Abstract

High quality for primary coolant pipes in fast reactors is ensured through utmost care taken in the design and manufacture. Demonstration of high structural reliability of them by extensive experimental and theoretical studies renders the double-ended guillotine rupture (DEGR) of a primary pipe a highly improbable event. However, as a defense in depth approach instantaneous DEGR of one of the pipes has been considered in design. Thermal hydraulic analyses of this event in a typical liquid metal cooled fast breeder have been carried out to study its consequences and to establish the availability of safety margins. Various uncertainties relevant to the event have been analysed to evaluate the sensitivity of each parameter. For this purpose, one-dimensional plant dynamics studies using thermal and hydraulic models of core subassemblies and primary sodium circuit have been performed. Validity of the assumptions made in the one-dimensional model like, uniform flow through all subassemblies in core under pipe ruptured condition and non possibility of sodium boiling by flashing have also been investigated through detailed three-dimensional and pressure transient studies. Analyses indicate the availability of good margins against the design safety limits in all the parametric cases analysed.

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1. Introduction

In LMFBRS, the primary pipes which connect the pumps to core inlet plenum are designed according to safety class 1 rules and to withstand design basis earthquake. High structural reliability is ensured by selecting highly ductile SS 316 LN material. Further, they are subjected to high quality manufacturing and relatively low operating temperature (less than 673 K) where in creep effects are insignificant during normal operation. Structural mechanics studies have indicated low operating stress. These aspects render the double-ended guillotine rupture (DEGR) of the pipe a very low probability event. However, due to the inability of leak before break (LBB) justification because of difficulty in leak detection and as a measure of defense in depth, instantaneous DEGR in a single primary pipe has been considered as a category 4 design basis event (DBE) and analysed to establish that the event is detected in time and the reactor is shutdown safely. The transient following the event being rapid reduction in coolant flow through core and sharp rise in temperature, the consequences following the event are sensitive to various data used in the analysis like; location of rupture, grid plate hydraulic resistance, incipient cavitation flow and amount of negative reactivity added during SCRAM, etc. Thus, the evaluation of sensitivity of various parameters is very important for the complete understanding of the event.

Thermal hydraulic consequences of similar event in some of the fast reactors in USA and France have been predicted and reported. Brookhaven National Laboratory (BNL) has carried out the analysis for the CRBRP (Dennis et al., 1978) and FFTF (Perkins et al., 1979) projects. Westinghouse has analysed for the CRBRP project (Dickson et al., 1983). Argonne National Laboratory (ANL) has carried out the analysis for the FFTF and SAFR projects (Dunn, 1990). CEA for SPX-1 (Kayser et al., 1981) and Novatome for EFR (Dominique et al., 1995) projects have carried out the analysis in France. These reports bring out the importance attached to the predictions apart from some specific features of the models and the results. These reports also bring out the differences in the predictions based on the features of the models employed. The Chinese, through the analysis of the event for the CEFR project (Yang and Xu, 2003) have shown that fuel cladding and coolant temperatures reached following the event are lower than sodium boiling temperature, thereby demonstrated that local boiling is also avoided. The KALIMER reactor design adopts gas expansion modules (GEM) as an inher-
In this paper, a comprehensive thermal and hydraulic study is presented to investigate the consequences that may arise due to unsymmetric net flow entry into the grid plate. Pressure transients due to a sudden guillotine rupture of a pipe and the complex hydraulic characteristics of the primary sodium circuit during a primary pipe rupture event in prototype fast breeder reactor (PFBR). The hydraulic characteristics of the primary sodium circuit is complex due to the parallel operation of two primary sodium pumps, interaction amongst the free sodium levels in hot pool, cold pool and pump stand pipes and two discharge pipes for each pump. This necessitated a suitable one-dimensional hydraulic model of the primary sodium circuit. The governing equations and the numerical solutions of this model alone has been described in detail in this paper.

