

Comparative Analysis of Scenario-Dependent Uncertainty in In-Vessel Severe Accident Phenomena Using the CINEMA Code

Ok Hyeon Lee^a, JinHo Song^a, Joon-Eon Yang^a, Sung Joong Kim^{a,b*}

^aDepartment of Nuclear Engineering, Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul 04763, Republic of Korea

^bInstitute of Nano Science and Technology, Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul 04763, Republic of Korea

*Corresponding author: sungkim@hanyang.ac.kr

***Keywords : CINEMA, Uncertainty Analysis, Severe Accident**

1. Introduction

Severe accidents involve complex interactions among various physical and chemical phenomena during accident progression. Severe accident analysis codes are used to predict accident progression, evaluate key phenomena, and support the development of accident management strategies. Various severe accident codes have been developed and applied worldwide for severe accident analysis and accident response [1]. In South Korea, the Korea Atomic Energy Research Institute (KAERI) has developed the CINEMA code, which integrates models for in-vessel phenomena, ex-vessel phenomena, and fission product behavior to perform comprehensive severe accident analysis [2].

Severe accident analysis involves various sources of uncertainty, and their effects can differ depending on the characteristics of the accident scenario. The dominant models and uncertain parameters may vary with the phenomena governing each scenario. Interactions among coupled phenomena can also lead to uncertainty propagation during accident progression. Uncertainties associated with earlier phenomena can affect subsequent phenomena through their initial or boundary conditions. Therefore, the effects of uncertain parameters should be evaluated in relation to the sequence of accident progression. In-vessel phenomena occur at an early stage of severe accident progression and can affect subsequent ex-vessel phenomena, making them an appropriate starting point for evaluating uncertainty propagation.

Uncertainty analysis is used to identify and quantify the effects of uncertain parameters and model uncertainties on severe accident progression [3]. A scenario-dependent uncertainty assessment of in-vessel phenomena can provide the basis for evaluating how uncertainties develop and propagate into subsequent accident stages. This study uses the CINEMA code to investigate the uncertainty characteristics of different severe accident scenarios, focusing on in-vessel phenomena. Uncertain parameters associated with in-vessel phenomena are identified, and their effects are compared among the considered scenarios. The results provide a basis for understanding scenario-dependent uncertainty and for extending the analysis to uncertainty propagation in subsequent stages of severe accident progression.

2. Methodology

The QUASAR (Quantification of Uncertainty and Sensitivity Analysis Results) methodology was used for uncertainty analysis in this study [4]. The QUASAR methodology determines the required number of samples based on the target confidence level and coverage rate using Wilks' formula. Input variables are then sampled according to their prescribed probability distributions, and code calculations are performed for the generated sample cases. The calculated results are statistically analyzed to quantify the uncertainty and identify the effects of the input variables.

A total of 93 sampling cases were generated using the 95/95 tolerance level with the second-order Wilks' formula. The probability distributions of the input variables were sampled using the Simple Random Sampling (SRS) technique. The Pearson Correlation Coefficient (PCC) and Spearman Rank Correlation Coefficient (SRCC) were used to evaluate the relationships between the input variables and the Figure of Merit (FOM). The correlation coefficients were used to quantify the influence of individual input variables on the FOM.

2.1 Uncertain Parameters

Five uncertain parameters related to in-vessel phenomena were selected for the uncertainty analysis based on previous studies. The selected parameters are the radiation heat transfer coefficient (VF_c), degree of flow blockage (Exp_blockage), and melting points of zircaloy (Zr_melt), oxidized zircaloy (ZrO₂_melt), and oxidized uranium (UO₂_melt). Radial radiative heat transfer within the core and flow blockage due to the solidification of relocated material introduce uncertainties in the process by which COMPASS represents heat transfer between adjacent rings only by radiation and simulates axially non-uniform solidification using input parameters. Since the uncertainties associated with these simplified approaches are concentrated in these parameters, VF_c and Exp_blockage were selected as uncertain parameters. In addition, during the core melting process, which determines the limit at which core materials such as Zircaloy, ZrO₂, and UO₂ maintain a solid state, the melting temperatures of each material determine the onset of relocation and were therefore selected as

uncertain parameters [5]. For Exp_blockage, experimental and analytical studies have reported partial blockage of approximately 40–60%, rather than complete blockage or negligible blockage. Therefore, a normal distribution centered within this range was applied, assuming that the midpoint of the range is more representative than its upper and lower bounds. For VF_c and the melting temperatures of each core material, the upper and lower bounds were determined based on the code default values and ranges reported in the literature. Since there was no sufficient basis for assigning different weights within these ranges, uniform distributions were applied, consistent with previous uncertainty studies under similar conditions. The uncertainty ranges and probability distributions of these parameters are summarized in Table 1.

