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# Thermal Load Analysis of Multilayered Corium in the Lower Head of Reactor Pressure Vessel during Severe Accident

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## 1. Introduction

In-Vessel Retention (IVR) is one of the severe accident management strategies to terminate or mitigate the severe accident which is also called 'core-melt accident'. The reactor vessel would be cooled by flooding the cavity with water. The molten core mixture is divided into two or three layers due to the density difference. Light metal layer which contains Fe and Zr is on the oxide layer which is consist of $UO_2$ and $ZrO_2$. Heavy metal layer which contains U, Fe and Zr is located under the oxide layer [1]. In oxide layer, the crust which is solidified material is formed along the boundary. Fig. 1 shows that conventional configuration of IVR.

The integrity of IVR is evaluated by comparing thermal load on the vessel with the critical heat flux (CHF) along the ex-vessel surface. The assessment of IVR for nuclear power plant has been conducted with lumped parameter method by Theofanous [2], Rempe [3] and Esmaili [4, 5].

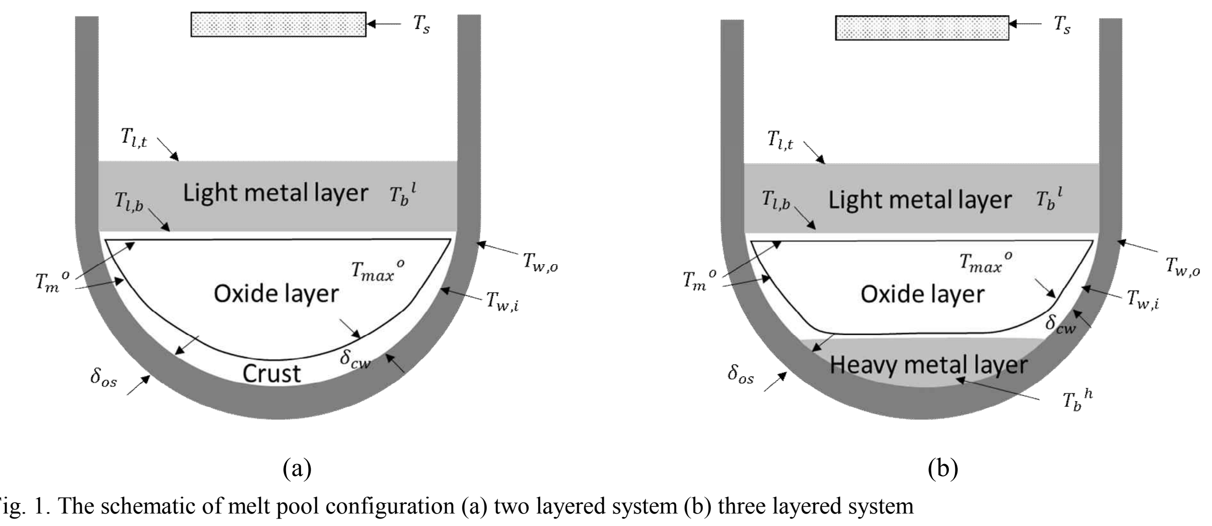
In this paper, the numerical analysis was performed and verified with the Esmaili's work [5] to analyze thermal load of multilayered corium in pressurized reactor vessel and also to examine the condition of in-vessel corium characteristic before the vessel failure that lead to ex-vessel severe accident progression for example, ex-vessel debris bed cooling. The in-vessel coolability analysis for several scenarios is conducted for the plant which has higher power than AP1000. Two sensitivity analyses are conducted, the first is emissivity of light metal layer and the second is the heat transfer coefficient correlations of oxide layer. The effect of three layered system also investigated.

## 2. Methods

Decay heat from the oxide layer and heavy metal layer due to the fission energy of uranium moves to the vessel wall and the light metal layer. In the conservative point of view, some of the heat is removed from the top surface by radiation and the most heat is transferred to the vessel wall in the light metal layer which is known as focusing effect. Every heat which is applied to the vessel is transferred to the ex-vessel coolant. The heat flux along the vessel wall was calculated by lumped parameter method. The heat transfer correlations, properties and assumptions for the in-vessel coolability analysis were based on the previous research [4, 5].

