Stress analysis of inner vessel for pool type fast reactor

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ABSTRACT

The reference design for the PFBR (Prototype Fast Breeder Reactor) inner vessel which seperates hot sodium from cold sodium, is a single wall concept. Preliminary elastic analysis indicated that the vessel does not meet the criteria of ASME code case N-47 as well as the French code RCC-MR. Detailed inelastic analysis including creep and plasticity effects indicated that single wall design can meet the above code requirements. This paper presents the details of the structural analyses that have been carried out to optimise the shape of the vessel and the results of elastic as well as inelastic analyses.

1. INTRODUCTION

The inner vessel of PFBR is a specially shaped fabrication that seperates hot sodium from cold sodium. Two concepts, viz., single wall concept and intermediate plenum concept are under consideration. This paper deals with the single wall concept which consists of a lower cylinderical shell, upper cylinderical shell and a conical step joining the above two shells. The conical portion has twelve penetrations with stand pipes for the passage of four pumps and eight heat exchangers. The vessel has to withstand the loads due to the self weight including the stand pipes, level difference between the hot and cold pool, axial and radial temperature gradients during normal operation, thermal shocks arising out of reactor scram and other thermal transients.

The present paper covers design conditions for PFBR inner vessel, shape improvement studies, elastic and inelastic analysis.

2. DESIGN CONDITIONS

Reactor inlet temperature	= 653 K (380°C)
Reactor outlet temperature	= 803 K (530°C)
Weight of the vessel with 12 stand pipes	= 85 tonnes
Life of vessel	= 2 X 10^5 hrs.

During normal operation, the radial and axial temperature gradients are assumed to be 60 K and 100 K/m and during reactor scram the radial temperature gradient goes to -60 K whereas the axial gradient vanishes. These temperatures are based on preliminary estimate. Detailed thermal hydraulic studies are in progress. In the present analysis the only thermal transient considered is that due to a reactor scram, whose frequency is assumed to be 1000 in the entire life. This number is on the higher side and the excess value assumed will take care of the effects of other possible transients.

3. SHAPE IMPROVEMENT STUDIES

In the first phase of analysis the inner vessel is approximated as an axisymmetric shell structure and analysed using conical shell elements. The effects of various parameters like radius of bend (toroid) joining the cylinderical and conical shells, cone angle and the shell thickness on the primary stress intensity have been studied and are presented in fig.1. to fig.3. The improved shape based on these studies is shown in fig.4. However, from fabrication considerations, the shape shown in fig.5. is preferred and the present paper refers to this. Other shape in fig.4. is also under study.

4. ELASTIC ANALYSIS

The axisymmetric model of the vessel is divided into 150 conical shell elements with more number of elements near the bend and stand pipe locations. A more realistic stress picture is obtained by analysing a 15° sector of the vessel. This is done using SAPIV thin plate/shell elements. Totally 574 elements are used in the analysis and this model is shown in fig.6.

Elastic stresses based on axisymmetric model as well as 15° sector model are compared in table.1. It is seen that the sector model gives lower stresses due to the stiffening effect of stand pipes which is not taken care in the axisymmetric model. Further the location of the maximum stress intensity has been shifted from the bend location (as predicted by axisymmetric model) to the location near the junction of stand pipe with the conical portion. Having elastically computed primary as well as secondary stresses in hand the vessel is checked for the design adequancy as per ASME code case N-47 (1983) as well as the French RCC-MR (1985) and further by using a simplified procedure which has been adopted for SNR-2 reactor (Vinzens 1986). The results of elastic analysis indicated that the vessel does not meet the above code rules.

Table 1. Comparison of results by axisymmetric model and 15° sector model

Details	Axisymmetric model		Sector model	
Tip displacements (mm)				
Radial	0.205		0.223	
Axial	-2.656		-2.373	
Stress values (MPa) at the bottom bend	σ_1	σ_θ	σ_1	σ_θ
Inner face	8.66	-28.35	7.9	-26.05
Neutral plane	-4.69	-32.33	-4.6	-28.99
Outer face	-18.05	-36.31	-16.94	-32.08

5. INELASTIC ANALYSIS

Since the inner vessel does not meet the code rules through elastic analysis, detailed inelastic analysis has been carried out by using an inelastic computer code 'CONE'. This code computes elastic-plastic-creep strain values for any axisymmetric structure subject to cyclic mechanical/thermal loads. It makes use of the interim guide lines laid down by O.R.N.L (Corum 1974). The material data for SS316 (material for vessel) are taken from RCC-MR. The stress-strain curve corresponding to monotonic loading condition is used for analysing first load cycle only and the calculations for the subsequent cycles have been based the cyclic stress-strain curve corresponding to the saturated cycle. The analysis has been carried out for the first four load cycles after which the accumulated inelastic strain increments are found to be stabilised and hence linear extrapolations have been done to get the total accumulated inelastic strains at the end of the life.

