

Bounding and Best-Estimate Analyses of Basemat Melt-Through during a Severe Accident in a Dry Reactor Cavity with a Concrete-Embedded Steel Liner

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***Keywords : Severe Accident, Basemat melt-through, Concrete**

1. Abstract

This paper presents a comprehensive evaluation methodology for predicting the concrete ablation depth caused by Molten Core-Concrete Interaction (MCCI) in a dry reactor cavity environment composed of concrete and embedded steel plates during a severe accident in a nuclear power plant. This study combines three approaches: a conservative upper bound, an optimistic lower bound, and a realistic best estimate that predicts the most likely outcome.

For the upper and lower bound analyses, analytical solutions were applied using constant heat flux and constant temperature boundary conditions [1], respectively. For the best-estimate analysis, the MAAP5 code [2] was used.

For general limestone concrete, the time for the 90 cm thick floor concrete to ablate under dry conditions was calculated to be approximately 3.44 hours for the upper bound model and 169 hours for the lower bound model. The best-estimate result using MAAP5 was about 7.8 hours, which, as expected, fell between the two bounds, thereby validating the effectiveness of the boundary analysis methodology.

Furthermore, the analysis was extended to a composite layered structure where carbon steel is embedded beneath the concrete, using the Finite Difference Method (FDM) [3] and the MAAP5 code. This analyzed the situation where the carbon steel acts as a heat spreader. To enhance safety and accident management response capabilities, a novel concept was proposed to delay the melt-through of the lower concrete by installing a ceramic composite layer instead of single carbon steel to secure insulation performance and limit heat conduction.

The multi-faceted analysis methodology presented in this study provides effective insights for future in-depth safety evaluations, from establishing initial accident response strategies for dry cavity concrete melt-through to cost-effectively predicting extremely conservative limit analyses that exclude the effects of coolant injection.

2. Introduction

In the event of a severe accident where the reactor core melts and molten material releases outside the reactor vessel, the high-temperature melt initiates an interaction with the concrete floor of the reactor cavity,

known as MCCI. This process can erode the concrete, potentially threatening the integrity of the liner plate, which is the final containment barrier. Therefore, accurately predicting the concrete ablation depth caused by the MCCI phenomenon is crucial for evaluating containment integrity and establishing severe accident management strategies.

The actual MCCI phenomenon involves a complex combination of physical processes such as molten pool convection, decay heat, metal-vapor chemical reactions, gas generation, and phase changes. Consequently, analysis using a comprehensive severe accident code is common. While these codes include detailed physical models, they require high computational costs and complexity.

Meanwhile, in the industry, best estimate analysis using integrated analysis codes like MAAP is widely used [4]. Best estimate codes realistically simulate the entire accident progression through empirical correlations and simplified physical models based on experimental data.

Dry reactor cavity conditions could unintentionally form in domestic operating nuclear power plants that use a strategy of flooding the cavity before reactor vessel failure, if the accident response equipment fails. This condition is also planned for application in Czech Republic export plant. To effectively stop the ablation of the floor concrete under dry conditions, sufficient coolant must be supplied to the reactor cavity as quickly as possible. Therefore, predicting the rate of rapid ablation of the floor concrete in a dry state is one of the important safety evaluation tasks.

Accordingly, this study proposes a bounding analysis using two analytical solutions under specific assumed conditions and an erosion analysis using a best estimate approach that utilizes integrated physical models. Through this, we aim to perform a multi-faceted analysis from a rapid, conservative evaluation to a realistic behavior prediction, and discuss the engineering significance and complementary relationship of each methodology. Based on this, we propose a feasible design solution to mitigate molten erosion.

3. Analysis Methodology

3.1. Bounding Analysis Approach

Bounding analysis aims to predict the range in which a real phenomenon will exist by modeling the most conservative scenario (fastest ablation) and the most optimistic scenario (slowest ablation). This approach assumes a one-dimensional heat flow in the direction of the concrete floor's depth.

