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Sensitivity Study of Zirconium Oxidation on Concrete Ablation during MCCI using MELCOR code

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1. Introduction

Since Fukushima nuclear power plant (NPP) accident occurred in 2011, significance of safety analyses for various phenomena during severe accidents in NPP has been emphasized. Among various phenomena during severe accidents, Molten Corium Concrete Interaction (MCCI) is considered as a prominent issue because MCCI can threaten the containment integrity due to cavity ablation and corresponding overpressure by a large amount of non-condensible gas and combustible gas. Therefore, more detailed analysis for MCCI using sophisticated code has been required.

For conservative analyses about hydrogen risk, zirconium is generally assumed to be fully oxidized in reactor core because this assumption implies that maximum amount of hydrogen is produced. From this perspective, the CCI-6 test conducted by OECD/NEA also adopted the same assumption [1]. In other words, of the composition of corium, all forms of zirconium exist as zirconium dioxide rather than zirconium metal.

However, this assumption may underestimate concrete ablation during MCCI. This is because if zirconium is oxidized in the cavity, additional oxidation heat increases the ablation depth [2]. Therefore, for conservative analyses about concrete ablation during the MCCI, consideration about the zirconium oxidation in reactor cavity can be judged reasonable.

Based on this consideration, this study investigated concrete ablation during MCCI according to the composition of zirconium using MELCOR code. In MELCOR simulation, zirconium was assumed to be oxidized in cavity. The sum of mass of zirconium metal and zirconium dioxide was maintained as same as the CCI-6 test and their ratio was changed for each case.

2. Methodology

2.1. MELCOR input

In this study, the MELCOR input for simulating MCCI was modified based on the benchmarking input for CCI-6 test conducted by OECD/NEA. Figure 1 represents the CCI-6 test apparatus. In CCI-6 test, the corium falls into the underlying concrete floor. The MCCI was evaluated in terms of concrete ablation depth, corium temperature, melt eruption, and water ingression.

In composition of corium in the benchmarking input for the CCI-6 test, zirconium exists only in the form of a zirconium dioxide. In this study, however, three cases were studied by considering the different metal water reactions (MWR) of zirconium: 100 %, 75 %, and 50 % MWR. Table 1 summarizes the composition of zirconium for each case. In addition, no flooding was modeled to simulate the maximum ablation.

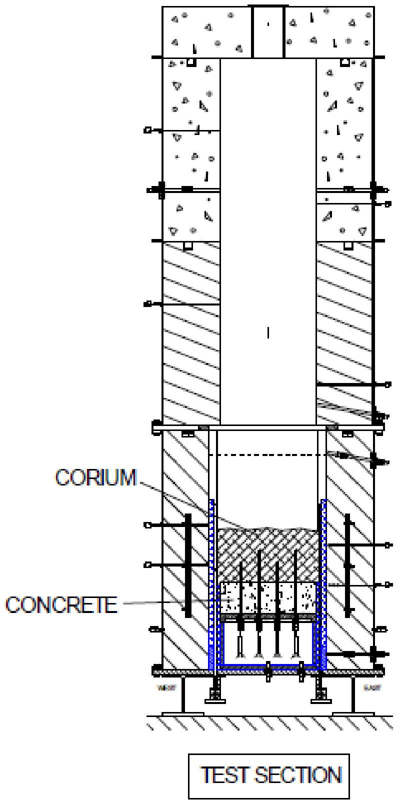

Fig 1. CCI-6 test apparatus [1]

Table 1. Composition of zirconium for each case

Case	100 % MWR	75 % MWR	50 % MWR
Zr (kg)	0	57.76	115.515
ZrO_2 (kg)	231.03	173.27	115.515
Total mass (kg)	231.03	231.03	231.03

2.2. Containment failure due to concrete ablation

In MELCOR, if either axial or radial ablation depth reaches their wall thickness, the simulation stops automatically because the containment building is judged to fail [3]. Based on this mechanism, this study evaluated the containment failure time and the final value of radial and axial ablation depth. It also means that the ablation rate varies as the oxidation heat of zirconium in cavity.

