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Uncertainty Quantification Framework for Systematic Source Term Assessment

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1. Introduction

In 2016, South Korea's nuclear regulatory authority introduced nuclear safety objectives, requiring that the total frequency of accidents resulting in Cs-137 releases exceeding 100 TBq must be less than 1.0E-6 per year. Unlike Canada and Finland, which apply similar safety goals only to new nuclear power plants, South Korea extends this regulation to both operating and new reactors [1].

However, the technical basis for the 100 TBq threshold remains unclear, and existing nuclear power plants face challenges in demonstrating compliance. Conventional probabilistic safety assessment (PSA) methods primarily focus on either release frequency or release quantity, limiting their ability to support comprehensive decision-making.

This study proposes a framework that incorporates uncertainty analysis to enhance risk assessment. By evaluating the uncertainty in Cs-137 release frequency and quantity for different Source Term Categories (STCs), the framework aggregates this data to generate a 'Risk Density Map.' This approach provides a structured method for integrating risk information and improving decision support.

The rest of this paper is organized as follows. Section 2 presents the development of the proposed framework. Section 3 applies it to an OPR-1000 case study, analyzing Cs-137 releases and discussing results. Section 4 concludes with potential applications and future improvements.

2. Framework and Methods

Fig. 1 illustrates the framework for optimizing source term assessment under uncertainty. The proposed framework consists of three main stages: (1) Release Mass Uncertainty Analysis, (2) Release Frequency Uncertainty Analysis, and (3) Aggregation of Result Distributions.

This framework provides a structured methodology for incorporating uncertainty into risk assessment, enhancing decision support. The following sections describe each step in detail, including the specific procedures and implementation methods.

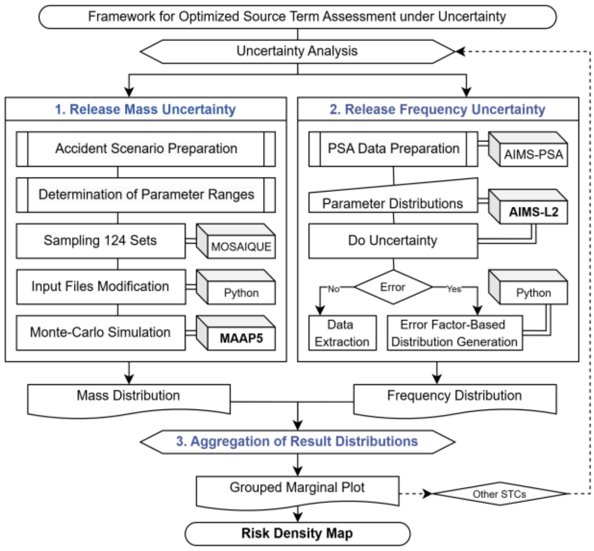

Fig. 1. Developed Uncertainty Quantification Framework for Risk-Informed Source Term Analysis.

2.1 Release Mass Uncertainty Analysis

The Release Mass Uncertainty Analysis quantifies the uncertainty in Cs-137 release during nuclear accident scenarios by integrating probabilistic sampling and computational simulations. This process involves several key steps to systematically assess and model uncertainty.

First, accident scenarios are prepared by defining representative cases that consider various initiating events, system failures, and external hazards. These scenarios form the basis for the uncertainty analysis by outlining potential accident progressions.

Next, the parameter ranges influencing source term release are determined. Key parameters, such as containment integrity and core damage progression, are identified, and their uncertainty ranges are established using experimental data and expert judgment. This step ensures that variations in accident conditions are realistically captured.

Following this, probabilistic sampling is conducted using MOSAIQUE to generate 124 parameter sets based on Wilks' formula [2]. This approach allows for the representation of a wide range of possible accident progressions by systematically varying key parameters within their respective uncertainty bounds.

The sampled values are then integrated into simulation input files, which are automated using Python to ensure consistency and efficiency.

Subsequently, Monte Carlo simulations are performed using MAAP5 [5] to estimate the probabilistic distribution of Cs-137 release mass for each sampled accident scenario.

The resulting release mass distribution serves as a fundamental input for risk assessment and will later be integrated with release frequency uncertainty analysis to construct the Risk Density Map, which provides a comprehensive representation of probabilistic risk.

