A FRACTURE MECHANICS METHOD OF EVALUATING STRUCTURAL INTEGRITY OF A REACTOR VESSEL DUE TO THERMAL SHOCK EFFECTS FOLLOWING LOCA CONDITION

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SUMMARY

The importance of knowledge of structural integrity of a reactor vessel due to thermal shock effects, is related to safety and operational requirements in assessing the adequacy and flawless functioning of the nuclear power systems. Following a loss-of-coolant accident (LOCA) condition the integrity of the reactor vessel, due to a sudden thermalshock induced by actuation of emergency core cooling system (ECCS), must be maintained to ensure safe and orderly shutdown of the reactor and its components.

The paper encompasses criteria underlaying a fracture mechanics method of analysis to evaluate structural integrity of a typical 950 MWe PWR vessel as a result of very drastic changes in thermal and mechanical stress levels in the reactor vessel wall. The main object of this investigation therefore consists in assessing the capability of a PWR vessel to withstand the most critical thermal shock without impairing its ability to conserve vital coolant owing to probable crack propagation.

The principal evaluation has been based on predicting nominal values of vessel parameters which are significant to the functional results. These parametric coefficients essentially consist of: heat transfer coefficient at the inside wall, the "NVT" incidence on the inside wall, the fracture mechanics model of the vessel wall and the fracture toughness of the vessel material. In addition, the effects of degree of conservation in these parameters on the outcome of the final solution were also examined. The complete procedure for this type of analytical approach demands an overall investigation of four general areas consisting of: LOCA analysis, thermal and hydraulic analysis, mechanical, residual and thermal stress analysis and finally failure mode analysis involving ductile yielding, fatigue as well as brittle fracture. In each mode of investigation, it is intended to evaluate significant parameters to be utilized in undertaking Linear Fracture Mechanics (LFM) method of analysis.

The results of the numerical evaluation of the present problem have indicated that the fracture toughness of the material is determined to have the greatest influence on the depth of crack propagation for variations of the parameters over ranges considered to be reasonable. Moreover, it is concluded that too much conservatism tends to be pyramided in this type of analysis when there are some uncertainties in significant parameters. Instead of therefore arbitrarily pyramiding conservatism, it was elected to consider two values, nominal values and conservative values, to best evaluate the behaviour of the PWR vessel. The nominal values represent the best judgement of the physical situation while the conservative values can be used to assess the sensitivity of significant parameters. Based on these results, it is concluded that the PWR vessel under investigation will not be impaired owing to crack propagation resulting from a thermal shock caused by actuation of ECCS following LOCA condition.

1. Introduction

In the event of occurrence of Loss of Coolant Accident (LOCA) due to a postulated double ended rupture of primary coolant pipe, the reactor coolant system suddently depressurizes, activating the Emergency Core Cooling System (ECCS) and thereby rapidly injecting the coolant into the reactor vessel. By flooding the pressure vessel with cold coolant, suddenly injected upon the warmer reactor vessel wall under normal operating condition prior to the occurrence of LOCA, a thermal transient takes place across the vessel wall. This causes a severe thermal shock, resulting in high induced thermal stresses momentarily superimposed upon the mechanical stresses, which eventually could trigger a brittle fracture causing crack propogation if a surface flaw of sizeable dimension preexisted in the reactor vessel wall.

While it must be ascertained that the Safety Injection System (SIS) is adequate to protect the core from melt-down, it must be invariably demonstrated that the transient thermal stresses will not cause crack instability in the vessel wall and eventually will not impair the ability of vessel to hold the core covered with coolant. A major problem in thermal cracking, therefore, receiving considerable attention of regulatory authorities (1, 16) lies in ascertaining the fracture resistance of the vessel wall material in the event of emergency core cooling. The application of fracture mechanics technology for evaluating the integrity of a thermally shocked vessel in terms of fracture mechanics parameters, involving relatively brittle and high-strength material, has received considerable attention in recent years. It is now generally accepted that the method when properly employed, can be utilized as a useful tool for the design of new pressure vessels or for assessing the criteria of brittle failure in the existing high-strength structures. Recently, some authors (2,5,8,18) have successfully described the state of the art of the Linear-Elastic-Fracture-Mechanics (LEFM) method to design against brittle fracture failure by means of a stress-intensity consideration in which certain criteria are established for fracture instability in presence of a crack. Consequently, the basic assumptions are that a crack or a crack-like defect may exist in the vessel wall and essentially the approach is to relate the stress field developed in the vicinity of the crack tip to the applied nominal stress, the material properties, and the size of the defect necessary to cause failure. The procedure for estimating the fracture resistance of a reactor vessel in the event of emergency core cooling, is to postulate a hypothetical surface crack (of certain aspect ratio), at the inner surface of the vessel wall. Such surface cracks are usually generated by means of low cycle fatigue, resulting from cyclic startups and shutdowns, along the irradiated embrittled inner surface of the vessel wall. The LEFM analysis usually includes a fatigue crack growth evaluation, determination of critical flaw sizes for specific design transients and postulated LOCA condition.

