Scenario-Specific Sensitivity of Uncertain Parameters in OPR1000 LOCA: A Comparative Study Using CINEMA

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1. Introduction

To ensure the accurate analysis of severe accidents and to establish effective accident management strategies, computational analysis codes such as MELCOR and CINEMA have been extensively utilized to investigate complex thermal-hydraulic phenomena. In particular, South Korea has developed and operated its own integrated severe accident analysis code, CINEMA (Code for INtegrated severe accident Evaluation and Management). The CINEMA code integrates dedicated modules for in-vessel phenomena (CSPACE), ex-vessel phenomena (SACAP), and fission product behavior (SIRIUS) to simulate the overall accident progression.

When applied to severe accident analysis, integrated codes such as CINEMA must represent multiple interacting physical processes. This complexity introduces thermal-hydraulic uncertainties, which propagate through the physical correlations and numerical schemes implemented in the code. Furthermore, because heat transfer and mass transport mechanisms differ significantly depending on the accident scenario, the sensitivity of key parameters—and their subsequent impact on accident progression—often exhibits scenario-dependency. Therefore, quantifying the contributions of these key parameters and verifying the numerical stability of the code for each specific scenario is essential to ensuring the reliability of the analysis and enhancing the understanding of accident phenomena.

In this study, an uncertainty analysis was performed for the OPR1000 reactor design, focusing on two distinct Loss Of Coolant Accident (LOCA) scenarios with varying break sizes: Large-Break LOCA (LBLOCA) and Small-Break LOCA (SBLOCA). This research identifies the core parameters that exert a dominant influence on severe accident progression for each scenario and quantitatively evaluates their correlations with Figures of Merit (FOMs).

2. Methodology

In this study, an uncertainty analysis was performed for LBLOCA and SBLOCA scenarios without mitigation strategies. Multiple input sets were generated using a self-developed sampling program. The minimum sample size was determined using the first-order Wilks' formula at a 95/95 confidence level, resulting in 59 input samples [1]. Simple Random Sampling (SRS) was adopted to generate the uncertain parameter sets. The influence of selected parameters was quantified using the Pearson Correlation Coefficient (PCC) and the Spearman Rank Correlation Coefficient (SRCC).

2.1 Uncertain Parameters

The uncertain parameters were selected by focusing on specific parameters within the SIRIUS and COMPASS modules of the CINEMA code.
SIRIUS is the module responsible for calculating the release, transport, deposition, and removal of radionuclides. The SIRIUS module models the release, transport, and deposition of radionuclides. The selected uncertain parameters focus primarily on aerosol behavior and chemical speciation, which significantly affect radionuclide transport within the containment. The parameter ranges were defined based on previous uncertainty and sensitivity studies performed with commercial severe accident codes such as MELCOR [2-4]. The selected variables and their distributions are summarized in Table 1 [5].

Table. 1: Uncertain parameters and ranges for the SIRIUS module

Variables	Range	Distribution
I -> CsI (CsI combination ratio)	0.0-1.0	Uniform
2Cs -> Cs_2MoO_4 (Cs_2MoO_4 combination ratio)	0.0-1.0	Uniform
CSF (Collision Shape Factor)	1.0-4.0	Uniform
SSF (Settling Shape Factor)	1.0-4.0	Uniform
PCE (Particle Capture Efficiency)	0.5-1.0	Uniform
DCF (Density Correction Factor)	0.5-1.0	Uniform

The COMPASS module calculates fuel and structural material behavior within the RCS and RPV through coupling with the thermal-hydraulic code SPACE. The uncertain parameters were selected to represent key physical processes governing core degradation and melt progression. Since the CINEMA code does not directly include a variable controlling the eutectic temperature, the melting points of major core constituents (Zr, ZrO$_2$, and UO$_2$) were treated as uncertain parameters to assess their influence on melt behavior. In addition, the radial radiative heat transfer coefficient and blockage-related parameters were included to account for uncertainties in heat transfer and melt relocation. The selected parameters for the COMPASS module are summarized in Table 2.

Table. 2: Uncertain parameters and ranges for the COMPASS module

Variables	Range	Distribution
VF_c (Sensitivity coefficient for radial heat transfer)	0.3-0.7	Uniform
Exp_blockage (Exponent for the calculation of flow blockage area)	1.0-4.0	Normal
TZr_melt (Zircaloy melting temperature)	2029-2229	Uniform
TZrO$_2$_melt (Oxidized Zircaloy melting temperature)	2199-2399	Uniform
TUO$_2$_melt (UO$_2$ melting temperature)	2400-2600	Uniform

2.2 FOMs (Figure Of Merit)

To evaluate the uncertainty of severe accident progression, three key FOMs were selected to represent critical phenomena. These FOMs were categorized based on the accident sequence and the physical integrity of the reactor system.

