*Transactions of the Korean Nuclear Society Autumn Meeting*
*Gyeongju, Korea, October 26-27, 2023*

# Core Material Interaction Effects in the MELCOR Code During a Station Blackout

Jaegu Lee, Juhyeok Choi, Dohyun Lim, Chanwoo Park, Minseop Song and Moosung Jae*
*Department of Nuclear Engineering, Hanyang University, Seoul, Republic of Korea.*
**Corresponding author: jae@hanyang.ac.kr*

***Keywords : Eutectics, Severe Accident, Core Material Interactions, Core Degradation**

## 1. Introduction

In a severe accident, the core degradation process is an important factor for the accident progression analysis. Recently, efforts have been made to enhance the consideration of material interactions in severe accident modeling. The degradation of the core could be affected by interactions among core materials. Within the core, a eutectic mixture of uranium dioxide ($UO_2$) and zirconium dioxide ($ZrO_2$) can melt at lower temperatures compared to the individual melting points of $UO_2$ and $ZrO_2$. Various accident phenomena have been observed, taking into account core degradation parameters such as degradation time, temperature behavior, debris volume, and hydrogen generation. These observations were made while considering the eutectic melting of $UO_2$ and $ZrO_2$ in a hypothetical station blackout (SBO) scenario. This study aims to effectively incorporate the insights gained from the U.S. state-of-the-art reactor consequence analysis (SOARCA) project into the MELCOR models used in Korean nuclear power plants.

## 2. Technical Background

MELCOR is a fully integrated, engineering-level computer code whose primary purpose is to model the progression of accidents in light water reactor nuclear power plants. A broad spectrum of severe accident phenomena in light water reactors (LWRs) is treated in the MELCOR in a unified framework [1].

In this study, the MELCOR code was used to model the eutectic melting phenomenon to take into account the core material interaction between uranium dioxide ($UO_2$) and zirconium dioxide ($ZrO_2$) by simulating a SBO accident scenario. The melting points of core materials could vary based on the composition of $ZrO_2$ and $UO_2$, with approximate melting points of 3000K and 3100K. The melting point of zirconium (Zr) before oxidation is 2150K approximately.

First, the material interaction for $UO_2$ and $ZrO_2$ was analyzed using the MELCOR eutectic model as incorporated in the MELCOR 2.2. An effective temperature of 2479K to form the eutectic was adopted from the mean value of the VERCOS test results [2]. However, it does not necessarily mean that the eutectic or the interaction model has lower melting points for all locations than the other case because the eutectic melting points vary according to the composition of the eutectic materials. In this model, the melting temperature of intact material uses its elemental melting point, while the conglomerate uses eutectic temperature following the composition ratio.

In addition, an alternative approach to material interactions was analyzed to compare the results, involving modifications to the interactive material temperatures (MELCOR variables - UO2-INT, ZrO2-INT) based on the VERCOS test results as well. In the alternative approach, the liquefaction temperature of the $UO_2$ and $ZrO_2$ was adjusted to simulate the eutectic melting phenomenon between $UO_2$ and $ZrO_2$ for the early failure of fuel rods.

The results of the two analyses above were compared with the base case analysis, which did not consider the eutectic melting for $UO_2$ and $ZrO_2$. The results obtained from the approaches for the material interaction were compared with the results of the based case analysis.

## 3. Analysis Results

In this study, the material interaction models were incorporated into the MELCOR analysis, and the base case was analyzed without the interaction model. The analyses were performed with an unmitigated SBO event scenario. The general accident sequences for the analysis cases are summarized in Table 1. From the results, it is found that the interaction models have an impact on the progression of in-vessel accidents resulting in a slight delay in the timing of the reactor vessel failure.

Table 1. SBO Accident Sequence Summary

| Accident Sequence | Base Model (sec) | Interactive Material Model (sec) | Eutectic Model (sec) |
|---|---|---|---|
| SBO / Rx Trip | 0 | 0 | 0 |
| PSV First Opening | 3906 | 3906 | 3906 |
| CET 922K | 6976 | 6976 | 6976 |
| RV Breach | 15936 | 16413 | 16674 |
| SIT Injection | 16027 | 16503 | 16767 |

Regarding the progression of core degradation, as presented in Figure 1, it is evident that the material interaction among core components accelerates the onset of core degradation during its initial phase. However, as the core degradation process advances to its later stages, deceleration becomes evident for the eutectic model, leading to a more protracted completion time compared to the base case scenario. As shown in Figure 2 and Figure 3, the interaction models exhibit higher temperatures of cladding and fuel than the base model. Notably, in the eutectic model, the fuel temperatures develop rapidly compared to the cladding temperatures, whereas the base model and interactive material model present with the same temperature profiles for both cladding and fuel.