The purpose of this paper is to estimate the factors of failure analysis in surface cracks at the inner surface of idealized cylindrical pressure vessel by means of superposition procedure of Erdogan (15) on the solutions of evaluating stress intensity factors as suggested by Paris (4,7) and Irwin (3,6). This evaluation of the structural integrity of the vessel wall is essentially based on computing nominal values of the parameters which are significant to numerical results of heat transfer coefficient at the inner surface of the wall, the NVT incident on the inside of vessel wall, the fracture mechanics model proposed and the fracture toughness of the material used. The paper, therefore, presents an integrated approach to an example of fracture mechanics evaluation of the crack propogation growth. The evaluation is done for a PWR vessel of the size and design shown in Figs. (1,3) and the analytical procedure deals with determination of stress levels by postulating a surface crack of sufficient magnitude usually generated by repeated reactor operations causing fatigue along the irradiation-embrittled inner wall. The intent of this paper is to provide an overall view of the current status of the fracture mechanics technology and its possible application for fracture prevention in large pressure vessels and other structures in the nuclear field. A fatigue crack growth analysis is performed on the most critically stressed locations (see Fig.3a,b) of the reactor vessel, assuming initial flaw sizes which are conservative upper bounds of commonly existing types.

2. Method of Analysis for Establishing LEFM-Criteria

In order to show the accuracy of predicting untolerable crack growth in the vessel wall, the failure analysis of a real structure has to be undertaken. Number of parameters assumed in the LEFM analysis greatly influence the numerical results of stress intensity factors. These parameters consist of the crack shape idealized geometry, stress concentration due to changes in the section geometry, residual stresses, thermal stresses, material properties and the influence of mean value of oscillating stresses.

The complete analysis for LEFM evaluation consists of four general areas: LOCA analysis, thermal and hydraulic analysis, stress (superposition) analysis and finally failure analysis. The method of analysis is to relate the complete stress field, developed in the vicinity of the propogating crack tip, to the applied nominal stress value on vessel wall, material properties and the size of defect necessary to cause failure. During the failure mode, ductile yielding, fatigue and brittle fracture approaches have been used. The criterion for brittle failure in the presence of a crack-like defect is that failure will occurr whenever the stress intensity factor, K_I, for vessel exceeds some critical value K_{IC}, which represents the opening mode of crack surface displacement. The elastic stress field in the vicinity of a crack-tip can be described by a single-term parameter designating the stress intensity factor K_I, for the PWR vessel wall. The magnitude of this parameter, obtained herein by considering different modes of analysis, is dependent on the geometrical configuration of the vessel containing the crack, location of such a crack and the distribution as well as the magnitude of the applied loads on the reactor vessel. The crack-tip stress intensity factors are estimated using the well-known continuous surface flaw expressions after linearizing the thermal and pressure stress distribution through the vessel wall during LOCA. For this analysis the crack was assumed to be located at the inner surface of the vessel wall (Figs. 3a, 3b), continuous to be in the longitudinal direction and propogating to the outward surface of the vessel.

2.1 Reactor Vessel Design Transients

Commonly used typical design transients for a 920 MWe PWR vessel have been adopted in this investigation. These transients, as required by the regulations of ASME-III Code, are classified are: (a) normal operation conditions, involving system startup, operation and shutdown, (b) upset conditions, involving deviations from normal conditions with the resulting loss of load, loss of flow and reactor trip, (c) faulted conditions, involving