Figure 2 shows the shape of cavity in the MELCOR input [4]. Especially, RW, RAD, HIT, and HBB are 0.635 m, 0.395 m, 1.2 m, and 0.5 m respectively. RW, RAD, HIT, and HBB are outer radius, inner radius, depth, and axial wall thickness of cavity, respectively. The radial wall thickness of cavity is the difference between RW and RAD, i.e. 0.24 m; the axial wall thickness of cavity is HBB, i.e. 0.5 m. Therefore, with the aforementioned thickness, the containment failure can be judged by evaluating the radial and axial ablation depth in the MELCOR simulation.

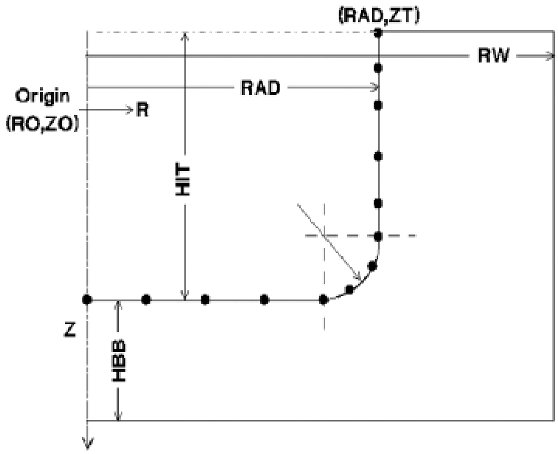

Fig 2. Cavity shape in MELCOR simulation [3]

3. Result and Discussion

Figure 3 shows heat loss to concreate in cavity for each case. This heat was contributed to the concrete ablation under the assumption of CORCON-Mod2 [4]. As zirconium MWR ranges from 100 % to 50 %, heat transfer to the concrete increases due to additional oxidation heat in cavity. Equations 1 to 3 describe the major reaction of zirconium incorporated in CORCON-Mod3 chemistry package [4]. Due to these reactions of zirconium, the additional oxidation heat was generated and transferred to concrete ablation.

$$Zr + 2H_2O \rightarrow ZrO_2 + 2H + 701\text{kJ/mole Zr} \quad (1)$$
$$Zr + 2CO_2 \rightarrow ZrO_2 + 2CO + 535\text{kJ/mole Zr} \quad (2)$$
$$Zr + SiO_2 \rightarrow ZrO_2 + Si + 190\text{kJ/mole Zr} \quad (3)$$

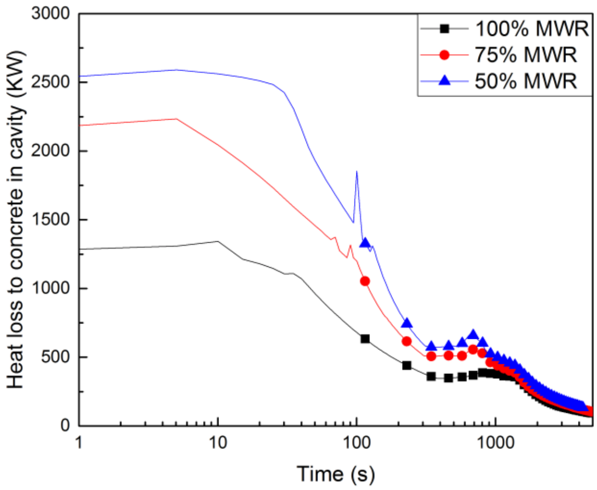

Fig 3. Heat loss to concrete in cavity for each case

Figures 4 and 5 represent radial and axial ablation depth for each case, respectively. As shown in Figure 4, as zirconium MWR decreased, radial ablation reached radial wall thickness, i.e. 0.24 m, more quickly so that the containment failure time was shortened. Because when zirconium MWR decreased from 100 % to 50 %, the ablation rate increased owing to the higher heat loss to concrete. The containment failure time was 22,675 s, 7,330 s, and 4,350 s for 100 %, 75 %, and 50 % MWR case, respectively.

As shown in Figure 5, axial ablation did not reach axial wall thickness, i.e. 0.5 m. It is attributed to the fact that the heat transfer to axial wall was lower than that to radial wall owing to the thicker crust. Figure 6 shows the average axial and radial crust thickness for three cases. In the section, where the difference between heat losses for three cases is outstanding, i.e. before about 5,000 s, the axial crust thickness was over twice thick compared to the radial crust thickness. When the crust was formed and maintained stably, heat transfer decreased due to the low thermal conductivity of crust. Therefore, the higher heat was lost to radial wall so that the containment failure occurred.

