Theoretical Explanation for the Acceptability of Steam Generator Tubesheet-Shell Junction under Manufacturing Deviation

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ABSTRACT

In 500 MWe Prototype Fast Breeder Reactor (PFBR), steam generator (SG) is a critical component as its availability decides the capacity factor of the plant. Nuclear heat generated with in reactor assembly is carried by secondary sodium to the SG. SG is a shell and tube type heat exchanger, where sodium is on the shell side and water/steam is on the tube side. The presence of the sodium and water on either side of the shell of SG will make the system very much important from the structural integrity considerations. The hot sodium (525°C) enters at the top of SG and leaves at the bottom at lower temperature (355 °C). The material of construction is modified 9 Cr–1 Mo (G91) steel.

The shape of SG tubesheet-shell junction with the dished end is optimized based on the detailed thermo mechanical calculations using 3D finite element method. While manufacturing the SG tubesheet header, a small circumferential notch (3.3 mm x 3.1 mm) has been found in the conical shell. Even at the cold end of SG (bottom header), the possibility of thermal shocks at the notch under transient cannot be avoided. Hence the notched geometry is not favored from the fatigue strength considerations.

This paper discuss about the measures carried out to accept notched header tubesheet-shell junction for the SG.

INTRODUCTION

A 500 MWe Prototype Fast Breeder Reactor (PFBR) is under construction at Kalpakkam. PFBR is a sodium cooled pool type reactor where the entire radioactive primary sodium circuit components including the core are housed within a single vessel called main vessel. In this reactor, nuclear heat generated is getting removed by means of primary sodium circuit, which is confined with in reactor assembly. The secondary sodium circuit brings nuclear heat out of reactor assembly. The PFBR flow chart is shown in Fig.1. In this circuit, steam generator (SG) is an important component, where in nuclear heat is transferred from sodium to water to produce steam. SG is a critical component because both sodium and steam co-exist, which can react violently in case of any direct contact and produce high temperature and pressure, threatening its structural integrity. The sodium leak from the SG, in case of shell rupture, can react with ambient air resulting in sodium fire and will lead to plant outage and non-availability of SG. Because of the above concerns of safety and economy, the structural integrity of SG shall be demonstrated in all respect.

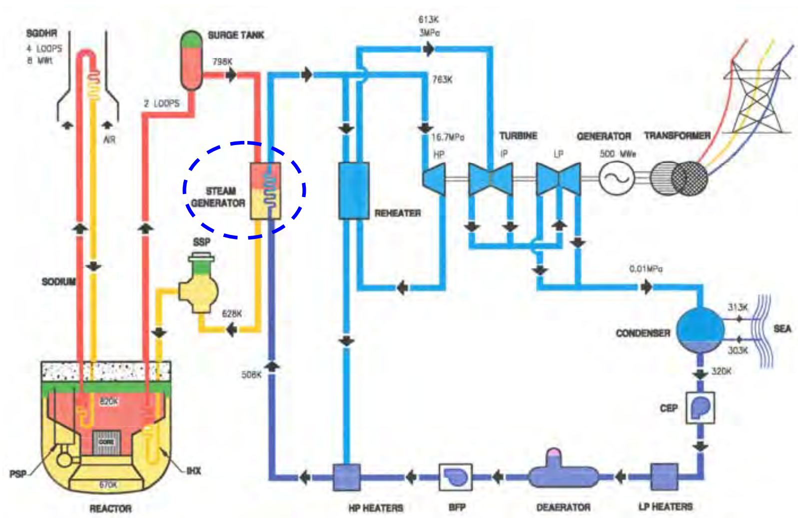

Fig.1: PFBR flow sheet

Steam Generator (SG) is a shell and tube, once through vertical heat exchanger (Fig.2). The material of construction is modified 9 Cr–1 Mo (G91) steel. The sodium enters the shell side at 525°C at the top and leaves at 355°C at the bottom. The water enters the tubes at 235°C at the bottom and leaves the tube bundle as superheated steam of 493°C at the top. Each tube has a sine wave bend to accommodate differential thermal expansion. All these 547 tubes are welded to thick perforated plates (tube sheets) at either end. The thickness of the tube sheet is provided as minimum as possible to reduce discontinuous stresses developed at the junction due to thermal transients and thereby to have better thermo-mechanical behavior. The details of these shape optimization studies carried out for the tube sheet-shell junction of SG header are available in ref.[1].