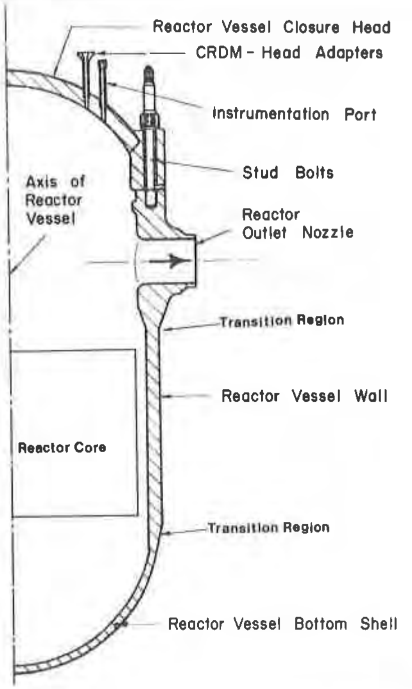

FIG. 1 Typical Pressurized Water Reactor Vessel

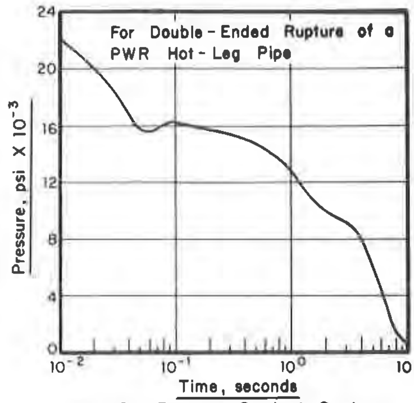

FIG 2 Reactor Coolant System Average Pressure Vs Time

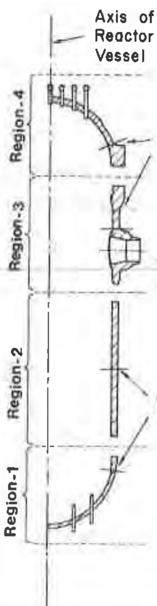

FIG.3.c PWR Vessel

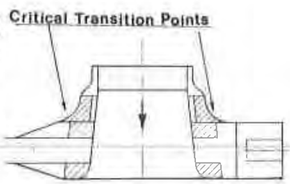

FIG 3.a Typical PWR Inlet Nozzle

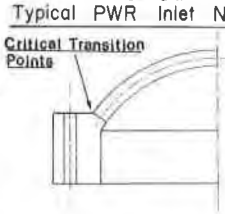

FIG 3.b Typical PWR Closure Head

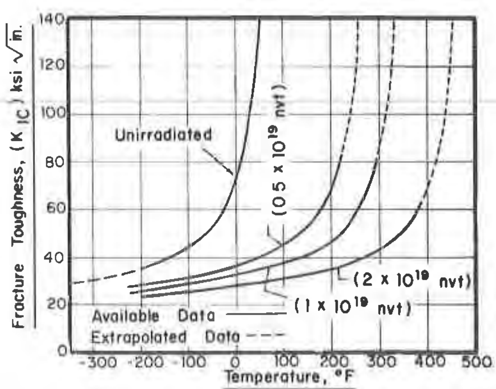

FIG 4 Material Temperature Data for a Nominal Case

critical combination associated with low probability postulated accidents and (d) test conditions, involving rigorous testing of the system both prior to and following initial startup. The structural integrity of the system under faulted condition is not considered in cyclic fatigue analysis and hence ignored herein. To provide the necessary high degree of integrity of the vessel, these transients are based on the most conservative estimates.

2.2 Loss-of-Coolant Accident (LOCA) Analysis

For critical LOCA analysis of the vessel, a double-ended rupture of the hot-leg pipe has been postulated. This condition creates the worst requirement on the emergency core cooling system (ECCS) and subjects the reactor vessel to the greatest thermal shock loading. In addition, four other pipe breaks of various sizes (0.40, 1,0, 3.0 and 8.5 ft^2) have been investigated to evaluate corresponding behaviour of the vessel wall. During LOCA, the system pressure load decays very rapidly. The reactor soon trips on low pressure before appreciable thermal stresses are built up in the vessel wall following actuation of high pressure injection (HPI) of cold water by the ECCS. The relatively low capacity of the HPI system has no significant effect on the characteristics of the blowdown. When the system has depressurized further to 600 psi, the check valves of the core flooding tank (CFT) remain open discharging additional emergency coolant into the annulus of core-support-shield and the reactor vessel wall, further depressurizing the system to 200 psi. Because of the rapid pressure drops and the resulting stresses reaching an insignificant level, only thermal stresses normal to the crack surface are of interest in the LEFM analysis. The figures 2 and 5 illustrate the reactor system average pressure and the coolant bulk temperature as functions of time after the postulated double-ended rupture of primary coolant hot-leg pipe.

2.3 Thermal Hydraulic Analysis of the System

During LOCA the heat transfer process occurring on the vessel wall is complicated by the interior surface being initially above the saturation temperature corresponding to the annulus coolant pressure. There is a likelihood of occurrence of two-phase boiling heat-transfer during the initial portion of LOCA transient. Film boiling probably does not occur since the minimum temperature differential, ΔT, required to support film boiling (17) from a vertical surface is about 380 $^{\circ}$ F. With reasonable heat transfer coefficient, the wall temperatures fall so rapidly during LOCA that such a large temperature differential cannot be easily established. A minimum heat transfer coefficient of 280 Btu/h-ft^{2}-^{o} F is needed during transition boiling. Since during actual blowdown a higher transition boiling heat transfer coefficient is expected, a conservative value of approximately 1,000 Btu/h-ft^{2}-^{o} F has been assumed herein. The most conservative assumption of the heat transfer process during ECC injection is based on the following heat transfer correlation for this situation and expressed as:

$$H_1 = 0.0292 \, \frac{k}{x} \left[\frac{\rho \; V1 \; x}{\mu} \right]^{0.8} P_r^{\;0.33} \qquad (1)$$

However, a more realistic assumption of the flow pattern during refilling consists of water jet spreading out and ultimately filling the entire annulus. In this nominal case the maximum velocity is assumed to be four times the average velocity computed from the mass flow rate, using well-known Dittus-Boelter correlation expressed as:

$$H_2 = 0.023 \frac{k}{D_e} \left[\frac{\rho\ v_2\ De}{\mu}\right]^{0.8} P_r^{\ 0.4} \quad (2)$$

The coefficients in the above equations are described as: k = thermal conductivity, D_e = hydraulic diameter, x = distance from center of inlet nozzle to critical point, ν_i = fluid velocity, μ = fluid viscosity, ρ = density of the fluid and P_r = Prandtl's number.

