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MCCI Analysis using Shape Model Implemented in MAAP 5.06 Code for WH-2 Loop

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1. Introduction

In the event of a severe accident causing core damage at a nuclear power plant, molten core debris, known as corium, will relocate downward and accumulate at the lower head of the reactor vessel. If adequate cooling is not available, the reactor vessel may fail, leading to the release of a large amount of molten core debris into the reactor cavity. The released corium will spread across the reactor cavity floor and erode the underlying concrete. Since the temperature of the molten core debris is significantly higher than the melting point of concrete, it induces concrete erosion. This phenomenon is referred to as Molten Core Concrete Interaction (MCCI).

MCCI can compromise the structural integrity of the containment building, potentially leading to the release of radioactive materials and threatening nuclear safety. Various factors influence MCCI, including chemical composition(L-S phase diagram) of the concrete. These are among the critical parameters affecting MCCI.

Additionally, the cooling characteristics of the corium pool are closely related to the depth of concrete erosion. Therefore, this study applies L-S phase diagram to analyze MCCI for a specific type of NPP. The concrete erosion depth was analyzed by comparing the existing model and the shape model. The nuclear power plant type used in this paper is WH-2Loop, and the analysis code used is the latest version, MAAP5.06.

2. Analysis Methodology and Results

The selected severe accident analysis scenario is LBLOCA (Large Break Loss Of Coolant Accident). The analysis considered severe accident mitigation facilities and mitigation strategies for active progression of MCCI. At the time of reactor vessel failure, the reactor cavity is in a post-flooding condition due to the characteristics of the WH-2 Loop severe accident management strategy. The total analysis duration is 72 hours.

2.1 Corium Thermal Property Evaluation

One of the key evaluations in the MCCI model is the determination of thermal properties in the corium mixture based on corium constituents and total internal energy. These properties include temperatures (corium temperature, solidus and liquidus temperatures), solid fraction, viscosity, density, thermal conductivity, and other properties. MAAP5 follows a partitioning and combining approach for property evaluation. It first partitions all the corium constituents into oxidic and metallic constituents. It then further partitions the oxidic materials into the core oxides (UO_2, ZrO_2) and concrete oxides (SiO_2, CaO, MgO, Al_2O_3, and other minor constituents). An empirical pseudo-binary phase diagram [1] in Fig 1 is used to represent the phases of the mixture of the two types of oxides. The metallic constituents are partitioned similarly into primary metal (Fe, Zr, and U) and secondary metal (Ag, In, Cd, and other minor constituents). Empirical phase diagrams are used to represent the metallic mixture phases. To determine corium temperature, it first interpolates in the phase diagrams to obtain the mass fraction of materials staying at the solid state (solid fraction). Then it calculates the internal energy for liquid and solid phases separately and combines them to get the total energy in the corium mixture. The total energy calculated in this way will not be identical to the total energy given at the specific time step. The MAAP code updates the corium temperature guess using the Newton-Raphson method until the calculated total energy converges to the given total energy. The properties of the corium mixture are then computed based on the mass fractions of the constituents, the corium temperature, and solid fraction.

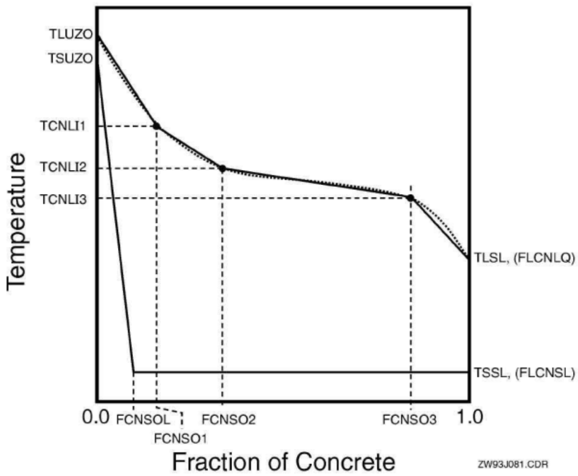


Fig 1. Pseudo-Binary Phase Diagram Model in MAAP

2.2 Shape Model for MCCI

Erosion shape contours in MCCI experiments generally show a curved contour in which the extent of downward erosion varies with radial distance from the centerline, and in which the extent of sideward erosion varies with elevation. The maximum extent of erosion in either direction is greater than the planar average extent. This means that the potential for liner or structural penetration is greater when a curved contour is considered compared to an idealized cylindrical geometry.

