EVALUATION OF IN-VESSEL MELT RELOCATION THROUGH EXTERNAL REACTOR VESSEL COOLING OF SMART REACTOR WITH CINEMA CODE PACKAGE IN KOREA

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ABSTRACT

In the present study, we evaluate IVR-ERVC (In-Vessel corium Retention through External Reactor Vessel Cooling) strategy on the SMART (System-integrated Modular Advanced ReacTor) reactor of Korea. Firstly, we analyze thermal load analysis at the lower plenum of the SMART, using SIMPLE (Severe In-vessel Melt Progression in Lower plenum Environment) code. As a bounding case, we assume that the entire core materials are relocated to the lower plenum, then resulting heat flux on the reactor vessel wall is calculated. Related to the thermal load analysis, ERVC maximal heat removal rate calculation and structural integrity analysis was performed. It shows IVR-ERVC of SMART is successful. For more realistic analysis, we used CINEMA (Code for INtegrated severe accident Evaluation and Management) code package to evaluate entire severe accident progression and IVR-ERVC. Detailed transient behavior of thermal-hydraulics and severe accident phenomena on the reactor is explored.

KEYWORDS
Severe Accident, CINEMA, IVR, ERVC

1. INTRODUCTION

The IVR-ERVC (In-Vessel corium Retention through External Reactor Vessel Cooling) 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 was 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 advanced power reactor (APR) 1400 and APR+ as an accident management strategy. It was also adopted in the Korean small integral reactor (SMART) as a design feature for severe accident management [2]. A success criterion of the IVR-ERVC during a severe accident 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 wall was performed to determine the heat flux distribution. The CHF (Critical Heat Flux) on the outer reactor vessel wall was determined to fix the maximum heat removal rate by the external coolant between the outer reactor vessel wall and the insulation of the reactor vessel. Finally, the thermal margin for success of the IVR-ERVC during a severe accident was evaluated through a comparison of the thermal load with the maximum heat removal rate of the CHF on the outer reactor vessel wall.

2. Description of the SMART ERVC

Figure 1 shows the conceptual diagram of SMART ERVC. The operator conducts the ERVC to prevent the reactor vessel failure. For ERVC, the safety depressurization system (automatic depressurization system, ADS) is opened to reduce the primary system pressure to below 1.0 MPa to prevent the reactor vessel creep damage that can occur when the reactor vessel is at high temperature and high pressure. For conservative manner, it is assumed that the operator manually activate ADS within 30 minutes later when the coolant temperature that passes through the core outlet exceeds 650 °C, which is the condition to enter the severe accident management guideline from the emergency operation procedure in SMART.

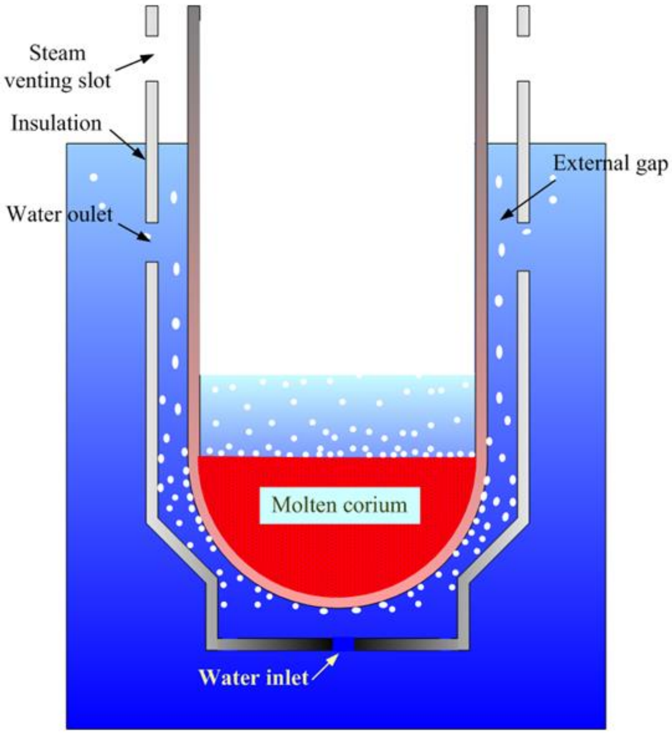

Figure 1. Conceptual design of SMART ERVC.