2. Analysis of the event in PFBR

PFBR is a 500 MWe, 1250 MWt, liquid sodium cooled, pool type fast breeder reactor currently under construction. The primary sodium circuit consists of hot and cold sodium pools with an inner vessel separating them. Sodium from the cold pool is circulated through core by two centrifugal primary sodium pumps (PPS) operating in parallel. Each PPS is located inside a stand pipe. Sodium flows from cold pool to the stand and then it is pumped to core inlet plenum known as grid plate that feeds all the core SA which are inserted into it. Each PPS supplies sodium to the grid plate through two primary pipes. Sodium absorbs the nuclear heat generated in the SA, becomes hot and enters the hot pool from where it flows through four intermediate heat exchangers (IHX) to cold pool. IHX transfers heat produced by the core to secondary sodium circuit. Schematic of primary sodium circuit is shown in Fig. 1. Schematic of stand pipe flow and PSP flow is shown in Fig. 2. Because of resistance offered by the stand pipe for flow, sodium level in the stand pipe would be lower than the cold pool level by a height equal to head drop suffered by sodium flow in the stand pipe.

In a DEGR of a single primary pipe, primary sodium flow bypasses core through the ruptured path and the core flow decreases to a low value at a rapid rate and in turn causes sodium and clad temperatures to rise. Any one of the SCRAM parameters (for automatic emergency shutdown of the reactor), viz. reactivity ($\rho$), linear power (Lin $P_n$) and central SA sodium outlet temperature ($\theta_{SA,0}$) would shutdown the reactor. As a consequence of pipe rupture, the resistance against which pumps have to supply comes down sharply leading to a sudden increase in pump flow and sudden decrease in stand pipe level and the available net positive suction head (NPSHA) for the pump. Increase in the pump flow demands an increase in required net positive suction head (NPSHA) of the pump. When NPSHA exceeds NPSHb, cavitation of the pump occurs. Also there is a concern of sudden decrease in sodium pressure in the core and the consequent sodium vapour bubble formation (due to flashing) resulting in reactivity addition.

Design safety limits (DSL) for a category 4 events are that the clad hotspot temperature ($T_{ch}$) should be less than 1473 K and SA mean sodium hotspot temperature ($T_{Na}$) should be less than the boiling point of sodium. With the cover gas pressure being maintained at 10 kPa (g) and a sodium column of ~5 m available above the SA top, boiling point of sodium at the core top is 1213 K. When these limiting conditions are fulfilled, a coolable geometry of fuel SA for post-shutdown decay heat removal is assured.

### Nomenclature

- A: flow inertial coefficient ($m^{-1}$)
- D: pump developed head (Pa)
- g: acceleration due to gravity (m s$^{-2}$)
- I: moment of inertia (kg m$^2$)
- K: Pressure drop coefficient (Pa kg s$^{-1}$)$^2$
- n: number of SA is a radial group
- P: pressure (Pa)
- $P_0$: normalised reactor power
- Q: mass flow rate (kg s$^{-1}$)
- $Q_{SP}$: normalised flow through core
- S: area of cross section (m$^2$)
- t: time (s)
- Z: elevation (m)
- $\alpha$: normalized current speed/nominal speed of pump
- $\beta$: torque (N m)
- $\rho$: density (kg m$^{-3}$)
- $\rho_e$: reactivity
- $\omega$: pump speed (rad s$^{-1}$)

### Subscripts

- C: core channel
- CE: core entry
- CG: cover gas
- CP: cold pool
- CT: core top
- HP: hot pool
- I: intermediate heat exchanger (IHX)
- IE: IHX entry
- IO: IHX outlet
- J1: pipe to header junction in pump 1
- L1: leak flow from grid plate to cold pool
- PE: primary pump entry
- Pj11: part of ruptured discharge pipe from pump 1
to header to ruptured end
- Pj12: intact discharge pipe of pump 1
- PP: primary pump
- PP1, PP2: primary pumps
- pps: primary pump suction
- RI: reactor entry
- SP: stand pipe
Transient hydraulic model of the primary circuit has been developed to obtain sodium flow evolution following the event. This model is interfaced with the core kinetics, reactivity feedback and thermal models of the plant dynamics code DYANA-P to obtain temperature evolution following the event. The details of other models are given elsewhere (Agarwal et al., 1977; Vaidyanathan et al., 1981). General methodologies adopted in the formulation of the DYANA-P code has also been validated through the commissioning tests carried out in the fast breeder test reactor (FBTR) in Kalpakkam (Vaidyanathan et al., 1994). Kazimi and Carelli’s (1980) correlation is considered for calculating film heat transfer coefficient from clad surface to sodium.

