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# Sensitivity Analysis of MCCI in PHWR using MELCOR code

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## 1. Introduction

When a molten corium-concrete interaction (MCCI) occurs, concrete of both cavity floor and sidewalls could be ablated and a large amount of non-condensable gas is generated by concrete erosion. The process of MCCI is driven by sensible heat of molten corium and the decay heat generated inside the melt by the radioactive decay of the fission products (FPs). Thus, the progression of MCCI plays a key role in threatening the integrity of the containment building because the concrete is the last barrier, which preserves FPs release to the environment [1].

Accordingly, several computer codes have been developed to simulate MCCI and to validate the experimental results such as CORCON, WECHSL, CORQUENCH, COSACO, TOLBIAC-ICB, ASTEC/MEDCIS, and MOCO [2-8]. In general, these codes were highly dependent of empirical heat transfer correlation developed based on experimental results. However, some discrepancies between various experimental data and computer code calculation still exist in the prediction of the MCCI behavior under various conditions.

Therefore, in this study, to address remaining uncertainties related to MCCI phenomena, severe accident analysis for pressurized heavy-water reactor (PHWR) with MELCOR version 2.1 was used to simulate the MCCI. Sensitivity analyses on MCCI were performed to investigate the effect of several important parameters, i.e., concrete type and corium concrete contents. For calculation methods, firstly, the verification and validation of the MELCOR code were performed based on the CCI-3 test from the OECD/MCCI projects; and then a reactor-scale simulation was carried out for MCCI behavior of a reference PHWR with Siliceous (SIL) concrete.

## 2. The CCI-3 Benchmark

Using severe accident code MELCOR, the benchmarking work regarding CCI-3 test was carried out within OECE/MCCI program. The OECD/MCCI program was intended to provide information in several areas, including: 1) lateral vs. axial power split during dry core-concrete interaction, 2) integral debris coolability data following later phase flooding, and 3) data regarding the nature and extent of the cooling transient following breach of the crust formed at the melt-water interface [9].

As one part of the PHWR MCCI behavior analysis, a series of validation calculation have been carried out. The verification of the MELCOR code was performed based on the CCI-3 in order to understand the code characteristics. The CCI-3 experimental approach was to investigate the interaction of PHWR core melts with specially designed 2-D concrete test section. Since the only option available at this time for the initial geometry of the concrete cavity is “flat-bottom cylinder” option of MELCOR as shown in Fig 1, the geometry is modeled as a cylinder with a diameter of 0.2821 m. The thickness of concrete walls at lateral direction and axial direction are 0.55 m. The initial concrete compositions mocked up based on the experimental data for CCI-3 test are shown in Table 1. Also, all gases arising from concrete decomposition are assumed to travel up through the melt. The cavity absolute pressure is 0.1 MPa. The initial melt temperature is set as 1,950 $^{o}$C. The density of concrete was calculated to be 2,330 kg/m$^3$ based on the measured mass and volume of the archive sample [9].