Table 1: Uncertain parameters and ranges

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
Zr_melt (Zircaloy melting temperature)	2029-2229	Uniform
ZrO ₂ _melt (Oxidized Zircaloy melting temperature)	2400-2600	Uniform
UO ₂ _melt (UO ₂ melting temperature)	2400-2600	Uniform

2.2 FOMs (Figure Of Merit)

The FOMs were defined to characterize the major in-vessel phenomena occurring before RPV failure during severe accidents, as summarized in Table 2. The correlations between the FOMs and uncertain parameters were evaluated to quantify the effects of uncertainty on in-vessel phenomena and compare the uncertainty characteristics among the considered scenarios. The selected FOMs and their definitions are summarized in Table 2.

Table 2: FOMs

FOM	
1	CSP to LH relocation residence time
2	LH relocation to RPV failure time
3	Corium mass
4	Hydrogen generation mass

2.3 Scenarios

The accident scenarios considered in this study are the Large Break Loss of Coolant Accident (LLOCA) with a 9.5-inch break size and the Station Blackout (SBO) base case. These scenarios were selected to represent high-pressure and low-pressure accident conditions, which exhibit distinct accident progression characteristics. Both cases represent accident conditions without mitigation measures. The accident conditions for the two scenarios

are summarized in Table 3. Uncertainty analysis was performed for these unmitigated cases to compare the uncertainty characteristics associated with the different accident progression paths.

Table 3: Accident Sequences of LLOCA and SBO

Accident Sequences	LLOCA (Time, s)	SBO (Time, s)
Reactor trip	0	0
Core dry-out	132	7153
Start of gap release	1817	7299
Initiation of oxidation	1821	7510
SAMG entry CET > 923.15K	2207	7514
Relocation to CSP	3074	9542
Relocation to LH	4319	15542
RPV failure	8433	18940

3. Result and Discussion

3.1 CSP to LH relocation residence time (FOM 1)

Correlation coefficients were evaluated by defining two time intervals based on the sequence of accident progression. The first interval was defined from Core Support Plate (CSP) collapse to Lower Head (LH) relocation, while the second interval was defined from LH relocation to Reactor Pressure Vessel (RPV) failure.

For the first time interval, LLOCA showed relatively weak correlations with the parameters, whereas SBO showed a negative correlation with Exp_blockage and a positive correlation with Zr_melt (Figure 1). These results show that a higher degree of flow path blockage tends to shorten the time interval between CSP collapse and LH relocation, while an increase in the zirconium melting point tends to prolong this interval.

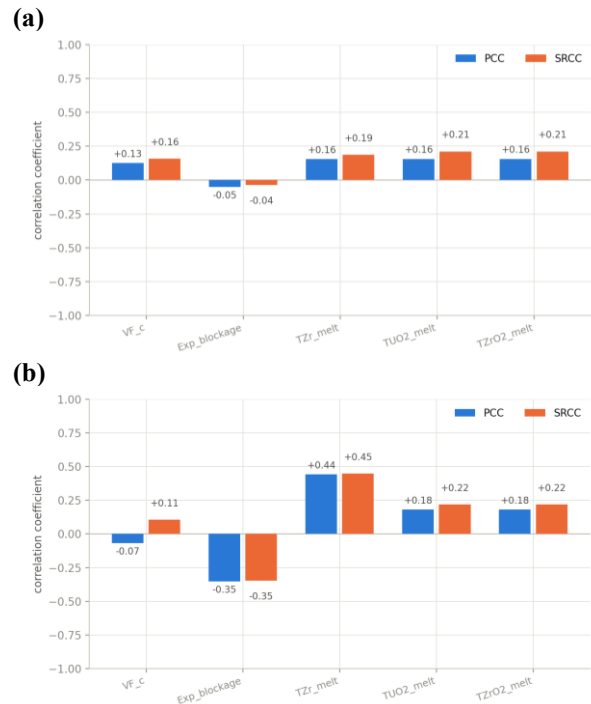


Fig. 1. Result of Correlation coefficient analysis of CSP to LH relocation residence time (a) LLOCA and (b) SBO

As shown in the scatter plot in Figure 2, the results are separated into two distinct clusters: upper and lower. The correlation coefficients were recalculated for the lower cluster. The correlation with Exp_blockage decreased, whereas the correlation with Zr_melt increased for the lower cluster (Figure 3). This result shows that the influence of the zirconium melting point becomes more pronounced in the lower cluster. In particular, an increase in Zr_melt is associated with a more substantial delay in the progression from CSP collapse to LH relocation.