2.1. Governing equations and solution procedure

The governing equations for the primary sodium circuit hydraulics schematised in Fig. 3 are derived from momentum balances (i) between IHX inlet and IHX outlet; (ii) between stand pipe entry and pump inlet; (iii) between pump inlet and core inlet; and (iv) between core inlet and core outlet, from mass balances for the stand pipe, hot pool and cold pool and from torque balance on the pump shaft. The resistance diagram of the flow circuit considered is shown in Fig. 4.

Governing equations

\[
\frac{dQ_{in}}{dt} = \left( Z_{HP} - Z_{IE} \right) \rho_{HP} g - \left( Z_{CP} - Z_{IO} \right) \rho_{CP} g - K_{I} Q_{in} / Q_{in} - \left( Z_{IO} \rho_{m} dZ, \right. \text{ for } m = 1, 2
\]

\[
\frac{dQ_{SP}}{dt} = \left( Z_{CP} - Z_{SP} \right) \rho_{CP} g - K_{SP} Q_{SP} / Q_{SP}, \text{ for } m = 1, 2
\]

\[
\frac{dQ_{PP1}}{dt} = \left( Z_{SP} - Z_{RI} \right) \rho_{CP} g - P_{P1} + D_{PP1} - K_{PP1} Q_{PP1} / Q_{PP1}
\]
Using the relation
\[ \frac{dQ_{Pi11}}{dr} = \frac{dQ_{Pi1}}{dr} + \frac{dQ_{Pi2}}{dr} \]
and
\[ \sum_{i=1}^{n} \frac{dQ_{Pi}}{dr} = \frac{dQ_{Pi11}}{dr} + \frac{dQ_{Pi2}}{dr} - \frac{dQ_{L1}}{dr} \]
detailed expression for \( \Delta P_{core} \) and \( P_{J1} \) can be obtained.

\[ \rho_{CP} S_{SP} \frac{dZ_{SP}}{dr} = Q_{SP1} - Q_{SP2}, \quad \text{for} \ m = 1, 2 \]
\[ \rho_{HP} S_{HP} \frac{dZ_{HP}}{dr} = \sum_{m=1}^{2} (Q_{PP1} - Q_{PP2}) = Q_{L1} + Q_{Pi11} \]
\[ \rho_{CP} S_{CP} \frac{dZ_{CP}}{dr} = \sum_{m=1}^{2} (Q_{I1} - Q_{SP1}) + Q_{L1} + Q_{Pi11} \]
The numerical solution of the primary circuit is obtained in two stages. In the first stage, IHX flow, pump flows, pump speeds and the sodium levels given above are solved utilizing a standard ordinary differential equation solver based on the Hamming’s predictor-corrector method (Hamming, 1986).

For individual core zone we have,

\[ \Delta Q_{C_{rj}} = \Delta P_{core} - K_{C_{rj}} Q_{C_{rj}} / \rho_{C_{rj}} - g \int_{Z_{CE}}^{Z_{CT}} \rho_{e} \, dh, \]

for \( r = 1 \) to \( 10 \)

\[ \sum_{r=1}^{10} Q_{C_{rj}} = Q_{Pr} - Q_{L1} - Q_{Pi1} \]

Total core flow obtained from the first stage is used as input for the second stage, where core zone flow equations are solved. For this, a semi-implicit finite differencing and linearisation technique (Agarwal et al., 1977) is applied for the individual core zone flows. By utilizing the fact that the change in the total core flow computed in the first stage described above to be equal to the total of the changes in the individual zone flows, the calculation of the current time individual zone flows are obtained as follows:

\[ \Delta P_{core} = \left[ \frac{\delta Q_{RI_j} + \sum_{r=1}^{10} b_{r} \delta Q_{RI_j} \delta Q_{RI_j}}{\sum_{r=1}^{10} b_{r} \delta Q_{RI_j}} \right] \]

\[ Q_{C_{rj}} = Q_{C_{rj-1}} + \Delta P_{core} \delta t \]

where, \( \delta t = t_{j} - t_{j-1} \); \( \delta Q_{RI} = Q_{RI} - Q_{RI-1} \)

\[ a_{r} = \frac{1}{(AC / \beta) + K_{C_{rj}} |Q_{C_{rj-1}}|} \]

\[ b_{r} = K_{C_{rj}} / Q_{C_{rj-1}} Q_{C_{rj-1}} + \Delta t \]

Fig. 3. Post rupture status of the primary sodium circuit with important elevations.

