPER. TANGENT. AS QUENCHED
 NO. IN. IN. D.P.A.M.R. STRESS PSI KI KIC KI/KIC

1	4.750	0.0	0.0	148.0	98737.	76550.	85201.	0.922
2	4.844	0.094	0.016	202.0	87654.	74825.	128808.	0.609
3	4.938	0.188	0.033	253.9	68043.	70149.	235000.	0.351
4	5.031	0.281	0.049	302.0	54467.	63113.	235000.	0.374
5	5.125	0.375	0.065	344.5	42621.	47533.	235000.	0.400
6	5.219	0.469	0.082	380.9	32850.	31345.	235000.	0.430
7	5.313	0.563	0.098	411.4	24231.	23708.	235000.	0.456
8	5.406	0.656	0.114	436.1	17569.	93364.	235000.	0.468
9	5.500	0.750	0.130	458.9	12774.	87460.	235000.	0.414

M/S TEMPS. EXP 12/12/75 TSE-2 DSN=A.5K104999.TEMPS(TSE2)
 TEMPERATURE INTERVAL NUMBER = 3. TIME = 5.000-01 MINUTES

GRID NO.	RADIUS INCHES	DELTA R	DELTA R/W	TEMPERATURE UEGR.FAMR.	AS QUENCHED KIC
1	4.7500	0.0	0.0	128.0	77373.
2	5.0375	0.2875	0.0500	260.0	225000.
3	5.3250	0.5750	0.1000	368.0	225000.
4	5.6125	0.8625	0.1500	440.0	225000.
5	5.9000	1.1500	0.2000	483.0	225000.
6	6.1875	1.4375	0.3000	530.0	225000.
7	6.4750	2.3000	0.4000	548.0	225000.
8	6.7625	2.6750	0.5000	551.0	225000.
9	7.0500	3.4500	0.6000	553.0	225000.
10	7.3375	4.0250	0.7000	553.0	225000.
11	7.6250	4.6000	0.8000	552.0	225000.
12	7.9125	5.2750	1.0000	546.0	225000.

*** NO. OF POINTS OF CONSTANT TEMP. FOUND = 2

NUMBER OF TEMPERATURES USED = 12
 NUMBER OF LAST GRID POINT USED = 12

TOTAL HEAT LOST UP TO & INCLUDING THIS TIME INTERVAL = 3.015450 62 BTU PER AXIAL INCH OF CYLINDER

M/S TEMPS. EXP 12/12/75 TSE-2 DSN=A.5K104999.TEMPS(TSE2)
 TEMPERATURE INTERVAL NUMBER = 3. TIME = 5.000-01 MINUTES M/A RATIO = 1.000 CRACK DEPTH = 0.750

STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSES AT SURFACE = 97266. STRESSES AT ROOT = 14279.
 SEQ NO. RADIUS IN. DEPTH IN. A/W TEMPER. URGENT. AS QUENCHED
 NO. IN. IN. D.FAMR. STRESS PSI KI KIC KI/KIC

1	4.750	0.0	0.0	128.0	101649.	100588.	77360.	1.340
2	4.844	0.094	0.016	172.3	88292.	88854.	96629.	0.920
3	4.938	0.188	0.033	215.7	75488.	80784.	149212.	0.541
4	5.031	0.281	0.049	257.3	63442.	73318.	225000.	0.320
5	5.125	0.375	0.065	296.3	52342.	66163.	225000.	0.294
6	5.219	0.469	0.082	332.0	42303.	59208.	225000.	0.263
7	5.313	0.563	0.098	364.0	33414.	52395.	225000.	0.233
8	5.406	0.656	0.114	392.0	26760.	45689.	225000.	0.203
9	5.500	0.750	0.130	416.0	19264.	39067.	225000.	0.174

M/S TEMPS. EXP 12/12/75 TSE-2 OSN-A-SKID4999.TEMPS(1562)
 TEMPERATURE INTERVAL NUMBER = 3. TIME = 5.0000-01 MINUTES B/A RATIO = 2.700 CRACK DEPTH = 0.750

STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSES AT SURFACE = 97200. STRESSES AT ROOT = 14279.
 CEO RADIUS DEPTH A/B TEMPER. TANGENT. AS QUENCHED
 NO. IN. IN. D.P.A.M.B. STRESS PSI KI KI/MIC

1	4.750	0.0	0.0	128.0	101649.	88780.	77380.	1.096
2	4.844	0.094	0.016	172.3	88292.	82847.	66629.	0.857
3	4.938	0.188	0.033	215.7	75688.	65699.	149212.	0.574
4	5.031	0.281	0.049	257.3	63642.	50238.	225000.	0.401
5	5.125	0.375	0.065	298.3	52342.	39117.	225000.	0.423
6	5.219	0.469	0.082	332.0	42303.	30406.	225000.	0.442
7	5.313	0.563	0.098	366.0	33619.	102472.	225000.	0.458
8	5.406	0.656	0.116	392.0	25760.	102573.	225000.	0.456
9	5.500	0.750	0.130	416.0	19264.	92329.	225000.	0.410

M/S TEMPS. EXP 12/12/75 TSE-2 OSN-A-SKID4999.TEMPS(1562)
 TEMPERATURE INTERVAL NUMBER = 3. TIME = 5.0000-01 MINUTES B/A RATIO = 3.700 CRACK DEPTH = 0.750

STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSES AT SURFACE = 97200. STRESSES AT ROOT = 14279.
 CEO RADIUS DEPTH A/B TEMPER. TANGENT. AS QUENCHED
 NO. IN. IN. D.P.A.M.B. STRESS PSI KI KI/MIC

1	4.750	0.0	0.0	128.0	101649.	75913.	77380.	0.981
2	4.844	0.094	0.016	172.3	88292.	76529.	54629.	0.792
3	4.938	0.188	0.033	215.7	75688.	63068.	149212.	0.537
4	5.031	0.281	0.049	257.3	63642.	51121.	225000.	0.405
5	5.125	0.375	0.065	298.3	52342.	39933.	225000.	0.440
6	5.219	0.469	0.082	332.0	42303.	106050.	225000.	0.471
7	5.313	0.563	0.098	366.0	33619.	181585.	225000.	0.496
8	5.406	0.656	0.116	392.0	25760.	114243.	225000.	0.508
9	5.500	0.750	0.130	416.0	19264.	103191.	225000.	0.498

DSNHA-SK104000.TEMPS(15E2)

M/S TEMPS. EXP 12/12/75 YSE-2

TEMPERATURE INTERVAL NUMBER = 4. TIME = 1.0000 00 MINUTES

GRID NO.	RADIUS INCHES	DELTA R	DELTA R/H	TEMPERATURE DEGR.FAHN.	AS QUENCHED KIC
1	4.7500	0.0	0.0	97.0	67197.
2	5.0375	0.2875	0.0500	288.0	123000.
3	5.3250	0.2875	0.1000	288.0	228000.
4	5.6125	0.2875	0.1500	350.0	228000.
5	5.9000	0.2875	0.2000	402.0	228000.
6	6.1875	0.2875	0.2500	481.0	228000.
7	6.4750	0.2875	0.3000	530.0	228000.
8	6.7625	0.2875	0.3500	549.0	228000.
9	7.0500	0.2875	0.4000	552.0	228000.
10	7.3375	0.2875	0.4500	552.0	228000.
11	7.6250	0.2875	0.5000	581.0	228000.
12	7.9125	0.2875	0.5500	586.0	228000.

