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Fracture assessment of reactor outlet header of 500 MWe PHWR

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ABSTRACT : The fracture mechanics evaluation of important nuclear components, having postulated cracks, is an essential part of safety analysis. Reactor Outlet Header is one of the important component in Primary Heat Transport system of 500 MWe Indian Pressurised Heavy Water Reactors. In the present study, a Header having postulated through wall crack of different lengths, at one of its crotches, was analysed for internal pressure. The Critical Pressure and Critical Crack Length was evaluated. These results were used for Leak-Before-Break assessment of Header.

INTRODUCTION :

The Indian Pressurised Heavy Water Reactors (PHWRs) are pressure tube type reactors. Its Primary Heat Transport (PHT) system comprises of following components : Pressure Tubes, containing Natural Uranium fuel. The Hot and pressurised heavy water coolant, from all the pressure tubes, gets collected in Outlet Headers and then flows to Steam Generator (SG) inlet pipe through Branch Connection Pipes ('Branch Pipe'). The inner diameter of Branch Pipe and Header is same and are connected perpendicular to each other so as to form a Tee-Junction. There are two such Tee-Junctions (well separated from each other) in a Header. From SG inlet pipe the coolant flows to SG U-tubes (where it exchanges heat with secondary Feed Water) and then further passes into Inlet Headers through Pumps. From Inlet headers the coolant finally gets distributed back into Pressure Tubes. In all there are 4 Outlet and 4 Inlet Headers in the PHT system.

As a part of Leak-Before-Break (LBB) assessment of PHT components the stress & fracture analysis was done for Outlet Header ('Header'), having postulated through wall axial crack. One of the Branch Pipe-Header Tee-Junction was modelled in detail, as shown in Fig.1.

STRUCTURAL DETAILS OF HEADER :

Header along with the Branch Pipe is made up of a single forging and is designed as per ASME B&PV Code Sec.III NB, [1]. The Inner Diameter of Header and Branch Pipe is 378 mm. The nominal thickness of Header is 65 mm and that of Branch Pipe is 38 mm. The thickness in reinforcement zone, near the junction, is 65 mm for both Header and Branch Pipe. The material used for construction conforms to Specification No. : SA-350 Gr.LF2 of ASME B&PV Code Sec.II, [1]. The nominal composition of material is C-0.26% ,Ni-275ppm, Mn-0.11%, Al-1.6%, Cu-620 ppm.

The Normal Operating and Design Pressures are 1.0 & 1.11 Kg(f)/mm^2, respectively, whereas Normal Operating and Design Temperatures are 304 & 323°C.

Material Properties :

The material properties used are based on actual material testing of specimens machined from rectangular block which inturn **was** cut out of forgings used to fabricate Headers, [2]. The typical Stress-Strain curve and **J-R** curve, indicating the salient properties, are shown in Fig. 2 & Fig.3 respectively. The material tests were done at different temperatures and it was observed that at 250°C the fracture toughness is slightly lower than that at 304°C, which could be because of strain ageing. Hence, for the present study, the material properties corresponding to the temperature of 250°C, were used. The Young's Modulus of Elasticity was taken as 1.8E04 Kg(f)/mm^2.

STRESS & FRACTURE ANALYSIS :

Stress & Fracture analysis was done using Finite Element (FE) computer code "ABAQUS", [3]. A mix of 20 & 8 noded Solid Hexahedron elements were used to model the symmetric half domain. The FE mesh is shown in Fig.1. The preliminary analysis indicated that, based on stress, the crotch is the most potential location at which crack can occur and grow in axial direction along the Header and Branch Pipe. Hence, a through wall axial crack was postulated at one of the crotches such that its length along the Header and Branch Pipe is same. For this crack, the contribution to crack driving force is mainly due to internal pressure whereas, the effect of moment loads is insignificant. The postulated crack type is shown in Fig.1. Therefore, from the FE modelling considerations the symmetric half model is justified.