2.2 Release Frequency Uncertainty Analysis

The Release Frequency Uncertainty Analysis evaluates uncertainties in the frequency of Cs-137 release during nuclear accident scenarios. This process consists of the following key steps:

First, PSA data is prepared using AIMS-PSA [6], gathering probabilistic safety assessment data relevant to accident scenarios and event sequences.

Next, parameter distributions are derived from AIMS-L2, defining statistical distributions for key parameters that influence release frequency while incorporating uncertainty factors.

Following this, an uncertainty evaluation is conducted to determine whether additional modeling is required. If no significant error factors are identified, data extraction proceeds directly. Otherwise, an error factor-based distribution generation method [4] is applied using Python to construct frequency distributions that account for uncertainty.

Finally, the results are compiled into a probabilistic frequency distribution, representing the variation of Cs-137 release frequency across different accident scenarios. This distribution serves as a key input for integration with the release mass uncertainty analysis in the next phase.

2.3 Aggregation of Result Distributions

The final step integrates the previously obtained mass and frequency distributions to construct a Risk Density Map, which provides a structured visualization of probabilistic risk.

First, these distributions are combined to analyze the probabilistic relationship between release mass and frequency. The results are visualized using a Grouped Marginal Plot, systematically representing the aggregated data while incorporating other STCs for a comprehensive risk assessment.

Ultimately, the Risk Density Map enhances decision-making and risk communication by providing a clear representation of the probabilistic risk landscape.

3. Application for OPR-1000 Case Study

The proposed framework was applied to the OPR-1000 nuclear power plant using Level 2 PSA data to evaluate Cs-137 release characteristics. Among the analyzed STCs, STC-02 (highest release frequency) and STC-20 (highest release amount) were selected as representative cases for detailed analysis (Table I).

Table I: STCs information from MAAP [5] simulation results for Cs-137 release from the OPR-1000. [1, 2, 3]

STCs of OPR-1000 and Containment failure mode			**Cs-137 Release (TBq)**	**Frequency (/RY)**
STC-1	NOCF		1.05 E+01	5.19 E-07
STC-2	**NOCF**		**5.33 E+01**	**1.20 E-06**
STC-3	ECF	LEAK, CS-YES	4.29 E+00	1.09 E-08
STC-4	ECF	LEAK, CS-NO	1.39 E+04	8.35 E-09
…	…	…	…	…
STC-18	NOISO	CS-YES	2.00 E+03	2.69 E-09
STC-19	NOISO	CS-NO	1.16 E+04	1.08 E-09
STC-20	**BYPASS**	**ISLOCA**	**2.19 E+05**	**1.01 E-08**
STC-21	BYPASS	SGTR	1.13 E+05	2.37 E-07

STC-02 corresponds to a No Containment Failure (NOCF) scenario, resulting in a relatively low release amount in conventional PSA. However, its high occurrence frequency necessitates further risk assessment.

STC-20 represents an Interfacing System Loss-of-Coolant Accident (ISLOCA), where a break in the low-pressure safety injection system leads to a direct environmental release of fission products. The absence of containment mitigation results in a significantly high release amount.

The following sections demonstrate the effectiveness of the proposed framework by applying Release Mass and Release Frequency Uncertainty Analyses to these selected STCs.

3.1 Release Mass Uncertainty – Case Study

To assess the uncertainty in Cs-137 release mass for STC-02 and STC-20, probabilistic Monte Carlo simulations were conducted using 124 sampled cases. The results demonstrate significant variability in release amounts, highlighting the necessity of uncertainty quantification in risk assessments.

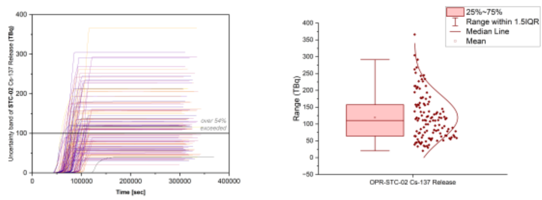

Fig. 2. STC-02 Cs-137 Release Mass[TBq] by Time[sec](Left) and Range[TBq](Right)

For STC-02, despite being classified as a No Containment Failure (NOCF) scenario, over 54% of cases exceeded 100 TBq, indicating substantial release variations (Fig. 2). The deterministic release mass

(39.93 TBq) is significantly lower than the P95 estimate (292.73 TBq), underscoring the limitations of deterministic PSA in capturing high-risk outliers. Given its high frequency, STC-02 presents non-negligible risks, warranting further evaluation.

