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MCCI Analysis under Pre-flooded Cavity Conditions during Severe Accidents

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1. Introduction

Severe accidents in nuclear power plants may lead to reactor vessel failure and relocation of molten core material (corium) into the reactor cavity. Once discharged, the molten corium interacts with the cavity coolant and concrete structures, initiating a sequence of ex-vessel phenomena. Among these, molten core–concrete interaction (MCCI) is a key process governing long-term containment integrity, as it determines concrete ablation, non-condensable gas generation, and the thermal evolution of the cavity region.

Under pre-flooded cavity conditions, water is present before vessel failure. In this scenario, falling corium first undergoes fuel–coolant interaction (FCI), which may fragment part of the corium and form a debris bed on the cavity floor. The relative amounts of fragmented debris and remaining molten corium depend on the initial water depth and jet breakup behavior. This mass distribution strongly influences subsequent MCCI progression, heat transfer characteristics, and corium coolability. In particular, at intermediate water depths, the coexistence of molten corium and a substantial coolant inventory becomes more pronounced, thereby enhancing the tendency for localized MCCI behavior beneath the debris bed.

Plant-scale evaluation of such scenarios is generally performed using integrated severe accident analysis codes based on lumped parameter approaches. However, in many conventional methodologies, either debris formation is neglected or the debris bed is assumed to spread uniformly across the cavity floor. These simplifications may limit the physical consistency of MCCI analysis under pre-flooding conditions, where the geometric configuration of the debris bed directly affects molten corium relocation and heat transfer.

The SAFARI code is currently being developed in Korea as a regulatory-grade integrated severe accident analysis tool. Within this code, a dedicated MCCI module has been developed as a core component for ex-vessel analysis. To provide physically consistent initial conditions under pre-flooded scenarios, the MCCI analysis is coupled with the FCI module, allowing the geometric characteristics of debris bed formation to be incorporated. This model enables plant-scale evaluation of corium configuration and concrete ablation behavior under pre-flooded cavity conditions.

The objective of this study is to assess MCCI behavior under representative pre-flooding severe accident scenarios using the coupled SAFARI model, and to apply the model to plant-level accident conditions in order to examine how initial cavity water depth influences long-term concrete ablation and containment response.

2. Overview of the MCCI module

The MCCI module used in this study has been developed within the SAFARI severe accident analysis code as a core component for ex-vessel progression analysis. The module is based on the lumped parameter method and solves mass and energy conservation equations for the corium pool and surrounding structures. Detailed descriptions of the model formulation and validation are provided in previous publications [1][2].

The module considers the molten corium pool, top crust, bottom crust, sidewall crust, and underlying concrete as primary nodes. Heat transfer between these regions is calculated through convective and conductive mechanisms, while thermochemical interactions between corium and concrete are incorporated to account for concrete ablation and non-condensable gas generation. Decay heat and potential corium inflow from the reactor vessel are also included in the governing equations.

In addition, the module supports both homogeneous and stratified corium configurations. The stratification model, which distinguishes metal and oxide layers, has been implemented to capture potential variations in heat transfer and ablation behavior under severe accident conditions. Validation against representative MCCI experiments has been previously performed and demonstrated reasonable agreement with measured ablation trends [1][2].

In the present study, the MCCI module serves as the primary analysis tool for evaluating concrete ablation behavior under pre-flooded cavity conditions.

3. Coupled MCCI-FCI analysis model

This section describes the coupling methodology between the MCCI and FCI modules [3] for analyzing the MCCI phenomenon that occurs sequentially after the FCI process under a pre-flooded severe accident scenario. The coupling approach can be fundamentally classified into one-way and two-way coupling schemes, and the final coupling methodology integrates both approaches.