Fig. 4. Equivalent resistance diagram for the primary sodium circuit with the rupture at header end.
maximum leakage flow through the ruptured ends. These assumptions are conservative and result in structures are not considered to be influencing the flow from the been considered to not influence each other. The surrounding fluid jets issuing from the two-ruptured ends of the pipe have been modeled by using a velocity head loss coefficient of unity. The pressure drop at the ruptured ends of the primary pipe is modeled as an instantaneous occurrence by invoking the grid plate is considered as a plenum with single pressure. (7). The pressure drop at the ruptured ends of the primary pipe is modeled by using a velocity head loss coefficient of unity. The fluid jets issuing from the two-ruptured ends of the pipe have been considered to not influence each other. The surrounding structures are not considered to be influencing the flow from the ruptured ends. These assumptions are conservative and result in maximum leakage flow through the ruptured ends.

The required net positive suction head NPSHb versus flow characteristics at nominal speed of the pump are obtained from the experimental studies carried out on a model impeller. The points in the nominal NPSHb curve beyond the available experimental data are obtained by extrapolating the curve by the relation NPSHb = A + BQ^2, where A and B are constants which fit the last few points of the available data. Similar NPSHb curves for various speeds of the pump have been obtained by applying the following affinity laws:

\[ Q \propto N \]

and NPSHb \propto N^2 on the nominal curve.

The head versus flow characteristics under cavitating conditions of the pump would follow a vertical drooping line passing through the incipient point of cavitation (the point at which NPSHb = NPSHa). The NPSHa at any instant during the transient is calculated as,

\[ NPSHa = Z_{SP} - Z_{IMP} + H_{CG} - H_{ASP} \]

where ZSP and ZIMP are the stand pipe sodium level and impeller elevations, respectively. HASP and HCG are the saturation vapor pressure head of sodium at the operating temperature and cover gas pressure head, respectively. The incipient point of cavitation at any instant is obtained by using the NPSHa value in the NPSHb versus flow characteristics for the corresponding speed of the pump at that instant. With this model, the changes in the pump-supplied flow due to the changes in the NPSHa in the circuit under cavitating conditions is accounted.

Torque consumed by the impeller under cavitating condition is assumed to be equal to the value evaluated at the incipient cavitation point. Torque consumed by friction in the drive system at various points is obtained through an empirical correlation (Agarwal and Khatib Rahbar, 1980). Pressure drop coefficients are taken as inversely proportional to Re^{0.25}. The flow inertial coefficients of various segments of the flow have been calculated as the summation of the ratio between length of path followed and the corresponding flow cross section. The flow inertial coefficient for the smaller segment of the ruptured pipe is considered as a small value that can give a numerically stable solution with a time step of 10 ms.

2.3. Input data

The characteristics of the pump viz. head versus flow and NPSHb versus flow are shown in Fig. 5. The hotspot temperature of sodium (TiNa) and clad (TiCl) are obtained by multiplying the nominal average central subassembly temperature rise (\( \Delta T_{CSA} \)), sodium film drop (\( \Delta T_{Na} \)) and clad middle to outer surface drop (\( \Delta T_{Cl} \)) with appropriate hotspot factors namely \( f_{Na} \), \( f_{Cl} \) and \( f_{film} \) as follows:

\[ T_{Na} = T_{IN} + f_{Na} \Delta T_{CSA} \]

\[ T_{Cl} = T_{IN} + f_{Cl} \Delta T_{CSA} + f_{film} \Delta T_{Na} + f_{film} \Delta T_{Cl} \]

Apart from the measurement time constant for the SCRAM parameters power to flow ratio (\( P/P_{0} \)) of 0.05 s, linear power (\( P_{0} \)) of 0.2 s, reactivity (\( \rho \)) of 0.2 and central SA sodium outlet temperature (\( \theta_{SAAM} \)) of 0.3 s an additional logic delay time of 0.2 s is also considered in the calculation for the actual movement of control rods after a SCRAM demand is originated.

