CHAPTER 7
CONCLUSIONS AND FUTURE SCOPE

7.1 FOREWORD

This research work has addressed a few important issues related to relocation of molten core materials in the downward direction following severe core melt down accidents by numerical analyses. Since the numerical simulations deal with accidents scenario, definition of input conditions is a difficult but vital task. This challenge is overcome indirectly by parameterizing the input conditions within certain physically realistic limits and assessing their influence on the output parameters. Grid independency tests and validation exercises have been performed for the computational models. The design of any safety device to mitigate the consequences of a core melt down considers the most conservative of the output values obtained. Major conclusions derived from the numerical analyses are summarized in this chapter.

7.2 CFD ANALYSIS IN SODIUM FILLED ENCLOSURES

Steady state natural convection heat transfer correlations are developed for liquid metal contained in a cylindrical cavity heated on the top surface and cooled along the curved side wall. The numerical analysis is carried out with a commercial CFD code and axisymmetric geometry is considered. The functional dependence of the Nusselt number on Boussinesq number is determined for isothermal and isoflux conditions on the top surface. It is seen that the power law dependence for the two cases are 1/5 and 1/10 respectively as listed below.

\[ Nu = 0.8715 (Bo)^{0.2029} \quad \text{for} \quad 2 \times 10^6 < Bo < 2 \times 10^{11} \] (7.1)

\[ Nu = 2.9 (Bo)^{0.096} \quad \text{for} \quad 4 \times 10^4 < Bo < 2 \times 10^9 \] (7.2)

These correlations are valid for thin top plate approximation.
Conjugate natural convection and conduction heat transfer analysis has also been carried out for the same geometry, with a hot plate of finite thickness at top boundary. This enclosure represents the lower sodium plenum within the main vessel of a FBR bounded by the 5 cm thick grid plate on top, core support structure as the side wall and main vessel bottom as the base. Both steady and transient analyses have been carried out. In the initial unsteady state, the Nusselt number is found to be inversely proportional to square root of dimensionless time.

\[
Nu = \left( \frac{t}{\tau} \right)^{-\frac{1}{2}}
\]

(7.3)

For steady state, a correlation has been developed considering the temperature at the lower surface of the thick plate. This correlation is further useful in grid plate melting studies and the Nusselt number dependence on Boussinesq number is found out as follows

\[
Nu = 0.4(Bo)^{0.2}
\]

(7.4)

Comparison of this correlation with Eqn. (7.1) shows that there is a considerable decrease in heat transfer to the underlying liquid, in the case of thick plates and the reason attributed is the reduced convective velocity of sodium. Increasing the conductivity of the material of the plate is found to enhance the heat transfer.

In the steady state, conductivity ratio and height ratio are found to influence the heat transfer along with Boussinesq number, for thick plate configuration. The following general correlation is derived accounting for their influence on Nusselt number for a downward facing hot thick plate heating a cylindrical enclosure containing liquid sodium

\[
Nu = 0.15(Bo)^{0.07} (l^*)^{-0.6} (\kappa^*)^{0.27}
\]

for \(3.6\times10^7 < Bo < 2\times10^8\); \(0.27 < \kappa^* < 5.4\) and \(6 < l^* < 60\)
7.3 CORE-MELT RELOCATION STUDIES

In the next part of research, the lower and upper bounds of melt relocation time to core catcher have been estimated from ULOFA and PLOHS accidents. A computer code is developed in explicit enthalpy formulation to handle melting phenomenon along with transient heat conduction. An improved algorithm proposed by Voller and Cross (1981) is inbuilt in the code to track the melting front. The code uses finite difference method for discretising the energy equation.

The developed code HEATRAN-1 is used to analyse grid plate heating and melting sequence when decay heat generating nuclear fuel settles on it following a severe accident encompassing the whole core. The code is validated with Stefan’s problem and benchmark data of BN 800 reactor. Thermal analysis including melting phenomenon predicts grid plate melt through time to 300 s when grid plate is exposed to constant temperature of 3020 K at its top surface. But when time varying decay heat is accounted within core-melt, melt through time is about 1150 s for evenly spread core-melt on the grid plate. Both these cases correspond to no heat transfer to the underlying sodium. To consider the effect of heavier fuel displacing the lighter molten stainless steel, a correlation developed by Moallemi and Viskanta (1985) for molten film thickness beneath a hot migrating source which buries itself in a melting substrate is utilized. The mesh is dynamically adapted to match the diminishing thickness of the grid plate. When molten material displacement model is adopted in the analysis, melt-through time decreases by about 15%-20% and it is about 1000 s for evenly spread core-melt. This analysis gives a conservative estimate of time for grid plate melt-through, assuming that heat transfer to underlying sodium is not possible.