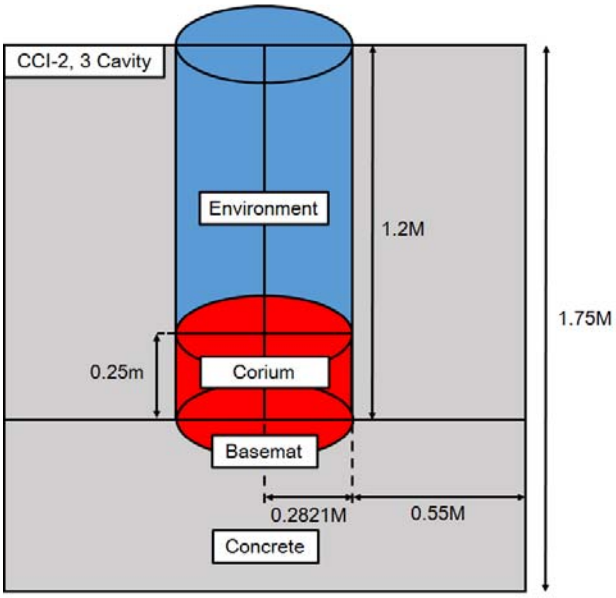

Fig.1. Cavity geometry in CCI-3

Table 1 Concrete composition for CCI-3 test used in experiments and MELCOR code

| Constituent | CCI-3 (Experimental) | CCI-3 (MELCOR) |
|---|---|---|
| $SiO_2$ | 59.91 | 61.32 |
| CaO | 16.79 | 17.19 |
| $Al_2O_3$ | 3.53 | 3.61 |
| $Fe_2O_3$ | 1.49 | 1.53 |
| MgO | 0.85 | 0.87 |
| MnO | 0.04 | 0.00 |
| SrO | 0.04 | 0.00 |
| $TiO_2$ | 0.155 | 0.16 |
| $SO_3$ | 0.434 | 0.00 |
| $Na_2O$ | 0.66 | 0.68 |
| $K_2O$ | 0.81 | 0.83 |
| $CO_2$ | 9.80 | 10.03 |
| $H_2O$, Free | 2.293 | 2.35 |
| $H_2O$, Bound | 1.40 | 1.43 |
| Total | 98.202 | 100.00 |

Table 2 shows timeline of significant events for CCI-3 tests. Examination of Figs. 1 and 2 indicate that CCI-3 test showed evidence of early crust formation phases that influenced the overall ablation behavior. Sidewall erosion commenced immediately upon contact with melt and progressed steadily throughout the balance of the test. However, the concrete basemat was protected by an insulating crust until approximately 50 minutes. After the crust failed, erosion commenced, albeit at a reduced rate relative to latera ablation.

Table 2. Timeline of significant events of CCI-3 tests [9]

| Time (min) | Event |
|---|---|
| 0.00 | Thermite burn completed, results in initial melt temperature is 1950 °C |
| 0.00-0.80 | Onset of ablation |
| 1.6 | Full DEH power reached |
| 104.7 | Crust lance probe used to break crust |
| 107.6 | Water addition started (29.2 cm ablation) |
| 146.4 | DEH power terminated, nearing max ablation limit of 35 cm |
| 173.3 | Data acquisition terminated |

Various sensitivity studies were performed for the CCI-3 test to obtain the optimum value. However, the current MELCOR code is limited in properly modelling a crust in user-specified variables of the CAV package. Therefore, the ablation rate in the axial and lateral direction was the same within the specific range as indicated in Figs. 2 and 3. Using the optimum value, the MELCOR calculation result of CCI-3 test showed a reasonable agreement with experimental data.

## 3. Results and Discussion

Following the verification and validation on the CCI-3 test, a MELCOR simulation was performed to predict the MCCI behavior in a reactor scale. To evaluate MCCI phenomena for PHWR, Wolsong unit 1 was selected as a reference nuclear power plant.

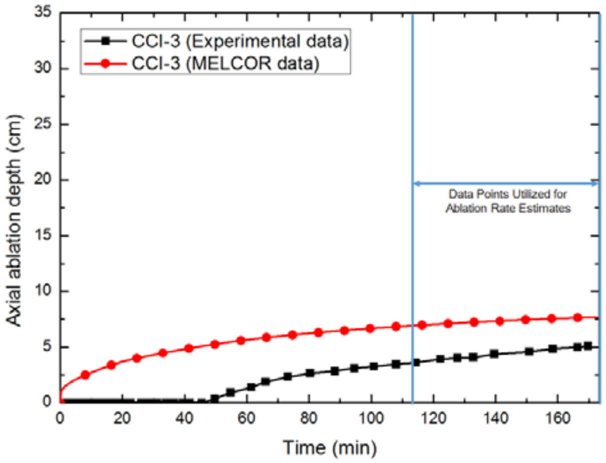

Fig.2. Axial ablation depth for CCI-3 test.

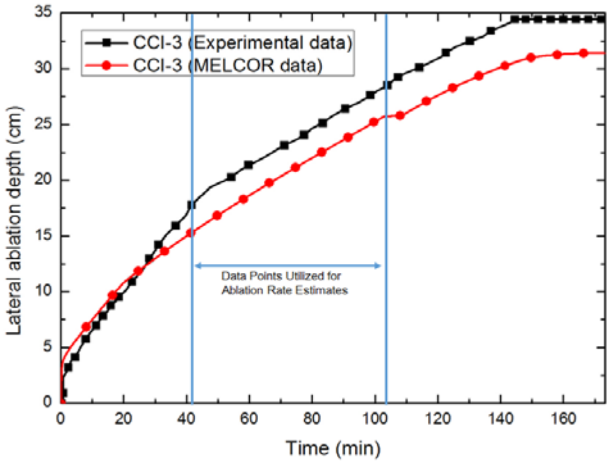

Fig.3. Lateral ablation depth for CCI-3 test.

