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Allowable temperature rise and lowering rates during startup and shutdown for FBTR

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ABSTRACT

The allowable temperature rise rate during reactor start up and lowering rate during reactor shutdown has got impact on the availability of reactor at full power and thus on the economy of the reactor. Based on detailed study of reactor vessel construction, three junctions have been selected for detailed thermo-mechanical analysis that are considered to affect the rates. The three critical junctions are analyzed for thermal transients. Considering the allowable stress for each junction for startup and shutdown, temperature rise rate and lowering rate are arrived at, while optimizing for total time for startup and shutdown

1.0 INTRODUCTION

Fast Breeder Test Reactor (FBTR) is a 40 MWt (13.2 MWe) fast reactor. The load cycles in FBTR consist of 1000 startup-shut down-startup and 250 reactor scrams for the design life of 20 years. The cold shut down temperature of sodium in the reactor vessel and primary piping is 453 K (180°C) and normal operating temperature of sodium for 40 MWt operation is 793 K (520°C) and inlet temperature for 40 MWt operation is 653 K (380°C). This paper deals with the allowable temperature rise rate during startup lowering rate during shutdown. With less rate at which the temperature is raised or lowered, the availability of reactor at full power is affected, resulting in decrease of capacity factor. High rise rate and lowering rate results in high transient thermal stresses at various junctions in the reactor vessel.

It is very important to establish the acceptable rate of temperature rise during start up operation and acceptable rate of temperature lowering during shutdown based on detailed investigation of transient thermal stresses at various junctions in the reactor vessel. Based on detailed study of reactor vessel construction, three junctions have been selected for detailed thermo-mechanical analysis. They are :

1. Junction of Upper shell and Main Flange of Reactor Vessel.
2. Junction of Reactor Vessel and Double Envelope.
3. Junction of Reactor Vessel and Primary Outlet Pipe.

These three junctions are indicated in the schematic reactor assembly in Fig.1 and are shown in detail in Fig.2, Fig.3 and Fig.4 respectively. Other junctions in reactor vessel are judged to be less or negligibly affected during start up and shutdown.

Detailed transient thermal and stress analyses are carried for the above three junctions and allowable temperature rise rate during start up and lowering rate during shutdown are arrived at.

2.0 ANALYSIS METHODOLOGY

If a structure, consisting of thick vessel and thin vessel joined together, is subjected to a thermal transient; during the transient, stresses are developed due to differential thermal expansion between thick part and thin part. This is due to the differences in transient thermal response of both the parts under isothermal heating of sodium. However, after the transient, when steady state is attained, the stresses reduce due to isothermal condition of the structure. So it is necessary to carry out transient thermal analysis and to find out the maximum stress value which occurs during the transient. Considering this, the reactor vessel construction is carefully observed for such junctions and the junction of reactor vessel and main flange has been selected for detailed analysis.

Also, if two shells are connected at a point and the annular space between them is filled with a gas of very low thermal conductivity (like Nitrogen), the outer shell responds very slowly than compared to the inner shell, when the inner shell is subjected to a thermal transient. This results in increase of stresses at the junction of two shells during transient but reduces finally to a low value during the subsequent steady state. Based on this, the junction of reactor vessel and double envelope is considered for detailed analysis.

Finally, if two concentric pipes are coupled together and the annular space between them is filled with a gas of very low thermal conductivity (like Nitrogen), the outer pipe responds very slowly than compared to inner pipe, when the inner pipe is subjected to thermal transient. This causes temperature difference between the two pipes to attain a maximum value during the transient and subsequently reducing to a low value when steady state is attained. This results in increased forces and moments at the junction of inner pipe and its connected component during transient due to higher temperature difference between inner and outer pipe. Based on this the junction of reactor vessel and primary outlet pipe has been selected for detailed analysis.

At all the junctions, the temperature of sodium is increased from 453 K (180°C) to 793 K (520°C) at different assumed rates. For the junction of reactor vessel and main flange the temperature below grid plate is increased from 453K (180°C) to 653 K (380°C) at the same rate as the outlet sodium temperature is increased.

3.0 SUMMARY OF RESULTS OF ANALYSES

3.1 Junction Of Upper Shell And Main Flange of Reactor Vessel

Schematic sketch of the junction of upper shell and main flange of reactor vessel subjected to temperature transients during start up operation is shown in Fig.2. The temperature above grid plate is varied from 180°C to 520°C while the temperature below grid plate is varied from 180°C to 380°C in the same time span at different rates of temperature rise. It is observed that stresses are of low order even for a rate of 300 K/h since the conductivity of sodium is very high and hence sodium wetted components immediately responds to the temperature transient, even if the components connected together are of different thickness. So, It can be concluded that sodium wetted components are not critical to decide the temperature rise rate and temperature lowering rate.

