Experimental Studies for SGDHR System of PFBR

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Outline of the presentation

- Decay Heat removal system for PFBR
- Program for experimental studies
- Similarity criteria
- Experimental studies with water
- Experimental studies with sodium
- Conclusion
Prototype Fast Breeder Reactor

SGDHR
4 LOOPS
8 MWT

SURGE TANK
796K

2 LOOPS

AIR

STEAM GENERATOR

SODIUM

SSP

628K

670K

PSP

820K

REACTOR

508K

763K

613K

16.7MPa

TL TURBINE

HP

IP

LP

500 MWe

GENERATOR

REHEATER

CONDENSER

313K

303K

0.01MPa

320K

SEA

313K

CEP

320K

HP HEATERS

BFP

DEAERATOR

LP HEATERS
Decay Heat Removal System

- Decay heat removed through Operational Grade Decay Heat Removal system (OGDHR) Under normal reactor shutdown conditions.
- Safety Grade Decay Heat Removal system (SGDHR) ensures the decay heat removal form reactor in the case of non availability of OGDHR heat transport path.
- This completely passive system will be put into operation by opening of dampers on the air side.
- Each SGDHR loop consists of
  - Sodium-sodium heat exchanger (DHX) dipped in hot pool,
  - Sodium to air heat exchanger (AHX) placed high elevation, outside the reactor containment building,
  - Air stack.

4 loops of 8 MWt each, Type A and Type B AHX and DHX
# Experimental Studies for DHR System

## Water Experimental Studies:
- Adequately simulate the hydraulics
- Simplified model fabrication and simpler instrumentation
- Easy to carry out the studies
- Cheaper to carry out the studies

## Sodium Experimental Studies:
- Heat transfer properties can be simulated
- Full scale components can be tested

<table>
<thead>
<tr>
<th>Test Facility</th>
<th>Country</th>
<th>Scale</th>
<th>Geometry</th>
<th>Fluid</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D, AQUARIS, EFR KfK Primary system.</td>
<td>Germany</td>
<td>1:20</td>
<td>SLAB</td>
<td>Water</td>
</tr>
<tr>
<td>3D, RAMONA, EFR KfK Primary system</td>
<td>Germany</td>
<td>1:20</td>
<td>360°</td>
<td>Water</td>
</tr>
<tr>
<td>3D, NEPTUN, EFR KfK Primary system</td>
<td>Germany</td>
<td>1:5</td>
<td>360°</td>
<td>Water</td>
</tr>
<tr>
<td>Model of SPX 1, Primary system</td>
<td>France</td>
<td>1:20</td>
<td>360°</td>
<td>Water</td>
</tr>
<tr>
<td>KIWA, EFR KfK,</td>
<td>Germany</td>
<td>1:10</td>
<td>60° (Slab)</td>
<td>Water</td>
</tr>
<tr>
<td>GODOM, CEA, Hot plenum</td>
<td>France</td>
<td>1:5</td>
<td>90°</td>
<td>Water</td>
</tr>
<tr>
<td>JANUS, secondary sodium circuit and AHX (SPX 1)</td>
<td>France</td>
<td>1:2</td>
<td></td>
<td>Sodium</td>
</tr>
<tr>
<td>ILONA, Testing AHX</td>
<td>Germany</td>
<td>1:3</td>
<td></td>
<td>Sodium</td>
</tr>
</tbody>
</table>
Experimental Studies for PFBR SGDHR System

Need for Experimental studies:

- Demonstration of heat removal by SGDHR
- Establishing the heat removal capacity of SGDHR system
- Generate Database for code validation
- Testing of individual components

<table>
<thead>
<tr>
<th>Test Facility</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAMRAT Model (Water model)</td>
<td>1:4 scaled model of PFBR pool for thermal hydraulic studies</td>
</tr>
<tr>
<td>IWF Slab Model (Water Model)</td>
<td>Slab Model of the core in 1:1 scale</td>
</tr>
<tr>
<td>SADHANA (Sodium facility)</td>
<td>Scaled facility (1:22 in power) of the Intermediate circuit and the AHX circuit</td>
</tr>
</tbody>
</table>
SAMRAT Model Studies:
- 1:4 Scaled & 360° model,
- Primary Circuit Components Simulated i.e. PP, IV, MV, Core Components, DHX, IHX, CP etc..

