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HYDRAULIC DEVELOPMENT OF PASSIVE SAFETY SHUTDOWN SYSTEM FOR INDIAN SFR

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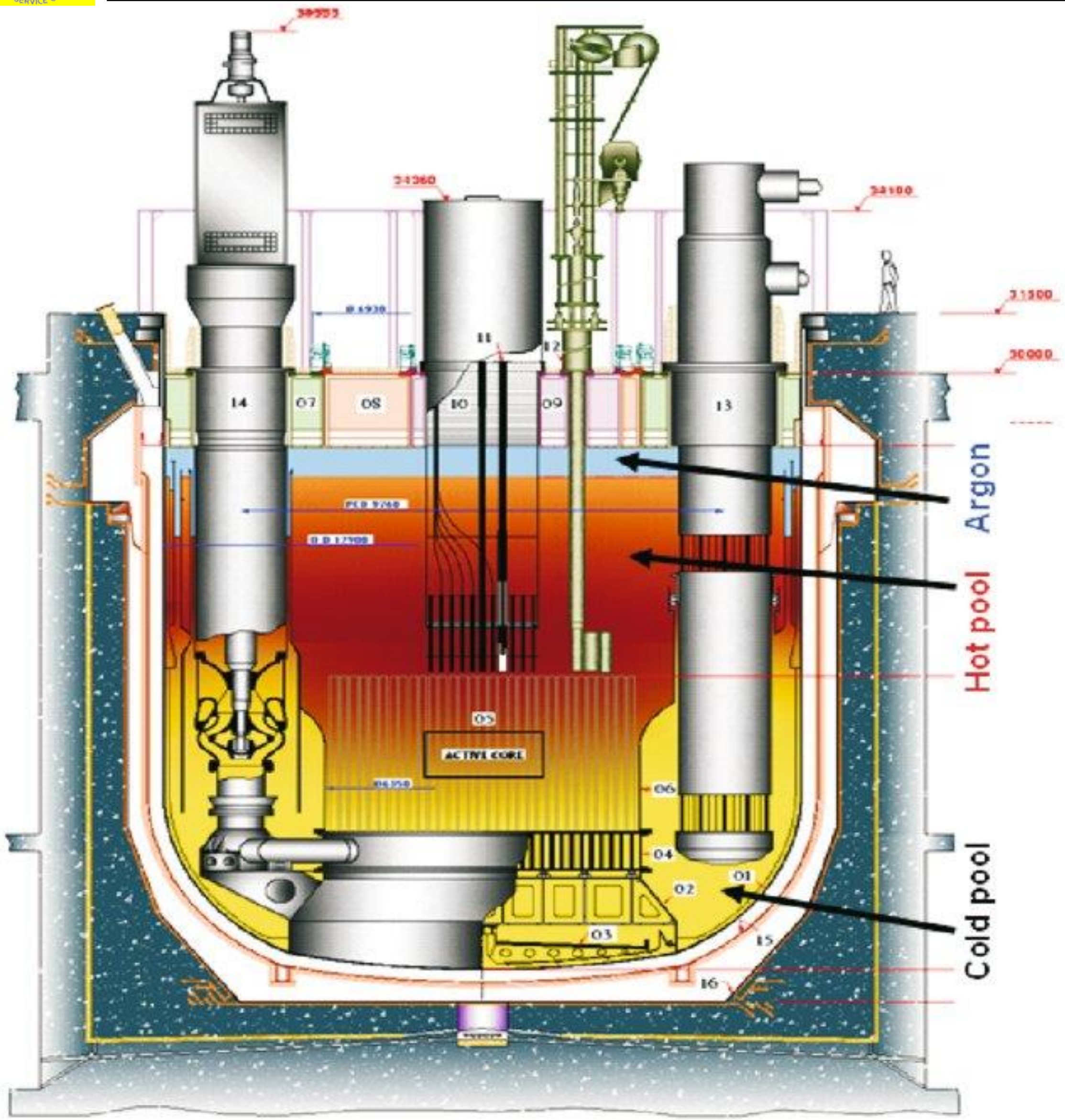
OUTLINE

- INTRODUCION
  - INDIAN SFR
  - REACTOR CORE
  - SHUT DOWN SYSTEMS
- NEED OF PASSIVE SHUTDOWN SYSTEM
- OPERATIONAL REQUIREMENTS
- DESIGN CRITERIA
- DEVELOPMENT PROCEDURE
- RESULTS
- CONCLUSION

