Transactions, **SMiRT 21, 6-11 November, 2011, New Delhi, India** ***Div-X: Paper ID# 511***

ROLE OF PASSIVE CONTAINMENT COOLING FEATURES DURING LOCA FOR ADVANCED NATURAL CIRCULATION REACTOR

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ABSTRACT

Recent inclination in nuclear industry is towards providing as many passive features as possible. These passive features enhance safety substantially. The Passive Containment Cooling System (PCCS) system limits the primary containment pressure by containment cooling post accident. The passive containment coolers are located below the Gravity Driven Water Pool (GDWP) and are connected to the GDWP inventory. During the LOCA, a mixture of hot air and steam flows over the passive containment coolers. Steam condenses and hot air cools down on the outer tube surfaces of the coolers due to natural circulation of GDWP water inside the tubes providing long-term containment cooling after the accident. The containment pressure during accident is important parameter as it directly affects the containment structural integrity and possible leak through it.

Other passive safety features like suppression pool and containment concrete also control the containment pressure. It is necessary to investigate the performance of all these safety features separately and together to get complete picture of containment loading during LOCA.

The paper elaborate first modelling of PCCS, suppression pool and concrete structure using system code i.e. RELAP5 and analyses of post LOCA scenario in containment. The containment loading in terms of pressure and temperature transients during LOCA are discussed in detail.

INTRODUCTION

The advanced reactors around the world are being designed with many passive safety features [1]. In the present reactor combination of passive features are used to limit the post LOCA consequences in the containment. These passive features include suppression pool i.e. GDWP, containment concrete and PCCS.

The reactor employs a double containment 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 general arrangement of the advanced reactor along with PCCS is shown in Fig. 1. The PCCS consists of a number of Passive External Coolers (PECs) suspended from the bottom of GDWP with appropriate valves, piping and headers. Fig.2 shows the schematic of working of PCCS in case of postulated accidental conditions. The PEC units kept in the V_2 volume consist of an inclined bank of cooling tubes that are connected with two headers. Each header is connected to the GDWP through a vertical pipe. These inlet and outlet pipes of PEC are insulated to provide sufficient buoyancy head for natural circulation of cooling water. The outlet pipe penetrates more inside the GDWP from the bottom as compared to the inlet pipe to increase the hot-leg height. This helps to increase the buoyancy head for natural circulation flow.

In the initial period of LOCA, the steam mixes with non-condensable present in the volume V_1 and enters the Gravity Driven Water Pool (GDWP) through the main vent shafts. BOPs open as differential pressure between V1 and V2 volume crosses 50 kPa soon after initiation of the transient. When the blow-out panels between V_1 and V_2 burst, it connects V1 directly to V2, and through this path steam-air mixture comes in contact with PCCS, concrete and different components present in V2 volume of the containment. From this period the steam condenses on the outer surfaces of the PEC tubes, concrete wall and on the surfaces of different components. Water inside the inclined tubes of the PEC gets heated-up and rises above the outlet pipe of the PCCS. Cooling water from GDWP enters from the inlet pipe of the PCCS and thus natural circulation gets established. In this way the cooling of the containment is achieved in a passive manner. The uncondensed steam and non-condensable gases passes through the vent pipe and accumulates in upper region of primary containment.

Vapor suppression and heat removal by condensation on concrete surface is used in most of the reactors worldwide. In this advanced reactor a new design feature PCCS has been introduced. In the present study an effort has been made to quantify the effectiveness of the PCCS along with other pressure suppressing mechanism mentioned above.