Similitude:
- $Ri^* = 1$, $Pe^* = \text{order of 10}$,
- $Re^* = \text{Order of } 10^2$

Objective:
- Demonstration Of Natural Convection in Primary Circuit during SGDHR condition
- Data generation for Code Validation

Model Internal View

Heat Removal Paths during SGDHR
## Experimental Details

<table>
<thead>
<tr>
<th>Case No</th>
<th>Core power (kW)</th>
<th>DHX secondary flow rate (m³/h)</th>
<th>Details</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>60</td>
<td>No DHX operation</td>
<td>All paths available</td>
<td>To study effect of DHX on core cooling</td>
</tr>
<tr>
<td>2</td>
<td>60</td>
<td>1</td>
<td>All paths available. Initial hot pool temperature 30°C.</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>90</td>
<td>1.3</td>
<td>(Storage+Blanket+IHX) paths Blocked. All DHX operating.</td>
<td>Only IWF path is available</td>
</tr>
<tr>
<td>4</td>
<td>90</td>
<td>1.3</td>
<td>(Storage+Blanket) paths unblocked, IHX Blocked. All DHX working</td>
<td>IWF + circulation in blanket and storage zone</td>
</tr>
<tr>
<td>5</td>
<td>90</td>
<td>1.3</td>
<td>(Storage+Blanket+IHX) paths unblocked. All DHX operating.</td>
<td>All flow paths are available</td>
</tr>
<tr>
<td>6</td>
<td>90</td>
<td>1.3</td>
<td>(Storage + Blanket) paths blocked, IHX path unblocked,</td>
<td>IWF + Primary flow path (path-A) available</td>
</tr>
</tbody>
</table>
Effect of DHX on core cooling

- These studies were carried out to understand the effect of operation of DHX on Core cooling.
- DHX is able to remove the heat from the hot pool to keep temperatures within control but it takes some time to establish the heat removal path.
Hot Pool Core Outlet temperature profile:

• Temperature Difference across hot pool in all cases is approximately same
• steady state temperature is achieved almost at the same time for all cases
• Heat removal by reverse flow through blanket and storage is also equally effective compared to other heat removal flow paths.
• It can be concluded that IWF also contributes to a great extent in heat removal. Hence, IWF has a major role in heat removal during the SGDHR
Inter Wrapper Spaces (IWS) Temperature profile:

- The slight increase in IWS temperature difference with the availability of only IWF path also suggests that the heat transfer by IWF is comparable with normal heat removal paths.
- The temperature gradient across IWS for other locations (IWS-II, IWS-III and IWS-IV) inside the non heated zone of the core is almost same for all the experimental conditions.

Summary of water model studies

- Steady state in the experimental studies can be achieved by Natural Convection
- All proposed heat transport paths have role in heat removal
- IWF has significant role in decay heat removal during SGDHR operation
Objective:
- Demonstration Of IWF During SGHDR condition.
- Code validation.

Model Details:
- 1:1 Scaled slab model of the reactor
- Only Fuel and Blanket SA simulated
- External geometry and size of the SA is same as Prototype
- Only active height of the core is simulated
- Ri Simulation for heater power calculation
- Experimental test runs were carried out under different conditions and temperature measurements was carried out at important locations and PIV measurements were also recorded
- Approximate contribution of the IWF in core heat removal is found to be 25 % as per PIV measurements.
- SADHANA is 1:22 scale model of SGDHR
- Richardson number similitude. \( \text{Ri} = \frac{\text{Buoyancy}}{\text{Inertia}} = \frac{g\beta\Delta T L}{V^2} \)
- The hot and cold leg temperatures maintained
- The capacity of SADHANA loop is 355 kW
- The thermal centre height difference between the DHX and AHX is 19.5 m.
- A 20 m high chimney develops the air flow required for AHX.
- The sodium in Test Vessel 4 (TV 4) simulates hot pool of PFBR is heated by immersion electrical heaters.
<table>
<thead>
<tr>
<th>Parameters</th>
<th>SGDHR of PFBR</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working fluid</td>
<td>Sodium</td>
<td>Sodium</td>
</tr>
<tr>
<td>Heat removal capacity</td>
<td>8 MW</td>
<td>355 kW</td>
</tr>
<tr>
<td>Inlet temperature of sodium in DHX</td>
<td>302 °C</td>
<td>302 °C</td>
</tr>
<tr>
<td>Outlet temperature of sodium from DHX</td>
<td>495° C</td>
<td>495° C</td>
</tr>
<tr>
<td>Inlet temperature of sodium in AHX</td>
<td>495° C</td>
<td>495° C</td>
</tr>
<tr>
<td>Outlet temperature of sodium from AHX</td>
<td>302 °C</td>
<td>302 °C</td>
</tr>
<tr>
<td>Height between thermal center</td>
<td>41m</td>
<td>19.5m</td>
</tr>
<tr>
<td>Inside diameter of intermediate loop pipe</td>
<td>200 mm</td>
<td>52.48 mm</td>
</tr>
<tr>
<td>Richardson number</td>
<td>15.66</td>
<td>16.67</td>
</tr>
<tr>
<td>Sodium velocity</td>
<td>1.2 m/s</td>
<td>0.78 m/s</td>
</tr>
<tr>
<td>Sodium mass flow rate</td>
<td>32.42 kg/s</td>
<td>1.45 kg/s</td>
</tr>
<tr>
<td>Air circulation in AHX</td>
<td>Natural</td>
<td>Natural</td>
</tr>
<tr>
<td></td>
<td>Circulation</td>
<td>Circulation</td>
</tr>
</tbody>
</table>
- Simulates hot pool of reactor
- Designed to withstand a pressure of 2 bar at 600°C and full vacuum at 250°C
- Houses the model of DHX, 30 Nos of 20kW electrical heaters and sensors
- Flange to vessel joint lip seal welded to achieve leak tightness required for sodium vessels
355kW heat transfer capacity at design conditions