Control rod drop time considered in the study is 0.8 s. Plant design incorporates two diverse shutdown systems of worth 8000 pcm (pcm stands for 10^-5 s) of control and safety rods (CSR) and 3000 pcm in diverse safety rods (DSR). There are nine CSR and three DSR in the plant design. On a SCRAM command, it is envisaged that both the shutdown systems are actuated and inserted into the core. However, safety criteria prescribes that

![Fig. 5. Pump characteristics at nominal speed.](image-url)
it is needed to consider that only one shutdown system works
and in the working system, the highest worth rod gets stuck.
Accordingly, analyses have been carried out for a negative reac-
tivity insertion of 2000 pcm following SCRAM corresponding
to the fall of two DSR alone. In all the studies, reactor trip action
is considered to be initiated by the action of the second available
SCRAM parameter.

2.4. Results

Evolutions of NPSH of pump, reactor power, reactivity, pri-
mary circuit flows and temperatures during DEGR of a primary
pipe near the header end are shown in Figs. 6–9. It can be seen
from Fig. 6 that NPSH\textsubscript{p} increases suddenly and exceeds NPSH\textsubscript{A}
Immediately following the rupture. However, the pump flow
reaches its maximum cavitating flow of 126% only at 0.05 s
due to the delay offered by the hydraulic inertia of the circuit.
NPSH\textsubscript{A} of the pump reduces due to the reduction in sodium free
level in stand pipe. This causes the pump flow and hence NPSH\textsubscript{p}
to reduce slightly. Core flow reaches a minimum value of 37%
of nominal at 0.6 s. The first SCRAM parameter available is \(P_0/Q_0\), which crosses its threshold of 1.1 at 0.06 s. However, the
SCRAM action is considered to be taken after the availability
of second SCRAM parameter, the reactivity, which crosses its
threshold of +10 pcm at 0.2 s. Due to the measurement and trip
logic delay time, a maximum reactivity of 38 pcm and a power
of 112% are reached at 0.6 s before they are rapidly reduced
by SCRAM action as seen in Fig. 7. Pump speed reduction fol-
lowing SCRAM causes NPSH\textsubscript{p} to fall and it becomes equal to
NPSH\textsubscript{A} at 0.6 s (Fig. 6). NPSH\textsubscript{A} increases during this time due to the recovery of the
stand pipe level. As the pump speed is also reducing, it enables
the NPSH\textsubscript{p} to fall sharply. This moves the pump operation well
away from the cavitating regime. The PSP speed and flow at this
time are 57 and 95%, respectively.

It may be mentioned that in order to confirm the stable oper-
atation of pump during cavitation, a 1:2.75 scaled model pump,
under severe cavitation (80% head drop) condition has been
tested. The pump was operated for about 10 min and no flow
fluctuation or vapour locking was observed.

Coolant and clad temperatures (Fig. 9) start increasing after
a slight delay following the event and continue to increase for
some more time even after SCRAM due to their thermal inertia.
Similar analyses have been carried out at various initial power
conditions between 15 and 100% also. It has been seen that at
least two SCRAM parameters are available for the event occur-
rning at all initial power conditions. At power levels less than
40%, clad and coolant DSL are not crossed even without any
safety action.

3. Parametric analysis

Various parametric cases considered to evaluate the sensitiv-
ity of the event are listed below and summary of results is given
in Table 1.
Table 1