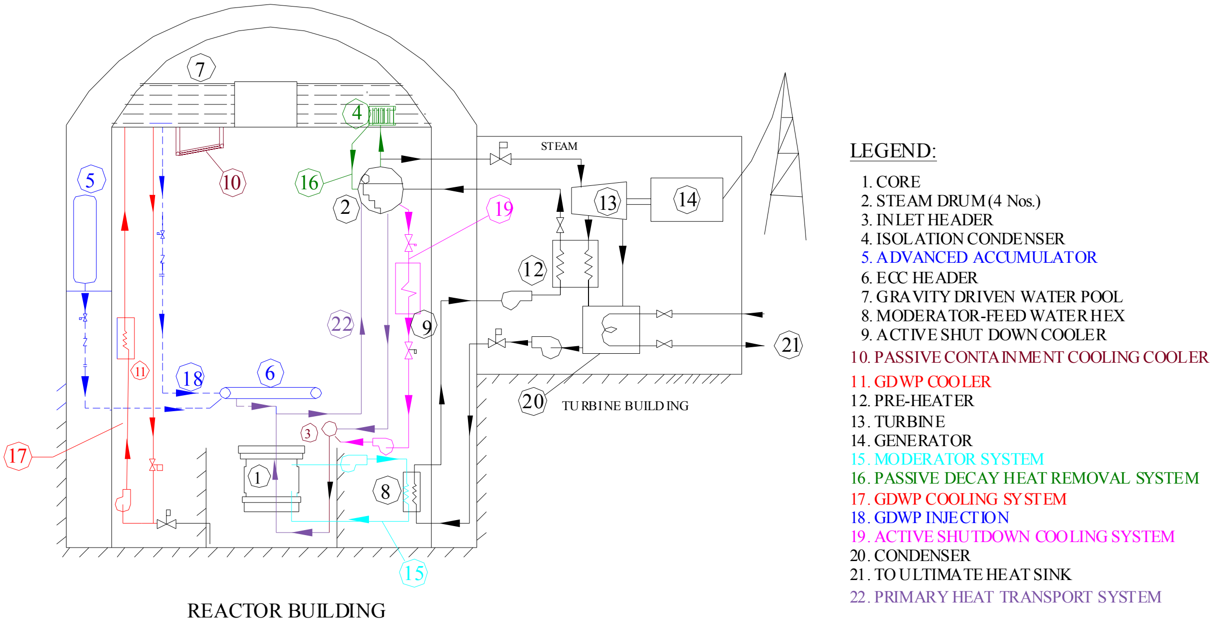

Fig.1: General Arrangement of advanced reactor with PCCS

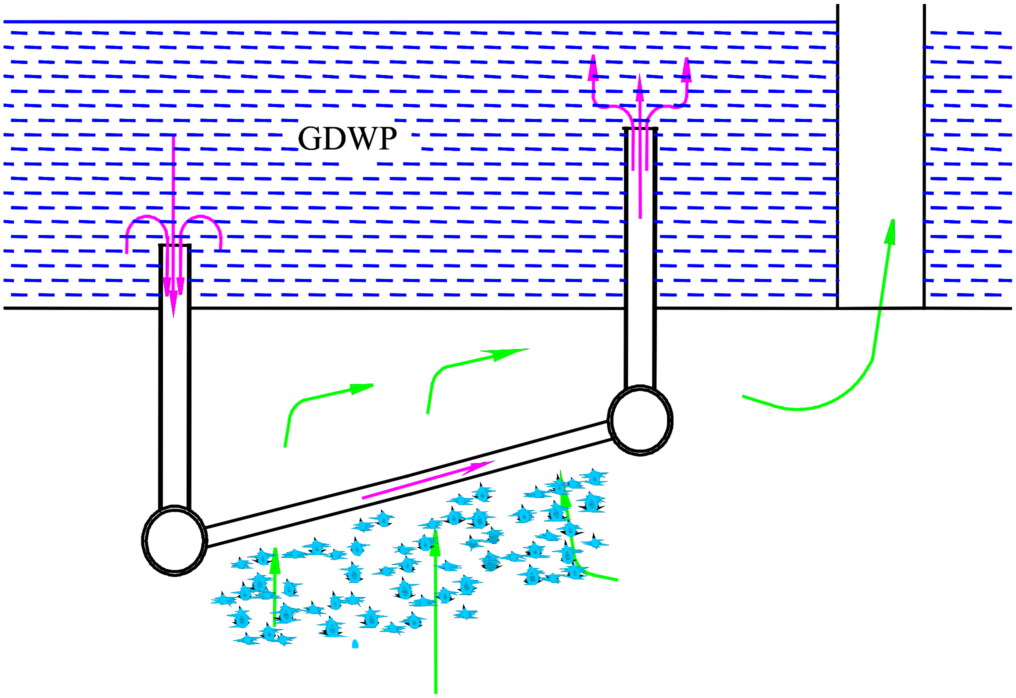

Fig.2: Schematic of Passive Containment Cooler

PRIMARY CONTAINMENT AND PCC SYSTEM MODELLING

RELAP5 code [2] has been used worldwide for analysing thermal hydraulic behavior of nuclear reactor systems. RELAP5 code’s use for containment application is reported in the literature. PANDA is a large-scale test facility having RPV, containment and Passive Safety Systems of an ALWR. RELAP5/Mod3.2 has been used with good success for pre- and post-test calculations for this facility [3]. Further, IRIS, which is a small-medium size, pressurized water reactor with an integral configuration, suitable for modular deployment. Its containment consists of different compartments, in particular the dry-well, the reactor cavity, and the pressure suppression systems. RELAP5 code has also been used to simulate the containment response of this reactor [4]. Hence, RELAP5 code is considered suitable for the present study.

