FRACTURE MECHANICS EVALUATION OF THE TRINO VERCELLESE REACTOR VESSEL FOLLOWING A POSTULATED MAIN COOLANT PIPE BREAK

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SUMMARY

In the event of a postulated double-ended main coolant pipe break, the Reactor Coolant System rapidly depressurizes. At an early stage in the depressurization transient, the Emergency Core Cooling System (EECS) rapidly injects coolant into the reactor vessel. If the reactor vessel is at its normal operating condition prior to the postulated Loss of Coolant Accident (LOCA), the reactor vessel will be hot (~539°F), thus the cold coolant rapidly injected into the reactor vessel would thermally shock the hot vessel, resulting in high thermal stresses in the reactor vessel wall. While it must be demonstrated that the Safety Injection System (SIS) is sufficient to keep the core from meltdown, it must also be demonstrated that the thermal stresses will not cause crack instability in the reactor vessel wall, such that the vessel can no longer hold the coolant and keep the core covered.

S.N. Ehrenpreis, P.C. Riccardella and T.R. Mager (ASME 1970 Annual Meeting, New York) evaluated a postulated LOCA in terms of fracture mechanics parameters and concluded that, if crack instability occurred, the crack would arrest prior to extending eighty percent through the shell course thickness. Ehrenpreis et al. considered only one SIS flow rate and coolant temperature. In addition, an upper shelf fracture toughness in excess of 300 ksi(in)$^{1/2}$ was used in the analysis for the limiting material properties. Ehrenpreis et al. recognized that by decreasing the SIS flow rate and/or increasing the SIS coolant temperature, the thermal stresses would be reduced such that crack instability would be of a low probability.

The Ente Nazionale per l'Energia Elettrica (ENEL) Trino Power Plant recently decided to upgrade the plant to 1000 MWT. Upgrading of the Trino Station will require backfitting of the present ECCS.

The Trino reactor vessel material exhibited an upper shelf impact energy level of approx. 36 ft/lb. Thus one would expect the reactor vessel material to exhibit relatively low fracture toughness, $K_{IC}(K_{ID})$ properties.

This paper presents the results of a parametric study performed on the Trino reactor vessel to evaluate the thermal effects resulting from a postulated LOCA. The parametric study included the variable of flow rate (9300, 12245 and 18700 gpm) and coolant temperature (53.6, 70 and 100°F). In addition, post-irradiation fracture toughness data were obtained on the Trino reactor vessel material to ensure completeness of the analysis. The material exhibited a post-irradiation upper shelf fracture toughness of 150 ksi (in)$^{1/2}$. The paper describes the potential of crack instability during a postulated LOCA condition considering the variables evaluated.

The results of the parametric study shows that by controlling the SIS coolant flow rate and/or coolant temperature, the critical flaw size is greater than 25 percent of the reactor vessel shell thickness.

1. INTRODUCTION

The Ente Nazionale per l'Energia Elettrica (ENEL) Trino Nuclear Power Plant went into operation in 1965. Although the Trino Nuclear Power Plant has been operating for four cycles and has been demonstrated to be one of the most efficient nuclear power plants in the world, it was proposed that the integrity of the reactor pressure vessel be evaluated in terms of fracture mechanics parameters. The analysis [1] included a fatigue crack growth evaluation, determination of critical flaw sizes for design (normal, upset and test) transients and a postulated loss-of-coolant accident (LOCA) condition. The results of the fracture mechanics analysis demonstrated the margin of safety for continued operation of the Trino Nuclear Power Plant.

Recently, ENEL decided to increase the power level of the Trino Nuclear Power Plant up to 1000 MWt and introduce Zircaloy-clad fuel assemblies to the core. Upgrading of the Trino Station will require backfitting of the present Emergency Core Cooling System (ECCS). In event of a LOCA, the Reactor Coolant System will rapidly depressurize and the loss of coolant may partially empty the reactor vessel. At some stage in the depressurization transient, the ECCS will rapidly inject cold coolant into the reactor vessel to prevent the core from meltdown. The present ECCS supplies water to the Trino vessel at a rate of 9300 gpm. The new safety injection system, which will consist of one accumulator and two new low-head pumps connected to the low-pressure injection header and two new high-head pumps, will inject the water through a high-pressure header initially at 18,700 gpm. If the reactor is at its normal operating condition prior to the postulated LOCA, the reactor vessel will be hot (500 to 550°F), thus the cold coolant rapidly injected into the reactor vessel would thermally shock the hot vessel, resulting in high thermal stresses in the reactor vessel wall.

