Thermal Design Analysis of Transfer Pot for Handling of Spent Fuel from Fast Reactors

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Abstract
In the proposed Prototype Fast Breeder Reactor, during off-load refuelling, spent fuel is to be transferred from the reactor vessel to the external storage vessel in a transfer pot. The fuel pin temperature starts rising as the fuel sub-assembly passes through the argon atmosphere on its way to the external storage vessel. Detailed steady-state and transient thermal analysis of the transfer pot has been carried out to estimate the maximum temperature attained in the fuel assembly during the transfer operation so as to ensure that the clad temperature does not exceed the prescribed limit. A two-dimensional finite element heat conduction code has been used for analysis. Transfer pots of three different sizes and of square, cylindrical and hexagonal shapes are analysed for different decay heat generation rates in the fuel. The results of these analyses are used to arrive at a suitable design of the transfer pot.

1. Introduction
In the proposed PFBR, during off-load refuelling, it is intended to transfer the spent fuel sub-assemblies from reactor vessel to external storage vessel without resorting to forced cooling. The spent fuel from the core is first kept in the internal storage area within the reactor vessel for about 240 days so as to bring down its decay heat generation rate to a substantial low value i.e. 10 kW. After this, the sub-assembly is first transferred into the transfer pot within the sodium pool and the transfer pot is then lifted up from the sodium pool and carried through argon cover to the storage vessel (Fig. 1). The normal transport time during which the transfer pot will remain in argon atmosphere is approximately ten minutes. But under upset conditions such as breakdown of the transport mechanism, the pot may have to be in argon atmosphere for longer durations. In order to ensure the safety and integrity of the fuel and cladding, the transfer pot should be such that the maximum clad temperature attained anywhere in the fuel sub-assembly does not exceed the prescribed limit. The design of the transfer pot which would meet the above two constraints is also influenced by the level of decay heat in the fuel which is a function of the amount of time spent by the fuel in the temporary position in the reactor.
2. Thermal Considerations

During the transfer operation, the change in the boundary condition from very good natural convective boundary in the sodium pool to poor natural convective-radiative boundary in the argon atmosphere causes the temperature of the fuel sub-assembly to rise with the maximum temperature occurring in the central fuel pin. The magnitude of temperature attained and the rate of temperature rise would be smaller, larger the pot size, due to increased heat transfer area and heat capacity of the pot respectively. However, size of the duct connecting the reactor vessel and the external storage vessel imposes a limitation on the maximum size of the transfer pot.

3. Complexity Of The Problem

The fuel sub-assembly under consideration is hexagonal and consists of 217 cladded fuel pins with liquid sodium in between them (fig. 2). While the most dominant mode of heat transfer within the transfer pot and the fuel sub-assembly would be by conduction; some natural convection currents may also be present in liquid sodium in between the fuel pins. However, the detailed thermal analysis based on the consideration of conduction as well as natural convection for the present complex geometry would be extremely difficult. Hence, analysis based on only heat conduction has been carried out to arrive at conservative result. Further since the dissipation of decay heat in the fuel sub-assembly is mainly in the radial direction, the thermal analysis has been carried out on the basis of two dimensional [r,θ] heat conduction model.

The present complex geometry is not amenable for analysis using computer codes based on finite difference methods. Hence a two dimensional heat conduction code WELTEM based on finite element technique has been used for these analyses. Some of the salient features of this code are: a) accounting of non-linearities in the heat conduction equation due to temperature dependent thermal properties, b) availability of multinode isoparametric finite elements, c) consideration of time and space dependent heat generation and initial temperature functions, d) consideration of constant temperature, convective/radiative and constant heat flux boundaries, and e) out of core solution scheme.

4. Method of Analysis

The aim of the analysis is to estimate the maximum temperatures reached when the pot is stuck in the argon atmosphere. This condition will be reached asymptotically. The maximum temperatures will correspond to the steady state condition wherein all the heat generated is dissipated to argon. Hence these temperatures can be estimated based on steady state analysis in argon atmosphere. Further, it is necessary to ensure that no temperature peaking occurs before this steady state is reached. This is ensured by carrying out a transient analysis over a limited period of time, starting from the initial steady state conditions in the sodium pool. The following assumptions were made for the analysis.

1) Steady-state temperature distribution is established in the loaded transfer pot in sodium pool before it is lifted up from sodium pool to argon.

