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Analysis of In-Vessel Cooling Effects of Gap Cooling Models in MAAP 5.06 Code

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1. Introduction

In the event of a severe accident in a nuclear power plant, core degradation leads to the relocation of molten fuel and structural materials to the lower plenum. During this process, a narrow gap may form between the relocated molten core materials and the intact reactor vessel wall, referred to as the gap region. Gap cooling denotes the phenomenon in which coolant typically from reactor coolant system depressurization or emergency reflooding penetrates this narrow gap and removes heat from the vessel wall through nucleate or film boiling.

This mechanism plays a significant role in mitigating the thermal load on the reactor pressure vessel (RPV) wall and can potentially delay or even prevent vessel failure during the in-vessel retention (IVR) phase. The effectiveness of gap cooling is influenced by several factors, including the gap width, coolant flooding rate, debris configuration, and boiling heat transfer characteristics within the constrained geometry.

Understanding gap cooling is critical for evaluating in-vessel retention strategies and for developing accurate severe accident models. Numerous experimental studies and numerical simulations have been conducted to investigate the heat transfer characteristics and two-phase flow behavior in the narrow annular gap, with results indicating that enhanced cooling within this region can significantly improve the integrity of the vessel during core melt progression.

2. Analysis Methodology and Results

2.1 Cooling of the RPV Lower Head by Gap Water

During the TMI-2 accident, molten core material relocated into the lower plenum, causing a localized increase in the reactor pressure vessel (RPV) wall temperature to approximately 1100 °C over a region with an estimated diameter of about 1 m. Following this rapid temperature escalation, the vessel wall exhibited comparatively fast cooling behavior. A plausible mechanism for this accelerated cooling is the limited material creep occurring in the vessel wall under such elevated temperatures. A modeling approach to represent this cooling phenomenon is described below.

When the steel vessel wall is heated to temperatures at which significant creep deformation is anticipated, a gap may form between the wall and the adjacent core material (Figure 1). This is particularly likely if the relocated debris is not firmly adhered to the RPV wall. Experimental evidence [1] involving molten aluminum oxide and molten steel indicates that molten material passing through water does not adhere well to a steel surface. The formation of contact resistance in such cases can be attributed to the vaporization of water trapped within surface cavities, as illustrated in Figure 2.

The development of significant contact resistance was observed in Electric Power Research Institute (EPRI) sponsored experiments investigating the behavior of lower head penetrations submerged in high-temperature molten material. Under similar conditions in an actual reactor system, relative motion between the vessel wall and the heat-generating material would be expected when the RPV wall undergoes creep.

A key technical question concerns the magnitude of the gap required to allow sufficient water ingress for effective cooling of the vessel wall, thereby halting further creep progression. The MAAP [2] creep rupture model represents material creep using a fractional approach to rupture at each time step; therefore, this fractional parameter must be related directly to the strain induced by creep deformation.

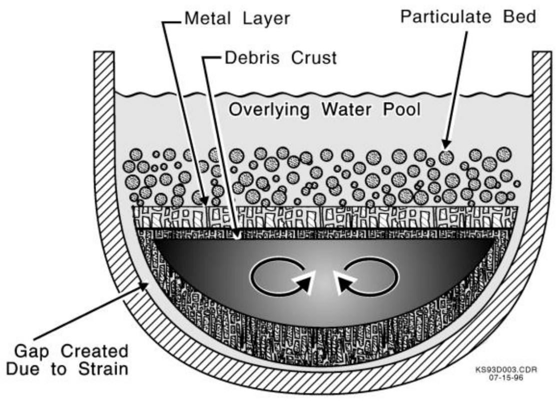

Fig 1. Quenching by Water Ingression to Debris Bed

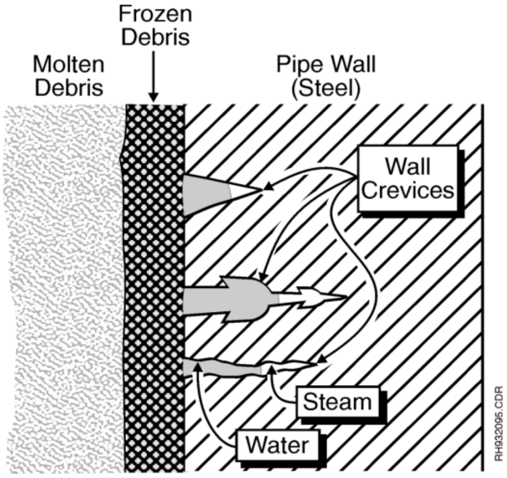

Fig 2. Schematic of Gap Created Between the Core Debris and the RPV Wall by Strain (Growth) of the Wall

2.2 Gap Cooling Models in MAAP

A gap may form between the crust of the oxidic pool and the reactor vessel wall either initially or as a result of vessel wall creep at elevated temperatures. This gap enhances the effectiveness of in-vessel injection cooling of the core debris. The ability of gap cooling to mitigate vessel wall heat-up depends on the amount of corium present in the lower plenum.