Leakage Crack Size :

For fracture analysis assessment, the reference crack length was taken as equal to Leakage Size Crack (LSC). The LSC was taken equal to crack size which yields Crack Opening Area (COA) such that resulting leak rate, under the normal operating conditions, is 0.5 Kg/sec, [4]. The leak rate of 0.5 Kg/sec is very high for Indian PHWRs since there is a reactor trip at much lower values of leak rate. However, for the present study value of 0.5 Kg/sec was used, to be in line with general international practice,[4], although some of the investigators have used a limiting value of 0.3 Kg/sec for PHWRs, [7]. A series of linear elastic stress analyses (on same FE model) were done for different crack lengths (under normal operating pressure) and corresponding COA and Centre of Crack Opening Displacement (CCOD) were calculated for each case. Using this information and simplified thermal-hydraulic analysis the leak rates were evaluated. In leak rate evaluation the dependence of COA and CCOD on crack morphology parameters was also considered. The crack morphology parameters considered were Local Surface Roughness (μ_L), Global Surface Roughness (μ_G), Local Average Path/Thickness Correction Factor (K_L), Global Average Path/Thickness Correction Factor (K_G), Coefficient of Discharge at Crack Entrance (C_D). The effect of COA & CCOD on these crack morphology parameters, has been brought about in the form piece-wise linear equations by Wilkowski et al, [5], in order to model the appropriate effect of small, medium and large crack opening on leak rates. For the present study the nominal values for these crack morphology parameters were taken as - μ_L=8E-3 mm, μ_G=40E-3 mm, K_L=1.02, K_G=1.06 & C_D=0.6, [5].

It was concluded that LSC is 400 mm (200 mm along the Branch Pipe and 200 mm along the Header Pipe).

Postulated Crack Lengths & FE Analysis :

The analysis was done for different postulated crack lengths, viz, 1xLSC, 2xLSC, 3xLSC, 4xLSC and 5xLSC. In each case the internal pressure was increased in small steps till the convergence can be achieved with tolerance of 1E-03 on residual forces. Fig.4 shows the Pressure v/s centre of crack deflection, for different crack lengths. Fig.5 shows J-integral (J) v/s Pressure for different crack lengths. The J values in Fig.5 are at crack tip in Branch Pipe. The J values at crack tip in Header are lower owing to its higher thickness. The J values shown here were averaged across the thickness, using Simpson's rule. The path to path variation, in J, is insignificant, if we neglect the first contour path, [3].

Instability assessment :

The PHT system of Indian PHWRs does not experience any significant Pressure Surge, due to process transients. Hence, the accident pressure was taken equal to Design Pressure (DPr). Instability assessment was done inorder to determine the Critical Pressure (Pcr) for 1xLSC and Critical Crack Length (CCL) for DPr. The instability criterion followed, is given below :

Plastic Instability : The pressure or crack length at which plastic collapse occurs, or
Tearing Instability : The pressure or crack length at which -
J (for applied pressure) > Ji (initiation J) **&** Tearing Modulus under applied pressure (Tapp) > Material Tearing Modulus (Tmat).

The Pcr and CCL were taken as, lesser of the two instability pressure and crack length. The Plastic Instability pressure or crack length was based on Twice-the-Elastic-Slope criteria, [1], and was evaluated form pressure v/s deflection curves.

The Tearing Instability pressure evaluation is shown in Fig.6 & Fig.7. Fig.6 shows the J v/s pressure for 1xLSC, whereas, Fig.7 shows the Tapp (for 1xLSC) and Tmat v/s J curves. The value of J, at which the two curves intersect, was projected on J v/s pressure curve (for 1xLSC) and corresponding instability pressure was evaluated.

The Tearing Instability crack length evaluation is shown in Fig.8 & Fig.9. Fig.8 shows the J v/s crack length curve, for DPr., whereas, Fig.9 shows the Tapp (for DPr) and Tmat v/s J curves. The value of J, at which the two curves intersect, was projected on J v/s crack length curve (for DPr) and corresponding instability crack length was determined.