2) The change in boundary condition from sodium pool to argon atmosphere is a step change.

3) The sodium pool and argon cover are infinite heat sinks at constant temperature of
259°C.

4) The decay heat generation rate in the fuel sub-assembly is uniform.

5) The effect of axial heat conduction is negligible.

6) The heat dissipation from the transfer pot to sodium pool is by natural convection only and to argon by combined natural convection and radiation.

Analyses have been carried out for hexagonal, cylindrical and square shapes of transfer pot for three different sizes characterised by the minimum clearance between the inner wall of the transfer pot and the outer wall of the fuel sub-assembly. Pots with minimum clearances of 3.0, 5.0, 10.0 cms have been considered for analysis. The effect of decay heat generation rates in the range of 10.0 to 20.0 Kw per fuel sub-assembly has also been studied for all the above cases. A 1/12 symmetry sector has been analysed for the case of cylindrical and hexagonal shapes of transfer pot and 1/4 symmetry sector for square shaped transfer pot. A typical detailed discretization of a loaded square shaped transfer pot consisting of 1455 elements and 1641 nodes is shown in figure 3.

5. Thermal Properties

The spent fuel in the fuel pins consists of burnt (U.Pu) Oxide. The temperature dependent thermal properties such as thermal conductivity, specific heat and density of the Fresh fuel at 98 % theoretical density have been obtained from literature [11]. The thermal properties of other materials such as cladding, liquid sodium and stainless steel are similarly obtained from literature as a function of temperature [2,3]. The gap conductance between the fuel and the cladding has been assumed to be 1.1358 W cm²K⁻¹[4] and clubbed with the thermal conductivity of clad material.

6. Results and Discussions

The results of the thermal analyses carried out for all the cases described earlier are in terms of maximum clad temperature attained in the fuel sub-assembly. It was observed that for both cylindrical and hexagonal transfer pots the maximum steady state clad temperatures attained in argon are nearly same. Hence, further comparisons are presented for only square and cylindrical shapes of transfer pots. The comparison of maximum clad temperatures attained for these two shapes during the transfer operation under upset conditions for different decay heat generation rates is shown in figure 4. It may be observed that on the basis of identical minimum clearance for both the shapes of transfer pots, the maximum clad temperatures attained for square pot are less than those obtained for cylindrical pot. However, with identical clearance for both the shapes of transfer pot, square shaped transfer pot has larger surface area than cylindrical pot. Figure 5 shows the comparison between square and cylindrical transfer pots having same heat transfer surface area. It may be seen that the maximum clad temperature attained are almost same for both the shapes of transfer pots.

Results of the transient analysis for a typical case of hexagonal shaped transfer pot with a minimum clearance of 10 cms are shown in figure 6. The actual transient analysis has been carried out up to 94 minutes of stay of loaded transfer pot in argon atmosphere. Beyond this time, the rate of temperature rise is much smaller. Also the trend of the curve indicates that no peaking of temperature is likely to occur before steady state temperatures are reached asymptotically. In view of this no transient analysis was carried
out beyond 96 minutes.

7. Concluding Remarks

The analysis shows that for all the cases considered the prescribed temperature limits are not exceeded for the design rated decay heat generation rate of 10 Kwe/fuel sub-assembly. The temperature trend during the transient indicates that the steady state clad temperature in argon atmosphere is likely to be reached asymptotically without any peaking in between. Within the range of shapes and sizes considered, no limitation is imposed on shape or size of transfer pot, from considerations of maximum permissible clad temperature.

6. References

2. Perry J.N., "Chemical Engineers' Handbook"
3. El-Wakil, "Nuclear Heat Transport"

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Figure 1. Schematic of Fuel Handling System For PFBR
Figure 2. Details of Fuel Sub-assembly For PFBR

Figure 3. A Typical Discretization of A Loaded Square Shaped Transfer Pot
Figure 4. Maximum Steady State Clad Temperatures Attained in Argon Atmosphere for Different Decay Heat Generation Rates

Figure 5. Maximum Steady State Clad Temperatures Attained in Argon Atmosphere as a Function of Heat Transfer Area of the Pit

Figure 6. Transient Variation of the Maximum Clad Surface Temperature in the Fuel Sub-assembly During Handling Through Argon Atmosphere