While manufacturing one of the SG headers, a small circumferential notch (3.3 mm x 3.1 mm) has been found in the conical shell. Even if the tube sheet with this notch(defect) is used in the bottom header (cold end), it will be subjected to hot shocks and hence the notched geometry is not favored from the structural integrity (fatigue damage) considerations.

Critical components having defects are not put in service particularly when they operate at high temperature and subjected to cyclic loadings. This paper discusses about the theoretical investigations and further modifications carried out to accept the SG tubesheet-shell junction under manufacturing deviation.

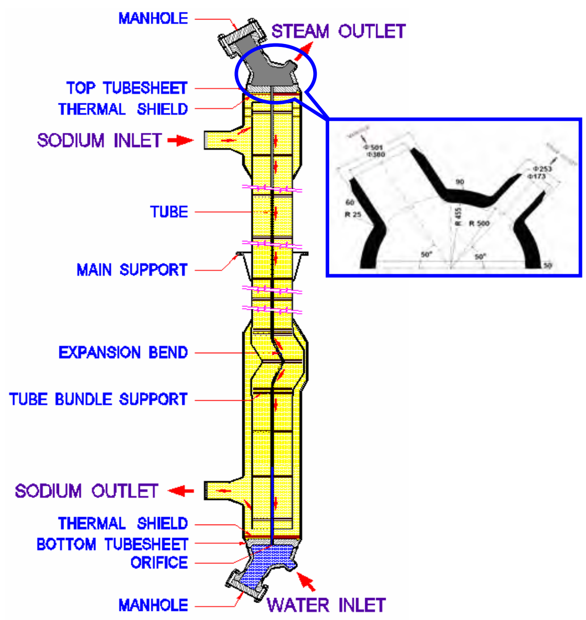

Fig.2: Schematic of the steam generator

GEOMETRICAL & MATERIAL DETAILS

Tubes and hence tube holes in SG tube sheets are arranged in equilateral triangular pitch. The pitch and diameter of the hole is 32.2 mm and 12.72 mm respectively. The effective radius of the perforated portion is 400 mm and its thickness is 150 mm. The geometrical detail of the notched geometry is given in Fig.3. The dimensions of the notch are 3.3 mm x 3.1 mm.

The material of construction is modified 9Cr–1Mo (G91) steel. For the perforated region, the ligament on one side is facing sodium at 525^{o}C and the tube hole inner surface and ligament on the other side are facing steam at a temperature of 498^{o}C (with 1% margin). Since the location-A (from Fig.4) is coming in contact with the sodium (which is at 525^{o}C), the following material properties are taken from ref.[2] at 525^{o}C for the analysis:

Modulus of elasticity (E) = 1.69 x 10^{+5} MPa
Poisson's ratio (ν) = 0.3
Allowable stress intensity (S_m) = 136 MPa

Tubesheet is modeled as equivalent solid plate with effective elastic constants E* and ν*. The E* and ν* are calculated as per ref.[3]. The calculated value of E*/E is 0.645 and ν* is 0.286, which are used for equivalent solid portion (up to 400 mm radius) of the tubesheet.

