# Safety Assessment of Passive features of Advanced Heavy Water Reactor

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**Abstract**

Advanced Heavy Water Reactor (AHWR) is a vertical, pressure tube type, heavy-water-moderated, boiling light-water-cooled reactor relying on natural circulation for core cooling in all operating and shutdown conditions. In addition, it incorporates various passive systems for decay heat removal, passive valving of isolation condenser at different pressures, passive poison injection system, High pressure passive accumulator, low pressure gravity driven pool, passive containment isolation system and passive containment cooling system. Emphasis is also laid on inherently safe characteristics (e.g. negative void coefficient, large Main Heat Transport (MHT) and deaerator inventory etc). This paper discusses assessment of various passive systems for different governing postulated initiating events in different categories [2]. Loss of Coolant Accident (LOCA) with spectrums of break sizes, station blackout scenarios and reactivity induced accidents are considered in this evaluation.

## 1. Introduction

The 300 MWe AHWR is a direct cycle, boiling-light-water-cooled, heavy water moderated, vertical-pressure-tube-type reactor with natural circulation as mode of heat removal from core under all conditions [1]. AHWR uses naturally available thorium as its main fuel resource, converts it into fissile $_{233}$U, which is burnt in-situ to generate energy. Main physics design objectives are maximization of power from Th/$_{233}$U, negative void coefficient of reactivity, minimization of initial inventory and consumption of plutonium, self-sustaining characteristic in $_{233}$U and high discharge burn-up with low excess reactivity. The design philosophy of the AHWR goes with the principle "safety-in-design". This is achieved by incorporation of inherent and passive safety in design such that in any abnormal operation including accidents, the reactor is brought back to a stable state without the danger of any release of radioactivity to the public. A schematic of different heat removal paths along with the passive systems are shown in Figures 1 and 2 respectively. The important Passive Safety Systems in AHWR are:

1. Core heat removal by natural circulation of coolant during normal operation and shutdown conditions.
2. Decay heat removal by Isolation Condensers (ICs) immersed in a large pool of water in a Gravity driven water pool (GDWP).
3. Direct injection of ECCS water in to fuel cluster in passive mode during postulated accident conditions like Loss of Coolant Accident (LOCA), initially from accumulators and later from GDWP.

4. Containment cooling by passive containment coolers during LOCA.
5. Passive containment isolation by formation of a water seal in ventilation ducts, following a large break LOCA
6. Passive shutdown by injection of poison in the moderator, by usage of system high-pressure steam in case of a low probability event of failure of wired mechanical shutdown system (SDS-1)and liquid poison injection system (SDS-2).
7. Passive concrete cooling system for protection of the concrete structure in high temperature zone (V1-volume).
8. Availability of large inventory of water in Gravity driven water pool (GDWP) at higher elevation inside the containment, facilitates sustenance of core decay heat removal, ECCS injection, and containment cooling for at least 72 hours without invoking any active systems or operator action.