### *2.1 Heat transfer in the general system*

Eq. 1 is the energy equation of oxide layer for the two layered system. Eq. 2~3 indicate the heat flux to the upper and side boundary, respectively. Those equations contain the heat transfer coefficient term from experimental correlations. The heat flux between ex-vessel surface and the coolant was calculated by using Rosenhow's nucleate boiling heat transfer coefficient, Eq. 4~5 [6].




(a) (b)

Fig. 1. The schematic of melt pool configuration (a) two layered system (b) three layered system

The evaluation of integrity of the vessel was conducted by comparing the calculated heat flux along the vessel wall with the CHF of the ex-vessel surface.

$$Q_o'''V_o = q_{o,t}''A_{o,t} + q_{o,w}''A_{o,w} \quad (1)$$

$$q_{o,t}'' = h_{o,t}(T_{\max}^o - T_m^o) \quad (2)$$

$$q_{o,w}'' = h_{o,w}(T_{\max}^o - T_m^o) \quad (3)$$

$$q_{w,o}'' = C_{boil}(T_{w,o} - T_{sat})^3 \quad (4)$$

$$C_{boil} = \left(\frac{g[\rho_l - \rho_v]}{\sigma_l}\right)^{\frac{1}{2}}\left(\frac{c_{p,l}}{h_{fg}C_{sf}\Pr_l}\right)(\mu_l h_{fg}) \quad (5)$$

*2.2 Three layered system*

The analysis of three layered system was conducted by defining $f_U$ , the fraction of U in oxide layer. The mass quantity of U and Zr in the heavy metal layer was determined according to the fraction of U in oxide layer. There are two important assumptions in this approach. The first one is that the mass of Fe in the heavy metal layer is fixed at 3,000 kg which is for the energy absorber structure in the lower head. The other one is the fixed mass fraction of U as 0.4. From Eq. 7, the decay heat was calculated for the oxide layer and heavy metal layer.

$$f_U = 1 - \frac{m_U}{m_{UO2}}\frac{270}{238} \quad (6)$$

$$\frac{Q_h'''V_h}{Q_o'''V_o} = \frac{m_U(270/238)}{m_{UO2}} \quad (7)$$

*2.3 Benchmark calculation result*

The present code was verified with the numerical analysis result of Esmaili's work [5]. Same conditions such as heat transfer correlations, properties and geometrical information were used to conduct this benchmark calculation. Fig. 2 shows that heat flux variation along the vessel wall, and the result showed a good agreement with the result of the previous research.

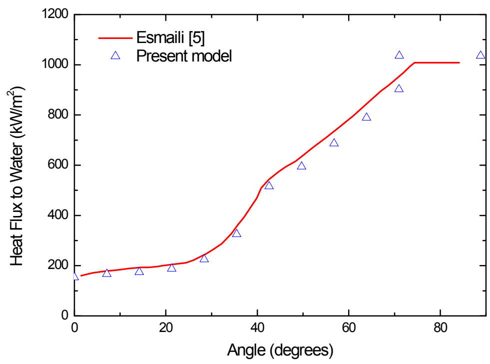



Fig. 2. Benchmark calculation result of the present model

## 3. Results

Thermal load along the vessel wall was investigated with the verified present model. The results include that thermal load analysis according to severe accident scenarios and three sensitivity analyses. First parameter is the emissivity of the light metal layer, second one is the heat transfer correlations of the oxide layer and the last one is the fraction of U in the oxide layer of three layered system.

*3.1 Thermal load analysis according to severe accident scenarios*

The in-vessel coolability analysis was conducted with different initial condition and the target plant has higher thermal power than AP1000.