In both the Tearing Instability analyses, it was observed that Tmat v/s J curve (see Fig.7 & Fig.9) had to be extrapolated because measured J-R data is available upto limited value of crack extension (=8 mm), [2]. The extrapolated Tmat v/s J curve is shown by dotted lines in Fig.7 & Fig.9. The extrapolation was done such that, the slope of extended Tmat v/s J curve is same as the slope at the point upto which measured data is available, [7]. The difference between the instability J for applied loads and maximum value of material measured J is not significant. In view of this it can be stated that effect of this approximation is not significant.

The results of Plastic Instability & Tearing Instability analyses and values of Pcr and CCL are shown in Table 1.

DISCUSSIONS :

For the LSC of 400 mm the margins against , initiation of stable crack growth (J > Ji), Pcr and CCL are shown in Table 2. The minimum required margins, as per SRP-3.6.3, USNRC, [6], are also shown. From these analyses and fracture assessment criterion, it can be stated that Reactor Outlet Headers of Indian PHWRs satisfy the LBB requirements and can be exempted from break postulation.

Table 1 : Summary of Analysis Results

Plastic Instability Pressure for 1 xLSC.	4.0 $Kg(f)/mm^2$
Plastic Instability Crack Length for Design Pressure (DPr).	1400 mm
Tearing Instability Pressure for 1 x LSC.	2.86 $Kg(f)/mm^2$
Tearing Instability Crack Length for DPr.	1473.7 mm
Critical Pressure (Pcr) for 1 x LSC	2.86 $Kg(f)/mm^2$
Critical Crack Length (CCL) for Design Pressure (DPr).	1400 mm

Table 2 : Summary of Available & Required Margins

Margin	Available	Required
Margin on Pcr (=Pcr/DPr)	2.58	1.44
Margin on CCL (=CCL/1xLSC)	3.50	2.00
Margin on Pressure to cause Initiation of Stable Crack Growth, for 1xLSC (=Pji/DPr)	1.62	------
Margin on Crack length resulting in Initiation of Stable Crack Growth, for DPr (=CLji / 1xLSC).	2.00	------

Notes : Pji : Pressure at which J > Ji ; CLji : Crack Length at which J > Ji

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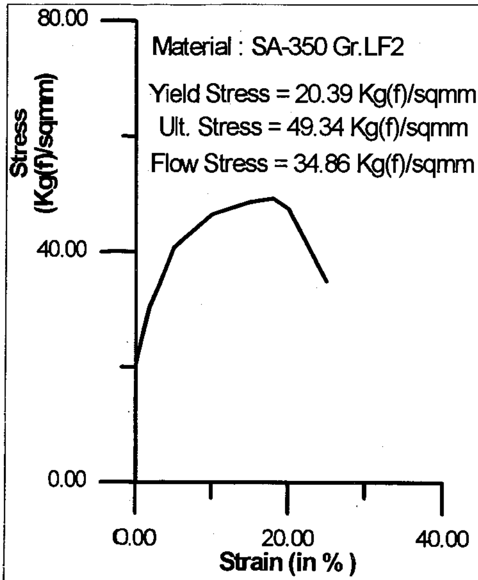