Based on the foregoing assumptions, the conservative and the nominal heat transfer coefficients were computed (see Figs. 3,4) after the occurrence of LOCA. As a conservative case, a heat transfer coefficient of 1000 Btu/h-ft^{2}-^{o} F was assumed for transition boiling until about 2.5 second at which time, the heat transfer coefficient from the jet becomes larger and was thus used for the remainder of the LOCA. In the nominal case however, a heat transfer coefficient of 1000 Btu/hr-ft^{2}-^{o}F was assumed for transition boiling up to 9.0 seconds at which time the blowdown is over and for the remaining time convective coefficient is used. Equations (1) and (2) are the classical equations used to calculate the heat transfer process, if the heat in the component wall is removed by forced convection.

2.4 Thermal, Mechanical and Residual Stress Analysis for the Reactor Vessel Wall

Approximate thermal stresses, in an infinitely long uncracked cylinder with radial temperature gradients during sudden chilling at its inside surface, may be calculated as furnished in the reference (12,19). Both circumferential and axial stresses ($\sigma_{\theta\theta}$ and σ_{zz} respectively) may be expressed as:

$$\sigma_{\theta\theta} = \frac{\alpha\ E}{(1-\nu)\ r^2} \left[\left\{\frac{r^2 + R_i^2}{R_o^2 - R_i^2}\right\} \int_{R_i}^{R_o} Trdr + \int_{R_i}^{r} Trdr - Tr^2\right] \quad (3)$$

$$\sigma_{zz} = \frac{\alpha\ E}{(1-\nu)} \left[\left\{\frac{2}{R_o^2 - R_i^2}\right\} \int_{R_i}^{R_o} Trdr - T\right] \quad (4)$$

in which α = linear coefficient of thermal expansion, ν = poisson's ratio, R_o = outer radius, R_i = inner radius, E = Young's Modulus and T = temperature distribution. Emery (12) has shown that these expressions are very accurate for $t/R_o < 1$ and that the temperature distribution in a cylinder initially at temperature T_o when instantaneously reduced to lower temperature T_1 may be obtained from the references (10,11). Since the infinite surface heat-transfer coefficients are not practical in the real system, the temperature response is lower than that predicted from the equations of this reference. However, the effects of delayed response reduce the heat transfer coefficients and do not change either the basic characteristics of the fracture response or the final superposition. Mechanical stresses resulting from internal pressure, dead weight and seismic loading have been also included in the overall analysis.

3. Method of Failure Analysis in the Reactor Vessel

The basic theory of Irwin (3,6) has led to the development of a linear fracture mechanics method which characterises the stress conditions in a very small region local to the crack by a single parameter, known as stress intensity factor, K_I. When the stress intensity factor increases to the critical value, K_c, which essentially is considered to be a material property, the rapid crack propagation process ensues and failure follows. However, the failure in real materials actually takes place over some distance rather than localised to a point and for engineering analysis, this distance may be small compared to the crack size. The actual failure takes place at some distance inside the vessel material in front of crack tip. Although this may involve some inadequacy, the overall evaluation with simple parameter K_c approach, will yield reasonably valid results with long crack lengths and low intensity stresses. Some investigators (3,6,7,9) recognised the inadequacies of a single material parameter (K_c) approach and to avoid singularity at the crack tip, used average conditions in conjunction with a critical stress parameters. Neuber successfully employed a two-parameter approach but Irwin (3,6) remedied the deficiencies by including the plastic zone corrections. The basic stress concentration theory adopted herein is based on both Paris (4,7) and Irwin (3,6).

3.1 Nil-Ductility Approach for Brittle Fracture Failure

The Nil-Ductility method for evaluating brittle fracture essentially consists of a stress analysis approach based on the most conservative aspects of the fracture analysis diagrams (14 to 20) and assumes a flaw size large enough to initiate a crack. The criterion adopted in the Nil-Ductility approach is based on the assumption that crack will not propagate beyond the point, where the applied stress is equal to or below the threshhold crack initiation stress or where the stress is principally compressive. This approach (5,18) involves the conservative assumption for the vessel material to support the crack propagation at a low-energy absorption or cleavage mode.

A crack arrest temperature curve through the thickness of the vessel wall has been developed on the basis of stress-temperature (σ, T) system. The maximum depth at which the material in the wall would be in tension or at which the stress in the material would exceed the threshhold stress for crack initiation may be determined from the crack tip intensity and fracture toughness distribution. It may be observed that crack could propagate through only the inner 35% to 40% depending upon the threshhold values for crack initiation. The outer 80% of the wall will reach a stage above design transition temperature without considering neutron shielding.