The selected FOMs are as follows: SAMG entry timing, Lower Plenum relocation timing, Reactor Pressure Vessel (RPV) failure timing.

3. Result and Discussion

This section compares the accident progression of unmitigated LBLOCA (9.5-inch break) and SBLOCA (2-inch break) scenarios. The major accident events corresponding to the selected FOMs are summarized in Table 3.

Table. 3: Accident Sequences of LB/SBLOCA

Accident Sequences	LBLOCA (Time, s)	SBLOCA (Time, s)
Reactor trip	0	0
Core dry-out	137	432
Start of gap release	1731	2088
Initiation of oxidation	1733	2093
SAMG entry CET > 923.15K	2020	2232
Relocation to CSP	2922	11196
Relocation to LP	3923	30780
RPV failure	6167	37692

Due to the rapid depressurization in LBLOCA and the sustained high-pressure conditions in SBLOCA, the accident progression rates differ significantly. These differences alter the dominant heat transfer mechanisms and consequently affect the correlations between uncertain parameters and FOMs.

3.1 SAMG entry timing (FOM 1)

The results regarding the SAMG entry timing are summarized in Table 4 and Figure 1. The SAMG entry timing in the SBLOCA scenario is, on average, delayed by approximately 200 seconds compared to the LBLOCA scenario.

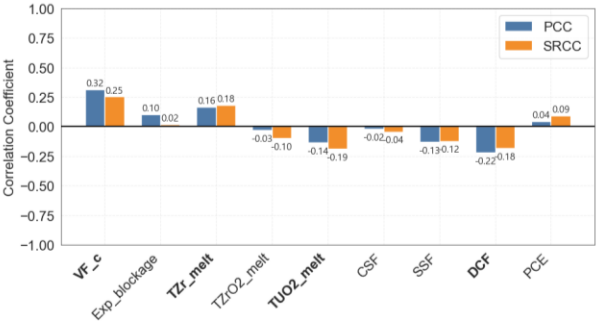
Among the uncertain parameters, the radial radiative heat transfer coefficient (VF_c) showed the most notable influence, exhibiting opposite correlations between the two scenarios. In LBLOCA, the rapid loss of coolant leads to low coolant density, causing radiative heat transfer to become the primary mechanism for core heat removal. An increase in VF_c enhances the heat removal capacity from the core center to the periphery, thereby slowing the rate of core temperature rise. Consequently, the core reaches the SAMG threshold temperature later, leading to a delayed SAMG entry timing and a positive correlation.

In contrast, in SBLOCA, the elevated RCS pressure necessitates that convection plays a significant role in heat removal, with the core temperature determined by the delicate balance between convective and radiative heat transfer. Although VF_c is a factor that enhances heat transfer, in the SBLOCA environment, the relatively lower overall heat removal rate can inadvertently accelerate the melting process. This promotes a more rapid core temperature increase, thereby advancing the SAMG entry timing and resulting in a negative correlation.

Table. 4: Analysis of SAMG entry timing

Target parameter	LBLOCA	SBLOCA
95/95	2193s	2351s
Mean	2046s	2279s
Median	2038s	2290s
Range	1944-2193s	2205-2357s

(a)



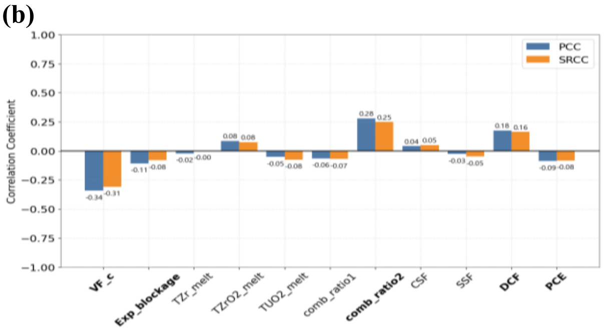


Fig. 1. Result of Correlation coefficient analysis of SAMG entry timing (a) LBLOCA and (b) SBLOCA

3.2 LH relocation timing (FOM 2)

The results for lower plenum relocation timing are summarized in Table 5 and Figure 2. In the LBLOCA scenario, this FOM exhibited a strong positive correlation with the parameter VF_c and a negative correlation with the UO_2 melting point.