000 NO. OF POINTS OF CONSTANT TEMP. FOUND = 3

NUMBER OF TEMPERATURES USED = 12

NUMBER OF LAST GRID POINT USED = 12

TOTAL HEAT LOST UP TO & INCLUDING THIS TIME INTERVAL = 4.691000 02 BTU PER ANIAL INCH OF CYLINDER

M/S TEMPS. EXP 12/12/75 YSE-2 DSNHA-SK104000.TEMPS(15E2)

TEMPERATURE INTERVAL NUMBER = 4. TIME = 1.0000 00 MINUTES M/A RATIO = 1.000 CRACK DEPTH = 0.750

STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSES AT SURFACE = 101007. STRESSES AT ROOT = 33080.
 SLO RADIUS DEPTH A/S TEMPER. TANGENT. AS QUENCHED
 NO. IN. IN. O.FAHN. STRESS PSI KI KIC KI/KIC

NO.	IN.	IN.	O.FAHN.	STRESS PSI	KI	KIC	KI/KIC
1	4.750	0.0	97.0	104509.	107742.	67101.	1.604
2	4.844	0.044	132.3	93423.	96727.	78001.	1.228
3	4.938	0.188	168.3	82930.	86627.	93266.	0.961
4	5.031	0.281	198.6	73307.	73102.	120312.	0.601
5	5.125	0.375	228.4	64750.	78002.	170070.	0.450
6	5.219	0.469	252.3	57045.	70906.	225000.	0.251
7	5.313	0.563	276.6	49554.	65043.	225000.	0.220
8	5.406	0.656	300.9	42912.	59329.	225000.	0.204
9	5.500	0.756	324.3	36314.	53682.	225000.	0.239

M/S TEMPS. EXP 12/12/76 TSE-2 DSN=A.5H104999.TEMPS(TSE2)

TEMPERATURE INTERVAL NUMBER = 4. TIME = 1.0000 00 MINUTES B/A RATIO = 2.700 CRACK DEPTH = 0.750

STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSES AT SURFACE = 101007. STRESSES AT ROOT = 33650.

SEQ	RADIUS	DEPTH	A/B	TEMPER.	TANGENT.	AS QUENCHED	
NO.	IN.	IN.		D.F.AMR.	STRESS PSI	KI	KI/KIC
1	4.750	0.0	0.0	97.0	104500.	90808.	07101. 1.352
2	4.044	0.074	0.016	132.3	93423.	89007.	78991. 1.127
3	4.930	0.106	0.033	166.3	82930.	92312.	93206. 0.990
4	5.031	0.201	0.049	198.0	73307.	97470.	120312. 0.810
5	5.125	0.375	0.065	226.4	64750.	103065.	170970. 0.603
6	5.219	0.469	0.082	252.3	57045.	108245.	225000. 0.461
7	5.313	0.563	0.098	276.8	49856.	112179.	225000. 0.409
8	5.406	0.656	0.114	303.9	42910.	113454.	225000. 0.364
9	5.500	0.750	0.130	324.3	36314.	105463.	225000. 0.469

M/S TEMPS. EXP 12/12/76 TSE-2 DSN=A.5H104999.TEMPS(TSE2)

TEMPERATURE INTERVAL NUMBER = 4. TIME = 1.0000 00 MINUTES B/A RATIO = 3.700 CRACK DEPTH = 0.750

STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSES AT SURFACE = 101007. STRESSES AT ROOT = 33650.

SEQ	RADIUS	DEPTH	A/B	TEMPER.	TANGENT.	AS QUENCHED	
NO.	IN.	IN.		D.F.AMR.	STRESS PSI	KI	KI/KIC
1	4.750	0.0	0.0	97.0	104500.	81305.	07101. 1.211
2	4.044	0.074	0.016	132.3	93423.	82131.	78991. 1.040
3	4.930	0.106	0.033	166.3	82930.	89205.	93206. 0.957
4	5.031	0.201	0.049	198.0	73307.	98101.	120312. 0.815
5	5.125	0.375	0.065	226.4	64750.	100010.	170970. 0.629
6	5.219	0.469	0.082	252.3	57045.	114054.	225000. 0.510
7	5.313	0.563	0.098	276.8	49856.	121046.	225000. 0.530
8	5.406	0.656	0.114	303.9	42910.	124700.	225000. 0.554
9	5.500	0.750	0.130	324.3	36314.	116723.	225000. 0.516

DSMHA-SK104999-TEMP(17822)

TSE-2

N/S TEMPS. SEP 12/12/75

S. TIME = 1.0000 00 MINUTES

TEMPERATURE INTERVAL NUMBER =

1

GRID NO.	RADIUS INCHES	DELTA R	DELTA T/ΔR	TEMPERATURE DEGR.FAHR.	AS QUENCHED KIC
1	4.7500	0.5	0.0	80.0	84250.
2	3.0375	0.2375	0.0000	172.0	90430.
3	0.3750	0.0375	0.10.0	240.0	220270.
4	0.0125	0.0025	0.100	310.0	225000.
5	0.0000	0.0000	0.2000	342.0	225000.
6	0.0375	1.7750	1.3000	430.0	225000.
7	7.0000	2.3300	1.0000	500.0	225000.
8	7.0250	2.3550	0.9000	532.0	225000.
9	0.2000	3.4100	0.0000	550.0	225000.
10	0.7250	0.0350	0.7000	550.0	225000.
11	0.3500	0.0100	0.0000	551.0	225000.
12	10.0000	0.7100	1.0000	550.0	225000.

000 NO. OF POINTS OF CONSTANT TEMP. POUND = 0

NUMBER OF TEMPERATURES USED = 12

NUMBER OF LAST GRID POINT USED = 12

TOTAL HEAT LOST UP TO 6 INCLUDING THIS TIME INTERVAL = 0.000010 00 BTU PER AXIAL INCH OF CYLINDER

DSMHA-SK104999-TEMP(17822)

TSE-2

N/S TEMPS. SEP 12/12/75

S. TIME = 1.0000 00 MINUTES

TEMPERATURE INTERVAL NUMBER =

1

B/A RATIO = 1.000 CRACK DEPTH = 0.750

STRESS INTENSITY CALCULATIONS FOR A LOWSIT. CRACK. STRESSES AT SURFACE = 101182. STRESSES AT ROOT = 36037.

NO.	IN.	DEPTH IN.	ΔT/ΔR	STRESS PSI	KI	AS QUENCHED KIC
1	4.750	0.0	0.0	100001.	100001.	84250.
2	4.000	0.000	0.010	90472.	90472.	72000.
3	4.030	0.100	0.033	82524.	82524.	63200.
4	3.031	0.381	0.040	76000.	76000.	58401.
5	3.026	0.376	0.040	67951.	67951.	51020.
6	3.210	0.400	0.002	61810.	61810.	46007.
7	3.113	0.503	0.000	56102.	56102.	413170.
8	4.000	0.000	0.110	47700.	47700.	220000.
9	3.300	0.750	0.130	41000.	41000.	220000.