FIG. 2 : Stress-Strain Curve at 250 deg. C

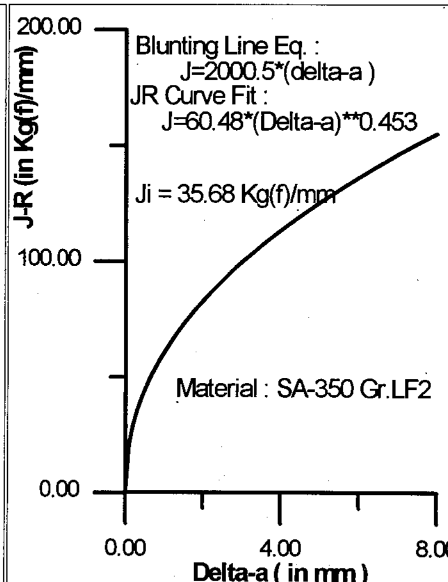

FIG. 3 : Material J-R Curve at 250 deg.C

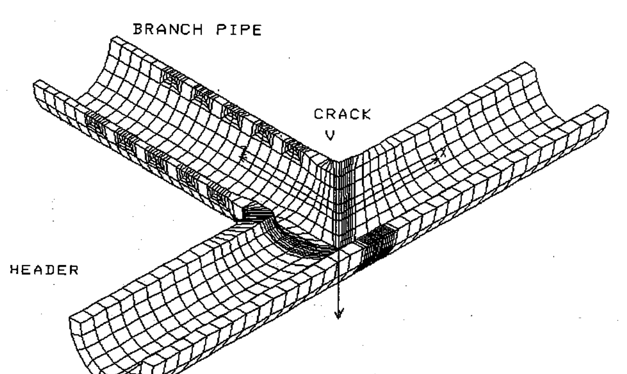

FIG. 1 : SYMM. HALF FE MESH OF REACTOR OUTLET HEADER WITH POSTULSTED THROUGH WALL CRACK AT CROTCH

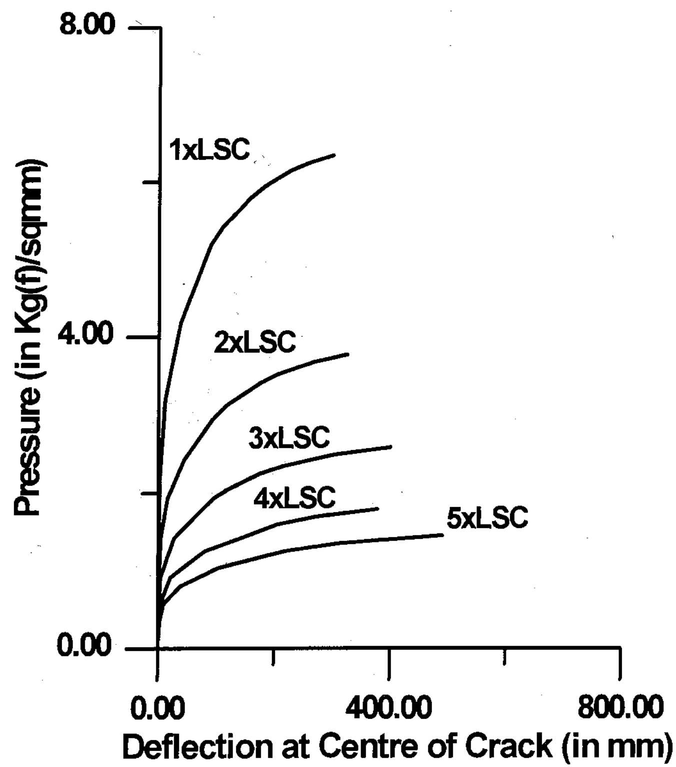