3.2 Upper Bound Model: Constant Heat Flux Ablation Analysis

This model is the most conservative approach for predicting the minimum time available for operators to respond. It assumes that the heat flux (q''_{mc}) from the molten material is applied directly and constantly to the concrete surface without any resistance or loss. Specifically, it treats the solid concrete below its melting point as an ideal insulator, assuming all energy reaching the surface is used solely to melt the concrete. Therefore, the results of this model are not considered a true physical outcome, as they completely ignore energy dissipation effects, and are thus not suitable for plant design or licensing. However, they provide an upper bound value that predicts the fastest hypothetical erosion rate. Unlike related experiments such as CCI-2 or MAAP5 code analysis, this paper performs the upper bound analysis by using a time-independent constant value for the interfacial heat flux.

The ablation depth at time t , $d(t)$, increases linearly with the ablation velocity (v_{abl}):

$$d(t) = v_{abl} \times (T - T_m),$$

where $v_{abl} = q''_{mc} / [\rho_c \{L + c_c(T_m - T_i)\}]$, T =temperature of concrete, T_m =melting temperature of concrete, ρ_c =concrete density, L =latent heat of fusion of concrete, c_c =specific heat of concrete, T_i = initial temperature of concrete.

3.3 Lower Bound Model: Constant Interfacial Temperature Analysis (Stefan problem)

This model sets a more optimistic "lower bound" by considering heat conduction into the solid interior, which is the most significant physical phenomenon for slowing the ablation rate.

The concrete surface in contact with the molten material is always maintained at the concrete's melting point (T_m). The thermal energy reaching the surface is divided into the latent heat used to melt the concrete and sensible heat transferred into and stored within the solid concrete below the melting point. Because the solid concrete acts as a heat sink, the energy available for ablation is reduced, slowing the rate.

The ablation depth, $d(t)$, increases proportionally to the square root of time.

$$d(t) = 2\lambda \sqrt{\alpha_c t}$$

where, α_c is thermal diffusivity of the concrete and λ is dimensionless solution of the transcendental equation for Gaussian error function [1].

$$\frac{q''_{mc} \sqrt{\pi} e^{\lambda^2} \text{erf}(\lambda)}{\rho_c c_c (T_m - T_i)} - \lambda = \frac{L \sqrt{\pi}}{c_c (T_m - T_i)} \lambda e^{\lambda^2} \text{erf}(\lambda)$$

This model shows an optimistic trend where the ablation rate gradually decreases over time, providing a 'lower bound' for the ablation rate.

3.4 Best Estimate Model: MAAP5 Code Analysis

The Best Estimate approach minimizes conservative assumptions and uses the best available physical models and correlations based on experimental data to predict accident phenomena as realistically as possible. This study selected MAAP5, a representative severe accident integrated analysis code, as the best-estimate tool [2][4].

The MAAP code uses a lumped-parameter model to analyze MCCI phenomena. This approach simplifies complex 3D phenomena while still including all key physical processes. It calculates the overall temperature of the molten pool by comprehensively considering all energy sources, including decay heat, chemical reaction heat, and heat losses to the top, bottom, and sides. Heat transfer to the lower concrete is modeled using a convective heat transfer model ($q''_{down} = h \cdot (T_{melt} - T_{conc})$). Here, the heat transfer coefficient (h) is not a simple constant but is calculated by a correlation that varies with the gas flow rate generated from concrete decomposition and the properties of the molten material (e.g., viscosity). MAPP code also considers the effects of concrete melting and mixing with the molten pool, which changes the mixture's density, viscosity, melting point, and other properties (eutectic effect). Because the MAAP code integrates various physical phenomena that were simplified in the bounding analysis models, it predicts the most likely accident progression scenario and ablation depth.

3.5 Numerical Analysis Model: Finite Difference Method (FDM)

To apply the bounding analysis models to a practical problem and analyze the composite concrete-embedded steel plate structure, this study implemented an explicit Finite Difference Method (FDM) code [3]. The FDM code fixed the Fourier number ($Fo = \alpha \Delta t / (\Delta x)^2 \leq 0.5$) at $Fo = 0.45$ to satisfy the stability condition. For analyzing composite material layers, the time step (Δt) was determined based on the material with the highest thermal diffusivity to ensure the stability of the entire calculation. The ablation phenomenon was simulated by a node removal method, where if the temperature of a surface node exceeds the melting point of that material,

the excess energy is calculated, converted into a depth, and the node is removed. This approach is also used by the MAAP5 code to analyze heat conduction phenomena within the heat sink.