A RELAP5 model of passive containment cooling system (PCCS) is developed. A detailed nodalisation of the model is shown in the Fig. 3. First, a complete model of primary containment with V1 and V2 zone of primary containment; suppression pool, vent pipe and blow off panel have been developed. The modeling of concrete structure to simulate large condensation taking place over concrete surface has been modeled. V1 and V2 have been modeled using RELAP pipe components with 10 volumes each. Suppression pool (GDWP) and vent pipes also modeled using RELAP pipe component with 6 volumes each. V1 is connected to suppression pool through vent pipe and connected to V2 through blow off panel modeled using trip valve. Condition of inlet header during 200% IH break LOCA has been simulated using time-dependent volume which is connected to V1 volume. PCCS model includes inlet pipe, PCCS inlet header, heat-exchanger tubes, PCCS outlet header and outlet pipe. One end of the inlet and outlet pipe have been connected to GDWP at their respective elevation while other end to their respective headers. Inclined PCCS heat exchanger tubes have been model using pipe component which is connected to inlet and outlet PCCS headers. Description of different components is shown in the Table 1.

Table 1 Description of the Hydrodynamic Components

Vol. No.	Description of the volume
109	Inlet Header of MHT
890-01 to 890-10	Volume V1
891-01 to 891-06	Vent pipe connection between V1 and GDWP
892-01 to 892-10	Volume V2
893-01 to 893-06	GDWP
101	PEC inlet pipe
102	PEC inlet header
103	PEC tubes
105	PEC outlet header
106	PEC outlet pipe

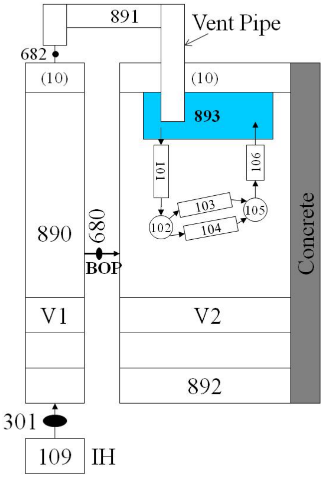

Fig.3: PCCS RELAP nodalisation

RESULT AND DISCUSSION

The model is initialized with atmospheric conditions i.e. normal operating condition and run for the 100 s to get the stabilized conditions in the circuit. After getting steady state, a transient analysis simulating post LOCA transient in primary containment has been performed. The Containment pressure transient has been obtained during 200% IH break LOCA for 24 hrs transient duration with all pressure suppressing system available.

To address the PCCS role, three distinct cases have been analysed post 200% LOCA transient. These cases are as follows;

- With PCCS and condensation by concrete structure available together
- With PCCS only (no condensation by concrete structure considered)
- With condensation by concrete structure only (no PCCS credit)

In all above cases, pressure suppression by suppression pool (GDWP) has been considered, since it is observed that this system takes major load during initial phase of the transient. It also helps in reducing the peak pressure in the containment and it limits the peak pressure below 2.6 bar.

Case 1: With PCCS and condensation by concrete structure available together

This is basic case which considers all the passive pressure suppressing features available. During the transient, large break flow initially as shown in Fig. 4 increases the pressure in V1 volume of the containment and large amount of heat load is taken by the suppression pool initially. With differential pressure across V1 and V2 crosses 50 kPa, BOP breaks and opens the direct path for the steam-air mixture to the V2 volume of the containment.