FIG. 4 : Pressure v/s Deflection for different crack lengths

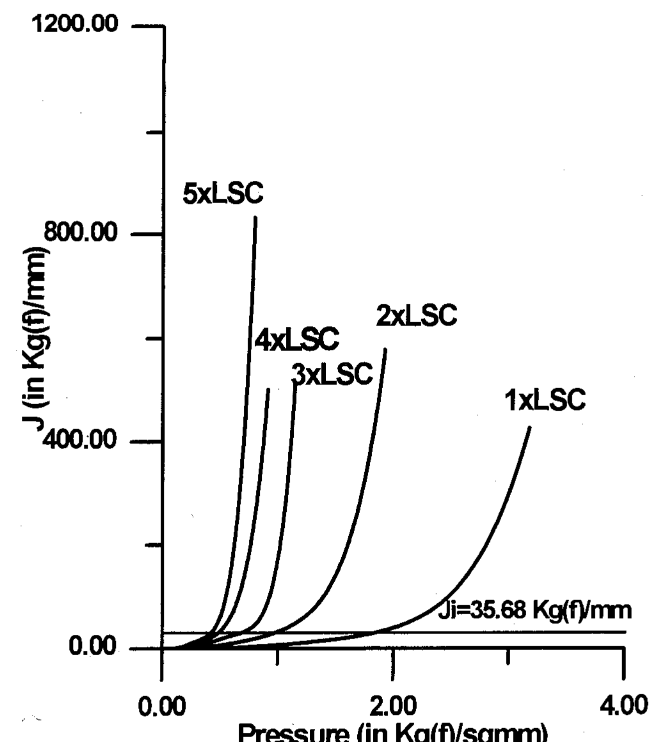

FIG. 5 : J v/s Pressure for Different crack lengths

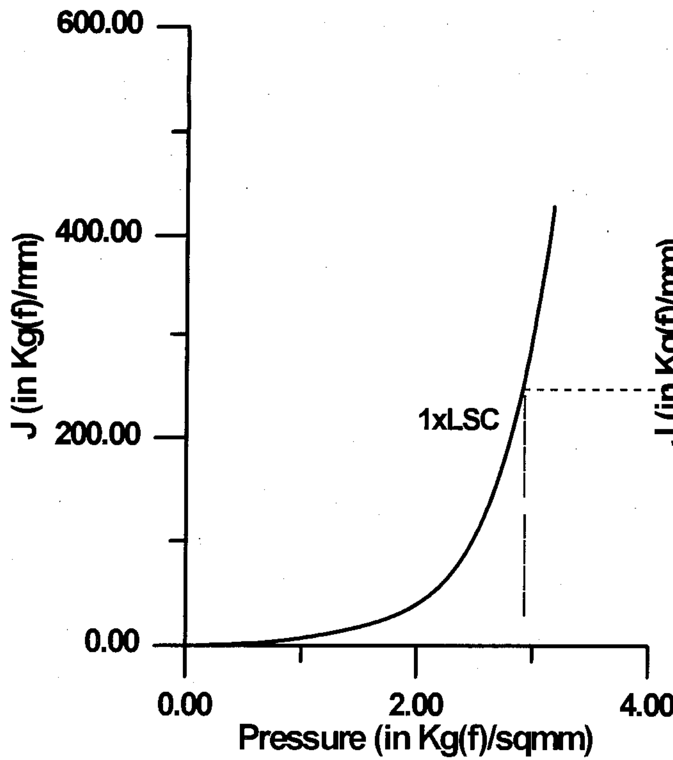

FIG. 6 : J v/s Pressure Curve
1xLSC

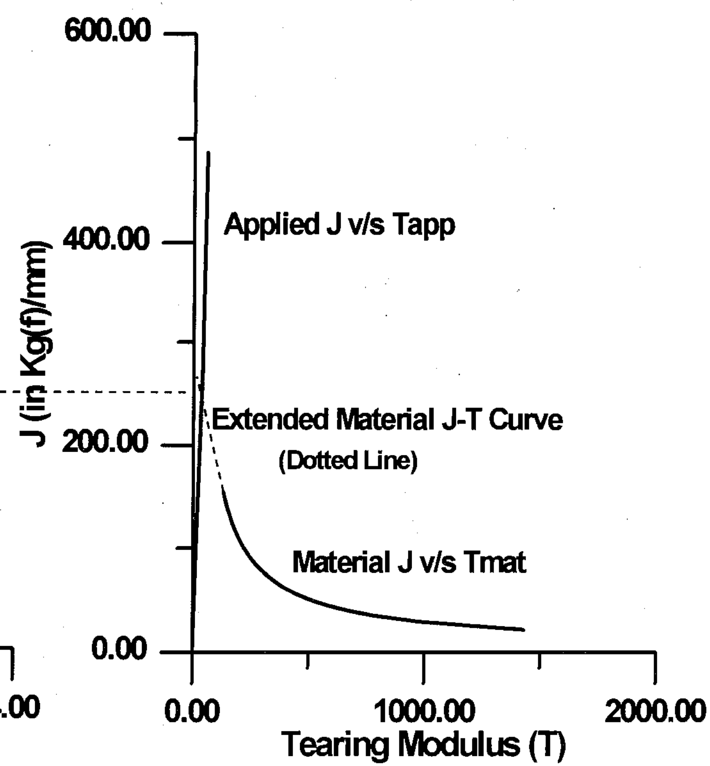

