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MCCI Analysis using Newly Developed Concrete Characteristic Model in MAAP Code

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1. Introduction

Among the severe accident phenomena, the MCCI (Molten-Core Concrete Interaction) phenomenon has still been remained unresolved issue. After the vessel failure, the molten-corium poured into the cavity start to attack the cavity floor concrete because the temperature of the molten-corium is much higher than the melting point of concrete. Since the concrete may be ablated with the emission of combustible gas into containment, the threats for containment due to MCCI are classified into two cases; one is BMT (Basemat Melt-Through) by concrete ablation, and the other is containment failure by over-pressurization.

There have been so many efforts to resolve the issues for MCCI, however, the experiments for MCCI are very difficult for the high temperature and emission of combustible gases. And also, the factors affecting the MCCI are various and complex.

The concrete characteristics including the chemical composition and Liquidus-Solidus temperature profile (L-S phase diagram) are known to be the important factors for MCCI. However, it is very difficult to find the exact characteristics for the operating plants because the original component data is not easy to find and the components themselves are continuously changed with time and condition, so the uncertainty issues have always been raised.

In MAAP5.04, new parameters are introduced to be able to develop the user specific detailed L-S phase diagram. So, KHNP developed the detailed L-S phase diagram for OPR1000 type concrete through the consultation from FAI (Fauske Associates, LLC) in order to reduce the uncertainties included in the MCCI analysis. In this paper, uncertainty analysis for default L-S phase diagram have been used in MAAP was performed and the MCCI effect due to newly developed L-S phase diagram was analyzed using MAAP5.04 code.

2. Methods and Results

The code used for this analysis is MAAP 5.04, and the accident scenario is SBO (Station Black Out) without any active safety injection including Aux. Feedwater injection and without any mitigation action including external emergency coolant injection into RCS and Cavity for active progression of MCCI. The total analysis time is set to 72 hours.

2.1 Concrete Characteristics

The major concrete characteristics is consist of 2 parts in MAAP. One is the composition and another is Liquidus-Solidus Phase diagram. For the composition of concrete of domestic NPPs, the parameters had been used in the previous MAAP (MAAP4 and MAAP5) analysis was compared. In general, the compositions of all domestic NPPs are known to be similar to Basaltic concrete.

2.2 Core Concrete Phase Diagram Model and Related Uncertainty

The previous input model for the composition of the corium pool at the temperature between the solidus and liquidus line used in the MAAP code was based on the best information available at the time of 1992. As shown in Figure 1 [1], MAAP has been used the pseudo-binary phase diagram for the estimation of core- concrete oxide status.

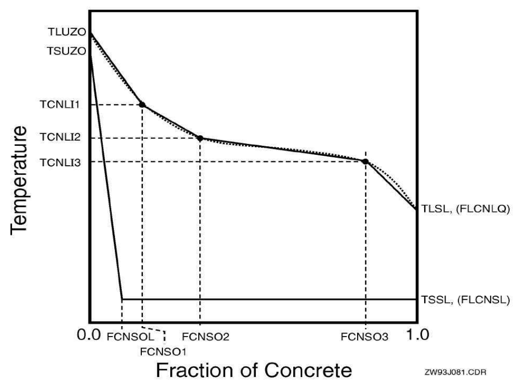

Fig 1. Pseudo-Binary Phase Diagram Model in MAAP

To investigate of effects and uncertainties for phase diagram, the uncertainty analysis for three liquidus point (FCNSO1, TCNLI1), (FCNSO2, TCNLI2), and (FCNSO3, TCNLI3) is performed. The range of FCNSO (Fraction of concrete composition) and TCNLI (temperature for FCNSO) was assumed to be uniformly distributed as ± 10% and ± 50K for Basaltic concrete MAAP5 recommendation values. The number of samples was set to 93 and sampling was performed using the Latin Hypercube sampling method.

After the sampling process, MAAP5 MCCI analysis were performed using 93 MAAP inputs with the change of sampled parameters. The uncertainty ranges for ablation depth is shown as Table 1 and Figure 2. As shown in these results, it can be judged that the uncertainty due to concrete fraction and the corresponding temperature is not so large.

Table 1: Results for Sample Sequences

Downward Erosion Depth in Cavity (M)	Mean	Min. (Sample #)	95th Percentile (Sample #)	Max. (Sample #)
	A	A-0.52 (# 84)	A+0.17 (# 66)	A+0.21 (# 22)

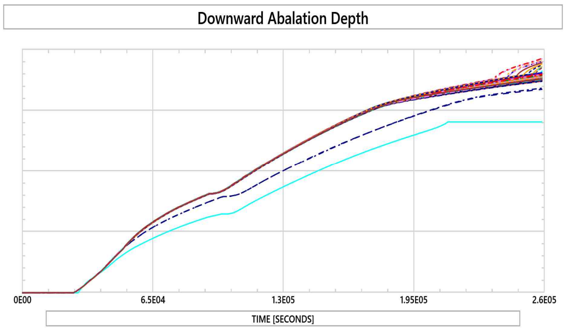

Fig 2. Uncertainty in Ablation Depth due to L-S Curve

2.3 Detailed Core Concrete Phase Diagram Development

The previously used phase diagram is good for simplicity, however, there are some problems in it such as too much conservatism. In MAAP5.04, new parameters are introduced to be able to develop the user specific detailed phase diagram.