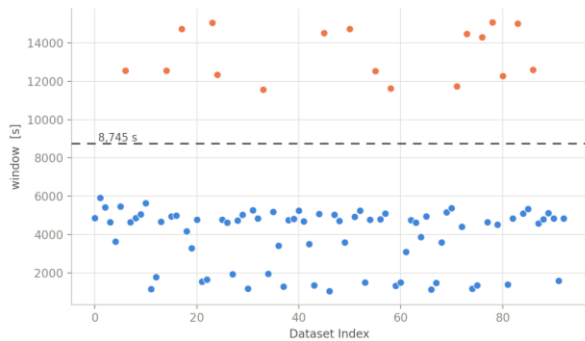


Fig. 2. Scatter plot result (SBO)

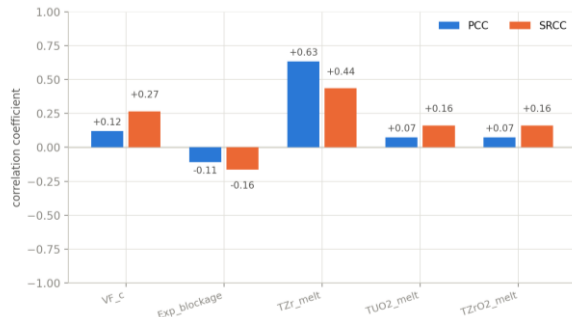


Fig. 3. Result of Correlation coefficient analysis of lower cluster (SBO)

3.2 LH relocation to RPV failure time (FOM 2)

For the time interval from LH relocation to RPV failure, LLOCA still shows a weak correlation with the parameters. In contrast, SBO showed a stronger negative correlation with Exp_blockage, while the correlation with Zr_melt decreased compared with the previous interval (Figure 4). The scatter plot in Figure 5 shows several cases vertically aligned on the right side, corresponding to conditions in which the flow paths are fully blocked. For these cases, the amount of heat transferred to the RPV increases along an upward-sloping trend as the degree of flow blockage increases. The increased heat transfer associated with greater blockage can consequently promote earlier RPV failure. In LLOCA, the dominant RPV failure mode differs from that observed in SBO, with penetration failure being the primary failure mode. In Figure 6, the locations of the

dominant RPV failure appear to be distributed closer to the outer surface of the RPV than to the inner surface. This distribution shows that RPV failure in LLOCA is governed by a more complex combination of failure mechanisms. Consequently, the effects of individual uncertain parameters are not clearly separated, resulting in relatively weak and less distinct correlations compared with those observed for SBO.

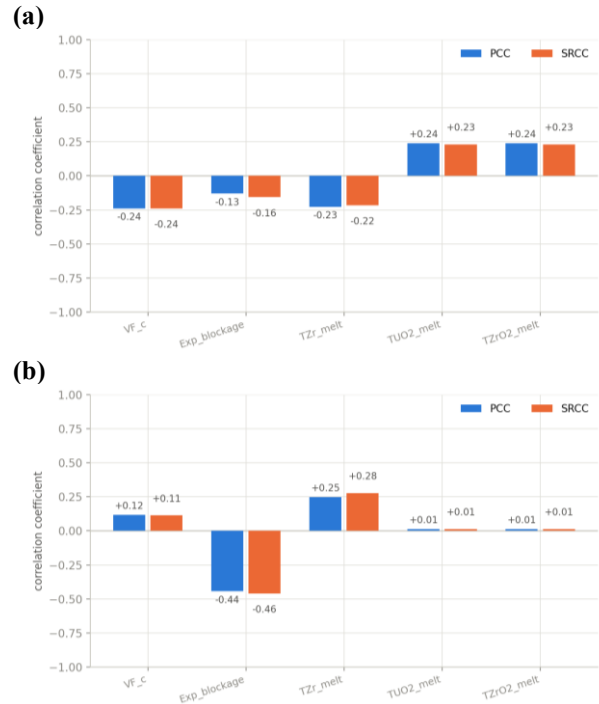


Fig. 4. Result of Correlation coefficient analysis of LH relocation to RPV failure time (a) LLOCA and (b) SBO