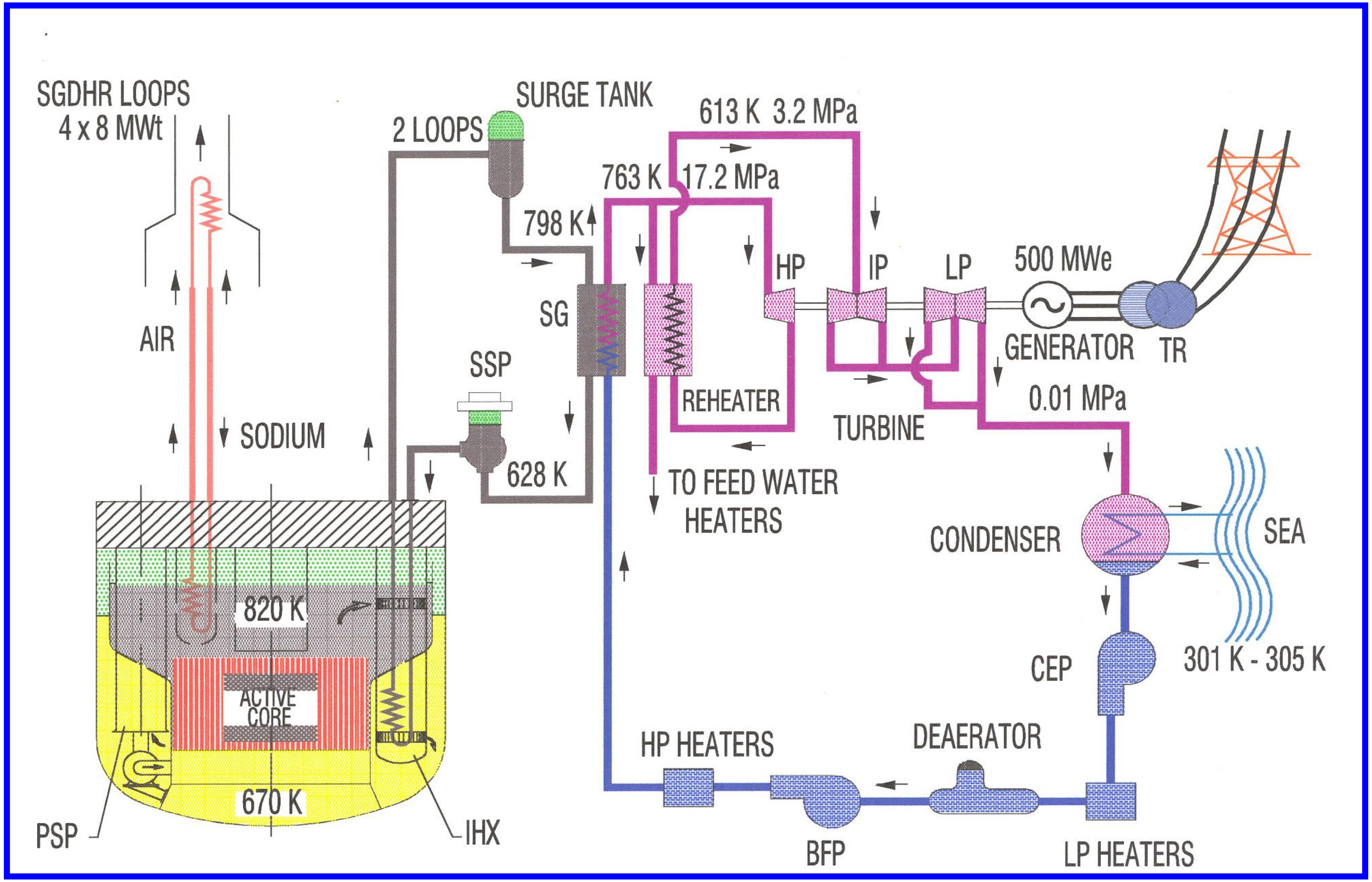
INDIAN SFR (PFBR)



