*Transactions of the Korean Nuclear Society Autumn Meeting*
*Goyang, Korea, October 24-25, 2019*

# Studies on the Design of Passive Containment Cooling System (PCCS) for Severe Accident Mitigation of APR+ Nuclear Power Plant

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## 1. Introduction

In the standard design of Advanced Power Reactor Plus (APR+), the Emergency Containment Spray Backup System (ECSBS) was designed as an alternate means to the containment spray system in the event of severe accidents in which all of the Shutdown Cooling /Containment Spray (SC/CS) pumps and the In-containment Refueling Water Storage Tank (IRWST) are unavailable. The ECSBS is to be aligned in 24 hours after a severe accident to prevent the containment failure by providing water to the dedicated spray headers [1]. However, portable pumping devices and operator actions to connect the pumping devices to the spray piping are necessary to ensure the ECSBS to operate properly.

The conceptual design of Passive Containment Cooling System (PCCS) is under developing as one of the passive features to control the containment pressure and temperature for long time even without the active components, AC power sources, and operator actions. Also, modifications to the existing APR+ design are being studied to verify the adequacy of the PCCS to mitigate the containment conditions in the case of severe accidents when the PCCS substitutes the ECSBS.

In this paper, the studies are presented for the important design modifications and additional analyses required when the PCCS is newly introduced into the APR+ standard design instead of the ECSBS.

## 2. PCCS Description

The PCCS consists of two trains which are connected to each Passive Condensation Cooling Tank (PCCT) of the Passive Auxiliary Feedwater System (PAFS), respectively. The PAFS is the passive safety features adopted in the APR+ standard design to completely replace the conventional active auxiliary feedwater system. The steam from the steam generator secondary side is condensed in the heat exchanger submerged in the PCCT, and the decay heat from the reactor core is eventually removed by introducing a natural driving force mechanism [1]. The two passive cooling systems of PCCS and PAFS share the PCCT as cooling water sources.

In the PCCS, the cooling water flows from the PCCT into the PCCS heat exchangers located inside the containment and returns to the PCCT by natural circulation, as the water temperature in the heat exchanger rises up due to the heat transfer from the containment atmosphere during severe accident. The heat transferred to the PCCT from the containment is finally discharged into the ultimate heat sink of atmosphere by the water boiling in the PCCT. In addition to the PCCT, each train of PCCS has heat exchangers, valves, connecting piping, and associated instrumentations. Fig. 1 shows the simplified diagram of the APR+ PCCS.

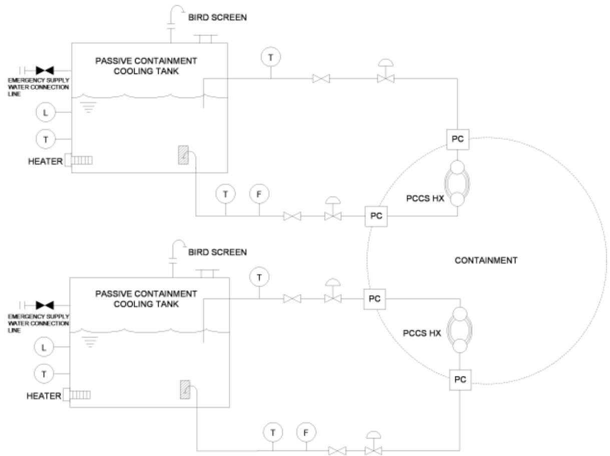


Fig. 1. Schematic diagram of the APR+ PCCS

## 3. Design Modifications and Analyses

### *3.1 System Performance*

For the test of the PCCS performance, new heat transfer model for the PCCS heat exchanger is developed and validated to the experimental data. The model consists of a new gas heat transfer correlation and a correlation to calculate natural circulation of water or water/steam two-phase mixture in the heat exchanger tube side. Since the heat exchanger tubes are bundled together, the new model can calculate the bundle effect on the overall heat transfer [2, 3].

The new model for the bundle array generally shows under-prediction for the heat transfer coefficient compared to the existing MAAP5 model and KAERI bundle test data [4], as shown in Fig. 2.