The newly developed phase diagram by the consultation contract to FAI is based on an investigation of the concrete composition for domestic NPPs versus temperature of the corium pool using the GEMINI2 (Thermodata, 2003) code and the NUCLEA (Thermodata, 2013) database. Given a mass, temperature and pressure, GEMINI2 software minimizes the Gibbs energy in the system composition at each equilibrium phase. From this output, the total solid fraction of the system can be obtained by summing the solid mass fraction at each phase [2].

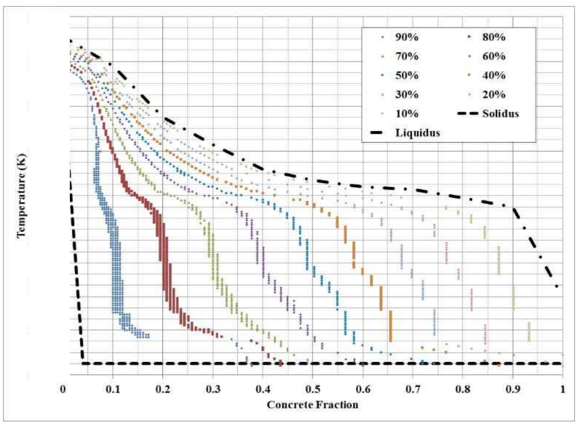

Fig 3. Newly Developed Core Concrete Phase Diagram

A temperature range from 1,000K to 3,000K. A set of 10,000 GEMINI sequences was analyzed at the various compositions and temperatures. The results of 10,000 individual GEMINI2 are reduced along a line constant solid fractions for each 10% data between the solid and liquid lines. Data is further reduced to a single data point of concrete fraction, temperature, and solid fraction for MAAP input as shown in Figure 3 and then, this data set is entered into the appropriate MAAP input variables for use in MAAP calculations.

2.4 Shape Model for MCCI

Another new feature adopted in MAAP5.04 MCCI Model is the introduction of erosion shape model. In MCCI experiments, the erosion contours generally show a curve such as the ablation depth varies with elevation or the radial distance from the centerline. In this model, the boundary coordinate set evolves with time based on the volume rate of concrete erosion, and explains the difference in the ratio of downward and sideward erosion. Two-dimensional representation allows downward and sideward movement of the angular point as shown in Figure 4 [2].

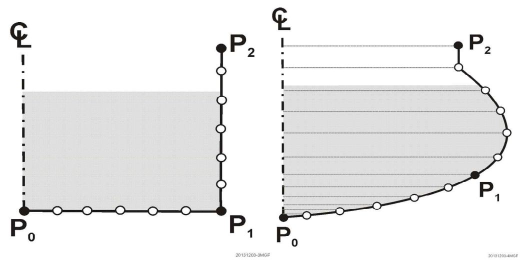

Figure 4. Shape Model Description

2.5 MCCI Analysis Results

The analysis cases are classified into 9 cases as shown in Table 2.

Table 2: Analysis Case

	Concrete Composition	L-S Curve
Case 1	W/H	MAAP4 Default
Case 2	OPR1000	MAAP4 Default
Case 3	OPR1000 rev	MAAP4 Default
Case 4	APR1400	MAAP5 Default (Limestone-Common sand)
Case 5	Newly revised OPR1000 (2019)	MAAP5 Default (Basaltic)
Case 6	Newly revised OPR1000 (2019)	Newly Developed L-S Curve
Case 7	Basaltic (MAAP5 Default)	Basaltic (MAAP5 Default)
Case 8	Limestone-Common sand (MAAP5 Default)	Limestone-Common sand (MAAP5 Default)
Case 9	Limestone (MAAP5 Default)	Limestone (MAAP5 Default)

The concrete compositions previously used in case1 ~ case 3 are little bit different due to the difference of site location. And, the concrete type for APR1400 is different one due to the design improvement for mitigation of MCCI.

The ablation depths due to MCCI for each case are shown in Figure 5. From these comparison results, we can find that the early stage of MCCI progression (before the dry-out of water in cavity) for domestic concrete is similar to that for default basaltic concrete in MAAP5. However, after the dry-out of water in cavity, there are some differences in the ablation depth. One of the reasons for these differenced is thought to be the usage of old L-S phase diagram for concrete as in the case 1, 2, and 3. From the results for case 5 and 6, the effect of application of newly developed detailed L-S phase diagram is clearly showed that the ablation depth is reduced.