3.2 Linear Fracture Mechanics Approach

The LEFM approach can be used to predict a crack growth phenomena when the net stress level is below 0.8 σ_y, where σ_y = minimum yield strength of the material at the higher temperature. When the stresses exceed 0.8 σ_y, then the critical stresses predicted from an elastic solution are always conservative. However, in thermo-shock problems the stresses being invariably in the vicinity of 0.8 σ_y level, the LEFM approach will be very suitable. This method is based on the elasticity solution for stress and strain distribution at the crack tip and involves reliable evaluation of one-parameter (stress intensity factor K_I) representation for the stress field. The LEFM involves predicting the initiation of structural failure based on determination of complete stress field near the crack tip and fracture toughness properties of the material used.

3.2.1 Computation of Stress Intensity Factor

A number of elasticity solutions exist in the literature (3,4,6,7,9) for computing the

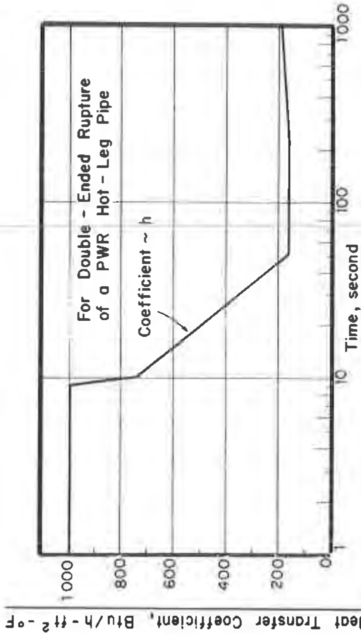

FIG.7 Heat Transfer Coefficient Vs Time for a Nominal Case

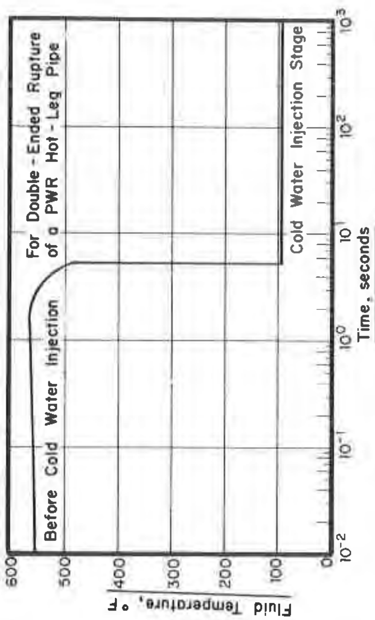

FIG.5 Reactor Coolant Bulk Fluid Temperature Vs Time

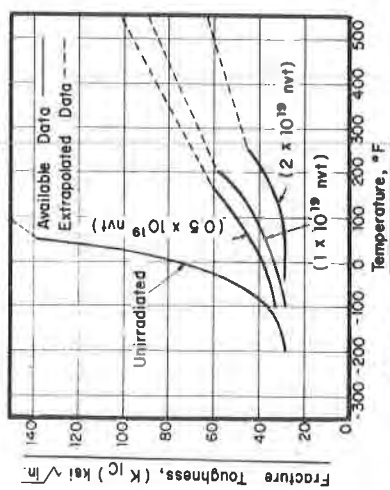

FIG.8 Material Thougness Temperature Data for a Conservative Case

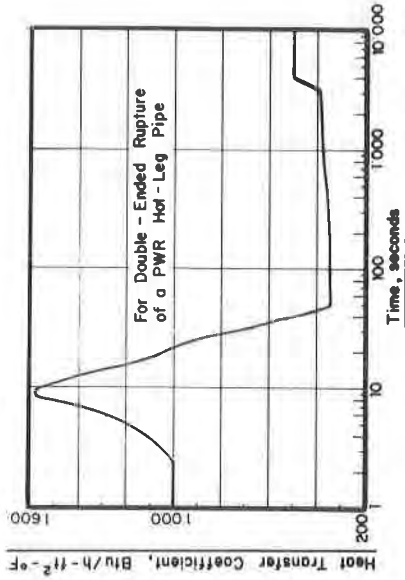

FIG 6 Heat Transfer Coefficient Vs Time for a Conservative Case

stress intensity factors and these solutions mainly apply to infinitely long bodies in which crack lengths are small in relation to the body. In some of these methods certain shortcomings limit the applications to cases where the length of the crack should not exceed 20% of the vessel wall thickness. Some of the factors contribute to the limitations of Emery's (11,12) solution and hence following relationship was developed for the stress intensity factor. The solution essentially deals with the nature of the wedge force on the surface of the cracks used in the superposition. It is entirely based on the methods proposed by Paris (4,7) and Irwin (3,6) and maybe expressed as:

$$K_I = 1.12\,\sigma_m\,\sqrt{\pi a}\left[\sqrt{(2b/\pi a)\tan(\pi a/2b) - (2\sqrt{2}/\pi)}\right] + \sqrt{(2/\pi)}\int_0^a \left(\frac{1}{\sqrt{c}}\,\sigma_c\right) dc \qquad (5)$$

in which σ_m = mechanical stress field, a = crack length, σ_c = combined thermal and residual stress field, c = distance along the crack, b = depth of the crack. The expression for σ_c can be expressed as a function of distance 'c' and integrated. Above equation was developed by applying superposition to the solution proposed by Erdogan (7,15) for a wedge type load to a semi-infinite crack in an infinite plane. The corrections proposed by Paris and Sih (9,4) were applied for the free surfaces present in the infinite-width plate. Since all the limitations of Emery's solution method have been eliminated, above equation represents the best nominal solution adopted herein.

3.2.2 Material Fracture Toughness for Vessel Wall

Knowledge of material fracture toughness data is of greatest importance. Since both the temperature and irradiation dosage vary through the thickness of the wall, it is necessary to know the combined effects of temperature and irradiation for a range of temperatures from 75 ^{o} F to 600 ^{o} F and for a dosage level of 0 to 5 x 10^{19} N/cm2. Most of the material fracture toughness data which will meet the ASTM specifications, is now available in the literature. Figure 4 presents the fracture toughness values for SA 533 (Grade B) steel calculated for the nominal case. The unirradiated data used in Fig. 4 represents the results from the HSST program and satisfy the ASTM requirements. In the extrapolation technique used, the valid unirradiated cruve was superimposed on the irradiated data, yielding a conservative limit of about 170 ksi in. The fracture toughness values calculated for the conservative case are shown in Fig. 8. In the conservative case it was assumed that the large transition of unirradiated case does not occur in the irradiated case and that the toughness would vary linearly with temperature.

3.3 Ductile Yielding and Fatigue Criteria

The criterion used for ductile yielding mode of failure is based on the condition that there shall be no gross yielding across the vessel wall when using the minimum yield strength specified in ASME-III code. As illustrated in Fig. 12, this comparison of maximum calculated stresses with material yield strength (σ_y) indicates that local yielding may occur only in the inner 8% to 10% of the vessel wall thickness. For the purpose of establishing fatigue failure criteria, the ASME-III code assumes the gross failure to occur when the cumulative usage factor (U) for all transients exceeds the allowable limit of 1.0. The safety injection

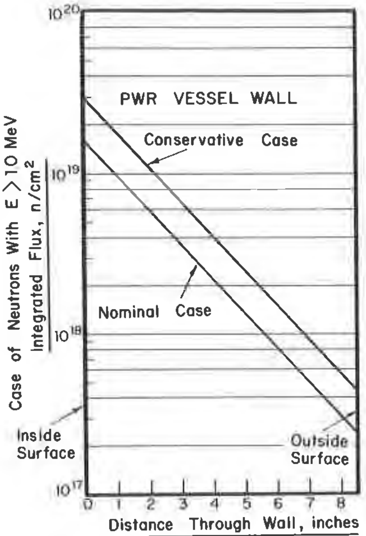

FIG 9 Integrated Neutron Flux Vs Wall Thickness

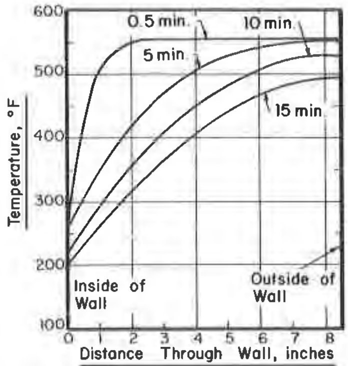

FIG 10 Temperature Distribution Across Wall (Nominal Heat Transfer Coefficient) For Each Time Interval

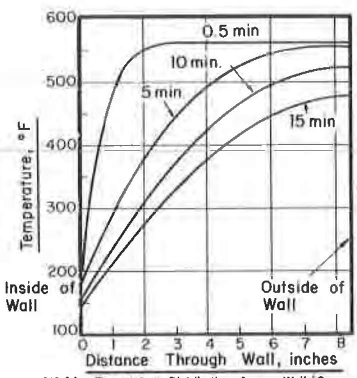

FIG 11 Temperature Distribution Across Wall (Conservative Heat Transfer Coefficient) For Each Time Interval

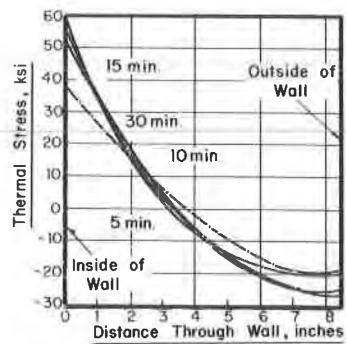

FIG 12 Thermal Stress Distribution Across Wall (Nominal Heat Transfer Coefficient)

transient is included as one of the criteria to which the wall may be subjected during its operating life. It is noted that the portion of the vessel wall (below the nozzle level attachment welds on the spherical bottom head) will experience the highest usage factor. The worst condition assumed is that the instrumentation tubes and attachment welds assume different temperature from that of the vessel wall.