The new heat transfer model of the PCCS has been implemented into the MAAP 5.05 and tested for representative sequences of APR+ severe accidents. The performance test results show that the PCCS has sufficient capability to remove the decay heat discharged into the containment atmosphere and therefore can prevent containment failure.

As an example, the containment pressure is maintained far below the APR+ factored load category (FLC) for LBLOCA accident, as seen in Fig. 3.

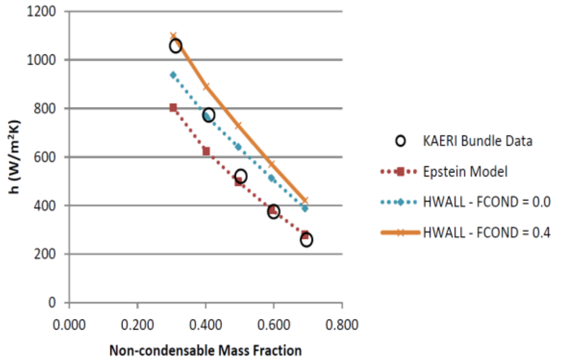


Fig. 2. Comparison of MAAP5 new model (Epstein Model) to existing condensation model for heat sink walls (HWALL) and KAERI data (4 bar, 50K subcooling conditions)

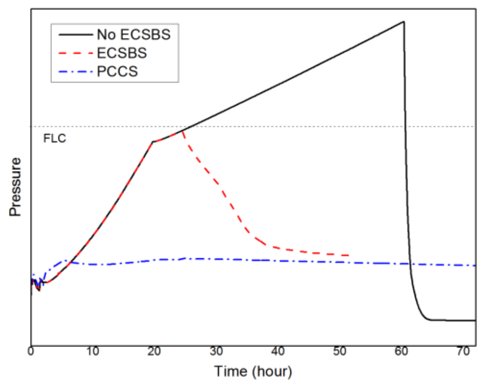


Fig. 3. PCCS performance in the case of LBLOCA

### *3.2 Aerosol Particulate Removal*

Since the ECSBS is substituted with the PCCS, the aerosol particulate species of iodine in the containment are removed by natural processes such as gravitational settling, diffusiophoresis and thermophoresis. The aerosol removal model is developed considering the removal mechanism on the surface of the PCCS heat exchangers in addition to the theory of the NUREG/CR-6189 [5] and NUREG/CR-6604 [6]. The parameters necessary to calculate the aerosol removal rate, such as condensation rate and thermo-hydraulic conditions of the containment atmosphere, are obtained based on the MAAP 5.05 calculations.

The effective aerosol removal coefficient for the case of LBLOCA is presented in Fig. 4, and it will be used as an input for the offsite dose calculation.

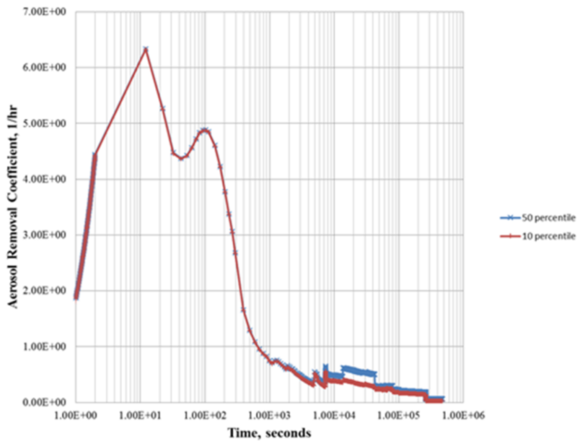


Fig. 4. Effective aerosol removal coefficient for LBLOCA

### *3.3 IRWST pH*

The pH of the IRWST should be maintained between 7.0 and 8.5 to ensure the iodine retention during the long-term cooling after accidents [7]. The pH calculations are performed for the severe accident following LBLOCA based on the conservative assumptions and considering Tri-Sodium Phosphate (TSP), boric acid, and other chemicals that can impact on the pH of the IRWST during the accident. The calculations show that the pH value can be maintained above 7.0 during the long-term cooling of 30 days. It is concluded, therefore, that the iodine is not to be re-evolved to the containment even in the case that the PCCS operates without the water spraying by the ECSBS.

