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Simulation of In-Vessel Corium Retention through External Reactor Vessel Cooling for SMART using SIMPLE

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1. Introduction

The in-vessel corium retention through external reactor vessel cooling (IVR-ERVC) is known to be effective means for maintaining reactor vessel integrity during a sever accident in a nuclear power plant. Also, IVR-ERVC is chosen in a Korean small integral reactor called SMART as a design feature for severe accident management [1]. And thermal load analysis from the corium pool to the outer reactor vessel in the lower plenum of the reactor vessel is necessary to evaluate the effect of the IVR-ERVC during a severe accident for SMART.

A computational code called SIMPLE (Sever In-vessel Melt Progression in Lower plenum Environment) has been developed for analyze transient behavior of molten corium in the lower plenum, interaction between corium and coolant, and heat-up and ablation of reactor vessel wall [2].

In this study, heat load analysis of the reactor vessel for SMART has been conducted using the SIMPLE.

2. SIMPLE code

The SIMPLE code calculates the lower plenum thermal hydraulics as well as the molten pool behavior after the melts relocated into the lower plenum from the core support plate during severe accidents. The scope and range of the SIMPLE calculation include the melt relocation from the core and the melt progression to the lower head vessel failure.

SIMPLE calculates the thermal hydraulic behavior of the relocated molten pool in the lower plenum based on the following steps [3].

- Read input for the geometry and thermal dynamic variables
- Initialize the geometry and state variables
- Read input for the core melt relocation into the lower plenum
- Melt Jet-Water Fuel Coolant Interaction (FCI)
- Debris formation, heat-up and melt
- Molten pool formation and separation
- Metallic pool behavior
- Oxidic pool behavior and crust formation
- Lower plenum mixture level
- Output File for Plot variables

3. Thermal load analysis

A thermal load analysis for IVR-ERVC evaluation in SMART was performed to determine the heat flux distribution from the corium pool to the outer reactor vessel in the lower plenum of the reactor vessel. Fig. 1 shows a corium pool formation in the lower plenum of the reactor vessel.

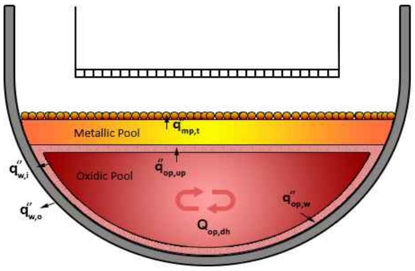

Fig. 1. Corium pool formation in the lower plenum of the reactor vessel.

In this study, corium pool is assumed to be divided into oxidic layer and metallic layer by a density difference in the lower plenum of the reactor vessel. Oxidic layer made up of UO_2 and ZrO_2 is a high density. Metallic layer made up of Zr and stainless steel is a low density. In this case, the entire core and lower plenum materials are melted and moved to the corium pool in the lower plenum. The lower oxidic layer thickness is determined by 16.8 tons of UO_2 and 3.3 tons of ZrO_2. The upper metallic layer thickness is determined by 2.5 tons of Zr and 14.5 tons of steel [4].

In previous study, the thermal margin for the success of the IVR-ERVC during a sever accident was known to be sufficient in SMART [1]. In this study, therefore, nuclear boiling has been considered only for heat transfer. The heat flux from the vessel wall to the reactor cavity water q_{out} can be expressed by the following nucleate boiling relations;

$$q_{out} = C_{boil}\left(T_{wall} - T_{sat}\right) \tag{1}$$

$$C_{boil} = \left(\frac{g\left[\rho_l - \rho_v\right]}{\sigma}\right)^{\frac{1}{2}} \left(\frac{c_p}{h_{lv} C_{sf} \Pr}\right)^{3} \left(\mu h_{lv}\right) \tag{2}$$

where C_{boil} is the nucleate boiling coefficient and is obtained from the properties of the saturated water in the reactor cavity.

4. Results

Fig. 2 shows the temperature of in-vessel wall of oxidic and metallic layer. Oxidic layer temperature shows the 963 K and metallic layer temperature shows the 1673 K is a melting temperature of vessel wall. Until the 14,000 seconds, metallic layer temperature has been reduced because the heat of metallic layer has been used to generate the debris bed. After the thermal equilibrium of the debris bed, metallic layer temperature was raised to the melting temperature of vessel wall.