3.4 Residual Stress

Residual stress amplitude and distribution in heavy welded sections have been experimentally investigated and their accurate distribution through the thickness of the welded section resemble a cosine function with maximum tensile stress at the surface and maximum compressive stress at the center of the wall. Thus, the residual stress at any point through the wall thickness is given by the function as:

$$\sigma_r = 8000 \cos (2\pi \, x/t) \tag{6}$$

The residual stress has been superimposed on the thermal stress to form a combined stress $\sigma(c)$, which is the basis for the failure analysis.

4. Numerical Results

4.1 Evaluation of Critical Performance of the Vessel during the Emergency Core Cooling Operation

The solution to the thermal shock problem for a typical 920 Mwe, PWR is based on the use of nominal values for all significant parameters, in which effects of conservatism on the overall solution has been examined. The parameters evaluated herein are: the heat transfer coefficient at the inside wall, the neutrons energy coefficients (NVT) incident on the inside of the wall, the fracture mechanics model (K_I) and the fracture toughness model (K_{IC}) of the vessel material. The time-dependent temperature distributions (see Figs. 10,11) in the vessel wall have been obtained during critical LOCA condition. These values represent for both nominal and conservative values of heat transfer coefficient at the inside wall. Using these temperature distributions, thermal stress levels for several time intervals of interest are evaluated as shown in Figs. 12 and 13. The residual stresses were computed using the Eqn. 6 and then superimposed on thermal and mechanical stress distribution to form a combined stress level denoted as $\sigma(c)$, which is then inserted into Paris-Sih (9) or Irwin (3,6) equation to evaluate the stress intensity factor K_I. The temperature, thermal stresses and stress intensity factors are calculated using computer codes through the vessel wall as a function of time. During the transient, the most critical time for crack propagation was obtained by comparison. The stress intensity (K_I) curves for the vessel wall for different time intervals, as calculated with nominal heat transfer coefficients,are shown in Figs. 14, 15, 16. These represent the stress intensity factors for a family of various crack lengths. Also shown are the curves for fracture toughness factors (K_{Ic}) based on nominal value of NVT including extrapolation. Evidently, K_{Ic}, is a function of both temperature and irradiation parameters and is found to increase sharply away from the inside surface of the wall. A crack may propagate at a point where K_I-curve rises above K_{Ic}-curve and then the crack will propagate to a depth where K_I-curve falls below the K_{Ic}-curve. This region represents the point of crack arrest. Examination of Figs. 14, 15 and 16 indicates that the stress intensity

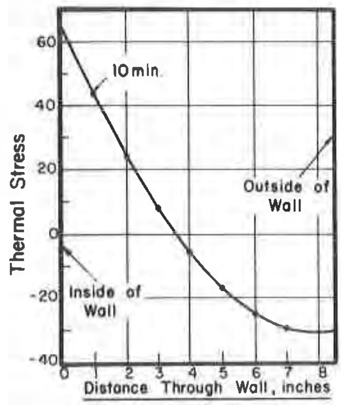

FIG.13 Thermal Stress Distribution Across Wall (Conservative Heat Transfer Coefficient)