2.1. General feature

Since SMART is an integral reactor, the steam generators, pressurizer, and reactor coolant pumps 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. For instance, SMART has around 1/10 of thermal power as compare to that of the conventional power plants (OPR1000, APR1400, etc.), but the size of the SMART reactor vessel is larger than that of these power plants. Also, SMART has no In-Core Instrumentation nozzle, which is negative effect on the IVR-ERVC.

2.2. System for the SMART ERVC

For the successful operation of the ERVC, some system components should be prepared. The safety-grade depressurization system (ADS) is designed to depressurize the reactor vessel to 1.0 MPa or less, which is the ERVC criterion of SMART. SMART has the CFS (cavity flooding system) for coolant injection from the IWRST (in-containment refueling water storage tank) into the reactor cavity. The reactor vessel insulator is designed with a coolant injection path, coolant circulation path, and steam discharge path for ERVC in

SMART. In this analysis, the areas of coolant injection hole, coolant circulation hole, and steam discharge hole are assumed to be 0.5 m^2 for each on the basis of the previous sensitivity calculation results [2]. Finally, SMART has a path to release the steam in the reactor cavity into the containment atmosphere for ERVC.

3. Evaluation of SMART ERVC

For the ERVC analysis in SMART, the heat flux applied from the reactor vessel to the lower plenum is evaluated when the corium is relocated. The amount of corium accumulated in the reactor vessel lower plenum is determined to evaluate the heat flux. The following table shows the initial mass of the SMART core materials.

Table I. List of initial SMART core materials

Component	UO_2	Zr	Steel	Control rod
Mass (ton)	16.3	4.5	9.9	0.5

Thermal load from the corium to the outer reactor vessel wall was analyzed using the lower head model of the CINEMA-SMART computer code [3]. We considered extreme case that the whole in-core materials are melted and relocated to the lower plenum of SMART.

3.1. Evaluation of Heat Flux from Lower Plenum to Outer Wall of Reactor Vessel

The lower head model of the CINEMA-SMART includes core melt relocation into the lower plenum, melt jet-water (or reactor vessel) Interaction, water boiling, debris bed formation, heat up, and re-melting, molten pool formation and separation, metallic pool behavior with crust formation, oxide pool behavior with crust formation, heat conduction in the lower head vessel wall, and lower head vessel melting & failure. Simulation target of the lower head model in the CINEMA-SMART computer code is debris bed, metallic pool with crust, oxide pool with crust, water level in the lower plenum, governing equations, heat transfer among water, debris bed, metallic, & oxide pools, and mass & energy balance in the water, debris bed, metallic and oxide pools [3, 4].

Figure 2 shows two corium layers which formed in the reactor vessel lower plenum during ERVC in SMART. This analysis assumed that all core materials had melted and relocated in the reactor vessel lower plenum. The following components are formed in these corium layers when the initial core material described in the section 5.1 are totally melted. In this analysis, metal corium layer at the top consists 4.0 tons of zirconium and 16.0 tons of iron. Oxidized corium layer at the bottom consists 16.3 tons of uranium dioxide and 2.0 tons of zirconium dioxide. The height of the metal corium layer is 0.28 m while the height of the oxidized corium layer is 0.47 m. The heat flux to the lower head of the reactor vessel when the corium layer is formed in the reactor vessel lower plenum as shown in the figure is calculated.