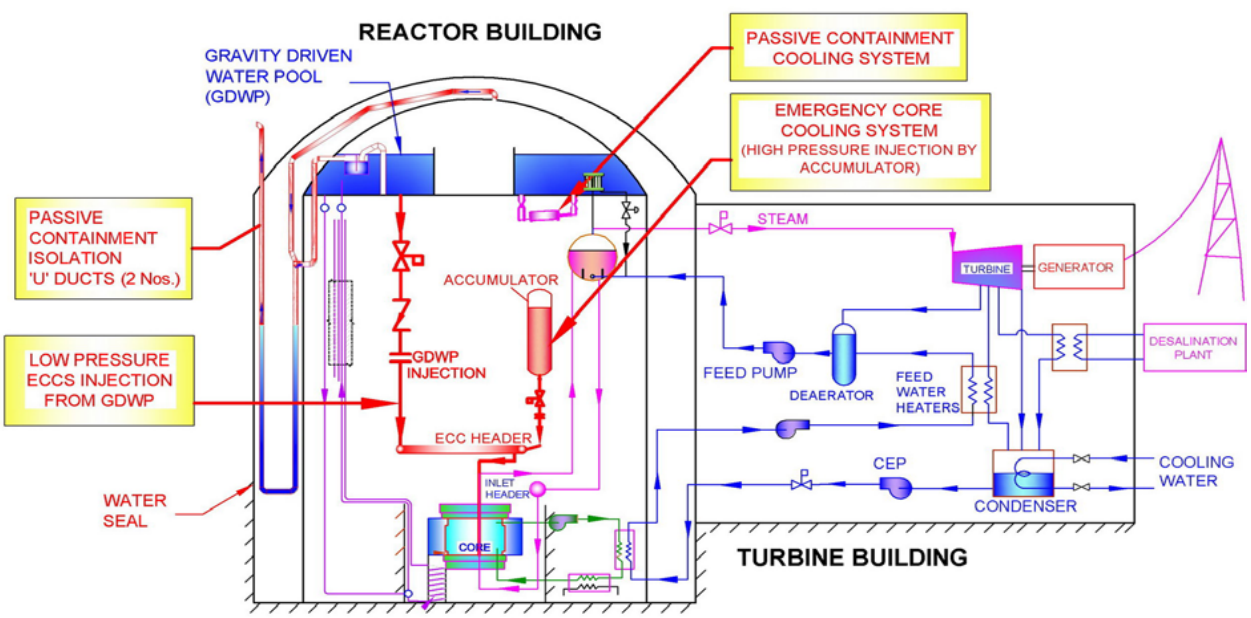


Fig.1 Schematic of AHWR Heat Removal Systems

Along with the passive safety, the reactor has several inherent safety features in the design which include:

1. Negative void coefficient of reactivity.
2. Negative fuel temperature coefficient of reactivity.
3. Negative power coefficient of reactivity.
4. Natural circulation driven heat removal during normal operation and hot shutdown condition.
5. Double containment system.
6. Four independent ECCS trains.
7. Direct injection of ECCS water into the fuel cluster.

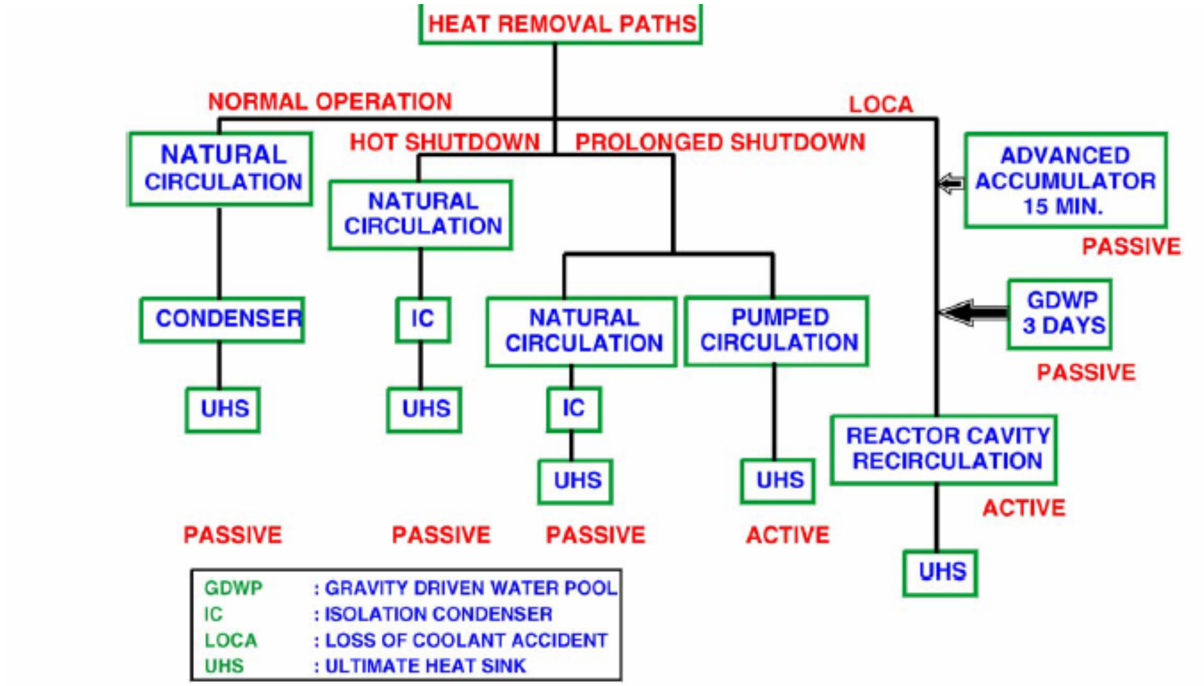

Fig 2 Passive heat removal paths in the AHWR

This paper describes safety evaluation of these passive and inherent safety features for some of the important postulated initiating events.

## 2. Evaluation of Decay Heat Removal system

In normal condition, main condensers remove decay heat and MHT pressure controller maintains hot shutdown condition by regulating turbine bypass valve. In case of Class IV power failure, bypass valve is not available due to low condenser vacuum. In case of Class IV power failure, decay heat can be removed by passive decay heat removal system for prolonged duration of 72 hours. The system consists of Isolation Condensers (ICs) submerged in a pool of water called Gravity Driven Water Pool (GDWP) with appropriate valves, piping and headers as shown in Fig. 3.