In this model, a set of boundary point coordinates is evolved with time based on the volume rate of concrete erosion and accounting for differences in the rates of downward and sideward erosion. A two-dimensional representation is used allowing downward (axial, z direction) and sideward (radial, r direction) movement of coordinate points.

The shape model has three main component parts:

1. Geometry of the MCCI. Given the corium volume and a current set of contour points, the model must provide the corium top surface elevation, the surface area for average downward erosion, the surface area for average sideward erosion, and the corium top surface area.
2. Rules for evolution of the eroding contour. Given the relative amounts of sideward and downward erosion, rules are prescribed to evolve the positions of the contour points.
3. Quantification of contour point motion. Given the volume of concrete eroded over a time step, find the next set of contour points using the rules for point movement and consistent with the volume of corium at the end of the time step.

The shape model is essentially a lookup table of debris volume versus height. A key function of the model is therefore to provide the debris elevation, debris surface area in contact with concrete, and debris upward facing surface area. The shape model is considered for reactor cavity modeled as a cylinder initially, as shown in Fig 2. The geometry of the shape evolving from the cylindrical cavity is discussed as the following:

2.3 Geometry in the Cavity

An example for cylindrical geometry is shown in Fig 2(a). It is necessary that this list of points includes a centerline floor point designated P_0, a point connecting the original floor with the original wall designated P_1, and a point above the maximum possible top surface of the debris along the wall, designated P_2.

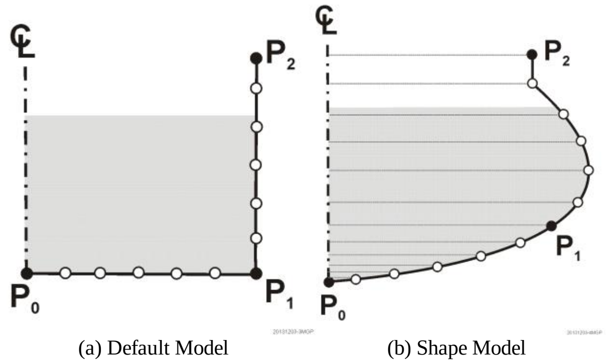


Fig 2. Shape Model Description [2]

In other words, the points must be specified so that the corium elevation will be within the specified geometry.

Referring to Fig 2(b), the contour points divide the corium into a set of axial slices. The debris volume is given by the sum of the volume of each “slice” of debris between any pair of elevations.

2.4 MAAP Evaluation Results for WH-2 Loop NPP

In this chapter, the MAAP analysis was conducted using the previously chapter described shape model. The concrete properties of the cavity used in the MAAP analysis were based on basaltic concrete characteristics reflecting the features of the Korean WH-2 Loop reactor type. The concrete thermal properties were adopted from the most recently developed data. Additionally, the heat transfer coefficient to the concrete was derived from the results of ACE tests [3] and BETA tests [4] conducted under dry cavity conditions.

Fig 3 shows the temporal evolution of the erosion depth in the side and bottom sections of the cavity. For this analysis, six reference points, were defined, and each segment between these reference points was further divided into six subpoints.

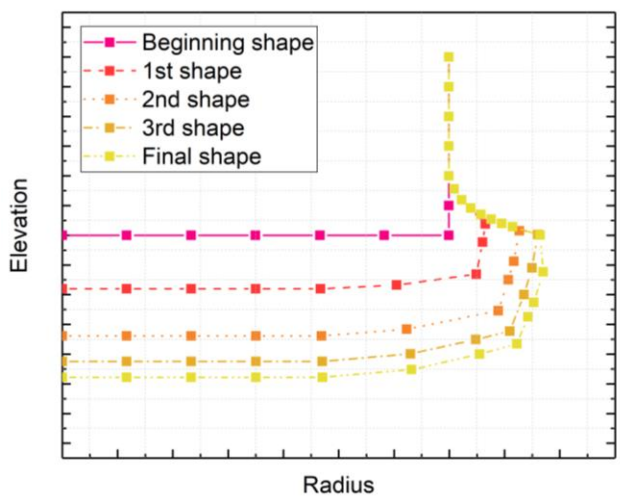
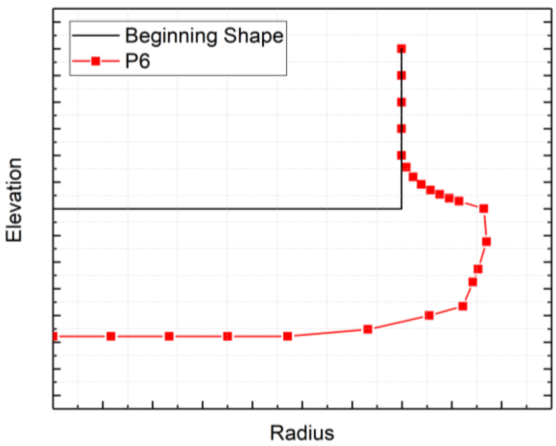


