

Preliminary Analysis on Thermal Margin for IVR-ERVC of i-SMR

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1. Introduction

The i-SMR (innovative Small Modular Reactor) has been developing in Korea. The design and safety concepts were explained in reference [1]. This small reactor adopted the IVR-ERVC (In-Vessel corium Retention through External Reactor Vessel Cooling) as a severe accident mitigation measure to prevent reactor vessel failure, which must demonstrate that the reactor vessel maintains its integrity in the event of a severe accident. The success criterion for IVR-ERVC in the event of a severe accident is sufficient thermal margin, which is determined by comparing and evaluating the thermal load applied to the outer wall of the reactor vessel from the core melt and the CHF (Critical Heat Flux), which is the maximum heat removal rate from the outer vessel wall. The thermal load analysis determines the heat flux distribution applied to the outer wall of the reactor vessel from the core melt. The CHF can be determined by thermal hydraulic phenomena between the outer wall of the reactor vessel and the containment vessel. This study is focused on a preliminary analysis on thermal margin for the IVR-ERVC of the i-SMR using CINEMA (Code for INTEGRated severe accident Management Analysis) computer code [2].

The CINEMA computer code is composed of CSPACE [3], SACAP (Severe Accident Containment Analysis Package) [4], and SIRIUS (SIMulation of Radioactive nuclide Interaction Under Severe accident) [5], which are capable of core melt progression with thermal hydraulic analysis of the RCS (Reactor Coolant System), severe accident analysis of the containment, and fission product analysis, respectively. The CSPACE is the result of merging the COMPASS (Core Meltdown Progression Accident Simulation Software) and SPACE (Safety and Performance Analysis Code for nuclear power plants) models [6, 7, 8], which is designed to calculate the severe accident situations of an overall RCS thermal-hydraulic response in SPACE modules and a core damage progression in COMPASS modules.

2. CINEMA Input Model

The input model for the CINEMA calculation of the i-SMR was a combination of the SPACE and COMPASS input models. Fig. 1 shows CINEMA input model for IVR-ERVC analysis of i-SMR. As shown in Fig.1, one SPACE volume is modelled for ERVC analysis. The lower reactor vessel is divided into 10 radial and 10 axial

nodes. Annular volume between the outer vessel wall and the inner containment wall is modelled by SPACE volumes. The PCCS (Passive Containment Cooling System) is modelled to control the pressure inside the containment.

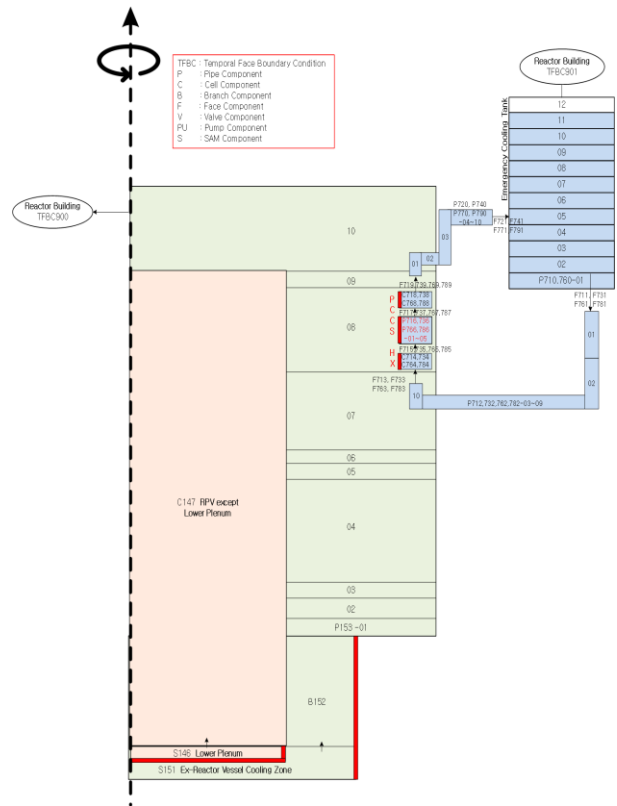


Fig. 1. CINEMA input model for IVR-ERVC analysis of i-SMR.

3. Results and Discussion

In this calculation, it is assumed that all molten core material relocated to the lower plenum of the reactor vessel at initial 10 sec at 6,804 sec (1.89 hours) for 300,000 sec (83.3 hours). Fig. 2 shows CINEMA results on layer height of the corium in lower plenum. Heights of the oxidic and metallic layers are 0.813m and 0.297m, respectively, which means the 61° and 72° from the bottom of the reactor vessel. Decay heat continued to decrease for 300,000 seconds after 1.89 hours of core melt relocation to the lower hemisphere of the reactor vessel.