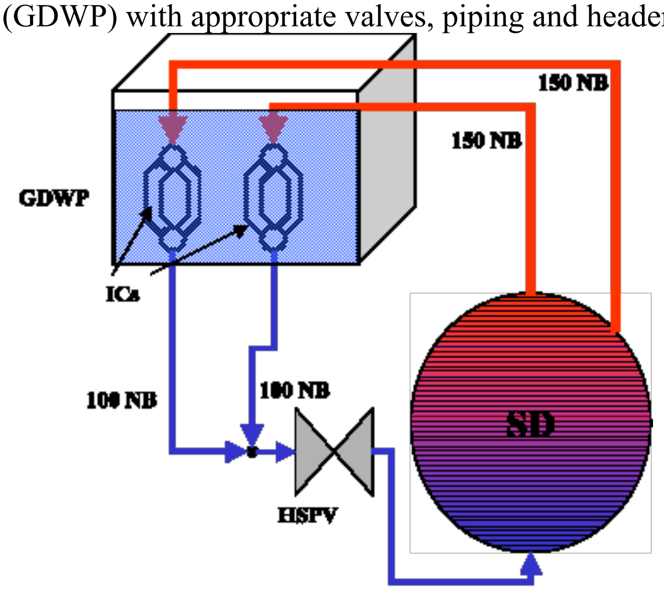

Fig. 3 Schematic of Isolation Condenser (IC) system

During Station blackout (class IV and class III power failure), system pressure rises to about 76.5 bar leading to opening of four passive valves connected between outlet of isolation condensers and inlet of steam drums [3] [4]. This valve regulates the flow depending upon amount of decay heat to be removed. Scenario involving class IV power failure, stopping of feed water flow, closure of combined isolation and emergency stop valve, pressure rise and subsequent reactor tripping on high pressure of 76.0 bar and valving in of passive valve of IC at 76.3 bar is simulated using RELAP5/MOD3.2. The pressure and temperature predictions for half hour are shown in Fig. 4 and 5 for 2000 seconds duration. Isolation condenser has capacity to remove decay heat for 72 hours without significant temperature rise.