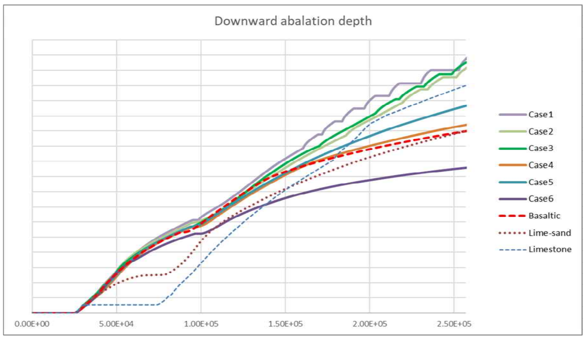

Fig 5. Comparison of Ablation Depth due to MCCI

The application of shape model is performed to only case 5 and case 6, and the results are shown in Figure 6 and Figure 7.

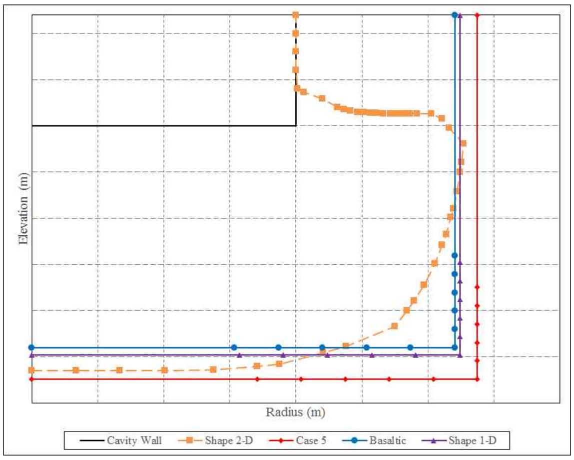

Fig 6. Results for Case 5 using Shape Model

Figure 6 shows the results of MCCI progression for case 5 using shape model. In the case 5, the specific concrete composition for OPR1000 and the default basaltic concrete phase diagram were used. The ablation depths are reduced in the case of using shape model. However, in the 2-D shape model, the ablation depth is slightly larger than the 1-D shape model.

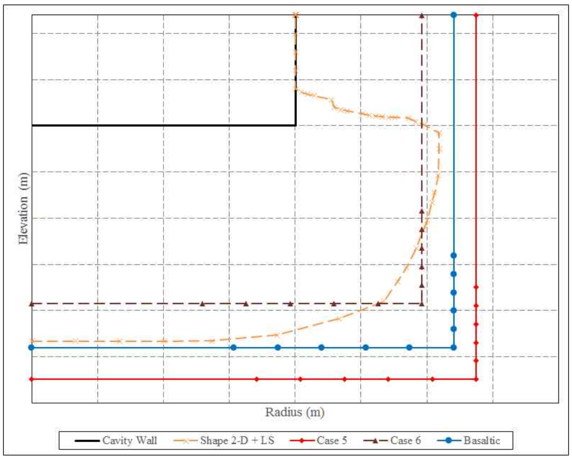

Figure 7. Results for Case 6 using Shape Model

Figure 7 shows the results of MCCI progression for case 6 using shape model. In the case 6, the specific concrete composition for OPR1000 and the newly developed L-S Phase diagram were used. The ablation depths are more reduced than that of case 5.

In case of using shape model, we can estimate the progression and shape of ablation similar to the shape founded in the CCI-2 and CCI-3 experiment.

3. Conclusions

It is known that the MCCI phenomena is the major threat to containment integrity in the late stage of severe accident progression and still remains one of the unresolved issues in the severe accident phenomenon. Recently, there have been so many efforts to find and reduce the uncertainty related MCCI.

In this analysis, we try to find the appropriate concrete characteristic model that is one of the major factors affecting MCCI progression. According to the results, the composition of concrete for domestic NPPs are slightly different from plant to plant, however, the pattern of ablation is similar to that for basaltic concrete. Actually, we can find that the major factor affecting the ablation depth is the Liquidus-Solidus phase diagram. In case of application of newly developed detailed L-S phase diagram for OPR1000 type concrete, it is found that the ablation depth is remarkably reduced. In addition, in case of application of newly introduced shape model, we can make some actual status for ablation due to MCCI.

It is judged that the more efforts in order to resolve the MCCI issues should be performed continuously for various conditions such as pre-flooding accompanied with experiments. Based on those efforts, it is expected that we can find the uncertainties included in the MCCI phenomena and effective accident management strategies to strengthen and enhance the safety of nuclear power plants can be derived.

REFERENCES

[1] MAAP5.04 User Manual: Oxide Properties, EPRI, December, 2015
[2] Hanul 5&6 Molten Corium Concrete Interaction Analysis, Rev0, FAI, May, 2019