Summary of results of the uncertainty analysis

<table>
<thead>
<tr>
<th>Case no.</th>
<th>Description of the case</th>
<th>First minimum core flow (% nominal)</th>
<th>Maximum temperatures</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>T(_c) (K)</td>
</tr>
<tr>
<td>1</td>
<td>Rupture near the grid plate</td>
<td>40</td>
<td>1215</td>
</tr>
<tr>
<td>2</td>
<td>Low grid plate pressure drop</td>
<td>34</td>
<td>1269</td>
</tr>
<tr>
<td>3</td>
<td>Low incipient cavitation flow</td>
<td>32</td>
<td>1291</td>
</tr>
<tr>
<td>4</td>
<td>SCRAM with all control rods</td>
<td>37</td>
<td>1269</td>
</tr>
<tr>
<td>5</td>
<td>Both pumps trip when cavitation occurs</td>
<td>37</td>
<td>1269</td>
</tr>
<tr>
<td>6</td>
<td>Reduced time delay for the reactivity signal</td>
<td>37</td>
<td>1269</td>
</tr>
<tr>
<td>7</td>
<td>Influence of grid plate resistance on the bypass leakage flow neglected</td>
<td>37</td>
<td>1319</td>
</tr>
</tbody>
</table>

3.1. Rupture near the grid plate end of the pipe

The guillotine rupture of the pipe can happen anywhere between the header and grid plate joints. Rupture at the grid plate end of the pipe is analysed by modifying the resistance values of the flow passages from grid plate to ruptured end and from pump header to ruptured end. The reduction in the resistance of the flow passage from grid plate to ruptured end causes leakage flow through the path to increase. However, increase in the flow resistance in the path from pump header to ruptured end causes the flow in the path to decrease and the flow through the other unruptured pipe to increase. As a consequence of these two effects the core flow falls to a minimum value of 40%, which is better than the reference case.

3.2. Low grid plate pressure drop

Sodium flow path in the grid plate is very complex due to presence of \(\sim 1750\) sleeves in it. Because of the uncertainty in the estimation of the hydraulic resistance of the grid plate, a case has been analysed by reducing the hydraulic resistance of the grid plate by 50% of nominal value. Lower grid plate resistance causes more flow to leak from grid plate to cold pool resulting in a net reduction in core flow to 34%.

3.3. Reduced cavitation margin for the pump

There is a possible uncertainty in the cavitation margin available for the pump due to the manufacturing tolerances of the impeller. Therefore, NPSH\(_a\) for the pump is increased such that the maximum sodium flow supplied by the pump under cavitation reduces from 126 to 110%. The minimum core flow observed during the case is 32% of nominal.

3.4. SCRAM with all control rods

Negative reactivity worth of all the rods are considered to be available for SCRAM. Even though this case does not give rise to any change in the minimum value of core flow reached, the temperatures reduce slightly.

3.5. Both pumps trip when cavitation occurs

Uncertainty exists on the continued operation of pumps under cavitation. The drive protection logic of the pumps may trip them. Hence, a case has been analysed by tripping both the pumps when they reach cavitation conditions. Since the pumps continue to provide maximum flow until their speeds fall below 81% of nominal, no changes are seen in the maximum temperatures.

3.6. Reduced time delay for reactivity signal measurement

A total time delay of 0.2 s (measurement and trip logic delay) has been considered in place of 0.4 s considered in the reference case. Even though this case does not give any change in the minimum core flow reached, the temperatures decrease due to the earlier SCRAM of the reactor.

3.7. Influence of grid plate resistance on the bypass leakage flow neglected

Considerable radial gap exists in the grid plate between the peripheral row of sleeves and the shell. This region, also known as calming zone, provides a conducive path for the sodium flow entering the grid plate through the intact pipes to flow to cold pool through the ruptured pipe without subjecting it to the hydraulic resistance of the sleeves. That is the leakage flow from grid plate would be subjected to comparatively lower resistance resulting in a higher leakage flow and hence lower core flow. Therefore, a case has been analysed with the influence of grid plate resistance on the leakage flow neglected, i.e. considering the grid plate resistance along with that of core SA as shown in Fig. 10. The bypass leakage flow increases due to reduced resistance and hence core flow falls to 30%. This being the worst case, the event has been analysed for this condition with SCRAM by various appearing parameters. Available SCRAM parameters, their time of appearance and maximum values of \(T\(_{c}\)\) and \(T\(_{n}\)\) reached during the event predicted by this model are given in Table 2. It can be observed that even with the fourth appearing SCRAM parameter, there is a margin of 67 and 4 K on clad and coolant hotspot temperatures from the respective DSL.