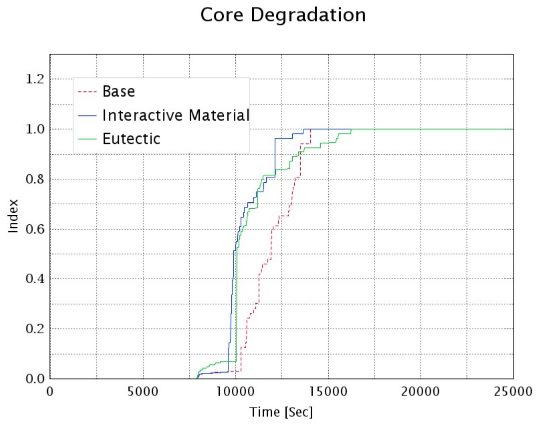

Figure 1. Core degradation index

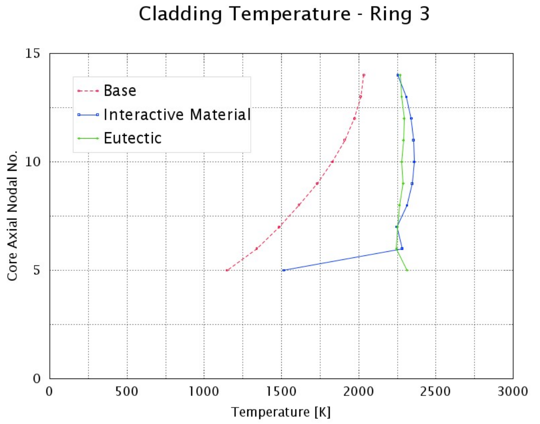

Figure 2. Cladding Temperatures at 2.5 hour (Ring 3)

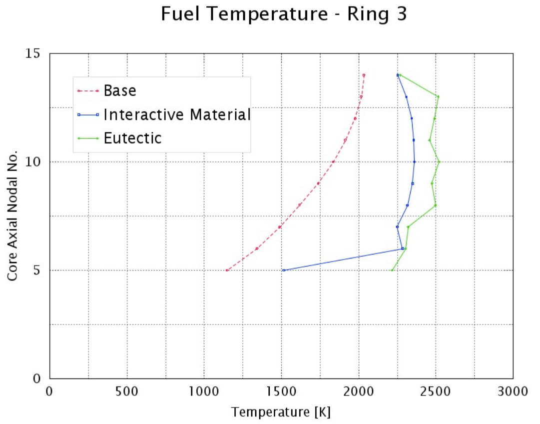

Figure 3. Fuel Temperatures at 2.5 hour (Ring 3)

In the MELCOR, after core components collapse, the materials that composed them are treated as particulate debris. Intact components are converted to particulate debris whenever that component's support is lost [1]. As illustrated in Figure 4, the degradation of the base case results in a large amount of particulate debris, while the interaction models exhibit the oxidic and metallic molten pools, indicating a different process of core degradation.

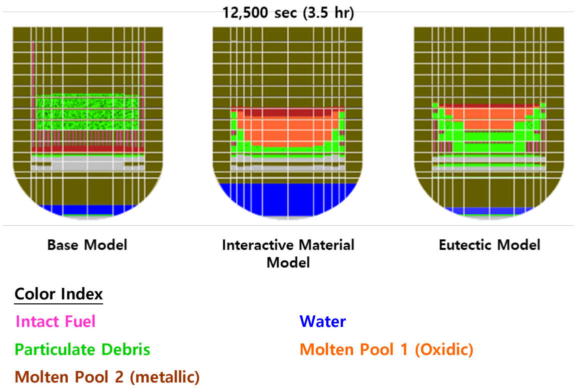

Figure 4. Core degradation status at 3.5 hours

In the context of hydrogen generation within the reactor core, Figure 5 shows that more hydrogen generation is observed during the initial phase of core degradation. Conversely, a marginal reduction in the magnitude of hydrogen production is observed during the later stages of core degradation when material interaction is considered.

In the interaction models, the core degradation occurs more actively in the early phase with higher temperatures than that of the base case, leading to more active hydrogen generation from zirconium (Zr) structures. This process is a dominant reaction in terms of the amount of hydrogen generation. However, during the late phase of core degradation, more hydrogen is generated from stainless steel (SS) structures in the base case than in the interaction models because these structures remain intact longer in the interaction models as shown in Figure 6.

In the base model without the material interaction, most core support structures fail before vessel breach. In contrast, more core support structures remain intact until the point of vessel breach in the interaction models, failing and releasing afterward. A similar behavior in hydrogen generation is also observed in the oxidation process of zirconium. The $ZrO_2$ masses in core are presented in Figure 7, showing greater oxidation amounts of zirconium in the interaction models than in the base case due to the higher core temperatures during the early phase of the core degradation.