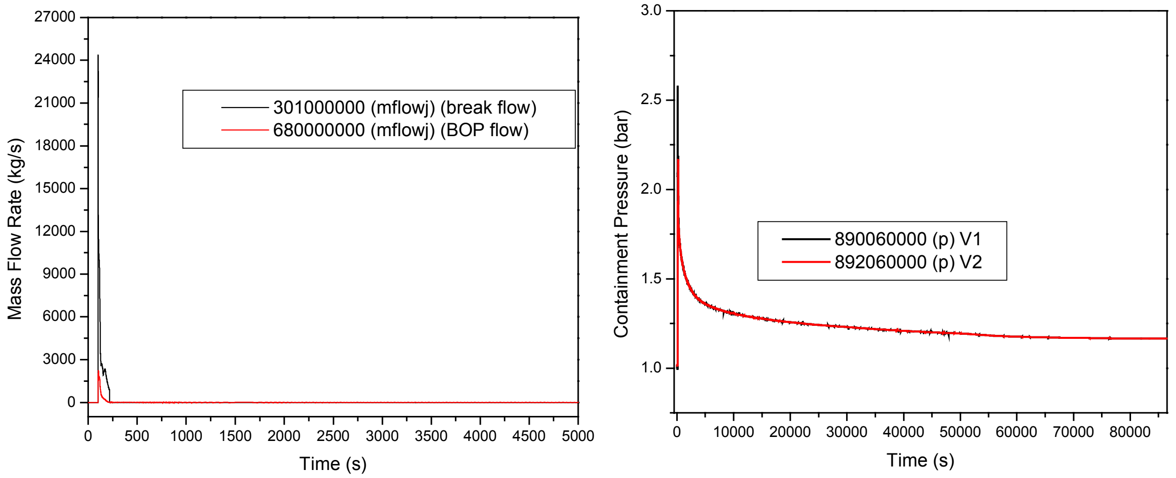

Fig.4: Mass flow rate and pressure transients in the containment post LOCA

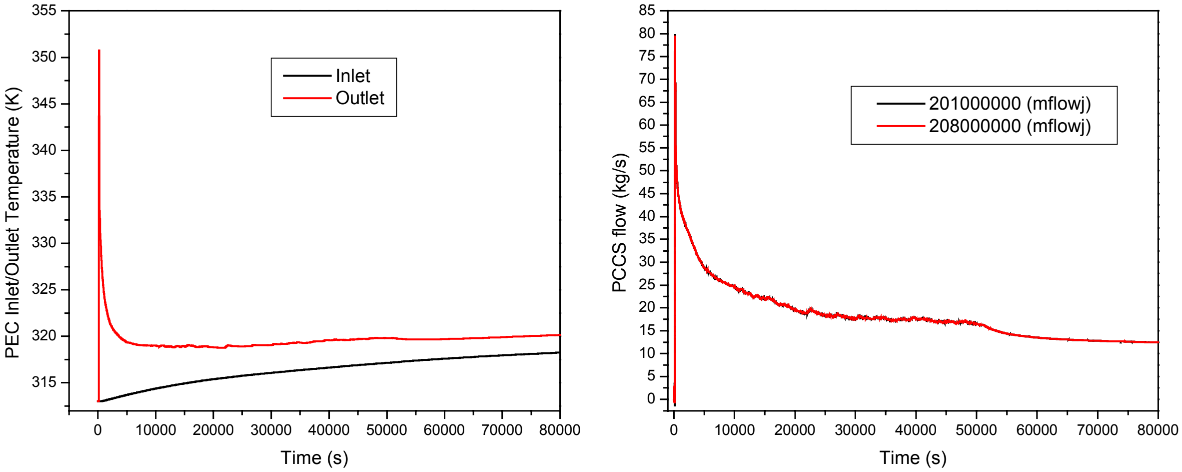

Fig.5: PCCS inlet and outlet mass flow rate and temperature transient

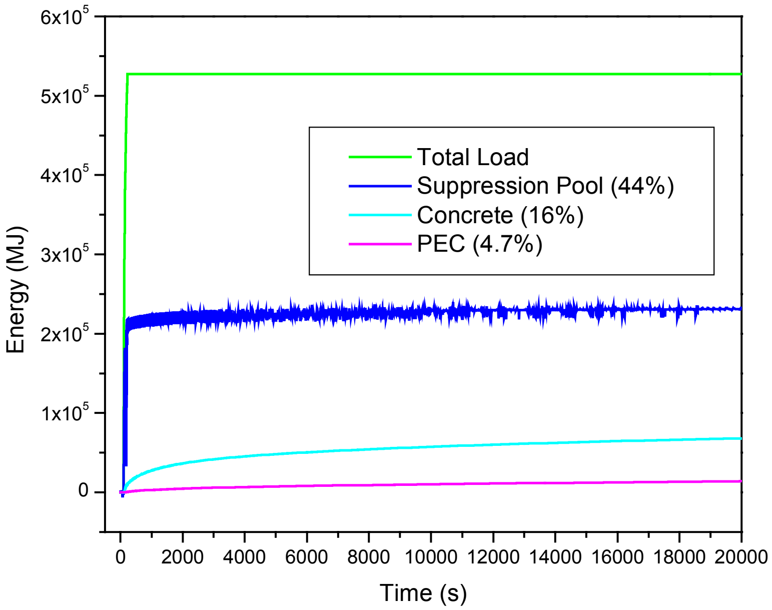

Fig.6: Heat removal contribution by different passive features in case 1

After opening of BOP other passive mechanism like concrete surface condensation as well as PCCS comes into the picture. Concrete takes major chunk of heat load from the V2 volume in its initial phase of performance owing to large surface area, thus forming second effective heat removal mechanism. Functionality of the PCCS can be observed in the Fig. 5. Large initial load and temperature difference between steam-air mixture and fluid inside the tubes causes more flow through PCCS, which decreases with time and stabilizes to lower value. Heat up of GDWP with time can also be observed in the figure.

Concrete condensation heat removal goes down slowly due to low thermal diffusivity of concrete. However, PCCS being heat exchanger does not have this limitation and so it continues to remove heat at a slow and steady pace. Fig. 6 shows the total heat load released through break junction and taken away by different passive features. This case study is not sufficient to bring out the clear picture over role of this new design feature i.e. PCCS. So other case studies as detailed below highlighting the individual contribution of PCCS and concrete has been carried out

Case 2: With PCCS only (no condensation by concrete structure considered)