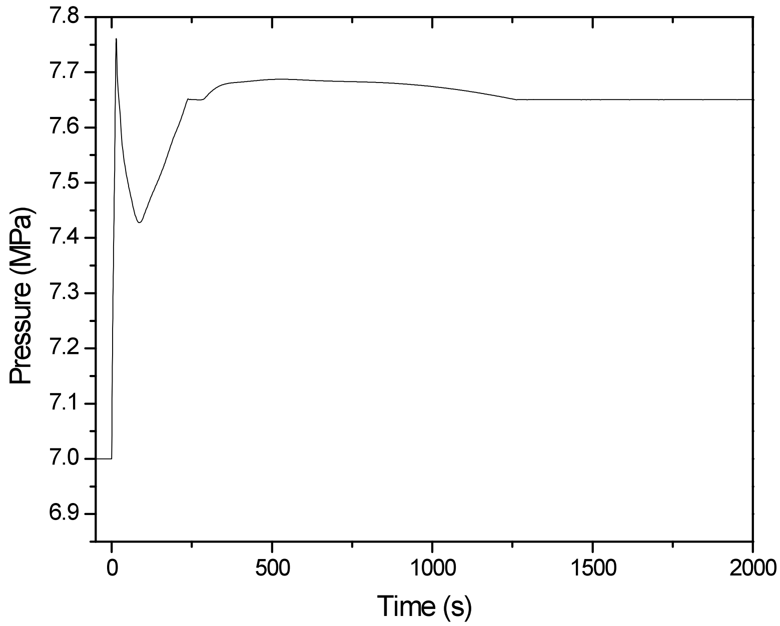


**Fig. 4: Steam Drum Pressure for Station Blackout**

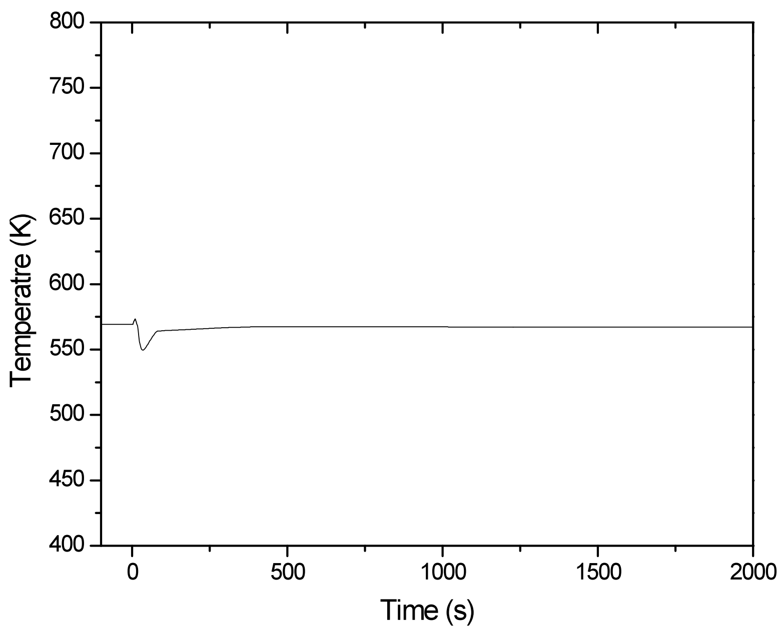


**Fig. 5: Clad Surface Temperature for Station Blackout**

## 3. Evaluation of Passive Poison Injection System:

Passive poison injection is important passive system which gets automatically actuated when both active shutdown system are not available during various accident situations. It involves injecting poison in calandria vessel when system pressure reaches to 84 bars. It plays important role in achieving large safety margins during various scenarios like Loss of regulation, Loss of feed water, turbine trip without bypass, station blackout and spectrum of breaks in inlet header.

Station blackout scenario without recovery and with failure of wired shut down system comprising of failure of various systems and components on Class IV and Class III power supply, increase in system pressure, actuation of isolation condenser at 76.5 bars and actuation of passive poison injection system at 84 bar is simulated. Typical and pressure and temperature predictions are shown in the following figures. In this case pressurization is quite effective due to bottling of system.

