STRUCTURAL INTEGRITY EVALUATION OF PRIMARY PUMP DISCHARGE PIPES OF PFBR

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1 INTRODUCTION

In the Reactor Assembly of Prototype Fast Breeder Reactor (PFBR), the primary pumps discharge cold sodium at 653 K to the fuel, blanket and reflector sub-assemblies, through four pipes which are termed here as 'primary pump discharge pipes'. The discharge pipe (OD is 670 mm) consists of a bend portion (bend radius is 900 mm) and a straight portion (2400 mm in length) as shown in Fig.1. While one end of the pipe is hinged to the pump discharge, the other end of the pipe is bolted to the grid plate. Structural integrity of this pipeline is very important from the safety point of view. Although it is highly unlikely that in normal conditions more than one of the discharge pipes could fail at one time, the breach would provide a low resistance by pass around the core which would greatly reduce the coolant flow to the core. In a severe seismic events, there is a possibility of simultaneous failure of two or more discharge pipes would arise. Apart from this, there is a great difficulty of access for inservice inspection of this component. Hence the material, design, manufacture, inspection and testing of these pipes are based on the highest quality standards.

A detailed structural analysis of this component under various operating conditions, including severe seismic loading has also been undertaken to ensure its integrity. This includes analysis for mechanical loading (mainly due to an internal pressure of 0.8 MPa & centrifugal force generated due to the rate of change of fluid momentum), thermal shocks following secondary/feed water pump trips and seismic loadings with 0.065g for OBE and 0.2g SSE. Analysis is further extended to demonstrate that there is no loss of integrity, even with the presence of an initial defect at the highly stressed zone with assumption of a severe violation of the manufacturing specifications. These detailed studies help to finalise the present concept (single wall concept) and dimension of the pump discharge pipe (particularly, the thickness).

In this paper, the results of various analyses performed towards assessing the integrity of primary pump discharge pipes are reported.
2 ANALYSES

2.1 Analysis for mechanical loading under normal operating condition

Calculations have been done to evaluate the stress distribution in the pipe bend portion under internal pressure of 0.8 MPa and also for the centrifugal force due to the change of fluid momentum. The bend portion of the structure has been modelled with 3D thin shell elements. A general view of the mesh is given in Fig.2. An elastic analysis has been performed with program BIIBO. The maximum positive hoop stress in the bend portion is about 43 MPa.

2.2 Analysis for thermal shock

Following secondary/feed water pump trips, the cold pool temperature is increased by 90 K in 100 s (Kasinathan.N, 1990). Transient heat conduction analysis has indicated that this transient induces a hot shock of about 40K in the thickness direction which results in 97 MPa (baxial tension in the outer surface of pipe).

2.3 Analysis for seismic loading

Analysis has been done for OBE of 0.065 g (ZPA) and SSE of 0.2 g (ZPA). First phase of analysis is for natural modal behaviour by considering the discharge pipe. The inertial effects of fluid, roof and core masses are all properly accounted using added mass approach. The analysis is done with shear deformable beam elements of PAFEC code. In order to validate the simplified approach followed here, the natural frequencies associated with the main vessel and core support structure, computed using simplified analysis with 3D beam elements are compared with those obtained by detailed fluid structure interaction analysis with INCA code. The natural frequency of first bending mode of main vessel with present simplified approach is 6.9 Hz, where as it is 6.5 Hz by detailed FSI analysis.

Two important modes that have contributed significantly in stressing the discharge ducts under seismic loadings are shown in Fig.3a and Fig.3b which correspond to 6.92 Hz and 18 Hz respectively. The analysis for seismic response is performed in two stages. In the first stage, the beam model is analysed for global response with the computed floor response spectra at support location of the conical skirt support at the reactor vault. Then the bend portion has been analysed for local stress distributions by imposing end displacements on the boundaries, which are computed with global analysis. It is to be noted that in case of response spectrum analysis which is followed here, local stress analysis has to be done for each mode and finally total stresses at the local critical locations are computed by SRSS method, in order to account for the proper sign for each displacements.

The important deformation in the bend portion is due to ovalisation mode which is shown in Fig.4 for the case of OBE. This ovalisation leads to circumferential bending stress which is depicted in Fig.5. The value shown in the Fig.4 & 5 are corresponding to the mode of frequency 6.9 Hz (Fig.3a). Analysis has been done similarly for other modes and finally SRSS values are used for the design verification calculations. The maximum circumferential stress at the critical location is 27.6 MPa for OBE of 0.065 g (ZPA) and 84.7 MPa for SSE of 0.2 g (ZPA)
2.4 Life prediction

The following load cycles are considered which are supposed to give a conservative estimate of life. Circumferential stress ranges associated with each load cycles are also included.

<table>
<thead>
<tr>
<th>No.</th>
<th>Load cycle</th>
<th>Stress Range</th>
<th>No. of cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Shut down - OBE during hot shock - Shut down</td>
<td>154.8</td>
<td>50</td>
</tr>
<tr>
<td>2.</td>
<td>Shut down - SSE during hot shock - Shut down</td>
<td>211.7</td>
<td>10</td>
</tr>
<tr>
<td>3.</td>
<td>Shut down - Hot shock              - Shut down</td>
<td>127.2</td>
<td>60</td>
</tr>
</tbody>
</table>

2.4.1 Initial crack definition

The location, configuration and dimension of artificial initial crack assured in the analysis is shown in Fig.6. This longitudinal crack is assumed at the location where the maximum stress in circumferential direction occurs. Based on the ASME Section XI criteria (ASME 1989) Japanese work towards MONJU reactor studies (Sakakibara 1981) and French work done towards SFK2 reactor pipe bends (Bhandari 1986), a longitudinal crack of depth (a) of 3 mm and length (2c) of 30 mm is assumed in the present analysis.

