Analyses on Flow Behavior inside the RPV insulator of the KSNP under the External Reactor Vessel Cooling

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1. Introduction

External reactor vessel cooling via cavity flooding is adopted as one of the major severe accident management strategies in the APR1400 and the current operating nuclear power plant, KSNP. The coolability through the external reactor vessel cooling is mainly determined by the thermal load from the molten pool and the accessibility and cooling capacity of water inside the RPV (Reactor Pressure Vessel) insulator. If steam generated via boiling at the RPV outer surface couldn't ventilate through the insulator, the pressure inside the annulus between the RPV and the insulator increased abruptly and consequently water swept out and steam dominated the flow path inside the annulus. In this case, effective heat removal through the external reactor vessel cooling can not be achieved and the evaluations on the thermal margin based on the CHF analyses are meaningless. Therefore, sufficient water ingression and steam venting through the insulator can be a key factor determining the success of the external reactor vessel cooling (ERVC) in the operating nuclear power plant, KSNP.

Flow analyses using RELAP5/MOD3 code were performed to investigate the occurrence and the effects of steam binding for the KSNP under the external reactor vessel cooling. And separate effect test was performed to examine the permeability through the typical RPV insulator mock-up. Flow area and energy loss coefficient, K through the insulation mock-up were evaluated from the separate effect test. And these values were directly used in the RELAP5 input. As the representative accident scenarios, the cases of SBO and 9.6 inch LBLOCA were evaluated in this study.

2. Permeability Check Test and Validation

Separate effect test was performed to examine the permeability through the typical RPV insulator mock-up. And flow analyses using RELAP5/MOD3 code were performed for the permeability check test to evaluate flow area and energy loss coefficient, K through the insulator mock-up. And these values were directly used in the flow analyses for the KSNP external reactor vessel cooling. The insulation mock-up is composed of two parts and jointed with buckles as shown in Fig. 1. Water can seep into the insulation through the buckled joint and the spot welding part in case of the ERVC. Once the insulator mock-up was full of water, the time-dependent variations of water height were measured. The tests were repeated by 10 times and produced averaged values.

In the RELAP calculation, water pool inside the insulator mock-up was composed of single volumes (V10). Water drains to external atmosphere surrounding the insulation mock-up which was simulated as the Time Dependent Volume. Fig. 1 shows calculation results for the changes of water pool height according to the various flow area and energy loss coefficient, K. In Fig. 1 "d" stands for the gap size between the two insulator panels which determines the flow area through the insulator mock-up by multiplying the total length of the individual panels joint. According to Fig. 1, ftest03 and ftest07 cases predicted well the experimental data. Based on these calculation results, flow analyses for the KSNP in case of external reactor vessel cooling were performed.

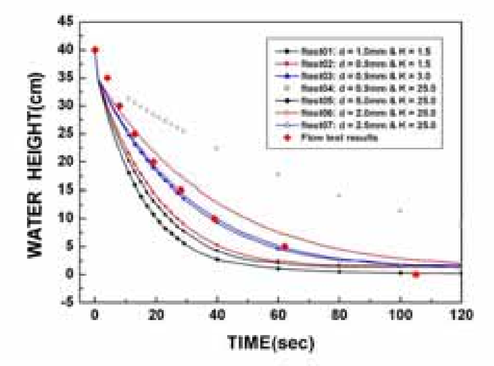

Fig. 1 Calculation results for the changes of water pool height in the permeability check test

3. Flow Analyses for the KSNP

Flow analyses using RELAP5/MOD3 code were performed to investigate the occurrence and the effects of steam binding for the KSNP under the external reactor vessel cooling. Annular flow path between the reactor pressure vessel and the insulation was composed of single volumes. And flow path inside the insulation and external water pool were connected with single junctions having cross flow. The spherical and cylindrical reactor pressure vessel was simulated heat structures, number 100 and 200, respectively. Heat flux was imposed to inner surface of the reactor lower plenum as a function of the angular position. Fig. 2 shows heat flux distribution as a function of the angular position. Once the value of corium mass and decay heat are quoted from SCDAP/RELAP5/MOD3.3 simulation results[1] for the sequence of large LOCA (9.6 inch) with safety injection failure and Station Black Out (SBO), the average downward heat flux was obtained. Finally, the local downward heat flux along the surface of the reactor lower plenum was calculated from the heat flux distribution as a function of the angular position using mini-ACOPO correlation[2].