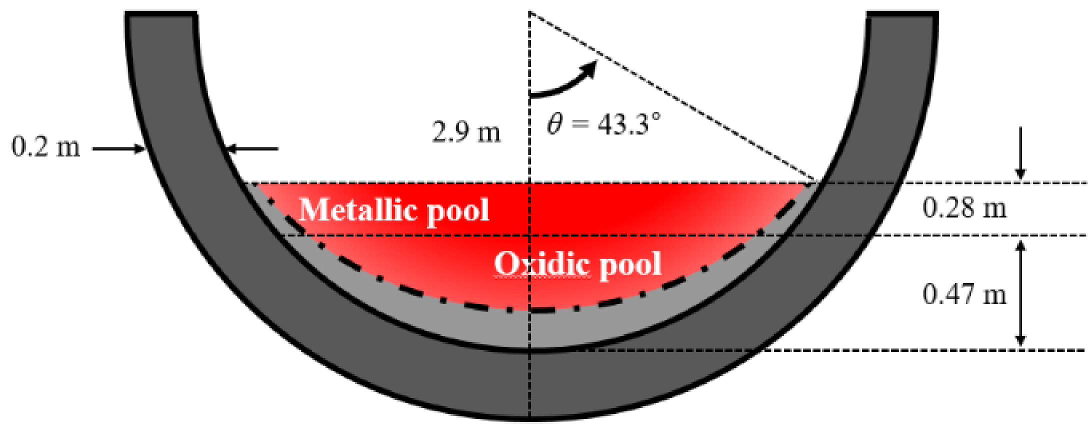

Figure 2 Two Corium Layers Formed in Reactor Vessel Lower Plenum

The total volume of corium accumulated in the reactor vessel lower plenum is 4.45 m^3, which is around 11.4 % of the volume of the lower plenum of the SMART reactor vessel and its height is 0.75 m. The predicted angle of the oxide pool and metallic pool are 34.03° and 43.34°, respectively.

Figure 3 shows the heat flux distribution in the lower head of the reactor vessel from the corium. As shown in the figure, the heat flux due to the focusing effect in the metal corium layer is about 0.5 MW/m^2 (node number 5, 6). At the top of the oxide pool (node number 4) shows the heat flux of 0.22 MW/m^2. Figure 4 shows the thickness of the solidified crust which forms on the oxidized corium layer. As shown in the figure, a crust of 1 - 9 cm forms on the oxidized corium layer by EVRC, and the higher crust gets thinner due to natural convection heat transfer inside the corium.