4. Analysis Results

4.1 Comparison of Ablation Analysis Results for Homogeneous Concrete

The time for a 90 cm thick homogeneous Limestone concrete layer to be completely ablated was calculated and compared using all three methodologies. For the constant heat flux boundary model, a heat flux of 600 kW/m² was used, assuming that 100% of the decay heat from a 1,400 MW electric output reactor 1.5 hours after reactor trip is applied to the reactor cavity floor area of 70 m². The thermal properties of the concrete used for the calculation are listed in Table I.

Table I: Thermal Properties of LCS Concrete used in the Calculation

Parameters	Value
Density	2,500 kg/m ³
Specific heat	1,000 J/(kg*K)
Thermal conductivity	2.5 W/(m*K)
Latent heat of fusion	1,800 kJ/kg
Melting temperature	1,827 K

The change in erosion depth over time is shown in Fig. 1. For the concrete erosion depth to reach 90 cm, the upper bound model, where erosion depth is linearly proportional to time, took approximately 3.44 hours. In contrast, the lower bound model, where erosion depth is proportional to the square root of time, showed a significantly reduced erosion rate, taking approximately 169 hours. The MAAP5 best-estimate analysis result, as expected, fell between the upper and lower bounds, requiring about 7.8 hours to reach 90 cm of erosion.

In the figure, the initial MAAP5 erosion is predicted to be even slower than the lower bound. This is because a small amount of coolant is initially present in the reactor cavity during the time when all the molten material in the lower reactor vessel plenum is being relocated to the reactor cavity, which limits concrete erosion. After this initial coolant evaporates over about 0.5 hours, the erosion rate (the slope of the curve in Fig. 1) becomes nearly as fast as the upper bound model, and over the long term, the erosion depth is predicted to follow a curve proportional to the square root of time. Additionally, the calculation results from the developed FDM code are shown, which exactly match the analytical solution.

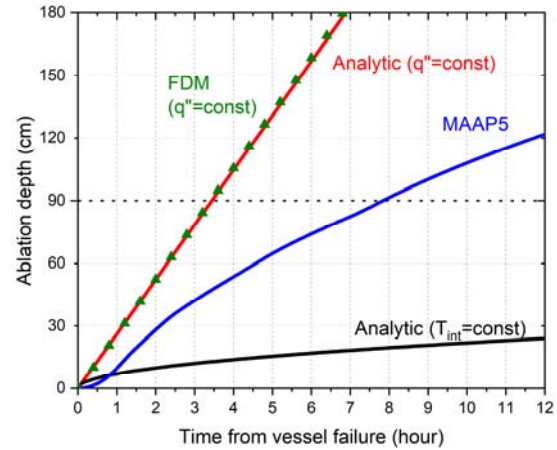


Fig. 1. Erosion depth of a homogeneous concrete layer according to the upper and lower bound models and the MAAP5 best-estimate model in a dry cavity. The triangle symbol represents the FDM analysis result for the upper bound model.

The erosion depth of the bounding models can change based on the concrete properties used in Table I and the applied heat flux. The effect of changes in density, specific heat, latent heat of fusion, and amount of heat flux on erosion depth is shown in Fig. 2. The heat flux applied to the boundary has the greatest influence on erosion depth, while the effects of specific heat and latent heat of fusion are negligible. The change in density showed a minor effect.

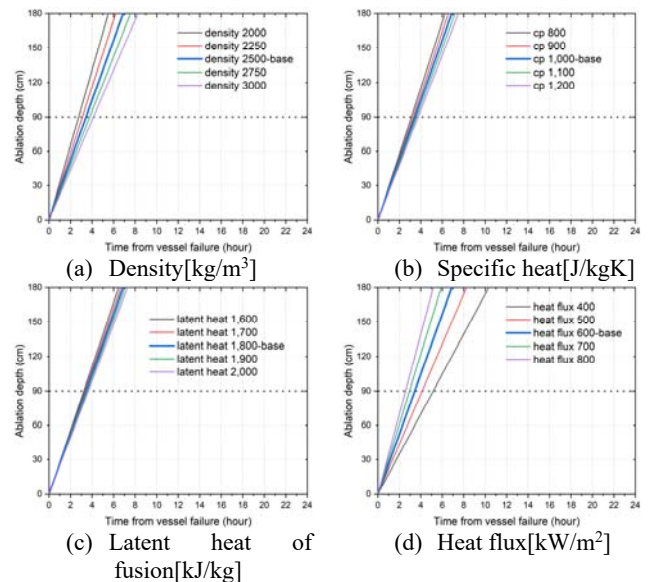


Fig. 2. Effects of concrete density, specific heat, latent heat of fusion, and applied interfacial heat flux on the upper bound model in a dry cavity.