For better understanding of this new design feature in overall containment cooling, this case study i.e. PCCS only has been considered. This will bring out the role of PCCS in limiting the pressure transient in containment post LOCA scenario. The transient duration considered is 24 hrs. Contribution of heat load is shown in Fig. 7 while pressure transient can be seen in Fig. 9. Being only pressure suppressing system in V2 and because of the higher pressure during the transient, PCCS can take away about 10.1% of the total heat load. PCCS takes heat at limited rate, but works steadily which is reflected in the pressure transient. It is observed that pressure remains high for longer duration compare to other cases but continuous decrease in the pressure is result of continuous functioning of PCCS.

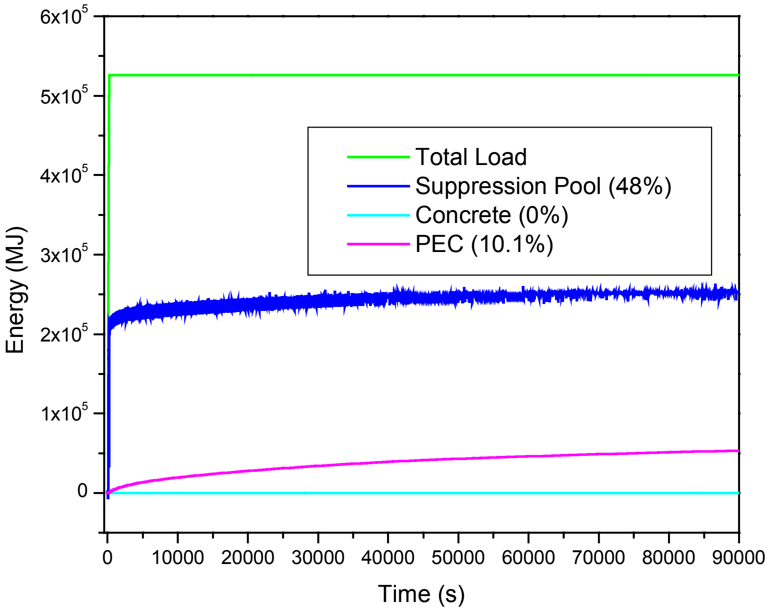

Fig.7: Heat removal contribution by different passive features in case 2

Case 3: With condensation by concrete structure only (no PCCS credit)

In this case concrete of V2 volume has been considered. This case study brings out capability of the concrete for pressure suppression and also clarifies necessity of the PCCS. Contribution of heat load is shown in Fig. 8 while pressure transient can be seen in Fig. 9. Since, concrete structure has large surface area compare to PCCS, it takes away heat quickly initially, which results in more pressure suppression than the pressure suppression caused in previous case. Unlike PCCS, higher pressure and hence higher temperature in the containment hampers the heat transfer to the concrete, and thus contribution by concrete reduces to about 15% than its contribution in the case 1 which is about 16%. At the later stage of the transient, since concrete is having low thermal diffusivity, heat taken away by the concrete is negligible and pressure remains steady at about 1.3 bar.