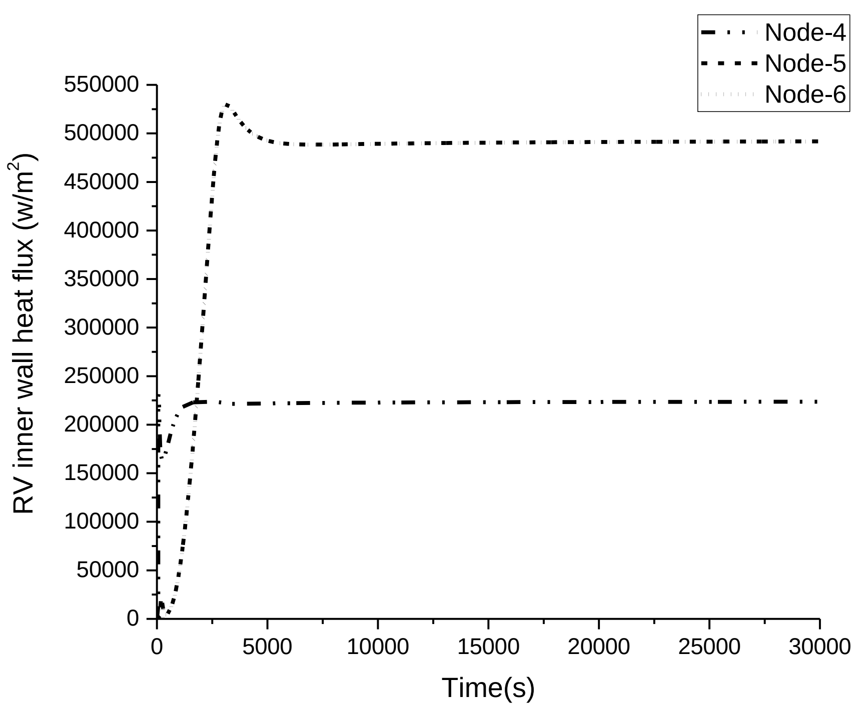

Figure 3 Heat flux from the Corium Pool to the RV Inner Wall

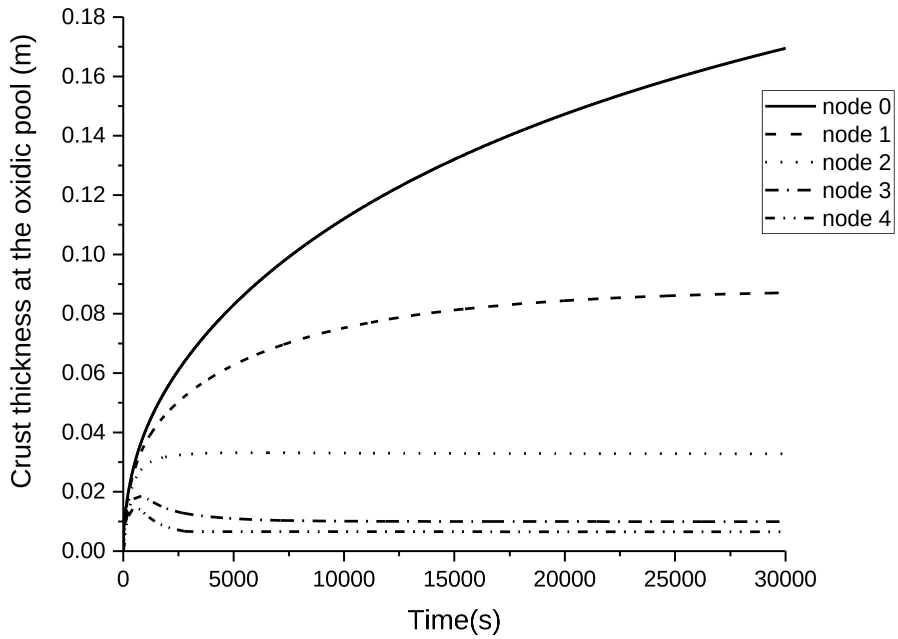

Figure 4 Crust thickness at the oxide pool

3.2. Evaluation of Two-Phase Natural Circulation in Reactor Cavity

The natural circulation flow of two-phase coolant in the annulus between the outer wall of the reactor vessel and insulator inside the reactor cavity during ERVC operation in SMART is analyzed using the CINEMA-SMART code. Figure 5 shows the CINEMA-SMART analysis result of coolant circulation flow change after the start of the ERVC operation. It is the analysis of the case of the heat flux to the outer wall of the plenum being 0.5 MW/m^2, the areas of coolant injection hole and coolant circulation hole of the reactor vessel insulator being 0.5 m^2, and the steam discharge hole in the reactor vessel insulator being 0.5 m^2. The annulus gap between the outer wall of the reactor vessel and insulator is approximately 10 and its cross sectional area is approximately 0.8 – 1.6 m^2. As shown in the figure, the coolant circulation flow converged at a certain value even though the fluctuation range is not small. Thus, the calculated mass flow rates through the coolant injection hole and the coolant circulation hole are approximately 460 kg/s ± 100 kg/s and approximately 460 kg/s ± 40 kg/s, respectively. A small flow of approximately 1.9 kg/s ± 0.6 kg/s is calculated in the steam discharge hole.