3.1. One-way coupling

The one-way coupling (Fig. 1) constitutes the core component of the MCCI–FCI integration. In this approach, the results of the FCI module are transferred to the MCCI module as initial conditions, enabling the analysis of MCCI behavior that occurs sequentially after the FCI process. The primary role of the FCI module in the one-way coupling is to determine how the corium mass entering the cavity is distributed between the debris bed (m_{deb}) and the underlying molten corium (m_{mc}), along with the corresponding temperatures of each layer (T_{deb}, T_{mc}). In addition, the geometry of the generated debris bed is determined within the FCI module. Based on a correlation used to evaluate the debris bed slope angle, a conical geometry is assumed to determine the debris bed radius (r_{deb}). The underlying molten corium is then assumed to occupy the cavity bottom within the radius defined by the debris bed.

Several key parameters (m_{mc}, T_{mc}, r_{deb}) calculated by the FCI module are transferred to the MCCI module after 10 minutes of simulation and used as initial conditions. The 10-minute time point is selected based on the assumption that the corium discharged from the RPV has been sufficiently partitioned into debris bed and molten corium by that time. Through this procedure, the mass and energy of molten corium effectively participating in MCCI, as well as the debris bed radius required for localized MCCI analysis, are determined while accounting for the initial cavity water depth. This enables a more physically consistent analysis of the MCCI phenomenon that occurs sequentially after FCI under pre-flooding conditions.

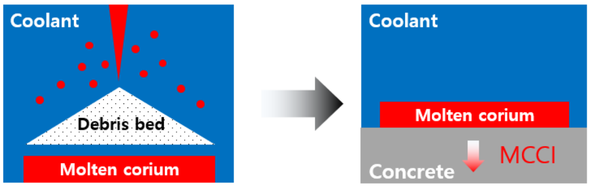

Figure 1. Schematic of MCCI with debris formation

3.2. Two-way coupling

Unlike the one-way approach, in which results are transferred only once, the two-way coupling approach involves continuous data exchange between the MCCI and FCI modules after the initial 10-minute period, which is assumed to be sufficient for the ejected corium from the reactor vessel to be stably settled on the cavity floor in the form of a molten corium pool and a debris bed. In this configuration, both modules interact at each time step. Figure 2 illustrates the physical concept of the two-way coupling, where the key aspect is the interaction between the debris bed and the underlying molten corium.

Physically, the molten corium is located beneath the debris bed. The top heat transfer generated from the molten corium influences the thermal behavior of the debris bed. In modeling heat transfer within the debris bed (Eq. 1 - $\dot{Q}_{deb}$), the concept of dry-out heat flux ($\dot{Q}_{dhf}$ – [4]) is applied to impose a limitation on heat removal. The heat flux originating from the underlying molten corium ($\dot{Q}_{mc}$) is treated as an additional internal heat source within the debris bed, effectively reducing the allowable heat removal capacity ($\dot{Q}_{lim}$ – Eq.2). Eq. 3 represents the heat transfer from all particles constituting the debris bed to the coolant.($\dot{Q}_{total}$)

Eq. 4 represents the upward heat transfer from the molten corium. In principle, the heat transfer term calculated in the MCCI module (Eq. 5) is used. However, the top heat flux from the molten corium is conservatively limited to approximately one-half of the dry-out heat flux of the debris bed. To reflect this physical interaction, debris bed calculations performed in the FCI module and molten corium calculations performed in the MCCI module are coupled through two-way data exchange.

$$\dot{Q}_{deb} = \min\left(\dot{Q}_{lim}, \dot{Q}_{total}\right) \tag{1}$$

$$\dot{Q}_{lim} = F_{dhf}\dot{Q}_{dhf} - \dot{Q}_{mc} \tag{2}$$

$$\dot{Q}_{total} = sum\left(A_{bed}h_{eff}(T_{deb} - T_{sat})\right) \tag{3}$$

$$\dot{Q}_{mc} = \min\left(\dot{Q}_t, F_{mc}\dot{Q}_{dhf}\right) \tag{4}$$

$$\dot{Q}_t = h_t A_t\left(T_c - T_{t,I}\right) \tag{5}$$

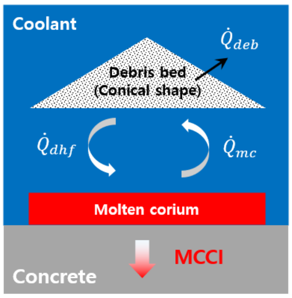

Figure 2. Schematic of the Interaction between the debris bed and molten corium

Figure 3 presents the overall MCCI–FCI coupling methodology, which combines both the one-way and two-way coupling approaches. Initially, the FCI module performs the calculation following corium relocation into the cavity. After the assumed saturation time of 10 minutes, the molten corium part of the FCI module is replaced by the MCCI module, and the MCCI calculation begins.