6. RESULTS AND DISCUSSIONS

ASME N-47 and RCC-MR impose certain limits on the accumulated inelastic strain values as well as the total creep and fatigue damage at the end of the life. The followings are some of the important results of the analysis:

i. Elastic analysis indicates:

a. the vessel does not meet ASME N-47 strain limits whereas it meets RCC-MR strain limits.

b. the total creep damage as per ASME N-47, RCC-MR and simplified proceedure are 1.33, 40 and 2.04 respectively.

c. the total fatigue damage as per N-47, RCC-MR and simplified proceedure are 5.0, 0.25 and 0.0625 respectively.

Hence the vessel does not meet the criteria of any of the above codes.

ii. Detailed inelastic analysis indicates at the end of life:

a. the wall averaged membrane strain	= 0.005%	(< 0.5%)
b. linearised membrane + bending strain	= 0.082%	(< 1.0%)
c. maximum local strain	= 0.090%	(< 2.5%)
d. total creep damage	= 0.6	(<0.77)
e. total fatigue damage	= 0.017	

The vessel meets the criteria of both the codes through inelastic analysis. The fig.7. and fig.8. show the variation of effective stress and accumulated membrane inelastic strain increment at each load cycle. In order to assess the conservatism involved in the 3 different procedures employed in the analysis, table.2 is constructed.

Benoist (1984) and Griffin (1985) quoted that the creep damage under compressive load can be reduced by factor 4 and 5 respectively. In the inner vessel the maximum creep damage occurs at the inner surface where temperature is high and stresses are compressive in nature. Hence the above reduction factors have been utilised to obtain the maximum permissible radial temperature gradient for which the vessel just meets the high temperature code criteria and this value works out to be around 95 K.

7. CONCLUSION

PFBR single wall concept of inner vessel has been shape optimised based on stress analysis and the detailed inelastic analyis indicated that the same can meet the high temperature code requirements provided temperatrue gradient across the wall is about 80 K - 90 K. Detailed thermal hydraulic studies are in progress to confirm this.

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Table 2. Comparison of permissible cycles by various procedures

	Elastic		Simplified	Inelastic
	B-47	RCC-MR	SNR-2	N-47/RCC-MR
Creep damage/ cycle (D_c)	$1.3x10^{-3}$	$40x10^{-3}$	$2x10^{-3}$	$0.6x10^{-3}$
Fatigue damage/ cycle (D_f)	$5.0x10^{-3}$	$0.25x10^{-3}$	$0.063x10^{-3}$	$0.017x10^{-3}$
Total damage/ cycle ($D=D_c+D_f$)	$6.3x10^{-3}$	$40.25x10^{-3}$	$2.063x10^{-3}$	$0.617x10^{-3}$
Admissible damage (D_m)	1.0	1.0	0.9612	0.9646
No of permissible cycles ($N=D_m/D$)	158	25	466	1563

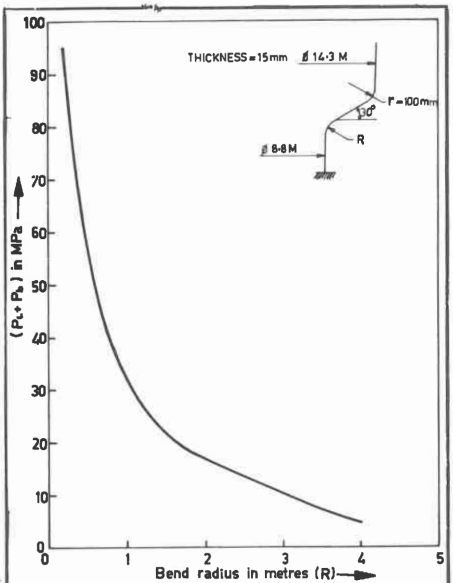

Fig-1- Effect of bend radius on primary stress intensity.

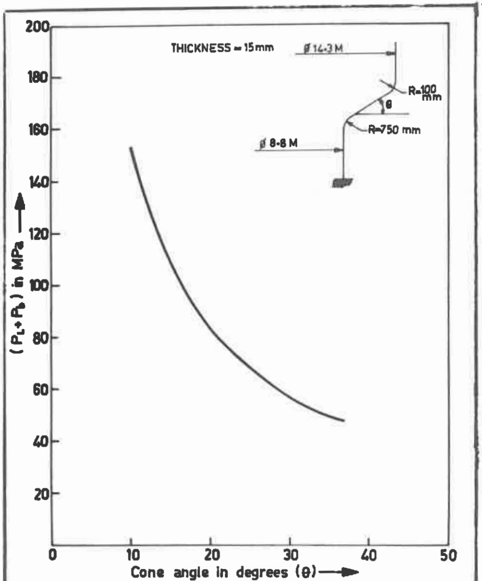

Fig-2- Effect of cone angle on primary stress intensity.