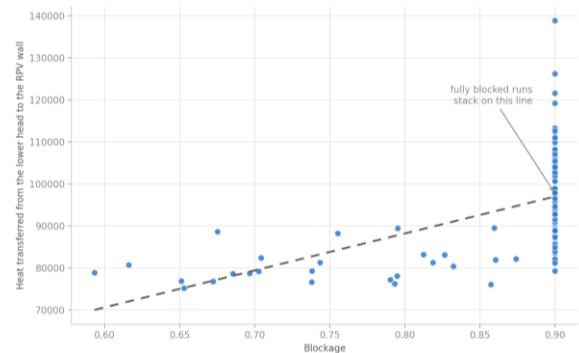


Fig. 5. Heat input to the RPV according to the degree of flow blockage (SBO)

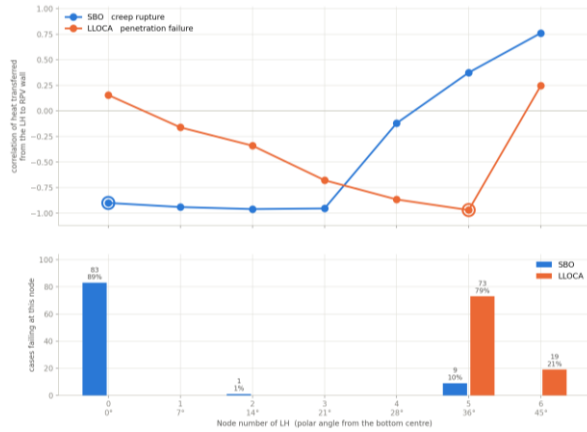


Fig. 6. RPV failure node according to scenario LLOCA and SBO

3.3 Corium mass (FOM 3)

For the corium mass, LLOCA shows weak correlation, whereas SBO showed negative correlations with ZrO_2_melt and UO_2_melt (Figure 7). The higher melting points of ZrO_2 and UO_2 may reduce the duration for which structural materials remain in molten state, thereby limiting the extent of structural erosion and resulting in a smaller amount of corium generation (Figure 8). The different correlation characteristics between the two scenarios may be associated with differences in the RPV failure behavior. In LLOCA, the failure mode differs from that observed in SBO, and the accident progression is less strongly influenced by the temperature-dependent behavior of the core materials. Consequently, the effects of material-property-related variables, including the melting points of UO_2 and ZrO_2 , are less pronounced in LLOCA.

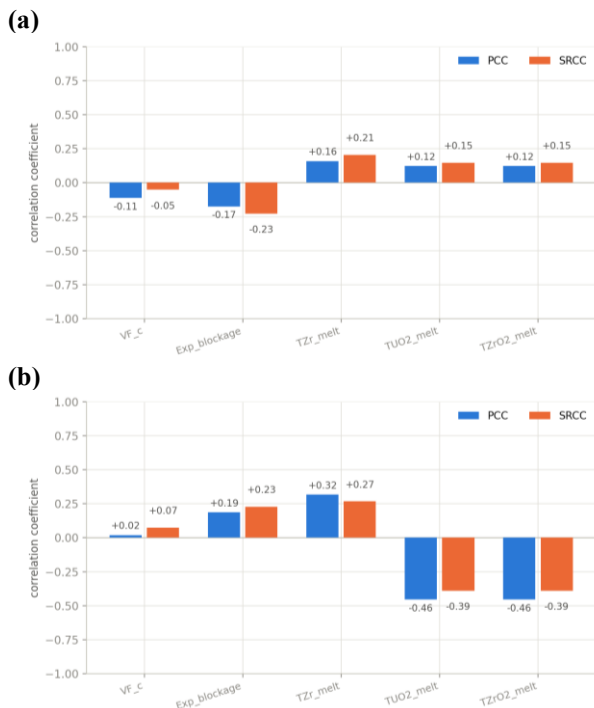


Fig. 7. Result of Correlation coefficient analysis of Corium mass (a) LLOCA and (b) SBO

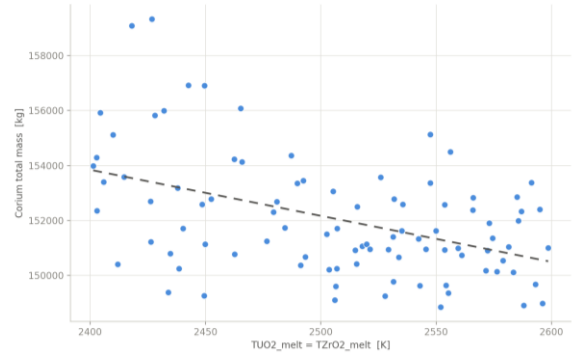
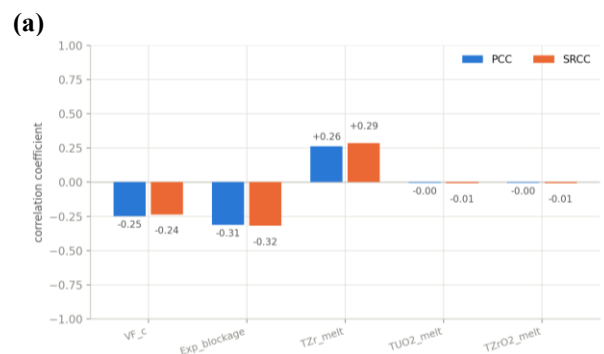