At the moment of this transition, the initial conditions for the MCCI module are transferred according to the one-way coupling approach. Thereafter, the calculation proceeds based on the two-way coupling scheme, in which the two modules exchange data at each time step to reflect the interaction between the debris bed and the molten corium.

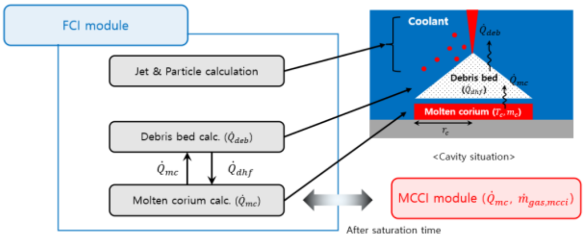

Figure 3. Schematic of the Coupling Methodology

4. Plant-scale application under pre-flooded conditions

This section describes the application of the developed coupling methodology to a pre-flooded severe accident scenario in a nuclear power plant and presents the corresponding analysis results. Since the present study does not include in-vessel analysis within its methodological development, the in-vessel calculation results used as input to the coupling framework were obtained from the MELCOR code [5].

The severe accident scenario was analyzed for a 1000 MWe class pressurized water reactor (PWR). The initial conditions and in-vessel analysis results adopted in this study are summarized in Table 1. The analysis focused solely on MCCI behavior, and variations in containment pressure and cavity water level were not taken into account.

Table 1. In-vessel conditions for actual NPP accident scenarios and calculation results of the FCI module

Category	Detailed
Core power at operation $[MWt]$	2,815
Containment volume $[m^3]$	78,395
Floor area $[m^2]$	67.6 (cylindrical cavity)
Total corium mass in RPV $[kg]$	141,000
Total corium mass entering the cavity $[kg]$	~98,000
Initial corium temp. $[K]$	3,010

4.1. Reference results

When corium is discharged from the RPV, the subsequent FCI process determines the mass distribution between the debris bed and the molten corium. The most influential parameter governing this distribution is the initial cavity water depth, which plays a critical role in severe accident management strategies. In this section, an initial cavity water depth of 2 m is selected as the reference case. Under this condition, approximately 98,000 kg of relocated corium was distributed into 57,579 kg of debris bed and 40,590 kg of molten corium. The molten corium accumulated at the cavity bottom with a radius of 2.32 m, leading to localized MCCI.

Figure 4 presents the concrete ablation depth for the reference case. To evaluate long-term cooling behavior, the analysis was performed for 72 hours. Due to the initially high temperature of the molten corium, rapid concrete ablation occurred during the early phase. As the molten corium cooled, the ablation rate decreased significantly. The final ablation depth reached approximately 119 cm. This relatively large ablation depth is attributed to the substantial amount of molten corium generated under the shallow initial water depth, which induced localized MCCI at the cavity bottom.

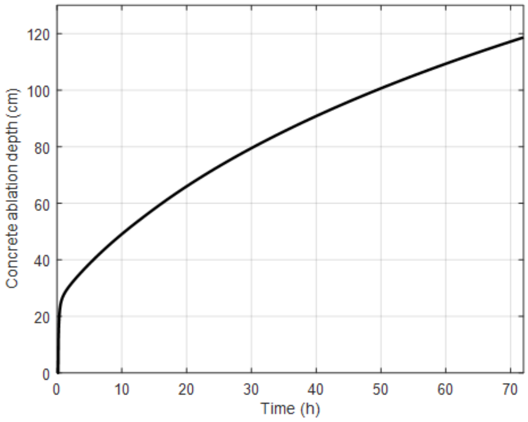

Figure 4. Concrete ablation depth for reference case

4.2. Effect of initial cavity water level

Since the initial cavity water depth plays a crucial role in determining the mass of molten corium directly participating in MCCI, it is important to examine the MCCI behavior as a function of water depth. Accordingly, additional analyses were performed for initial cavity water depths of 2 m (ref), 3 m, 4 m, and 5 m. The results were further compared with a post-flooding scenario.