3.2 Junction Of Reactor Vessel And Double Envelope

Schematic sketch of the junction is shown in Fig. 2. 2-D Axisymmetric Finite Element(FE) model is used for both thermal and stress analysis. The FE code PAFEC is used for transient thermal analysis and the FE code INCA is used for subsequent stress analysis. Temperature is increased from 180°C to 520°C over a typical length of inside surface of reactor vessel at the bottom end of model at different rates. It is observed that it takes very long time for maximum stress value to reach at the junction which can be concluded as steady state value. Associated highest stresses over the transient for that rate are extracted and a curve is plotted for Stress Intensity Vs Startup Rate. Temperature distribution at the junction for a rate of 60 K/h is shown in Fig.6 and associated stress distribution is shown in Fig.7.

3.2.1 Determination Of Allowable Rates

Since this junction is subjected to low temperatures creep damage is negligible. Only fatigue damage is significant. The allowable strain range for this junction corresponding to computed elastic stress of 670.0 MPa (According to RCC MR 1995) and considering a fatigue strength reduction factor of 1.25 for full penetration welds, is 0.494 . The allowable stress range for this strain range is 568.0 MPa. It was found out that for this allowable stress the allowable temperature rise rate and allowable temperature lowering rate for this junction are more than 150 K/h.

3.3 Junction Of Reactor Vessel And Primary Outlet Pipe

Schematic sketch of the junction of reactor vessel and primary pipe is shown in Fig.4. Transient thermal stresses due to transient temperature distribution at the junction for reactor scram are found to be very low and hence damage due to reactor scram is negligible. However, stresses due to piping reaction forces and moments during transient are high and hence detailed analysis for them is carried out. Analysis model of primary pipe and double envelope for transient axial temperature distribution is schematically shown in Fig.5. Radiation heat transfer between primary pipe and double envelope is considered in the analysis. Temperature of sodium in the primary pipe is increased from 180°C to 520°C at different rates of temperature rising and lowering. The finite difference heat transfer analysis code HEATING is used for the analysis. Temperature of primary pipe, double envelope and difference of temperature between them are shown in Fig.9, for a typical temperature rise rate and lowering rate. Maximum temperature difference for a rate is extracted and associated stress intensity at the junction of reactor vessel and primary pipe is computed by FE analysis. The superimposed original and deformed shape of the junction and Von Mises stress distribution for a moment loading on the primary pipe is shown in Fig.8

3.3.1 Determination Of Allowable Rate

According to RCC MR 1995,

Stress to rupture corresponding to 10^5 h at 520°C = 348.0 MPa

After accounting for creep strength reduction factor of 0.97, the acceptable stress to rupture = 337.6 MPa

The allowable strain range for 10^5 h at 520°C = 0.260

After allowing for fatigue strength reduction factor of 1.25 over strain range, the allowable strain range = 0.208

Equivalent elastic stress range for above stress to rupture and allowable strain range = 284.0 MPa

From Fig.9 it can be seen that the temperature difference between primary pipe and double envelope reverses its sign during shutdown and hence causing reverse of sign in stresses at the junction. Therefore, essentially the allowable stress intensity range should be distributed between startup and shutdown in such a way that the total time taken to startup and shutdown operations obtained from temperature rise and lowering rates which are in turn obtained from the allowable temperature differences between primary pipe and double envelope for the particular individual allowable stress intensity, should be minimum. This requires that the allowable temperature rise and lowering rates should be optimized for the total time for startup and shutdown.

Variation of total time with temperature rise rate during startup operation and variation of temperature rise rate with temperature lowering rate during shutdown to satisfy the allowable stress range limit, are shown in Fig.10. It can be seen that minimum total time occurs at a startup temperature rise rate of about 81 K/h and corresponding shutdown temperature lowering rate is 90 K/h.

4.0 CONCLUSION

Three critical junctions in reactor vessel are analyzed for thermal transients to find allowable temperature rise rate during startup and lowering rate during shutdown. It is found that sodium wetted components are not deciding the allowable rates due to high thermal conductivity of sodium. The allowable temperature rise rate and lowering rate for this junction are well above 300 K/h. The junction of reactor vessel and double envelope is stressed highly during a transient but it is also not crucial for deciding the allowable rates because it causes only fatigue damage and creep damage is negligible. The allowable rates for this junction are more than 150 K/h. The junction of reactor vessel and primary outlet pipe is highly stressed at high temperatures where in creep damage is also significant. Considering the allowable peak stress intensity at this junction, and optimizing the temperature rise and lowering rates for minimum total time of startup and shutdown, a temperature rise rate of 81 K/h during startup and a temperature lowering rate of 90 K/h during shutdown is arrived at.