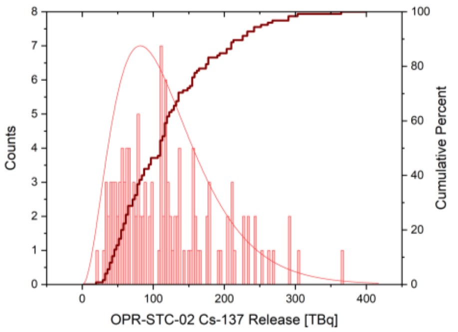

Fig. 3. STC-02 Release Mass Histogram and Distribution

In contrast, STC-20 corresponds to an Interfacing System Loss-of-Coolant Accident (ISLOCA), characterized by direct environmental release due to containment bypass. The scenario exhibits a rapid and large-scale release, with most cases exceeding 250,000 TBq (Fig. 4). The deterministic release mass (263,741 TBq) is lower than the P95 estimate (312,474 TBq), reinforcing the need for probabilistic assessment in ISLOCA-type accidents.

The Cs-137 release distribution (Fig. 5) shows that most cases fall within 250,000 to 300,000 TBq, with some exceeding 320,000 TBq. These findings emphasize the critical role of uncertainty analysis in evaluating extreme release scenarios and improving risk-informed decision-making.

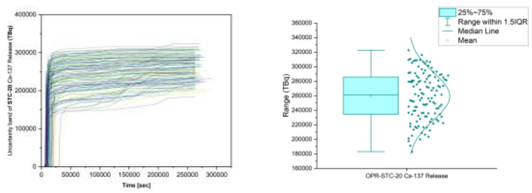

Fig. 4. STC-20 Cs-137 Release Mass[TBq] by Time[sec](Left) and Range[TBq](Right)

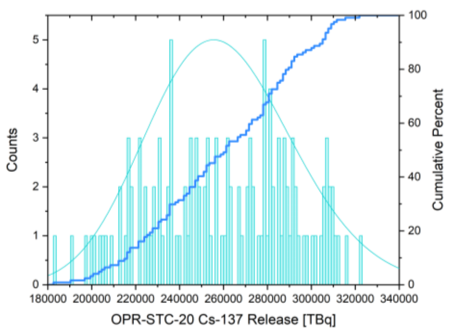

Fig. 5. STC-20 Release Mass Histogram and Distribution

3.2 Release Frequency Uncertainty – Case Study

To assess the uncertainty in release frequency, a batch-processing approach was applied in AIMS-L2 uncertainty analysis, systematically extracting frequency distributions for multiple Source Term STCs.

For STC-02, the frequency distribution was successfully derived without errors (Fig. 6). The mean release frequency was 8.5E-9/RY, while the median (P50) was 8.2E-9/RY, showing slight asymmetry. The 5th percentile (P5) was 5.5E-9/RY, meaning 95% of cases exceeded this level, whereas the 95th percentile (P95) was 1.2E-8/RY, indicating only 5% of cases surpassed this threshold. These values suggest a minor bias due to batch processing effects, highlighting the need for future sensitivity analysis and model refinement.

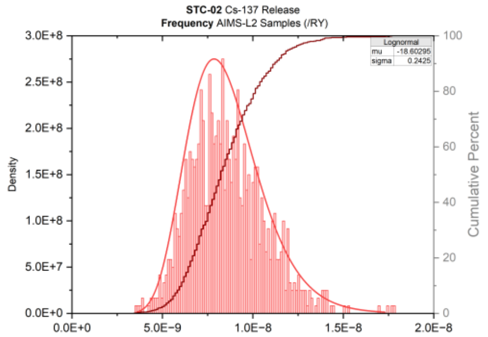

Fig. 6. STC-02 Frequency Distribution of Cs-137 Release (Results derived from AIMS-L2 uncertainty analysis)

For STC-20 (ISLOCA scenario), where no predefined frequency distribution was available, an Error Factor (EF)-based approach was used to generate a lognormal distribution (Fig. 7). The median release frequency (1.01E-8/RY) was obtained from PSA results, while the EF value (207.3), based on KHNP's APR-1400 data [7], was adopted to estimate P95 (1.29E-8/RY) and P5 (4.87E-9/RY). A lognormal distribution was then constructed via a Python-based method, ensuring a probabilistic representation of uncertainty.