While it must be demonstrated that the safety injection system is sufficient to keep the core from meltdown, it must also be dmonstrated that the thermal stresses will not cause crack instability in the reactor vessel wall such that the vessel can no longer hold the coolant and keep the core covered. This report presents the results of an analysis performed on the Trino reactor vessel to evaluate the thermal effects resulting from a postulated LOCA. The report describes the potential of crack instability during a postulated LOCA condition with the proposed ECCS operative.

2. METHOD OF ANALYSIS

2.1. General

The analysis performed used linear-elastic fracture mechanics (LEFM) technology. The LEFM approach to the design against failure is basically a stress intensity consideration in which criteria are established for fracture instability in the presence of a crack. Consequently, a basic assumption employed in LEFM is that a crack or crack-like defect exists in the structure. The essence of the approach is to relate the stress field developed in the vicinity of the crack tip to the applied nominal stress on the structure, the material properties and the size of defect necessary to cause failure.

The elastic stress field at the crack tip in any cracked body can be described by a single parameter designated as the stress intensity factor, K. The magnitude of K is a function of the geometry of the body containing the crack, the size and location of the crack and the magnitude and distribution of the stress. The criterion for failure in the presence of a crack is that failure will occur whenever K exceeds some critical value.

For the opening mode of loading (stresses perpendicular to the major plane of the crack) the stress intensity factor is designated as K_I and the critical stress intensity factor is designated K_{Ic}. Commonly called the fracture toughness, K_{Ic} is an inherent material property which is a function of temperature and strain rate. Any combination of applied load, structural configuration, crack geometry and size which yields a stress intensity factor greater than K_{1c} for the material will result in crack instability.

For this analysis the crack was assumed to be located at the inner surface of the vessel wall and to be continuous in the longitudinal direction. These conditions correspond to the maximum stress intensity factor normal to the plane of a crack during a postulated LOCA.

2.2. Stress Intensity Factor Expression

The stress intensity factor for a continuous, through-the-thickness crack in an infinite body subjected to an arbitrary nominal stress field (x,o) is given by the eq. 1 :

$$K_1 = \frac{1}{\sqrt{\pi c}} \int_{-c}^{+c} \sigma(x,o) \left(\frac{c+x}{c-x}\right)^{1/2} dx \qquad (1)$$

where c is half the crack length.

The applied stress, σ, can be written in a polynomial form:

$$\sigma(x,o) = A_o + A_1 x + A_2 x^2 + A_3 x^3 \qquad (2)$$

Correcting for the free surface and the finite thickness, eq.(1) becomes after integration:

$$1.12 K_1 = 1.9851\, A_o a^{1/2} F_1 + 1.2638\, A_1 a^{3/2} F_2 + 0.9926\, A_2 a^{5/2} F_3 + 0.8425\, A_3 a^{7/2} F_4. \qquad (3)$$

F_1, F_2, F_3 and F_4 are the finite thickness correction vectors relative to $\sigma = 1$, $\sigma = x$, $\sigma = x^2$ and $\sigma = x^3$, respectively.

In a cylindrical reactor pressure vessel the bending effect due to the introduction of the crack becomes important, if the crack depth exceeds 20 percent of the wall thickness. Using a finite element computer program, Buchalet [2] recently determined the magnification factors F_1, F_2, F_3 and F_4 in eq. 3 for a cylindrical vessel containing longitudinal inside surface cracks of depths ranging from 2.5 to 80 percent of the vessel wall thickness. Axisymmetric finite element models with a highly refined grid in the vicinity of the crack tip were used to provide a high degree of resolution of the stress and strain gradients in that region. The F factors obtained using these models are presented in Fig.1.

In the present analysis the stress intensity factor K_1 is calculated by a computer code for discrete crack depths and calculated stress profiles using the expression given in eq.(3) and the magnification factors F_1, F_2, F_3, F_4 from Fig. 1.