Based on all the above values, a temperature rise rate of 81 K/h (1.4 K/min) during reactor startup and a temperature lowering rate of 90 K/h (1.5 K/min) during reactor shutdown can be considered for allowable rates. However, for practical purposes, a temperature rise rate of 60 K/h during startup and corresponding temperature lowering rate of 120 K/h which is obtained form graph (Fig. 10), are recommended as the maximum allowable rates.

The analysis carried out above is for sodium systems only. Temperature rise and lowering limits from water-steam system (in particular, turbine) has to be assessed separately and respected.

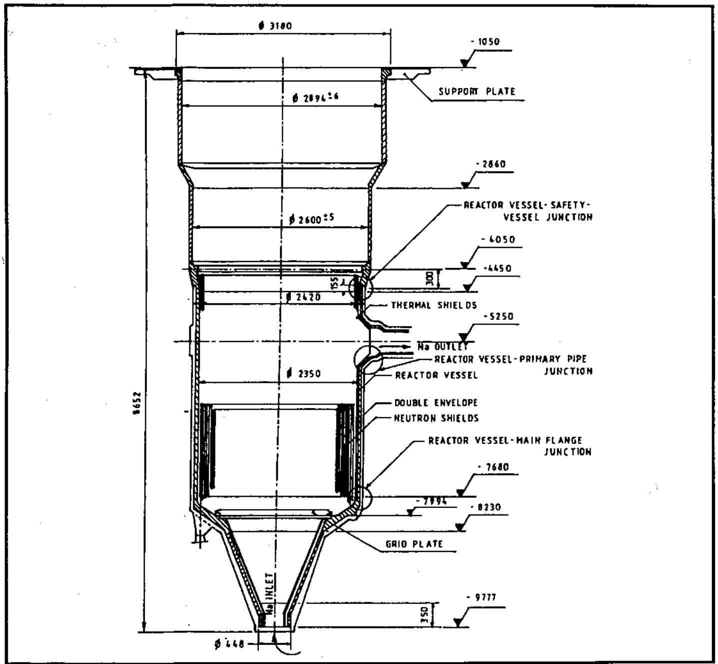