3.8. Summary of parametric studies

It can be observed from these parametric studies that grid plate resistance on the bypass leakage flow, grid plate pressure drop and incipient cavitation flow supplied by the pump
are the critical parameters affecting the consequences following the event. However, in all these parametric studies, clad and coolant temperatures are observed to be below their corresponding design limits.

As already mentioned, the cavitation margin of the pump has been investigated through experimental studies on model impeller and it has been confirmed that the incipient cavitation flow would be more than that considered in the reference case (126%). The grid plate resistance has been confirmed through experimental studies. Neglecting the grid plate resistance on bypass leakage flow and considering the same along with core resistance (Section 3.7) leads to the lowest core flow. Because of the multi-dimensional nature of flow profile in grid plate, the calming zone may bypass considerable amount of sodium flow from grid plate. In order to estimate a realistic core flow a detailed 3D hydraulic analysis of grid plate under pipe ruptured conditions has been carried out. Another objective of this study is to investigate the possible redistribution in the core flow among various SA as a result of asymmetric pressure distribution inside the grid plate due to one pipe rupture.

4. Investigation of flow distribution in grid plate

The three-dimensional hydraulic analysis of grid plate under pipe ruptured conditions (Natesan et al., 2000a,b) has been carried out using the CFD code PHOENICS (CHAM/TR200, 1991).

4.1. Mathematical model

Under pipe ruptured conditions, the flows rate of sodium through four pipes connected to the grid plate are different from each other. Hence, there is no symmetry in the angular direction for the pipe ruptured state of the grid plate. Therefore, a full 360° numerical model has been considered for this study. Grid pattern and the boundary conditions adopted are shown in Fig. 11. The input flow to the grid plate is specified at the location of three intact pipes. The outflow from the grid plate is specified at the ruptured pipe location and in the top plane of the grid plate, which represents core flow. Position and flow rate through various SA mounted in the grid plate are shown in Fig. 12. Presence of sleeves in the grid plate has been represented by porosities in various coordinate directions. Pressure drop in the radial and angular directions are modeled using Zukauskas correlation (1983) for cross flow over a bank of sleeves. Pressure drop coefficients for various SA are calculated from the core pressure drop of 64 m and IHX pressure drop of 1.5 m of sodium for the nominal flows through them. The effective pressure drop coefficient for various control volumes at the top of the grid plate has been calculated considering the parallel resistance offered by various SA housed in each of the control volume. These resistances are considered to vary inversely proportional to $Re^{0.25}$. Grid pattern considered for the study in the cylindrical polar coordinate direction $(r-\theta-Z)$ is $24 \times 52 \times 8$, respectively. Standard high Reynolds number K-€ turbulence model has been used to take care of turbulent effects.

4.2. Results

4.2.1. Nominal condition

Equal flow boundary condition corresponding to the flow at nominal full power is applied at the location of all the four pipes. The velocity vector profile in the plane of the primary pipes is shown in Fig. 13. It can be observed that there is an increase in the velocity immediately after the pipe within grid plate due to
the reduction in the flow area as a result of presence of sleeves. Velocity reduces subsequently as sodium leaves the grid plate axially through the SA. The pressure contours inside the grid plate are shown in Fig. 14. It can be seen that the maximum radial pressure drop across the grid plate is 4.6 m of sodium column.

4.2.2. Pipe ruptured condition

Under pipe rupture, a flow rate of 126% of nominal (PSP flow under cavitating conditions) has been considered through pipe-1 and pipe-2 supplying to the grid plate. A flow rate of 16% of nominal is considered to enter the grid plate through pipe-3. Pipe-4 is ruptured. These flow rate boundary conditions are obtained from the transient study described in Section 2. The resulting velocity field in the grid plate is shown in Fig. 15. It can be seen that sodium in the grid plate flows towards the calming zone without subjecting itself to the resistance in the sleeves. Core flow under this condition has been estimated to be 33% of nominal while the rest of the flow bypasses the core to cold pool through the ruptured pipe. The final steady state core flow estimated for the reference case through the DYANA-P calculation is 31%. The 3D estimate of 33% compares well with the later. Thus, it can be concluded that the approach of neglecting grid plate resistance on the bypass leak flow and considering the same along with that of core SA would yield a pessimistic core flow in 1D calculation.