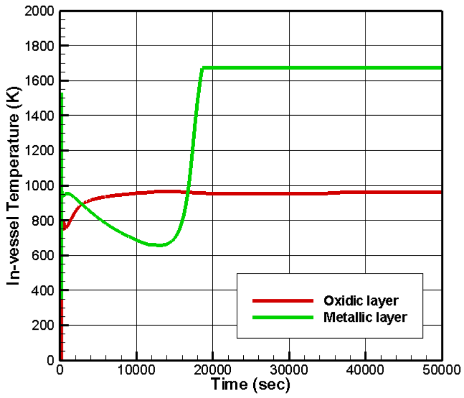

Fig. 2. Temperature of in-vessel wall of oxidic and metallic layer.

Fig. 3 shows the temperature of ex-vessel wall of oxidic and metallic layer. Oxidic layer temperature shows the 377 K and metallic layer temperature shows the 390 K respectively. Like the in-vessel wall, metallic layer temperature shows higher than oxidic layer.

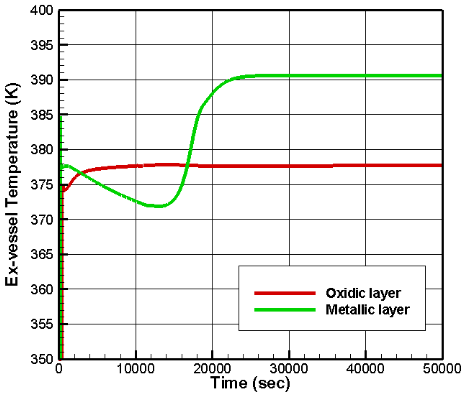

Fig. 3. Temperature of ex-vessel wall of oxidic and metallic layer.

Fig. 4 shows the heat flux to water of oxidic and metallic layer. Heat flux of oxidic layer shows the 93 kW/m^2 and metallic layer heat flux shows the 293 kW/m^2. Effect of the heat flux has been reflected in the vessel temperature.

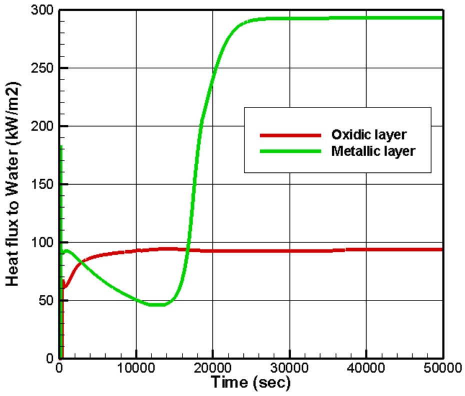

Fig. 4. Heat flux to water of oxidic and metallic layer.

Fig. 5 shows the vessel thickness of oxidic and metallic layer. Initial thickness of the vessel is 20 cm. Vessel wall of metallic layer melting started at 19,000 second and remaining vessel wall is about 14 cm. At the oxidic layer, there is no ablation because the in-vessel temperature of the oxidic layer did not reach the melting temperature of the vessel wall.

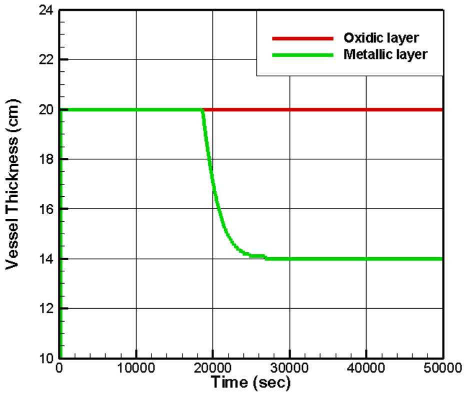

Fig. 5. Vessel thickness of oxidic and metallic layer.

5. Conclusion

Transient behavior of the molten corium in the lower plenum and IVR-ERVC for SMART has been simulated using SIMPLE.

Heat flux from the corium pool to the outer reactor vessel is concentrated in metallic layer by the focusing effect. As a result, metallic layer shows higher temperature than the oxidic layer. Also, vessel wall of metallic layer has been ablated by the high in-vessel temperature.

Ex-vessel temperature of the metallic layer was maintained 390 K and vessel thickness was maintained 14 cm. It means that the reactor vessel integrity is maintained by the IVR-ERVC.

More qualitative and quantitative validation of the SIMPLE is required using experimental data. It is scheduled to be carried out through the future of research.

ACKNOWLEGEMENT

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