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Uncertainty and Sensitivity Analysis of Source Term Evaluation Using MELCOR 2.2 Based on Benchmarking with the PHEBUS FPT-1 Experiment

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1. Introduction

A severe accident is an event that occurs beyond Design Basis Accident (DBA), leading to significant core melting and the release of a considerable amount of fission products. If these fission products are released into the environment, they can pose serious risks to both the public and the ecosystem. The 2011 Fukushima Daiichi accident clearly demonstrated these hazards, reinforcing the critical importance of severe accident management and response on a global scale.

Recently, research on utilizing AI technology to support severe accident diagnosis and operator decision-making has been actively conducted [1, 2]. In the development of such AI technologies, a large-scale training dataset is essential; however, since severe accidents are extremely rare, obtaining empirical data for AI training is challenging. Therefore, it is inevitable to generate data based on severe accident analysis codes such as MELCOR, MAAP, and ASTEC.

However, severe accident analysis codes inherently contain uncertainties due to the application of various physical models and dimensional distortions within the code, which can significantly impact simulation results. If the data generated using these analysis codes lack reliability, the AI model trained on such data is also likely to suffer from reduced reliability. Therefore, to ensure the reliability of AI models, it is essential to quantitatively assess the uncertainties in the code and conduct sensitivity analysis on key parameters.

Therefore, this study conducted benchmarking of the PHEBUS FPT-1 experiment using MELCOR and focused on uncertainty and sensitivity analysis for source term evaluation. A total of 140 simulations were performed, and the sensitivity of uncertain parameters was assessed through multiple regression analysis and correlation coefficient analysis.

2. Methods

2.1 Reference input modeling

The PHEBUS experiment was conducted to observe the release, transport, and deposition of fission products. The experiment was performed using a scaled-down model of a 900 MW pressurized water reactor (PWR) at approximately 1/5000 of its actual size [3]. A total of five experiments were carried out, and this study focuses on the PHEBUS FPT-1 experiment.

In the FPT-1 experiment, a total of 20 fuel rods were used, consisting of 18 irradiated fuel rods with a burn-up of 23.4 GWd/tU and 2 fresh fuel rods. The control rod material was an AIC (Ag-In-Cd) alloy, which was embedded at the center of the fuel bundle. The experiment was conducted under steam-rich conditions, with the steam flow rate varying between 0.5 and 2.2 g/s throughout the experiment.

In this study, the benchmarking of the PHEBUS FPT-1 experiment was conducted using the MELCOR 2.2 code. The input model was modified based on the FPT-3 input model developed by Bae et al [4]. Prior to model development, the key differences between the FPT-1 and FPT-3 experiments were examined, as summarized in Table 1. Based on this analysis, the input data were refined, and additional modifications were made according to user-defined adjustments.

For example, core heat transfer modeling is a critical factor in simulating the degradation process. Therefore, in this study, the radiation exchange factor was redefined to more accurately reflect radiative heat transfer within the core. Specifically, the FCELR parameter, which models radial heat transfer in the core, was adjusted to 0.75. This value was determined based on the number of fuel rods used in the FPT-1 experiment and the MELCOR assessment report [5, 6]. Additionally, experimental results indicated the formation of Cs-Mo compounds. To simulate this phenomenon, the MELCOR was modified to allow Cs and Mo to combine and form Cs_2MoO_4.

Table I: FPT-1 and FPT-3 experiments conditions

Conditions	FPT-1	FPT-3
Type of fuel	BR3 ≈ 23.4 Gwd/tU, AIC control rod Re-irradiation	As FPT-1 with B_4C
Degradation	Steam-rich	Steam-poor
Steam flow rate (g/s)	From 0.5 to 2.2	0.5
Bundle power (kW)	34.4 (max)	32.3 (max)

2.2 Uncertainty analysis method

In this study, three Figures of Merit (FOM) were selected prior to conducting the uncertainty analysis. These FOMs represent the release fractions of cesium (Cs), iodine (I), and total fission products (FP) to the containment. In the uncertainty analysis, the distribution of the FOMs was evaluated to quantitatively assess the impact of input variable variations on the results. The uncertain variables were selected from the RN (Radionuclide) package parameters in MELCOR, which significantly influence the release of fission products [7]. Each parameter, along with its corresponding range and distribution, was determined based on previous studies, as summarized in Table 2 [8, 9, 10].