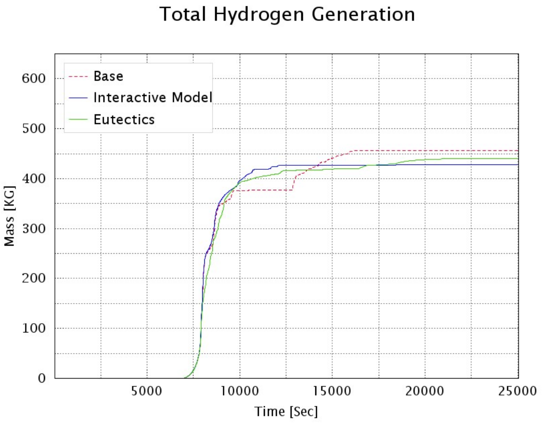

Figure 5. Total $H_2$ generation mass

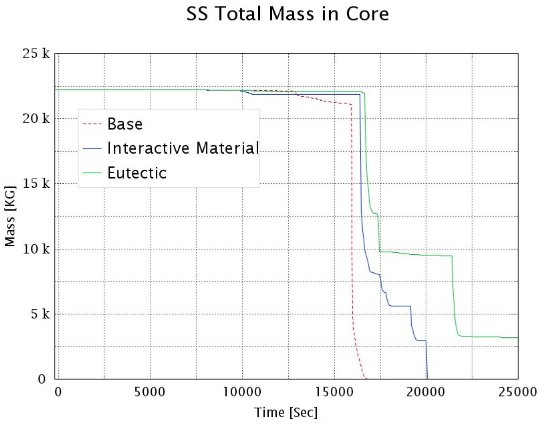

Figure 6. Stainless steel (SS) total mass in core

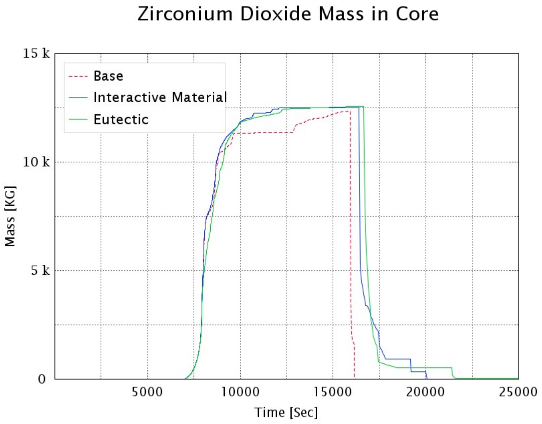

Figure 7. $ZrO_2$ mass in core

When the reactor vessel fails, most of the debris is ejected. With respect to the molten debris ejection process, all models demonstrate significant amounts of debris release as shown in Figure 8. In the base case, the ejection involves the majority of the debris. However, in the interaction models, the ejection process exhibits a gradual decrease in ejection rate, leading to a longer release duration.

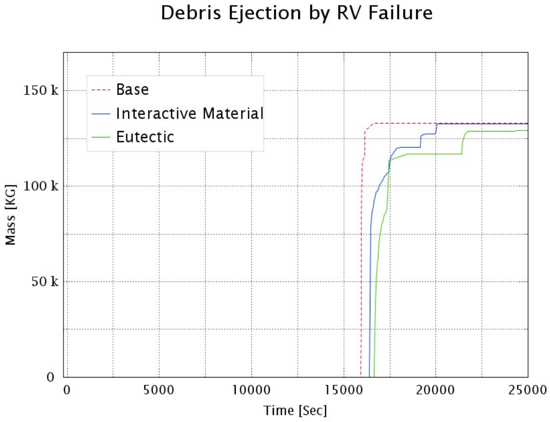

Figure 8. Debris ejection mass

## 8. Conclusion

In this study, a SBO induced severe accident was analyzed by incorporating the core material interaction models between uranium dioxide ($UO_2$) and zirconium dioxide ($ZrO_2$). The analysis results indicate the different core degradation processes depending on the modeling approaches of the core components' material interaction. According to the results of this study, it is evident that the core material interaction certainly impacts the progression of in-vessel accidents, including the overall core degradation process and its rate as per the degradation stages, and the timing of vessel breach.

## Acknowledgments

This work was supported by the Nuclear Safety Research Program through the Korea Foundation Of Nuclear Safety (KOFONS Grant No. 2101052), Republic of Korea

## REFERENCES

[1] L.L. Humphries, et al., "MELCOR Computer Code Manuals Vol 1: Primer and Users' Guide, Version 2.2.14959" SAND2019-12536, Sandia National Laboratories, Albuquerque, NM., 2019.

[2] S. Tina Ghosh, "State-of-the-Art Reactor Consequence Analyses Project, Uncertainty Analysis of the Unmitigated Short-Term Station Blackout of the Surry Power Station", NUREG/CR-7262, U.S. NRC, Washington, DC, 2022.

[3] Lucas I. Albright, et al., "Material Interactions in Severe Accidents – Benchmarking the MELCOR V2.2 Eutectics Model for a BWR-3 MARK-I Station Blackout: Part I – Single Case Analysis", Sandia National Laboratories, Albuquerque, NM., 2021.