2.3. Stress Analysis

Following the postulated LOCA the vessel wall will be subjected to high thermal stresses due to the rapid injection of cold water by the ECCS. Because the pressure drops to an insignificant level before the thermal stresses build up, there are no pressure stresses in the vessel following the LOCA. With respect to the orientation of the assumed cracks in the vessel wall, only the thermal stresses normal to the crack surface are of interest for this analysis. The appropriate thermal stress profiles were obtained numerically using a computer code.

In the computer code the forced convection heat transfer coefficients were calculated using the Dittus-Boelter equation

$$h = 0.23\, f \frac{k}{D}\, Re^{0.8} Pr^{0.4} \qquad (4)$$

where:

f = safety coefficient = 1.5

k = thermal conductivity of the fluid (Btu/hr.ft.°F)

D = hydraulic diameter (ft)

$Re = \frac{\rho V D}{\mu}$ = Reynolds' number

ρ = density of the fluid (lb/ft^3)

V = fluid velocity (ft/hr)

μ = fluid viscosity (lb/ft)

$P_r = \frac{C_p \mu}{k}$ = Prandtls' number

C_p = specific heat (Btu/lb.°F)

Equation 4 is the classical equation to calculate the heat transfer coefficients, if the heat in the component wall is removed by forced convection. The safety factor, f, is the conservatism introduced in the calculated value of h.

In the case of a postulated LOCA the vessel interior surface is initially above the saturation temperature corresponding to the vessel-barrel annulus pressure. Therefore, two-phase boiling heat transfer may occur during the initial portion of the LOCA transient. Nucleate boiling with a heat transfer coefficient of 10,000 $Btu/hr.ft^2.°F$ is assumed initially in the transient until the heat transfer rate from the vessel wall by forced convection becomes dominant. The 10,000 $Btu/hr.ft^2°F$ heat transfer coefficient is considered conservative, in that any increase in the heat transfer coefficient does not produce any changes in vessel wall thermal stresses or temperature profiles.

2.4. Material Input

The Trino reactor pressure vessel was fabricated from A302, Grade B steel. Fracture toughness data for Trino reactor vessel material are given in reference [1]. The fracture toughness, K_{1c}, results are summarized in Fig.2. Also given in Fig.2 is the K_{1c} computed for end-of-life fluence at the vessel surface of $3.8 \times 10^{19} n/cm^2$, at 1/10 wall thickness fluence of $2.7 \times 10^{19} n/cm^2$ and at 1/4 wall thickness fluence of $1.4 \times 10^{19} n/cm^2$.

3. RESULTS.

In the event of a postulated double-ended main coolant pipe break the Reactor Coolant System rapidly depressurizes. If the reactor vessel is at normal operating conditions (1000 MWt) before the postulated accident, the reactor vessel temperature is approximately 539.6°F and the beltline region of the Trino reactor is irradiated. At an early stage in the depressurization transient, the ECCS rapidly injects coolant into the reactor vessel. The flow rate as a function of time for the proposed Trino Power Plant safety injection system is given in Fig.3. For the initial evaluation, the safety injection system (SIS) water temperature was assumed to be 53.6°F. The minimum time at which the recirculation system can be put into operation is 1700 seconds and it was assumed that the recirculation water temperature was 158°F. The analysis was performed utilizing the concept of linear elastic fracture mechanics and considered the proposed ECCS operative. As part of the parametric study, three initial water temperatures were considered for the safety injection system: 53.6°F, 70°F and 100°F. The results of the analysis are summarized in Table[I]

Initially, the analysis was performed for two cases: (1) assuming the flow rate of the safety injection system was a constant 18,700 gpm,and (2) the flow rate of the SIS was a constant 12,245 gpm. The temperature distribution and the resulting thermal stress distributions were computerized at various discrete time intervals following the postulated LOCA. The most severe stress distribution was used for the calculation of the stress intensity factors.

The K_1 was calculated as a function of crack depth through the wall, using the expression as in eq. 3 . The critical time occurs at 800 seconds for the 18,700 gpm flow rate and at 1200 seconds for the 12,245 gpm flow rate. The results of the analysis are presented in Fig. 4 and 5. The temperature distribution through the wall at time of the most severe gradient is also plotted in Fig. 4 and 5. Also given in these figures is the K_{1c} as a function of distance through the Trino reactor vessel wall computed for an end-of-life surface fluence of $3.8 \times 10^{19} n/cm^2$.