The LBLOCA scenario is characterized by a rapid discharge of coolant, which severely limits convective cooling. Under these conditions, a higher VF_c facilitates the dispersion of thermal energy from the core center, effectively preventing localized heat stagnation.

This energy dispersion delays the onset of oxidation and allows for the immediate dissipation of the exothermic heat generated during the zirconium-steam oxidation reaction, thereby mitigating the rapid excursion of cladding temperatures. Consequently, the time required for core structures to reach their melting points is extended, and the structural integrity of the core support is maintained for a longer duration. These mechanisms collectively result in a positive correlation by retarding the physical timing of molten core relocation to the lower plenum.

Conversely, a higher UO_2 melting point allows the fuel to remain in a solid state for an extended duration, leading to the significant accumulation of decay heat within the core. During this period, the surrounding support structures, unable to be cooled due to the rapid loss of coolant, continuously absorb the intense radiative heat emitted from the fuel and reach their critical yield temperatures prematurely. Once the fuel finally reaches its melting point and commences liquefaction, the supporting structures have already become thermally vulnerable and lose their load-bearing capacity. Consequently, the core debris collapses into the lower plenum in a massive slumping event, which is expected to paradoxically advance the timing of relocation.

In the SBLOCA scenario, it was confirmed that the Zr melting point has a negative correlation with the relocation timing. Under the high-pressure conditions and relatively gradual accident progression of SBLOCA, a higher Zr melting point allows the cladding to remain in a solid state for a longer duration, thereby accumulating more energy. Once melting initiates, the accumulated thermal energy accelerates structural degradation and melt relocation. Unlike LBLOCA, where relocation timing is largely governed by heat removal efficiency, SBLOCA behavior is more strongly controlled by phase-change thresholds and energy storage dynamics.

Table. 5: Analysis of LH relocation timing

Target parameter	LBLOCA	SBLOCA
95/95	4259s	39821s
Mean	4001s	31416s
Median	3981s	31344s
Range	3750-4259s	19578-41923s

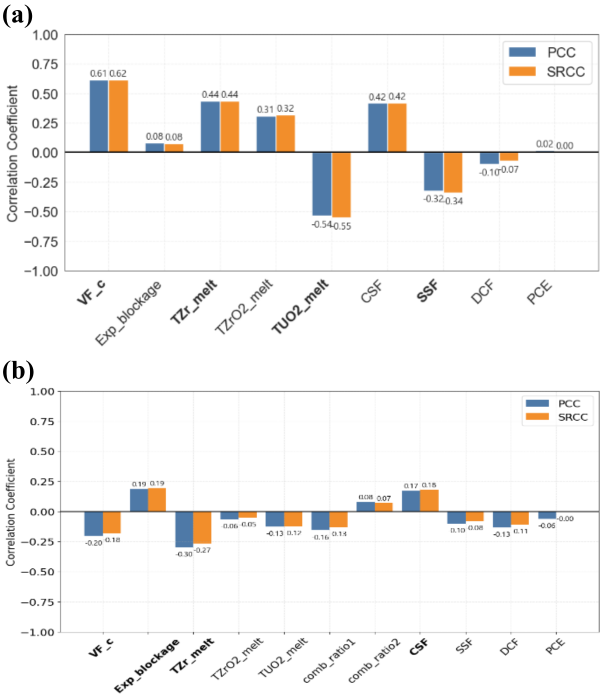


Fig. 2. Result of Correlation coefficient analysis of LH relocation timing (a) LBLOCA and (b) SBLOCA

3.3 Reactor Pressure Vessel failure timing (FOM 3)

The results regarding the RPV failure timing are summarized in Table 6 and Figure 3. In LBLOCA, the melting points of ZrO_2 and UO_2 exhibited a positive correlation with RPV failure timing. A higher melting point for ZrO_2 is expected to delay the initial formation of the melt, thereby retarding the relocation to the lower plenum and subsequently postponing the RPV failure timing.

In contrast, UO_2 exhibits a complex behavior where a higher melting point advances the relocation timing while paradoxically delaying the final RPV failure. As previously analyzed, the substantial energy accumulated due to the higher melting point induces the premature failure of surrounding support structures, which accelerates the initial slumping process. However, this results in a relocated melt where high-temperature solid phases coexist with the liquid. This mixture acts as a thermal barrier that reduces the efficiency of convective heat transfer to the RPV wall. Consequently, once the melt reaches the lower plenum, it functions as a mechanism that extends the time required for the final failure by slowing the thermal ablation of the RPV wall.