M/S TEMPS. EXP 12/12/75 TSE-2 DSNMA-SK104000-TEMPS(TSE2)
 TEMPERATURE INTERVAL NUMBER = 5. TIME = 1-5000 00 MINUTES O/A RATIO = 2.700 CRACK DEPTH = 0.700
 STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSES AT SURFACE = 10119. STRESSES AT ROOT = 30637.
 SMO RADIUS DEPTH A/S TEMPER. TANGENT. AS QUENCHED
 NO. IN. IN. D.P.A.M. STRESS PSI KI KI/KIC

1	4.750	0.0	0.0	00.0	103201.	91035.	64027.	1.017
2	4.044	0.004	0.016	110.0	94072.	90100.	72000.	1.236
3	4.030	0.100	0.033	143.3	84572.	83572.	63200.	1.123
4	5.031	0.201	0.049	170.2	74000.	68040.	53302.	1.036
5	5.125	0.375	0.069	190.4	60700.	104032.	114200.	0.908
6	5.219	0.469	0.082	221.4	51210.	110000.	160020.	0.806
7	5.313	0.563	0.098	245.0	41100.	114211.	212172.	0.736
8	5.406	0.656	0.114	266.9	47750.	118074.	226000.	0.618
9	5.500	0.750	0.130	287.3	41044.	100723.	236000.	0.493

M/S TEMPS. EXP 12/12/75 TSE-2 DSNMA-SK104000-TEMPS(TSE2)
 TEMPERATURE INTERVAL NUMBER = 5. TIME = 1-5000 00 MINUTES O/A RATIO = 3.700 CRACK DEPTH = 0.750
 STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSES AT SURFACE = 10119. STRESSES AT ROOT = 30637.
 SMO RADIUS DEPTH A/S TEMPER. TANGENT. AS QUENCHED
 NO. IN. IN. D.P.A.M. STRESS PSI KI KI/KIC

1	4.750	0.0	0.0	00.0	103201.	91035.	64027.	1.200
2	4.044	0.004	0.016	113.0	94072.	90100.	72000.	1.130
3	4.030	0.100	0.033	143.3	84572.	83572.	63200.	1.085
4	5.031	0.201	0.049	170.2	74000.	68040.	53302.	1.002
5	5.125	0.375	0.069	190.4	60700.	104032.	114200.	0.916
6	5.219	0.469	0.082	221.4	51210.	110000.	160020.	0.725
7	5.313	0.563	0.098	245.0	41100.	114211.	212172.	0.677
8	5.406	0.656	0.114	266.9	47750.	118074.	226000.	0.504
9	5.500	0.750	0.130	287.3	41044.	100723.	236000.	0.527

DSMA-SKID0000-TEMP8(1522)

M/S TEMPS. EXP 12/12/75 TSE-2

TEMPERATURE INTERVAL NUMBER = 6. TIME = 2.0000 00 MINUTES

GRID NO.	RADIUS INCHES	DELTA R	DELTA R/V	TEMPERATURE DEGR-FAHM.	AS QUENCHED KIC
1	4.7500	0.0	0.0	80.0	62961.
2	5.0375	0.2875	0.0500	185.0	68050.
3	5.3250	0.2875	0.1000	222.0	161661.
4	5.6125	0.2875	0.1500	282.0	225000.
5	5.9000	0.2875	0.2000	332.0	225000.
6	6.1875	0.2875	0.2500	418.0	225000.
7	6.4750	0.2875	0.3000	476.0	225000.
8	6.7625	0.2875	0.3500	516.0	225000.
9	7.0500	0.2875	0.4000	533.0	225000.
10	7.3375	0.2875	0.4500	547.0	225000.
11	7.6250	0.2875	0.5000	547.0	225000.
12	7.9125	0.2875	0.5500	546.0	225000.

*** NO. OF POINTS OF CONSTANT TEMP. FOUND = 5

NUMBER OF TEMPERATURES USED = 12
NUMBER OF LAST GRID POINT USED = 12

TOTAL HEAT LOSS UP TO 6 INCLUDING THIS TIME INTERVAL = 7.08580 02 BTU PER AREA- INCH OF CYLINDER

M/S TEMPS. EXP 12/12/75 TSE-2 DSMA-SKID0000-TEMP8(1522)

TEMPERATURE INTERVAL NUMBER = 6. TIME = 2.0000 00 MINUTES S/A RATIO = 1.000 CRACK DEPTH = 0.750

STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSES AT SURFACE = V0809. STRESSES AT ROOT = 01476.
 SEC RADIUS DEPTH A/V TEMPER. TANGENT.
 NO. IN. IN. D.FAHM. STRESS PSI K1 KIC K1/KIC

NO.	IN.	IN.	D.FAHM.	STRESS PSI	K1	KIC	K1/KIC
1	4.750	0.0	0.0	101410.	108290.	42063.	1.720
2	4.944	0.094	0.316	93230.	98152.	69483.	1.413
3	5.138	0.188	0.633	85175.	91775.	77078.	1.177
4	5.331	0.281	0.949	77520.	86010.	87609.	0.984
5	5.525	0.375	1.265	70340.	80577.	90172.	0.883
6	5.719	0.469	1.581	63560.	75343.	120432.	0.524
7	5.913	0.563	1.897	57141.	70285.	150852.	0.450
8	6.106	0.656	2.214	50990.	65276.	201040.	0.325
9	6.299	0.750	2.530	45175.	60385.	225000.	0.268

M/S TEMPS. EXP 12/12/75 YSE-2 DSMA-SH104000-TEMP5(1522)
 TEMPERATURE INTERVAL NUMBER = 0. TIME = 3.0000 00 MINUTES B/A RATIO = 2.730 CRACK DEPTH = 0.750
 STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSES AT SURFACE = 00000. STRESSES AT ROOT = 03070.
 SLO RADIUS DEPTH A/B TEMPER. YASSENT. AS QUENCHED
 NO. IN. IN. O-PAMP. STRESS PSI KI MIC MI/KIC

1	4.750	0.0	0.0	101010.	01270.	02003.	1.000
2	4.000	0.004	0.016	03230.	00017.	00003.	1.000
3	4.030	0.100	4.033	05170.	03070.	77070.	1.104
4	5.021	0.201	0.049	75020.	00032.	07000.	1.120
5	5.120	0.375	0.005	70300.	100277.	00170.	1.001
6	5.210	0.449	0.002	43000.	100730.	120430.	0.911
7	5.313	0.503	0.000	07141.	110077.	100002.	0.731
8	5.400	0.550	0.114	00000.	110000.	201000.	0.077
9	5.500	0.750	0.130	05170.	100570.	120000.	0.007

M/S TEMPS. EXP 12/12/75 YSE-2 DSMA-SH104000-TEMP5(1522)
 TEMPERATURE INTERVAL NUMBER = 0. TIME = 0.0000 00 MINUTES B/A RATIO = 3.700 CRACK DEPTH = 0.750
 STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSES AT SURFACE = 00000. STRESSES AT ROOT = 03070.
 SLO RADIUS DEPTH A/B TEMPER. YASSENT. AS QUENCHED
 NO. IN. IN. O-PAMP. STRESS PSI KI MIC MI/KIC

1	4.750	0.0	0.0	101010.	01270.	02003.	1.000
2	4.000	0.004	0.016	03230.	00017.	00003.	1.000
3	4.030	0.100	0.033	05170.	03070.	77070.	1.104
4	5.021	0.201	0.049	75020.	00032.	07000.	1.121
5	5.120	0.375	0.005	70300.	100277.	00170.	1.007
6	5.210	0.449	0.002	43000.	110077.	120430.	0.902
7	5.313	0.503	0.000	07141.	120077.	100002.	0.700
8	5.400	0.550	0.114	00000.	120022.	201000.	0.030
9	5.500	0.750	0.130	05170.	110170.	220000.	0.030

DSMWA.SM104999.TEMPS(152)

N/S TEMPS. EXP 12/12/78 152-2

TEMPERATURE INTERVAL NUMBER = 7. TIME = 3.0000 00 MINUTES

GRID NO. RADIUS DELTA R DELTA R/V TEMPERATURE AS QUENCHED
INCHES O-F-PANH. KIC

1	0.7500	0.0	0.0	65.9	50461.
2	0.3750	0.275	0.000	130.0	70129.
3	0.3750	0.375	0.100	190.0	110006.
4	0.6125	0.6125	0.100	242.0	204150.
5	0.0000	1.1000	0.200	260.0	220000.
6	0.7500	1.7200	0.300	370.0	225000.
7	0.0000	2.3000	0.400	430.0	225000.
8	1.4375	3.0750	0.500	481.0	225000.
9	0.2000	3.4500	0.600	513.0	225000.
10	0.7750	4.0250	0.700	521.0	225000.
11	0.3500	4.0000	0.800	540.0	225000.
12	10.5000	5.7500	1.000	542.0	225000.