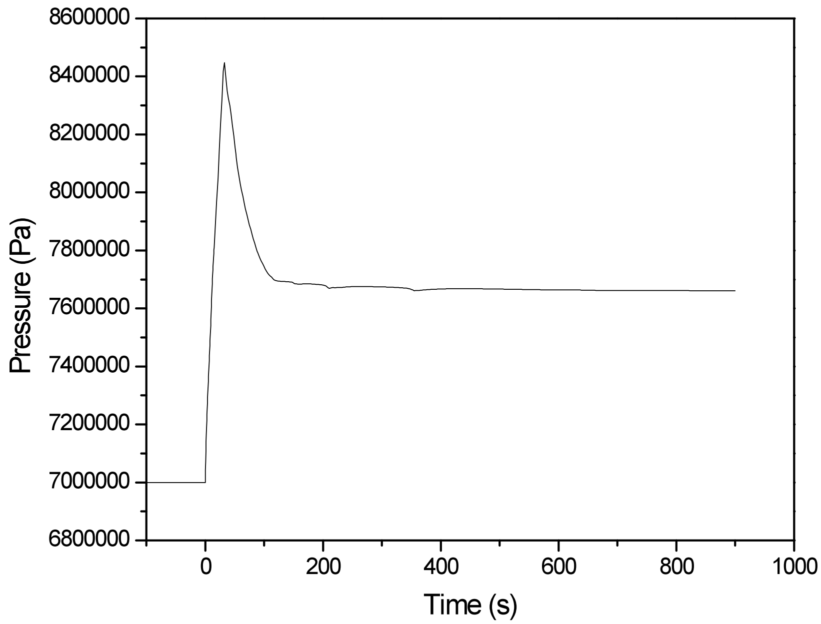


**Fig. 6: Steam Drum Pressure for Station Blackout with failure of active shutdown systems**

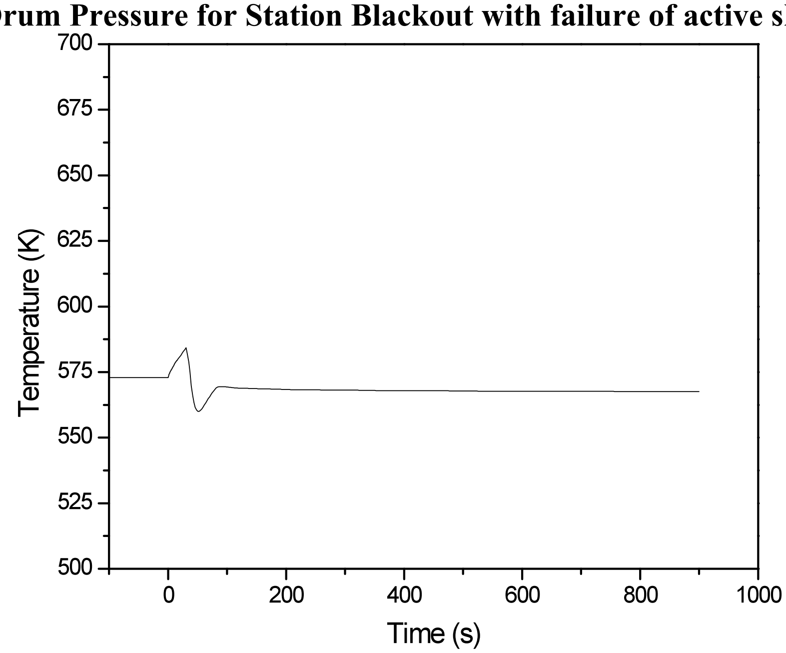


**Fig. 7: Maximum Clad Surface Temperature for Station Blackout with failure of active shutdown systems**

Scenario for LORA with failure of wired shut down and without trip involves insertion of positive reactivity, rise in power and system pressure. System pressurisation in this case is comparatively slower due availability of turbine bypass. However closure of Main steam isolation valve on high steam flow signal lead to rapid pressurization and actuation of passive poison injection system. Predictions for system pressure and clad surface temperatures are shown in the following figures.

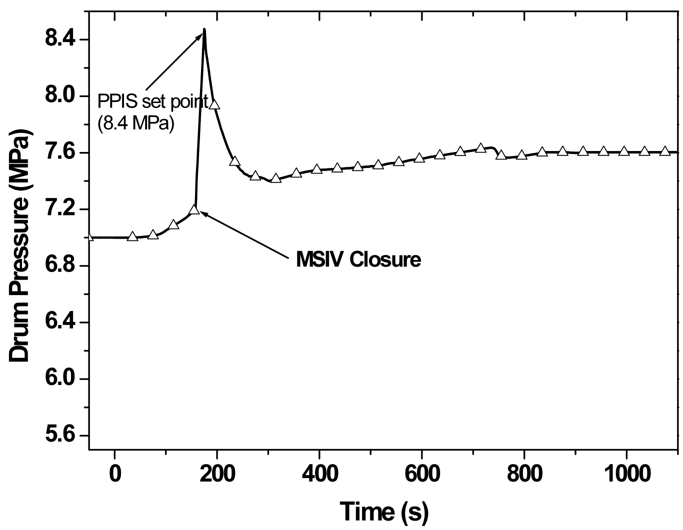


**Fig. 8: Steam Drum Pressure for LORA with failure of active shutdown systems**

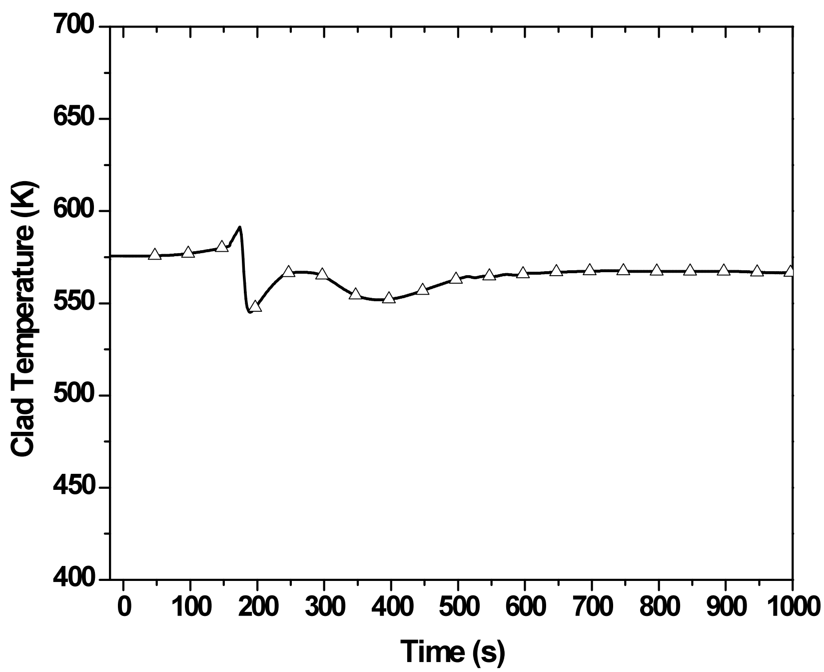


**Fig. 9: Maximum Clad Surface Temperature for LORA with failure of active shutdown systems**

In case of LOCA scenario actuation of PPIS scenario depends upon break size. Scenario involves depressurization due to loss of coolant from break. However closure main steam isolation valve on high containment pressure leads to pressure rise and actuation of passive poison injection system for break size up to 25 % of inlet header. Safety parameters are within acceptance limit for break size up to 20 % break. Pressure and temperature behavior for 20 % break are shown in the following figures.