Table I is the result of the SCDAP/RELAP5 which is one of the severe accident analysis code. The eight scenarios are divided into two part, high pressure (HP) and low pressure (LP) accident. In HP accident, there are loss of feed water (LOFW) accident with or without radiation control safety program (RCSP) and station black out (SBO). In LP accident, there are loss of coolant accident (LOCA) and the numbers indicates pipe break size [7].

Fig. 3 shows that the heat flux distribution result based on the SCDAP/RELAP5. The solid line is CHF line along the outer vessel wall from the ULPU-V experiment [8]. In the result, the focusing effect occurs in the light metal layer at every scenarios. In large break LOCA (9") scenario, the heat flux on the vessel wall is almost two times larger than the CHF values.

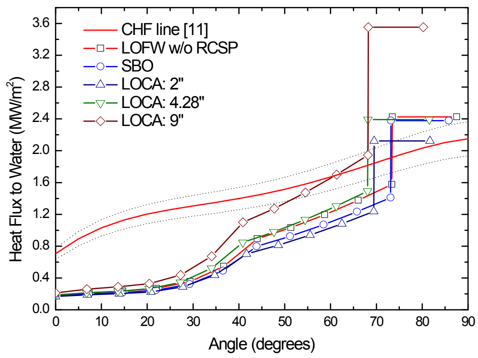



Fig. 3. Heat flux distribution based on SCDAP/RELAP5

*3.2 Sensitivity analysis for emissivity of the light metal layer*

One of the heat removal mechanism in the light metal layer is radiation through the top surface. The emissivity determines heat flux to the upper structure. However, large uncertainty makes difficult to define certain emissivity value.

The effect of emissivity is investigated when the value is changing from 0.3 to 0.9. Fig. 4 shows that focusing effect becomes intensive with low emissivity value. The integrity of system is determined according to emissivity value at the same LOCA (2") condition in Table I.

Table I: Melt pool values before vessel failure in the SCDAP/RELAP5

| Parameter | HP | | | LP | | | | |
|---|---|---|---|---|---|---|---|---|
| | LOFW | | SBO | LOCA (inch) | | | | |
| | w/o RCSP | w/ RCSP | | 1.35" | 2" | 3" | 4.28" | 9.6" |
| Decay heat ( $MW/m^3$ ) | 2.91 | 2.95 | 2.62 | 2.32 | 2.54 | 2.53 | 3.19 | 4.15 |
| Oxide pool degrees ( ° ) | 72.9 | 66.9 | 72.7 | 71.9 | 69 | 68.3 | 67.3 | 67.2 |
| Metal layer thickness (m) | 0.59 | 0.63 | 0.58 | 0.6 | 0.55 | 0.59 | 0.61 | 0.54 |

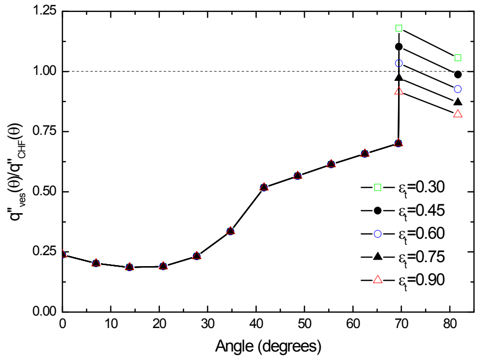



Fig. 4. Comparison of CHF ratio with light metal layer surface emissivity

### *3.3 Sensitivity analysis for heat transfer correlations of the oxide layer*

Experimental correlations are required to determine the heat transfer coefficients for the lumped parameter method. In this study, the effect of correlation which determines heat energy split in the oxide layer is investigated. There are experimental correlations to describe upward and downward heat flux in Table II.

Fig. 5 shows the result of sensitivity analysis for the heat transfer correlations. The upward Nusselt number determines the total heat flux to the light metal layer which causes focusing effect in that layer. In the result with ACOPO correlation, significant focusing effect occurs because large amount of heat is transported to the upper layer.