000 NO. OF POINTS OF CONSTANT TEMP. FOUND = 0

NUMBER OF TEMPERATURES USED = 12

NUMBER OF LAST GRID POINT USED = 12

TOTAL HEAT LOST UP TO & INCLUDING THIS TIME INTERVAL = 0.920000 02 BTU PER AXIAL INCH OF CYLINDER

N/S TEMPS. EXP 12/12/78 152-2 DSMWA.SM104999.TEMPS(152)

TEMPERATURE INTERVAL NUMBER = 7. TIME = 3.0000 00 MINUTES O/A RATIO = 1.000 CRACK DEPTH = 0.750

STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSED AT SURFACE = 97702. STRESSES AT ROOT = 47003.
SEQ RADIUS DEPTH A/V TEMPER. AS QUENCHED
NO. IN. IN. O-F-PANH. STRESS P21 K1 KIC KIC/KIC

1	0.750	0.0	0.0	98000.	100000.	80402.	1.700
2	0.000	0.000	0.016	91702.	97202.	80001.	1.499
3	0.000	0.000	0.033	84004.	91302.	70003.	1.394
4	0.000	0.000	0.049	78178.	86027.	77001.	1.100
5	0.125	0.375	0.000	71000.	81000.	60010.	0.907
6	0.210	0.400	0.002	63300.	74228.	50007.	0.807
7	0.313	0.000	0.000	50002.	71000.	40031.	0.600
8	0.400	0.000	0.114	40000.	67010.	31100.	0.511
9	0.500	0.750	0.130	40076.	62000.	20000.	0.500

M/S TEMPS. EXP 12/12/75 TSE-2 DSM-A-38104999-TEMP(S1SE2)
 TEMPERATURE INTERVAL NUMBER = 7. TIME = 3.0000 00 MINUTES S/A RATIO = 2.700 CRACK DEPTH = 0.750
 STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSES AT SURFACE = 97702. STRESSES AT ROOT = 67463.
 SEQ RADIUS DEPTH A/B TEMPER. TANGENT. AS QUENCHED
 NO. IN. IN. D.F.AMR. STRESS PSI KI KI/MIC

1	4.750	0.0	0.0	68.0	90078.	90078.	60442.	1.490
2	4.844	0.094	0.016	68.2	91783.	80505.	64881.	1.364
3	4.938	0.188	0.032	100.4	84804.	91901.	70503.	1.304
4	5.031	0.281	0.049	128.7	76176.	97343.	77621.	1.254
5	5.125	0.375	0.065	148.8	71056.	103206.	85519.	1.207
6	5.219	0.469	0.082	168.6	65399.	108720.	94487.	1.151
7	5.313	0.563	0.098	187.6	59492.	113182.	104431.	1.094
8	5.406	0.656	0.114	205.4	54004.	118372.	131130.	0.980
9	5.500	0.750	0.130	222.4	48874.	100750.	162462.	0.878

M/S TEMPS. EXP 12/12/75 TSE-2 DSM-A-38104999-TEMP(S1SE2)
 TEMPERATURE INTERVAL NUMBER = 7. TIME = 3.0000 00 MINUTES S/A RATIO = 3.700 CRACK DEPTH = 0.750
 STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSES AT SURFACE = 97702. STRESSES AT ROOT = 67463.
 SEQ RADIUS DEPTH A/B TEMPER. TANGENT. AS QUENCHED
 NO. IN. IN. D.F.AMR. STRESS PSI KI KI/MIC

1	4.750	0.0	0.0	68.0	90078.	90078.	60442.	1.334
2	4.844	0.094	0.016	68.2	91783.	81599.	64881.	1.258
3	4.938	0.188	0.032	100.4	84804.	86795.	70503.	1.208
4	5.031	0.281	0.049	128.7	76176.	97709.	77621.	1.259
5	5.125	0.375	0.065	148.8	71056.	104546.	85519.	1.246
6	5.219	0.469	0.082	168.6	65399.	110571.	94487.	1.213
7	5.313	0.563	0.098	187.6	59492.	121275.	104431.	1.118
8	5.406	0.656	0.114	205.4	54004.	125541.	131130.	0.987
9	5.500	0.750	0.130	222.4	48874.	118910.	162462.	0.732

M/S TEMPS. EXP 12/12/78 T52-2 DSN=A.5KID4999.TEMPS(T522)
 TEMPERATURE INTERVAL NUMBER = 0. TIME = 5.0000 00 MINUTES

GRID NO.	RADIUS INCHES	DELTA R	DELTA R/U	TEMPERATURE DEGR.FAHR.	AS QUENCHED KIC
1	4.7500	0.0	0.0	50.0	58883.
2	5.0375	0.2875	0.0500	100.0	70419.
3	5.3250	0.2875	0.1000	150.0	89327.
4	5.6125	0.2875	0.1500	200.0	123000.
5	5.9000	0.2875	0.2000	241.0	203882.
6	6.1875	0.2875	0.2500	310.0	228000.
7	6.4750	0.2875	0.3000	380.0	228000.
8	6.7625	0.2875	0.3500	432.0	228000.
9	7.0500	0.2875	0.4000	472.0	228000.
10	7.3375	0.2875	0.4500	496.0	228000.
11	7.6250	0.2875	0.5000	511.0	228000.
12	7.9125	0.2875	0.5500	518.0	228000.

*** NO. OF POINTS OF CONSTANT TEMP. FOUND = 0

NUMBER OF TEMPERATURES USED = 12
 NUMBER OF LAST GRID POINT USED = 12

TOTAL HEAT LOST UP TO & INCLUDING THIS TIME INTERVAL = 1.200020 03 BTU PER AXIAL INCH OF CYLINDER

M/S TEMPS. EXP 12/12/78 T52-2 DSN=A.5KID4999.TEMPS(T522)
 TEMPERATURE INTERVAL NUMBER = 0. TIME = 5.0000 00 MINUTES Q/A RATIO = 1.000 CRACK DEPTH = 0.750

STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSES AT SURFACE = 90496. STRESSES AT FOOT = 48316.
 SEQ RADIUS DEPTH A/U TEMPER. TANGENT. AS QUENCHED
 NO. IN. IN. O.FAHR. STRESS PSI K1 KIC K1/KIC

SEQ NO.	RADIUS IN.	DEPTH IN.	A/U	TEMPER. O.FAHR.	TANGENT. STRESS PSI	AS QUENCHED K1	STRESSES AT SURFACE K1	STRESSES AT FOOT K1	K1/KIC
1	4.750	0.0	0.0	50.0	91179.	99752.	58884.	1.694	
2	4.944	0.094	0.016	75.3	85482.	91147.	61949.	1.471	
3	5.138	0.188	0.033	100.5	79899.	85952.	65547.	1.311	
4	5.331	0.281	0.049	125.9	74358.	81318.	70078.	1.160	
5	5.525	0.375	0.065	151.3	68824.	76975.	75709.	1.017	
6	5.719	0.469	0.082	176.1	63289.	72516.	82025.	0.888	
7	5.913	0.563	0.098	200.0	57744.	68790.	88461.	0.778	
8	6.106	0.656	0.114	224.8	52204.	64643.	95604.	0.678	
9	6.300	0.750	0.130	249.2	46637.	61016.	105384.	0.579	

