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PRESSURE VESSEL FRACTURE STUDIES PERTAINING TO A PWR
LOCA-ECC THERMAL SHOCK: EXPERIMENTS TSE-3 AND TSE-4
AND UPDATE OF TSE-1 AND TSE-2 ANALYSIS

R. D. Cheverton S. E. Bolt

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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.

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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, TN 37830.

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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 four 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, in the absence of warm prestressing, long flaws might propagate more than halfway through the wall. However, if warm prestressing is assumed to be effective, flaws with a fractional depth greater than 0.2 could not initiate. If it is further assumed that the arrest toughness is equal to K_{IR} , the maximum penetration would be 0.35. In view of these results, the Thermal Shock Program was oriented toward determining the validity of linear elastic fracture mechanics for shallow cracks under LOCA-ECC thermal shock conditions, with a subsequent effort on demonstrating warm prestressing under basically the same conditions.

In the first experiment, initiation was not expected and did not occur, although there was a small amount of subcritical crack growth. In the second experiment, initiation of a semi-circular flaw took place as expected; the final length along the surface was about four times the initial length, but there was no radial growth. The third and fourth experiments were similar, and the long axial flaw initiated in good agreement with predictions.

1. INTRODUCTION AND SUMMARY

In the event of a loss-of-coolant accident (LOCA) in a light-water reactor, 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 ECCS coolant enters the vessel through the main coolant lines and passes over the inner surface of the

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Fig. 1. Schematic of typical PWR showing flow path for emergency core coolant.

vessel wall prior to reaching the core. Thus, a portion of the initially hot vessel is quenched by the emergency core coolant. As shown in Fig. 2, this quenching action, or thermal shock, results in rather steep positive temperature gradients through the wall and thus high tensile stresses in the inner portion of the vessel wall.

The reduction in temperature and the high fast-neutron fluence that accumulates over many years of reactor operation tend to reduce the fracture toughness (K_{Ic}) of the vessel material. Because of the sensitivity of fracture toughness to temperature and fluence, as shown in Fig. 3, and the positive gradient in temperature and the attenuation of the fluence, as shown in Fig. 2, there is a net positive gradient in toughness in the vessel wall, as shown in Fig. 4.

Fig. 2. Typical fast-neutron fluence attenuation and LOCA-ECC thermal shock temperature and stress distributions in a PWR (1 ksi = 6.895 MPa).

Fig. 3. Static fracture toughness vs $T - RT_{NDT}$ for no fluence and a fluence of 4×10^{19} neutrons/cm² considering high and low copper concentrations. Data used in LOCA-ECC thermal shock studies for PWR analysis (Refs. 4, 6, 7).

If there is a flaw (crack) on the inner surface (below the cladding) of the vessel wall, the high, thermally induced tensile stress will result in an appreciable stress-intensity factor (K_I) at the tip of the flaw. This is illustrated in Fig. 5 for long axial and continuous circumferential cracks. The combined effect of high stress-intensity factor and low fracture toughness may result in propagation of the preexisting flaw. However, the steep positive gradient in toughness, as shown in Fig. 4, tends to provide a mechanism for arresting the crack.

The tendency for fracture to occur also depends on the impurity content (primarily copper) of the vessel material because of the effect that impurities have on the reduction in toughness due to neutron irradiation.

Fig. 4. K_{IC} vs fractional wall depth ($\Delta r/w$) for the reference calculational model with high copper concentration.

This effect is illustrated in Fig. 3 by showing the fracture toughness vs temperature curves for low- and high-copper materials with a maximum expected inner-surface fluence of 4×10^{19} neutrons/cm².

Another factor that influences crack propagation is warm prestressing, a phenomenon that may prove to be very important in limiting the extent of crack propagation.

The need to investigate crack propagation and arrest in connection with an ECC thermal shock depends upon the likelihood of crack propagation and the state of the art of calculational techniques for predicting crack

Fig. 5. $(K_I)_{max}$ (maximum with respect to time) vs a/w for long axial and continuous circumferential flaws in the reference calculational model.

behavior. There was concern regarding the accuracy of linear elastic fracture mechanics in a thermal shock situation – not because thermal stresses per se are unique, but because the stress field (nearly equal biaxial stresses) and the very steep gradients in temperature and stress comprise a unique situation that may influence fracture behavior. Also, preliminary calculations indicated that, under some circumstances, the probability of crack propagation in PWRs during a LOCA-ECC incident was high. For these reasons, the LOCA-ECC Thermal Shock Program was established, and it was deemed advisable to conduct experiments that would reveal the behavior of PWR vessels under specific thermal shock conditions. The particular LOCA-ECC event being considered at this time is the double-ended pipe break, for

which the primary-system pressure is essentially zero by the time the thermal shock is under way.

An initial step in the thermal shock studies at Oak Ridge National Laboratory (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 calculations¹ 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. If propagation of the crack is not limited by warm-prestressing effects, the crack could penetrate through at least half the vessel wall thickness. 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. An outside diameter of 0.99 m (39 in.) was specified, but procurement time was longer than desired. In order to expedite the program, it was decided to conduct experiments with two smaller specimens [0.53 m OD (21 in.)] that would be adequate for the study of shallow cracks and that could be machined from existing forgings.

The possibility that warm prestressing might have a significant effect in limiting crack propagation was not considered until the thermal shock studies were well under way. Since that time, it has been reasoned that, if warm prestressing is as effective as presently indicated, there will not be as much incentive for studying propagation and arrest of deep cracks,

which require the use of the larger test specimens. Instead, a demonstration of warm-prestressing effects under appropriate conditions would be sufficient. It is not clear at this time just how this might be done.

As an initial step, warm-prestressing effects are being studied by Loss^{2,3} using a three-point-loaded beam.

In order to simulate the PWR fracture mechanics parameters as closely as possible in the ORNL thermal shock experiments, the test specimens were fabricated from PWR pressure vessel material, were given a quench-only heat treatment to reduce the toughness and increase the yield strength (simulating irradiation effects to some extent), and were subjected to thermal shocks more severe than those imposed on PWR vessels in order to further reduce the toughness and to enhance K_{Ic} ; these latter two measures were necessary because the test specimen material, even in the quench-only condition, was tougher than the irradiated material.

An important aspect of the experimental program was the determination of fracture toughness for the test specimen material. Figure 6 shows the K_{Ic} vs temperature curve based on measurements of K_{Ic} for the test specimen prolongations. Additional measurements are being made for the test specimens themselves.

Four thermal shock experiments have been conducted with the 0.53-m-OD (21-in.) specimens. The first (TSE-1) is referred to as the noninitiation experiment, because the calculated maximum K ratio (K_I/K_{Ic}) was less than unity (initiation takes place when $K_I/K_{Ic} = 1$). The flaw was a long axial crack of optimum depth, and the specific maximum K ratio selected was the same as that calculated for the PWR reference calculational model, assuming a low concentration of copper. In the second experiment (TSE-2), 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 (1.5-in.) diameter. A summary of test conditions for these first two thermal shock experiments is presented in Table 1.

Acoustic-emission (AE) and crack-opening-displacement (COD) instrumentation indicated that unstable crack growth did not take place during TSE-1. Metallographic examination showed some extension, but it has been identified as subcritical crack growth.

Fig. 6. Static fracture toughness curve used in analysis of thermal shock experiments TSE-1, -2, -3, and -4. The curve is based on data from A533 and A508 (V-1, TSV-1, and TSV-2 prolongations) in the as-quenched condition [quenched in water from $871^{\circ}C$ ($1600^{\circ}F$)]. (See Ref. 1 for additional information.)

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

Test conditions	TSE-1	TSE-2
Test specimen	TSV-1	TSV-2
Test specimen dimensions, μ (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, $a = 11 \text{ mm}$ (0.42 in.)	Semicircular axial crack, $a = 19 \text{ mm}$ (0.75 in.)
Temperatures, °C (°F)		
Wall (initial)	288 (550)	289 (552)
Sink (initial)	2 (40)	-23 (-9.5)
Sink (final)	7 (45)	-15 (-2.5)
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)	917 (133)
Back-pressure orifice diameter, mm (in.)	25.43 (1.001)	43.18 (1.700)
Heat transfer coefficient, $\text{W}\cdot\text{m}^{-2}\cdot^\circ\text{C}^{-1}$ ($\text{Btu}\cdot\text{hr}^{-1}\cdot\text{ft}^{-2}\cdot^\circ\text{F}^{-1}$)	12800 (~ 500)	15700 ($\sim 10^3$)
$(K_I/K_{Ic})_{\text{max}}$	0.74	1.33 ($\phi = 75^\circ$)
Time of occurrence of $(K_I/K_{Ic})_{\text{max}}$, min	18	14
Duration of experiment, min	30	30

In the second experiment, the AE and COD instrumentation indicated axial extension of the semicircular flaw in two events: first at the downstream end and then at the upstream end. The sequence of events and the various flaw shapes and sizes are depicted in Fig. 7. There are indications that warm prestressing restricted the axial extension and that the running-crack dynamic toughness, and thus the arrest toughness, was significantly less than the static fracture toughness.

The third experiment (TSE-3) constituted a second and more severe thermal shock to the test specimen and flaw used in TSE-1. Crack initiation

Fig. 7. Sketch of original semicircular flaw and flaw extension in TSV-2 (TSE-2).

was expected and occurred; however, there were unforeseen complications that made interpretation of the results difficult. The fourth experiment (TSE-4) was a repeat of TSE-3, using another test specimen (TSV-2) and a virgin flaw. Results of this experiment agree reasonably well with predictions. Test conditions for TSE-3 and TSE-4 are summarized in Table 2.

Detailed information relating to results from TSE-1 and TSE-2, the methods of analysis, the PWR analysis, the thermal shock test facility, test specimen material properties, and data retrieval is included in Ref. 1. Experiments TSE-3 and TSE-4 are discussed in this report, along with further interpretive comments regarding TSE-1 and TSE-2. Also included in this report is additional information on the PWR analysis, particularly with regard to warm prestressing.

Table 2. Test conditions for TSE-3 and TSE-4

Test conditions	TSE-3	TSE-4
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.)	Long axial crack a = 11 mm (0.42 in.)
Temperatures, °C (°F)		
Wall (initial)	291 (555)	291 (555)
Sink (initial)	-23 (-10)	-25 (-13)
Sink (final)	-15 (4.5)	-19 (-2)
Coolant	40 wt % methyl alcohol 60 wt % water	40 wt % methyl alcohol 60 wt % water
Coolant flow rate, m ³ /hr (gpm)	~114 (500)	~114 (500)
Coolant pressure in test section, kPa (psi)	917 (140)	1000 (145)
Back-pressure orifice diameter, mm (in.)	43.18 (1.700)	43.18 (1.700)
Heat transfer coefficient, W·m ⁻² ·K ⁻¹ (Btu·hr ⁻¹ ·ft ⁻² ·°F ⁻¹)	~5700 (~10 ⁵)	~5700 (~10 ⁵)
(K _I /K _{Ic}) _{max}	1.13	1.29
Time of occurrence ^a of (K _I /K _{Ic}) = 1, min	~3	1.7
Time of occurrence ^a of (K _I /K _{Ic}) _{max} , min	~6	5
Duration of experiment, min	30	30

^aCalculated times based on measured temperature distributions. For TSE-3, the effect of core holes is not included.

2. ANALYSIS OF THE PWR AND ITS INFLUENCE ON THE EXPERIMENTAL PROGRAM

An apparently practical approach to the analysis of the PWR LOCA-ECC thermal shock problem was to consider a two-dimensional linear elastic fracture mechanics model with long axial and continuous circumferential flaws, the reasons being that, in most respects, this model represented conservative worst-possible conditions and accurate methods of analysis (two-dimensional finite-element) were available. If the PWRs could survive this approach, the LOCA-ECC thermal shock problem would be solved, and a reasonable method of analysis would have been established.

As a part of the Thermal Shock Program, ORNL defined a reference calculational model (RCM) that was intended to represent typical PWR conditions (see Table 3), and then performed the type of analysis described above. The results indicated that, in the absence of warm prestressing (a phenomenon that was not considered until rather late in the program), a long axial crack would penetrate about 90% of the wall and a continuous circumferential crack about 70%. Initially, there had been a desire to limit crack propagation to 50%; thus, the results of the analysis created some concern over the possibly excessive degree of conservatism in the calculational model.

Several approaches to a more realistic model were considered and are summarized as follows:

1. Include the three-dimensional aspects of the long-axial-crack problem. There are axial gradients in temperature and fluence, and thus in stress and toughness, that will tend to limit crack propagation. Restraint afforded by the vessel heads will also tend to limit propagation relative to the two-dimensional model. Unfortunately, a three-dimensional model of this type is probably out of the question because of present computer limitations.

2. The two-dimensional linear elastic model analysis indicates that the long axial crack will not go all the way through the wall. The error in applying linear elastic fracture mechanics to such a deep crack is not known. However, a simple plastic analysis performed by Merkle⁸ for a very deep flaw resulted in about the same K_I values, thus indicating that the crack will not penetrate the outer surface.

Table 3. 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	$4 \times 10^{19} e^{-0.013 \Delta r \cdot \text{cm}^{-1}}$
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), $\text{W}\cdot\text{m}^{-2}\cdot\text{°C}^{-1}$ ($\text{Btu}\cdot\text{hr}^{-1}\cdot\text{ft}^{-2}\cdot\text{°F}^{-1}$)	1140 (200)
Wall temperature (initial), °C (°F)	288 (550)
Pressure (gage)	0
Fracture toughness	
K_{Ic} source (unirradiated)	WCAP-7414 (Ref. 4)
K_{Ir} source (unirradiated)	ASME Code, Section III, Subsection NA, App. G, and Ref. 5
$K_{Ia} = K_{Ir}$	
RT_{NDT} (unirradiated), °C (°F)	4 (40)
ΔRT_{NDT} vs fluence and copper concentration (source)	Litton (October 1973), Refs. 6, 7
Copper concentration extremes, %	
Low copper (ASTM Spec. A533-72a)	0.1
High copper (unrestricted residual)	≥ 0.25
Residual stresses	≤ 0 , assumed zero

Under emergency core-cooling conditions, it may be that a very deep axially oriented crack that does not leak would be acceptable, since in most respects the vessel would be structurally sound and would contain the emergency core coolant. If this approach were adopted, it would be necessary to demonstrate further that, indeed, the crack would not penetrate the outer surface. It is not likely that a more sophisticated analysis (finite-element, elastic-plastic fracture mechanics analysis) would provide

the necessary assurance, and thermal shock experiments of the type considered for this program would not suffice.

Another type of experiment proposed was based on the notion that rotation of the crack faces, as shown in Fig. 8, is limited by the net thermal moment and the stiffness of the wall. Under these conditions, there must be some uncracked ligament that can withstand the limiting angle. This was suggested some time ago, and Loss⁹ conducted beam experiments in which angles up to 4° were used. The beam cross section was 38×76 mm (1.5×3.0 in.), and $a/w = 0.42$. The material was tempered A533 (plate 02), and the test temperatures were on the upper shelf [$82-121^\circ\text{C}$ ($180-250^\circ\text{F}$)].

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Fig. 8. Bending which occurs in a long cylinder containing a long axial crack when it is subjected to a thermal quench on the inner surface.

Crack extension was no greater than 5 mm (0.2 in.). At ORNL, two 150 × 150 mm (6 × 6 in.) beams made from A533 in the quench-only condition and with a crack depth of 51 mm (2 in.) were loaded at room temperature [$K_{Ic} = 55 \text{ MN}\cdot\text{m}^{-3/2}$ (50 ksi $\sqrt{\text{in.}}$)] through a limiting angle of 4°. Fracture took place, but the crack did not penetrate the back surface.

For $a/w = 0.90$, the maximum angle of rotation calculated for the RCM is 2.6°. Thus, there is some experimental evidence that a two-dimensional, long axial crack in a PWR could not penetrate the outer surface.

There is at least one reservation with regard to interpretation of the above data. When the thermal moment is being applied and the crack is opening, the uncracked ligament is subjected to a rather large compressive load. This tends to result in plastic deformation as the ligament grows thinner. When the thermal gradient is gone, the crack will be closed, and a residual tensile stress will exist in the uncracked ligament that may be large enough to crack the ligament.

3. Perhaps an axially oriented through crack would be acceptable, since in most respects the vessel would still be sound, and the crack would be tight enough during and after the transient to limit leakage of the coolant.

4. Even if complete penetration of an axial crack were acceptable, very deep penetration of a continuous circumferential crack could not be tolerated, since it could result in detachment of the lower portion of the vessel. A sensitivity analysis, including the uncertainties in K_{Ic} and K_{Ia} , would have to be conducted to determine the maximum likely depth of penetration. Unfortunately, K_{Ia} data for irradiated material are not too abundant at this time.

5. Another possible approach is to relegate long cracks to a very improbable category and concentrate on finite-length cracks. Although calculations¹ indicate that, in the absence of warm prestressing, finite cracks might grow to become long cracks and then propagate radially, the results from TSE-2 seem to indicate otherwise or that warm prestressing was effective in limiting propagation. At ORNL, a three-dimensional, finite-element fracture mechanics method of analysis for more accurately interpreting the results of TSE-2 is being developed.

6. The final approach is to demonstrate that warm prestressing will be effective in substantially limiting crack propagation. Recent experiments by Loss^{2,3} and earlier ones by Brothers and Yukawa¹⁰ and Harrison and Fearnough¹¹ demonstrated how warm prestressing may effectively increase the static fracture toughness of a pressure vessel under thermal shock conditions. The process is illustrated in Fig. 9. If a flawed specimen is loaded at an elevated temperature to a load greater than the fracture load corresponding to a lower temperature and then is loaded at the lower temperature, the fracture load will be greater than that obtained without applying the preload. Furthermore, for certain loading and temperature conditions, the fracture load will be greater than the preload. Loss³ reports that these latter conditions exist during the PWR LOCA-ECC thermal shock. Thus, if a K_I ratio of unity is not achieved until after K_{Ic} has passed through its maximum value, crack propagation cannot occur. If

Fig. 9. Graphical illustration of warm prestressing for a simple test specimen.

it were possible to demonstrate that warm prestressing would be this effective under the conditions assumed for the RCM, then perhaps none of the five alternative approaches to achieving a more realistic analytical model would have to be pursued.

The first task in assessing the possible benefits of warm prestressing was to calculate the locus of points for $K_I/K_{Ic} = 1$ on a plot of K_I vs time with crack depth as a parameter. Such a graph for the high-copper RCM with a long axial flaw is shown in Fig. 10. It is observed that, for fractional crack depths greater than ~0.2, a K ratio of unity is achieved only after K_I has reached a maximum value. Thus, if it is assumed that Loss's data are applicable to a vessel under thermal shock loading, long axial and continuous circumferential cracks with fractional depths greater than ~0.2 will not initiate.