Fig.1 Schematic sketch of reactor vessel construction

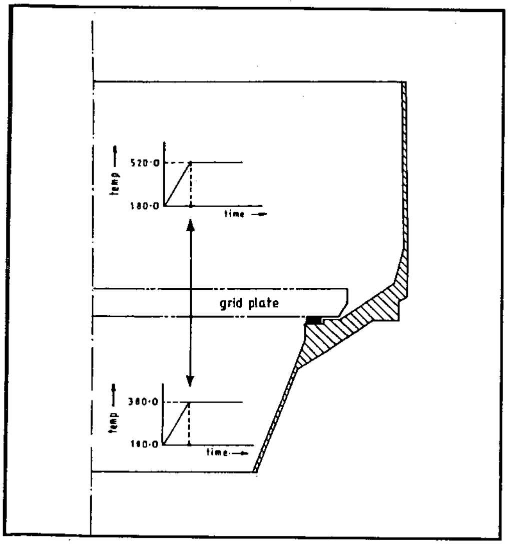

Fig.2 Details of the junction of upper shell and Main Flange of reactor vessel

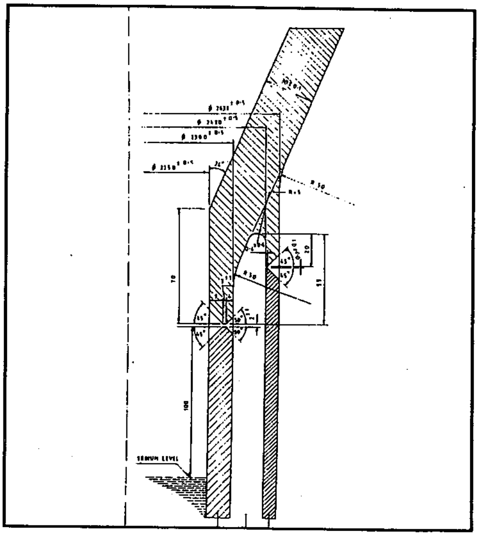

Fig.3 Details of the junction of Reactor Vessel and Double Envelope

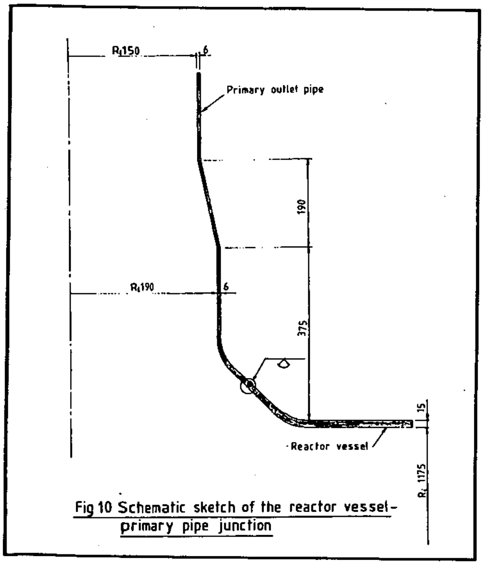

Fig.4 Details of the junction of Reactor Vessel and Primary Outlet pipe

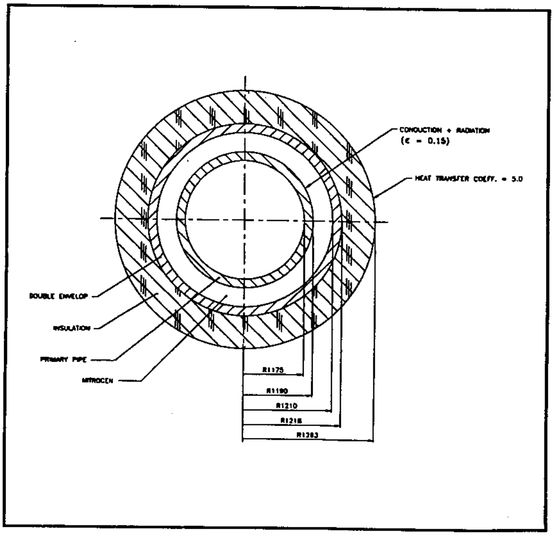

Fig.5 Details of thermal analysis model for Primary Pipe and Double Envelope cross section

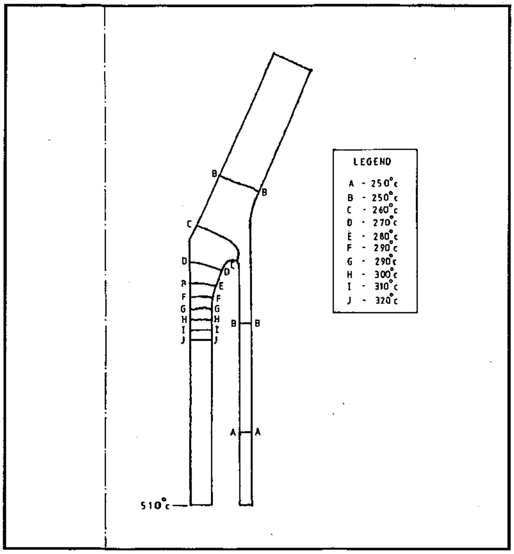

Fig.6 Temp. Distribution at the end of startup at the junction of Reactor Vessel and Double Envelope for the rate of 60 K/h