M/S TEMPS. EXP 12/12/75 TSC-2 DSNWA-SKID0000-TEMPSTSEZ)
 TEMPERATURE INTERVAL NUMBER = 0. TIME = 8.0000 00 MINUTES G/A RATIO = 3.700 CRACK DEPTH = 0.750
 STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSES AT SURFACE = 90000. STRESSES AT ROOT = 00310.
 SEQ RADIIUS DEPTH A/B TEMPER. TANGENT. AS QUENCHED
 NO. IN. IN. D.P.A.M.R. STRESS PSI KI MIC KI/KIC

1	4.750	0.0	0.0	80.0	91170.	84081.	40000.	1.428
2	4.000	0.094	0.014	75.3	85483.	82670.	61409.	1.235
3	4.030	0.100	0.033	68.9	79899.	85977.	65847.	1.212
4	5.031	0.201	0.049	106.9	74350.	91049.	70070.	1.209
5	5.125	0.375	0.048	123.5	68820.	94007.	78709.	1.270
6	5.219	0.409	0.082	140.1	63426.	101000.	82020.	1.242
7	5.313	0.543	0.098	156.0	58344.	106109.	88061.	1.209
8	5.406	0.684	0.114	170.0	53700.	108494.	88000.	1.138
9	5.500	0.750	0.120	184.2	49437.	102932.	103304.	0.907

M/S TEMPS. EXP 12/12/75 TSC-2 DSNWA-SKID0000-TEMPSTSEZ)
 TEMPERATURE INTERVAL NUMBER = 0. TIME = 8.0000 00 MINUTES G/A RATIO = 3.700 CRACK DEPTH = 0.750
 STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSES AT SURFACE = 90000. STRESSES AT ROOT = 00310.
 SEQ RADIIUS DEPTH A/B TEMPER. TANGENT. AS QUENCHED
 NO. IN. IN. D.P.A.M.R. STRESS PSI KI MIC KI/KIC

1	4.750	0.0	0.0	80.0	91170.	78202.	54000.	1.270
2	4.000	0.094	0.014	75.3	85483.	76205.	61000.	1.230
3	4.030	0.100	0.033	68.9	79899.	82456.	65047.	1.264
4	5.031	0.201	0.049	106.9	74350.	91319.	70070.	1.203
5	5.125	0.375	0.048	123.5	68820.	96020.	75709.	1.316
6	5.219	0.409	0.082	140.1	63426.	107104.	82020.	1.207
7	5.313	0.543	0.098	156.0	58344.	113845.	88061.	1.204
8	5.406	0.684	0.114	170.0	53700.	117707.	93000.	1.231
9	5.500	0.750	0.120	184.2	49437.	112172.	103304.	1.065

H/S TEMPS. EXP 12/12/75 TSW-2 DSM-A.SK104999.TEMPS(TSE2)

TEMPERATURE INTERVAL NUMBER = 9. TIME = 0.0000 00 MINUTES

GRID NO.	RADIUS INCHES	DELTA R	DELTA R/R	TEMPERATURE DEGR.FAHR.	AS QUENCHED KIC
1	4.7500	0.0	0.0	55.0	57037.
2	5.0375	0.2875	0.0500	95.0	66614.
3	5.3250	0.3750	0.1000	132.0	70885.
4	5.6125	0.2875	0.1500	171.0	95834.
5	5.9000	1.1500	0.2000	207.0	133657.
6	6.4750	1.7250	0.3000	271.0	225000.
7	7.0500	2.3000	0.4000	330.0	225000.
8	7.6250	2.8750	0.5000	370.0	225000.
9	8.2000	3.4500	0.6000	415.0	225000.
10	8.7750	4.0250	0.7000	441.0	225000.
11	9.3500	4.6000	0.8000	457.0	225000.
12	10.5000	5.7500	1.0000	466.0	225000.

*** NO. OF POINTS OF CONSTANT TEMP. FOUND = 0

NUMBER OF TEMPERATURES USED = 12
NUMBER OF LAST GRID POINT USED = 12

TOTAL HEAT LOST UP TO & INCLUDING THIS TIME INTERVAL = 1.609930 03 BTU PER AXIAL INCH OF CYLINDER

178

H/S TEMPS. EXP 12/12/75 TSE-2 DSM-A.SK104999.TEMPS(TSP2)

TEMPERATURE INTERVAL NUMBER = 9. TIME = 0.0000 00 MINUTES S/A RATIO = 1.000 CRACK DEPTH = 0.750

STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSES AT SURFACE = 70181. STRESSES AT ROOT = 44837.
 SEQ RADIUS DEPTH A/R TEMPER. TANGENT. AS QUENCHED
 NO. IN. IN. O.FAHR. STRESS PSI KI KIC KI/KIC

1	4.750	0.0	0.0	55.0	70996.	87731.	57936.	1.514
2	4.841	0.094	0.016	68.3	75038.	80371.	60508.	1.328
3	4.938	0.188	0.033	81.5	78268.	78995.	63289.	1.201
4	5.031	0.281	0.049	93.2	85747.	72109.	66395.	1.086
5	5.125	0.375	0.066	104.4	81493.	68477.	69902.	0.980
6	5.219	0.469	0.082	118.3	87416.	65006.	73653.	0.880
7	5.313	0.563	0.099	130.4	83405.	61654.	78261.	0.788
8	5.406	0.656	0.114	142.9	49771.	58387.	83152.	0.707
9	5.500	0.750	0.130	155.0	45358.	55190.	86368.	0.625

M/S TEMPS. EXP 12/12/75 YSE-2 DSN=A-SK104999-TEMP(S1SE2)

TEMPERATURE INTERVAL NUMBER = 9. TIME = 8.0000 00 MINUTES B/A RATIO = 2.700 CRACK DEPTH = 0.750

STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSES AT SURFACE = 79181. STRESSES AT ROOT = 99837.

NO.	IN.	DEPTH	A/B	TEMP.	TANGENT.	STRESS PSI	KI	KIC	KI/KIC
1	4.750	0.0	0.1	58.0	78996.	73948.	97938.	1.276	
2	4.804	0.094	0.016	68.3	75030.	72798.	60508.	1.202	
3	4.938	0.188	0.033	81.5	70266.	70484.	63289.	1.196	
4	5.031	0.281	0.049	94.2	65747.	68184.	66395.	1.208	
5	5.125	0.375	0.065	106.4	61492.	68122.	69902.	1.216	
6	5.219	0.469	0.082	118.3	57413.	69812.	73883.	1.214	
7	5.313	0.563	0.098	130.4	53405.	63705.	14261.	1.197	
8	5.406	0.656	0.114	142.9	49371.	95886.	93132.	1.153	
9	5.500	0.750	0.130	155.6	45358.	92756.	88368.	1.044	

M/S TEMPS. EXP 12/12/75 YSE-2 DSN=A-SK104999-TEMP(S1SE2)

TEMPERATURE INTERVAL NUMBER = 9. TIME = 8.0000 00 MINUTES B/A RATIO = 3.700 CRACK DEPTH = 0.750

STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSES AT SURFACE = 79181. STRESSES AT ROOT = 99837.