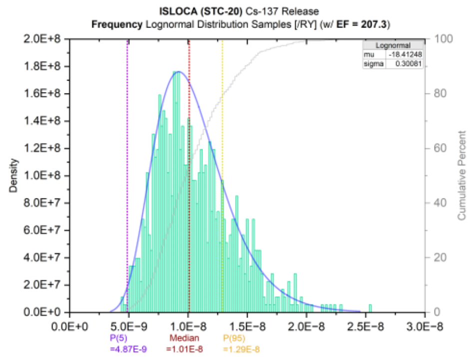

Fig. 7. STC-20 Frequency Distribution of Cs-137 Release (Results derived from error factor calculations [7])

These results demonstrate the feasibility of an EF-based approach for generating probabilistic frequency distributions, supporting a more comprehensive risk assessment framework.

3.3 Aggregation Results

The Risk Density Maps for STC-02 and STC-20 (Fig. 8 and Fig. 9) demonstrate the proposed framework's effectiveness in integrating frequency and release mass distributions for risk evaluation. This approach enables a spatial representation of probabilistic risk, improving risk interpretation.

STC-02 exhibits a peak density of 25.9, approximately five times higher than STC-20 (4.97), indicating that risk is more localized in high-frequency, low-release scenarios. In contrast, STC-20 shows a more dispersed distribution due to its lower occurrence probability but larger release mass. The contour patterns confirm this distinction.

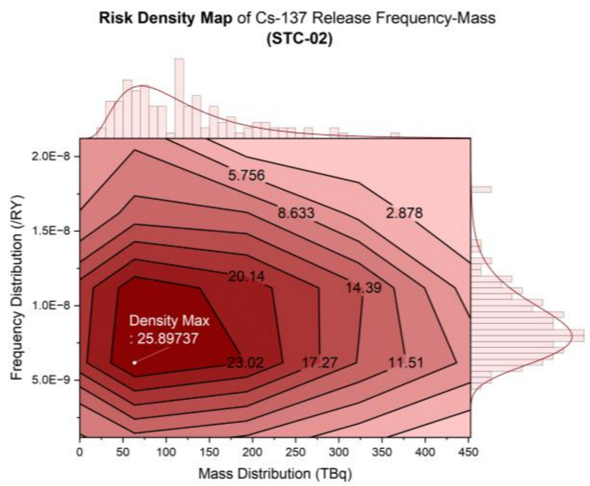

Fig. 8. STC-02 Risk Density Map of Cs-137 Release

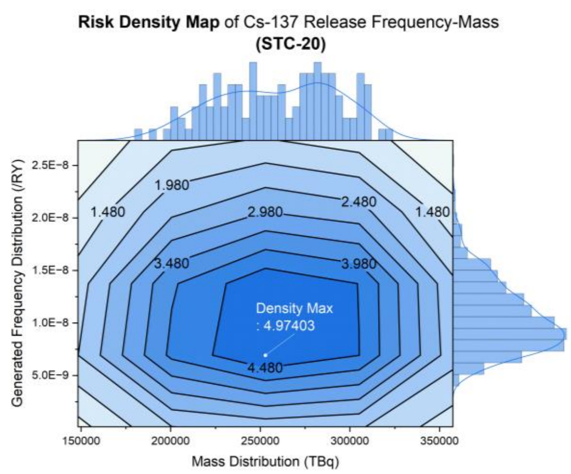

Fig. 9. STC-20 Risk Density Map of Cs-137 Release

Fig. 10 presents the aggregated Risk Density Maps, utilizing Kernel Density Estimation (KDE) to visualize the relationship between release frequency and mass distribution. This representation highlights the probabilistic characteristics of risk concentration, demonstrating the framework's capability to integrate multiple accident scenarios into a unified risk assessment model.

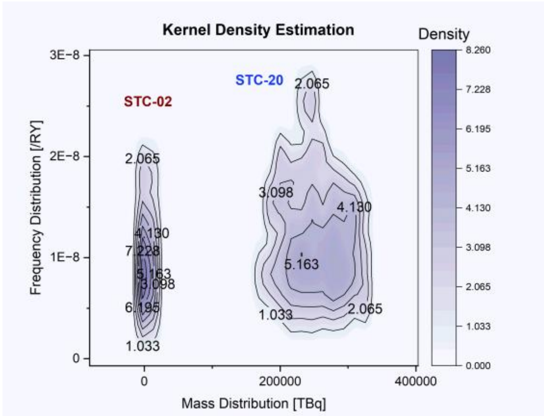

Fig. 10. Unified Kernel Density Estimation for Release Frequency-Mass Relationship (STC-02 and STC-20)

3.4 Discussion

The comparison between STC-02 and STC-20 demonstrates the impact of frequency distribution and uncertainty propagation on risk density estimation. STC-02 shows a higher density peak due to frequent low-release-mass events, whereas STC-20 exhibits a broader distribution with a lower peak due to its lower occurrence probability and larger uncertainty range. The application of Kernel Density Estimation effectively visualizes these probabilistic differences, highlighting the role of event frequency and error factor selection in risk assessment.