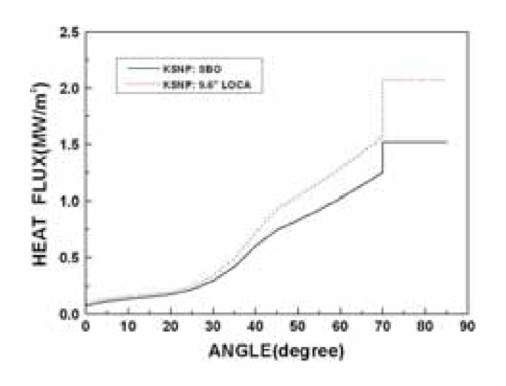

Fig. 2 Heat flux distribution from the corium

Fig. 3 shows the variations of collapsed water level inside the annulus between the RPV and the insulator in the base cases of KSNP_SBO and KSNP_LBLOCA. In case of KSNP_LBLOCA analysis, water level dropped quickly below the 65^o angle of the hemispherical lower head vessel earlier than 40 minutes as shown in Fig. 3. This drastic drop of water level can be characterized by the steam binding which was occurred in the LAVA-ERVC tests in case of limited steam venting through the insulator. In both the cases, water level eventually dropped below the middle part of the hemispherical lower head vessel, i.e. 35^o angle earlier than 2 hours, which could be attributed to the reason that the mass of steam generated was beyond the capacity of steam ventilation through the insulator.

Fig. 4 shows the temperature variations at the outer surface of the RPV lower plenum. Once the steam binding occurred, water could not access the outer surface of the RPV lower plenum and heat removal via boiling could not be basically achieved. After all, the temperatures of the outer surface increase to the melting point in case of limited steam ventilation. Fig. 5 shows the variations of collapsed water level inside the annulus between the RPV and the insulator in the cases which were assigned the additional flow path in the insulator. Contrary to the base case the water level maintained steadily above the RPV lower plenum in both the cases.

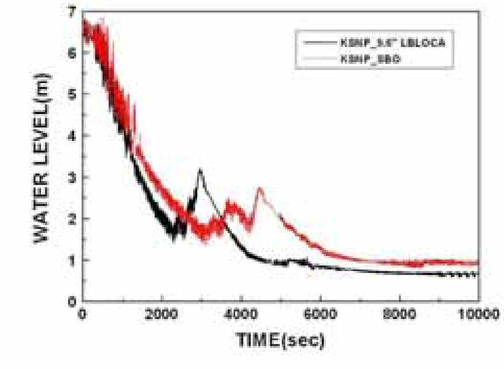

Fig. 3 Variation of water level in the base case

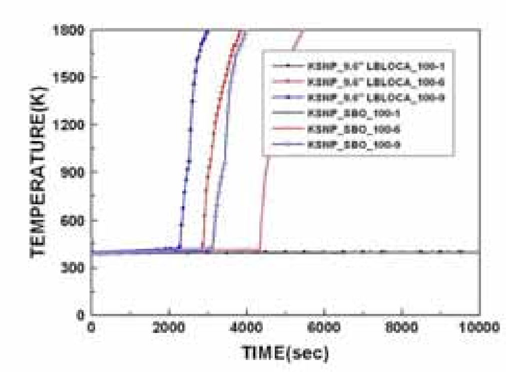

Fig. 4 Temperature variations of the PRV surface

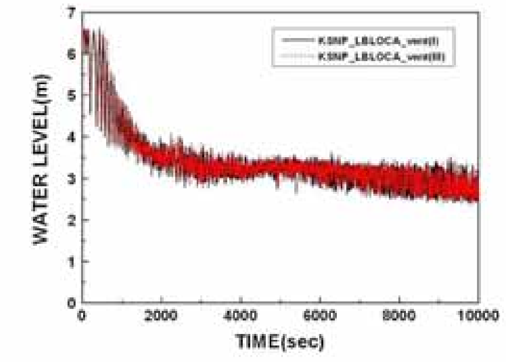

Fig. 5 Variation of water level in the case having additional flow path

4. Conclusion

Flow analyses results for the KSNP under the external reactor vessel cooling address that water ingression and steam ventilation through the insulator are crucial factors determining the effective cool down via boiling heat removal at the outer surface of the RPV lower plenum. Once the steam binding occurred, water could not access the outer surface of the RPV lower plenum and heat removal via boiling could not be basically achieved. Current flow analyses results for the KSNP under the external reactor vessel cooling emphasize the importance of flow behavior inside the annulus between the RPV and the insulator. Prevention of steam bininding phenomena should be settled first for the in-vessel corium retention through the external reactor vessel cooling in the operating nuclear power plant. Implementation of additional flow path for the effective steam ventilation can be one of the most promising countermeasures.

REFERENCES

[1] Park, R. J., et al. 2004. Detailed Analysis of In-Vessel Melt Progression in the LOCA of the KSNP using the SCDAP/RELAP5, *Proceedings of KNS fall meeting,* Yopong, Korea, May 27-28.

[2] Theofanous, T. G., et al. 1995. *In-Vessel Coolability and Retention of a Core Melt*, DOE/ID-10460.