The extent to which propagation might take place (final arrest depth) is evaluated with the critical-crack-depth set of curves as illustrated in Figs. 11 and 12 for the long axial and continuous circumferential cracks in the high-copper RCM. In these figures, a_c/w is the fractional crack depth for which K_I/K_{Ic} and K_I/K_{Ia} are equal to unity for specific times in the thermal transient. Selecting a time provides a crack depth for initiation and the corresponding arrest depth. Maximum depths are not shown for the long axial flaw because the method of analysis breaks down for very deep cracks, but it is clear that, in the absence of warm prestressing, the penetration is greater than 50%. For the circumferential flaw, the maximum depth for initiation is just under 50% and the corresponding arrest depth is ~70%. On the other hand, if warm prestressing limits the maximum crack depth for initiation to 20%, then, as illustrated by Figs. 11 and 12, the maximum penetration (arrest depth) will be limited to ~35%.

If warm prestressing is as effective as indicated above, and if the actual arrest toughness is similar to that assumed for the RCM analysis, then the LOCA-FCC thermal shock problem ceases to exist, and it should not be necessary to experimentally investigate the arrest behavior of deep cracks ($a/w \geq 0.5$). It will be necessary, however, to adequately demonstrate warm prestressing under appropriate conditions; to obtain K_{Ia} data

Fig. 10. Stress-intensity factor vs time in transient and fractional flaw depth (a/w) for a long axial flaw in the reference calculational model. The locus of points for $K_I/K_{Ic} = 1$ is shown for the case of high-copper material. Points to right of peak in K_I curve indicate warm pre-stressing.

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Fig. 11. Fractional critical crack depth (a_c/w) vs time in transient for long axial flaws in the high-copper reference calculational model, illustrating stepwise crack propagation in the absence of warm prestressing.

Fig. 12. Fractional critical crack depth (a_c/w) vs time in transient for continuous circumferential flaws in the high-copper reference calculational model, assuming no warm prestressing.

for irradiated pressure vessel material; and, of course, to verify that linear elastic fracture mechanics (LEFM) is applicable under LOCA-ECC thermal shock conditions, considering relatively shallow flaw propagation. The latter task is the purpose of the present Thermal Shock Program.

3. SYNOPSIS OF EXPERIMENTAL TECHNIQUES AND PROCEDURES

As mentioned in the preceding chapter, details of experimental techniques and procedures are covered in Ref. 1. However, a few changes were made for TSE-3 and TSE-4, which need to be mentioned, and a brief review of the entire subject will help to orient the reader and will make this report more complete.

The thermal shock is applied to the inner surface of the cylindrical test specimens by suddenly pumping cold fluid through a narrow annulus formed by the inner surface of the test specimen and a flow baffle, as illustrated schematically in Fig. 13. Prior to quenching, the test specimen is gradually heated to 288°C (550°F) with an electric furnace, and the coolant is chilled to the desired sink temperature. Heat removed from the test specimen is stored in the large quantity of circulating coolant. A photograph of the test facility showing the major components is presented in Fig. 14.

Two types of data must be retrieved from a test specimen during the thermal transient: radial temperature distributions in the wall and indications of crack propagation. The temperature distributions are used to obtain fracture toughness distributions and to calculate the thermal stresses, which in turn are used to calculate the stress-intensity factors. These temperature distributions are obtained with numerous thermocouples located at different depths in the wall. Thermal-hydraulic experiments were conducted with a special test specimen to ensure that quenching was symmetrical and uniform (see Appendix A).

Indications of crack initiation and arrest were obtained with strain gages placed across the flaw (COD gages) and with acoustic-emission instrumentation. For TSE-1, -2, and -3, the COD gages were mounted in such a way that crack initiation could result in gage failure, and thus subsequent events would not be detected. For TSE-4, modifications were made that prevented gage failure and thus not only permitted measurements subsequent to crack initiation detections but also permitted estimates of propagation depth. A detailed discussion of the development of the improved COD gages is included in Appendix B.

Fig. 13. Schematic of thermal shock test facility.

Fig. 14. Photograph of thermal shock test facility during early stages of assembly, showing basic components of system.

The acoustic-emission work was contracted to Southwest Research Institute (SwRI) for all four tests, and Battelle Pacific Northwest Laboratories (BNW) was invited to participate in TSE-4. SwRI modified their technique for TSE-3 and TSE-4 relative to that used in TSE-1 and TSE-2. Details with regard to modifications in the AE instrumentation are included in Appendix B.

The initial flaws for TSE-1, -2, and -3 were prepared by first machining a rectangular groove and then placing an electron-beam (EB) weld at the bottom. The welds cracked during the welding operation as the heated material cooled. This initial cracking is the result of very low toughness in the fusion zone (very rapid self-quenching rate) and residual stresses which develop during the quenching. Although much of the residual stress in the fusion zone is relieved when the crack pops in, residual stresses remain in a very narrow region at the crack tip after arrest. However, because of their localized nature, it is believed that these stresses have no significant effect on crack propagation other than to contribute to subcritical crack growth early in the thermal shock transient. Photomicrographs of the flaw prepared for TSE-1 and the subcritical growth that occurred during TSE-1 are shown in Fig. 15.

The weld groove was used in preparing the flaws for TSE-1, -2, and -3 because at the time the test specimens were prepared for these tests, the EB weld could not otherwise penetrate to the desired depth. Additional EB weld development efforts¹² resulted in deeper penetration capability, and the long axial flaw for TSE-4 was made without the weld groove. This was an improvement because the weld groove introduced uncertainties with regard to localized temperature and stress distributions.

Fig. 15. Posttest examination of the electron-beam (EB) weld from trepanned core TSV-1-1 removed from TSV-1 following TSE-1. (a) EB weld showing crack and extension (total effective initial flaw depth extends to inner surface); EB fusion zone in this photomicrograph is 6.70 mm (0.264 in.) deep (fusion zone only). (b) Region of crack-tip extension [0.91 mm (0.036 in.)] at this location.

4. THERMAL SHOCK EXPERIMENT TSE-1

The purpose of TSE-1 was to demonstrate that a long axial flaw with a maximum K ratio of ~ 0.7 would not experience unstable crack growth. The AE and COD instrumentation indicated that, if crack extension took place, it was very early in the transient, when temperatures were too high for brittle fracture. Metallographic examination of a core removed from the wall of the test specimen showed a very short extension [~ 2 mm (0.08 in.)], and it was hypothesized that the combined effect of thermal stress and EB weld residual stress resulted in subcritical crack growth at upper-shelf temperatures. The combined stress appeared to be adequate, and the depth of penetration was quite shallow because of the very steep gradient in residual stress at the tip of the original flaw. However, an examination by scanning electron microscopy (SEM) of a portion of the removed core that was split to reveal the fracture surfaces indicated frangible fracture.¹ The core specimen was not ideal, and it was intended that additional samples be removed and examined following TSE-3, which was conducted on the same test specimen using the same flaw in its slightly extended condition. An SEM examination of the additional sample showed that the portion of the fracture that occurred during TSE-1 was ductile, and the portion that occurred during TSE-3 was brittle. Additional proof regarding the fracture mode for TSE-1 was obtained by examining another core specimen which had been removed from TSV-1 following TSE-1 and which was well preserved. The SEM examination of this specimen revealed ductile fracture. Thus, it can now be concluded that unstable crack growth did not take place during TSE-1; this is in agreement with what was expected on the basis of the LEFM analysis.

Detailed information regarding the metallographic examinations is included in Chapter 8.

5. THERMAL SHOCK EXPERIMENT TSE-2

The purpose of TSE-2 was to determine whether an axially oriented finite-length flaw with a portion of its crack front having maximum K_I ratios in excess of unity would propagate axially to become a "long" flaw and then propagate radially. The initial flaw was semicircular with a radius of 19 mm (0.75 in.), and the thermal shock was severe enough that the flaw initiated. As illustrated in Fig. 7, propagation took place in two events, there was essentially no extension radially beyond the deepest point of the flaw, and the final length was 142 mm (5.6 in.). Calculations that excluded the effects of warm prestressing and assumed semielliptical geometry for the extended flaw indicated that the flaw would become long enough to grow radially [$(K_I/K_{Ic})_{\max}$ for a long axial flaw with $a = 19$ mm was ~ 1.2] and, with the effects of warm prestressing included, there were indications that the flaw would not extend the length of the cylinder and would not propagate radially.

The potential for warm prestressing of the final crack front ($b/a = 3.7$) is illustrated in Fig. 16, which is a plot of K_I vs time for several points on the crack front. At the time that the final crack front first existed (86 sec), K_I for each point on the crack front is close to a maximum value. This means that for times greater than 86 sec or thereabout, K_I all along the crack front will be decreasing with time, and thus presumably crack initiation cannot take place even though the calculated K ratios eventually may be equal to or greater than unity.

Since warm prestressing may play a very important role in mitigating the LOCA-ECC thermal shock problem, it is important to understand that TSE-2 should not be classified as an adequate demonstration of warm prestressing under thermal shock conditions. It may be that warm prestressing did limit propagation; however, there were too many uncertainties associated with K_I and K_{Ic} to permit a firm conclusion. For instance, the K_I calculations are based on a semielliptical crack-front shape for the two extended flaw shapes, and, as indicated by Fig. 7, the intermediate and final crack shapes are not actually semielliptical. Furthermore, the method for calculating K_I has been compared with a three-dimensional finite-element analysis developed by Ayres,¹³ and it was found that, for identical semielliptical geometries, our method¹⁴ overestimates K_I over most of the crack

Fig. 16. K_I vs time for TSE-2; semielliptical flaw with an aspect ratio $(b/a) = 3.7$ and a maximum depth (a) of 19 mm (0.75 in.).

front. If these differences in the two methods of analysis are considered, it is quite possible that the maximum K ratios along the crack front for the final flaw shape were simply less than unity and that warm prestressing did not play a part in limiting crack extension.

As discussed in Ref. 1, the results from TSE-2 indicated that the running-crack dynamic toughness and thus the arrest toughness of the test

specimen material was considerably less than the static fracture toughness. This appeared to be the case because the flaw propagated through areas where the calculated K ratio based on K_{Ic} was considerably less than unity. Arrest toughness values based on results from TSE-2 are presented in Fig. 17 along with the static fracture toughness curve.

Two K_{Ia} vs T curves were obtained, one for each of the two arrest events. The K_I calculation for the intermediate crack shape was expected to be more accurate than that for the final crack shape, and thus the lower of the two K_{Ia} curves would be more nearly accurate. The results from TSE-3 and TSE-4 provided additional proof that $K_{Ia} \ll K_{Ic}$, and the single value of K_{Ia} deduced from TSE-4 is also plotted in Fig. 17. This value agrees

Fig. 17. Comparison of K_I and K_{Ia} for as-quenched A508; K_{Ia} curves are based on data from the dual crack extension in TSE-2, while a single point was obtained from TSE-4.

better with the higher of the two K_{Ia} curves. The K_I calculation for TSE-4 is considered to be much more accurate than that for TSE-2, and thus the K_{Ia} point derived from TSE-4 should be more accurate.

6. THERMAL SHOCK EXPERIMENT TSE-3

The purpose of TSE-3 was (1) to determine whether a long axial flaw will propagate under the specified thermal shock conditions when the maximum K ratio is ~ 1.2 and (2) if the crack does propagate, to determine what the nominal calculated K ratio was at the time of initiation, and (3) to obtain a measurement of the arrest toughness.

The third thermal shock experiment (TSE-3) was a companion to TSE-1 in the sense that the same test specimen (TSV-1) and flaw were used, and for TSE-1 the maximum K ratio (K_I/K_{Ic}) was less than unity, while for TSE-3 it was greater than unity. In other words, unstable crack growth was predicted for TSE-3 but not for TSE-1.

Following TSE-1, two 25-mm-diam (1-in.) core holes were trepanned from the flaw zone, as shown in Fig. 18, to permit examination of the fracture. The high stress-concentration factors at these holes were expected to result in localized "premature" crack initiation during a subsequent thermal shock (TSE-3). However, at the time TSE-3 was being planned, it was believed that K_{Ia} for this quench-only material was essentially equal to K_{Ic} , and thus the core-hole stress concentration would not trigger premature cracking along much of the crack front. The holes were plugged with snug-fitting bars that were seal-welded at the outer surface, and TSE-3 was conducted as planned.

Shortly before TSE-3 was conducted, it was tentatively concluded on the basis of data from TSE-2 that K_{Ia} was substantially less than K_{Ic} for the test specimen material. The temperature shift in the region of interest [66 to 204°C (150 to 400°F)] appears to be in the range of 38 to 149°C (100 to 300°F), and the corresponding calculated crack jump range is $a/w = 0.2$ to 0.4 , neglecting the effect of the core holes. If the crack jumped deeper than 17%, it could not reinitiate because, even in the absence of warm-prestressing effects, the K ratio for cracks deeper than 17% never exceeds unity.

Typical temperature distributions obtained from TSE-3 are shown in Figs. 19 through 21, and tabulated temperatures and the results of fracture mechanics calculations based on these temperatures are included in Appendix C. According to calculations using the measured temperature distributions,

Fig. 18. Cross section of TSV-1 showing location of COD gages and core holes in TSE-3 (1 mm = 0.039 in.).

Fig. 19. TSE-3 temperature distribution at 59 sec into transient.

Fig. 20. TSE-3 temperature distribution at 181 sec into transient.

Fig. 21. TSE-3 temperature distribution at 300 sec into transient.

a maximum K ratio of 1.13 was obtained, and a K ratio of unity was achieved at 3.0 min into the transient. The calculated K_I values given in Appendix C do not include stress concentrations around the core holes where cores were trepanned following TSE-1. Thus, higher K ratios would be expected in the vicinity of the holes, and a value of unity would occur sooner.

The maximum nominal calculated K ratio achieved during TSE-3 was less than that intended (~ 1.2) as a result of problems encountered with operation of the quick-opening valve. The valve opened long enough for the

test section to fill with coolant and then closed; about 14 sec later, the valve opened again and remained open. The result was a thermal shock that was less severe than intended.

Output from the COD gages is shown in Fig. 22 (note that gage XE-33 was not operable during the test), and the precise location of the gages is indicated in Fig. 18. The two initial COD events shown in Fig. 22 are the

Fig. 22. COD output in TSE-3 showing time of occurrence of major time-integrated bursts of acoustic energy.

result of thermal effects on the gages, thermal stress, and perhaps subcritical crack growth at the times the dual thermal shock was applied. A few seconds later (24 sec into the transient), COD gage XE-31 opened (the gage filament parted), indicating a relatively large amount of crack opening. Shortly thereafter, the other gages began indicating very small crack-opening and arrest events. Gage XE-32 opened at 110 sec into the transient, and XE-34 opened at 178 sec. Gage XE-30 did not open, but continued to indicate small events up to ~250 sec, which indicates substantially less crack propagation near the inlet end than elsewhere.

The numerous small events shown in Fig. 22 could be crack-straightening events prompted by locally high values of K_I , or they could be an indication of initiation-arrest events near the core holes. Many of these events took place early in the transient when the nominal K ratio was too small for initiation, and in some cases when the temperature corresponded to upper-shelf toughness. As shown in Fig. 6, the upper-shelf temperature (based on 2T CT specimens) is 120°C (250°F). The temperature at the tip of the initial flaw did not fall below 120°C until 1.4 min into the transient. The larger dimensions of the thermal shock test specimen would probably result in a somewhat higher upper-shelf toughness, but not much increase in the corresponding temperature.

The AE data are presented in Fig. 23, which shows the acoustic energy emitted in a 10-sec period, as a function of time, divided by the total energy emitted over a 300-sec period, the latter time period starting 32 sec before initiation of the thermal shock. As shown in Fig. 22, the peaks in the AE curve correspond to events or groups of events indicated by the COD instrumentation. A detailed interpretation of the AE data is presented in Appendix B.

After the test specimen was removed from the test facility, the COD gages were inspected before they were removed. It was determined that the 1.6-mm-OD (0.062-in.) sheath portion of the XE-32 gage was buckled longitudinally over a short [~1.3-mm (~0.05-in.)] length located directly over the crack. Also, the 0.13-mm (0.005-in.) flange was broken directly over the crack, and the ends were overlapped. This indicates that substantial crack opening took place during the thermal transient, and the extended gage buckled during crack closure.

Fig. 23. Acoustic energy emitted in 10 sec, as a function of time, divided by the total acoustic energy emitted over a 300-sec period.

The next step was to trepan two 25-mm-diam (1-in.) cores from the locations shown in Fig. 24 (cores 3 and 4). Inspection of these cores revealed that the total fractional crack depth was about 25%. This was considered excessive from the standpoint of using the test specimen (TSV-1) for another thermal shock test; therefore, three more cores were removed, and finally a narrow axial section containing the entire crack region was cut from the specimen. The cores and the section were split apart at

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Fig. 24. Location of 25-mm-diam (1-in.) cores trepanned from TSV-1 following TSE-1 (cores 1 and 2) and TSE-3 (cores 3 through 7). (1 mm = 0.039 in.).

cryogenic temperatures to reveal the fracture surfaces. Locations of the additional cores are shown in Figs. 24 and 25, and photographs of the core fracture surfaces and the section fracture surface are presented in Figs. 26 and 27. Note that the crack depth is reasonably uniform along the length of the test specimen except near the ends of the cylinder and adjacent to the core holes that were machined prior to TSE-3. At these latter locations, there is essentially no propagation of the initial flaw. The absence of propagation at the edges of the holes presumably is a result of free surface effects that more than compensate for the stress concentration around the holes. The lack of penetration at the ends of the test specimen probably results from a lack of restraint at the ends of the cylindrical test specimen as well as from free surface effects.

The several "early" initiation events shown in Fig. 22, particularly the one corresponding to COD gage XE-31, indicate that the stress concentration around the holes had an effect on the time of initiation. COD gage XE-34 indicated a large crack opening (extension) at about the predicted time (180 sec); however, initiation in this area, even though affected by the presence of the core hole, could have been delayed by the proximity of the area to the end of the cylinder. COD gage XE-30, which was located the same distance from the end of the cylinder but much farther away from a core hole, registered less penetration, assuming that failure of the COD gage (XE-34) implies a considerably larger crack opening than was recorded up to the time of failure. It is also of interest to note in Fig. 27 that there is a substantial length [76 mm (3 in.)] of flaw at the inlet end that did not initiate, while at the outlet end the penetration tapers off to zero. This difference in behavior at the two ends probably results from the relatively close proximity of a core hole at the upper end.

An SEM examination of the fracture surfaces showed that the fractures were of a brittle nature.

Based on the above observations, it seems reasonable to conclude that the presence of the core holes (1 and 2) had a significant effect on crack propagation, and it is not possible to determine whether the flaw would have initiated in the absence of the core holes. Also, since the COD gages in the central region of the test specimens failed prior to the time that initiation events ceased, it is not possible to deduce values of K_{Ia} .

Fig. 25. Section of wall containing the long longitudinal flaw cut from TSV-1 following TSE-3 (1 cm = 0.394 in.).

PHOTO 5429 76

Fig. 26. TSE-3 core fracture surfaces (1 cm = 0.394 in.).