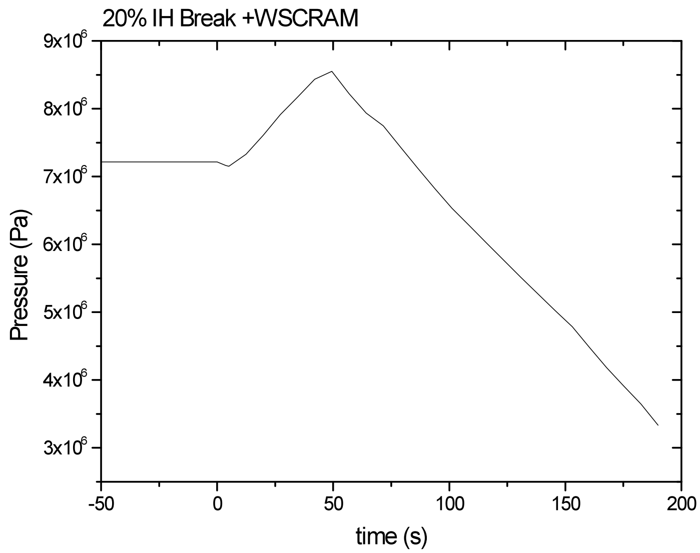


**Fig. 10: Steam Drum Pressure for LOCA with failure of active shutdown systems**

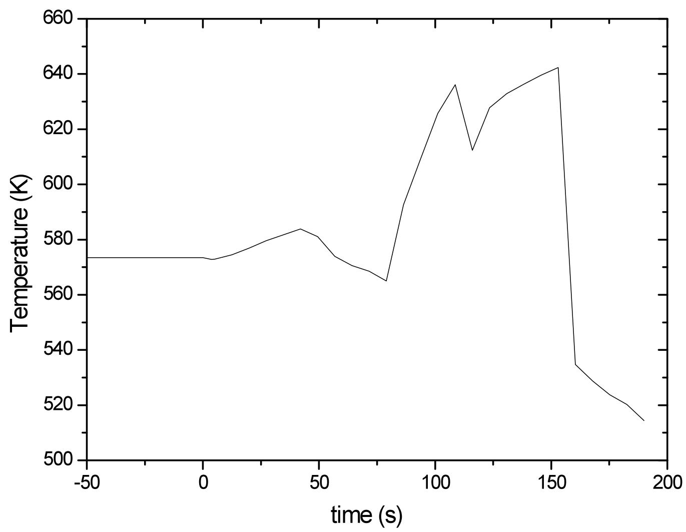


**Fig. 11: Maximum Clad Surface Temperature for LOCA with failure of active shutdown systems**

## 4. Evaluation of Passive accumulators and GDWP and isolation condensers for spectrum of breaks in inlet header

ECCS system of AHWR comprises of high-pressure accumulators, Gravity driven pool. In addition auto depressurisation is done by passive actuation of 4 isolation condensers at 35 bars, for early establishment of long term cooling for small breaks (break size less than 5 %). Predicted system pressure and clad surface temperature are shown in the following figures.

