Procedure Development of IVR-ERVC Analysis and Its Results in SMART100

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1. Introduction

An In-Vessel corium Retention through External Reactor Vessel Cooling (IVR-ERVC) is known to be an effective means for maintaining the reactor vessel integrity during a severe accident in a nuclear power plant [1]. This measure has been adopted in low-power reactors of the AP600 and Loviisa nuclear power plants, in the medium-power reactor of the AP1000 as a design feature for severe accident mitigation, and in the high-power reactors of the APR (Advanced Power Reactor) 1400 and APR+ as an accident management strategy. It is also adopted in the SMART100. Analysis method of the IVR-ERVC was developed and applied to the SMART100.

2. Description of SMART for IVR-ERVC

Since SMART100 is an integral reactor, the steam generators, pressurizer, and RCP (Reactor Coolant Pump) s are installed inside the reactor vessel. As such, the reactor vessel size according to the thermal output of the core is larger than the conventional pressurized water reactor. Table I shows the key design parameters related to ERVC compared to other power plants in Korea. As shown in the table, the thermal output of SMART is 365 MW_{th} which is only around 1/10 of Optimized Power Reactor (OPR) 1000 and APR (Advanced Power Reactor) 1400. However, the size of the SMART reactor vessel is larger than that of these power plants. Specifically, the internal diameter of the ART reactor vessel is 5.3 m, which is larger than the 4.7 m of APR1400, and the thickness 0.2 m is larger than APR1400 0.165 m. As such, the heat flux to the outer wall of the reactor vessel is smaller than OPR1000 or APR1400 when the core corium is relocated in the lower plenum of the reactor vessel. SMART has no In-Core Instrumentation (ICI) nozzle, which is negative effect on the IVR-ERVC.

If a severe accident occurs in SMART100 and the core exit temperature exceeds 923 K that is the condition to apply Severe Accident Management Guideline (SAMG) from Emergency Operation Procedure (EOP), the operator makes actions for the ERVC to prevent a reactor vessel failure. In order to prevent the creep failure of the reactor vessel, which can be generated at high temperature and high pressure, the RCS pressure should be reduced to 1 MPa or lower by opening the RRT (Radioactive material Removal Tank) discharge line valve of the ADS before supplying cooling water to the reactor cavity using the Cavity Flooding System (CFS). The coolant in the reactor cavity is injected in the annular space gap between the external reactor vessel wall and insulator through the hole installed at the insulator of reactor vessel. The steam produced at the external wall of the reactor vessel is discharged through the steam-venting hole to the reactor cavity. The coolant is circulated through the water circulation hole installed at the insulator in order to increase the maximum heat removal from the external reactor pressure vessel wall. The steam released from the annular gap space between outer reactor vessel wall and insulator is released to the Upper Containment Area (UCA) of containment through associated piping and the RRT water. Fig. 1 shows a concept of the IVR-ERVC.