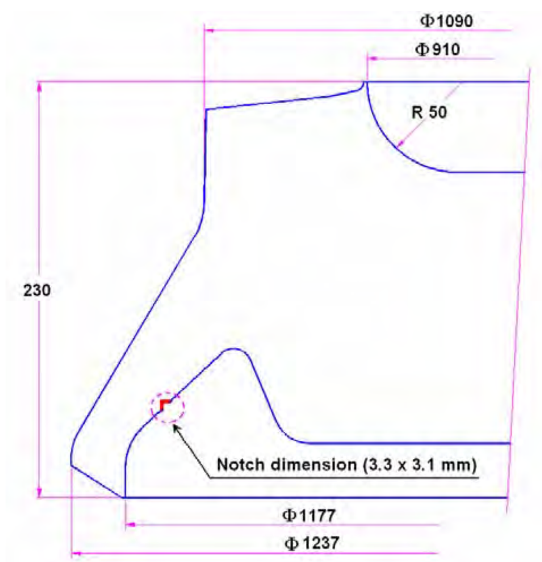

Fig.3: Notch details

NOTCH IMPLICATION

The presence of the notch acts as the area of stress riser in a component. Hence it is the weakest part in a component from the life consideration. Even if the tube sheet with notch(defect) is used in the bottom header (cold end), it will be subjected to hot shocks and hence the notched geometry is not favored from the fatigue considerations. Critical components having defects are not put in service particularly when they operate at high temperature and subjected to cyclic loadings.

LOADING CONDITION

The maximum pressure on the top surface of tubesheet is 18.6 MPa and that of bottom side is 0.4 MPa. Since the tubesheet is perforated in nature, the equivalent pressure of 15.6 MPa is applied on the top surface of equivalent solid plate and the respective pressures are applied on the remaining surfaces.

STRESS ANALYSIS

The stress analysis is carried out under pressure loading to determine the effect of the notch (increase in stress due to stress concentration) in the conical shell of SG tubesheet-shell junction using the software CAST3M. The initial geometry and defective geometry are analysed and compared.

Initial Geometry

FE model of the geometry along with the conical shell (location of notch in defective geometry is identified by point ‘A’) is shown in Fig.4. Analysis has been done for the loading conditions mentioned above. The hoop, axial and radial stress at the concerned location (location-A from Fig.4) is –4 MPa, -13 MPa and –19 MPa respectively. The respective Von-Mises stress at this location is 13.1 MPa.

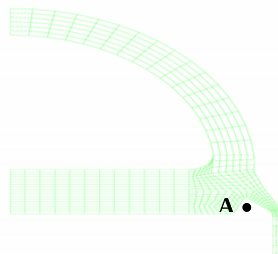

Fig.4: FE model of the initial geometry

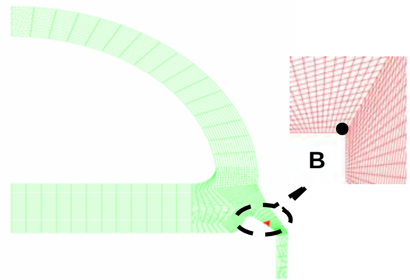

Fig.5: FE model of the notched geometry

Defective Geometry

FE model of the geometry along with the notch is shown in Fig.5. Analysis has been done for the loading conditions mentioned above. The hoop, axial and radial stress at the root of the notch is –80 MPa, -130.5 MPa and –160.6 MPa respectively. The respective Von-Mises stress at this location is 70.5 MPa. The Von-Mises stress distribution is given in Fig.6. If we further refine the mesh, the stresses at the notch location will go up. It shows that, very high stress concentration exist at the conical shell of SG header, which will lead to the reduction in fatigue strength.

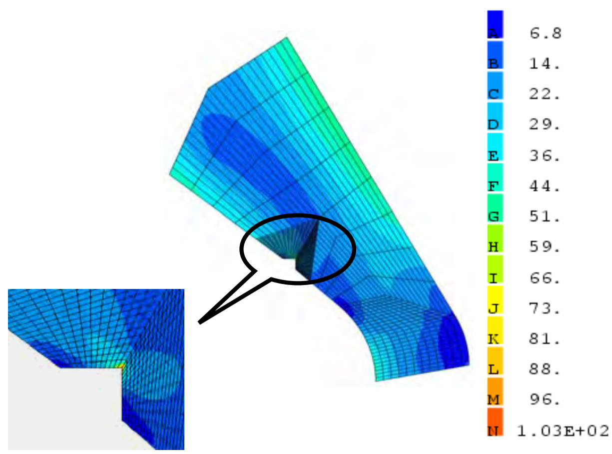

Fig.6: Von-Mises stress distribution

Results and Discussion

It may be seen that the hoop stress in the vicinity of the notch increases around 20 times and the axial /radial stress increases around 10 times than that of the initial geometry. If we further refine the mesh, the stresses at the notch location will go up indicating a very high stress concentration. Thus the presence of notch reduces the fatigue strength of the component. Hence such notch is not favored in case of critical components like SG to have high reliability.