FIG. 7 : Tearing Analysis for evaluating
Critical Pressure for 1xLSC

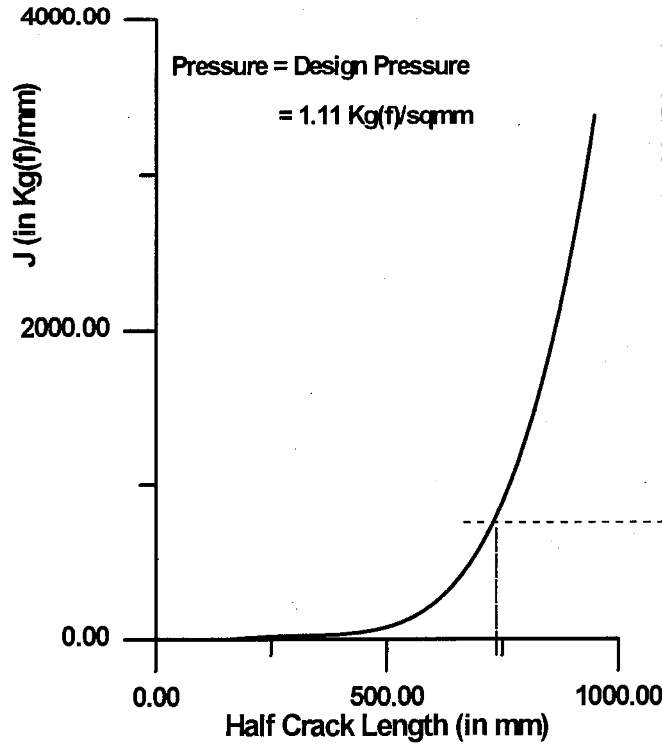

FIG. 8 : J v/s Half Crack length (c) for normal operating pressure

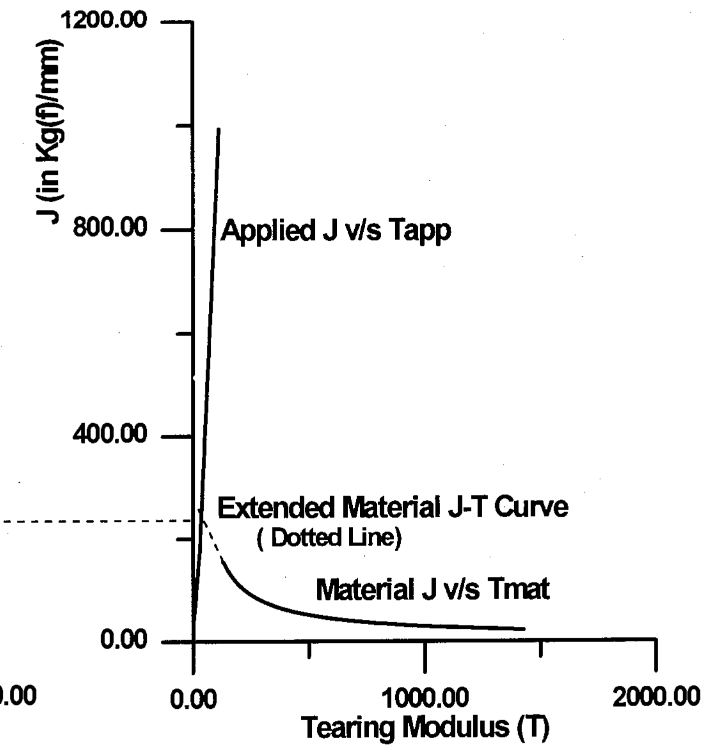

FIG. 9 : Tearing analysis for evaluating Critical Crack length for Normal Operating Pr.