### *3.1 Effect of concrete type*

The type of concrete used for the basemat material is one of the most important factors governing the progression of MCCI. The SIL concrete has been used as the base concrete type for the PHWR. Other than SIL concrete type, Limestone/Common sand (LCS) concrete which is based on the base concrete type of optimized pressurized reactor 1000 MWe (OPR1000) was chosen for sensitivity analysis. The chemical compositions of each concrete type are shown in Table 3.

Figs. 4 and 5 show the axial and lateral ablation depths calculated with different types of concrete. For all concretes, the basemat melt-through was predicted. The containment failure times were estimated at about 41 and 50 hours for SIL and LCS concrete, respectively after the RPV failure. For the SIL concrete, most of the ablation was concentrated in the lateral direction. However, for the LCS concrete, the ablation was nearly uniformly. This is because the content of $SiO_2$ is more than LCS concrete. When the content of $SiO_2$ was high in the concrete, the spreading of molten corium increased due to low viscosity of $SiO_2$. It showed a good example by the results of the CCI test in OECD/MCCI programs [9].

Table 3 Chemical Composition of Concretes (wt %)

| Constituent | SIL (Tag_01) | LCS (Tag_02) |
|---|---|---|
| $SiO_2$ | 60.63 | 22.01 |
| CaO | 13.64 | 26.42 |
| $Al_2O_3$ | 10.10 | 2.54 |
| $Fe_2O_3$ | 2.31 | 1.42 |
| MgO | 1.18 | 11.71 |
| $TiO_2$ | 1.18 | 0.14 |
| $Na_2O$ | 2.13 | 0.32 |
| $K_2O$ | 1.11 | 0.56 |
| $CO_2$ | 2.22 | 30.42 |
| $H_2O$, Free | 3.40 | 3.33 |
| $H_2O$, Bound | 2.10 | 1.13 |
| Total | 100.00 | 100.00 |

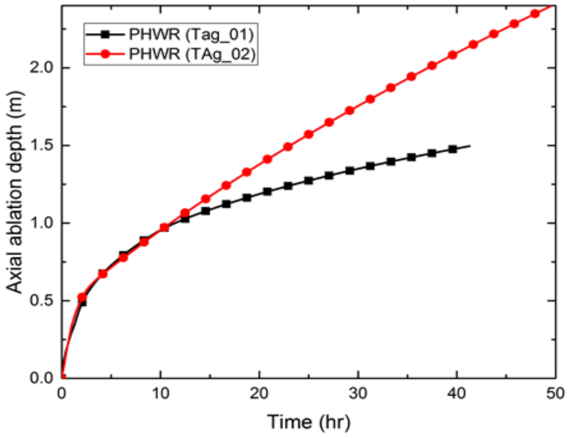

Fig 4. Axial ablation depth with concrete types

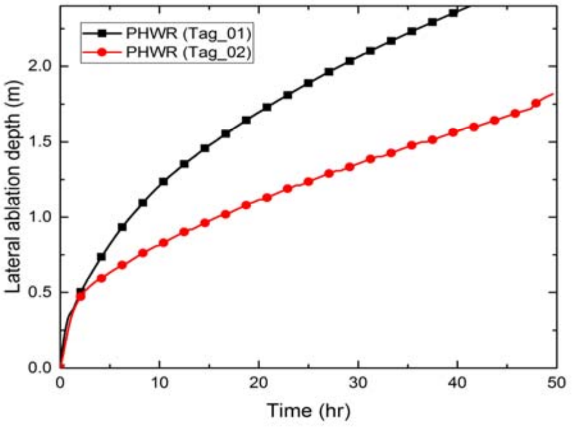

Fig 5. Lateral ablation depth with concrete types

### *3.2 Effect of corium concrete contents*

When the corium is relocated into the cavity, the molten corium concrete contents are currently not fully understood and large uncertainties exist in this aspect. Thus sensitivity analysis using the MELCOR has been carried out in the cases of various molten corium concrete contents. For a given initial condition, the corium concrete contents at the time of reactor pressure vessel failure was systematically varied over the range of 0-20 wt % in increments of 5 wt %. The corium concrete contents are specified as indicated in Table 4.