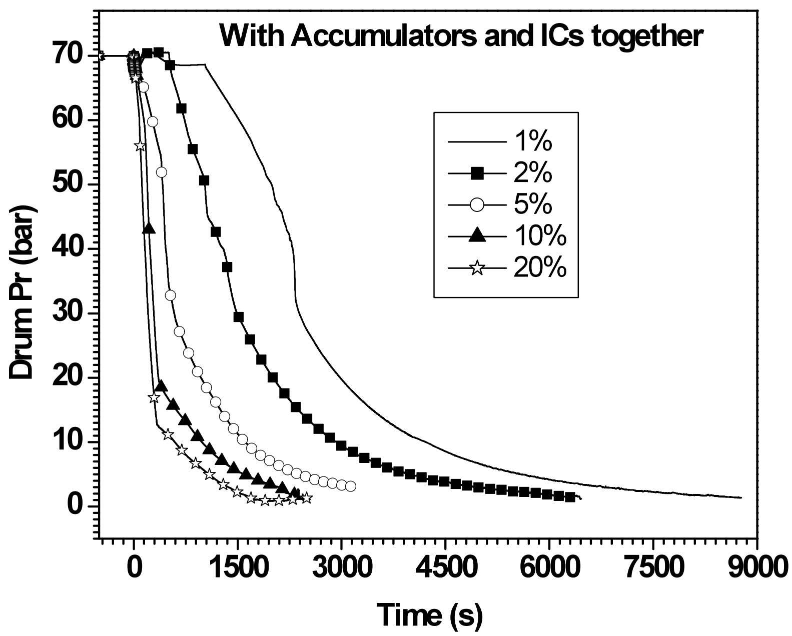


**Fig. 12: Drum Pressure for Spectrum of Break Sizes**

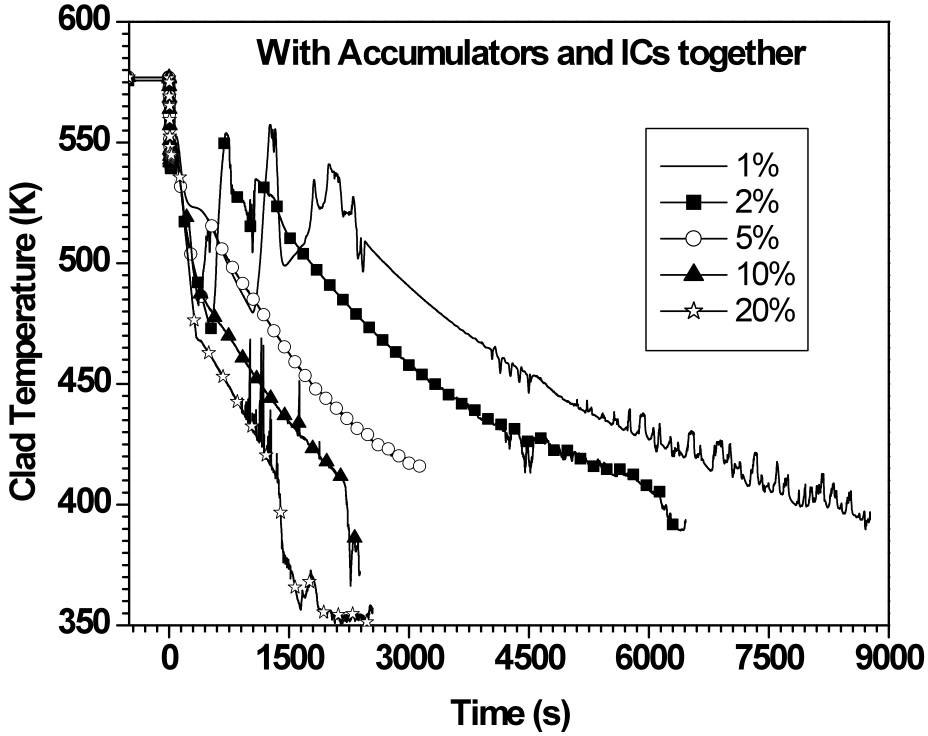


**Fig. 13: Maximum Clad Surface Tempertures for Different Break Sizes**

## 5. Evaluation of passive features of AHWR for LOCA without ECCS

Combination of passive and inherent features is helpful in mitigating consequence of the above event. Large inventory, negative void coefficient of reactivity and effective radiation heat transfer from fuel to pressure tube and pressure tube to calandria tube are helpful in keeping safety parameters within acceptance limit. Typical behavior for clad surface temperature, pressure tube temperature and calandria tube temperature is shown in the following figure. Effect of feeling of cavity between pressure tube and calandria tube is also indicated [5] [6].