### *3.4 Arrangement of Heat Exchangers*

The heat exchangers in one train are composed of seven modules and should be located vertically inside the containment. All of the modules in each train are connected to the common header piping which are at the inlet and outlet part of the heat exchangers respectively. The heat exchangers and associated piping of the two trains should be arranged in the containment without interferences with existing APR+ structures, equipment or components. Generally, the symmetric arrangement is ideal, but the eccentric arrangement such as Fig. 5 is selected as the best optimized design to avoid the interference with the Main steam/Feedwater (MS/FW) piping support and also to consider narrow space around the reactor containment fan cooler (RCFC).

### *3.5 Seismic Analysis*

The seismic analysis model for the containment building of the APR+ standard design is revised considering the PCCS heat exchangers. Since the severe accident may cause cracks in the concrete structure, the effect of the potential concrete cracks is incorporated in the seismic analysis. The comparison of the in-structure response spectra from the existing and the revised seismic analysis model is presented in Fig. 6. The figure shows that the PCCS heat exchangers do not cause significant impact on the seismic analysis results.

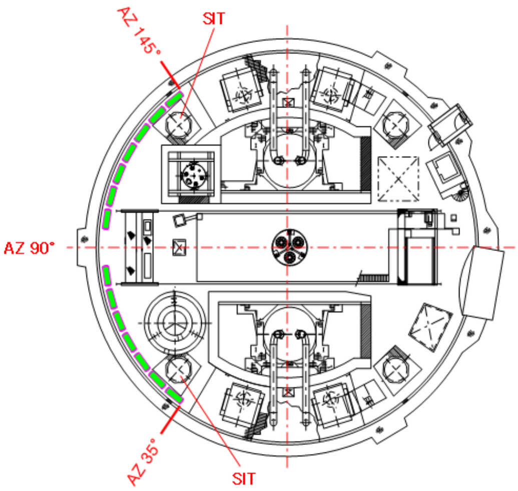


Fig. 5. Arrangement of APR+ PCCS heat exchangers

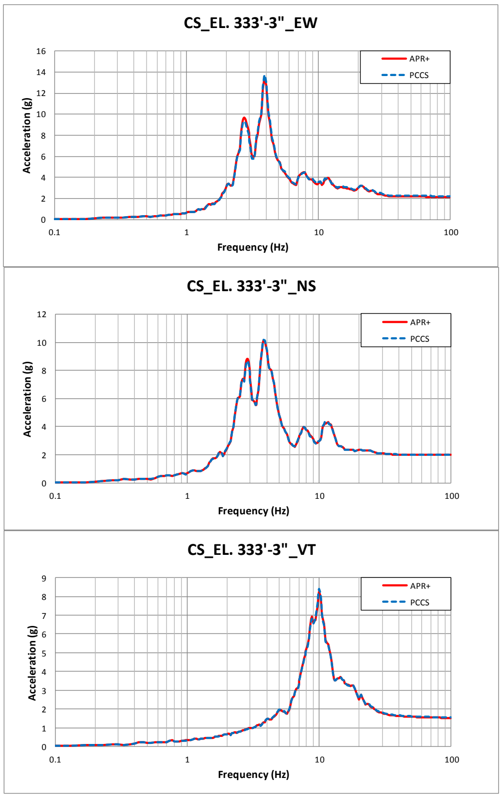


Fig. 6. Comparison of in-structure response spectra for containment building at EL. 333'-3"

## 4. Conclusions

The design modifications and additional analyses to the APR+ standard design are studied on the case that the PCCS is adopted instead of the ECSBS. The study indicates that the PCCS has sufficient capability to control the containment atmosphere and maintain the containment integrity during the severe accident, and the expected design changes to the existing APR+ design are within an acceptable level.

In addition, it should be noted that the analyses for the offsite dose and the aircraft crash, which are important licensing issues, are also going to be performed and considered in the design modifications to the existing APR+ nuclear power plant.

## ACKNOWLEDGEMENT

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (No. 20161510400120).

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