2.4.2. Conventional fatigue approach for crack initiation

The number of cycles to crack initiation (No) is calculated using the concept developed by R.L.Roche(Roche 1989). The equivalent stress range is calculated at the distance d from the notch root. The value of d = 0.04 mm is assumed here based on the reference (Bhandari, 1986). In the present case, small scale yielding is approximately assumed and hence simple elastic calculation is found to be sufficient. The equivalent stress range at distance d from crack tip is calculated following the procedure given in (Bhandari 1986) which is worked out to be 711 MPa for SS 316 IN with associated strain range as 0.47 %. From the design fatigue curve No is equal to 8.8x10 cycles. The variation of number of cycles due to possible variations in d, R (fillet radius at crack tip) etc., is in the range of 8.0 x 10 to 9.6 x 10. These many number of cycles are required to cause crack initiation which may be conservatively assumed to cause leakage. These cycles cover 760 to 800 plant lives. As per ASME design philosophy, it is sufficient if we have a factor of safety on life 20, i.e., crack initiation should not occur before 20 plant lives.

However detailed fracture mechanics analysis is carried out subsequently to verify the above approach.

2.4.3 Fracture mechanics analysis

a. Analysis for ligament instability

In a structural component with an initial surface crack, the leakage is said to occur if the ligament, i.e., uncracked portion in the thickness, becomes unstable. For defining the ligament instability, two mechanisms, viz., formation of plastic hinge and local plastic instability at the section, are considered. Two approaches: one based on fracture mechanics
and another based on limit load analysis, are generally used. Fracture mechanics approach is considered for the formation of plastic hinge and limit load analysis is applied for the local plastic instability at section of our interest. Based on thorough investigations on both the approaches, the ligament instability criteria, i.e. criteria for leakage, defined by 'BATTELLE MODEL' gives an conservative estimate. Based on this model, critical combinations of a/t (ratio of crack depth and thickness) & 2c (crack length) which result in ligament rupture or leakage, have been obtained and this is indicated in Fig.8. Subsequently surface crack propagation analysis has been done with the initial crack size assumed as a/t = 0.3 & a/c = 0.2 (this corresponds to crack depth of 3 mm and length of 30 mm). For the crack propagation analysis, the relevant PARIS equation is integrated over load cycles defined earlier. Cycles correspond to more than one plant life are considered in the crack propagation studies in order to obtain the crack size which satisfies the leakage criteria. Analysis indicated that ligament rupture or leakage is possible only after 820 plant lives, i.e., after 820 times the operating load cycles defined earlier. The development of initially assumed surface crack to reach a size at which it meets the ligament instability criteria under cyclic loading conditions, is illustrated in Fig.7a and 7b.

It is to be noted that the well simplified conventional fatigue approach has predicted this as 760 - 800 plant lives which is very much interesting and encouraging. The resulting crack size at the time of leakage has crack length is equal to about 100 mm (corresponds to point C in Fig.8). Sodium which is at pressure of 0.8 MPa will leak through this crack and the computed leakage rate is about 740 g/s.

b. Analysis for global instability

Analysis has also been performed to estimate the crack size, in this context, it is through crack length to cause global rupture. For this, calculations have been done with Fracture Mechanics Approach (wherein the effects of gross yielding ahead of crack tip has been considered) and also using Tearing Modulus Approach. The analysis indicated that pipe will rupture globally if the through crack length of 475 mm is formed (corresponds to point E in Fig.8). Even after 820 plant lives, the crack length formed at the time of leakage is only 100 mm and hence there is sufficient margins between the crack length at leakage and crack length for rupture.

3 CONCLUSION

Detailed analyses for pressure, thermal transient and seismic loadings indicate:

- A single wall with 10 mm thickness is needed to meet the ASME/RCC-MR code rules under all the possible loading conditions including seismic loadings corresponding to 0.065 g OBE & 0.2 g SSE (horizontal).
- The design loading cycles can not cause crack initiation before 760 plant life cycles.
- Sodium leakage is possible only after 820 plant life cycles at which there is insignificant leakage (about 740 g/s).
- The margin between the crack length developed at the time of leakage (≈475 mm) and the final size which causes global rupture (≈100 mm) is very large and there is no risk of global rupture.
REFERENCES


![Diagram of a reactor assembly](image1)

**Fig1**

![Diagram of a geometrical detail of primary pump discharge pipe](image2)

**Fig2. Finite element mesh of discharge pipe portion**
Fig 3a. Coupled vibration mode of discharged pipe at 6.92 Hz

Fig 3b. Coupled vibration mode of discharged pipe at 18 Hz

Fig 4. Ovalisation in the bend pipe at the critical section due to OBE of 0.065g

Fig 5. Circumferential stress distribution in the bend pipe due to OBE of 0.065g ZPA.
Fig 6. Crack characterisation in the pipe bend portion

Fig 7. Development of crack propagation

Fig 8. Fracture assessment chart for primary pump discharge pipe