4. Conclusions

4.1 Summary and Conclusions

This study developed a framework for nuclear power plant risk assessment by analyzing the uncertainties in Cs-137 release quantity and frequency across different Source Term Categories (STCs). The results were aggregated into Risk Density Maps, providing a structured method for quantifying probabilistic risk.

A case study on OPR-1000 validated the approach, demonstrating its applicability in integrating uncertainty analysis into risk assessment. By aligning with international standards such as NEI 18-04, this framework contributes to the standardization of nuclear risk methodologies, ensuring consistency across evaluations.

Furthermore, the proposed framework is adaptable to various reactor types, including currently operating plants, Generation-IV reactors, and Small Modular Reactors (SMRs). Its implementation is expected to enhance risk communication and decision-making, supporting both domestic and international regulatory and operational practices.

4.2 Further Work

To enhance risk communication, future work will integrate the Frequency-Release Mass distribution aggregation results from this study with the Frequency-Consequence (F-C) Curve based on the Risk-Informed Performance-Based (RIPB) Approach. By utilizing empirical data from NRC, DOE, and ICRP, a refined visualization method will be developed to unify radiological release and human health impact metrics within a single framework.

This advancement is expected to improve the practical application of PSA uncertainty quantification and facilitate more effective decision-making. This research direction can be linked to the frequency-consequence target setting of NEI 18-04 [8], and the application concept of the Risk Density Map reflecting this is presented in Fig. 11.

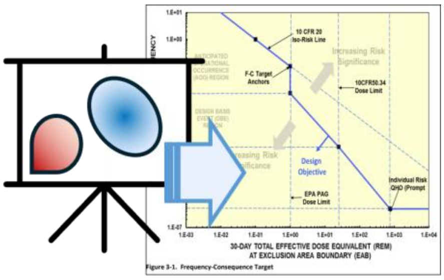

Fig. 11. Concept of Ongoing Work: Application of the Risk Density Map to NEI 18-04 using the Dose Conversion Factor, facilitating risk communication in the TI-RIPB framework.

Acknowledgements

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REFERENCES

[1] J. Yang, Development of an integrated framework to implement the nuclear safety goals with various safety criteria, Nuclear Engineering and Technology, Vol. 57, March 2025.
[2] W. Vechgama, J. Cho, Realistic estimation framework of radioactive release distributions into the environment during nuclear power plant accidents, Nuclear Engineering and Technology, Vol. 56, p. 3097-3111, August 2024.
[3] J. Cho, S. H. Lee, Y. Bang, S. W. Lee, S. Park, Exhaustive simulation approach for severe accident risk in nuclear power plants: OPR-1000 full-power internal events, Reliability Engineering and System Safety, Vol. 225, September 2022
[4] U.S. Nuclear Regulatory Commission (NRC), Estimating Loss-of-Coolant Accident (LOCA) Frequencies Through the Elicitation Process (NUREG-1829), April 2008.
[5] Fauske & Associates LLC (FAI), Modular Accident Analysis Program 5.05 (MAAP5.05), Electric Power Research Institute (EPRI), Washington DC, 2019.
[6] S. Han, H. Lim and J. Yang, AIMS-PSA: A Software for Integrating Various Types of PSA, PSAM9, 2008.
[7] Korea Electric Power Corporation / Korea Hydro & Nuclear Power Co., LTD (KEPCO/KHNP), RESPONSE TO REQUEST FOR ADDITIONAL INFORMATION, APR1400 DCD TIER 2 Revised Table 19.1-6, RAI 410-8357 - Question 19-34, Attatchment (7/10), February 2016.
[8] Nuclear Energy Institute (NEI), Risk-Informed Performance-Based Technology Inclusive Guidance for Non-Light Water Reactor Licensing Basis Development, Technical Report, NEI 18-04 (rev. 1), August 2019.