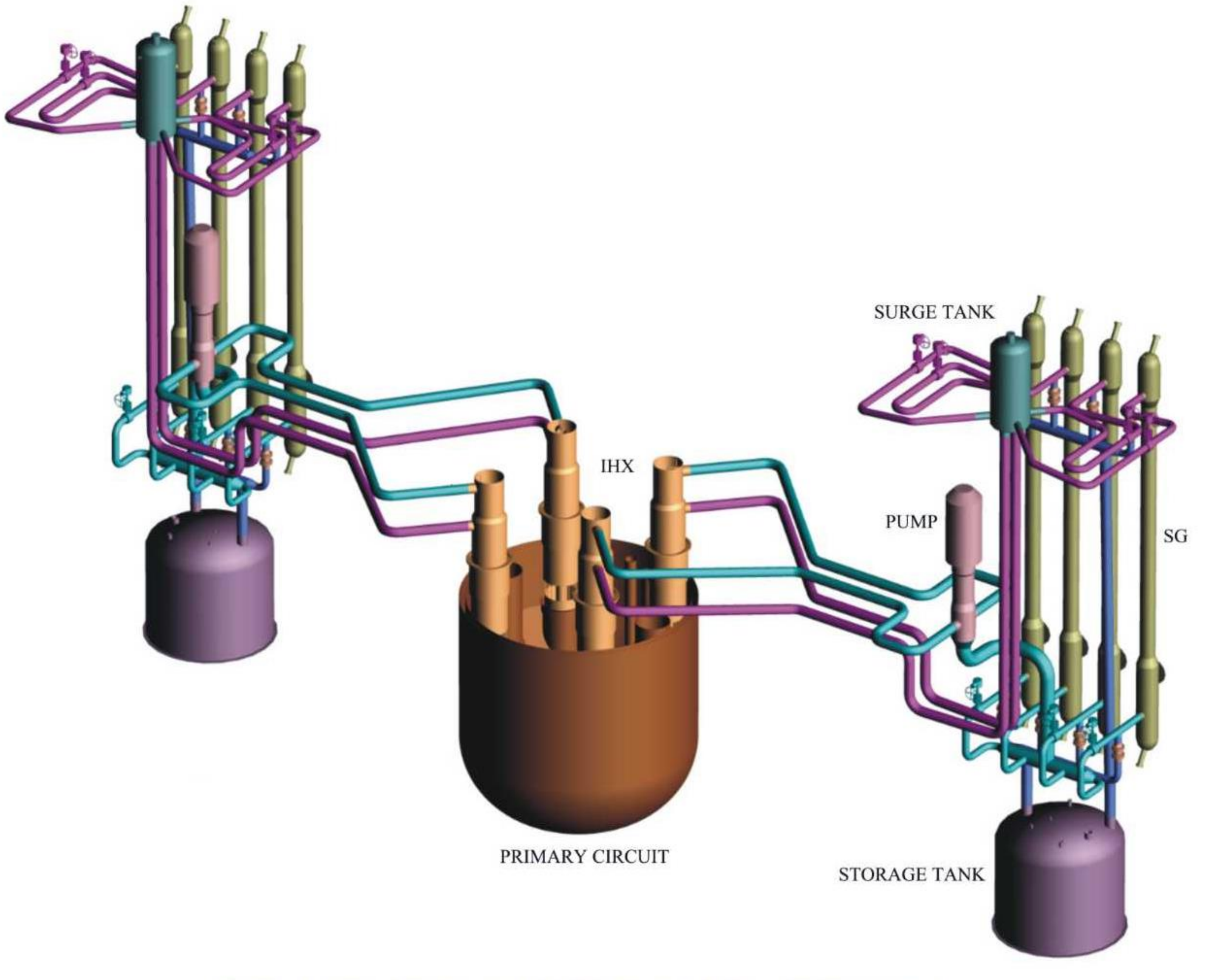
LEGEND

01. MAIN VESSEL
02. CORE SUPPORT STRUCURE
03. CORE CATCHER
04. GRID PLATE
05. CORE
06. INNER VESSEL
07. ROOF SLAB
08. LARGE ROTATABLE PLUG
09. SMALL ROTATABLE PLUG
10. CONTROL PLUG
11. CONTROL & SAFETY ROD MECHANISM
12. IN-VESSEL TRANSFER MACHINE
13. INTERMEDIATE HEAT EXCHANGER
14. PRIMARY SODIUM PUMP
15. SAFETY VESSEL
16. REACTOR VAULT