Table II: Heat transfer correlations for the oxide layer

| Top surface | Bottom surface |
|---|---|
| Kulacki-Emara [9] $Nu_u = 0.345(Ra_{q,u})^{0.226}$ | Mayinger [10] $Nu_d = 0.55(Ra_{q,d})^{0.2}$ |
| Mini-ACOPO [11] $Nu_u = 0.345(Ra)^{0.233}$ | Mini-ACOPO $Nu_d = 0.0038Ra^{0.35}\left(\frac{H}{R}\right)^{0.25}$ |
| ACOPO [11] $Nu_u = 2.4415Ra'^{\,0.1772}_p$ | ACOPO $Nu_d = 0.1857Ra'^{\,0.2304}_p\left(\frac{H}{R}\right)^{0.25}$ |

Table III: Fraction of uranium in the oxide layer and calculated thickness of the light metal layer

| $f_U$ | 0.85 | 0.90 | 0.95 | 1.0 |
|---|---|---|---|---|
| Metal layer thickness (m) | 0.45 | 0.51 | 0.57 | 0.61 |

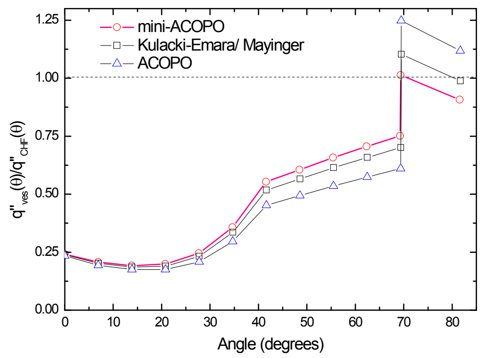



Fig. 5. Comparison of CHF ratio with heat transfer correlation of the oxide layer

### *3.4 Sensitivity analysis for the fraction of U in the oxide layer of three layered system*

The fraction of U in oxide layer and the calculated thickness of metal layer are listed in Table III. As the fraction decreases, the quantity of U in the heavy metal layer increases, therefore, the thickness of light metal layer decreases. Fig. 6 is the result of sensitivity analysis for the fraction of U in the oxide layer. The fraction of U decides the quantity of the light metal layer, as a result, the intensity of focusing effect is determined. Although the decay heat is generated in the heavy metal layer, the effect is not critical in that region.

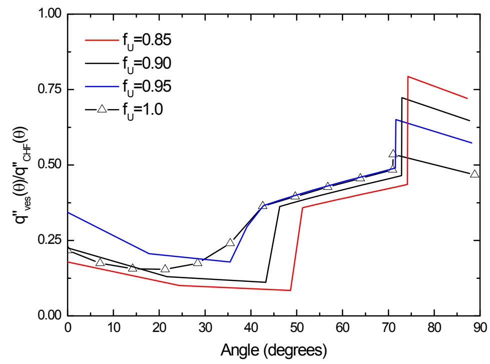



Fig. 6. Comparison of CHF ratio with fraction of uranium in the oxide layer

## 4. Conclusions

In this paper, the numerical analysis was performed and verified with Esmaili's model [5] to analyze thermal load of multilayered corium in pressurized reactor vessel. For two layered system, thermal load was analyzed according to the severe accident scenarios, emissivity of the light metal layer and heat transfer correlations of the oxide layer. For three layered system, the effect of fraction of U in the oxide layer is considered.

The in-vessel coolability is analyzed with various severe accident scenarios for the high power plant. From the result, the focusing effect occurs at every high power plant, and it is confirmed that the large difference occurs according to the accident scenarios. Thermal load is influenced by the emissivity in the light metal layer and the fraction of U in the oxide layer which could not be decided certain values. Thermal load is also affected by the heat transfer correlations, therefore, it is required the more accurate investigation which can describe the thermal energy split to decrease the uncertainty. It is necessary to conduct uncertainty analysis with key parameters as a future work.

## ACKNOWLEDGEMENT

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