RECOMMENDATION BASED ON ANALYSIS

Based on the analysis, it is recommended to machine the conical shell with a larger radius of 175 mm so as to eliminate the notch so that the stress concentration is avoided. In the recommended geometry high stress concentration is removed (by machining the notch) and the increase in stresses due to reduction in thickness has to be checked with the acceptable limit of RCC MR [4].

ANALYSIS OF THE MODIFIED GEOMETRY

The analysis has been done for the modified geometry of the SG header with the same loading condition. The hoop, axial and radial stress at the concerned location is –7.2 MPa, -17.6 MPa and –28 MPa respectively. The respective Von-Mises stress at this location is 18 MPa. The Von-Mises stress distribution is given in Fig.7.

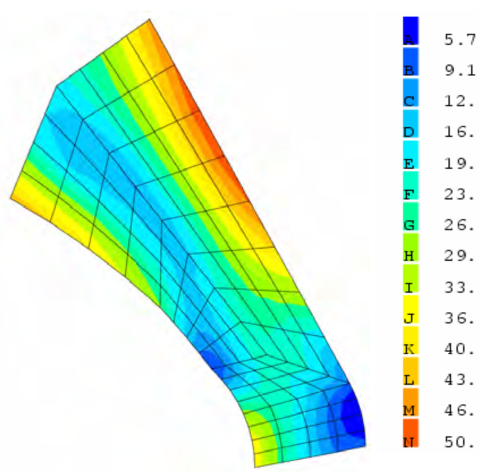

Fig.7: Von-Mises stress distribution for the modified geometry

The analysis indicates that the stress contour in the modified geometry is smooth without any stress concentration.

Thus the recommended modifications to avoid the notch in the SG header are acceptable. The machining at the conical shell with a larger radius of 175 mm so as to eliminate the notch is reducing the net thickness. However the increase in membrane plus bending stress intensity is insignificant (13 MPa to 18 MPa) and the value is much below the acceptable limit of RCC-MR. Thus the modified geometry is recommended to use at the cold end (bottom tube sheet header portion) of SG with out any fear of structural integrity.

CONCLUSION

SG is a critical component as its availability decides the capacity factor of the plant. While manufacturing the tube sheet-shell junction of SG header, a small circumferential notch (3.3 mm x 3.1 mm) has been found in the conical shell on sodium side. Even if it is used in the cold end (as the bottom header), the notch location will be subjected to hot shocks. Analysis shows that the stresses in the vicinity of the notch increase around 20 times than that of the actual geometry. If we further refine the mesh, the stresses at the notch location will go up and thus the presence of notch reduces the fatigue strength of the component. One has to treat this geometry as sharp discontinuity and follow σ-d approach for analysis. However a component with an observed notch is not used (installed) in critical applications. Hence the notch is to be removed.

It is proposed to machine the conical shell to remove the notch with the criteria of avoiding sharp / sudden change in geometry so as to have smooth stress contour and minimum machining. Towards these, the conical shell having notch is to be machined with a larger radius of 175 mm. The analysis indicates that the stress contour in the recommended geometry is smooth without any stress concentration. Further the increase in membrane plus bending stress intensity due to reduction in thickness after machining is insignificant (13 MPa to 18 MPa) and the value is much below the acceptable limit of RCC-MR.

REFERENCES

1. P.Chellapandi, et al. 'Tubesheet design for PFBR steam generator ', SMiRT 11 Transactions Vol.E. Tokyo, Japan, 1999 .
2. RCC-MR Section I, Subsection Z, "Technical Appendix A3", 2002.
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