Table II: Uncertain parameters

Parameter	Field	Min	Max	PDF
RN1_ASP	DMIN	1.0E-07	2.0E-06	Uniform
	RHONOM	1000	5000	Uniform
RN1_MS00	CHI	1.0	5.0	Beta, α=1, β=1.5
	GAMMA	1.0	5.0	Beta, α=1, β=1.5
	FSLIP	1.2	1.3	Beta, α=4, β=4
	STICK	0.5	1.0	Beta, α=2.5, β=1
RN1_MS01	TURBDS	0.00075	0.00125	Uniform
	TKGOP	0.006	0.06	Log-uniform
	FTHERM	2.0	2.5	Uniform
	DELDIF	5.0E-06	2.0E-05	Uniform

2.3 Sensitivity analysis method

Sensitivity analysis is used to evaluate the impact of each input variable on the FOMs and identify the most influential variables. In this study, multiple regression analysis and correlation analysis were performed to conduct the sensitivity analysis.

In multiple regression analysis, the coefficient of determination (R^2) was used to assess the goodness of fit of the regression model, while the p-value was utilized to quantitatively evaluate the relationship between independent and dependent variables. As the R^2 value approaches 1, the model explains the variability of the data more effectively, whereas a p-value below 0.05 signifies a significant correlation between independent and dependent variables.

For correlation analysis, Pearson, Spearman, PRCC (Partial Rank Regression Coefficient), and SRRC (Standardized Rank Regression Coefficient) coefficients were utilized to quantitatively assess the relationships between variables.

3. Results and discussion

3.1 Reference results

The calculation results of the standard input are presented in Figures 1 and 2, showing the release fractions of cesium (Cs) and iodine (I). The release fraction of Cs was approximately 43% in the experimental data, while the MELCOR simulation yielded about 37%, exhibiting a similar trend to the experimental results. On the other hand, the simulated release fraction of I was around 40%, which differed by approximately 20% from the experimental value of 64%, indicating a relatively large discrepancy. This difference is presumed to be due to the complex chemical behavior of iodine, suggesting that further research is necessary to improve the accuracy of its prediction. Although this paper presents only the release fractions of Cs and I, additional analysis confirmed that the model also provided reasonably accurate predictions for the core degradation process and the release behavior of other fission products.

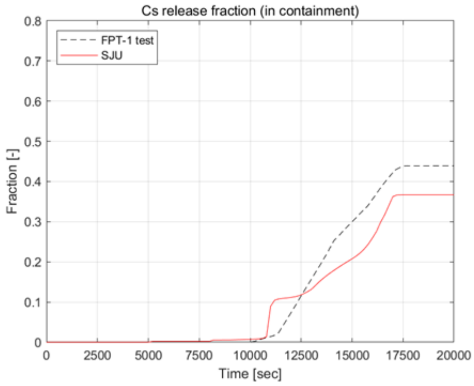

Fig. 1. Cs release fraction to the containment

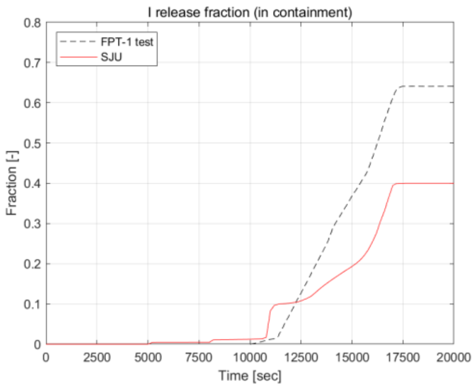

Fig. 2. I release fraction to the containment

3.2 Uncertainty analysis results

In this study, a total of 140 calculations were performed for the uncertainty analysis, and all calculations were successfully completed. As shown in Figures 3 and 4, the uncertainty calculation results include statistical data. The release fractions of cesium (Cs) and iodine (I) were found to be distributed within approximately 15% and 10%, respectively. The reference case was observed to generate results close to the minimum value. This suggests that since the MELCOR default values were primarily used in this case, the defaults of MELCOR tend to produce somewhat non-conservative results.