Fig 3. Erosion Depth Geometry Variation using Shape Model

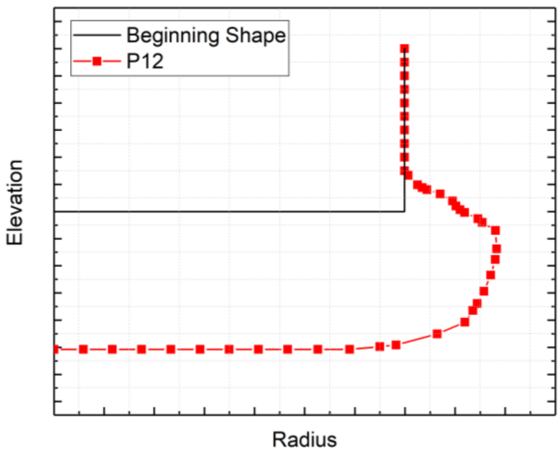
The analysis results indicate that, starting from the initial cavity configuration (beginning shape), rapid erosion occurs in both the sideward and bottom sections during the early phase. As time progresses, the erosion depth continues to increase; however, the rate of increase gradually decreases. The obtained results exhibit a shape similar to that observed in previous experimental studies [5].

Fig 4 presents the analysis results of the final erosion shape when applying six reference points and when increasing the number of reference points to twelve. As shown in Fig 4(b), the erosion shape shows a more rounded sideward erosion pattern compared to Fig 4(a), where the six reference points were used.

Fig 5 compares the erosion depth at the bottom of the cavity when applying a cylindrical default model versus the shape model. As evident from the results, the final erosion depth obtained using the default model is more conservative than that obtained using the shape model.



(a) 6 reference points



(b) 12 reference points

Fig 4. Erosion Shape Geometry Based on the Number of Plotting Points

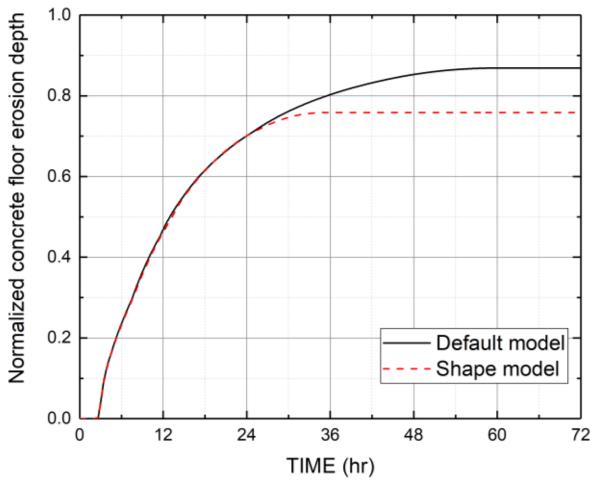


Fig 5. Normalized bottom of cavity concrete erosion depth

3. Conclusions

In this study, an analysis of concrete erosion caused by molten core-concrete interaction (MCCI) during severe accidents was conducted for the WH-2 Loop reactor using the MAAP code. To accurately evaluate the erosion of the reactor cavity floor, the thermal properties of corium and the composition of concrete are the most critical factors. Therefore, this study applied the most recently developed thermal properties and the basaltic concrete composition, which is used in the Korean WH-2 Loop reactor cavity, for the analysis.

The default geometric model for erosion depth analysis in the MAAP code is a cylindrical shape. However, when applying the default model, the erosion shape differs from the results of previous experimental studied. To address this issue, this study applied the shape model embedded in the MAAP code to analyze the time-dependent erosion depth. The results confirmed that the erosion shape predicted using the shape model closely resembled the patterns observed in previous MCCI experiments.

Additionally, a sensitivity analysis was conducted regarding the number of subdivision points in the shape model. The results indicated that as the number of subdivision points increased, the erosion pattern became smoother.

Finally, a large break loss-of-coolant accident (LBLOCA) scenario was selected to compare the erosion depths calculated using the default cylindrical erosion model and the shape model. The results demonstrated that the default cylindrical erosion model produced more conservative estimates than the shape model.

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