PHOTO 5078 78

Fig. 27. Fracture surfaces revealed following TSE-3 by splitting long section containing flaw region. Flow inlet is at left (1 cm = 0.394 in.).

7. THERMAL SHOCK EXPERIMENT TSE-4

The purpose of TSE-4 was the same as that for TSE-3. The biggest difference in the two experiments was the exclusion in TSE-4 of the two core holes that were present in the TSE-3 test specimen. The TSE-4 test specimen was TSV-2, which had been used in TSE-2 and at that time contained an axially oriented semicircular flaw. Following TSE-2, the 150-mm-long (6-in.) flawed region was removed by electrodischarge machining (EDM) and the hole was plugged (see Fig. 28). The long axial flaw for TSE-4 was placed 180° from the plugged core hole. Other differences in TSE-4 were a more severe thermal shock (the same as that intended for TSE-3) and a flaw generated without the EB weld groove. Another difference was in the mounting of the COD gages (see Appendix B). In TSE-4, the gages did not fail, and thus all multiple events, if any, could be detected. Furthermore, the potential existed for making rough estimates of crack propagation depths on the basis of COD gage output.

Predictions of crack propagation were made for TSE-4 based on calculated temperature distributions, an estimated initial flaw depth, and a K_{Ia} vs temperature curve deduced from TSE-2 results. These calculations indicated that crack initiation would take place at 102 sec into the transient and that arrest would take place at a fractional wall depth of 0.23. They also indicated that a single step, exclusive of subcritical crack growth and possible unstable crack growth associated with EB weld residual stresses, would take place, and reinitiation would not be possible because the maximum K ratio for the arrested crack depth would be less than unity.

The output from the COD gages is summarized in Fig. 29 and Table 4, and the location of the gages is shown in Fig. 30. The initial COD event (0-6 sec) is the result of thermal effects on the gages, thermal stress, and perhaps subcritical crack growth. In the time range 60-80 sec, there were small step changes indicated by gages XE-31, -32, and -33, and XE-32 indicated a second step that was considerably larger. At 150 sec, all five COD gages indicated relatively large steps, the three in the midregion being considerably larger than those near the ends.

Acoustic-emission data obtained by SwRI indicated that there were several "high level" emissions in the time period 40-90 sec and then again

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Fig. 28. Plug and flaw details in TSV-2 as prepared for TSE-4.

Fig. 29. Illustration of changes in indicated strain from COD gages during TSE-4 (not quantitatively precise).

Table 4. Step changes in COD output during TSE-4

COD gage	Change in strain (microstrain)			
	Time (sec): 0-6	64-68	74-76	150-152
XE-30	6400			3700
XE-31	7000		280	6600
XE-32	6700	150	2000	4800
XE-33	7000			5700
XE-34	6500			3700

Fig. 30. Location of COD gages on TSV-2 for TSE-4.

at ~150 sec. Several events occurred from 160 to 240 sec but were of lower magnitude. It is possible that some of the acoustic emissions emanated from the core-hole plug located 180° from the long axial crack. It was not possible to differentiate between the acoustic emissions emanating from these two locations.

Very little AE data were collected by Battelle Pacific Northwest Laboratories because a necessary last-minute relocation of waveguides apparently resulted in one of their two waveguides not seating properly against the test specimen. No AE data were recorded, but visual observations of the scope indicated that events occurred at ~154, 224, and 235 sec, the first emission being much greater than the other two. More details regarding the AE data are included in Appendix B.

There was one other acoustic emission detected during the thermal transient: at approximately 150 sec into the transient, several observers within 5 m (15 ft) of the test specimen heard a single loud ping, which was similar to, but louder than, those heard during TSE-3.

After removal of the test specimen from the test facility, it was observed that all COD gages were buckled along their unbonded length (see Figs. 31 and 32). This would be expected because of the large indicated local strain (1.7%). This does not imply that the strain measurements during the transient were inaccurate; laboratory tests have shown that, while under tension, the partially bonded gage has good accuracy to 2% strain and is a satisfactory event indicator to 5% strain (see Appendix B).

In order to permit examination of the fracture surfaces, five 25-mm-diam (1-in.) cores were trepanned from the flawed area following the thermal shock experiment. As shown in Fig. 33, the cores were taken from regions of the test specimen close to each of the COD gages. The core closest to the center of the specimen was located directly under COD gage XE-32 and is shown in Fig. 32. A short section of the core containing the extended crack was separated from the rest of the core and then split at cryogenic temperatures to reveal the fracture surfaces. These surfaces for the three centrally located cores are shown in Fig. 34, and the actual initial and final crack depths that were determined from an examination of the exposed surfaces are listed in Table 5. As indicated, the initial flaw depth was about as expected (0.076), and the final depth (0.14-0.17) was reasonably

Fig. 31. View of inner surface of TSV-2 following TSE-4 showing electron-beam weld flaw and COD gages. Gages buckled during experiment.

Fig. 32. Core trepanned from TSV-2 following TSE-4 showing initial and final crack depth and a buckled COD gage; location at midlength of test specimen.

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Fig. 33. Location of 25-mm-diam (1-in.) cores trepanned from TSV-2 following TSE-4.

Fig. 34. Fracture surfaces revealed by splitting short sections of 25-mm-diam (1-in.) cores at cryogenic temperatures. Cores trepanned from TSV-2 following TSE-4. Refer to Fig. 33.

Table 5. Measured flaw depths at locations of core holes

Core	Fractional flaw depth (a/w)	
	Initial	Final
AA	0.076	0.163
A	0.082	0.174
B	0.071	0.158
C	0.071	0.152
CC	0.071	0.141

uniform over the region containing the cores. The shallowest penetration (0.14) was near one end, as would be expected on the basis of TSE-3 results. Of particular interest is the uniformity of final depth over most of the length, which demonstrates that the cylinder is effectively infinitely long.

Calculations made using the measured transient temperature distributions (see Figs. 35, 36, and 37 for typical distributions and Appendix C for detailed results of the calculations) and the nominal K_{Ic} vs T curve in Fig. 6 indicate a K ratio of ~ 1.10 at 140 sec for $a/w = 0.076$. The fractional crack depth corresponding to a K ratio of 1.00 at 150 sec is ~ 0.090 , and the calculated time at which $K_I/K_{Ic} = 1$ for $a/w = 0.076$ is ~ 125 sec. At 75 sec into the transient, the K ratio for $a/w = 0.076$ is ~ 0.6 , and the maximum K ratio at that time is ~ 0.8 and corresponds to $a/w = 0.03$. The maximum K ratio calculated for $a/w = 0.076$ was 1.29 and occurred at ~ 5 min.

Fig. 35. Radial temperature distribution measured during TSE-4 at 40 sec into the transient.

Fig. 36. Radial temperature distribution measured during TSE-4 at 162 sec into the transient.

Fig. 37. Radial temperature distribution measured during TSE-4 at 302 sec into the transient.

The test specimen temperature corresponding to $a/w = 0.076$ and $t = 150$ sec was $\sim 74^{\circ}\text{C}$ ($\sim 165^{\circ}\text{F}$). At this temperature, a 10% variation in K_{Ic} corresponds to an 8°C (15°F) change in temperature. All things considered, the accuracy of the temperature measurement is not much better than this. Thus, inaccuracies in temperature measurements could account for the apparent 10% "error" in the above calculated K ratio ($K_I/K_{Ic} = 1.10$ for $a/w = 0.076$ and $t = 150$ sec). However, it is more likely that most of the error is associated with the scatter in the K_{Ic} vs T data.

Before the five cores were removed from the test specimen, an indication of final crack depth was obtained by combining the COD output with the calculated (finite-element) crack openings for various crack depths. By this process, the final fractional crack depth near the central portion of the test specimen was estimated to be 0.15, assuming an initial fractional crack depth of 0.076. The total calculated crack opening from initiation of the transient to $t = 150$ sec for $a/w = 0.15$ is 0.30 mm (12×10^{-3} in.), and the COD output also indicates a value of 0.30 mm.

Once the actual final crack depth was known, it was possible to obtain an estimate of the arrest toughness for a specific temperature. For $a/w = 0.15$ and $t = 150$ sec, the temperature was 126°C (258°F), and $K_I = 127 \text{ MN}\cdot\text{m}^{-3/2}$ ($116 \text{ ksi}\sqrt{\text{in.}}$) = K_{Ia} . This value of K_{Ia} is about 25% greater than the value deduced from TSE-2, as shown in Fig. 17.

Based upon these results and with only nominal values of the various parameters considered, it would appear that the predictive methods of analysis used in connection with TSE-4 are quite accurate.

8. FRACTOGRAPHIC EXAMINATION OF THE FRACTURE SURFACES DEVELOPED DURING TSE-1, TSE-3, and TSE-4

D. A Canonico^{*} R. S. Crouse^{*}

Two thermal shock test cylinders (TSV-1 and TSV-2) were used for the four thermal shock experiments. TSV-1 was used for thermal shock experiments 1 and 3 (TSE-1 and TSE-3); TSV-2 was used for thermal shock experiments 2 and 4 (TSE-2 and TSE-4). A description of the processing history and mechanical properties of these test cylinders was previously provided.¹ Metallographic examinations were conducted on specimens removed from the test cylinders after the experiments were completed. The examinations made after completion of TSE-1 and TSE-2 were previously recorded.^{1,15} Since that time, additional studies have been conducted on the metallographic specimens from TSE-1.

The intent of this study is to ascertain the mode of fracture that occurred as a consequence of the thermal shock. The metallographic examinations included scanning electron microscopy (SEM) for samples from TSE-1, -3, and -4 and light microscopy examinations of samples from TSE-4.

Test cylinder TSV-1 contained a long axial flaw. The same flaw was used in both TSE-1 and TSE-3. Following TSE-1, three 25-mm-diam (1-in.) cores were removed from the flawed region of the test cylinder. These cores were metallographically examined, and a slight crack extension was noted. Reference 15 describes the examination of these cores. There was some question regarding the mode of the slight crack extension that was found, and this area has been examined more thoroughly following TSE-3. Prior to TSE-3, the core holes were plugged. Following TSE-3, in which the test cylinder was subjected to a more severe thermal shock than in TSE-1, the entire crack region was removed from the cylinder and opened to reveal the fracture surfaces. Samples of the fracture surface were removed from near the central region of the vessel and examined by means of SEM and light microscopy.

The test cylinder used for TSE-2 and TSE-4 had two different flaws 180° apart. In TSE-2, the initial flaw was semicircular with a radius of

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19 mm (0.75 in.), and, as a result of the thermal shock, the flaw extended to a length of ~140 mm. A core containing the entire flaw was removed for metallographic examination, the results of which are discussed in Ref. 1. Prior to TSE-4, the oblong core hole was plugged, and a long axial flaw was generated at a position 180° from the plug. Following TSE-4, which was basically the same experiment as TSE-3, three 25-mm-diam (1-in.) cores were removed from the central portion of the crack zone for examination.

As an aid in understanding the role of SEM in determining the fracture mode during crack propagation, the fracture appearance of Charpy V-notch (C_V) specimens of the same material used in the thermal shock experiments was documented. The C_V data from these tests were previously reported.¹⁶ The specimens were obtained from near the inner wall of the prolongation from one of the thermal shock cylinders. The prolongations had been exposed to exactly the same austenitizing and quench treatment as the cylinders. Further, they were held at 288°C (550°F) for 24 hr to simulate any "temper" that the cylinders would undergo as a consequence of being held at 288°C prior to the thermal shock.

Three tested C_V specimens were selected for this discussion. Specimen identification, test temperatures, and recorded toughnesses are given in Table 6. The specimens represent material behavior that is essentially on the lower shelf (ITS-154), in the transition region (ITS-159), and on the upper shelf (ITS-161). SEM photomicrographs of the fracture surfaces of the C_V specimens at a magnification of 300× are shown in Fig. 38. The

Table 6. Charpy V-notch test specimens used in scanning electron microscopy study of TSE-3 and TSE-4

Specimen identification	Test temperature [°C (°F)]	Charpy V-notch impact energy [J (ft-lb)]
ITS-154	-46 (-50)	11.5 (8.5)
ITS-159	93 (200)	22 (16)
ITS-161	177 (350)	43 (31.5)

	TEST TEMPERATURE [°C (°F)]	ENERGY ABSORBED [J (ft-lb)]
(a)	-46 (-60)	11 (8.5)
(b)	93 (200)	22 (16)
(c)	177 (350)	43 (31.5)

Fig. 38. Scanning electron micrographs of Charpy V-notch specimens tested at the temperatures indicated (magnification 300×). The impact energy absorbed at the test temperature is given. (Original reduced 20.5%)

specimen tested at the highest temperature (ITS-161) exhibits a dimple fracture mode. This mode is indicative of a ductile failure and, indeed, was tested at a temperature on the upper shelf for this material. The other two specimens are somewhat similar in appearance; both contain a predominately cleavage fracture surface with some small regions that failed in a dimple mode. The percent of dimple fracture, although small in both samples, appears to be greater in the specimen tested at 93°C. These SEM photomicrographs will be used for comparative purposes during the discussion of the fractures that occurred in TSE-3 and TSE-4.

8.1 Thermal Shock Experiments TSE-1 and TSE-3

The section of the fracture surface from TSV-1 that was removed for examination following TSE-3 is shown in Fig. 39. Three specimens were removed for SEM examination, and the photomicrographs of the surface (magnification $\sim 2\times$) are shown in Fig. 40. An extensive SEM examination was made of each surface. This examination identified the shallow (~ 2 mm) extension attributed to TSE-1 and revealed that the fracture mode for this narrow region was predominately ductile (dimple structure).

Additional proof regarding the fracture mode for TSE-1 was obtained by examining a cored specimen that had been removed from the test cylinder following TSE-1 and mounted in epoxy for metallographic examination of the crack line. This well-preserved specimen was demounted, and the fracture surfaces exposed by completing the fracture mechanically at cryogenic temperatures. An SEM examination revealed that the extension that took place during TSE-1 was ductile. These recent findings are contrary to SEM observations reported earlier for a different specimen.¹ However, the fracture surfaces examined earlier were partially obscured by a protective film, and a final conclusion was deferred until the recent examinations could be completed.

Figure 41 shows SEM photomicrographs taken at a magnification of $300\times$ of representative areas from specimens TSE-3-1 and TSE-3-2 (see Fig. 40) that correspond to the TSE-3 crack extension. The similarity between the areas is evident, and a third specimen (TSE-3-3), which is not shown, had a fracture appearance nearly identical to the two shown in Fig. 41. The

Fig. 39. Photograph of a section of the fracture surface from TSV-1 following TSE-3 (1 in. = 25.4 mm).

fracture was essentially by the cleavage mode, with a small percentage of the area exhibiting a dimple morphology. These SEM photomicrographs can be compared to those shown in Fig. 38. The similarity between the photomicrographs in Fig. 41 and the C_V specimen fractured at 93°C (Fig. 38b) is evident.

Specimen TSE-3-1 was selected for a more extensive study of the fracture surface. Figure 42 contains SEM photomicrographs of the same region of the fracture surface in the TSE-3-1 specimen shown in Fig. 40. The photomicrographs were taken at progressively higher magnification in order to distinguish the character of the fracture. The fracture is predominately in the cleavage mode; however, there are areas that exhibit what appears to be a dimple mode of fracture. These areas were examined at magnifications as high as 3000 $\times$, and the fact that they do, indeed, contain small regions that exhibit a dimple mode of fracture was substantiated.

8.2 Thermal Shock Experiment TSE-4

Samples of the fracture resulting from TSE-4 were obtained by trepanning three cores from the central region of the fracture (see Fig. 33). The configuration of the core samples is similar to that shown in Fig. 43, which depicts the cores removed following TSE-1 (Refs. 1, 15). The only difference in the appearance of the TSE-4 and TSE-1 cores is the slot

(a) TSE-3-1

(b) TSE-3-2

(c) TSE-3-3

Fig. 40. Photomicrographs of the three surfaces examined by scanning electron microscopy. The specimens were designated TSE-3-1, TSE-3-2, and TSE-3-3 (1 in. = 25.4 mm). (Original reduced 22.5%).

(a) TSE-3-1

(b) TSE-3-2

Fig. 41. Scanning electron micrographs of representative areas of the fracture surface from TSE-3 (magnification 300 $\times$). The fracture is predominately by the cleavage mode with small regions exhibiting a dimple mode of fracture.

PHOTO 3874-77

Fig. 42. Scanning electron micrographs of a representative region of the fracture surface from TSE-3. The micrographs are all taken in the same area of specimen TSE-3-1. The regions in 42a that appear to have fractured in a dimple mode do, indeed, exhibit a ductile fracture appearance at higher magnification. (Original reduced 21%)

Fig. 43. Trepanned core from TSV-1. The cores removed from TSV-2 following TSE-4 are identical except that the machined slot was omitted for TSE-4. The section obtained from the cut along AA was used for light microscopy examinations. Section BB was broken open at -196°C and the surface examined by scanning electron microscopy.

across the top. For TSE-4, a slot was not machined along the length of the inner wall prior to making the EB crack-initiation weld.

One-half of each of the three core specimens was used for light microscopy examination of the fracture (cut along section AA); the remainder of each core was broken along the fracture at -196°C and the surfaces examined by SEM. Photomicrographs showing the crack that was generated during the thermal shock are shown in Fig. 44. They were taken at a magnification of $4\times$ with the sample in the unetched and etched (2% nital) conditions. The cracks in all three cores propagated in an irregular fashion and in this regard are very similar to those observed in connection with TSE-2 (Refs. 1, 15).

Photomicrographs of the fracture surfaces (magnification $2\times$) are shown in Fig. 45. An extensive examination of each surface was made with the scanning electron microscope. As shown in Fig. 45, the fracture modes for each core are quite similar. The fracture is predominately by the cleavage mode with some small percentage of the surface exhibiting a dimple appearance. Figure 46 shows a series of SEM photomicrographs at progressively higher magnification. A region that appeared to contain dimple fracture was specifically selected for the higher magnification photomicrographs. The photomicrographs taken at higher magnification [$300\times$ and $1000\times$ (Figs. 46c and 46d)] confirm the presence of some ductile fracture in a surface exhibiting predominately cleavage-mode fracture.

In the course of the SEM investigation of the fracture in TSE-4, we examined the region just below the electron-beam crack-initiation weld. Figure 47 shows a series of SEM photomicrographs taken of this region at progressively higher magnification ($100\times$, $300\times$, and $1000\times$). These photomicrographs identify a region $\sim 0.5\text{ mm}$ (0.02 in.) deep that failed in the dimple mode. This is the region of the fracture that initially propagated as a consequence of the thermal shock. Beyond this 0.5-mm region, the crack morphology appears to change to that of predominately cleavage mode. This cleavage mode of fracture is shown in Fig. 46.

(a) UNETCHED

(b) ETCHED (2% NITAL)

Fig. 44. Photomicrographs of core TSE-4a (magnification 4x). The crack that resulted from the thermal shock is irregular.