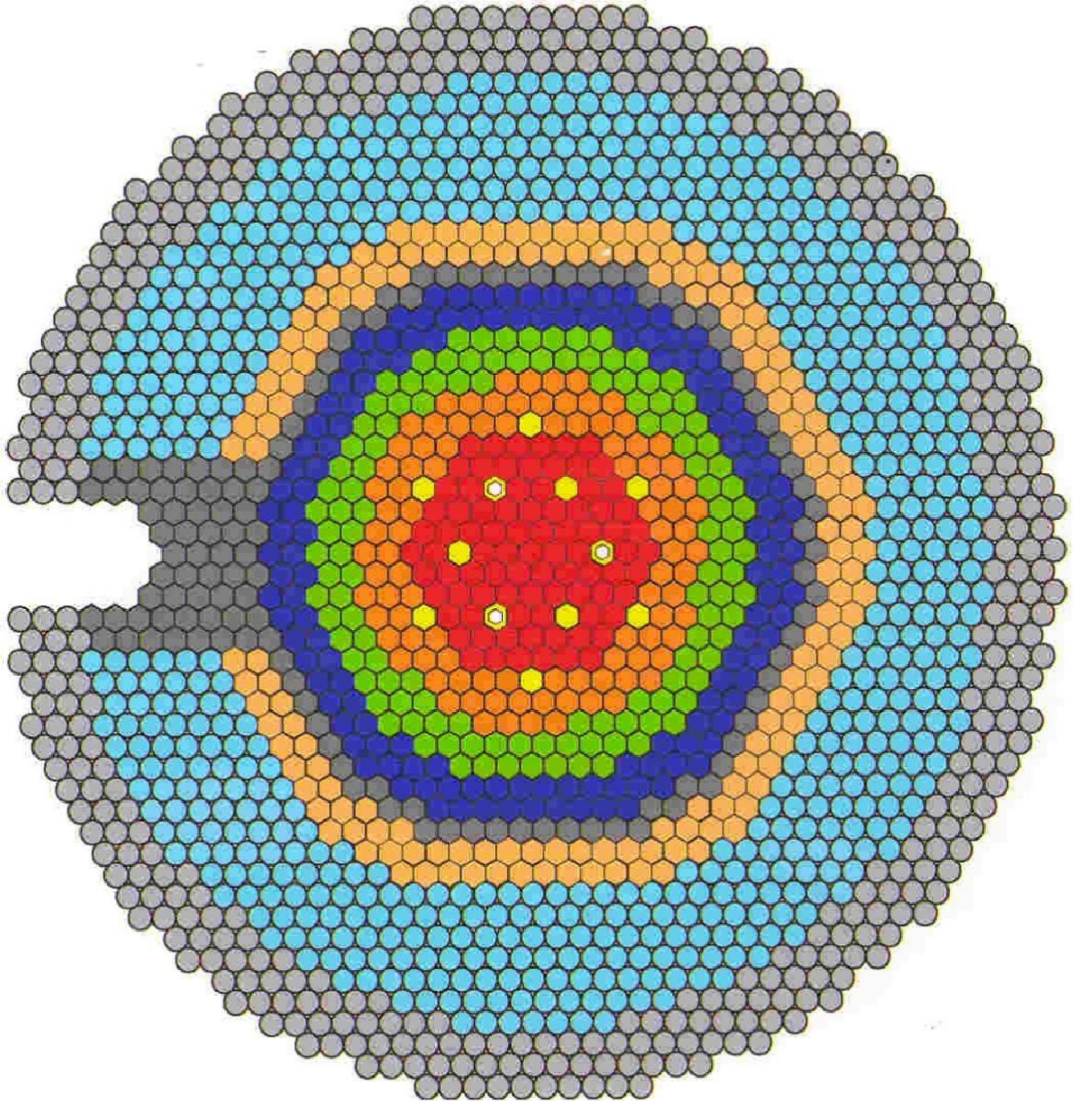
PFBR HEAT TRANSPORT CIRCUIT



PFBR FLOW DIAGRAM



PFBR REACTOR CORE



SYMBOL	TYPE OF SUBASSEMBLY	No.
	FUEL (INNER)	85
	FUEL (OUTER)	96
	CONTROL AND SAFETY ROD	9
	DIVERSE SAFETY ROD	3
	BLANKET	120
	STEEL REFLECTOR	138
	B_4C SHIELDING (INNER)	125
	STORAGE LOCATION	156
	STEEL SHIELDING	609
	B_4C SHIELDING (OUTER)	417
	TOTAL SUBASSEMBLIES	1758

SHUT DOWN SYSTEM

- Two independent, redundant, fast acting diverse shutdown systems (SDS-1, SDS-2)
- Each system is capable of shutting down the reactor independently
- SDS consists of Sensors, Signal Processing Systems, Safety Logic Systems, Drive Mechanisms and Absorber Rods
- Absorber rods of SDS-1 are Control and Safety Rods (CSRs) and the absorber rods of SDS-2 are called as Diverse Safety Rods (DSRs)
- There are 9-CSRs and 3-DSRs. CSRs are used for startup, control of reactor power, controlled shutdown and SCRAM, where as DSRs are used only for SCRAM. (N-1) Sufficient for shutdown.
- The respective drive mechanisms are called as CSRDM & DSRDM

NEED OF PASSIVE SHUTDOWN SYSTEM

- To comply with the GIF SFR Safety Design Criteria for Generation-IV (Gen-IV) Sodium-cooled Fast Reactor (SFR) systems

- As per guidelines the Design Extension Conditions (DECs)– Accident conditions that are typically of lower probability than design basis accidents and involve the failure of more than one SSC important to safety or part of a safety system.

- Design extension conditions are considered for the development of design measures for Defence-in-Depth Level 4

- The following two major groups of accidents merit special attention due to challenges in designing an SFR

  1) Failure to reduce power or shut down the reactor following an off-normal initiating event

  2) Inability to remove heat from the core

NEED OF PASSIVE SHUTDOWN SYSTEM

- ATWS combined with failure of a reactor protection system (RPS), would lead to coolant boiling and a core melting scenario
- Passive devices can significantly lower the likelihood of a Core Disruptive Accident (CDA) and substantially enhance the overall safety
- While designing the G-IV of advanced nuclear reactors such systems are considered .
- In Indian SFRs, a passive shutdown system to address the Unprotected Loss of Flow (ULOF) event
- Positive Void coefficient
- Not operating at the most reactive configuration
- Passive shutdown system will ensure shutdown of reactor if primary shutdown systems failed to act

FUNCTIONAL REQUIREMENTS FOR PASSIVE SHUTDOWN SYSTEM

- **Sufficient worth to induced enough negative reactivity and shutdown the reactor from any postulated accident conditions.**
- **Satisfy the 2/3 logic of the shutdown system**
- **Time taken to shut down system the reactor shall be close to time taken by primary shutdown systems**
- **No electronic of mechanical feedback mechanism to initiate the shutdown**
- **No human intervention to stop or initiate the activation once reactor is in operation**
- **Totally independent system with respect to primary shut down system**
- **Operate in fail-safe condition.**
- **Diversity from other shutdown system and redundant in nature.**

DESIGN CRITERIA FOR PASSIVE SHUTDOWN SYSTEM

- ✓ **Once mobile absorber rod deposited in the reactor core, it shall not come out even at 110% of nominal flow rate condition**
- ✓ **Loading and unloading similar to primary shutdown sytems**
- ✓ **Design and operation shall be simple, sound, reliable and robust**
- ✓ **Construction material similar to the other shut down system**
- ✓ **Design life shall be equal to more that the other shutdown system subassembly.**
- ✓ **Shall meet the other design conditions of shutdown system like functionality during seismic loading and bowing of the core sub assembly.**
- ✓ **The mobile rods shall fall into the core to shutdown reactor at specified flow rate.**

PASSIVE SHUTDOWN SYSTEM

- Mobile rod, which consists of B4C pellets enriched with B-10
- Mobile rod raised manually to its operating position using the drive mechanism.
- Once the nominal flow established, the drive mechanism detaches
- mobile rod remains suspended from its top seat due to the drag forces generated by the flowing sodium.
- Coolant mass flow rate falls below 50%, mobile rod descend by gravity into the core
- At the end, mobile rod decelerated by a sodium dashpot
- Auxiliary shutdown system to address ULOFA