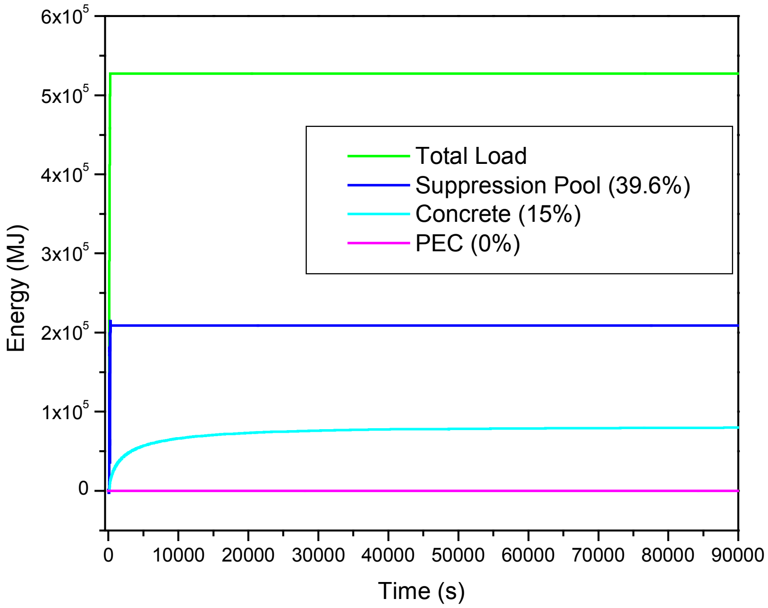

Fig.8: Heat removal contribution by different passive features in case 3

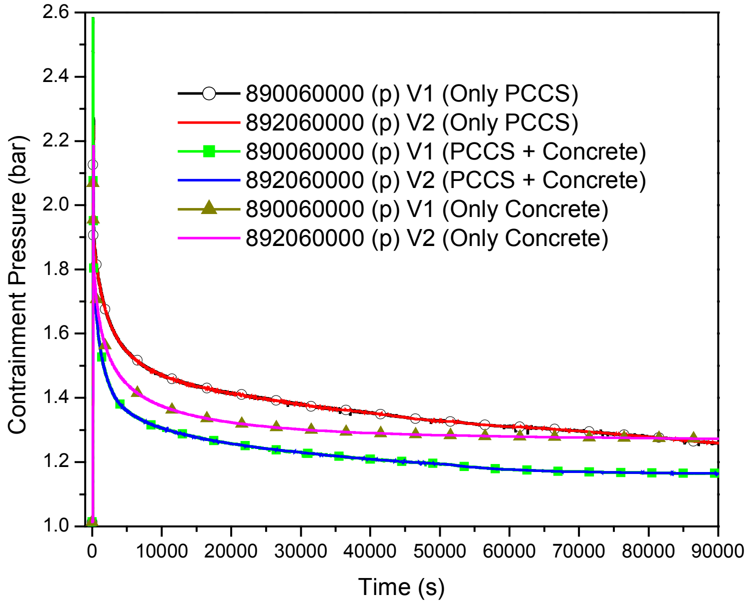

Fig.9: Comparison of containment pressure transient for V1 and V2 (all cases)

If only concrete is considered then pressure suppression is better initially but it suffers in the later stage due to lower thermal diffusivity of the concrete, while slow but steady performance of PCCS continuously reduces pressure in the containment. This is clearly visible in pressure curve that time comes when containment cooling by the case when only PCCS considered is more than the case when only concrete is considered.

CONCLUSION

Suppression pool takes most of the load in beginning of the transient and helps in reducing the peak pressure in the containment. This serves as the best pressure suppression features. However, as soon as connection between V1 and V2 establishes, contribution by suppression pool is negligible. Owing to large surface area concrete also takes significant load but for initial phase of the transient. Due to its lower thermal diffusivity its performance gets hindered in the later stage of the transient. PCCS on the other hand works steadily and continuously suppresses the pressure in the containment. However, its lower rate of heat removal keeps the containment pressure higher for considerable time.

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