In the constant temperature boundary problem, the heat flux ($q''_{\text{down}}(t)$) into the solid concrete as the ablation boundary moves is expressed by Fourier's law of conduction.

$$q''_{down}(t) = k_c(T_m - T_{int}) \frac{e^{-\lambda^2}}{\sqrt{\pi \alpha t} \text{erfc}(\lambda)}$$

The downward heat flux applied at the boundary in all three methods is compared in Fig. 3. The figure confirms the conservativeness of the constant heat flux boundary model and validates that the downward heat flux calculated by the MAAP5 code shows a reasonable trend.

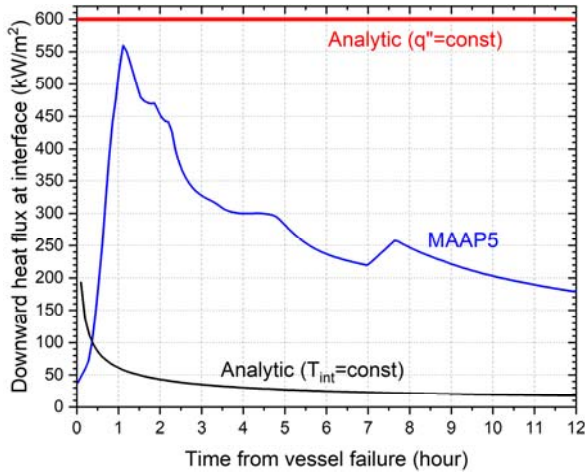


Fig. 3. Comparison of downward heat flux - The boundary heat flux used in the upper and lower bound analyses and the transient heat flux derived from MAAP5.

4.2 Extended Scenario: FDM and MAAP5 Analysis for a Concrete-Embedded Steel Plate Composite Layer

To increase the realism of the severe accident scenario, an analysis was performed on a composite layer consisting of 90 cm of concrete with a 6 mm thick carbon steel plate embedded beneath it. Since it is difficult to obtain analytical solutions for such a complex layered structure, the FDM code with the upper bound assumption and the MAAP5 best-estimate code were used. As a reference, the developed FDM code was validated by comparing its results to the analytical solution for the single concrete material shown in Fig. 1.

Before the FDM calculation, a rough prediction of the carbon steel melting reaction was performed. Given that the temperature difference between the surface and the interior of the carbon steel is expected to be at least 1,000 K, the Biot number of the carbon steel under a 600 kW/m² heat flux is $Bi=0.04$ (h = heat flux/temperature difference $\approx 600,000/1,000 = 600$ W/(m²K), $Bi = 600 \times 0.003/45 = 0.04$). Therefore, the lumped capacitance method can be applied. Based on the properties in Table II, the total energy required to melt a unit area of 6 mm thick carbon steel starting from an initial temperature of 323 K is approximately 46 MJ/m² ($[490 \times (1773-323) + 270,000] \times (7850 \times 0.006) = 46.18$ MJ/m²). At a heat flux of 600 kW/m², it

is calculated that all the carbon steel would melt in about 77 seconds. Considering heat conduction loss to surrounding materials, it is expected that the carbon steel would fully melt in a short time of just a few minutes. In other words, from a heat transfer perspective, the carbon steel acts only as a heat spreading layer, not a heat shield.

Table II: Thermal Properties of carbon steel used in the Calculation

Parameters	Value
Density	7,850 kg/m ³
Specific heat	490 J/(kg*K)
Thermal conductivity	45 W/(m*K)
Latent heat of fusion	270 kJ/kg
Melting temperature	1,773 K

The FDM code predicted the melting of the 6 mm carbon steel to be completed in approximately 36 seconds. The MAAP5 analysis predicted 233 seconds, which is likely due to heat dissipation to surrounding materials and the slightly reduced heat flux compared to the FDM conditions. This means the carbon steel plate melts in a short period of less than 4 minutes.