In the SBLOCA scenario, it was confirmed that the melting point of Zr has a negative correlation with the RPV failure timing. As discussed, a higher Zr melting point causes the surrounding support structures to reach their critical temperatures and melt first, leading to early relocation into the lower plenum. This relocated mass exerts a continuous and concentrated thermal load on the RPV wall, serving as the primary mechanism that accelerates the timing of the RPV failure.

Table. 6: Analysis of RPV failure timing

Target parameter	LBLOCA	SBLOCA
95/95	6158s	48660s
Mean	5762s	40001s
Median	5718s	39058s
Range	4527-6158s	29715-49954s

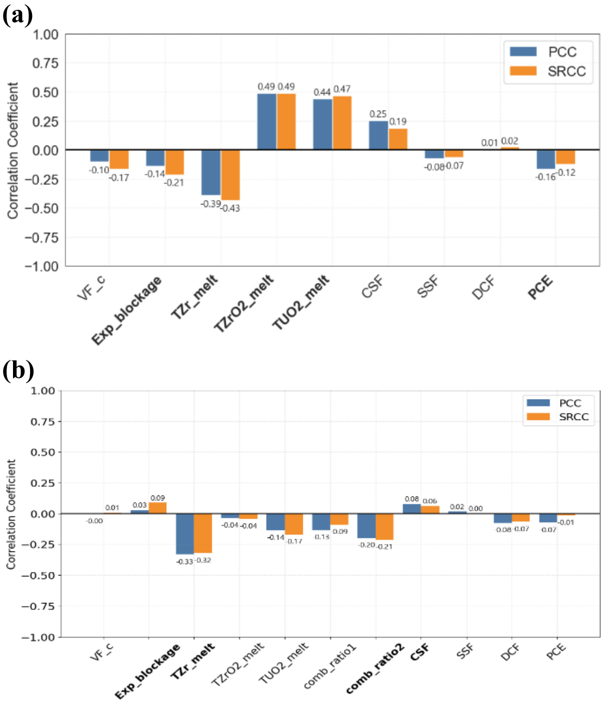


Fig. 3. Result of Correlation coefficient analysis of RPV failure timing (a) LBLOCA and (b) SBLOCA

4. Conclusions

In this study, an uncertainty analysis was performed for the OPR1000 reactor design, focusing on two Loss-of-Coolant Accident (LOCA) scenarios with varying break sizes: Large-Break LOCA (LBLOCA) and Small-Break LOCA (SBLOCA). The principal conclusions of this research are as follows:

First, we identified the scenario-dependency of parameter influence based on the specific characteristics of each accident.

Second, we elucidated the roles of the VF_c and the UO_2 melting point in determining the timing of SAMG entry and core relocation.

Third, in the LBLOCA, the UO_2 melting point exhibits opposing trends regarding the lower plenum relocation and RPV failure timings.

These findings demonstrate that the CINEMA code consistently captures the distinct thermal-hydraulic and degradation mechanisms inherent to different LOCA scenarios and provides stable and physically coherent uncertainty responses under severe accident conditions.

Future work will focus on refined sensitivity analyses of the dominant parameters and expansion of the scenario set, including SBO and IBLOCA sequences, to further improve statistical robustness and support comprehensive severe accident uncertainty quantification.

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REFERENCES

[1] Helton, Jon C., and Freddie Joe Davis. "Latin hypercube sampling and the propagation of uncertainty in analyses of complex systems." Reliability Engineering & System Safety 81.1(2003): 23-69.

[2] Hong, In Seob, and Adrian Connolly. "Generalized Tolerance Limit Evaluation Method to Determine Statistically Meaningful Minimum Code Simulations." Proceedings of the 16th International Conference on Nuclear Engineering(ICONE16), 2008. ASME Digital Collection.

[3] Darnowski, P., Włostowski, M., Zukowska, Z., & Kaczmarek, J.(2021). Parametric MELCOR 2.2 sensitivity and uncertainty study with a focus on aerosols based on Phébus test FPT1. Nuclear Engineering and Design, 378, 111030.

[4] Sánchez-Sáez, F., Sánchez, A. I., Ramos, R., & Ceballos, R.(2018). Uncertainty analysis of a large break loss of coolant accident in a pressurized water reactor using non-parametric methods. Reliability Engineering & System Safety, 169, 100-113.

[5] Michael Epstein, Phillip G. Ellison, Robert E. Henry, Correlation of Aerosol Sedimentation, January of Colloid and Interface Science, 113(1986) 342-355.