When heat transfer to the lower sodium plenum is accounted for, by means of including heat transfer coefficient obtained from the CFD study using PHOENICS code
as the boundary condition at the bottom side of the grid plate, grid plate melt through does not occur and it reaches a maximum temperature of 1120 K, which is about 580 K less than the melting point of grid plate material. But even in this case grid plate failure cannot be ruled out because the grid plate bottom temperature is in the creep regime. Therefore this analysis shows that grid plate cannot serve as a permanent hold up place for the core-melt expected from a whole core melt down accident. But it can substantially decrease the thermal load expected on the core catcher plate because the time delay involved in melting of grid plate decreases the decay heat content of core-melt.

The core-melt progression in the downward direction following a PLOHS accident has been analysed numerically by a heat conduction model incorporating porous body formulation with effective properties. The core-melt melts through lower axial blanket region, lower fission gas plenum, tail piece of subassembly, discriminator and grid plate top regions sequentially. A few possible cases are studied - the first one without displacement of molten region and the next one considering the displacement of different regions with the melting of the stainless steel which is the structural material. In both these cases the bottom of the grid plate is kept adiabatic. In the first case melting temperature of uranium dioxide is not reached at the bottom of lower axial blanket region even after 16 hours of heating by core-melt on its top. But the grid plate bottom crosses 1073 K after 15.5 hours which is taken as the time of its failure due to thermal creep. After the grid plate breaches, the subassemblies which are supported on the grid plate cannot remain in place and hence core-melt relocation to the sodium plenum and then to the core catcher follows immediately.

In the next case, clad melting point of 1700 K is fixed as the threshold for the core-melt penetration to the successive regions and the analysis is repeated. Each region is displaced when its bottom temperature touches 1700 K and core-melt is placed in
contact with the next layer, thus quickening the melt relocation process. In this case, molten material relocation time is estimated to be about 5.5 hours, assuming sodium rewetting of the subassemblies at all times.

In the third case study with convection to sodium below grid plate, though melting of steel propagates through the first four regions, it is seen that grid plate bottom temperature reaches a steady temperature of 944 K only. Considering the results from all the case studies, it is concluded that the minimum time required for core-melt relocation to the core catcher is 5.5 hours following a PLOHS accident with conservative inputs. As per this time estimate, for a whole core accident, the heat load on the core catcher is about 14 MW which is about one third of the thermal load due to an ULOFA where the relocation time is taken to be 300 s.

**7.4 MULTI LAYER CORE CATCHER**

Finally, the concept of multi layer core catcher is put forth, after considering the available options, to qualify the core catcher for a whole core accident. The adequacy of the same has been established purely from thermal considerations. Core-melt relocation times obtained from ULOFA analysis are given as input for defining the initial decay heat load on the core catcher. The relative merits and demerits of a few candidate materials for the different layers of core catcher are highlighted. The proposed multi layer core catcher consists of a top sacrificial layer, a middle refractory ceramic layer (which can itself be single / multiple layers) and a base structural layer. For the thermal analysis, molybdenum is taken as the top layer material, magnesia and thoria are considered as the middle layer acting as the delay bed. The base layer is stainless steel (SS 316LN) which supports the entire core catcher assembly.

Thermal analysis predicts that a delay bed of thoria, 4 cm in thickness or of magnesia 5 cm in thickness, can cater to the need of restricting the core catcher base
temperature below design safety limit of 923 K, when the whole core debris spreads evenly on the entire core catcher. Even for a conservative case of the debris occupying two thirds radius of core catcher, with 4 cm thickness of either thoria or magnesia delay bed, the base SS layer temperature does not exceed sodium boiling point which rules out downward sodium boiling. The multi layer core catcher concept proposed above has to be subjected to rigorous feasibility study, considering the metallurgical and manufacturing aspects and validated with experiments before being put into use. The concept of adding a delay bed layer in the internal core catcher is new to FBRs. The present numerical analysis has indicated that thoria is better than magnesia based upon its ability to produce large thermal gradients.

7.5 FUTURE SCOPE

- The code HEATRAN-1 can be improved further to solve energy equation in implicit formulation so that large time steps can be accommodated when dealing with long drawn transients such as a PLOHS accident.
- Combined thermal hydraulic study of upper and lower sodium plena of reactor main vessel during accidental conditions can be carried out.
- Evaluation of new core catcher concepts such as refractory material coated core catcher and multi tray concepts can be evaluated before finalizing the core catcher for future reactors.
PAHR Comic Strip by Kayser (Muller and Gunther, 1982)

This cartoon portrays the different possible (but not exhaustive) configurations of core debris on the core catcher. The composition of core debris, the size distribution, density stratification of the debris due to travel through sodium column and several other factors influence the settling aspects of the debris on the core catcher. Initially, the debris may form a heap which may later get levelled due to sodium boiling within the bed. If the decay heat is high enough leading to sodium dryout, re-melting can happen within the debris, fusing the debris into lumps. This picture is shown to signify the plethora of initial conditions that can be defined for the settling aspects of core debris. The same can be true for any physical processes / phenomena that are postulated for an accident progression.