Fig. 8. Scatter plot of ZrO_2 and UO_2 melting temperature parameter (SBO)

3.4 Hydrogen generation mass (FOM 4)

For hydrogen generation, LLOCA showed a weak negative correlation with $Exp_blockage$, whereas SBO showed a relatively strong positive correlation with the zirconium melting point (Figure 9). The positive correlation in SBO may be attributed to the effect of the zirconium melting point on Zircaloy oxidation. A higher melting point can prolong the period during which the Zircaloy cladding remains intact, allowing oxidation to proceed for a longer duration and resulting in greater hydrogen generation. In LLOCA, the accident progresses more rapidly, resulting in a relatively narrow range of variation in hydrogen. As a result, the influence of individual uncertain parameters is less readily distinguished. This behavior shows that hydrogen generation in LLOCA may be affected by the combined interactions of multiple parameters during the relatively rapid accident progression.



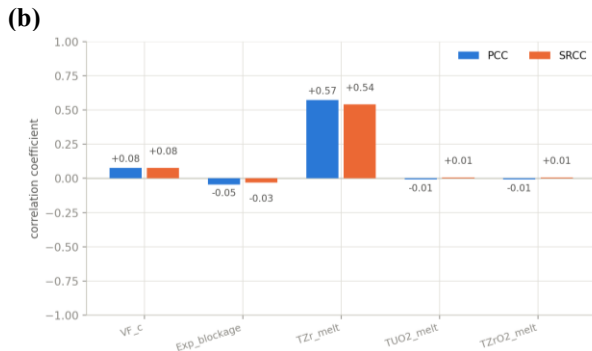


Fig. 9. Result of Correlation coefficient analysis of Hydrogen generation mass (a) LLOCA and (b) SBO

4. Conclusions

This study evaluated the uncertainty characteristics of in-vessel phenomena for two representative severe accident scenarios, LLOCA and SBO. The results showed that Exp_blockage and Zr_melt had dominant effects on the FOMs in the SBO scenario, whereas no single uncertain parameter showed a dominant influence in the LLOCA scenario. These results indicate that the effects of uncertain parameters can differ depending on the accident scenario and that uncertainty analysis should account for scenario-dependent accident progression.

The present analysis was limited to two accident scenarios and five uncertain parameters. Further studies with a broader range of accident scenarios and uncertain parameters are required to improve the generality of the results. Sequential uncertainty propagation from in-vessel to subsequent accident phenomena will also be investigated to further assess the scenario-dependent uncertainty characteristics of severe accidents.

ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT: Ministry of Science and ICT) (No. RS-2022-00144202) and the Nuclear Safety Research Program through the Korea Foundation Of Nuclear Safety (KoFONS) using the financial resource granted by the Nuclear Safety and Security Commission (NSSC) of the Republic of Korea (RS-2026-25539178).

REFERENCES

- [1] Kim, H. D., Cho, S. W., Park, J. H., Hong, S. W., & Yu, D. H. (2000). The development of a severe accident analysis code-research on the improvement of nuclear safety. *Journal of the Korean Nuclear Society*, 32(4), 422-435.
- [2] Song, J., Son, D. G., Bae, J., Bae, S. W., Ha, K., Chung, B. D., & Choi, Y. (2016). CSPACE for a simulation of core damage progression during severe accidents. *Nuclear Engineering and Design*, 298, 51-60.
- [3] Pourgol-Mohammad, M. (2009). Thermal-hydraulics system codes uncertainty assessment: A

review of the methodologies. *Annals of Nuclear Energy*, 36(11-12), 1774-1786.

[4] Glaeser, H. (2008). GRS method for uncertainty and sensitivity evaluation of code results and applications. *Science and Technology of Nuclear Installations*, 2008, Article ID 798901.

[5] Korea Hydro & Nuclear Power Co., Ltd., Theory Manual for CINEMA 2.3, 2025.