Development of a Source Term Assessment Framework Integrating Uncertainty Analysis

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EXTENDED ABSTRACT

When assessing source terms in various nuclear power plants accident scenarios, the importance of risk-informed approaches has been increasingly emphasized. Although current probabilistic safety assessment (PSA) systems have been systematically developed and advanced, there is a growing recognition of the need for a framework that can quantify uncertainties, systematically manage risks, and effectively support decision-making processes. In response, this study aims to extend conventional PSA by proposing an integrated framework that incorporates uncertainty quantification into the assessment of safety goals. A case study on Cs-137 is conducted to demonstrate the application of the proposed framework.

The developed framework consists of three major parts. First, the release amount or mass distribution of the source term is quantified using the MAAP5 code combined with sampling techniques. Second, the uncertainty in accident frequency is derived by applying PSA results along with a predefined error factor. Finally, the integrated risk information is visualized as a Risk Density Map, disaggregated by source term categories (STCs).

The case study focuses on the OPR-1000, a pressurized water reactor (PWR) design developed in Korea. The table below shows source term category results from the Level 2 PSA for Hanul Units 3 and 4. Based on these results, two representative STCs were selected for analysis: STC-02, which has the highest release frequency, and STC-20, which shows the highest release magnitude. Specifically, STC-02 corresponds to a scenario within a station blackout (SBO) accident, while STC-20 represents an interfacing system loss-of-coolant accident (ISLOCA).

TABLE I. OPR-1000 STCs Level 2 PSA data

STCs of OPR-1000 and Containment failure mode			Cs-137 Release (TBq)	Frequency (/RY)
STC-01	NOCF	MBLOCA	1.05E+01	5.19E-07
STC-02	NOCF	SBO	5.33E+01	1.20E-06
STC-03	ECF	LEAK, CS-YES	4.29E+00	1.09E-08
... *(omitted for brevity)*				
STC-19	NOISO	CS-NO	1.16E+04	1.08E-09
STC-20	BYPASS	ISLOCA	2.19E+05	1.01E-08
STC-21	BYPASS	SGTR	1.13E+05	2.37E-07

In the second part of the framework, which addresses the uncertainty of frequency, the parameters of the frequency distribution are generally determined based on expert judgment. However, in some cases, detailed statistical data required for precise analysis may not be available. To address this limitation, frequency distributions were constructed using error factor values referenced from U.S.NRC and Korea Hydro & Nuclear Power Co. (KHNP) design certification documents, applying the following formula.

$$Error\ Factor\ (EF) = \frac{P_{95}}{Median} = \frac{Median}{P_5} = 207.3 = \frac{2.09E-6}{1.01E-8} = \frac{1.01E-8}{4.87E-11} \quad (1)$$

To integrate the two distributions, release mass and frequency distributions, a Kernel Density Estimation (KDE) method was applied. The release amount of Cs-137 corresponds to the consequence metric, and together with frequency, it constitutes the primary components of risk. The resulting Risk Density Map, derived from the combined uncertainty distributions of each STC, is visualized as shown in the following figure.

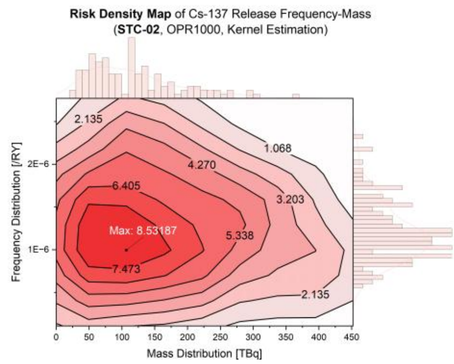

FIGURE 1. Cs-137 Release Risk Distribution (STC-2)

This type of risk visualization helps identify which scenarios or risk contributors require closer attention by explicitly reflecting the range of uncertainties. It ultimately contributes to enhancing the technical basis for data-driven safety management.

A key advantage of the risk density map, a primary output of this framework, is its ability to overcome the limitations of deterministic point estimate assessments. For instance, conventional Level 2 PSA data present the risk of the STC-02 scenario as a single point: a release of 53.3 TBq with a frequency of 1.20E-06 /RY. However, the Risk Density Map, which incorporates uncertainties, provides a much richer set of information.

The map reveals that the highest risk density (Max: 8.53187) occurs at a release of approximately 100 TBq, a value different from the original point estimate. More importantly, the contour lines effectively classify the level of risk. The dense inner contours (value > 6.405) delineate the most critical risk region, while the outer contours (value > 2.135) identify potential risk areas that, despite having lower probability, cannot be ignored. This allows for the quantitative understanding that even scenarios with releases as high as 250 TBq, far from the initial point estimate, fall within a significant risk boundary that warrants consideration.

Such analysis offers more powerful insights when comparing different risk profiles, such as the high-frequency STC-02 and the low-frequency, high-consequence STC-20. Ultimately, the proposed framework provides the technical basis for establishing safety management priorities and developing more robust response strategies by considering the entire spectrum of plausible risk scenarios, rather than focusing on a single accident outcome.

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REFERENCES

[1] J. Cho, S. H. Lee, Y. Bang, S. W. Lee and 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 (2022).

[2] International Atomic Energy Agency (IAEA), *Experience in the Development and Application of Level 2 Probabilistic Safety Assessment for Nuclear Power Plants*, IAEA-TECDOC-2081, IAEA, Vienna (2025).

[3] J. Yang, "Development of an integrated framework to implement the nuclear safety goals with various safety criteria," *Nuclear Engineering and Technology*, Vol. 57 (2025).

[4] 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 (2024).