NO.	IN.	DEPTH	A/B	TEMP.	TANGENT.	STRESS PSI	KI	KIC	KI/KIC
1	4.750	0.0	0.2	58.0	79996.	60210.	97938.	1.143	
2	4.804	0.094	0.016	68.3	75030.	67033.	60508.	1.108	
3	4.938	0.188	0.033	81.5	70266.	73000.	63289.	1.183	
4	5.031	0.281	0.049	94.2	65747.	80380.	66395.	1.211	
5	5.125	0.375	0.065	106.4	61492.	87713.	69902.	1.209	
6	5.219	0.469	0.082	118.3	57413.	96606.	73883.	1.278	
7	5.313	0.563	0.098	130.4	53405.	100600.	78241.	1.279	
8	5.406	0.656	0.114	142.9	49371.	103825.	83132.	1.249	
9	5.500	0.750	0.130	155.6	45358.	90332.	88368.	1.126	

DSM-A-101100000, TIME-1154.21

M/S TEMPS. EXP 12/12/75 TSE-2

TEMPERATURE INTERVAL NUMBER = 10. TIME = 1.5000 OI MINUTES

GRID NO.	RADIUS INCHES	DELTA R	DELTA T/W	TEMPERATURE DEGR.FAH.	AS QUENCHED KIC
1	4.7500	0.0	C.C	18.0	56799.
2	5.0375	0.2875	0.0500	65.0	59888.
3	5.3250	0.2875	0.1000	95.0	66814.
4	5.6125	0.2875	0.1500	122.0	74172.
5	5.9000	1.1500	0.2000	150.0	86000.
6	6.1875	1.7250	0.3000	201.0	124412.
7	6.4750	2.1000	0.4000	247.0	217917.
8	6.7625	2.4750	0.5000	282.0	225000.
9	7.0500	3.4500	0.6000	311.0	225000.
10	7.3375	4.1250	0.7000	330.0	225000.
11	7.6250	4.8000	0.8000	342.0	225000.
12	7.9125	5.4750	1.0000	355.0	225000.

SEE NO. OF POINTS OF CONSTANT TEMP. PUUNC = 0

NUMBER OF TEMPERATURES USED = 12
NUMBER OF LAST GRID POINT USED = 12

TOTAL HEAT LOST UP TO L INCLUDING THIS TIME INTERVAL = 2.379100 OI BTU PER AXIAL INCH OF CYLINDER

M/S TEMPS. EXP 12/12/75 TSE-2 DSM-A-101100000, TEMPS (TSE-2)

TEMPERATURE INTERVAL NUMBER = 10. TIME = 1.5000 OI MINUTES B/A RATIO = 1.0000 CRACK DEPTH = 0.750

STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSES AT SURFACE = 60316. STRESSES AT MONT = 34477.
SEQ RADIUS DEPTH A/W TEMPER. TANGENT. AS QUENCHED
NO. IN. IN. O-FAMP. STRESS PSI KI KIC KI/KIC

NO.	IN.	IN.	O-FAMP.	STRESS PSI	KI	KIC	KI/KIC
1	4.750	0.0	0.0	60327.	68886.	56786.	1.222
2	4.844	0.04	0.016	57178.	61301.	56185.	1.084
3	4.938	0.10	0.033	53879.	57988.	57979.	1.000
4	5.031	0.20	0.049	60567.	60567.	59726.	0.922
5	5.125	0.375	0.065	47204.	52505.	61684.	0.848
6	5.219	0.489	0.082	43871.	49681.	63874.	0.774
7	5.313	0.563	0.098	40681.	47150.	66282.	0.711
8	5.406	0.616	0.116	37723.	44647.	68860.	0.649
9	5.500	0.750	0.130	34943.	42264.	71473.	0.591

M/S TEMPS. EXP 12/12/75 TSE-2 OSMMA-SKID0000-TEMPS(1522)
 TEMPERATURE INTERVAL NUMBER = 10. TIME = 1-5000 01 MINUTES B/A RATIO = 2.700 CRACK DEPTH = 0.750
 STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSES AT SURFACE = 60316. STRESSES AT ROOT = 34677.
 SEC RADIUS DEPTH A/W TEMPER. TANGENT-
 NO. IN. IN. O.P.A.M. STRESS PSI KI M/KIC

1	4.750	0.0	0.0	38.0	60527.	56378.	54756.	1.030
2	4.844	0.094	0.016	46.5	57178.	55448.	54345.	0.984
3	4.938	0.188	0.033	55.2	53875.	53710.	53779.	0.995
4	5.031	0.281	0.049	64.4	50567.	61145.	59726.	1.024
5	5.125	0.375	0.065	74.1	47206.	64916.	61684.	1.052
6	5.219	0.469	0.082	84.0	43871.	68500.	63878.	1.072
7	5.313	0.563	0.098	93.6	40601.	71480.	66282.	1.078
8	5.406	0.656	0.114	102.9	37723.	73140.	68440.	1.063
9	5.500	0.750	0.130	111.6	34943.	70443.	71873.	0.984

M/S TEMPS. EXP 12/12/75 TSE-2 OSMMA-SKID0000-TEMPS(1522)
 TEMPERATURE INTERVAL NUMBER = 10. TIME = 1-5000 01 MINUTES B/A RATIO = 3.700 CRACK DEPTH = 0.750
 STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSES AT SURFACE = 60316. STRESSES AT ROOT = 34677.
 SEC RADIUS DEPTH A/W TEMPER. TANGENT-
 NO. IN. IN. O.P.A.M. STRESS PSI KI M/KIC

1	4.750	0.0	0.0	38.0	60527.	56378.	54756.	0.922
2	4.844	0.094	0.016	46.5	57178.	55448.	54345.	0.907
3	4.938	0.188	0.033	55.2	53875.	53460.	52979.	0.980
4	5.031	0.281	0.049	64.4	50567.	61200.	59726.	1.026
5	5.125	0.375	0.065	74.1	47206.	66884.	61684.	1.084
6	5.219	0.469	0.082	84.0	43871.	71902.	63878.	1.127
7	5.313	0.563	0.098	93.6	40601.	76310.	66282.	1.181
8	5.406	0.656	0.114	102.9	37723.	79194.	68840.	1.157
9	5.500	0.750	0.130	111.6	34943.	75416.	71575.	1.059

OSMA-SKID4999.TEMPS(TSE2)

TSE-2

TEMPERATURE INTERVAL NUMBER = 11.

EXP 12/12/75

2-5000 01 MINUTES

GRID NO. RADIUS INCHES DELTA R DELTA T/° TEMP. DEGR.FAH. AS QUENCHED KIC

.....

1	0.7500	0.0	0.0	25.0	52390.
2	0.0378	0.2878	0.0500	48.0	50638.
3	0.3250	0.5750	0.1000	85.0	59840.
4	0.6128	0.8628	0.1500	101.0	63871.
5	0.9000	1.1500	0.2000	130.0	69389.
6	0.4750	1.7250	0.3000	130.0	70432.
7	0.0000	2.3000	0.4000	112.0	71718.
8	0.6250	2.8750	0.5000	108.0	108882.
9	0.2000	3.4500	0.6000	202.0	128882.
10	0.7750	4.0250	0.7000	219.0	158888.
11	0.3500	4.6000	0.8000	275.0	174379.
12	0.5000	5.7500	1.0000	230.0	187713.

NO. OF POINTS OF CONSTANT TEMP. FOUND = 0

NUMBER OF TEMPERATURES USED = 12

NUMBER OF LAST GRID POINT USED = 12

TOTAL HEAT LOST UP TO 6 INCLUDING THIS TIME INTERVAL = 3.101100 03 BTU PER AXIAL INCH OF CYLINDER

OSMA-SKID4999.TEMPS(TSE2)

TSE-2

TEMPERATURE INTERVAL NUMBER = 11.

EXP 12/12/75

2-5000 01 MINUTES

STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSES AT SURFACE = 38178. STRESSES AT ROOT = 21117.