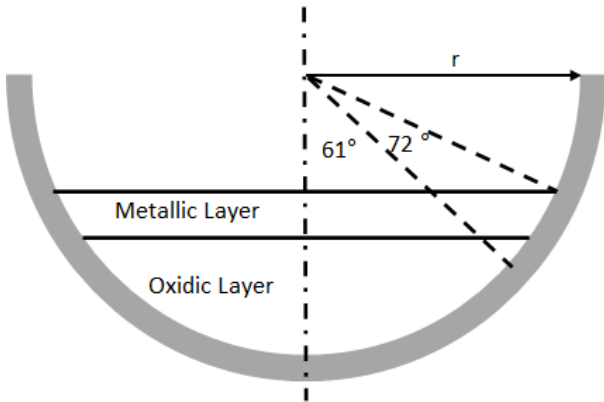


Fig. 2. CINEMA results on configuration of layer height in lower plenum.

Fig. 3 shows CINEMA results on heat flux from the outer vessel wall to water inside containment. Nodes 1 to 7 are oxidic layer, and nodes 8 and 9 are metallic layer. Node 10 is no corium in the lower plenum. Maximum heat flux is approximately 1.6 MW/m^2 in the initial relocation time at Node 6 while very short time, which is a metallic layer. This maximum value comes from the focusing effect of the metallic layer. More detailed results show in reference [9].

The gap between the outer wall of the lower hemisphere reactor vessel and the interior of the containment vessel has a high value without the CCFL(Counter Current Flow Limit), and the reactor vessel support is installed. Unlike the APR1400 and SMART100, which have reactor vessel insulation installed, the i-SMR does not have insulation. Consequently, co-current flow occurs on the outer wall of the reactor vessel with reactor vessel insulation in the APR1400. However, in the i-SMR, coolant from above is injected into the containment vessel, and the steam generated on the outer wall of the reactor vessel moves upward, forming a counter-current flow. While extensive research has been conducted on the critical heat flux at the outer wall of a reactor vessel where co-current flow occurs, less research has been conducted on the critical heat flux at the outer wall of a reactor vessel where counter-current flow occurs. However, the results of research on the CHF during downward pool boiling are believed to be applicable, because distance between the outer vessel wall and inner containment is large. In the event of a severe accident in an i-SMR, the pressure inside and outside the reactor vessel can rise to approximately 50 bars. To apply the CHF correlation developed at atmospheric pressure to high pressure, it is necessary to accurately predict the pressure-dependent CHF at high pressure conditions.

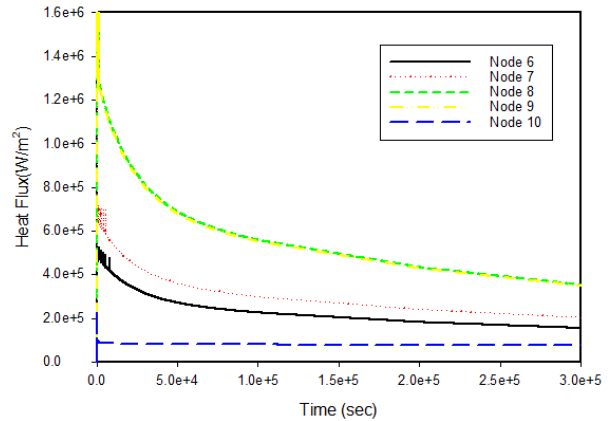
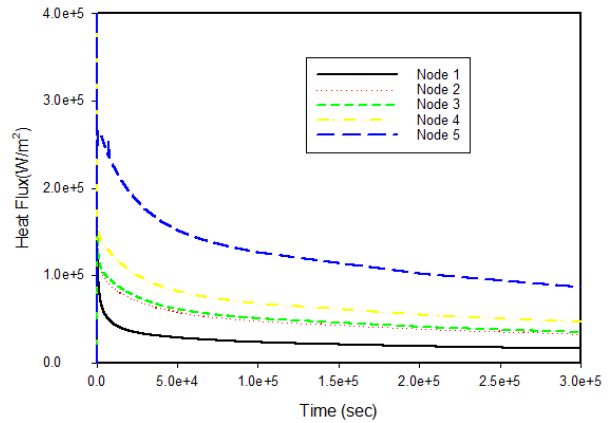


Fig. 3. CINEMA results on heat flux from the outer vessel wall to water inside containment.