The critical crack depth, a_c, is obtained at the first intersection between the K_1 curve and the K_{1c} curve. Fig. 4 and 5 show that the critical crack depth is equal to approximately 0.17 inch - for the 18,700 gpm flow rate,and approximately 0.35 inch for the 12,245 gpm flow rate.

Table[I]indicates that there is essentially no difference in critical flaw size for instability, if a safety injection system water temperature of 53.6°F is compared to a SIS water temperature of 70°F. The results indicate that the flow is the governing factor. Decreasing the flow rate from 18,700 to 12,245 gpm increases the critical flaw size by a factor of two, 0.17 inch versus 0.35 inch. However, by increasing the SIS water temperature to 100°F, the critical flaw size becomes of the order of 2.3 to 2.6 inches in depth.

Recognizing that the thermal shock to the reactor vessel would be reduced by increasing the SIS water temperature of the refueling water storage tanks and therefore the thermal stresses would be less severe, the analysis was again performed, using higher SIS temperatures. For the re-evaluation, it was assumed that the temperature of the SIS water was 70°F and 100°F. As in the initial analysis, two flow rates were considered: 18,700 gpm and 12,245 gpm.

K_1 as a function of crack depth through the Trino reactor vessel wall is given in Fig. 6 and 7 for a flow rate of 18,700 gpm and SIS water temperatures of 70°F and 100°F respectively. The increase in SIS water temperature from 53.6°F to 70°F increased the critical time from 800 seconds to 1200 seconds after beginning of the LOCA, however, the critical crack depth remained the same - 0.17 inch. If the SIS water temperature is increased to 100°F, the critical crack depth becomes 2.3 inches.

K_1 as a function of crack depth through the vessel wall is given in Fig. 8 and 9 for a flow rate of 12,245gpm and SIS water temperatures of 70°F and 100°F respectively. Increasing the SIS water temperature from 53.6°F to 70°F increased the critical time from 1200 to 1600 seconds after the postulated LOCA; however, the critical crack depth remained the same, approximately 0.35 inch. If the SIS water temperature is increased to 100°F, the critical crack depth becomes approximately 2.6 inches.

Reference[I]considered the stress intensity factor expression (K_I) to be identical for either a circumferential flaw or a longitudinal flaw. However, Buchalet [2] demonstrated analytically that a longitudinal surface flaw is more severe thana circumferential surface flaw. The loss-of-coolant accident analysis of Reference[I]was again performed, utilizing Buchalet magnification factors for a continuous longitudinal surface flaw (eq. 3). These results are also presented in Table[I]

4. CONCLUSIONS.

A parametric study was performed to evaluate the effect of thermal shock to the Trino reactor vessel following a postulated LOCA. Both the current and proposed ECCS were considered. The parametric study included the variables flow rate and safety injection system water temperature.

Based on the fracture mechanics analysis performed, it was concluded that if the Trino Vercellese plant were to sustain a LOCA, the integrity of the reactor beltline would be maintained provided either:

(1) The safety injection system water temperature and/or system flow rate is controlled such that the critical flaw size is greater than 2.15 inches in depth (25 percent of reactor vessel beltline wall thickness).

(2) In-service inspection is performed to ensure that the vessel beltline does not contain surface flaws of the order of 0.17 inch in depth.

TABLE I

SUMMARY OF ANALYTICAL RESULTS

SIS Water Temperature (°F)	Flow Rate (gpm)	Critical Flaw Size (inches)
53.6	18,700	0.17
70.0	18,700	0.17
100.0	18,700	2.30
53.6	12,245	0.35
70.0	12,245	0.35
100.0	12,245	2.60
40.0	9,300	0.17
70.0	9,300	2.60
100.0	9,300	2.85

REFERENCES.

1 Mager, T.R., Bamford, W.H. and Yanichko, S.E. "Fracture Mechanics Evaluation of the Trino Reactor Vessel"; Westinghouse Nuclear Energy Systems WCAP-8189, June 1974.

2 Buchalet, C.B. and Bamford, W.H. "Stress Intensity Factor Solutions for Continuous Surface Flaws in Reactor Pressure Vessels"; Westinghouse Nuclear Energy Systems WCAP-5292, August 1974.