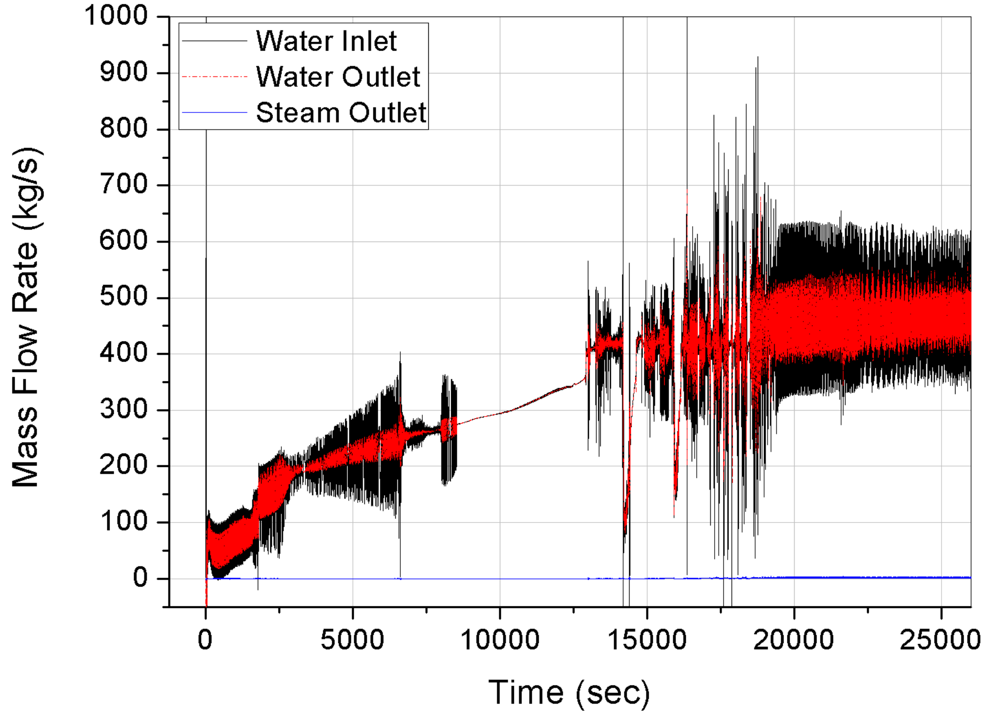

Figure 5 SPACE Result of Coolant Circulation Flow

Table II shows the estimated CHF on outer wall of the SMART. The basic calculation is the case of the heat flux of 0.5 MW/m^2 applied to the outer wall of the reactor vessel. From Table II, we found that the coolant circulation flow. By the previous experimental measurement of the CHF (SULTAN[5] and KAIST[6]), estimated CHF based on the coolant mass flux (or mass flow rate) in table II is about 2.8 times than the heat input from the corium pool. The CHF, the maximum heat removal from the outer wall, during the ERVC operation is approximately 1.4 MW/m^2 or larger. Therefore, ERVC in SMART reactor can ensure the integrity of the reactor vessel.

Table II. Estimated CHF on Outer Wall of the Reactor Vessel in SMART

Mean heat flux to lower hemisphere of reactor vessel (MW/m^2)	Coolant recirculation flow rate (kg/s)	Coolant mass flux (kg/m^{2}s)	Estimated CHF (MW/m^2)	
			Result of SULTAN Test	Result of KAIST Test
Baseline Thermal Flux (0.5 MW/m^2**)**	460	287 - 575	About 1.4	About 1.4

4. CONCLUSIONS

The maximum heat removal rate of the CHF at the external reactor vessel wall is approximately 1.4 MW/m^2 for every heat flux, which is significantly large compared with the heat flux of 0.5 MW/m^2 from the core melt the external reactor vessel wall. Therefore, we can conclude if coolant is properly supplied to the reactor cavity of SMART, the core melt can be sufficiently cooled by ERVC. The thermal margin for success of the

IVR-ERVC is sufficient in the SMART, which means that the reactor vessel integrity is maintained during severe accidents. A comprehensive thermal-structural analysis using ANSYS computer code under the IVR-ERVC condition shows 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 for maintaining the SMART reactor vessel integrity during severe accidents.

ACKNOWLEDGMENTS

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (Ministry of Science and ICT; Grant No. 2016M2C6A1004893).

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