PHOTO 3876-77

Fig. 45. Photomicrographs of the fracture surfaces of the three cores removed from the fracture associated with TSE-4 (1 in. = 25.4 mm).

PHOTO 3877-77

Fig. 46. Scanning electron micrographs, at progressively higher magnification, of an area representative of the fracture surface in core TSE-4c. The surface appears to show evidence of some dimple-mode fracture, an observation that is confirmed at the higher magnification. Figure 46d is a scanning electron micrograph of the area identified in 46a, b, and c. (Original reduced 23.5%)

PHOTO 3878-77

Fig. 47. Scanning electron micrographs of the region just below the electron-beam crack-initiation weld in the TSE-4c core. The electron-beam weld is apparent in Fig. 47a. The region of interest is about 0.5 mm (0.02 in.) in depth and is the area of initial crack extension. (Original reduced 25.5%)

8.3 Discussion and Summary

The investigation of the crack surfaces from TSE-1, -3, and -4 showed the short crack extension in TSE-1 to be by the dimple mode and the fractures in TSE-3 and TSE-4 to be primarily by the cleavage mode. An extensive SEM examination of the region just below the EB weld in TSE-4 showed that there is a narrow band of ductile tearing prior to the onset of the main fracture. This feature of the crack extension in TSE-4 is shown in Fig. 47. The TSE-3 and TSE-4 fractures contained areas, perhaps as large as 10 to 15%, that exhibited a dimple mode of fracture. This distinction between the ductile and cleavage fracture modes is most easily discerned at a magnification of about 300 $\times$.

The fractures that occurred as a consequence of the thermal shock are not "brittle" in the glasslike sense of the word. Rather, the thermal shock fracture is best reproduced in a C_V specimen of material removed from the prolongation of the heat-treated cylinders used in the thermal shock experiments and tested in the transition temperature region ($\sim 93^\circ\text{C}$). A comparison of the SEM photomicrographs taken at 300 $\times$ of the fracture surface of a C_V specimen tested at 93°C (Fig. 38) and the fracture surfaces from TSE-3 and TSE-4 (Figs. 42b and 46c, respectively) illustrates this point. Finally, a comparison of the fracture surface that corresponds to the region of the TSE-3-2 specimen that was broken at -196°C (-320°F) and the fracture surface of the C_V specimen tested at -46°C (-50°F) shows the difference in the amount of dimple-mode fracture. This comparison is made in Fig. 48. A brittle fracture (in the glasslike sense of the word) would exhibit a fracture mode similar to that shown in Fig. 48.

PHOTO 3879-77

Fig. 48. Comparison between the appearance of fracture surfaces generated at two temperatures: (a) -46°C (-50°F) and (b) -196°C (-320°F). Both scanning electron micrographs were taken at a magnification of $1000\times$. The difference in the amount of dimple fracture on each surface is evident.

9. DISCUSSION OF RESULTS

All of the K ratios and other fracture-toughness-dependent numbers reported here for the test specimen material are based on a K_{Ic} curve that represents a best average of the available data for the test specimen material and do not reflect the rather wide scatter band that is usually associated with the transition region. The scatter band for the TSV-1 and TSV-2 test specimens has not yet been established, but a statistical analysis performed in connection with a round robin program¹⁷ indicates a 2 σ band width of about $\pm 43\%$ corresponding to the transition region.

In each of the four thermal shock experiments, the K ratios of interest (either close to unity or maximum values) were associated with fracture toughness values in the transition region and thus must include a rather large uncertainty. Based on nominal values of fracture toughness and the results of TSE-4, it appears that the linear elastic fracture mechanics (LEFM) model used to predict the outcome of TSE-4 is quite accurate. In the case of TSE-1, the maximum K ratio was only 0.74, and thus the accuracy of the method of analysis cannot be established with an accuracy better than 26%. In other words, it is not known what calculated value of the K ratio above 0.74 would be required for unstable crack growth to occur. However, this experiment indicated that, if the K ratio for a long axial crack is 26% below the critical value as it is for the low-copper RCM (typical PWR), crack extension has a low probability of occurring.

To deduce a degree of accuracy from TSE-2 would require an analytical model that could be used to predict the conditions for initiation when the K ratio varies over a wide range along the crack front. No such model has been applied thus far. It was believed that crack initiation would take place during TSE-2 because the maximum K ratio at a point somewhat removed from the surface (one-quarter of the flaw depth) was substantially above unity (1.3). At the time of the first propagation, the calculated K ratio at the surface (making no allowance for lack of restraint at the surface) was 1.4, and that at the bottom of the semicircle was less than 0.5. Nevertheless, the results of this experiment indicate that typical finite-length flaws will not grow to become long cracks in the sense that they

will not extend axially indefinitely and will not propagate radially beyond the initial maximum depth.

Aside from the fact that only one of the thermal shock experiments (TSE-4) permits a precise verification of the method of analysis (LEFM), it is important to note that none of the experiments revealed significant anomalies. Furthermore, since TSE-4 included the unique conditions associated with a severe thermal shock (nearly equal biaxial stresses and steep gradients in toughness and stress-intensity factor that vary with time), the validity of LEFM for application to thermal shock problems can be established with the one type of experiment (TSE-4).

The studies performed at ORNL using LEFM and neglecting warm prestressing indicate that a long axial crack will propagate nearly through the wall of the high-copper PWR vessel after many years of accumulated radiation damage and that a continuous circumferential crack will penetrate 70% of the wall thickness. In the case of an axial flaw, complete penetration might be tolerated because presumably only minor leakage of coolant would result, and cooling of the core would not be impaired. It is also quite likely that reducing the conservatism in the RCM (for instance, by applying a three-dimensional analysis) would result in much less calculated penetration of the flaw, or it might be demonstrated experimentally that the last small amount of relatively tough material (low neutron fluence) could not fracture under any reasonable circumstances.

In the case of a continuous circumferential flaw, deep penetration cannot be tolerated because complete penetration would result in the loss of the bottom portion of the vessel, and thus coolant for the core could not be contained. The RCM for a continuous circumferential flaw does not contain the conservatism associated with a long axial flaw, and thus benefits are not to be derived therefrom. However, it might be argued that long flaws in either direction are highly unlikely, and the results of TSE-2 indicate that the much more probable finite-length flaws will not propagate radially.

The path to acceptance of these concepts and the development of a more realistic three-dimensional model could be long and wearisome. However, the warm-prestressing phenomenon may provide a solution to the LOCA-ECC thermal shock problem. All that remains to be done is an adequate

demonstration under actual or simulated thermal shock conditions, and that effort is under way.

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APPENDIX A

THERMAL-HYDRAULIC EXPERIMENTS FOR INVESTIGATING
DEGREE OF SYMMETRY IN QUENCHING THE 533-~~mm~~-OD
THERMAL SHOCK TEST SPECIMENS

Before the thermal shock experiments were conducted with test specimens TSV-1 and -2, thermal-hydraulic experiments were conducted with an identical test specimen, TSV-F. Thermocouples were included to obtain radial and axial temperature gradients, but since there was no reason to believe that significant circumferential variations in temperature would exist, TSV-F was not adequately instrumented to allow a thorough investigation of the degree of symmetry around the test specimen.

Results from each of the thermal shock and thermal-hydraulic experiments have indicated a significant amount of asymmetry in quenching. The indications were believed to be associated with inaccuracies in measuring surface temperatures during a thermal transient and/or perhaps with a poor design of the inlet flow plenum. Eventually, the design of the plenum was modified, but indications of asymmetry persisted. Finally, the flow-test specimen (TSV-F) was modified to include a set of thermocouples at each 45° position around the test specimen at the horizontal midplane. Each set consisted of three thermocouples located radially 2.5 mm (0.1 in.), 5.1 mm (0.2 in.), and 7.6 mm (0.3 in.) from the inner surface. All thermocouples penetrated the wall from the outer surface.

The proximity of the thermocouples to the inner surface was such that significant changes in temperature and thus significant degrees of quenching asymmetry would be recorded during times of interest in the transient ($t > 10$ sec). Results from tests conducted with the modified flow-test specimen showed no significant signs of quenching asymmetry, and thus all previous indications of asymmetry are attributed to inaccuracies in measuring transient surface temperatures. Since all measured temperature distributions used in connection with the evaluation of the thermal shock experiments (TSE-1, -2, -3, -4) were based primarily on in-wall thermocouple positions, those evaluations are considered to be unaffected by the erroneous indications of asymmetry.

APPENDIX B

INSTRUMENTATION FOR DETECTING CRACK PROPAGATION

B.1 DEVELOPMENT OF IMPROVED COD GAGE INSTALLATION

Weldable strain gages have been used in the thermal shock experiments as event detectors and, in general, were successful in determining the initial onset of crack extension. The gage used is the Ailtech SG-125, which is a quarter-bridge, 120- Ω , self-compensated, hermetically sealed strain gage utilizing a nickel-chrome alloy as a strain filament (see Fig. B-1). The gages were installed on the inside surface of the cylindrical test specimen (in shallow depressions) directly across the EB weld and transverse to the axis in TSE-1 and TSE-3, and were located directly on the specimen inner surface transverse to and in the path of the expected extension of the flaw in TSE-2 (see Ref. 1). They were installed in the normal manner, that is, by an almost continuous spot welding of the mounting flange to the test specimen surface. This technique prevents flutter when the gage is subjected to hydraulic turbulence, but results in a very short effective gage length across the crack itself. Upon crack opening, the local strain in the gage is large enough in some cases to cause failure of the filament, strain tube, and flange, as might be expected.

Since the crack arrest toughness of the test specimen material appears to be considerably less than the static fracture toughness, contrary to

Fig. B-1. Ailtech SG-125 quarter-bridge gage.

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what was expected earlier in the program, there was a need to detect greater crack opening (depth) than previously anticipated. Furthermore, the inclusion of warm-prestressing experiments also required greater COD gage capability. For instance, calculations indicated that fractional flaw depths as great as 30% had to be considered, and the corresponding crack opening at the inner surface was 0.51 mm (0.020 in.). It was expected that the gages would withstand 5% local strain before failure. Thus, an effective gage length of 10.2 mm (0.4 in.) was required.

The effective gage length, and thus the displacement-measuring capability of the gage, can be increased by leaving a central portion of the gage (flange) unbonded to the test specimen surface. Limitations in this regard are associated with the possible flutter problem and the amount of attachment required to prevent spot-weld failure. Tests were conducted to determine if the Ailtech SG-125 could be utilized in the above manner. In the first test, four gages were mounted on a "necked-down" tensile specimen. Spot welding of the flange was omitted for a length of 5 mm (0.2 in.) on two of the gages and for 10 mm (0.4 in.) on two other gages. The unbonded length spanned the necked-down portion of the tensile specimen. (Necking the specimen prevents plastic deformation of the specimen in the spot-weld region.) Under no-load conditions, the specimen was heated slowly by means of an electric furnace to 288°C (550°F) to determine the effects of differential expansion, which put the gage in compression. There were no detrimental effects. Then with the specimen still at a temperature of 288°C, a tensile load was slowly applied. All four gages failed at an indicated strain of ~6% and thus at a local strain in the unbonded region well in excess of 6%. There were no failures of the spot welds.

The potential problem of flutter in the gage as a result of fluid impingement against the unbonded portion of the flange was investigated in a flow test, using the flow test specimen (TSV-F). Three gages with an unbonded length of 10 mm (0.4 in.) were installed in the flow test specimen, two directly on the inner surface and one in a slight depression. All were placed normal to the direction of flow. No detrimental effects were encountered in the flow test, and the technique subsequently was used for TSE-4, in which case five gages were mounted directly on the inner surface.

No failures occurred even though there was considerable crack extension. In a similar experiment (TSE-3), in which the total-attachment mounting technique was used, four of the five gages failed.

B.2 ACOUSTIC EMISSION

Southwest Research Institute (SwRI) was contracted to install and operate acoustic-emission equipment for TSE-1, -2, -3, and -4 and to analyze the data obtained from these experiments. At the request of the Nuclear Regulatory Commission (NRC), Battelle Pacific Northwest Laboratories (BNW) made independent acoustic-emission measurements during TSE-4. Final reports submitted by SwRI for TSE-3 and TSE-4 and by BNW for TSE-4 are included as a part of this appendix.

In all cases, the acoustic-emission transducer assembly consisted of a transducer attached to the outboard end of a 3.2-mm-diam (0.13-in.) steel waveguide that penetrated the test facility furnace with the inboard end spring loaded against the outer surface of the thermal shock test specimen. For TSE-1 and TSE-2, SwRI used four of these assemblies, located as shown in Fig. B-2 (positions a, b, c, and d), and for TSE-3 and TSE-4, only positions a, b, and c were used. BNW used positions d and e.

Fig. B-2. Developed view of outer surface of test specimen showing locations of contact points for acoustic-emission waveguides for TSE-1, -2, -3, and -4.

SOUTHWEST RESEARCH INSTITUTE

8500 CULEBRA ROAD • POST OFFICE DRAWER 20510 • SAN ANTONIO, TEXAS 78204

QUALITY ASSURANCE PROGRAM
AND ENGINEERING DESIGN

August 24, 1976

RECEIVED
AUG 30 1976

Mr. R. D. Cheverton
Oak Ridge National Laboratory
Post Office Box Y
Oak Ridge, Tennessee 37830

Subject: Southwest Research Institute Projects 17-9165-002 and 17-4400-019
Trip Report Number 1/76

Enclosed is a copy of my preliminary trip report on the acoustic emission data from the Thermal Shock Test and the Notched Beam Test conducted at Oak Ridge National Laboratory on August 4, 1976. I will make a follow-up report after we receive your data from these tests.

Very truly yours,

Don Jolly
AE Group
R&D Section

cl
Encls.

SAN ANTONIO, HOUSTON, CORPUS CHRISTI, TEXAS, AND WASHINGTON, D.C.

SOUTHWEST RESEARCH INSTITUTE

8500 CULEBRA ROAD • POST OFFICE DRAWER 1610 • SAN ANTONIO TEXAS 78284

QUALITY ASSURANCE SYSTEM
AND PROJECTING DIVISION

August 23, 1976

TRIP REPORT NUMBER 1/76

Southwest Research Institute Projects 17-9165-002 (labor)
17-4400-019 (travel expense)

SPONSOR: Southwest Research Institute and
Union Carbide Corp. jointly

TRIP TO: Oak Ridge National Laboratory
Oak Ridge, Tennessee

DATES: August 2 - 5, 1976

BY: Don Jolly
Acoustic Emission Systems Specialist

H. L. Jacoby
Senior Technician

**PURPOSE
OF TRIP:** Acoustic Emission Monitoring of a Thermal
Shock Test

**PERSONNEL
CONTACTED:** Union Carbide Corp. - Oak Ridge, Tennessee
R. D. Cheverton

SUMMARY: This trip to Oak Ridge National Laboratory (ORNL) was made for the purpose of collecting acoustic emission (AE) data in a Thermal Shock Test and a Notched Beam Test in support of the continuing Heavy Section Technology Program.

AE data from the Thermal Shock Test appeared to indicate that discontinuous crack growth followed the propagation of thermal stresses through the cylindrical specimen.

AE data from the Notched Beam Test indicated that sub-critical crack growth increased in growth rate until unstable crack growth occurred.

SAN ANTONIO, HOUSTON, DALLAS, AUSTIN, EL PASO, TEXAS AND BIRMINGHAM, ALABAMA

Trip Report Number 1-7
Southwest Research Projects 17-4165-002 and 17-4400-019

SUMMARY:
(continued)

The AE data discussed in this Trip Report has not been correlated with other test parameters which were recorded by ORNL personnel. The purpose of this report is to transmit the AE data to ORNL.

It is anticipated that a preliminary report of other recorded test data will be received from ORNL in the near future. The analysis of AE data will be completed at that time and a follow-up report will be issued.

Trip Report Number 1/76
Southwest Research Institute Project 17-9165-002 and 17-4400-019
Page Three

I. THERMAL SHOCK TEST

The Thermal Shock Test was performed on a flawed cylindrical specimen of A508 forging steel; 36 in. long, 5.75-in. wall thickness, and 9.5-in. inside diameter. The specimen was cooled from 550 deg F by introduction of coolant (-10 deg F) at 500 gal./min. The specimen contained a full length flaw approximately 0.5 in. deep on the inside diameter.

Acoustic emission (AE) activity was recorded on a two-pen strip chart recorder and real-time source location data were observed on a FLIC-3 display.

Because of the coolant flow noise, only high-intensity, burst-type AEs resulting from crack growth were observed. Sheet 1 (AE Rate - %/10 sec-) of the attached data sheets shows that rapid crack growth started approximately 50 sec after continuous coolant flow was established. Rapid crack growth proceeded discontinuously in five discrete periods of growth/arrest for approximately 200 sec after initiation. Sheet 2 (Relative Crack Growth) shows the relative extent of crack growth in each discrete crack step. The crack growth rate appears to decrease linearly with time from the initial crack step.

It appears that the initiated crack advanced rapidly beyond the zone of maximum thermal stress and arrested only to be initiated again as the zone of maximum thermal stress (decreasing in intensity) progressed through the specimen.

A graph of the cumulative AE activity is shown on Sheet 3. Where it is known that the AEs recorded were caused by discontinuous crack growth, the graph of cumulative AE activity is expected to be proportional to the total area of crack extension.

The FLIC-3 flaw locating and imaging computer was used to record the location of AE events along the length of the crack. Due to rapidly changing coolant flow noise, the source location computer was saturated during the first two periods of rapid crack growth. Accurate source locations were observed during the subsequent periods of rapid growth (105 to 260 sec after continuous flow was established). A total of 10 to 12 high intensity events were observed in the central one-third of the crack length during this time. An unexpected increase in flow noise saturated the display screen again after rapid crack growth had stopped and before a photographic record was made of the source location display.

Trip Report Number 1/76
Southwest Research Institute Projects 17-9165-002 and 17-4400-019
Page Four

The observed real-time source location data were sufficient, however, to demonstrate that the high-intensity events originated from the longitudinal crack and were not spurious noise.

II. NOTCHED BEAM TEST

AE data were recorded from a notched beam (30x6x6 in.) loaded in three-point bending. The notched beam contained a starter crack in the root of the notch (approximately 0.5 in. depth). The crack was made by an electron beam welding procedure designed so that residual stress remained at the crack tip after cooling.

The shape of the specimen prevented direct two-dimensional triangulation of the AE signals, but it was possible to calibrate the FLIC-3 display so that AE signals from the crack could be distinguished from the AE signals originating at the center bearing point.

Photographic records of the AE data are shown on Sheet 4 (AE Location Data). AE signals from the center bearing point are displayed in a vertical line near the display center while AE signals from the crack are displayed in the encircled areas above and below the display center. The number of triangulated events from the crack increased as the load increased. The rate of AE activity is plotted as a function of load on Sheet 5. The recorded activity is composed of burst-type AE associated with stepwise crack growth. The graph of Sheet 5 illustrates patterns of step-arrest associated with subcritical crack growth. The rate of growth increased discontinuously up to the point of unstable crack growth at approximately 77,000 lb. The cumulative AE as a function of load shown on Sheet 6 is expected to be proportioned to the area of subcritical crack growth.