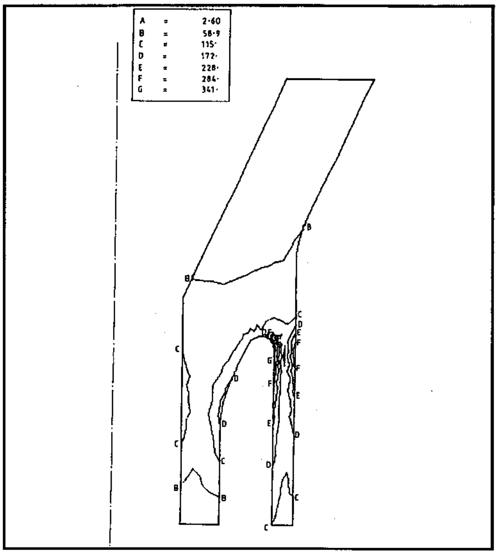

Fig.7 Von-Mises Stress distribution

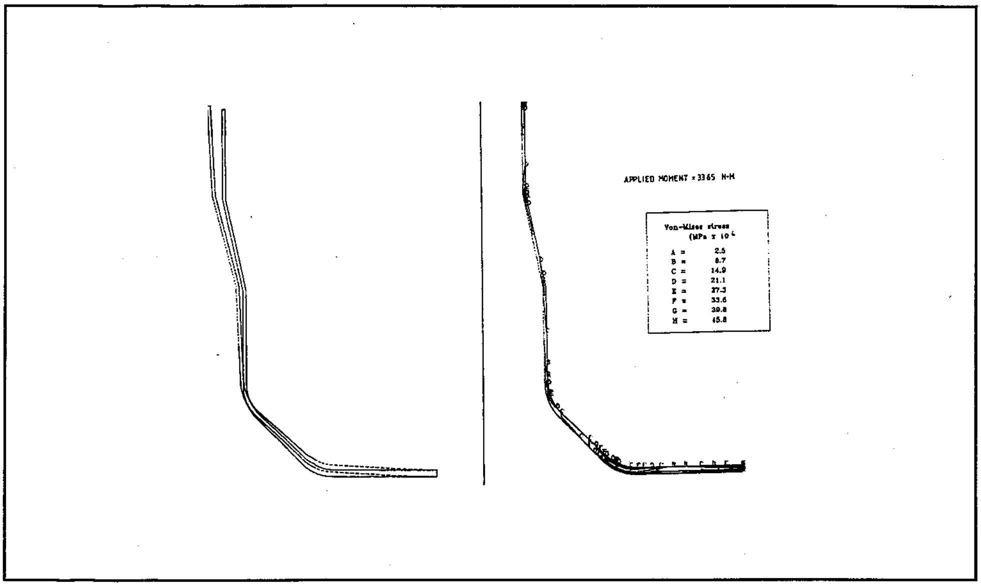

Fig.8 Original and Deformed shape and Von-Mises stress distribution for moment loading on Primary Outlet Pipe

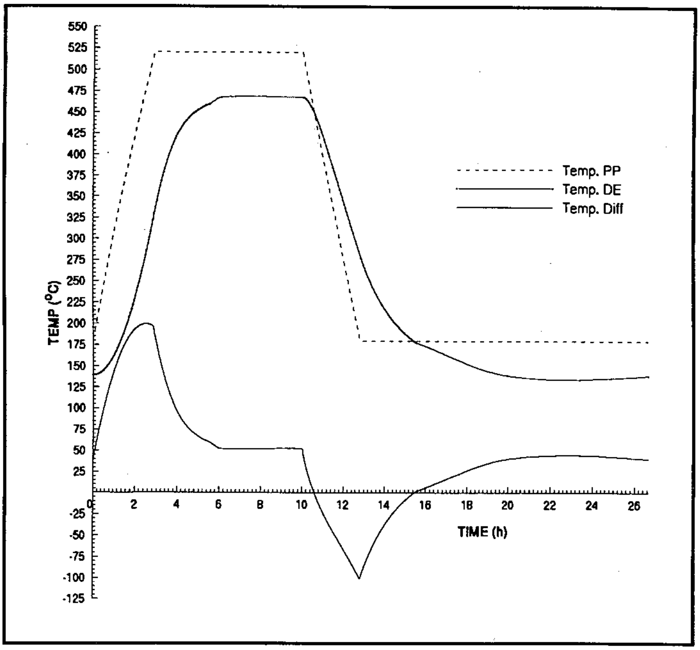

Fig.9 Variation of Temp. of Primary Pipe, Double Envelope and Temp. Difference

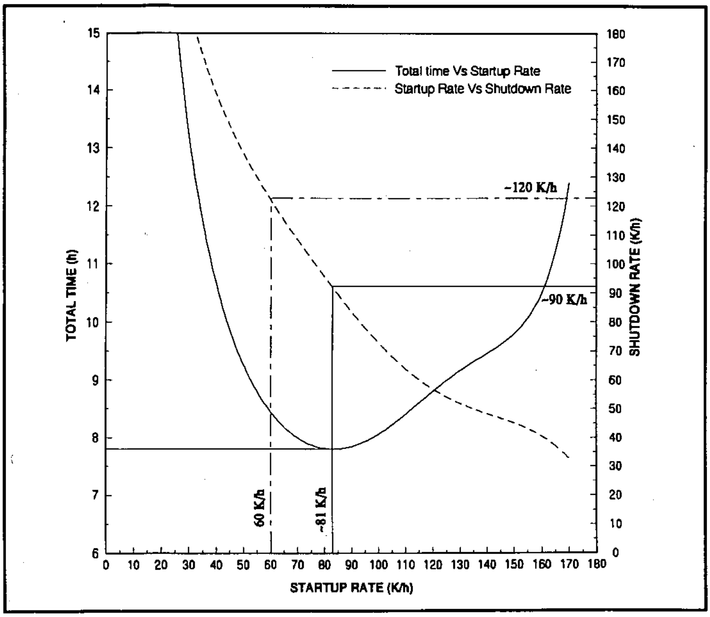

Fig.10 Variation of Total Time with Startup rate and startup rate with shutdown rate