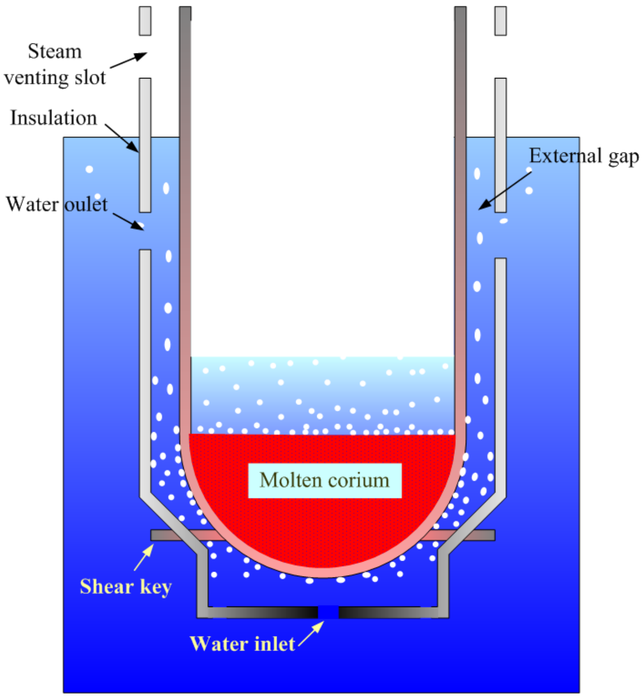

Fig.1 IVER-ERVC concept for SMART100

For this reason, the SMART100 is designed to have the safety grade safety depressurization system of the ADS in order to reduce the pressure in the Reactor Coolant System (RCS). SMART100 has the CFS to inject the coolant from the IRWST into the reactor cavity for the IVR-ERVC. The reactor pressure vessel insulator of

SMART100 has coolant injection hole, steam vent hole, and coolant circulation hole for the IVR-ERVC. SMART100 has the pathway to release the steam of the reactor cavity to the UCA of the containment through associated piping and the RRT water for the IVR-ERVC.

Table I: Comparison of Design Parameters of ERVC between SMART and Other Reactors

Design Parameters	SMART 100	OPR 1000	APR 1400
Core Thermal Power (MW)	365	2815	3983
Fuel (UO_2) Mass (ton)	16.3	85.6	120.0
Active Core Zry4 Mass (ton)	4.5	23.9	33.6
Bottom Head Inner Diameter(m)	5.3	4.2	4.7
Bottom Head Thickness (m)	0.2	0.152	0.165
Number of ICI Nozzle	0	45	61

3. Development of Analysis Method and Results

A success criterion of IVR-ERVC during a severe accident for SMART100 was evaluated to determine the thermal margin for the prevention of a reactor vessel failure. A thermal load analysis from the corium pool to the outer reactor vessel in the lower plenum of the reactor vessel was performed to determine the heat flux distribution. The Critical Heat Flux (CHF) on the outer reactor vessel wall was determined to fix the maximum heat removal rate by the external coolant between the outer reactor vessel and the insulation of the reactor vessel. The thermal margin for success of IVR-ERVC during a severe accident in SMART100 was evaluated through a comparison of the thermal load with the maximum heat removal rate of CHF on the outer reactor vessel wall. Finally, the integrity of the reactor vessel wall by ERVC was estimated by structure analysis.
The following methods are used in order to satisfy the analysis goal.

- The thermal load from the corium to the external reactor vessel wall when the molten core material is relocated in the lower hemisphere plenum of the reactor vessel during a severe accident is estimated using CINEMA-SMART computer code [2].

- The natural circulation mass flow rate, which is formed in the annular gap between the external reactor vessel wall and insulator, is estimated using SPACE computer code [3].

- CHF, which corresponds to the maximum heat removal from the external reactor vessel wall depending on the estimated natural circulation mass flow rate, is determined using SULTAN and KAIST experimental results.

- The success criteria of IVR-ERVC to prevent reactor vessel failure during a severe accident is determined by comparing of the thermal load with CHF.

- Finally, structure analysis on reactor vessel wall performs to evaluate the structure integrity of the reactor vessel wall in ERVC condition using ANSYS computer code [4].

4. Analysis Results

The CINEMA-SMART results shows the heat flux on the vessel wall inner surface at different locations. Fig. 2 shows the heat flux distribution from corium pool to the outer reactor vessel wall during the IVR-ERVC as a function of time. Maximum heat flux is approximately 0.489 MW/m^2 at the metallic layer, because of focusing effect. At the top of oxide layer, maximum heat flux is approximately 0.223 MW/m^2.