Similar to PFBR design Type A

21 tubes with 4 passes

Tube OD is 38.1mm with 2.6mm thickness

SS 316L tubes with helically welded fins

197 fins/m with 12.5mm fin height and 1.22mm thickness.

SS 409 fins are welded by electric resistance welding
Decay Heat Exchanger (DHX)

- Same design concept as Type A DHX of PFBR
- Vertically mounted 12 tube Sodium to sodium counter flow shell and tube heat exchanger
- Shell side and tube side sodium flows due to buoyancy head developed by the temperature gradient
- 12 numbers of tubes with OD 24mm with 1mm wall thickness
- Length of tube is 1.4m
- Construction material is SS 316L

Installation of DHX in Test vessel
The system has operated at a temperature of 550°C for more than 3000hrs.

The primary and secondary sodium flows established by natural circulation qualitatively and quantitatively as expected.

Chimney developed the natural draft required to remove the heat from sodium to air through AHX.

The performance of DHX and AHX was as per the design expectations.
At 550°C sodium pool temperature 6.7m³/h sodium flow was induced in the secondary loop with a DHX outlet temperature of 520 °C and AHX outlet temperature of 317°C.
Steady state heat transport

Steady state power transport of 425kW from the sodium pool. This is 19.4% more power than its rated capacity and 11% higher than design prediction.
Response of SGDHR system on sudden opening of dampers

- The system was fully functional in around 510 seconds after the initiation of opening the dampers.

- Air flow attained the steady state value in 80 seconds.

- The time taken to open the outlet damper was 70 seconds.

- The setting up of sodium flow, air flow and various temperatures after the sudden opening of the damper were smooth and has not indicated major oscillations.
Heat transport under low sodium levels in hot pool

- Low sodium level in the pool will result in a reduction of effective heat transfer area of the DHX in the perforated inlet window region.

- The results from these studies have indicated that 88% reduction in sodium level at inlet window region causes 2% reduction in secondary flow and 5% reduction in power transported by the system.

- The reduction in heat transfer area is in the region where the heat transfer from the primary sodium to secondary sodium is less effective.
Heat Removal with partial Damper opening

• At lower damper openings such as less than 30% damper opening, the increase in power transport with respect to the increase in damper opening is high.
• At 50% damper opening the heat transport capability of system is stabilized and further no appreciable change has been observed.
Conclusion

✓ The viability of the fully passive PFBR decay heat removal system was successfully demonstrated by experiments with water medium in different facilities and with sodium in SADHANA facility.

✓ Experimental studies were carried out to understand Core – Hot Pool – DHX interaction during SGDHR operation in scaled models of the PFBR.

✓ In 1:4 scaled model of the reactor, experiments were carried out to demonstrate decay heat removal and to understand influence of complicated phenomenon like IWF. Experimental results have shown that all the proposed heat transport paths have influence on core cooling.

✓ Approximate estimation of IWF contribution is found to be 25% of total in heat removal.

✓ Performance of SGDHR system at steady state, transients and some of the off normal conditions were studied and characterized by the in sodium experiments conducted in SADHANA facility.

✓ These experiments revealed the adequacy and capability of SGDHR system to remove the decay heat from the fast breeder reactor core after its shutdown.
THANKS