III. CONCLUSIONS

The AE data described in this Trip Report must be correlated with other test parameters such as thermal stress, crack opening displacement, and strain before definite conclusions can be drawn.

Don Jolly
AE Group
R&D Section

Approved by:

cl

RESEARCH INSTITUTE SHEET NO. 2 OF 6 SHEETS
 DATA SHEET PROJECT 17-245-CC-2
 THERMAL SHOCK TEST DATE AUG 4, 1976
 TEST RATE - 70/10 SEC BY WD Jolly

SCOUT

SUBJECT: [illegible]

RELATIVE [illegible]

DATE: [illegible]

TIME: [illegible]

[illegible]

[illegible]

SDC EST RESEARCH INSTITUTE
DATA SHEET

SUBJECT INTERNAL SHOCK TEST
AE - CUMULATIVE -

SHEET

PROJECT

DATE Aug 4 - 70

BY W.D. Tally

**SOUTHWEST RESEARCH INSTITUTE
DATA SHEET**

SUBJECT MODIFIED BEAM TEST
RE LOCATION DATA

SHEET NO 4 OF 6 SHEETS
PROJECT 17-322-002
DATE AUG - 97
BY WJ JERRY

THE MARKS ENCIRCLED
REPRESENT LOCATION WHERE
THE ORIGIN SCALY SHOULD
BE DISPLAYED.

LOAD RANGE 0-20K 15.

LOAD RANGE 0-40K 16.

LOAD RANGE 40-60K 17.

LOAD RANGE 60-77K 18.
INITIAL RANGE AT
17K 18.

SOUTHWEST RESEARCH INSTITUTE DATA SHEET

SUBJECT RESIDUAL STRESS TEST
OF CONCRETE BEAMS - 3 POINT BENDING

SHEET

PROJECT

DATE 5/4/72BY M. D. JOLLY

PC-4
(5mR.7)

SOUTHWEST RESE

SHEETS

DATE 5 1961

SUBJECT RESIDUAL STRESS TEST - F

30x6x6 BEAM - 3 POINT BENDING

CITY

PC 4
(Rev. 7)

SOUTHWEST RESEARCH INSTITUTE

8500 CULEBRA ROAD - POST OFFICE DRAWER 2810 - SAN ANTONIO, TEXAS 78228

QUALITY REQUIREMENTS SYSTEM
INDUSTRIAL MEDICAL DIVISION

March 1, 1977

TRIP REPORT NUMBER 1/77

Southwest Research Institute Projects 17-9165-002 (labor)

17-4400-019 (travel expenses)

SPONSOR: Southwest Research Institute and
Union Carbide Corp. jointly

TRIP TO: Oak Ridge National Laboratory
Oak Ridge, Tennessee

DATES: January 18 - 21, 1977

BY: H. L. Jacoby
Senior Technician

**PURPOSE
OF TRIP:** Acoustic Emission Monitoring of Thermal Shock
Test Number 4 (TSE-4)

**PERSONNEL
CONTACTED:** Union Carbide Corp. - Oak Ridge, Tennessee

R. D. Cheverton

SAN ANTONIO, HOUSTON, CORPUS CHRISTI, TEXAS, AND WASHINGTON, D.C.

Trip Report Number 1/77

Southwest Research Institute Projects 17-9165-002 and 17-4400-016

Page Two

1.0 SCOPE

- 1.1 A trip was made to Oak Ridge National Laboratory to collect acoustic emission (AE) data during a thermal shock test (TSE-4) and a notched-beam test in support of the Heavy Section Steel Technology Program.

2.0 THERMAL SHOCK TEST

2.1 Test and Specimen Description

The thermal shock test was performed on a flawed, cylindrical specimen of A508 forging steel, 91.44 cm long, 14.6-cm wall thickness, 24.11-cm inside diameter, and 167.6 cm in circumference. The specimen contained a flaw along its length consisting of an electron beam (EB) weld used as a crack starter. For the test, the specimen was cooled from 550 deg F by introduction of coolant at a temperature of -10 deg F at 500 gal/min.

2.2 Equipment Description

AE signals during the test were coupled to the sensors by three, 38-cm long, pointed steel waveguides which were pressure coupled to the vessel surface. The three waveguides were located so as to form a triangle enclosing the flaw area. (See Figure 1.) Attached to the outer ends of the waveguides were 27-mm diameter sensors. As shown in Figure 2, the outputs of the sensors were connected to Southwest Research Institute (SwRI) Model 82077 preamps, having a gain of approximately 35 dB at 500 kHz. The amplified AE signals from the preamps were connected to an SwRI Flaw Locating and Imaging Computer (FLIC-3). The FLIC-3 amplifies the AE signals (up to 40 dB), and an envelope detector presents a video output for strip chart recording and for threshold detection in the computer section. The computer section performs time difference (Δt) measurement and computes the origin of AE signals. The computed origin is then displayed on the cathode ray tube (CRT) screen momentarily, showing the spatial relationship to the sensor locations already displayed on the CRT screen. The CRT is a storage type which enables the computed locations (dots) to be stored for a long period of time.

Trip Report Number 1777

Southwest Research Institute Projects 17-9165-002 and 17-4400-01-

Page Three

In conjunction with the stored hits on the CRT, a video tape recording was made of the CRT face so that individual signals could be reviewed later in stop-motion video records. A chronometer was also included in the video taped display to provide time of occurrence of individual AE locations. As the AE locations were recorded, they presented brighter dots than surrounding stored locations.

The video output of Channel B from the FLIC-3 was recorded on one channel of a two-channel strip chart recorder. The other channel of the strip chart recorded the accumulated count of AE events within a spatial window area. The window area of the FLIC-3 display, as shown in Figure 3, was sized and positioned to accumulate AE locations in an area which included the expected flaw location. The "window count" is an analog voltage which is proportional to the number of AE event locations within the window area. In addition, the strip chart record has 1-sec interval event marks for correlation of individual AE locations between the strip chart and the video taped CRT display.

Prior to the experiment, an AE system calibration was performed. A simulated AE pulse was introduced at several points along the surface of the vessel, near the flaw line. The computed locations are shown in Figure 4.

2.3 Test Data (TSE-4)

For the discussion of the actual test, it will be necessary to refer to Figures 5A through 5F, which are copies of the strip chart recording made during TSE-4 from T_0 (valve opened) to +240 sec.

During the initial part of the test (Figure 5A), there was a very high background noise level. At +33 sec the strip chart recording of the video output was changed from 2 mV/div to 10 mV/div in order to see the crests of the noise signals. At +41 and +47 sec low-level AE bursts were recorded. It was not possible to locate these signals because the background noise level was above the 0.1 V threshold of the FLIC-3 4:1 measurement section. It is believed these signals were insignificant because of their relatively low amplitude. At +60 sec (Figure 5B) the attenuation on the FLIC-3 was increased to -46 dB to enable the 4:1 section to perform locations.

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Southwest Research Institute Projects 17-0165-002 and 17-4400-014

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At +64 sec the first large burst-type emissions occurred which appeared to coincide with crack initiation. This signal has been labeled as well-defined Event 1. The term "well defined" designates AE events that could be located with absolute certainty on both the strip chart and the CRT display. Therefore, the burst-type AE signals, after Event 1, from +64 to +76 sec, represented as high-amplitude spikes on the strip chart, have not been assigned locations because they occurred during a period of noise which prevented a precise correlation of time and position.

At +88 sec another well-defined event occurred which located within 2 cm of Event 1. At +90 sec the attenuation of the FLIC-3 was increased to -52 dB. This setting was found to be too low. At +100 sec (Figure 5C) the attenuation was decreased to -40 dB. By this time, the background noise had subsided substantially.

At +150 sec (Figure 5D) there was a high-amplitude burst which located about 7 cm below Event 2. At +151 sec a low-amplitude series of bursts occurred (Events 3 and 4). At +160 sec a series of bursts occurred over a period of 18 sec (Events 5 through 8). These signals ranged from medium to low amplitudes. Some of the signals were not of sufficient amplitude to exceed the threshold and show locations. At +175 sec a medium amplitude burst occurred (Event 9) in the same area as previous bursts in the lower portion of the central one-third of the EB weld line.

At +240 sec (see Figure 5F) a medium amplitude burst (Event 10) occurred adjacent to Events 5, 6, and 9. This was the last signal of sufficient amplitude to be recorded. Data recording ceased after a period of 15 min from T_0 .

2.4 Test Summary

The AE instrument data show that large increment crack growth occurred in the period from +64 sec to +151 sec. The period from +152 sec to +240 sec is characterized as intermittent, small-step crack growth. The spatial location, with reference to the waveguide contact points, of the well-defined AE events is presented in Figure 6.

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Southwest Research Institute Projects 17-9185-002 and 17-4400-018

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2.5 Conclusions

AE data from the thermal shock test indicated crack growth along a portion of the EB weld. The principle sources of AE appeared to be approximately 10 cm either side of a line describing the midpoint of the weld path. Crack initiation appeared to occur 64 sec after thermal shock started. Recordable AE activity ceased at 240 sec after thermal shock started.

3.0 NOTCHED-BEAM TEST

3.1 Test and Specimen Description

AE data were recorded from a notched beam in three-point bending. The beam dimensions were 76.5 cm long, 10.1 cm wide, and 15.2 cm thick. The notched beam contained a starter crack in the root of the notch as illustrated in Figure 7. The crack was made by an EB welding procedure designed so that residual stress remained at the crack tip.

3.2 Equipment Description

The AE instrumentation was the same as used for the TSE-4 (see Figure 2) with the exception of the sensors. The sensors used were standard SwRI manufacture, magnetic mount AE sensors using point contact, pressure coupling. (See Figure 7 for sensor placement on the specimen.)

The shape of the specimen prevented direct two-dimensional triangulation of the AE signals, but it was possible to calibrate the FLIC-3 display, as illustrated in Figure 8, so that AE signals from the crack could be distinguished from AE signals originating at the center bearing point.

Prior to the test, sensitivity and location surveys were made using a new AE source simulator. The simulation was accomplished by breaking a 1.5-mm extension of 0.3-mm pencil lead from a mechanical pencil. The pencil lead was placed on the surface at a 45-deg angle, and pressure was applied until the pencil lead fractured. This method provided a highly repeatable, fast-rise, AE signal simulation.

Using the AE simulator, channel sensitivities were equalized, and it was determined that signals originating from the notch

Trip Report Number 1/77

Southwest Research Institute Projects 17-9165-002 and 17-4400-014

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would be displaced from signals originating from the loading mechanism. (See Figure 9.) During the entire test, signal gains for each channel were as follows: Channel A, 56 dB; Channel B, 54 dB; and Channel C, 54 dB.

3.3 Test Data

During the test, the load was increased smoothly from 0 (zero) to 86,000 lbs. Fast fracture occurred at 86,000 lbs' load. At the conclusion of the tests a photograph, shown in Figure 10, was made of the FLIC-3 CRT display with the stored AE source locations. A plot of load versus accumulated AE event count is presented in Figure 11.

3.4 Test Summary

In summary, the AE event rate increased at 35,000 lbs and again at 65,000 lbs' load. A rapid increase in rate after 85,000 lbs' load indicated fast fracture. All AE events recorded on the CRT display could be correlated in time with AE events recorded on the strip chart. Most of the signals came from one end of the EB weld area as illustrated by Figure 10.

3.5 Conclusions

AE data from the notched-beam test indicated that subcritical crack growth probably started at 65,000 lbs' load and increased in rate until unstable crack growth occurred at 86,000 lbs' load.

4.0 CONCLUSIONS

- 4.1 The FLIC-3 by triangulating and storing AE events in real time demonstrated the ability to determine crack initiation and growth while the tests are in progress. The "window" analog output also furnishes an immediate indication of AE activity rate during tests.

The use of a video camera, recorder, and monitor to correlate data presented on the strip chart recording further enhances the use of the FLIC-3 by providing an extensive post-test data analysis technique.

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Southwest Research Institute Projects 17-9185-002 and 17-4400-01
Page Seven

5.0 RECOMMENDATIONS

- 5.1 In subsequent thermal shock tests to be conducted, it is recommended that initial attenuator settings of the FLIC-3 be at least 52 dB.

It is further recommended that the video recording of the FLIC-3 CRT display be used. This proved to be a valuable aid in post-test analysis of data.

For three-point beam loading tests it is recommended that the FLIC-3 be used because of its ability to separate noise from the center load point (directly opposite the crack starter notch) and valid AE events from the growing crack.

Harper L. Jacoby
Senior Technician
AE Group

Approved by:

cl

FIGURE 1. DEVELOPED SURFACE OF TSE-4 VESSEL SHOWING POSITION OF AE SENSORS AND EB WELD FLAW.

SONY CAMERA USED TO RECORD
REAL TIME DISPLAY OF FLIC-3

FIGURE 2. BLOCK DIAGRAM OF AE EQUIPMENT USED ON TSE-4.

WINDOW
AE events in this
area are also re-
lated in context.

FIGURE 3. AE EVENTS DURING WAVEGUIDE SOURCE LOCATIONS
AND WINDOW USED ON CHANNEL 4.
10/1/84

CORRELATION
Used to correlate
videotaped AE C-3
display with strip
chart record.

FIGURE 4. STORED AE SOURCE LOCATIONS USING WAVE-
GUIDE PROBE AT VARIOUS POINTS ALONG
INSULATION CABLE.

FIGURE 5A. STRIP CHART RECORD OF AE DATA DURING TSE-4.

FIGURE 5B. STRIP CHART RECORD OF AE DATA DURING TSE-4.

FIGURE 5C. STRIP CHART RECORD OF AE DATA DURING TSE-4.

FIGURE 5D. STRIP CHART RECORD OF AE DATA DURING TSE-4.

FIGURE 5E. STRIP CHART RECORD OF AE DATA DURING TSE-4.

FIGURE 5F. STRIP CHART RECORD OF AG DATA DURING TSE-4.

1	64 sec
2	88 sec
3	150 sec
4	151 sec
5	161 sec
6	165 sec
7	166 sec
8	166 sec
9	175 sec
10	240 sec

FIGURE 6. LOCATION OF AE EVENTS CORRELATED WITH STRIP CHART RECORD OF TSE-4.

FIGURE 7. NOTCHED-BEAM SPECIMEN ILLUSTRATING POSITION OF STARTER CRACK AND AE SENSORS.

FIGURE 8. FLC-3 SETUP USED ON THREE-POINT BEAM LOADING SPECIMEN. WINDOW AREA USED FOR ACCUMULATED AE COUNT. 10 cm/div on display

FIGURE 9. STORED LOCATIONS USING MECHANICAL PENCIL LEAD BREAK AT OUTER SURFACE OF NOTCH TIP AND POINT OF CONTACT ON LOADING BAR.

FIGURE 10. CRACKED LOCATIONS AT COMPLETION OF
CAM TEST.

FIGURE 11. ACCUMULATIVE AE EVENT COUNT VERSUS LOAD FROM THE THREE-POINT BEAM SPECIMEN.

ACCUMULATIVE AE EVENT COUNT

1/31/77 Kc: SEBolt
GDWhitman
RDC

Pacific Northwest Laboratories
Battelle Boulevard
Richland, Washington 99352
Telephone 509 946-2157
Telex 12645

January 26, 1977

Mr. R. D. Cheverton
Oak Ridge National Laboratory
P. O. Box Y
Oak Ridge, Tennessee 37830

Dear Dick:

ACOUSTIC EMISSION-HSST THERMAL SHOCK TEST - OAK RIDGE 1/19/77

As part of an acoustic emission (AE) characterization research program which we are performing for the Nuclear Regulatory Commission (NRC) we are required to obtain AE data from HSST tests. The subject test was the first of these since initiation of NRC program. The purpose of this letter report is to summarize our participation in the subject test.

SUMMARY

AE data was detected and observed with the BAW digital monitor system during the thermal shock test, however a record of the data was not obtained due to one faulty sensing point. Observed periods of AE activity were identified and reported on a time scale relative to start of coolant injection. These appear to correlate with periods of expected crack activity. Output from one COD gauge was satisfactorily recorded. Coolant flow noise was not a problem to the BAW system.

These efforts were supported by excellent cooperation from staff members at Oak Ridge.

DISCUSSION

J. F. Dawson, Test Technician, and I visited Oak Ridge 1/11/77 to preview the test arrangement. Subsequently, Mr. Dawson and J. R. Skorpik, Electronic Engineer, returned to Oak Ridge 1/18/77 to install AE instrumentation and monitor the test. Two criteria we imposed were:

- Our participation could not in any way interfere with the basic test.
- Our instrument system could not compromise AE monitoring by Southwest Research Institute (SWRI) who were monitoring this test as they had done on previous similar tests.

Mr. R. D. Cheverton
January 26, 1977
Page 2

The BNW AE monitor system consisted of:

- Sensors - two 1/8" dia. x 15" lng. carbon steel pressure coupled wave guides with 2 MHz cut PZT-5 crystals mounted on the outer end.
- Preamplifiers - 400 KHZ high pass with 48 dB amplification.
- Main Amplifier - 400 KHZ high pass with 16 dB amplification.
- Analyzer - BNW digital memory monitor with capability to analyze and record four AE parameters (count, energy, rise time and signal amplitude) plus one mechanical parameter (COD gauge voltage). Threshold set to monitor signals >1.5 volts peak.
- Source Isolator - analyzes difference in time of signal arrival (Δt) at the two sensors and limits acceptable data to that falling within a preselected range of Δt . This effectively restricts accepted data to that originating within a preselected area of the specimen.

Figure 1 shows a sketch of the test arrangement relative to AE monitoring. Points A, B, C, & D were sleeves installed through the heater jacket to allow mounting metal wave guide AE sensors. Point E was a supplemental wave guide mounting fixture installed by Oak Ridge personnel. Point E' is the ultimate location of the point E fixture as discussed later. BNW was assigned points D & E to allow use of AE source isolation to restrict accepted data to that originating from the flaw line.

The BNW AE monitor system was installed on 1/18/77 with wave guides inserted at points D & E. The system checked out satisfactorily in all respects. SWRI installed their AE monitor in the afternoon of 1/19/77 using points A, B, & C. It was discovered mid-afternoon that they required points A, C, D to achieve source location on AE from the flaw. It was thus necessary to move the BNW sensors to points B and E'. By the time this was completed, start of the thermal shock test was imminent. Sensitivity on point E' was poor but there was no time remaining to make adjustments. The net result was that point B showed good response during the test but point E' was so insensitive that it did not provide the source isolator with a second input required to validate AE signals from the flaw area. Hence, no AE data was programmed into the memories. Data from the center COD gauge being monitored was independent of source isolation and it was programmed into memory. The printout of that information is given in Figure 2-A, B, & C.