Fig. 4 shows the CHF at the outer wall of the reactor vessel over time of the i-SMR. As mentioned above, the CHF at the outer wall of the reactor vessel is closely related to the pressure between the outer vessel wall and the inner wall of the containment vessel. In this simulation, the pressure in lower part of inside containment maintains approximately 17-20 bars. Specifically, the CHF changes with pressure changes. As can be seen in the figure, the CHF increases as the height increases, and except for Node 1 where the reactor vessel support is installed, the critical heat flux is $2.3 - 2.6 \text{ MW/m}^2$, in the metallic layer (Nodes 8, 9), which is much larger than the maximum heat load of 1.6 MW/m^2 applied to the reactor vessel from the core melt in the previous section.

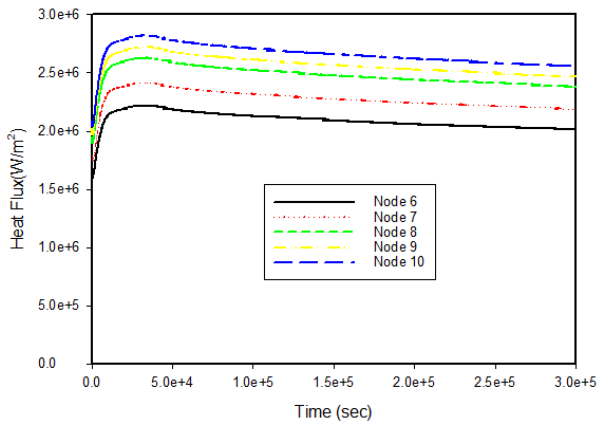
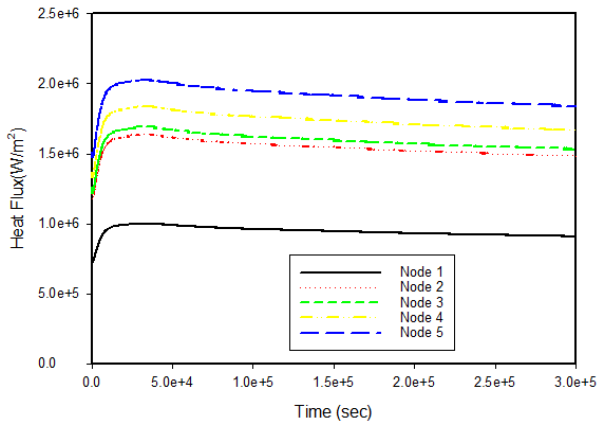


Fig. 4. CINEMA results on CHF on outer reactor vessel wall.

To prevent damage to the reactor vessel in the event of a severe accident in the i-SMR, the thermal margin must be assessed when the reactor vessel's outer wall is cooled. Thermal margin is assessed by comparing and evaluating the heat load applied to the lower hemisphere of the reactor vessel from the core melt with the CHF, which is the maximum heat removal rate from the outer wall of the reactor vessel. In other words, the heat flux applied to the lower hemisphere of the reactor vessel from the corium must be less than the CHF at the outer wall of the reactor vessel. To this end, quantitatively, it is verified that the local heat flux from the core melt remains below 85% of the critical heat flux. This indicates a margin of at least 15%. The calculation formula for this is as follows:

- Thermal margin [%] = $[1 - (\text{Local heat flux at the bottom of the reactor vessel}) / (\text{CHF})] \times 100$

Fig. 5 shows the change in thermal margin over time for the i-SMR, where the core melt is relocated from the core to the lower hemisphere of the reactor vessel in 1.89 hours. In all Nodes, it is indicating sufficient thermal margin. As the time for the core molten material to be relocated to the lower hemisphere of the reactor vessel increases, the thermal load increases, which reduces the thermal margin. The thermal margin, where the core melt is relocated from the core to the lower hemisphere of the reactor vessel in 1.89 hours, were sufficient, with averages of 77.6% and 47.6% at Node 8, where contact with the molten metal leads to heat concentration and maximum local heat flux. Where the thermal load, as shown in Fig.3, exhibited nearly identical average thermal margin, where the melt is relocated in 1.89 hours, because the decay heat continues to decrease until the end of the calculation at 300,000 seconds.