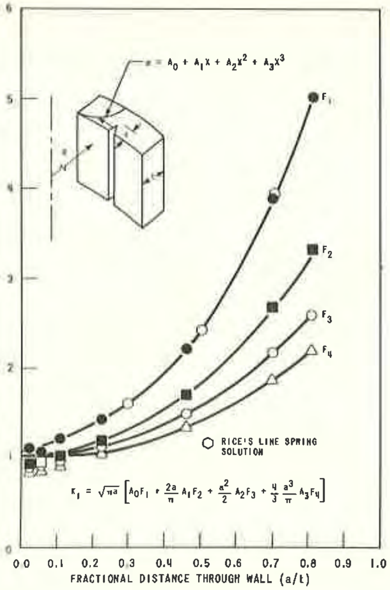

Fig. 1 - Longitudinal Crack in Cylinder (t/R = 0.1)

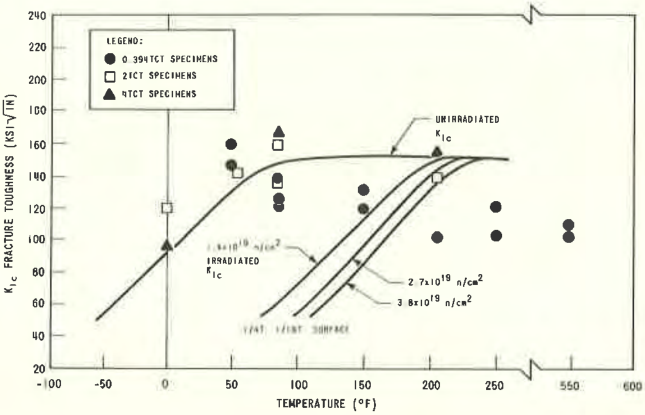

Fig. 2 - Trino Reactor Vessel Material Fracture Toughness as a Function of Fluence and Temperature.

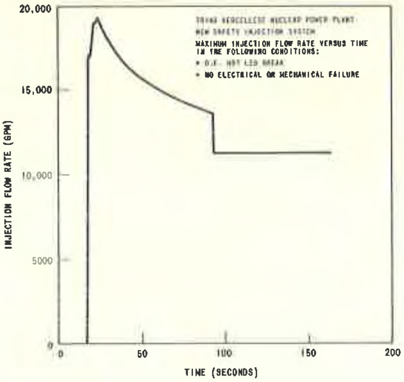

Fig. 4 - Critical Stress Intensity Factor for 18,700 gpm Flow Rate and SIS Water Temperature at 53.6°F.

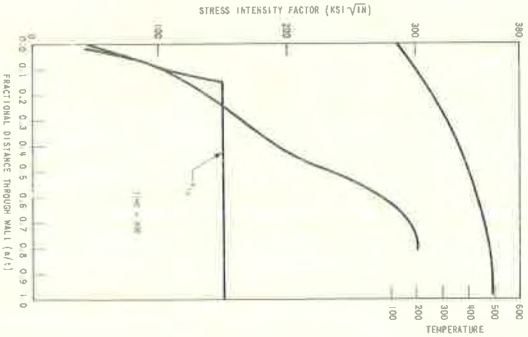

Fig. 3 - Flow Rate as a Function of Time for Proposed Safety Injection System.

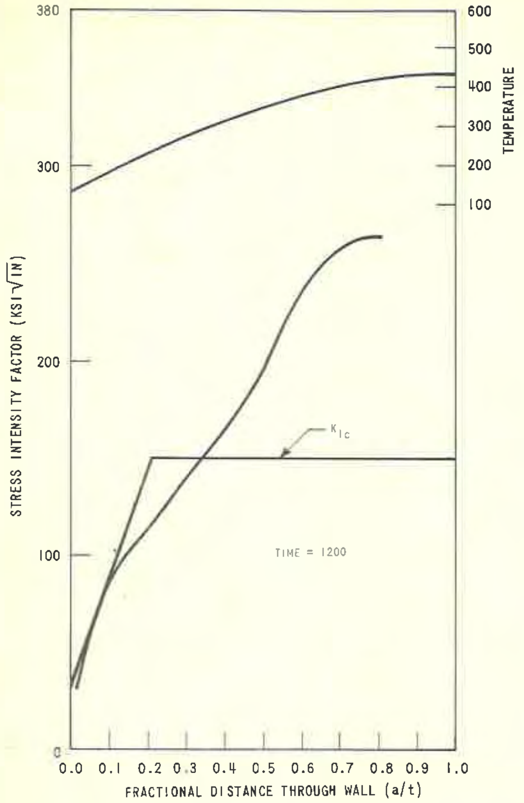

Fig. 5 - Critical Stress Intensity Factor for 12,245 gpm Flow Rate and SIS Water Temperature at 53.6°F.