W/S TEMPS. EXP 12/12/75 TSE-2 OSMA-SKID4999.TEMPS(TSE2)

TEMPERATURE INTERVAL NUMBER = 11. TIME = 2-5000 01 MINUTES S/A RATIO = 1.000 CRACK DEPTH = 0.750

GRID NO.	RADIUS IN.	DEPTH IN.	TEMP. DEG.F.	STRESS PSI	KI	KI/KIC
1	0.750	0.0	25.0	39998.	42200.	1.1937 0.800
2	0.044	0.04	33.0	36182.	36427.	0.9333 0.718
3	0.330	0.160	49.7	33048.	34084.	0.9287 0.660
4	0.621	0.489	101.0	31170.	34378.	0.9357 0.611
5	0.910	0.878	130.0	29129.	32704.	0.9489 0.589
6	0.210	0.449	130.0	27276.	31080.	0.9656 0.530
7	0.313	0.603	108.0	25084.	29038.	0.9699 0.493
8	0.400	0.750	108.0	23010.	27031.	0.9900 0.487
9	0.500	0.130	70.7	21034.	26294.	0.9233 0.422

1	0.750	0.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
2	0.000	0.000	20.0	20.0	20.0	20.0	20.0	20.0	20.0
3	0.000	0.000	20.0	20.0	20.0	20.0	20.0	20.0	20.0
4	0.000	0.000	20.0	20.0	20.0	20.0	20.0	20.0	20.0
5	0.000	0.000	20.0	20.0	20.0	20.0	20.0	20.0	20.0
6	0.000	0.000	20.0	20.0	20.0	20.0	20.0	20.0	20.0
7	0.000	0.000	20.0	20.0	20.0	20.0	20.0	20.0	20.0
8	0.000	0.000	20.0	20.0	20.0	20.0	20.0	20.0	20.0
9	0.000	0.000	20.0	20.0	20.0	20.0	20.0	20.0	20.0
10	0.000	0.000	20.0	20.0	20.0	20.0	20.0	20.0	20.0

STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSSES AT SURFACE = 30175. STRESSSES AT ROOT = 21117.
 NO. IN. IN. A/R REMOVED. 1/2 INCHES. 1/2 INCHES. 1/2 INCHES. 1/2 INCHES. 1/2 INCHES. 1/2 INCHES. 1/2 INCHES. 1/2 INCHES. 1/2 INCHES. 1/2 INCHES.

TEMPERATURE INTERVAL NUMBER = 11. TIME = 2.5000 OF MINUTES. B/A RATIO = 2.700 CRACK DEPTH = 0.750
 M/S TEMPS. EXP 12/12/75 150-2 DEMA-5A100009-10005113221

1	0.750	0.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
2	0.000	0.000	20.0	20.0	20.0	20.0	20.0	20.0	20.0
3	0.000	0.000	20.0	20.0	20.0	20.0	20.0	20.0	20.0
4	0.000	0.000	20.0	20.0	20.0	20.0	20.0	20.0	20.0
5	0.000	0.000	20.0	20.0	20.0	20.0	20.0	20.0	20.0
6	0.000	0.000	20.0	20.0	20.0	20.0	20.0	20.0	20.0
7	0.000	0.000	20.0	20.0	20.0	20.0	20.0	20.0	20.0
8	0.000	0.000	20.0	20.0	20.0	20.0	20.0	20.0	20.0
9	0.000	0.000	20.0	20.0	20.0	20.0	20.0	20.0	20.0
10	0.000	0.000	20.0	20.0	20.0	20.0	20.0	20.0	20.0

STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK. STRESSSES AT SURFACE = 30175. STRESSSES AT ROOT = 21117.
 NO. IN. IN. A/R REMOVED. 1/2 INCHES. 1/2 INCHES. 1/2 INCHES. 1/2 INCHES. 1/2 INCHES. 1/2 INCHES. 1/2 INCHES. 1/2 INCHES. 1/2 INCHES. 1/2 INCHES.

TEMPERATURE INTERVAL NUMBER = 11. TIME = 2.5000 OF MINUTES. B/A RATIO = 2.700 CRACK DEPTH = 0.750
 M/S TEMPS. EXP 12/12/75 150-2 DEMA-5A100009-10005113221

APPENDIX C
POSTTEST EXAMINATION OF FLAWED AREA IN
THERMAL SHOCK SPECIMENS TSV-1 AND -2

D. A. Canonico*

1. INTRODUCTION

Following the thermal shock testing (TSE-1 and -2) of TSV-1 and -2, cores were trepanned from the flawed region and subjected to a metallogical examination. The examination included both light and scanning electron microscopy (SEM) of the morphology of the crack propagation and the appearance of the fracture surfaces.

2. THERMAL SHOCK VESSEL 1

As shown in Fig. G-1, two cylindrical cores identified as TSV-1-1 and TSV-1-2 were removed from TSV-1. Figure G-2 shows the detailed shape and size of the cores and indicates the sectioning procedures used to provide specimens for the metallographic examination. The smaller pieces were mounted and polished to permit an examination of the flaw in the direction indicated by projection AA. The larger piece was cooled considerably below its nil ductility temperature (NDT) and broken to expose the flawed interface.

The metallographic samples from TSV-1-1 and TSV-1-2 are shown in Figs. G-3 and G-4, respectively. Complete cross sections of the electron-beam (EB) weld are shown in Figs. G-3a and G-4a, and Figs. G-3b and G-4b are photomicrographs of the flaw tip area. (The EB weld is delineated by etching in both photomicrographs.) As shown in these figures, a relatively wide crack extends to or just beyond the fusion zone and a much narrower crack continues on a short distance. This tends to indicate that the crack was generated in two events, and the wider one is known to have occurred immediately following the EB weld placement. Examination of the fracture surfaces shows that the surfaces corresponding to the wider crack were heavily oxidized but that the others were not.

*Metals and Ceramics Division.

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Fig. G-1. Location of trepanned cores in TSV-1 following TSE-1.

Presumably the oxide was formed during heating of the test specimen (TSV-1) in preparation for the thermal shock experiment (TSE-1). Thus, it is concluded that the narrower crack extension took place during the thermal shock. Additional evidence supporting this conclusion is derived from the following metallurgical analysis.

Reference is made to Fig. G-5, which is a photomicrograph of the tip area of a flaw in an EB weld prior to subsequent loading. (Note the magnification difference between Figs. G-3b and G-4b and Fig. G-5.) The flaw (crack) has extended only slightly [0.01 cm (0.004 in.)] beyond the EB fusion line, while the extensions in Figs. G-3 and G-4 are 0.091 cm (0.036 in.) and 0.183 cm (0.072 in.). Notice also the difference in the morphology of the cracks in Figs. G-3 and G-4 and Fig. G-5. The crack in Fig. G-5 is not continuous (in this plane of the structure); that is, it is bridged in a number of areas as it approaches the bottom. The thermally shocked crack (Figs. G-3b and G-4b) is continuous to and through the bottom of the EB weld; the bridged areas seen in Fig. G-5 are not evident in Figs. G-3b and G-4b. These differences between Figs. G-3 and G-4 and Fig. G-5 are attributed to crack extension during the TSE-1 thermal shock.

Fig. G-2. Sample of trepanned core from TSV-1. Metallographic view along Section A-A; scanning electron microscopy examination along Section B-B.

Fig. G-3. Posttest examination of the electron-beam (EB) weld from trepanned core TSV-1-1 from TSV-1. (a) EB weld showing crack and extension; EB fusion zone in this photomicrograph is 0.670 cm (0.264 in.) deep. (b) Region of crack tip extension; crack has extended 0.091 cm (0.036 in.) at this location.

PHOTO 0478 /6

Fig. G-4. Posttest examination of the electron-beam (EB) weld from trepanned core TSV-1-2 from TSV-1. (a) EB weld showing crack and extension; EB fusion zone in this photomicrograph is 0.731 cm (0.288 in.) in depth. (b) Region of crack tip extension; crack has extended 0.183 cm (0.072 in.) at this location.