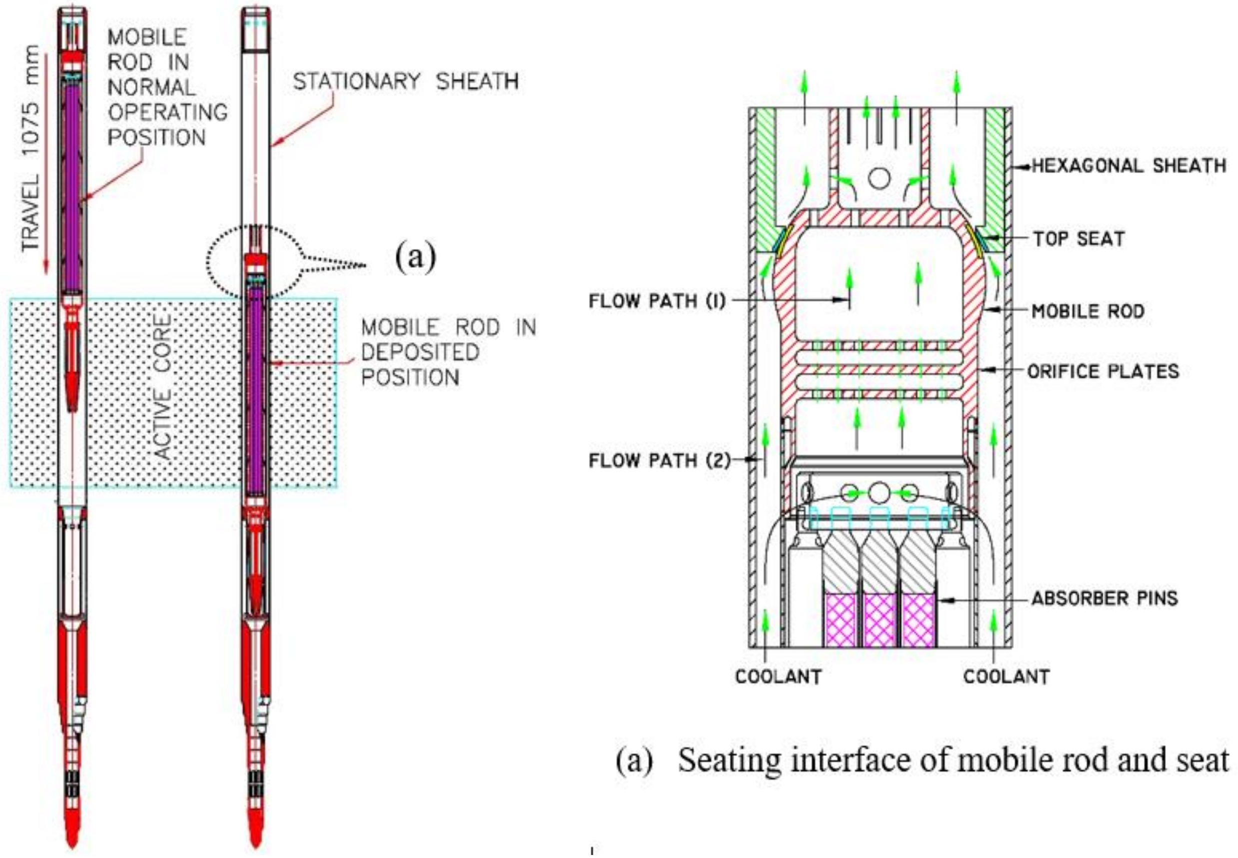


FIG. 1. Schematic of Passive shutdown system in Dropped condition and suspended condition

DEVELOPMENT PROCEDURE

1. DESIGN AND DEVELOPMENT OF PRESSURE DROP DEVICE

- Design based on MOP (Multi-Orifice Plate) assembly
- Testing in water to check drag force equal to the apparent weight of mobile rod at specific flow rate

2. DEVELOPMENT OF SEATING INTERFACE

- Development of seating interface between mobile rod and Top seat to minimize leakage
- Testing in water to ensure the suspension of mobile rod till specific flow rate

3. DEMONSTRATION OF FUNCTIONALITY OF THE SYSTEM

The functionality of the system demonstrated in two steps.

3.1 Functionality Test

- Fabrication of 1:1 scale model of passive shutdown dummy subassembly
- Testing in water to demonstrate the suspension of mobile rod and falling at specific flow rate

3.2 Measurement of Drop Time

- Experimental measurement of time taken by the mobile rod releasing from the top seat till deposited in the dashpot in flowing water condition

1. Design and Development of Pressure Drop Device

- **Designed to generate sufficient drag to keep mobile rod remains suspended from its seat until a specific flow rate is achieved**
- **Based on Multiple Orifices Plates (MOP) assembly**
- **Initial design evolved empirically, involving iterative adjustments to orifice hole dia, number of holes, number of plates, and thickness of the plates.**
- **Individual orifice plates are arranged in staggered manner for effective utilization and space constraint**
- **Testing of models in water for required pressure drop and Cavitation free performance**
- **The development was an iterative process, which involves CFD analysis & validation with experimental studies**