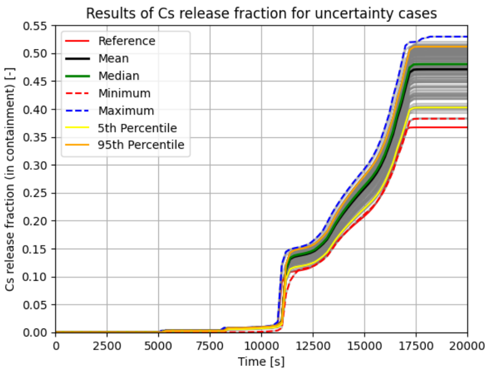

Fig. 3. Uncertainty analysis results for Cs

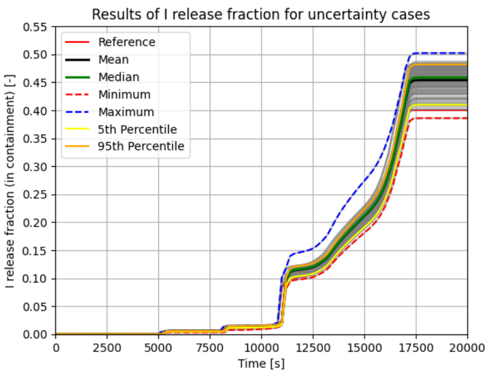

Fig. 4. Uncertainty analysis results for I

3.3 Sensitivity analysis results

Through multiple regression analysis, scatter plots including trend lines were generated to depict the relationships between each uncertainty variable and the FOMs. Among them, the scatter plots of the variable with the highest correlation are presented in Figures 5 and 6. The coefficient of determination (R^2) values for Cs and I were 0.87 and 0.85, respectively, indicating a very high predictive capability. Out of the 10 analyzed variables, the CHI variable was identified as the most influential factor. The p-value of the CHI variable was 1.01×10^{-54} in the Cs and 1.95×10^{-48} in the I analysis, showing extremely low values. Additionally, as shown in Figures 7 and 8, the correlation analysis also indicated that the CHI variable exhibited a strong positive correlation close to +1, which was consistent with the results of the multiple regression analysis.

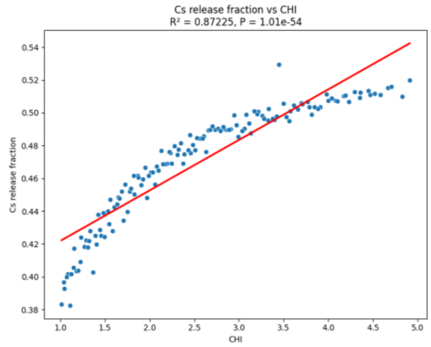

Fig. 5. Multiple regression results for Cs

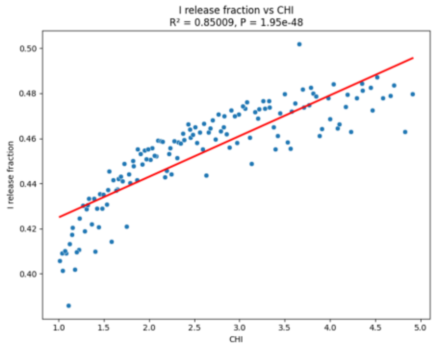

Fig. 6. Multiple regression results for I

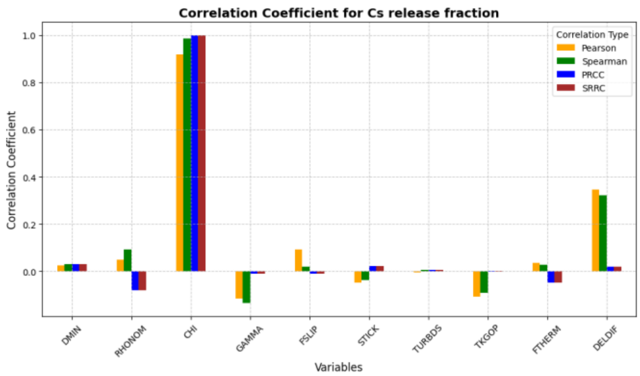

Fig. 7. Correlation analysis results for Cs

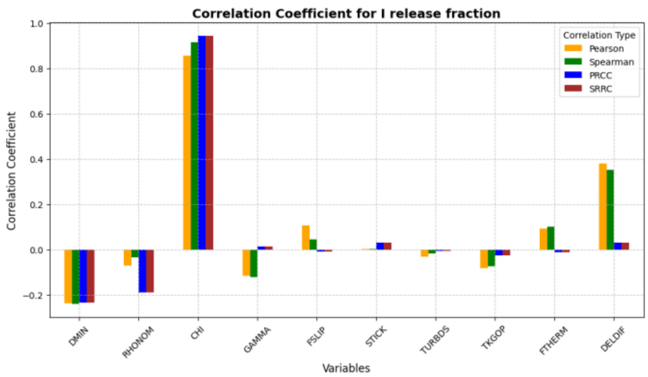

Fig. 8. Correlation analysis results for I

4. Conclusions

In this study, uncertainty and sensitivity analyses were conducted for source term evaluation based on the benchmarking of the PHEBUS FPT-1 experiment.

The benchmarking results confirmed that MELCOR provided relatively accurate predictions for the release fractions of fission products and the degradation process, except for iodine. Additionally, a total of 140 calculations were performed for the uncertainty analysis were successfully completed. Based on these results, a sensitivity analysis identified the CHI variable as the most influential factor. The CHI variable exhibited a strong positive correlation with the release fractions of Cs and I.

However, this study identified a significant discrepancy in the predicted release fraction of iodine, highlighting the need for further analysis. Future research will focus on improving the MELCOR model and expanding the list of uncertainty variables for further investigation.

Furthermore, the findings of this study can be utilized as data for developing AI-based technologies to support operator decision-making and accident prediction in the future.

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