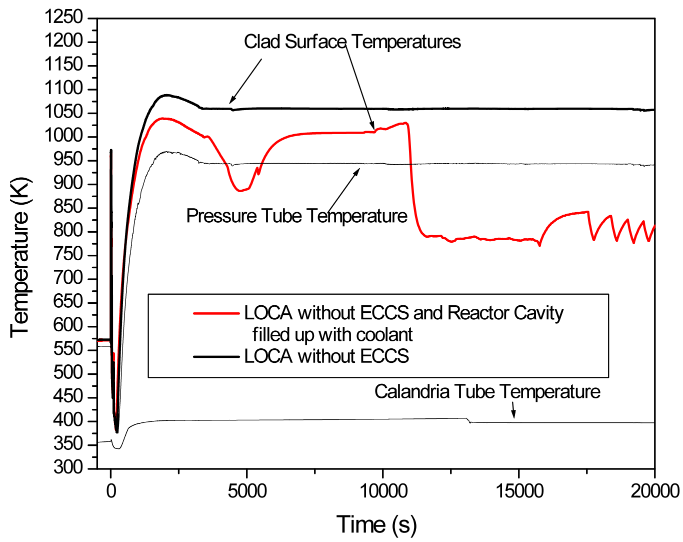


**Fig. 14: Maximum Clad Surface Tempertures for LOCA without ECC**

## 6. Evaluation of Passive Containment Isolation System

The PCIS system is one of the important passive systems in the conceptual design of AHWR. This system isolates the primary containment from the atmosphere in the event of LOCA, thus reducing the possible escape of radioactivity outside containment and is shown in Fig. 15. AHWR employs a double containment system i.e. primary containment & secondary containment. The primary containment is further zoned as V1 (high enthalpy) and V2 (low enthalpy) regions. Under normal operating conditions, the V1 and V2 regions are connected only through vent shafts, with downstream ends of vent shafts submerged in GDWP that also acts as a suppression pool. Blow Out Panels (BOP) are also provided in the reactor building to limit the pressure on the containment building structure under accidental conditions by directly connecting V1 and V2 volumes. The V2 volume is normally ventilated to atmosphere through a ventilation U-duct. Under postulated LOCA conditions, V1 and V2 regions undergo a pressure transient. The V1 pressure rises more rapidly than V2 pressure. However after opening of BOPs, the pressures tend to equalize as V1 and V2 are brought in direct communication. Under normal operating conditions, V2 is in communication with the atmosphere with the help of ventilation duct. The high-pressure condition in the V2 demands for the quick isolation of containment system from atmosphere to prevent any eventual release to the atmosphere. The isolation of containment is achieved by establishing a liquid U- seal in the ventilation duct. The predictions for levels in the ventilation duct in both leg and V2 pressure for 200 % break are shown in Fig.16. It indicates effective isolation.

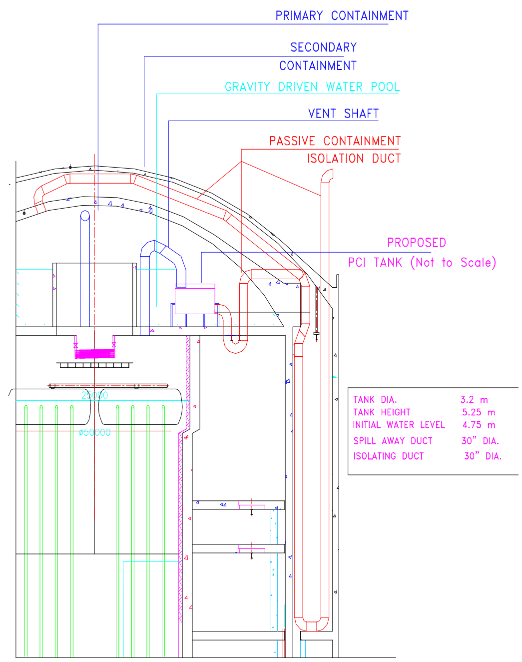


Fig.1 Passive Containment Isolation System

**Fig. 15: Passive Containment Isolation System**

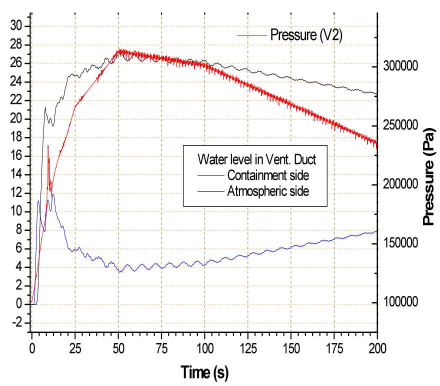


**Fig. 16: Passive Containment Isolation System Behaviour**

## 7. Evaluation of Passive Concrete Cooling System

The passive cooling features of AHWR containment comprises of suppression pool, Passive Containment Cooling System (PCCS) and condensation on concrete structures. Fig.17 shows behaviour of containment pressures. It can be seen both PCCS and cooling due to condensation on concrete structures contributes towards containing containment pressure.

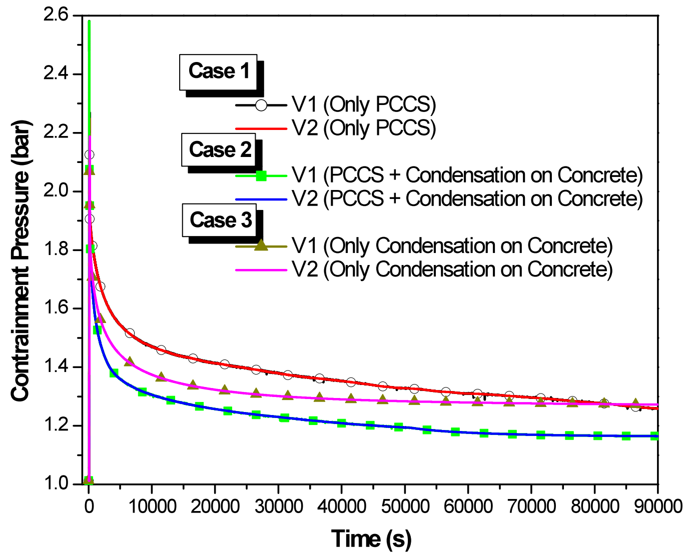


**Fig. 17: Passive Containment Cooler System Behaviour**

## 8. Concluding Remarks

Events in different categories with varying frequencies have been analysed for assessment of passive features of AHWR. It is observed that for all transients and accidents clad surface temperatures are within the limit of $800^0$ C. Acceptance criteria are also met for very low probable events like transients and accidents with failure of wired shutdown system, for almost entire range of events. Apart from ensuring integrity of first barrier, appropriate containment isolation and containment cooling is ascertained.

## 9. References


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