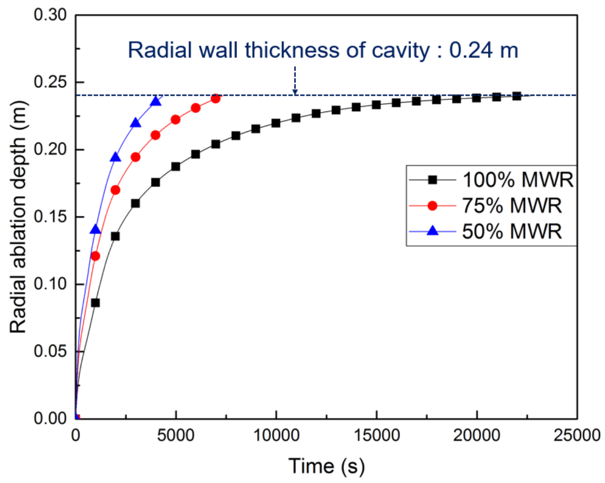

Fig 4. Radial ablation depth for each case

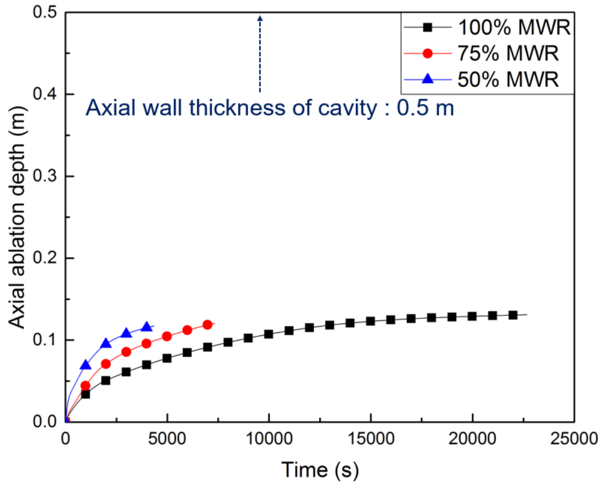

Fig 5. Axial ablation depth for each case

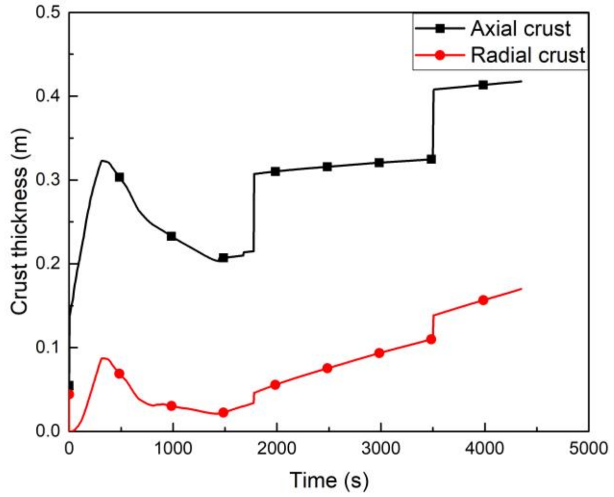

Fig 6. Average axial and radial crust thickness

4. Conclusions

In this study, concrete ablation during MCCI was investigated with MELCOR simulation according to zirconium MWR in corium: 100 %, 75 %, and 50 % MWR. For conservative analysis of the MCCI, it was assumed that the Zirconium was also oxidized in reactor cavity. The major findings in this study can be summarized as follows.

(1) As zirconium MWR decreased from 100 % to 50 %, radial ablation reached radial wall thickness, i.e. 0.24 m, more quickly so that the containment failure time was shortened. Because of the higher heat loss to radial wall due to additional oxidation heat, the ablation rate is expected to increase.

(2) Axial ablation did not reach axial wall thickness, i.e. 0.5 m. This is because the heat transfer to axial wall was lower than that to radial wall owing to the thicker crust. When the crust was formed and maintained stably, heat transfer decreased due to low thermal conductivity of crust.

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