Mr. R. D. Cheverton
January 26, 1977
Page 3

Visual observations were made of the point B sensor output on an oscilloscope. These observations are correlated with the COD gauge data in Figure 2. By 90 seconds after opening of the coolant valve, the hydraulic noise had subsided below the 1.5 Volt peak threshold setting on the monitor. Noise signal amplitude was estimated to be about 1.8 to 1.9 volts peak during the first 90 seconds. A technique for adjusting sensor system impedance proved to be quite effective in suppressing hydraulic noise below 400 KHZ. Three major AE activity areas were observed on the oscilloscope monitoring the "B" sensor output. These occurred at 154, 224, and 235 seconds after the coolant valve was opened.

It is still not clear why the E' sensing point was so ineffective. Examination of the wave guide showed evidence that it may have slipped past a set screw holding a mounting collar in place. Also, the springs on the mounting fixture that provided coupling force to the wave guide were fully compressed when the wave guide was installed. If the wave guide did slip in the collar, the springs fully compressed in this particular fixture would have been unable to compensate. Post test examination confirmed that the wave guide through some cause was not in contact with the vessel wall.

There were several positive results from this test even though recorded AE data was not obtained.

- Observed AE appears to agree well with predicted crack growth sequence.
- Adjusting the sensing system impedance proved to be effective in overcoming the hydraulic noise interference problem.
- The wave guide configuration used is basically an effective method for sensing AE from a high temperature surface.
- The digital memory system recorded information from the COD gauge as expected.

Cooperation and assistance provided by the staff at Oak Ridge was outstanding. We appreciate this very much.

Yours very truly,

P. H. Hutton
Senior Development Engineer
Nondestructive Testing

PHH:jmb

cc: J. Muscara (NRC)

Figure 1 Sketch of AE Monitoring Arrangement for Thermal Shock Test

Figure 2-B COD Gauge Data

APPENDIX C

THERMAL AND FRACTURE MECHANICS DATA
PERTAINING TO TSE-3 AND TSE-4

Following each thermal shock experiment, fracture mechanics calculations were made using the temperatures measured during the experiment and the static fracture toughness curve in Fig. 6. Tabulated radial temperature distributions and all of the fracture mechanics data are included in the enclosed sets of computer output for TSE-3 and TSE-4.

TSL-3 EXP 8/6/7c TIME 2240=17.55-16

[illegible]

CASH		
THIRD PAID US	10	0.750
FOUR PAID US	10	10.500
SIX PAID US	10	0.00

2007-10-12 14:00:00 55504

INTERNAL AND SAME IN PS-1 - 100

WATER-14 PROPERTIES		
MODULUS OF ELASTICITY	E	= 2.9E+06
POISSON'S RATIO	NU	= 0.300
COEFFICIENT OF EXPANSION	ALTA	= 7E-06
SPECIFIC HEAT	CP	= 1.7E+01
DENSITY	DEN	= 0.284

INTERNAL MESSAGE CODING CONDITION MAP

- = 0 NO INTERNAL MESSAGE
- = 1 INT-MESSAGE OPEN ENDS
- = 2 INT-MESSAGE CLOSED ENDS

MAP = 0

[illegible]