Table 4 Corium concrete contents (wt %)

| Constituent | Tag_01 | Tag_03 | Tag_04 | Tag_05 | Tag_06 |
|---|---|---|---|---|---|
| $UO_2$ | 69.00 | 64.00 | 60.00 | 56.00 | 52.00 |
| Zr | 26.00 | 25.00 | 24.00 | 23.00 | 22.00 |
| $ZrO_2$ | 5.00 | 6.00 | 6.00 | 6.00 | 6.00 |
| $SiO_2$ | 0.00 | 3.55 | 7.10 | 10.65 | 14.20 |
| CaO | 0.00 | 0.80 | 1.60 | 2.40 | 3.20 |
| $Al_2O_3$ | 0.00 | 0.60 | 1.20 | 1.80 | 2.40 |
| MgO | 0.00 | 0.05 | 0.10 | 0.15 | 0.20 |
| Total | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |

Figs. 6 and 7 show the axial and lateral ablation depth with variation of corium concrete contents for five cases. As shown in Figs. 6 and 7, the initial erosion behavior of the core melt was found to increase in the lateral direction with increasing content of concrete in the corium. Accordingly, ablation depth in the axial direction has been decreased slightly. Also, as soon as the MELCOR calculation started, the erosion of about 40 cm was rapidly occurred in the axial direction, and then the ablation rate gradually decreased. In the case of the lateral direction, it is confirmed that the erosion rate is constant from the beginning of the calculation to the end of the calculation by the basemat-melt through. The time for basemat-melt through was estimated; the shortest at about 41 hours with the optimum value (Tag_01) and the longest at about 44 hours in the corium containing the largest amount of concrete (Tag_06). This tendency could be due to decreasing amount of corium reacting with concrete as increasing the amount of concrete contained in the corium.

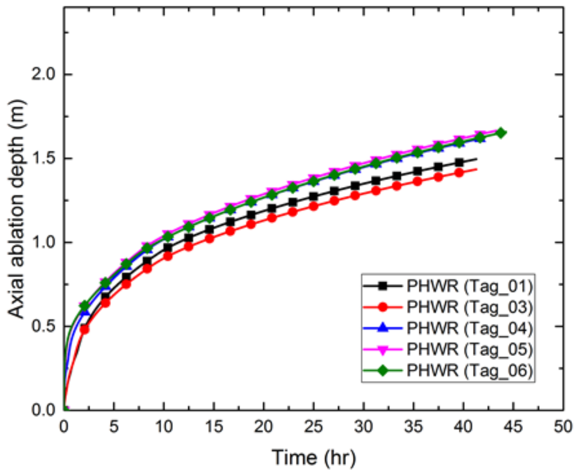

Fig. 6 Axial ablation depth with corium concrete contents

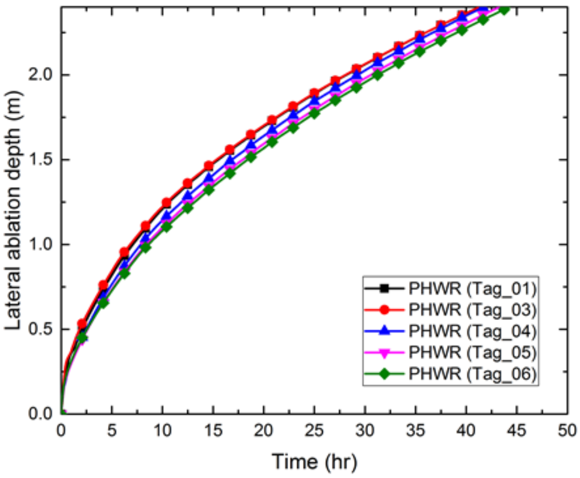

Fig. 7 Lateral ablation depth with corium concrete contents

## 4. Conclusions

In this study, the MCCI behavior of a reference PHWR with SIL concrete was predicted using severe accident code MELCOR, version 2.1. The main conclusions can be summarized as followed.

(1) As one part of the PHWR MCCI behavior analysis, the verification of the MELCOR code was performed based on the CCI-3. Using the optimum value, the MELCOR calculation result of CCI-3 test showed a reasonable agreement with experimental data.

(2) In view of concrete types, for the SIL concrete, most of the ablation was concentrated in the lateral direction. However, for the LCS concrete, the ablation was relatively uniform compared to SIL concrete. This is because the content of $SiO_2$ is more than LCS concrete. When the content of $SiO_2$ was high in the concrete, the spreading of molten corium increased due to low viscosity of $SiO_2$.

(3) In the case of the corium concrete contents, as decreasing the amount of concrete contained in the corium, the ablation depth was increased.

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