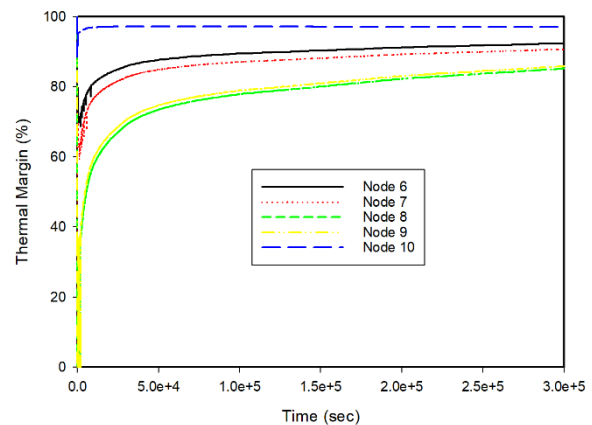
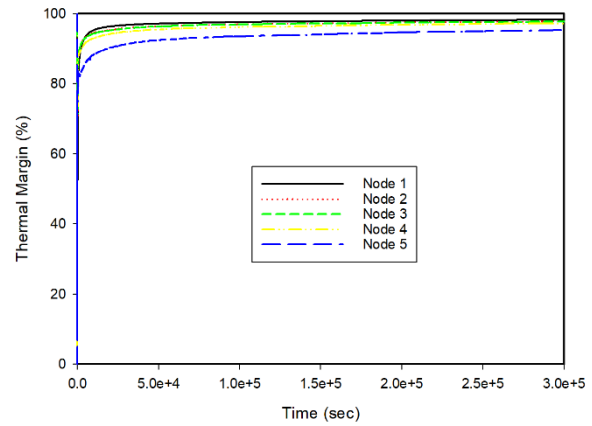


Fig. 5. Thermal margin for IVR-ERVC of i-SMR.

Fig. 6 show CINEMA results on reactor vessel thickness. The reactor vessel temperature reaches 1,700 K, which is the melting temperature of the steel, it melts

in this simulation. The reactor vessel did not fail by ERVC. However, the reactor vessel was melted to 50 % of the initial thickness at Nodes 8 and 9 of the metallic layers.

of the initial thickness. More detailed analysis on the thermal margin is necessary for the evaluation of the IVR-ERVC of the i-SMR.

ACKNOWLEDGMENTS

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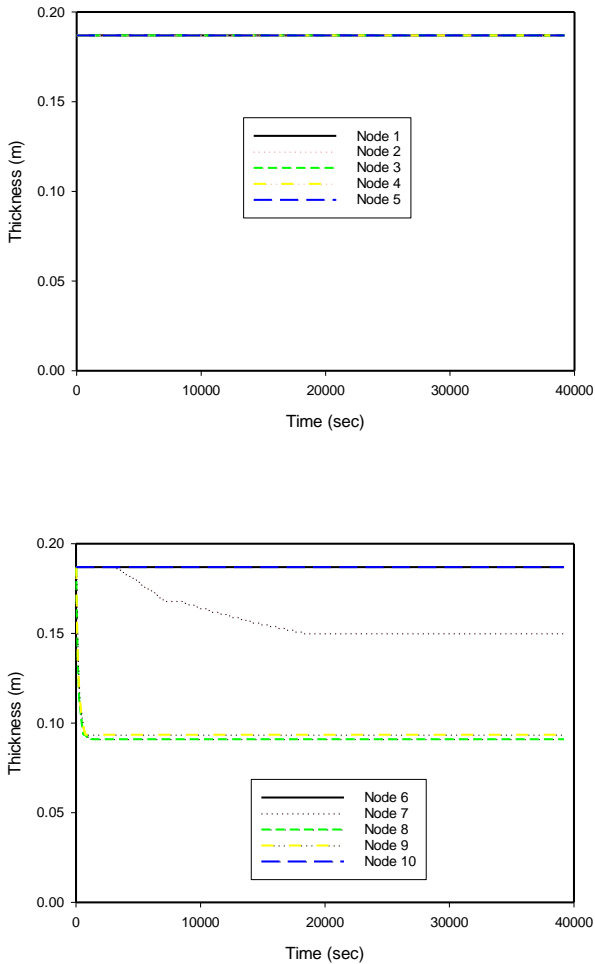


Fig. 6. CINEMA results on reactor vessel thickness.

4. Conclusion

This study is focused on a preliminary analysis on thermal margin for the IVR-ERVC of the i-SMR using CINEMA computer code. Thermal margin is assessed by comparing and evaluating the heat load applied to the lower hemisphere of the reactor vessel from the core melt with the CHF, which is the maximum heat removal rate from the outer wall of the reactor vessel. The thermal margin, where the core melt is relocated from the core to the lower hemisphere of the reactor vessel in 1.89 hours, were sufficient, with averages of 77.6% and 47.6% at Node 8, where contact with the molten metal leads to heat concentration and maximum local heat flux. The reactor vessel did not fail by the ERVC in spite of some melting of the reactor vessel. The reactor vessel was melted to 50 %