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MISCELLANEOUS PARAMETERS USED IN THIS VERSION
BASE FLUENCE 1710 = 4614
COORDINATE IN THERM 30 = 40 DEGREE FH
DATE ON CURVES FOR CURETHERM *** 10-20-79
DATE ON EXPRESSIONS FOR TOL (EQUATION 42584) *** 8-12-79
DATE ON EXPRESSION FOR TOL 1 *** 7-21-79
NUMBER OF DATA POINTS TO BE PROCESSED NOW = 1
DATA VALUES = 1.000
NUMBER OF CRACK DEPTHS TO BE PROCESSED NOW = 10
CRACK DEPTH VALUES = 0-0 0-152 0-321 0-434 0-589 0-863 1-180 1-732 2-580 3-875

```

000 WALL THICKNESS --- 0.7 INCHES

NUMBER OF GIRD POINTS = 12
NUMBER OF THE INSIDE WALL GIRD POINT = 1

ON-IC GEOMETRY OVER CYLINDER WALL

SEA NO.	GRAD NO.	GRADUS	INCLEMENT
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1	1	9-7500	0-0
2	2	9-0375	207-50-03
3	3	9-3250	207-50-03
4	4	9-9000	975-00-03
5	5	9-7500	975-00-03
6	6	7-0500	975-00-03
7	7	7-0250	975-00-03
8	8	8-2000	975-00-03
9	9	9-7750	975-00-03
10	10	9-3500	975-00-03
11	11	9-9250	975-00-03
12	12	10-5000	975-00-03

43. SUBMITTED NRC VALUES FOR RECTYPING 434-10-7044 47 CTS ONTR

1	-300.	27.
2	-250.	28.
3	-200.	30.
4	-150.	32.
5	-100.	30.
6	-50.	31.
7	0.	38.
8	50.	57.
9	100.	68.
10	150.	80.
11	200.	113.
12	250.	227.5.

TEMPERATURE INTERVAL NUMBER = 11 TIME = 3.33333E-01 MINUTES

SEMI NO. RADIUS DEPTH UELTAN/0 TEMPERATURE AS QUENCHED
INCHES INCHES

1	0.7500	0.0	0.0	0.0	4800	190000
2	0.7500	0.0	0.0	0.0	4800	220000
3	0.7500	0.0	0.0	0.0	4800	220000
4	0.7500	0.0	0.0	0.0	4800	220000
5	0.7500	0.0	0.0	0.0	4800	220000
6	0.7500	0.0	0.0	0.0	4800	220000
7	0.7500	0.0	0.0	0.0	4800	220000
8	0.7500	0.0	0.0	0.0	4800	220000
9	0.7500	0.0	0.0	0.0	4800	220000
10	0.7500	0.0	0.0	0.0	4800	220000
11	0.7500	0.0	0.0	0.0	4800	220000
12	0.7500	0.0	0.0	0.0	4800	220000

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

TOTAL HEAT LOST UP TO & INCLUDING THIS TIME INTERVAL = 7.16543300E-01 BTU PER AXIAL INCH OF CYLINDER

P.C. VALUES READ IN FOR TIME INTERVAL NO. = 1
0.0 30.06 40.77 35.06 32.01 20.70 22.77 19.00 11.00 0.73 0.0 0.0

TEMPERATURE INTERVAL NUMBER = 11 TIME = 3.33333E-01 MINUTES

STRESS INTENSITY CALCULATIONS FOR A LENGTH, LENGTH, STRESSES AT SURFACE = 70500,
SEMI NO. RADIUS DEPTH UELTAN/0 TEMPERATURE AS QUENCHED
INCHES INCHES

1	0.7500	0.0	0.0	0.0	4800	190000
2	0.7500	0.0	0.0	0.0	4800	220000
3	0.7500	0.0	0.0	0.0	4800	220000
4	0.7500	0.0	0.0	0.0	4800	220000
5	0.7500	0.0	0.0	0.0	4800	220000
6	0.7500	0.0	0.0	0.0	4800	220000
7	0.7500	0.0	0.0	0.0	4800	220000
8	0.7500	0.0	0.0	0.0	4800	220000
9	0.7500	0.0	0.0	0.0	4800	220000
10	0.7500	0.0	0.0	0.0	4800	220000

1	0.7500	0.0	0.0	0.0	4800	190000
2	0.7500	0.0	0.0	0.0	4800	220000
3	0.7500	0.0	0.0	0.0	4800	220000
4	0.7500	0.0	0.0	0.0	4800	220000
5	0.7500	0.0	0.0	0.0	4800	220000
6	0.7500	0.0	0.0	0.0	4800	220000
7	0.7500	0.0	0.0	0.0	4800	220000
8	0.7500	0.0	0.0	0.0	4800	220000
9	0.7500	0.0	0.0	0.0	4800	220000
10	0.7500	0.0	0.0	0.0	4800	220000

TEMPERATURE INTERVAL NUMBER = 2, TIME = 0.0070-01 MINUTES

ORIG NO. RADIUS DELTA R UELTAH/B TEMPERATURE AS QUENCHED
INCHES DEGR/FAH R/C

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1	0.7500	0.0	0.0	100.0	00000
2	0.0375	0.0075	0.0000	315.0	00000
3	0.0350	0.0750	0.1000	000.0	00000
4	0.0000	1.1500	0.0000	000.0	00000
5	0.0750	1.7250	0.3000	500.0	00000
6	0.0000	2.3000	0.0000	557.0	00000
7	0.0250	2.8750	0.0000	500.0	00000
8	0.0000	3.4500	0.0000	550.0	00000
9	0.0750	4.0250	0.7000	555.0	00000
10	0.0000	4.6000	0.0000	550.0	00000
11	0.0250	5.1750	0.0000	500.0	00000
12	0.0000	5.7500	1.0000	500.0	00000

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

TOTAL HEAT LOSS UP TO & INCLUDING THIS TIME INTERVAL = 220050002 BTU PER AIAL INCH OF CYLINDER

P.D. VALUES READ IN FOR TIME INTERVAL NO. = 2
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0

TEMPERATURE INTERVAL NUMBER = 2, TIME = 0.0070-01 MINUTES

STRESS INTENSITY CALCULATIONS FOR A LENGTH, GAUGE, STRESSES AT SURFACE = 00019,
SEC RADIUS TEMPER. TANGENT, AS QUENCHED
NO. IN. O. IN. STRESS PSI R/C R/C

.....

1	0.750	0.0	100.0	00019	00000	0.0
2	0.000	0.000	0.000	57000	00000	0.000
3	0.001	0.031	0.050	71000	00000	0.000
4	0.000	0.000	0.000	30010	00000	0.000
5	0.000	0.000	0.000	00000	00000	0.000
6	0.000	0.000	0.000	00000	00000	0.000
7	0.000	0.000	0.000	00000	00000	0.000
8	0.000	0.000	0.000	00000	00000	0.000
9	0.000	0.000	0.000	00000	00000	0.000
10	0.000	0.000	0.000	00000	00000	0.000

ISE-3 EXP 8/8/76 TIME ZERO=17:39:10

TEMPERATURE INTERVAL NUMBER = 4, TIME = 1.390000 MINUTES

GRU NO.	RADIUS INCHES	DELTA H	DELTA H/ INCH	TEMPERATURE DEGR.FAHN.	AS QUENCHED R/C

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1	0.7500	0.0	0.0	110.0	71000.
2	0.8375	0.2075	0.0500	212.0	142200.
3	0.9250	0.5750	0.1000	293.0	229000.
4	0.9000	1.1500	0.1000	410.0	229000.
5	0.8750	1.7250	0.3000	482.0	229000.
6	0.8500	2.3000	0.4000	530.0	229000.
7	0.8250	2.8750	0.5000	550.0	229000.
8	0.8000	3.4500	0.6000	553.0	229000.
9	0.7750	4.0250	0.7000	550.0	229000.
10	0.7500	4.6000	0.8000	550.0	229000.
11	0.7250	5.1750	0.9000	550.0	229000.
12	0.7000	5.7500	1.0000	550.0	229000.

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

TOTAL HEAT LOST UP TO & INCLUDING THIS TIME INTERVAL = 0.3657NDI02 BTU PER AXIAL INCH OF CYLINDER

FILE VALUES READ IN FOR TIME INTERVAL NO. = 4
0.0 66.64 87.64 13.36 97.06 36.27 87.52 70.29 59.04 40.44 0.0 0.0 1.0

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ISE-3 EXP 8/8/76 TIME ZERO=17:35:10

TEMPERATURE INTERVAL NUMBER = 4, TIME = 1.350000 MINUTES

STRESS INTENSITY CALCULATION: FOR A LONGIT. CRACK, STRESSES AT SURFACE = 102100.

GRU NO.	RADIUS IN.	DEPTH IN.	AS TEMPER.	INCHES/ DEGR.FAHN.	STRESS PSI	AS QUENCHED R/C	AS QUENCHED R/C

////////////////////////////////////

1	0.750	0.0	0.0	110.0	102100.	0.0	71000.
2	0.800	0.152	0.026	165.7	80761.	0.0600	12900.
3	0.871	0.321	0.056	222.6	67335.	0.1600	16216.
4	0.939	0.439	0.076	271.3	57224.	0.3300	225000.
5	0.934	0.584	0.102	275.2	46134.	0.7300	225000.
6	0.913	0.663	0.150	350.1	28334.	0.8700	225000.
7	0.900	1.150	0.201	411.3	13350.	0.7300	225000.
8	0.882	1.732	0.301	482.7	-4110.	1.4513	225000.
9	0.850	2.300	0.401	530.5	-14244.	0.5400	225000.
10	0.825	2.875	0.500	550.0	-10111.	0.4400	225000.

15E-1 EXP 8/8/78 TIME 180017.150119

TEMPERATURE INTERVAL NUMBER = 51 TIME = 1.067000 MINUTES

DEPTH IN	RADIUS IN	DEPTH IN	TEMPERATURE DEGREES F	AS QUENCHED R/C
1	0.7500	0.0	310	4610
2	0.7500	0.075	0.0500	15010
3	0.7500	0.150	0.1000	4610
4	0.7500	0.225	0.1500	4610
5	0.7500	0.300	0.2000	4610
6	0.7500	0.375	0.2500	4610
7	0.7500	0.450	0.3000	4610
8	0.7500	0.525	0.3500	4610
9	0.7500	0.600	0.4000	4610
10	0.7500	0.675	0.4500	4610
11	0.7500	0.750	0.5000	4610
12	0.7500	0.825	0.5500	4610

000 NJ, OF POINTS LA CONSTANT TEMP, FUNDU = 0

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

TOTAL HEAT LOSS UP TO & INCLUDING THIS TIME INTERVAL = 5.12075002 BTU PER AREA: INCH UP CYLINDER

PIE VALUES READ IN FOR TIME INTERVAL NO. = 5
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0

15E-2 EXP 8/8/78 TIME 180017.150119

TEMPERATURE INTERVAL NUMBER = 14 TIME = 1.067000 MINUTES

STRESS INTENSITY CALCULATIONS FOR A LENGTH, CRACK, TIME-TEMPERATURE AS QUENCHED
SE, RADIUS DEPTH A/B TEMPER, TANGENT, AS QUENCHED
NO, IN, IN, STRESS PSI, R/C

1	0.750	0.10	0.00	0.00	105061	04	66881	010
2	0.750	0.152	0.026	0.010	105061	04	66881	010
3	0.750	0.204	0.052	0.020	105061	04	66881	010
4	0.750	0.256	0.078	0.030	105061	04	66881	010
5	0.750	0.308	0.104	0.040	105061	04	66881	010
6	0.750	0.360	0.130	0.050	105061	04	66881	010
7	0.750	0.412	0.156	0.060	105061	04	66881	010
8	0.750	0.464	0.182	0.070	105061	04	66881	010
9	0.750	0.516	0.208	0.080	105061	04	66881	010
10	0.750	0.568	0.234	0.090	105061	04	66881	010
11	0.750	0.620	0.260	0.100	105061	04	66881	010
12	0.750	0.672	0.286	0.110	105061	04	66881	010
13	0.750	0.724	0.312	0.120	105061	04	66881	010
14	0.750	0.776	0.338	0.130	105061	04	66881	010

TEMPERATURE INTERVAL NUMBER = 74 TIME = 3007000 MINUTES

TEMPERATURE INTERVAL NUMBER = 74 TIME = 3007000 MINUTES

TEMPERATURE INTERVAL NUMBER = 74 TIME = 3007000 MINUTES

GRID NO.	RADIUS (INCHES)	DELTA H	DELTA H/0	TEMPERATURE UEGH:PAHH	AS QUENCHED RIC
1	47500	0.00	0.00	7800	65210
2	54035	0.0275	0.00500	7850	65950
3	54350	0.0750	0.01000	2030	187300
4	57000	1.1500	0.02000	3100	250000
5	64750	1.2750	0.03000	3900	250000
6	70500	2.3000	0.04000	4520	250000
7	74650	2.0750	0.05000	4920	250000
8	82000	3.0500	0.06000	5140	250000
9	87750	4.0250	0.07000	5370	250000
10	94500	4.6000	0.08000	5430	250000
11	99250	5.1750	0.09000	5480	250000
12	103000	5.7500	0.10000	5500	250000

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 6 INCLUDING THIS TIME INTERVAL = 312216002 BTU PER ARIAL INCH UP CYLINDER

P/E VALUES REL IN FWH TIME INTERVAL NO. = 7
0.0 60.73 60.68 60.58 60.48 60.38 60.28 60.18 60.08 59.98 59.88 59.78

0.0

0.0

0.0

0.0

0.0

0.0

0.0

0.0

0.0

0.0

0.0

0.0

0.0

0.0

TEMPERATURE INTERVAL NUMBER = 74 TIME = 3007000 MINUTES

TEMPERATURE INTERVAL NUMBER = 74 TIME = 3007000 MINUTES

STRESS INTENSITY CALCULATIONS FOR A CIRCULAR CRACK: STRESSES AT SURFACE = 987900
SEE RADIUS DEPTH A/B TEMPER. TANGENT, AS QUENCHED
NO. IN. UFAHR. STRESS PSI AT RIC R/RIE

STRESS INTENSITY CALCULATIONS FOR A CIRCULAR CRACK: STRESSES AT SURFACE = 987900
SEE RADIUS DEPTH A/B TEMPER. TANGENT, AS QUENCHED
NO. IN. UFAHR. STRESS PSI AT RIC R/RIE

GRID NO.	RADIUS (INCHES)	DELTA H	DELTA H/0	TEMPERATURE UEGH:PAHH	AS QUENCHED RIC
1	47500	0.00	0.00	7800	65210
2	54035	0.0275	0.00500	7850	65950
3	54350	0.0750	0.01000	2030	187300
4	57000	1.1500	0.02000	3100	250000
5	64750	1.2750	0.03000	3900	250000
6	70500	2.3000	0.04000	4520	250000
7	74650	2.0750	0.05000	4920	250000
8	82000	3.0500	0.06000	5140	250000
9	87750	4.0250	0.07000	5370	250000
10	94500	4.6000	0.08000	5430	250000
11	99250	5.1750	0.09000	5480	250000
12	103000	5.7500	0.10000	5500	250000

ISE-J EAP 8/4/76 TIME LENU=17.39.19

TEMPERATURE INTERVAL NUMBER = 0: TIME = 4.0000000 MINUTES

GRID NO.	RADIUS INCHES	DELTA N	DELTA H/W	TEMPERATURE JEGR, FAHR.	AS QUENCHED RIC

*****

1	4.7500	0.0	0.0	70.0	60043.
2	5.0375	0.2875	0.0500	135.0	80034.
3	5.3250	0.5750	0.1000	188.0	100002.
4	5.6000	1.1500	0.2000	285.0	225000.
5	6.0750	1.7250	0.3000	364.0	225000.
6	7.0500	2.3000	0.4000	427.0	225000.
7	7.0250	2.0750	0.5000	471.0	225000.
8	8.2000	3.4500	0.6000	499.0	225000.
9	8.7750	4.0250	0.7000	518.0	225000.
10	9.3500	4.6000	0.8000	530.0	225000.
11	9.9250	5.1750	0.9000	538.0	225000.
12	10.5000	5.7500	1.0000	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 = 9.95254002 BTU PER AIAL INCH OF CYLINDER

FIG. VALUES READ IN FOR TIME INTERVAL NO. = 0

0.0	63.17	88.91	97.43	104.93	111.60	108.66	100.00	88.02	76.83	61.0	41.0	21.0

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ISE-J EAP 8/4/76 TIME LENU=17.39.19

TEMPERATURE INTERVAL NUMBER = 0: TIME = 4.0000000 MINUTES

STRESS INTENSITY CALCULATIONS FOR A LENGTH CRACK: STRESSES AT SURFACE = 90031.

GRID NO.	RADIUS IN.	DEPTH IN.	A/W	TEMPER. DIFFER.	TARGET STRESS PSI	RI	AS QUENCHED RIC	RI/RI

*****

1	4.750	0.0	0.0	70.0	90031.	0.	60043.	0.0
2	4.902	0.152	0.022	105.5	80395.	0.3170.	60043.	0.007
3	5.071	0.321	0.056	141.0	72459.	0.2510.	82600.	1.070
4	5.189	0.439	0.076	164.0	65231.	0.7430.	94000.	1.090
5	5.334	0.584	0.102	190.6	57105.	1.0430.	110001.	0.250
6	5.613	0.863	0.150	238.0	42461.	1.1100.	196795.	0.117
7	5.700	1.190	0.271	286.6	28659.	1.0860.	225000.	0.483
8	6.402	1.732	0.301	364.9	7601.	1.0440.	225000.	0.404
9	7.050	2.300	0.401	427.7	-7647.	0.8820.	225000.	0.394
10	7.625	2.875	0.500	471.0	-17116.	0.6530.	225000.	0.300

TSE-J EXP 8/4/76 TIME 120017.35.19

TEMPERATURE INTERVAL NUMBER = 91 TIME = 51000000 MINUTES

GRID NO. RADIUS DELTA H DELTA T/W TEMPERATURE AS QUENCHED
INCHES DEGREE FAHRENHEIT R/C

1	4.750	0.0	0.0	0.0	66.0	60000
2	5.0375	0.2075	0.0500	120.0	74000	74000
3	5.3250	0.5750	0.1000	165.0	75000	75000
4	5.6000	1.1900	0.2000	250.0	75000	75000
5	6.0750	1.7250	0.3000	330.0	75000	75000
6	7.0500	2.3100	0.4000	360.0	75000	75000
7	7.6250	2.8750	0.5000	402.0	75000	75000
8	8.2000	3.4500	0.6000	473.0	75000	75000
9	8.7750	4.0250	0.7000	490.0	75000	75000
10	9.3500	4.6000	0.8000	512.0	75000	75000
11	9.9250	5.1750	0.9000	521.0	75000	75000
12	10.5000	5.7500	1.0000	520.0	75000	75000

600 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 = 1.185123001 BTU PER AXIAL INCH UP CYLINDER

P.E. VALUES READ IN FOR TIME INTERVAL NO. = 91
0.0 60.51 85.48 94.81 102.07 110.50 100.32 108.75 91.89 80.90 0.0 0.0

TSE-J EXP 8/4/76 TIME 120017.35.19

TEMPERATURE INTERVAL NUMBER = 91 TIME = 51000000 MINUTES

STRESS INTENSITY CALCULATIONS FOR A LUNGT, CRACK, STRESSES AT SURFACE = 91570,
S.E.D. RADIUS DEPTH A/B TEMPER. TANGENT, AS QUENCHED
NO. IN. IN. DEGREE FAHRENHEIT STRESS PSI R/C R/C R/C

1	4.750	0.0	5.7	66.0	91570	04	60000	0.0
2	4.902	0.152	0.046	95.5	81221	60510	66755	0.006
3	5.071	0.321	0.2056	125.6	70360	85400	76481	1.118
4	5.189	0.439	0.4076	146.2	64703	94810	83057	1.213
5	5.310	0.508	0.6102	166.4	57882	102470	93301	1.103
6	5.613	0.843	0.8150	212.4	43385	110500	142961	0.773
7	5.908	1.190	1.2001	280.2	29636	108320	225000	0.481
8	6.402	1.732	0.301	310.0	95714	109750	225000	0.470
9	7.058	2.300	0.401	390.0	-5676	91450	225000	0.406
10	7.625	2.875	0.500	482.0	-15772	80403	225000	0.180

TEMPERATURE INTERVAL NUMBER = 10, TIME = 1.000000 MINUTES

GRID NO. RADIIUS INCHES DELTA IN DELTA/° TEMPERATURE AS QUENCHED R/C

1	0.7500	0.0	0.0	0.0	56450
2	0.8375	0.2875	0.0500	910	59710
3	0.9250	0.5750	0.1000	1310	78900
4	0.9600	1.1500	0.2000	2030	127350
5	0.9750	1.7250	0.3000	2630	229000
6	1.0500	2.3000	0.4000	3120	229000
7	1.0250	2.8750	0.5000	3920	229000
8	0.9200	3.4500	0.6000	3030	229000
9	0.7750	4.0250	0.7000	4100	229000
10	0.5500	4.6000	0.8000	4200	229000
11	0.3250	5.1750	0.9000	4200	229000
12	0.1000	5.7500	1.0000	4230	229000

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

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

TOTAL HEAT LOST UP TO 6 INCLUDING THIS TIME INTERVAL = 1.780750000 BTU PER ARIAL INCH OF CYLINDER

P.B. VALUES READ IN FOR TIME INTERVAL NO. = 10
0.0 30.60 71.00 78.95 86.00 88.50 91.00 91.15 91.00 78.55 81.00 81.00 81.0

TEMPERATURE INTERVAL NUMBER = 10, TIME = 1.000000 MINUTES

STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK, STRESSES AT SURFACE = 163200

GRID NO. RADIIUS INCHES DELTA IN DELTA/° TEMPERATURE AS QUENCHED R/C

1	0.7500	0.0	0.0	0.0	56450
2	0.8375	0.2875	0.0500	910	59710
3	0.9250	0.5750	0.1000	1310	78900
4	0.9600	1.1500	0.2000	2030	127350
5	0.9750	1.7250	0.3000	2630	229000
6	1.0500	2.3000	0.4000	3120	229000
7	1.0250	2.8750	0.5000	3920	229000
8	0.9200	3.4500	0.6000	3030	229000
9	0.7750	4.0250	0.7000	4100	229000
10	0.5500	4.6000	0.8000	4200	229000
11	0.3250	5.1750	0.9000	4200	229000
12	0.1000	5.7500	1.0000	4230	229000

ISE-3 EXP 8/4/76 TIME ZERO=17.39.14

TEMPERATURE INTERVAL NUMBER = 11 TIME = 1.5000001 MINUTES

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

=====

1	4.7500	0.0	0.0	40.0	55120.1
2	5.0375	0.2875	0.0500	75.0	61077.1
3	5.3250	0.5750	0.1000	105.0	69480.1
4	5.6000	1.1500	0.2000	165.0	72387.1
5	6.0750	1.7250	0.3000	216.0	74975.1
6	7.0500	2.3000	0.4000	259.0	72300.1
7	7.6250	2.8750	0.5000	291.0	72300.1
8	8.2000	3.4500	0.6000	317.0	72300.1
9	8.77.0	4.0250	0.7000	334.0	72300.1
10	9.3500	4.6000	0.8000	344.0	72300.1
11	9.9250	5.1750	0.9000	350.0	72300.1
12	10.5000	5.7500	1.0000	361.0	72300.1

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 = 2.30465015 BTU PER AXIAL INCH OF CYLINDER

FOR VALUES READ IN FOR TIME INTERVAL NO. = 11
0.0 41.31 50.50 65.01 70.64 76.38 79.52 79.80 69.80 59.77 0.0 0.0 0.0

133

ISE-3 EXP 8/4/76 TIME ZERO=17.39.14

TEMPERATURE INTERVAL NUMBER = 11 TIME = 1.5000001 MINUTES

STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK: STRESSES AT SURFACE = 63320.1

GRID NO.	RADIUS IN.	DEPTH IN.	A/R	TEMPERATURE DEGR. FAHR.	TANGENTIAL STRESS PSI	AS QUENCHED R/C	R/R/C

=====

1	4.750	0.0	0.0	40.0	63320.1	0.1	55120.1 0.1
2	4.900	0.154	0.026	59.0	55540.1	41113.1	58697.1 0.1704
3	5.071	0.321	0.056	78.7	48759.1	52500.1	62670.1 0.1733
4	5.159	0.439	0.076	91.1	44542.1	64310.1	65608.1 0.1731
5	5.334	0.584	0.102	105.7	39676.1	70643.1	64769.1 1.012
6	5.613	0.863	0.150	135.3	30550.1	76380.1	60164.1 0.1493
7	5.900	1.150	0.201	165.8	21670.1	75550.1	42480.1 0.1813
8	6.482	1.732	0.301	216.6	7406.1	75000.1	15082.1 0.1441
9	7.050	2.300	0.401	259.5	-2753.1	65400.1	22500.1 0.1292
10	7.625	2.875	0.500	291.0	-4854.1	54770.1	22500.1 0.1286

000TOTAL NUMBER OF TEMPERATURE INTERVALS PROCESSED = 11

TABLE 1 - WALL - JUNE 1967 TIME ZERO - 170000H

WALL THICKNESS OF CALCULATING THE WALL PLATE

WALL THICKNESS OF CALCULATING THE WALL PLATE

WALL THICKNESS OF CALCULATING THE WALL PLATE

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WALL THICKNESS OF CALCULATING THE WALL PLATE

WALL THICKNESS OF CALCULATING THE WALL PLATE

TEMPERATURE INTERVAL NUMBER = 1, TIME = 4.0000-01 MINUTES

TEMPERATURE INTERVAL NUMBER = 1, TIME = 4.0000-01 MINUTES

TEMPERATURE INTERVAL NUMBER = 1, TIME = 4.0000-01 MINUTES

ORIG NU	RADIUS IN.	DELTA T	TEMPERATURE UELTAN/0	TEMPERATURE UELTAN/0	AS QUENCHED R/C
1	4.750	0.0	0.0	142.0	77.73
2	4.0375	0.0075	0.0500	170.0	42.000
3	3.3250	0.0150	0.1000	37.70	42.000
4	2.6125	0.0225	0.1500	49.00	42.000
5	1.9000	0.0300	0.2000	50.00	42.000
6	1.1875	0.0375	0.2500	34.00	42.000
7	0.4750	0.0450	0.3000	55.00	42.000
8	0.0000	0.0500	0.3500	55.00	42.000
9	0.0000	0.0500	0.4000	55.00	42.000
10	0.0000	0.0500	0.4500	55.00	42.000
11	0.0000	0.0500	0.5000	55.00	42.000