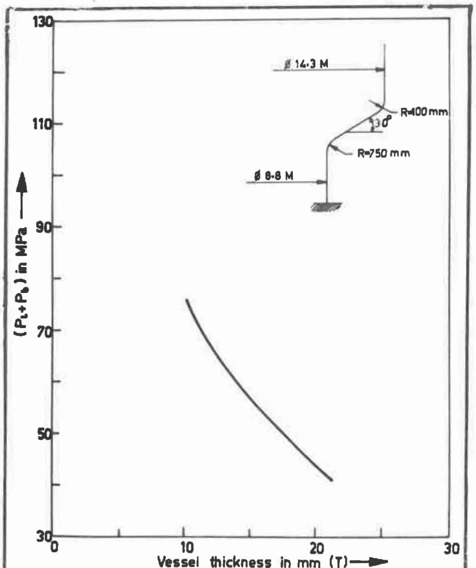

Fig-3- Effect of vessel thickness on primary stress intensity.

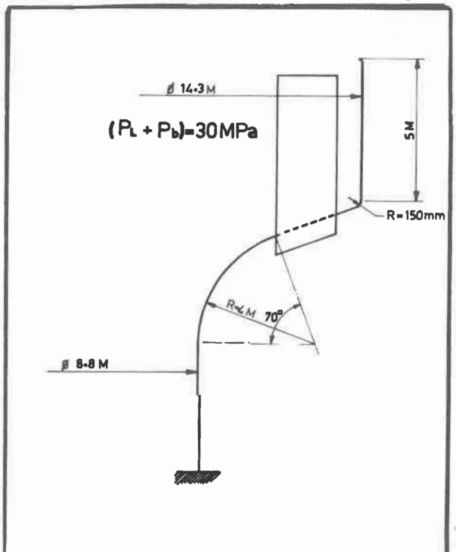

Fig-4- Improved shape for inner vessel.

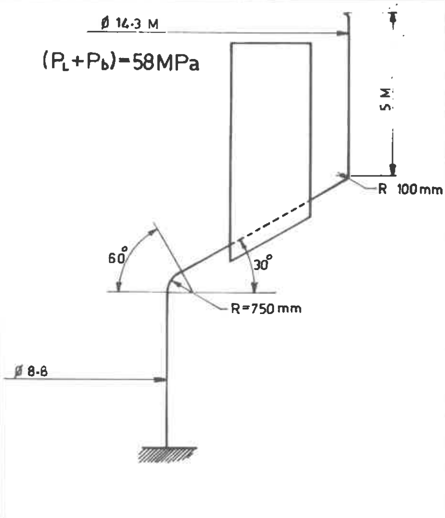

Fig-5- Proposed shape for PFBR inner vessel.

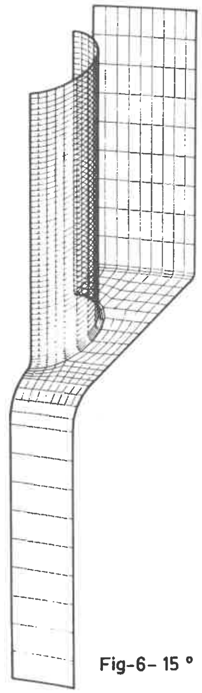

Fig-6- 15° Sector model of inner vessel.

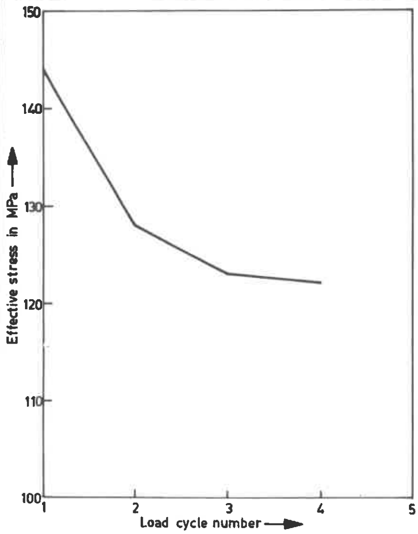

Fig-7- Effective stress at each load cycle during normal operation.

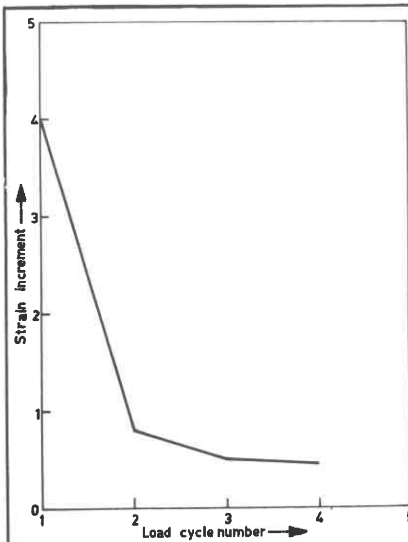

Fig-8- Inelastic membrane strain increment at each load cycle.