Fig. G-5. Photomicrograph of an unstressed electron-beam weld. The acuity of the unstressed crack tip is evident. The crack in this example is 0.010 cm (0.004 in.) beyond the EB fusion line.

The pieces from TSV-1 that were broken to expose the fracture surfaces were examined at a magnification of about 5.5. Figure G-6 contains the photomicrographs of the fracture surfaces from the two EDM cores. The dark band (just below the porosity in the two specimens) is the region that underwent crack extension. The lighter colored area in which the pore(s) reside is the original EB weld crack. The light area below the

Fig. G-6. Photomacrographs of the fracture surfaces from two cores removed from TSV-1 by the electrodischarge machining process. The dark band located near the middle of the two specimens is the area of crack extension. The surface in this area exhibited a cleavage appearance, a crack mode indicative of frangible fracture.

band is the base metal that was exposed when the pieces were cooled below their NDT and broken.

The crack extension surfaces were examined in the SEM and found to contain a predominantly cleavage appearance. This fracture surface appearance is indicative of a frangible fracture.

3. THERMAL SHOCK VESSEL 2

Following the second thermal shock experiment (TSE-2), it was evident from visual inspection of the inner surface of TSV-2 that the semicircular flaw had extended axially and was ~140 mm (5.6 in.) long. The flaw had

extended 6.6 cm (2.6 in.) in the direction of the flow of the coolant medium and 4.1 cm (1.6 in.) in the opposite direction. An oblong core approximately 17 cm (6.8 in.) long by 2.5 cm (1 in.) wide containing the extended crack was trepanned from TSV-2 by EDM procedures. Figure G-7 is a photograph of the trepanned core. The original machined groove and the crack extensions are evident. (The five marks perpendicular to the crack indicate locations where COD strain gages were in place during the thermal shock experiment.)

Metallographic samples were prepared at a number of sites across the crack. The specimens were oriented in such a manner that the crack was viewed in its direction of propagation. Figure G-8 contains both unetched (Fig. G-8a) and etched (Fig. G-8b) photomicrographs of the extended crack near its termination. The top of the crack is the inner surface of TSV-2. The crack tends to be tighter at the top and bottom than near its center. This appearance was true for all the areas of the crack that were examined. Figure G-9 contains a photomicrograph of a location about 2.5 cm (1.0 in.) closer to the EB flaw. The difference in crack width between the top and bottom and center is even more evident in this photomicrograph. The metallographic examination of the extended crack suggested that the crack had a tendency to tunnel as it propagated. The crack depth at the locations shown in Figs. G-8 and G-9 are 0.89 cm (0.35 in.) and 1.19 cm (0.47 in.), respectively.

Figure G-10 contains etched and unetched photomicrographs of the EB weld after the thermal shock. The original EB weld is evident in the etched photomicrograph. The crack extended approximately 0.178 mm (0.07 in.) in depth at this, the deepest point of the flaw. (The EB weld and hence the original 3.81-cm-long by 1.90-cm-deep flaw was slightly askew of the center line of the machined groove.)

An extensive examination of each crack location was undertaken. Figure G-11 is representative of the morphology of the extended crack. The crack is not straight nor sharp, but rather tends to run in a jagged and irregular mode. Indeed, as can be seen in the montage of photomicrographs in Fig. G-11, there are locations within the vessel wall where the crack is propagating parallel to the inner surface. Further, the propagating crack tends to preferentially seek manganese sulfide inclusions as

PHOTO Y138676

Fig. G-7. Photograph of the core containing the propagated crack from TSV-2. The machined groove on the inner surface of the vessel is evident. The crack can be seen on the inner surface extending in both directions away from the groove.

Fig. G-8. Photomacrographs of the metallographic specimen removed from the area in Fig. G-12 that indicates a crack depth of 0.89 cm (0.35 in.). (a) Unetched, (b) etched with 2% nital.

PHOTO Y137921

Fig. G-9. Photomicrograph of a specimen removed from the area in Fig. G-12 that indicates a crack depth in the vessel wall of 1.19 cm (0.47 in.). The crack width appears greater toward its center. The crack "ends" both at the vessel surface (top) and at the arrest location within the vessel appear to be much tighter. This crack appearance suggests that crack propagation could have occurred by tunneling.

Fig. G-10. Photomicrographs of the EB weld flaw from TSV-2. The "original" EB crack is evident in (a); the EB weld and the crack extension beyond the fusion line are evident in (b) (etched with 2% nital). Original magnification 5x.

PHOTO Y137523

Fig. G-11. Metallographic examination of the crack that occurred in TSV-2 as a consequence of the thermal shock experiment. The crack morphology is typical of that seen in all the crack locations examined metallographically. The crack at this location is 15.0 mm (0.59 in.) deep. The propagating crack appears to follow the manganese sulfide inclusions in the steel. Further, there does appear to be a tendency for the crack to tunnel, as suggested by the extremely tight crack at the inner surface of the vessel.

it extends into the vessel. No doubt these inclusions provide an easy path for the propagating crack.

After the examination of the crack specimens by light microscopy was completed, the specimens were removed from their mounts and the crack opened. Figure G-12 is a sketch of the fracture surface, showing that the crack arrest front is not uniform but rather irregular. The arrows identify the locations at which crack depth measurements were made. The "average" crack depth is about 1.27 cm (0.5 in.). The deepest point of the crack, about 2.02 cm (0.8 in.), occurred beneath the center of the EB weld flaw where the crack extension was only 0.18 cm (0.07 in.).

Figure G-13 is a photograph of the fracture. (The specimens are supported in silica sand to permit them to be arranged into their proper

Fig. G-12. Sketch illustrating the profile of the crack that occurred in TSV-2 as a consequence of the thermal shock experiment. The dimensions are exact measurements of the crack depths at the locations indicated. It is evident that the crack front is not uniform. The semiellipse toward the left of center is the machined notch; the cross-hatched region below it is the electron-beam weld crack.

PHOTO Y138132

Fig. G-13. Photograph of fracture surface from TSV-2. The original flaw is evident toward the left center of the photograph. The irregular depth of crack penetration can be seen.

position.) The machined groove, the EB weld, and the extended crack are evident in this figure.

A SEM examination was made of the area just below the EB weld flaw. Figure G-14 identifies the region of the crack that was examined. The fracture appearance at the crack initiation site (that location just below the original EB crack) was found to be mixed mode. As shown in Fig. G-14, there are areas of dimple fracture (indicating ductile failure), but these are localized. There is no evidence of continuous dimple fracture. Other locations from the same area show regions of mixed mode that are predominantly cleavage with some dimple. Most of the fracture surface is cleavage. This is particularly true for regions remote from the initiation site (EB weld flaw).

4. SUMMARY

There is evidence that crack initiation was achieved in both TSV-1 and TSV-2. The propagation of the crack in TSV-1 was in the range of 0.25 cm (0.10 in.), an irresolvable distance by any nondestructive measurement technique. The flaw in TSV-2 extended nearly 10.2 cm (4.0 in.) along the inner surface of the vessel. The crack penetrated the vessel to a nominal depth of about 1.27 cm (0.5 in.). Extension of the flaw at its deepest point was approximately 0.18 cm (0.07 in.) and the fracture was frangible. Examinations of the fracture surface showed it to have a predominantly cleavage appearance. Some mixed-mode (localized) and some dimple fracture (isolated regions) were observed along the original crack front.

PHOTO Y138414

Fig. G-14. Scanning electron microscopy examination of the fracture surface just below the original flaw. The fracture in this area appeared to contain isolated regions of ductile (dimple fracture appearance) failure and other regions which underwent a mixed mode (dimple and cleavage). The appearance of the entire fracture surface, however, is nearly 100% cleavage, which indicates a frangible mode of failure.