12	0.0000	0.0500	0.5500	55.00	42.000
13	0.0000	0.0500	0.6000	55.00	42.000

NUMBER OF TEMPERATURES USED = 10
NUMBER OF LAST GRID POINT USED = 10

TOTAL HEAT LOSS UP TO 6 INCLUDING THIS TIME INTERVAL = 2.0376/0002 BTU PER AXIAL INCH UP CYLINDER

ORIG. VALUES READ IN FOR TIME INTERVAL NO. = 1, 01.02 03.07 15.00 00.00 01.00 30.00 00.00 0.00

TEMPERATURE INTERVAL NUMBER = 1, TIME = 4.0000-01 MINUTES

TEMPERATURE INTERVAL NUMBER = 1, TIME = 4.0000-01 MINUTES

STRESS INTENSITY CALCULATIONS FOR A LUNULA, CRACK, SIMULATED AT SURFACE = 100000, TEMPER. YAGUENI, AS QUENCHED R/C

ORIG NU	RADIUS IN.	DELTA T	TEMPERATURE UELTAN/0	TEMPERATURE UELTAN/0	AS QUENCHED R/C
1	4.750	0.0	0.0	142.0	77.73
2	4.0375	0.0075	0.0500	170.0	42.000
3	3.3250	0.0150	0.1000	37.70	42.000
4	2.6125	0.0225	0.1500	49.00	42.000
5	1.9000	0.0300	0.2000	50.00	42.000
6	1.1875	0.0375	0.2500	34.00	42.000
7	0.4750	0.0450	0.3000	55.00	42.000
8	0.0000	0.0500	0.3500	55.00	42.000
9	0.0000	0.0500	0.4000	55.00	42.000
10	0.0000	0.0500	0.4500	55.00	42.000

TEMPERATURE INTERVAL NUMBER = 2, TIME = 0.0070-0.1 MINUTES

198-0 EXPERIMENT JAN, 1967 TIME ZERU = 17.00.10

GRID NO.	RADIUS INCHES	DELTA M	DELTA T/0	TEMPERATURE	AS OBTAINED	RIC
1	0.7500	0.0	0.0	112.0	112.0	71719
2	0.875	0.0075	0.0500	430.0	170700	71719
3	0.9750	0.0150	0.1000	322.0	420000	71719
4	0.0125	0.0025	0.1500	400.0	420000	71719
5	0.0000	1.1500	0.2000	457.0	420000	71719
6	0.0750	1.7250	0.3000	522.0	420000	71719
7	0.0500	2.3000	0.4000	500.0	420000	71719
8	0.0250	2.8750	0.5000	500.0	420000	71719
9	0.0000	3.4500	0.6000	559.0	420000	71719
10	0.0750	4.0250	0.7000	559.0	420000	71719
11	0.0500	4.6000	0.8000	559.0	420000	71719
12	0.0250	5.1750	0.9000	559.0	420000	71719
13	0.0000	5.7500	1.0000	559.0	420000	71719

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

TOTAL HEAT TEST UP TO & INCLUDING THIS TIME INTERVAL = 3.2000000 BTU PER AXIAL INCH OF CYLINDER

P.B. VALUES READ IN PER TIME INTERVAL NO. = 2
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0

0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0

198-0 EXPERIMENT JAN, 1967 TIME ZERU = 17.00.10

TEMPERATURE INTERVAL NUMBER = 2, TIME = 0.0070-0.1 MINUTES

STRESS INTENSITY CALCULATIONS FOR A LONGIT. CHAIR, STRESSES AT SURFACE = 100701.0
S40 RADIUS DEPTH TEMPER. TANGENT. AS OBTAINED
NO. IN. IN. IN. STRESS PSI AT RIC R1/RIC

NO.	RADIUS IN.	DEPTH IN.	TEMPER. IN.	TANGENT. IN.	STRESS PSI	AT	RIC	R1/RIC
1	0.750	0.0	0.0	100701.0	0.0	0.0	71719	0.0
2	0.875	0.0125	0.0500	85000.0	0.0500	0.0500	0.0500	0.0500
3	0.975	0.0250	0.1000	65000.0	0.1000	0.1000	0.1000	0.1000
4	0.0125	0.0375	0.1500	50000.0	0.1500	0.1500	0.1500	0.1500
5	0.0000	0.0500	0.2000	40000.0	0.2000	0.2000	0.2000	0.2000
6	0.0750	0.0625	0.2500	30000.0	0.2500	0.2500	0.2500	0.2500
7	0.0500	0.0750	0.3000	20000.0	0.3000	0.3000	0.3000	0.3000
8	0.0250	0.0875	0.3500	10000.0	0.3500	0.3500	0.3500	0.3500
9	0.0000	0.1000	0.4000	0.0000.0	0.4000	0.4000	0.4000	0.4000
10	0.0750	0.1125	0.4500	-10000.0	0.4500	0.4500	0.4500	0.4500
11	0.0500	0.1250	0.5000	-20000.0	0.5000	0.5000	0.5000	0.5000
12	0.0250	0.1375	0.5500	-30000.0	0.5500	0.5500	0.5500	0.5500
13	0.0000	0.1500	0.6000	-40000.0	0.6000	0.6000	0.6000	0.6000

19E-8 EXPERIMENT JAN, 19, 1977 TIME ZERO = 17.02.10

TEMPERATURE INTERVAL NUMBER = 3, TIME = 1.000000 MINUTES

GRID NO. RADIUS DELTA R DELTA T TEMPERATURE AS QUENCHED
INCHES DEGREES F R/C

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.....
1  4.7500  0.00  0.00  0.00  67157  0.00  67157
2  5.0375  0.2675  0.0500  200.0  123000  0.00  123000
3  5.3250  0.5550  0.1000  400.0  229000  0.00  229000
4  5.6125  0.8425  0.1500  355.0  229000  0.00  229000
5  5.9000  1.1300  0.2000  410.0  225000  0.00  225000
6  6.1875  1.4175  0.2500  480.0  229000  0.00  229000
7  6.4750  1.7050  0.3000  531.0  229000  0.00  229000
8  6.7625  1.9925  0.3500  547.0  229000  0.00  229000
9  7.0500  2.2800  0.4000  553.0  229000  0.00  229000
10  7.3375  2.5675  0.4500  559.0  229000  0.00  229000
11  7.6250  2.8550  0.5000  555.0  229000  0.00  229000
12  7.9125  3.1425  0.5500  555.0  229000  0.00  229000
13  8.2000  3.4300  0.6000  555.0  229000  0.00  229000
.....

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NUMBER OF TEMPERATURES USED = 13
NUMBER OF LAST GRID POINT USED = 13

TOTAL HEAT LOSS UP TO & INCLUDING THIS TIME INTERVAL = 8435410022 BTU PER AXIAL INCH UP CYLINDER

P.R. VALUES READ IN FOR TIME INTERVAL NO. = 3
0.0 66.00 88.00 97.10 101.20 110.3 120.5 130.0 137.0 143.0 153.0 157.0 160.0

19E-8 EXPERIMENT JAN, 19, 1977 TIME ZERO = 17.02.10

TEMPERATURE INTERVAL NUMBER = 3, TIME = 1.000000 MINUTES

STRESS INTENSITY CALCULATIONS FOR A LUNY, CHAIR, STRESSES AT SURFACE = 105501,
SEE RADIUS DEPTH A/O TEMPER. YAKENET, AS QUENCHED
NO. IN, IN, O/FAMH, STRESS PSI K/ R/C R/C

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.....
1  4.750  0.00  0.00  97.0  105501  0.0  67157  0.00
2  4.902  0.152  0.026  193.3  67006  67006  17347  0.760
3  5.071  0.321  0.056  210.7  70857  90320  14432  0.950
4  5.169  0.439  0.076  243.7  50086  97180  21998  0.952
5  5.336  0.588  0.102  285.4  46385  101480  22500  0.850
6  5.613  0.863  0.150  359.1  48773  99930  22500  0.840
7  5.900  1.158  0.201  411.0  40450  40450  22500  0.801
8  6.402  1.732  0.301  490.7  -6371  74300  22500  0.733
9  7.000  2.306  0.401  531.0  -15240  59900  22500  0.287
10  7.625  2.875  0.500  540.0  -17460  43700  22500  0.195
.....

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ESTIMATED INTERVAL NUMBER = 0, TIME = 1,367,000 MINUTES

[illegible][illegible]

000 AND, OF POINTS OF CONSTANT TEMPERATURE = 3

NUMBER OF TEMPERATURES USED	NUMBER OF -ASY GRID POINTS USED
13	13

THESE HEAD LIES UP TO A INCLUDING THIS TIME INTERVAL = SECONDS OF HYPER ADIAL INCH UP CYLINDER

THE VALUES READ IN FOR TIME INTERVAL NO. =

010 010 010

15-0 EXPERIMENT JAN 1961 TIME ZERO = 100010

TEMPERATURE INTERVAL NUMBER = 40 TIME = 1.5670400 VIBRATES

STRESS INTENSITY CALCULATIONS FOR A LENGTH CRACK, STRESSES AT SURFACE = 10000 PSI
 MAXIMUM DEPTH AND TEMPERATURE TARGETED AS UNSTRESSED
 IN JAPAN, STRESS SET AT AIR FRICTION

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[illegible]

[illegible]

ISE-8 EXPERIMENT JAN. 19, 1977 TIME END = 17:00:10

TEMPERATURE INTERVAL NUMBER = 6, TIME = 2.033000 MINUTES

GRID NO.	RADIUS INCHES	DELTA R	DELTA R/S	TEMPERATURE TEMPERATURE	AS QUENCHED RIG
1	4.7500	0.0	0.0	70.0	60000.0
2	5.0375	0.2875	0.0500	140.0	60191.0
3	5.3250	0.5750	0.1000	215.0	147000.0
4	5.6125	0.8625	0.1500	280.0	225000.0
5	5.9000	1.1500	0.2000	332.0	225000.0
6	6.1875	1.4375	0.3000	420.0	225000.0
7	7.0000	2.3000	0.4000	481.0	225000.0
8	7.5250	2.8750	0.5000	510.0	225000.0
9	8.2000	3.4500	0.6000	537.0	225000.0
10	8.7750	4.0250	0.7000	548.0	225000.0
11	9.3900	4.6000	0.8000	551.0	225000.0
12	9.9250	5.1750	0.9000	555.0	225000.0
13	10.5000	5.7500	1.0000	555.0	225000.0

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

NUMBER OF TEMPERATURES USED = 13
NUMBER OF LAST GRID POINT USED = 13

TOTAL HEAT LOST UP TO INCLUDING THIS TIME INTERVAL = 0.15200002 BTU PER AXIAL INCH OF CYLINDER

FIG. VALUES READ IN RUN TIME INTERVAL NO. = 6
0.0 60.41 99.40 104.00 110.87 114.67 108.03 99.63 80.32 65.00 0.0 0.0 0.0

140

ISE-8 EXPERIMENT JAN. 19, 1977 TIME END = 17:00:10

TEMPERATURE INTERVAL NUMBER = 6, TIME = 2.033000 MINUTES

STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK, STRESSES AT SURFACE = 105120,
SEE RADIUS DEPTH A/S TEMPER. TANGENT, AS QUENCHED
NO. IN. IN. U.P.A.M. STRESS PSI AT R/L R/L

NO.	RADIUS IN.	DEPTH IN.	A/S	TEMPER. U.P.A.M.	TANGENT, STRESS PSI	AT R/L	AS QUENCHED R/L	R/L
1	4.750	0.0	0.0	70.0	105120.0	0.0	60000.0	0.0
2	5.0375	0.2875	0.026	140.0	61007.0	60410.0	71005.0	0.302
3	5.3250	0.5750	0.056	215.0	76966.0	94400.0	88500.0	1.079
4	5.6125	0.8625	0.076	280.0	67238.0	100000.0	105157.0	0.480
5	5.9000	1.1500	0.102	332.0	54117.0	110070.0	121001.0	0.730
6	6.1875	1.4375	0.150	420.0	39766.0	114670.0	125000.0	0.910
7	7.0000	2.3000	0.201	481.0	24046.0	100000.0	125000.0	0.400
8	7.5250	2.8750	0.301	510.0	1907.0	90030.0	125000.0	0.143
9	8.2000	3.4500	0.401	537.0	-12356.0	80320.0	125000.0	0.357
10	8.7750	4.0250	0.500	548.0	-19796.0	65000.0	125000.0	0.203

TEMPERATURE INTERVAL NUMBER = 8, TIME = 3.033000 MINUTES

YSE=0 EXPERIMENT JAN, 19,1977 TIME ZERO = 17,00,10

GRID NO, RADIIUS DELTA H DELTA R/W TEMPERATURE AS QUENCHED
INCHES U/P/AMR, R/C

1	0.1500	0.10	0.10	0.10	5050.0
2	0.1500	0.10	0.10	0.10	5050.0
3	0.1500	0.10	0.10	0.10	5050.0
4	0.1500	0.10	0.10	0.10	5050.0
5	0.1500	0.10	0.10	0.10	5050.0
6	0.1500	0.10	0.10	0.10	5050.0
7	0.1500	0.10	0.10	0.10	5050.0
8	0.1500	0.10	0.10	0.10	5050.0
9	0.1500	0.10	0.10	0.10	5050.0
10	0.1500	0.10	0.10	0.10	5050.0
11	0.1500	0.10	0.10	0.10	5050.0
12	0.1500	0.10	0.10	0.10	5050.0
13	0.1500	0.10	0.10	0.10	5050.0

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

NUMBER OF TEMPERATURES USED = 13
NUMBER OF LAST GRID POINT USED = 13

TOTAL HEAT LOST UP TO & INCLUDING THIS TIME INTERVAL = 3.65760002 BTU PER AXIAL INCH OF CYLINDER

P10. VALUES READ IN FOR TIME INTERVAL NO. = 8
0.0 0.1500 0.10 0.10 0.10 0.10 0.10 0.10 0.10 0.10 0.10 0.10 0.10

YSE=0 EXPERIMENT JAN, 19,1977 TIME ZERO = 17,00,10

TEMPERATURE INTERVAL NUMBER = 8, TIME = 3.033000 MINUTES

STRESS INTENSITY CALCULATIONS FOR A CIRCULAR CRACK: STRESSES AT SURFACE = 101700,
S/C RADIIUS DEPTH A/B TEMPER. TANGENT, STRESS PSI R/C R/C
IN. IN. U/P/AMR, R/C

1	0.150	0.10	0.10	0.10	101700	0	5050.0	0.10
2	0.150	0.10	0.10	0.10	101700	0	5050.0	0.10
3	0.150	0.10	0.10	0.10	101700	0	5050.0	0.10
4	0.150	0.10	0.10	0.10	101700	0	5050.0	0.10
5	0.150	0.10	0.10	0.10	101700	0	5050.0	0.10
6	0.150	0.10	0.10	0.10	101700	0	5050.0	0.10
7	0.150	0.10	0.10	0.10	101700	0	5050.0	0.10
8	0.150	0.10	0.10	0.10	101700	0	5050.0	0.10
9	0.150	0.10	0.10	0.10	101700	0	5050.0	0.10
10	0.150	0.10	0.10	0.10	101700	0	5050.0	0.10

TSE-4 EXPERIMENT JAN. 19, 1977 TIME ZERO = 17.00.14

TEMPERATURE INTERVAL NUMBER = 9. TIME = 4.033000 MINUTES

GRID NO.	RADIUS INCHES	DELTA R	DELTA R/R	TEMPERATURE DEGR.FAHN.	AS QUENCHED R/C
1	4.7500	0.00	0.00	52.0	57374.
2	4.0375	0.2875	0.0710	112.0	71719.
3	3.3250	0.5750	0.1000	189.0	72902.
4	2.6125	0.8625	0.1300	216.0	149729.
5	1.9000	1.1500	0.2000	262.0	229000.
6	1.1875	1.7250	0.3000	342.0	229000.
7	0.4750	2.3000	0.4000	408.0	229000.
8	0.1625	2.8750	0.5000	457.0	229000.
9	0.0000	3.4500	0.6000	499.0	229000.
10	0.7750	4.0250	0.7000	510.0	229000.
11	0.3300	4.6000	0.8000	526.0	229000.
12	0.0250	5.1750	0.9000	535.0	229000.
13	10.9000	9.7500	1.0000	540.0	229000.

NO. OF POINTS OF CONSTANT TEMP. FOUND = 0

NUMBER OF TEMPERATURES USED = 13
NUMBER OF LAST GRID POINT USED = 13

TOTAL HEAT LOST OF TC 6 INCLUDING THIS TIME INTERVAL = 1.05635003 BTU PER AXIAL INCH OF CYLINDER

P/E VALUES MEAN IN FOR TIME INTERVAL NO. = 9

0.0	64.64	91.07	100.64	108.64	115.93	117.57	118.02	99.25	82.15	0.0	0.0	0.0

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TSE-4 EXPERIMENT JAN. 19, 1977 TIME ZERO = 17.00.14

TEMPERATURE INTERVAL NUMBER = 9. TIME = 4.033000 MINUTES

STRESS INTENSITY CALCULATIONS FOR A LONGIT. CRACK, STRESSES AT SURFACE = 97971.
GRID RADIUS DEPTH A/R TEMPER. TANGENT AS QUENCHED
NO. IN. IN. U/FAHN. STRESS PSI R/R R/R/R/C

1	4.750	0.0	0.0	52.0	97971.	0.	57374.	0.0
2	4.002	0.112	0.026	84.4	86683.	84040.	63967.	1.011
3	3.071	0.323	0.056	110.5	75222.	91070.	73924.	1.232
4	2.100	0.439	0.076	140.5	67998.	100640.	42193.	1.224
5	1.334	0.584	0.102	186.6	59662.	108690.	93404.	1.163
6	0.813	0.863	0.150	216.1	44634.	113730.	149889.	0.773
7	0.400	1.150	0.201	263.2	31039.	113790.	229000.	0.505
8	0.162	1.732	0.301	342.4	9628.	110820.	229000.	0.403
9	0.025	2.300	0.401	408.8	-6362.	95290.	229000.	0.423
10	0.625	2.875	0.500	457.0	-17244.	82190.	229000.	0.339

TSR-4 EXPERIMENT JAN. 19, 1977 TIME ZERO = 17,00,10

TEMPERATURE INTERVAL NUMBER = 10. TIME = 8,033,000 MINUTES

GRIP NO. RADIIUS DELTA N DELTA T/E TEMPERATURE AS QUENCHED
INCHES DEGR. F. AIR

1	0.7500	0.0	0.0	0.0	50.0	57000
2	0.0375	0.0275	0.0250	0.0250	100.0	60000
3	0.0350	0.0750	0.1000	0.1000	100.0	60000
4	0.0125	0.0425	0.1500	0.1500	105.0	114000
5	0.0000	0.1300	0.3000	0.3000	50.0	134173
6	0.04750	1.17500	0.3500	0.3500	310.0	221000
7	7.0500	2.3000	0.4000	0.4000	301.0	220000
8	7.0250	2.0750	0.5000	0.5000	324.0	220000
9	0.2000	3.4000	0.6000	0.6000	070.0	220000
10	0.0750	4.0250	0.7000	0.7000	490.0	220000
11	0.0500	4.0000	0.8000	0.8000	511.0	220000
12	0.0250	5.1750	0.9000	0.9000	520.0	220000
13	10.0000	5.7500	1.0000	1.0000	520.0	220000

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

NUMBER OF TEMPERATURES USED = 13
NUMBER ON LAST GRIP POINT USED = 13

TOTAL HEAT LOST UP TO & INCLUDING THIS TIME INTERVAL = 1,212,000.0 BTU PER AXIAL INCH OF CYLINDER

P.E. VALUES READ IN FOR TIME INTERVAL NO. = 10
0.0 02.33 00.00 00.27 106.56 110.73 113.33 111.00 07.70 00.70 0.0 0.0

TSR-4 EXPERIMENT JAN. 19, 1977 TIME ZERO = 17,00,10

TEMPERATURE INTERVAL NUMBER = 10. TIME = 8,033,000 MINUTES

STRESS INTENSITY CALCULATIONS FOR A LENGTH, ENGR. STRESSES AT SURFACE = 0.0000,
END RADIIUS DENIN A/S TANGENT, AS QUENCHED
NO. IN. IN. DIAM. STRESS PSI AI RIC AIR/AL

1	0.750	0.0	0.0	0.000	0	57000	0.0
2	0.002	0.12	0.050	0.007	0.030	6220	1.00
3	0.071	0.321	0.050	0.000	0.000	6000	1.00
4	0.100	0.430	0.070	0.0250	0.0270	7000	1.00
5	0.334	0.500	0.100	0.000	0.0500	0570	1.00
6	0.003	0.003	0.100	0.000	1.0730	11000	0.00
7	0.000	1.100	0.201	0.000	1.1330	001000	0.00
8	0.002	1.720	0.301	0.000	1.1000	220000	0.00
9	7.050	2.300	0.401	0.000	0.7500	220000	0.00
10	7.025	2.075	0.500	0.000	0.5700	220000	0.00

TEMPERATURE INTERVAL NUMBER = 11, TIME = 1.003000 MINUTES

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TEMPERATURE INTERVAL NUMBER = 11, TIME = 1.003000 MINUTES
=====
CND NO, RADIUS DELTA R TEMPERATURE AS UNHEATED
IN, IN, IN, R/R
=====
1 0.1500 0.0 0.0 32.0 5300.1
2 0.0375 0.0075 0.0030 19.0 6107.1
3 0.1350 0.0575 0.0100 10.0 7100.0
4 0.0125 0.0025 0.0150 10.0 8507.5
5 0.0000 1.1500 0.0000 10.0 10307.0
6 0.0750 1.1750 0.1000 20.0 22007.0
7 0.0500 2.1500 0.0000 30.0 22500.0
8 0.0150 2.0750 0.0500 30.0 22500.0
9 0.0000 3.0500 0.0000 30.0 22500.0
10 0.0750 4.0250 0.1000 40.0 22500.0
11 0.0500 4.0000 0.0000 42.0 22500.0
12 0.0250 5.1750 0.0000 43.0 22500.0
13 0.0000 5.1500 1.0000 40.0 22500.0
=====
000 NO, OF POINTS OF CONSTANT TEMP, PUNCH = 0
NUMBER OF TEMPERATURES USED = 13
NUMBER OF LAST GRID POINT USED = 13
TOTAL HEAT LOST UP TO & INCLUDING THIS TIME INTERVAL = 1.46001000 BTU PER AXIAL INCH OF CYLINDER
PAB, VALUES READ IN FOR TIME INTERVAL NO. = 11
0.0 51.06 73.55 81.96 89.36 96.74 98.50 98.80 89.77 75.00 0.0 0.0 0.0
=====

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TEMPERATURE INTERVAL NUMBER = 11, TIME = 1.003000 MINUTES

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TEMPERATURE INTERVAL NUMBER = 11, TIME = 1.003000 MINUTES
=====
STRESS INTENSIVITY CALCULATIONS FOR A CIRCULAR CRYSTAL STRESSES AT SURFACE = 10000
SHEAR RADIUS TEMPERATURE TARGET, AS UNHEATED
NO, IN, IN, U/FAM, STRESS PSI AT R/R
=====
1 0.1500 0.0 32.0 78.00 0. 5300.1 0.0
2 0.0375 0.0075 19.0 6107.1 0.0 6107.1 0.0
3 0.1350 0.0575 10.0 7100.0 7350.1 1.171
4 0.0125 0.0025 10.0 8507.5 8100.1 1.238
5 0.0000 1.1500 0.0000 10307.0 8500.1 1.251
6 0.0750 1.1750 0.1000 22007.0 9678.0 1.130
7 0.0500 2.1500 0.0000 22500.0 10220.1 0.920
8 0.0150 2.0750 0.0500 22500.0 22203.1 0.936
9 0.0000 3.0500 0.0000 22500.0 22500.1 0.981
10 0.0750 4.0250 0.1000 22500.0 22500.1 0.937
=====

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13E-4 EXPERIMENT JAN: 19:1977 TIME ZERU = 17:00:10

TEMPERATURE INTERVAL NUMBER = 12. TIME = 1:50:00:01 MINUTES

GRID NO. RADIUS DELTA R DELTA T TEMPERATURE AS QUENCHED
INCHES U.P.A.M.M. R/C

1	0.7500	0.0	0.0	45.0	58300
2	0.8375	0.0	0.0500	60.0	58100
3	0.9250	0.0750	0.1000	90.0	60310
4	0.9625	0.0625	0.1500	180.0	74400
5	0.9500	1.1500	0.2000	180.0	69100
6	0.8750	1.7250	0.3000	200.0	123000
7	0.9500	2.3000	0.4000	400.0	131000
8	0.8250	2.8750	0.5000	400.0	225000
9	0.8000	3.4500	0.6000	310.0	225000
10	0.7750	4.0250	0.7000	320.0	225000
11	0.7500	4.6000	0.8000	300.0	225000
12	0.7250	5.1750	0.9000	320.0	225000
13	0.7000	5.7500	1.0000	350.0	445000

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

NUMBER OF TEMPERATURES USED = 13
NUMBER OF LAST GRID POINT USED = 13

TOTAL HEAT LOST UP TO & INCLUDING THIS TIME INTERVAL = 4.37000000 BTU PER AXIAL INCH OF CYLINDER

P.O. VALUES READ IN FOR TIME INTERVAL NO. = 12
0.0 02.03 00.10 06.00 72.00 73.00 70.00 70.00 70.00 70.00 70.00 70.00 70.00

13E-4 EXPERIMENT JAN: 19:1977 TIME ZERU = 17:00:10

TEMPERATURE INTERVAL NUMBER = 12. TIME = 1:50:00:01 MINUTES

STRESS INTENSITY CALCULATIONS FOR A LENGTH, ENGRA. STRESSES AT SURFACE = 0.9019,
S.D. RADIUS DEPTH A/O TEMER. TANGENT. AS QUENCHED
NO. IN. U.P.A.M.M. STRESS PSI R1 R/C R1/R/C

1	0.750	0.0	0.0	25.0	63010	0	58300	0.0
2	0.800	0.100	0.000	40.0	57000	42420	58000	0.750
3	0.875	0.375	0.050	63.7	50850	60100	50500	1.100
4	0.910	0.430	0.070	70.1	46010	60400	60100	1.070
5	0.930	0.500	0.100	60.0	41100	72000	65500	1.111
6	0.813	0.843	0.150	120.1	32001	70000	74400	1.001
7	0.900	1.100	0.200	100.0	43010	70000	69000	0.900
8	0.800	1.700	0.300	200.0	4310	70100	14000	0.601
9	0.800	2.300	0.400	300.0	-19100	70000	215000	0.500
10	0.825	2.875	0.500	400.0	-10000	68700	225000	0.675

000000 NUMBER OF TEMPERATURE INTERVALS PROCESSED = 12

SOUT

SUBJECT: [illegible]

REPT. NO. [illegible]

21-2-1973

[illegible]

[illegible]

[illegible]