4.3 Future Research Proposal for Enhanced Safety: Considering a Concrete-Ceramic Insulating Layer-Embedded Steel Plate Composite Layer

In a dry cavity state, a sufficient amount of coolant must be supplied as soon as possible after reactor vessel failure to remove a significant amount of heat. However, from a safety design perspective, it is advantageous to introduce a measure that can delay the ablation of the dry floor as much as possible, assuming a situation where coolants supply is delayed. As analyzed in the previous section, the current embedded carbon steel acts only as a heat spreading layer. Safety can be enhanced by utilizing materials that can secure an insulating effect even under accident conditions. In addition to insulation, a key consideration is to prevent the concrete located below the insulating material from melting first and causing structural instability.

With these two conflicting requirements, this paper proposes practical target values for a ceramic material and thickness: a target delay time of 1 hour for the insulating layer to melt, while simultaneously preventing the premature melting of the concrete underneath. To maximize the insulating effect, a multi-layered structure can be assumed, with an upper ceramic layer for insulation and a lower layer with a very low thermal conductivity, such as Calcium Silicate, which has numerous micro-pores, to prevent the underlying concrete from melting first. However, under a constant heat flux boundary condition, ablation due to the overall heat applied is inevitable. Therefore, a time-dependent heat source (like the MAAP5 data in Fig. 3) or convective heat transfer conditions within the molten

corium would have to be applied. A detailed evaluation to determine the appropriate materials and thickness by applying these conditions to the FDM and MAAP5 codes is currently underway.

5. Discussion

This study analyzed the MCCI phenomenon from multiple perspectives using three different levels of models. The bounding analysis results showed an approximately 50-times difference in time between the upper and lower bound models, which clearly demonstrates that the heat sink role of solid concrete is a crucial variable in determining the ablation rate.

The results from the MAAP5 best-estimate code fell between the two bounds, showing a behavior that partially incorporates both the conservativeness of the upper bound and the realism of the lower bound. This suggests that bounding analysis can be a very useful cross-validation tool for quickly grasping the scope of the entire phenomenon before running complex codes and for reviewing the plausibility of best-estimate results.

The upper bound model, while overly conservative on its own, provides critical information on the 'minimum time' available for operators to take action in terms of accident management. Conversely, the lower bound model illustrates the physical phenomena that govern long-term behavior, and a best-estimate code like MAAP5 synthesizes all these effects to present the most realistic change in erosion depth. The analysis results from the MAAP5 code further refined the physical behavior (firewall and heat spreading plate effects) predicted by FDM, highlighting the importance of best-estimate codes for MCCI analysis of structures with complex material compositions.

6. Conclusion

This study presented a comprehensive framework for evaluating concrete melt-through phenomena in a dry reactor cavity by combining bounding analysis and best-estimate methodologies.

The upper bound model (constant heat flux) is a useful, fast, and conservative tool for predicting the minimum time for accident response.

The lower bound model (constant interfacial temperature) considers the effect of heat conduction into the concrete, providing a more optimistic lower limit for long-term ablation behavior.

The best-estimate model (MAAP5) integrates various physical phenomena such as decay heat, chemical reactions, and convection to predict the most likely and realistic accident scenario.

By using all three methodologies together, it's possible to set a predictive range for a specific scenario (bounding analysis), pinpoint the most likely outcome within that range (best estimate), and increase the confidence in the results.

FDM was confirmed to be an effective preliminary evaluation tool for extending the bounding analysis model to complex problems like composite layers and for detailed design purposes, requiring less effort and cost.

This multi-faceted analysis approach is expected to contribute to effectively evaluating MCCI phenomena and establishing severe accident management strategies for various purposes, from rapid initial decision-making to in-depth regulatory verification. Finally, as a future research topic, the development of a composite layer with ceramic-based materials is underway to enhance safety and provide additional time for operator actions during accident management.

ACKNOWLEDGEMENTS

This work was supported by Korea Institute of Energy Technology Evaluation and Planning(KETEP) grant funded by the Korea government(MOTIE) (No. 20224B10100130).

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