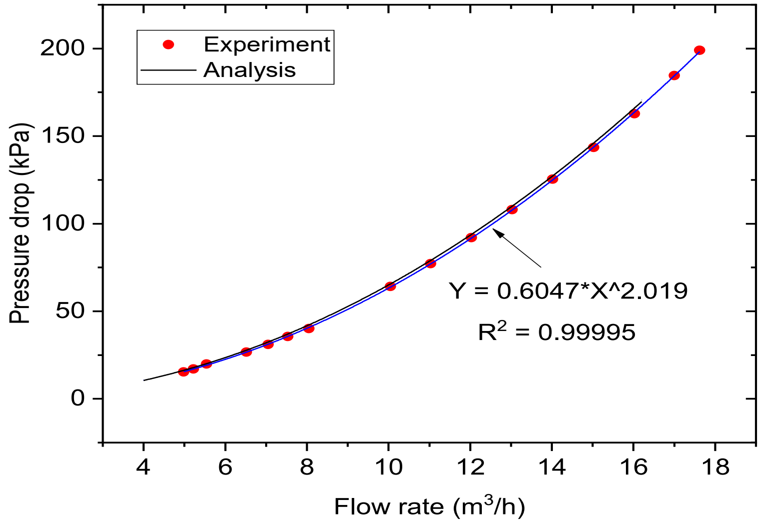


FIG. 2. Pressure drop vs flow rate for model

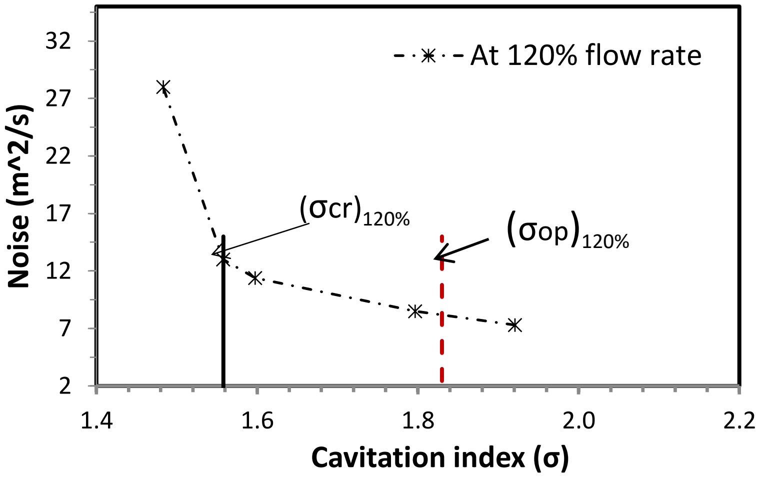


FIG. 3. Noise vs cavitation index

2. Development of Seating Interface

- **Coolant enters into the passive shutdown system subassembly through grid plate sleeve and later bifurcated into two parallel paths**
- **One path is leakage through the seating interface and other through the mobile rod**
- **Major portion of the coolant shall pass through the mobile rod to generate the sufficient drag force**
- **Designed the seating interface to minimized the leakage and testing in water**
- **Mobile rod may hang from the seat in tilted position therefore leakage at tilted condition also measured**
- **It was found that leakage through seat is < 0.1% of nominal flow rate, which is very well acceptable.**

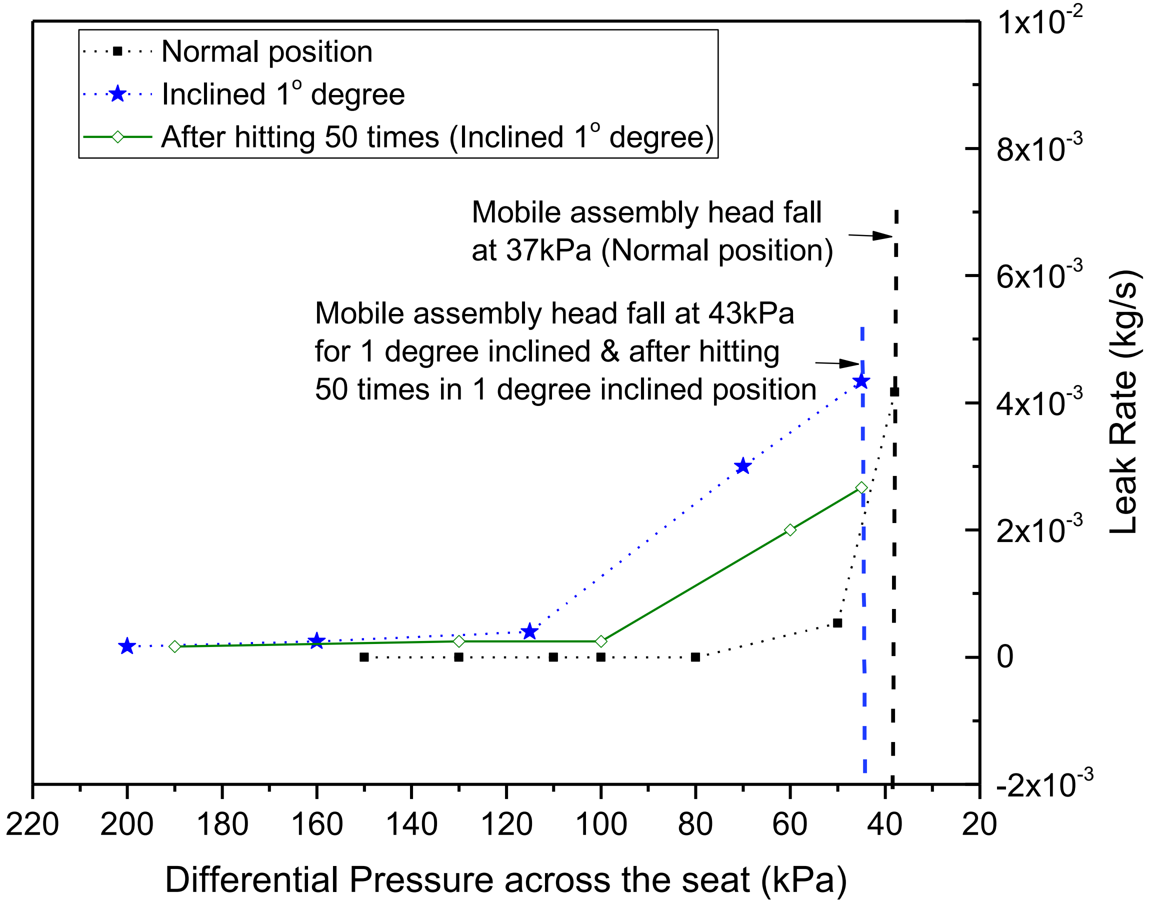


FIG. 4. Typical seat leakage plot for mobile rod seating in normal position and at tilted position on handling head