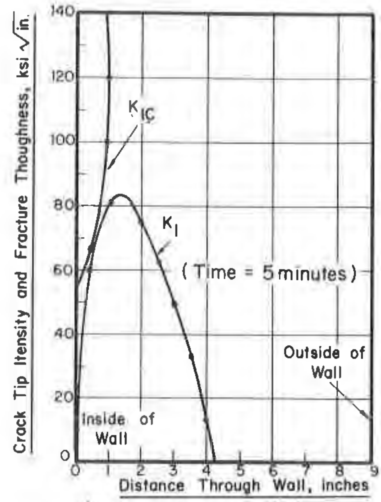

FIG 14 Fracture Analysis Case - I

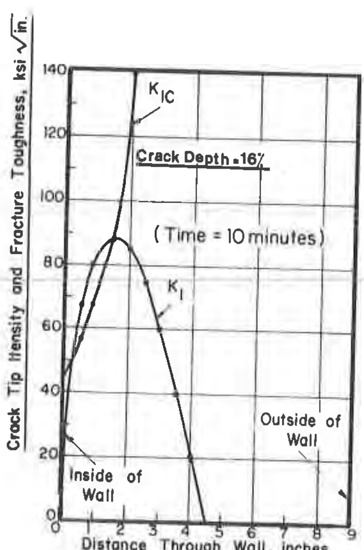

FIG 15 Fracture Analysis Case - I

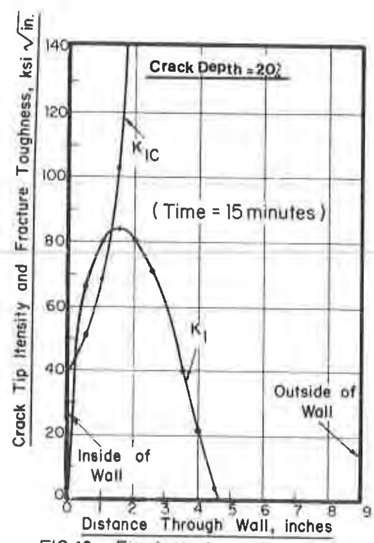

FIG.16 Fracture Analysis Case - I

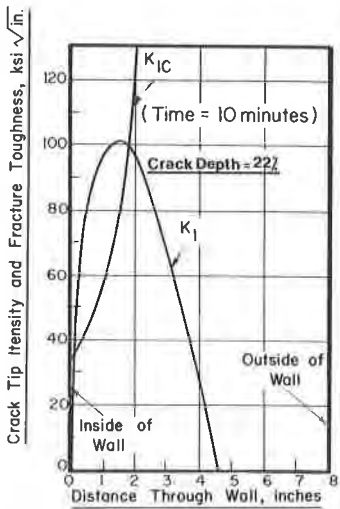

FIG.17 Fracture Analysis Case - II

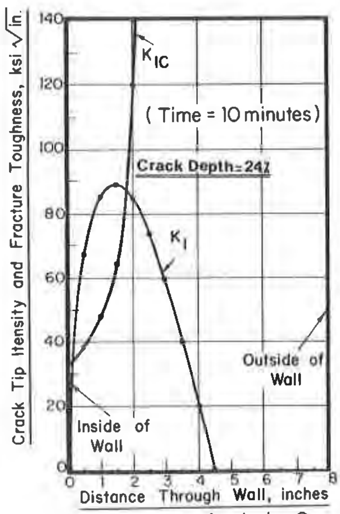

FIG 18 Fracture Analysis Case - III

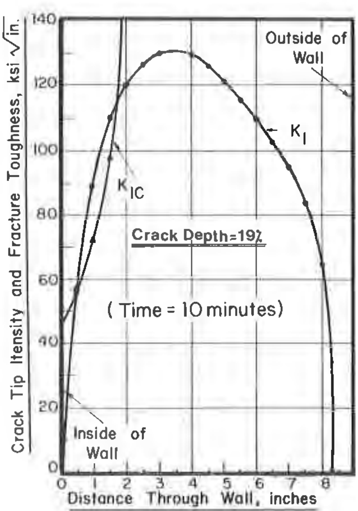

FIG 19 Fracture Analysis Case - IV

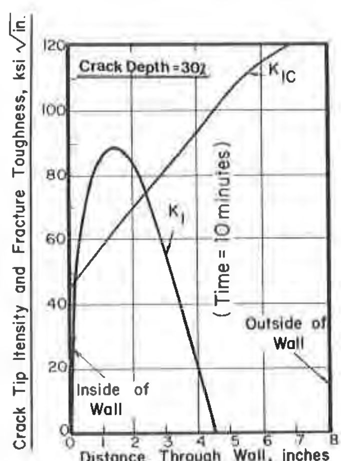

FIG.20 Fracture Analysis Case - V

factor (K_I) and the crack propagation depth would be maximum at 10 minutes after the pipe rupture. At this time, the maximum crack penetration depth would reach about 18% of the vessel wall thickness and represent the most critical condition that could occur to the vessel wall (containing a flaw) due to thermo-shock by ECCS operating during the life-time. To assess the influence of the significant parameters on the overall results, number of conditions are analysed and examined in Figs. 16 to 20.

4.2 Discussions and Conclusions

The critical penetration depths for longitudinal cracks (occurring in a circumferential stress field) are circumferential cracks (occurring in a longitudinal stress field) have indicated that circumferential cracks would not propagate as critically as would longitudinal cracks. The nominal or conservative values for each of the significant parameters used and the maximum penetration depth for longitudinal cracks are illustrated in Figs. 14 to 20., in which crack penetration varies from a low of 16% to a high of 28%. Based on the present investigation, it is concluded that the reactor vessel (920 MWe) will not lose its structural integrity due to a thermo-shock caused by ECCS, during or at the end of operational time of the vessel wall even if it contained a flaw of critical dimensions. It is noticed that the maximum crack penetration depth for the material used will not exceed 28% of the wall thickness under the action of severe ECCS operation and based on the conservative case. Also for variations of the parameters significant to the outcome of the solution over ranges considered to be reasonable, variations in fracture toughness have a much greater influence on the depth of crack penetration than do variations in the heat transfer coefficient, the integrated neutron flux and the fracture mechanics model.

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