Mean axial velocities at the top of the grid plate normalized with respect to nominal values at various radial and angular locations are shown in Fig. 16. From this it can be seen that the normalised (with respect to the individual nominal values) velocity and hence flow rate through various fuel and blanket SA varies from 33.5 to 32%. Thus, the deviation in the normalised flow through various SA from the mean core flow value (33%) is +0.5% to −1% in the fuel and blanket region. The deviation is more in the peripheral SA (reflector and shielding) where sodium flow itself is very small. Thus, it can be concluded that there is no significant flow redistribution among the various SA under pipe ruptured condition. This is in agreement with the experimental observations made in a 1/3-scale air model.
Fig. 12. Position and flow rate through various SA mounted in grid plate.

Fig. 13. Velocity profile in grid plate at nominal conditions.
Experimental study on 1/3-scale model of grid plate assembly was carried out at a Reynolds number of $3.05 \times 10^5$. In this air model the resistance offered by various SA were simulated using orifices at the corresponding locations. The same orifices were used in conjunction with micro manometers as means for measurement of flow rate through various SA. Experiment was carried out with three pipes supplying flow to grid plate and the fourth one bypassing flow from grid plate to ambient. Maximum deviation in the flow through individual SA from the average core flow value observed was 2% (peripheral SA) only. Even in the case with two pipes feeding grid plate and the other two pipes blocked, no redistribution in the flow among various SA was observed.
observed. Therefore, the one-dimensional model assumption of treating the grid plate as a single pressure point for the estimation of core flow distribution is realistic.

5. Investigation of void formation

As already explained, there is a concern of sudden decrease in sodium pressure in the core and the consequent sodium vapour bubble formation (due to flashing) resulting in reactivity addition. For this purpose, the computer code SWEPT (Selvaraj et al., 1996) is used. SWEPT is a system pressure wave propagation analysis code for the analysis of short-term transients like sudden valve closure, sodium water reaction and pump start up in closed networks. Primary sodium circuit is modeled as a closed piping network with hot pool, cold pool and PSP forming pipe junctions. The pipe rupture is modeled by equating the pressure at the break point to the cold pool pressure at the corresponding elevation and kept constant. The flow velocity from the both ends are then calculated. The cold pool and hot pool free surfaces are modeled as common gas pressure plenum. Isentropic compression or expansion of gas is considered. Sodium is assumed to be isothermal at an average temperature of 745 K. Pipe rupture at the header end is considered.

Following pipe rupture, pump flow increases due to reduced flow resistance. Flow through core reduces as a consequence of flow being diverted to cold pool via ruptured pipe. Following the breach in the pipe, primary system is suddenly exposed to low pressure at the leakage point. This low-pressure wave travels both upstream and downstream pipes causing pressure fluctuations at various system components. Fig. 17 shows the variation of pressure at the inlet, middle point and at the exit of core SA. As and when the pump flow, leakage flow and core flow stabilise, pressure fluctuation also subsides. It can be seen that there is no void formation in any SA since pressure at all points in the system stays well above vapour pressure of sodium at the operating temperature (278 Pa). The minimum core flow estimated from this study is 37.5% and it compares well with the incompressible flow model (reference case discussed under Section 2.4) estimate of 37.6. It can also be observed that the cover gas pressure and pressure at the SA top, which is the common pressure point in hot pool for the outlets of various subassemblies in core, remains constant during the transient. This is due to the complete attenuation of pressure fluctuations in the large volume of cover gas.

6. Conclusion

DEGR of one of the four primary pipes is considered as a category 4 event in spite of the fact that the structural integrity of the pipe is ensured under all the conditions with comfortable factor of safety. A comprehensive mathematical model has been developed to study this event. Detailed parametric studies have been carried out to bring out the sensitivity of various data used in the analysis. Important features of the model viz. single phase incompressible flow of sodium and single pressure point assumption for grid plate have been verified through detailed pressure transient analysis and 3D hydraulic analysis of grid plate. It has been established that there is no flow redistribution among various SA and no void formation during the event. Effective detection of the event and availability of comfortable margins against DSL have been established through this study.

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References

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