In earlier versions of MAAP5, the gap cooling model estimated the gap thickness from the damage fraction determined by the creep rupture model, and calculated the critical heat flux (CHF) in the gap using the correlation developed by Monde [3]. This correlation model assumes a rectangular channel open to a water pool at both the top and bottom ends. More recent experimental findings and improved understanding of CHF have led to the inclusion of two additional correlation models in MAAP5.03: the FAI [4] and Okano [5] correlation models.

All available gap cooling correlations in MAAP are implemented with the assumption that the water penetration depth in the gap is limited by the Counter-Current Flooding Limitation (CCFL) at the upper end of the gap. The Monde et al. correlation limits the CHF according to the gap size at the top surface of the oxidic debris pool. The correlations by FAI and Okano et al. also base the CHF calculation on the gap size at the top surface, but further limit it according to the gap size at each node below the top node. As a result of these implementations, the code is capable of predicting the formation of a dryout front beneath which water penetration does not occur.

2.3 MAAP Evaluation Results for APR1400 NPP

In this chapter, the heat transfer from the debris crust to the RPV wall was calculated using MAAP for three gap cooling correlation models Monde, FAI, and

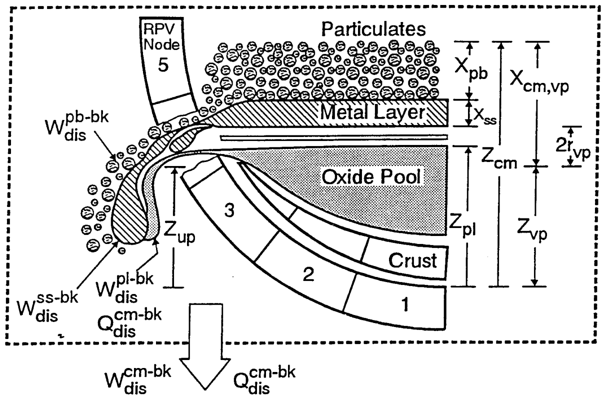

Fig 3. Schematic of debris layer configuration and RPV wall nodalization

Okano. The severe accident scenario considered was a large-break loss-of-coolant accident (LLOCA), and the calculation time covered the period from the initial event occurrence to RPV failure. In MAAP, as illustrated in Fig. 3, the debris bed is modeled as three distinct layers (corium pool, metal layer, and particulate bed), while the RPV wall is divided into 25 nodes for analysis.

For the Monde correlation model, the heat transfer rate at each node is shown in Fig. 4. The lowest heat transfer was observed at Node 1 (the lowest node), with the rate increasing toward the upper nodes. The maximum heat transfer occurred at Node 12, after which the values gradually decreased. The variation in heat transfer among nodes is attributed to the differences in layer-specific heat transfer calculated in MAAP, as well as the influence of gap cooling, which depends on the crust thickness. In particular, the presence of the metal layer at Node 12 results in the highest wall heat transfer.

The results for the FAI and Okano correlation models are presented in Figs. 5 and 6, respectively. While the overall trends are similar to those of the Monde correlation model, node-by-node variations were observed. All three correlation models showed the highest heat transfer at Node 12, where RPV failure also occurred.

A comparison of the three analyses, shown in Fig. 7, reveals node-dependent differences in heat transfer. When summing the total heat transferred to the RPV wall, the Okano correlation model yielded the highest value, followed by Monde and FAI, in that order. The difference between the Okano and Monde correlation models was relatively small, leading to RPV creep rupture at Node 12 at similar times. In contrast, the FAI correlation model, which produced the lowest total heat transfer, predicted the latest failure at the same node.

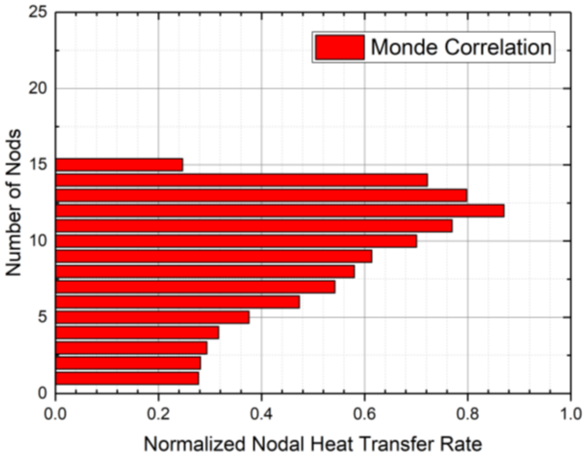

Fig 4. Node-wise normalized heat transfer from debris crust to RPV wall (Monde)