3. Demonstration of Functionality of the System

The functionality of the system demonstrated in two steps

3.1 Functionality Test

- 1:1 scale model of passive shutdown dummy subassembly with reproducing all features as in prototype fabricated
- Experimental study was conducted in flowing water
- The apparent weight of the mobile rod was simulated
- Mobile rod was raised manually to its top position, using a nylon rope with relatively negligible weight and pulley arrangement
- Once the volumetric flow rate above the specific flow rate was developed, the rope completely loosened for the mobile rod
- The flow rate reduced slowly with the help of VFD driven pump and pressure drop with flow rate recorded simultaneously
- Experimental testing also shows mobile rod released from its seat at 47.96% ± 1.74% volumetric flow rate with 99.7% confidence level.

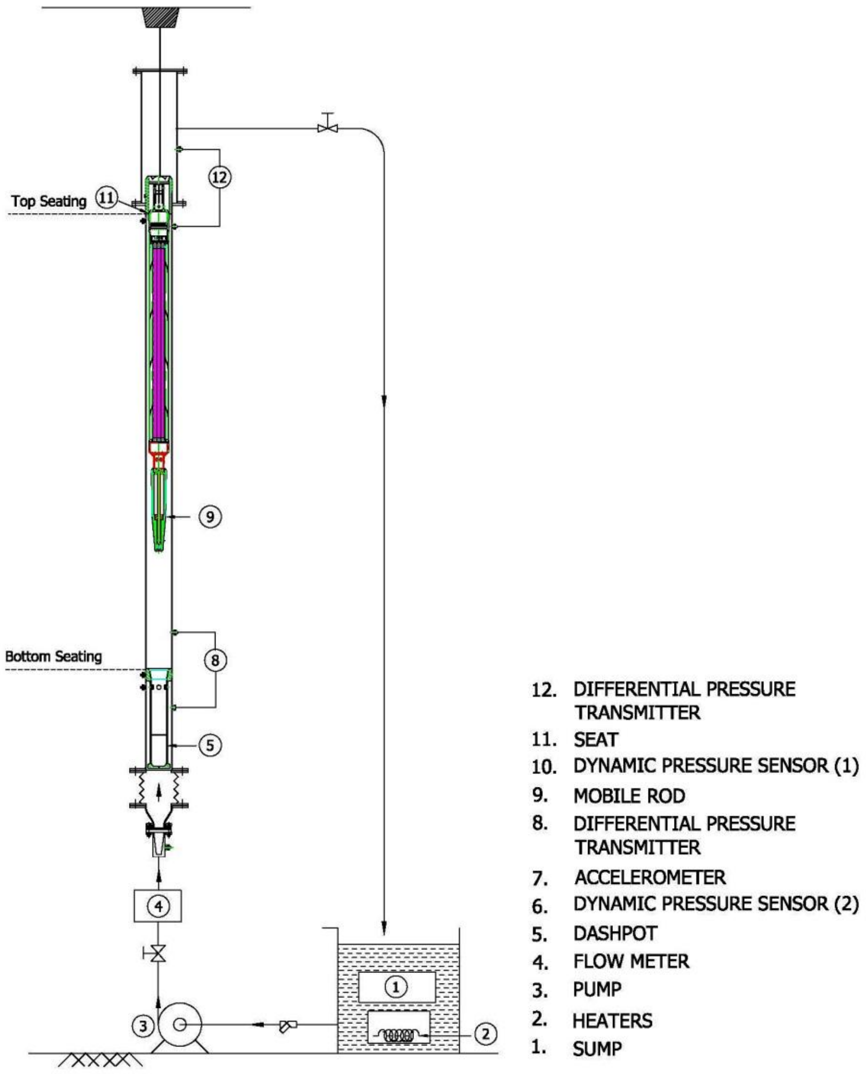


FIG. 5. Schematic of Test Setup

3.2 Measurement of Drop Time

- The measurement was conducted in flowing water, using 1:1 scale model of passive shutdown dummy subassembly
- Dynamic Pressure Sensors (DPS) were positioned to capture variations in static pressure.
- Charge-type accelerometer was installed to detect any noise generated by the mobile rod rubbing against the outer sheath
- Readings from all the instruments recorded simultaneously and a representative time-travel plot is presented in Figure 6
- Point 1: Beginning of mobile rod detachment from its seat
- Point 2: Mobile rod is fully detached from its seat
- Point 3: Rubbing of mobile rod with outer sheath