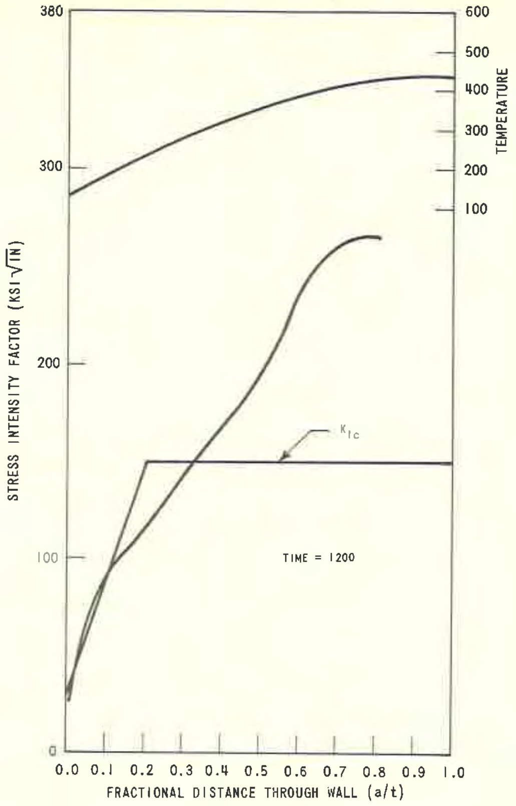

Fig. 6 - Critical Stress Intensity Factor for 18,700 gpm Flow-Rate and SIS Water Temperature of 70°F.

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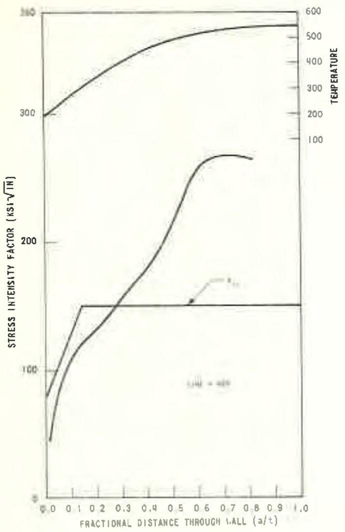

Fig. 7 - Critical Stress Intensity Factor for 18,700 gpm Flow Rate and SIS Water Temperature of 100°F.

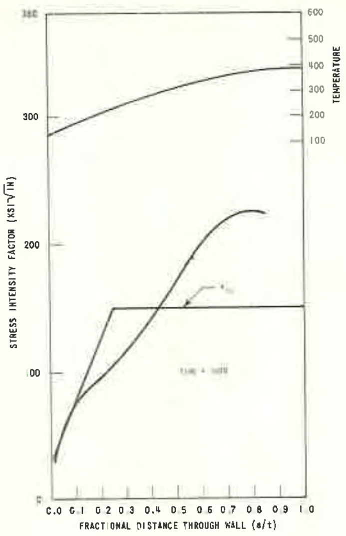

Fig. 8 - Critical Stress Intensity Factor for 12,245 gpm Flow Rate and SIS Water Temperature of 70°F.

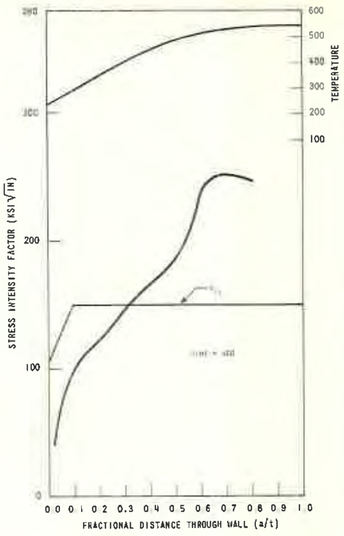

Fig. 9 - Critical Stress Intensity Factor for 12,245 gpm Flow Rate and SIS Water Temperature of 100°F.