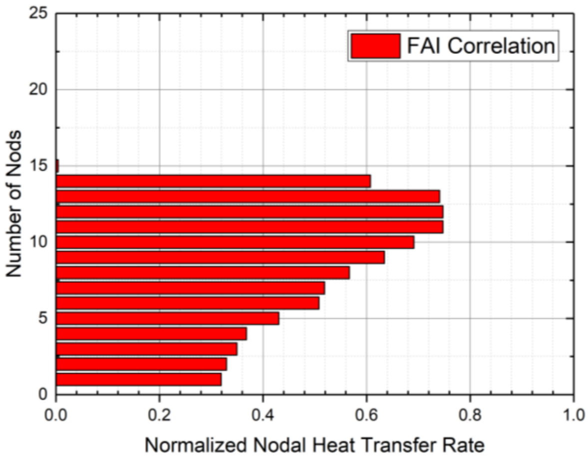

Fig 5. Node-wise normalized heat transfer from debris crust to RPV wall (FAI)

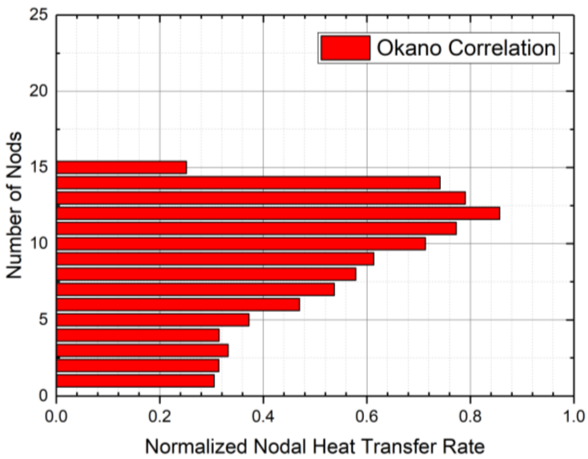

Fig 6. Node-wise normalized heat transfer from debris crust to RPV wall (Okano)

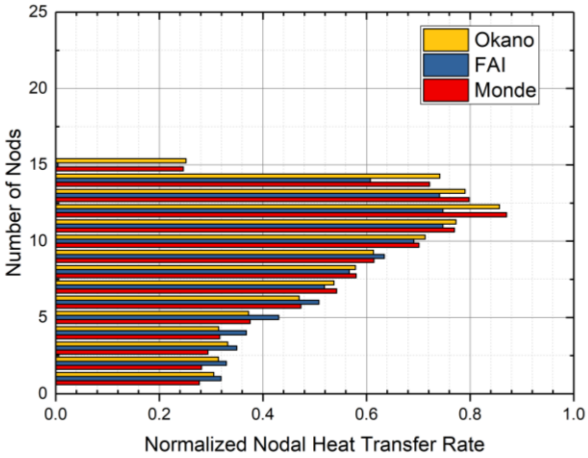

Fig 7. Comparison of normalized node-wise heat transfer from debris to RPV wall

3. Conclusions

This study examined the mechanism of creep-induced gap formation observed in the TMI-2 accident and reviewed the gap cooling models implemented in MAAP. Thermal-hydraulic analyses were performed for three correlation models Monde, FAI, and Okano under a large loss-of-coolant accident (LLOCA) scenario, covering the period from the onset of the event to reactor pressure vessel (RPV) failure.

In the MAAP calculations, the debris was modeled as three layers corium pool, metal layer, and particulate bed while the RPV wall was discretized into 25 nodes. The results from the Monde correlation model showed that the lowest heat transfer rate occurred at the bottom node (Node 1) and gradually increased toward the upper nodes, peaking at Node 12 before decreasing. This distribution was attributed to the differences in heat transfer among debris layers and the influence of gap cooling depending on crust thickness, with the metal layer at Node 12 delivering the highest heat transfer to the wall.

The FAI and Okano correlation models exhibited similar overall trends to the Monde correlation model but with variations in the magnitude and distribution of heat transfer across nodes. In all three correlation models, the maximum heat transfer occurred at Node 12, where RPV failure was also observed. Comparison of the total heat transfer to the RPV wall showed that the Okano correlation model produced the highest value, followed by Monde and FAI. The total heat transfer predicted by the Okano and Monde correlation models was comparable, leading to similar creep rupture timing at Node 12, whereas the lower heat transfer predicted by the FAI correlation model resulted in a delayed failure at the same location.

These results indicate that the choice of correlation model in MAAP gap cooling analysis directly influences the predicted timing of RPV failure and the distribution of heat transfer, particularly in regions containing a metal layer.

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