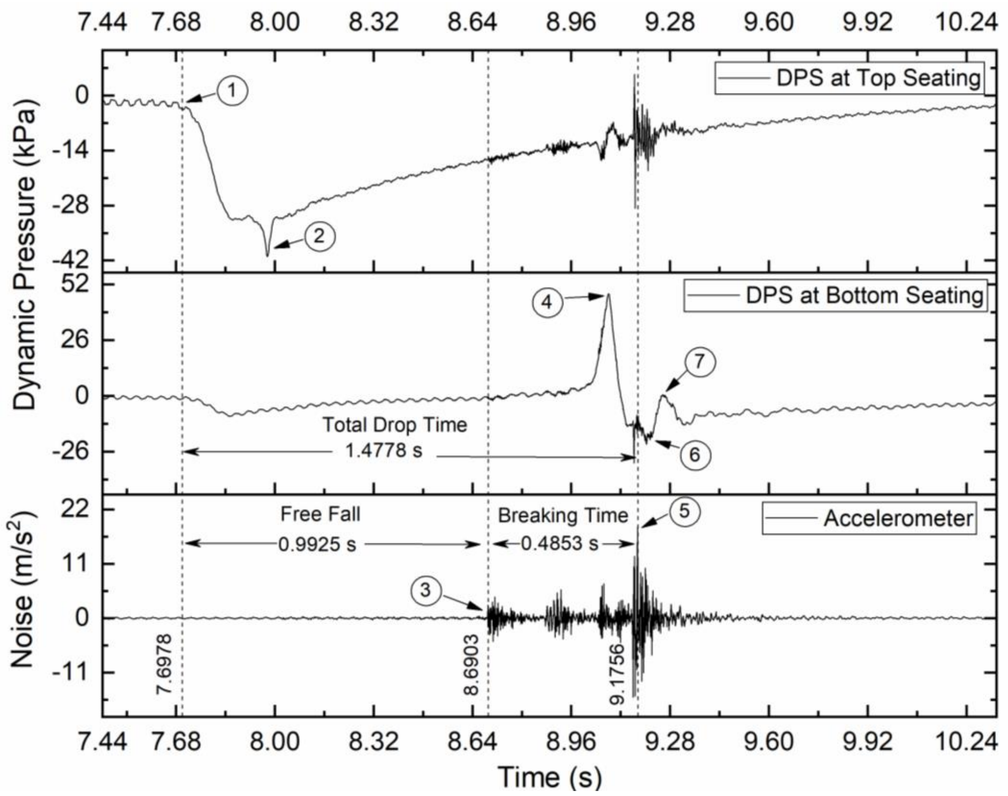


FIG. 6. Falling of mobile rod on time scale

- Point 4: Mobile rod enters into the dashpot and the coolant flow path is blocked
- Point 5: Mobile rod hits the dashpot seat, producing a sharp noise detected by the accelerometer
- Point 6: Mobile rod sits on the dashpot and coolant flowing through mobile rod

RESULTS

- Full scale passive shutdown system dummy subassembly was fabricated and hydraulic performance of the same was characterized.
- No chattering observed on mobile rod during sitting on top seat at any flow condition
- Class IV leak tightness with metal to metal contact joint achieved at seating interface
- The operation of raising mobile rod manually, holding at the seat due to differential pressure and falling at reduction of flow rate was repeated around 100 times.

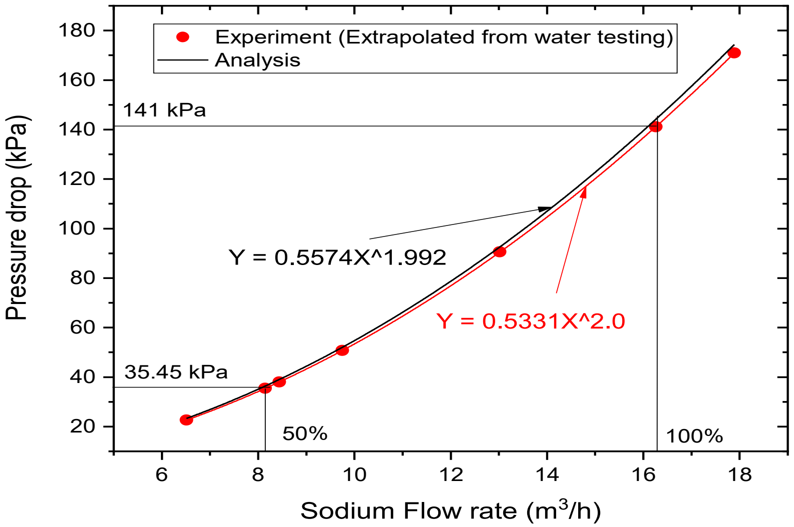


FIG. 7. Falling of mobile rod on time scale

- Experimental studies also confirm cavitation free operation of the pressure drop device.
- After extrapolation of experimental measurement to reactor conditions, the mobile rod release from its seat at 49.10% ± 2% of nominal sodium mass flow rate at 400oC with 99.7% confidence level.
- The total travel time of the mobile rod from the top seat to its final position in the bottom dashpot seat is 1.5 seconds, with a variation of ±3.771% at a 99.7% confidence level

CONCLUSION

- A passive shutdown system sub assembly has been developed to address the Unprotected Loss of Flow (ULOF) event.
- The characterization of hydraulic performance and qualification of the hydraulic design were confirmed through full-scale experiments conducted in water.
- A state-of-the-art instrumentation scheme was deployed to accurately measure the experimental outcomes.
- This system will serve as an auxiliary shutdown mechanism, addressing the event of ULOFA
- The passive shut down system shall meet the other design conditions of shutdown system like functionality during seismic loading and bowing of the core sub assembly.
- It meets the safety measures in Defence-in-Depth Level 4 and design criteria of Gen –IV reactor for design extension conditions
- The likelihood of a low probabilistic Core Disruptive Accident (CDA) reduced significantly and enhance the overall safety profile of nuclear reactor systems
- It ensures the safe shutdown of the reactor and tackle the criticality issue due to poisitive sodium and prevent sodium boiling in the reactor

ACKNOLEDGEMENT

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