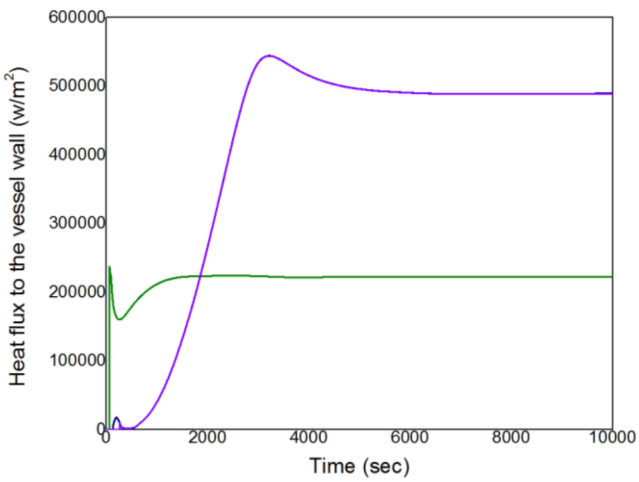

Fig. 2. Heat flux distribution from corium pool to the outer reactor vessel wall during IVR-ERVC

As the thermal load given to the external reactor vessel wall is determined, the two-phase natural circulation flow of coolant between external reactor vessel wall and insulator, and the corresponding CHF which results in the maximum heat removal from external reactor vessel wall have been assessed. As the natural circulation flow increases between external reactor vessel wall and insulator, the CHF which removes heat from the external reactor vessel wall increases. In order to increase the natural circulation flow between the external reactor vessel wall and insulator, optimum reactor vessel insulator design is accomplished such as installation of coolant injection hole, steam exhaust, and coolant circulation hole in the reactor vessel insulator.

According to the result of SULTAN experiment performed in CEA, France, and the result of KAIST experiment, when the natural circulation flow rate increases between external reactor vessel wall and insulator, the CHF increases. The CHF at the external reactor vessel wall is approximately 1.3-1.4 MW/m^2 for every heat flux indicating that the CHF is significantly large compared with the heat flux of 0.489 MW/m^2 from the core melt in the lower hemisphere of the reactor vessel to the external reactor vessel wall. Therefore, we can conclude if coolant is properly supplied to the reactor cavity of SMART100, the core melt can be sufficiently cooled by ERVC.

A comprehensive thermal-structural analysis using ANSYS computer code under the IVR-ERVC condition has been performed to investigate SMART100 reactor vessel integrity during a severe accident. Fig. 3 shows ANSYS results on deformed geometry of lower reactor vessel wall by thermal and mechanical load under ERVC condition. It was found that in spite of high thermal and mechanical loads exerted by large amount of corium relocated into the lower head, a long-term creep rupture failure does not take place by means of ERVC. Consequently, the IVR-ERVC strategy turned out an effective means to maintain SMART100 reactor vessel integrity during a severe accident.

5. Conclusions

It can be concluded if coolant is properly supplied to the reactor cavity of the SMART100, the core melt can be sufficiently cooled by the ERVC. The thermal margin for success of the IVR-ERVC is sufficient in the SMART100, which means that the reactor vessel integrity is maintained during severe accidents. Consequently, the IVR-ERVC strategy turned out to be an effective means for maintaining the SMART100 reactor vessel integrity during severe accidents from the thermal lad analysis, CHF analysis, and structure integrity analysis.

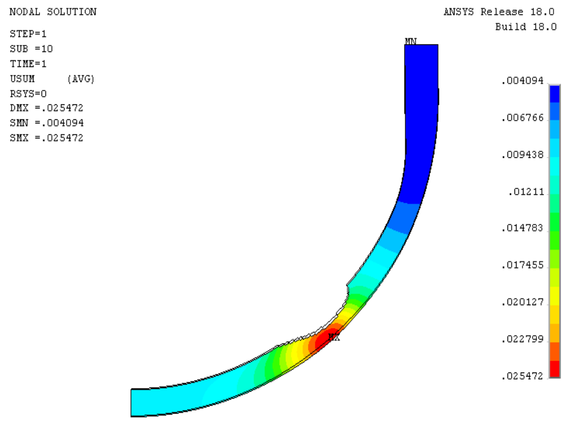

Fig. 3. ANSYS results on deformed geometry of lower reactor vessel wall by thermal and mechanical load under ERVC condition

ACKNOWLEDGEMENT

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