In the post-flooding case, it was assumed that corium discharged from the RPV falls into a dry cavity and spreads uniformly across the cavity floor, after which an unlimited amount of water is introduced above the molten corium.

Figure 5 compares the concrete ablation depths for the pre-flooding cases with different initial cavity water depths and the post-flooding scenario. For the pre-flooding cases, the ablation depth decreases as the initial water depth increases, due to the reduced mass of molten corium available to induce MCCI. In the post-flooding case, although a larger amount of molten corium remains because no FCI-induced fragmentation occurs, the corium spreads over the entire cavity floor, preventing localized MCCI. As a result, the ablation depth is lower than that of the 2 m pre-flooding case but higher than that of the 3 m case.

These results indicate that, from the perspective of MCCI behavior, neither pre-flooding nor post-flooding strategies can be considered universally superior. Instead, the severity of MCCI under pre-flooding conditions strongly depends on the initial cavity water depth. In particular, beyond a certain water depth, pre-flooding may provide relatively more favorable outcomes in terms of concrete ablation.

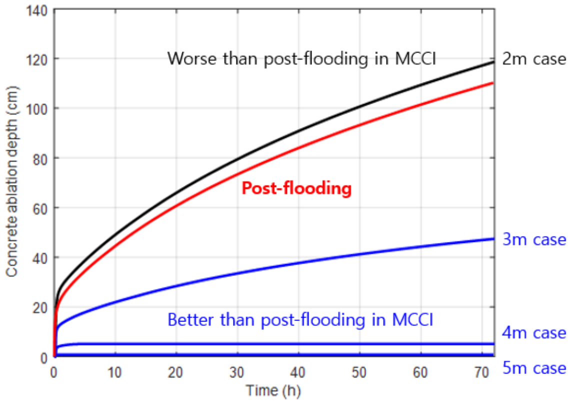

Figure 5. Concrete ablation results for pre-flooding scenarios with various initial cavity water levels and the post-flooding scenario

5. Conclusions

In this study, the MCCI module developed within the SAFARI severe accident analysis project was coupled with the FCI module to enable integrated analysis of ex-vessel phenomena under pre-flooded conditions. The proposed coupling methodology, which combines one-way and two-way coupling approaches, allows debris bed formation predicted by the FCI module to be consistently reflected in subsequent MCCI calculations, including the thermal interaction between the debris bed and the underlying molten corium. The coupled model was applied to a representative pre-flooding severe accident scenario for a 1000 MWe class pressurized water reactor (PWR) to evaluate MCCI behavior under plant-scale conditions.

Sensitivity analyses with varying initial cavity water depths (2 m–5 m) demonstrated that the mass of molten corium directly participating in MCCI strongly depends on the initial water level. As the water depth increases, the molten corium mass decreases, resulting in reduced concrete ablation. In particular, localized MCCI behavior was observed under relatively shallow water conditions, leading to larger ablation depths.

Comparison with the post-flooding scenario indicates that neither pre-flooding nor post-flooding strategies can be regarded as universally superior from the perspective of MCCI. Instead, the effectiveness of pre-flooding is highly dependent on the initial cavity water depth, and beyond a certain depth, pre-flooding may provide more favorable outcomes in terms of concrete ablation.

The present analysis focused on MCCI behavior without considering containment pressure evolution or cavity water level variation. Nevertheless, the results demonstrate that the developed coupling approach provides a useful basis for evaluating ex-vessel accident progression and supporting severe accident management strategies.

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