Risk Profile Development of accident sequences using Source Term Release-to-Consequence Correlation

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1. Introduction

Traditional risk assessment in nuclear power plants (NPPs) is primarily conducted using probabilistic safety assessment (PSA). Severe accident analysis codes (like MELCOR and MAAP) are used for level 1 and 2 PSA to analyze accident progressions and source term releases, while offsite consequences analysis codes (like MACCS) are used for level 3 PSA [1]. Despite its strengths, the traditional PSA framework is not always directly applicable to small modular reactors (SMRs) or Gen IV reactors and can be inefficient for design optimization during the early design phase. Additionally, multi-unit risk assessments, which require evaluating numerous accident scenarios, can be highly time-consuming. To address these challenges, a risk assessment methodology that is universally applicable and computationally efficient is needed to complement the existing PSA framework. Such a methodology would provide intuitive risk profiles for accident sequences, improving risk communication, optimizing design, and reducing computational time.

The framework consists of four main steps: identifying accident sequences, analyzing source terms and uncertainties, quantifying accident consequences, and developing risk profiles. These profiles are represented in the form of frequency-consequence (F-C) curves, allowing for intuitive risk comparisons across different accident sequences. Unlike traditional offsite consequence analysis methods that rely on codes like MACCS, this framework simplifies consequence quantification by establishing a correlation between source terms and accident consequences.

To demonstrate its applicability, the framework was applied to an OPR-1000 Level 1 PSA model, specifically focusing on core damage accident sequences initiated by two events: Loss of Feedwater (LOFW) and Small Break Loss of Coolant Accident (SLOCA).

2. Methodology

Fig. 1 shows the framework to develop risk profiles of NPP accidents. There are four main steps in this overall structure as follows: 1) accident scenarios identification, 2) source term analysis, 3) uncertainty analysis, 4) consequence quantification, 4) risk quantification, and developing risk profile.

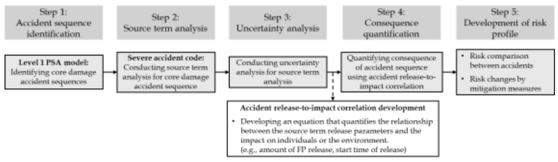


Fig. 1. Framework of risk profile development for accident sequences.

3. Release-to-Consequence Correlation

As previously mentioned, this study utilizes a simplified source term release-to-consequence correlation to quantify accident consequences. This section presents the process of establishing this correlation.

In this study, a correlation between source term release and accident consequences was established using regression analysis based on the SOARCA study [2,3,4]. Only Cs-137, the most representative radioactive isotope, was considered for consequence analysis. The original equation was simplified to:

$$C = k_{env} \cdot \left(k_q \cdot Q + \frac{k_t}{{t_{release}}^{a}} \right) \quad (1)$$

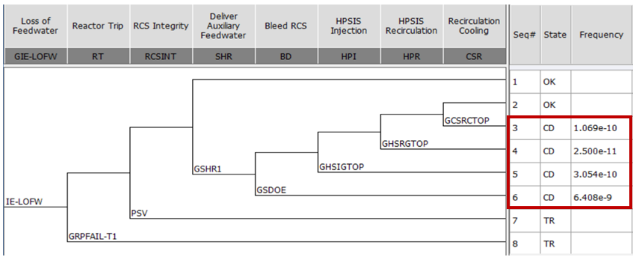
where C is the accident consequence, Q is the Cs-137 release amount, $t_{release}$ is the release start time, and k_{env} is an environmental adjustment coefficient. Parameters k_q, k_t, and a were optimized using MATLAB nonlinear least squares function "lsqnonlin", based on SOARCA data from Surry and Peach Bottom NPPs. The final equation, with optimized parameters ($k_q = 0.79 \times 10^{-8}$, $k_t = 3.55 \times 10^{-4}$, $a = 0.655$), quantifies the probability of latent cancer fatality (LCF) within 10 miles.

4. Result and discussion

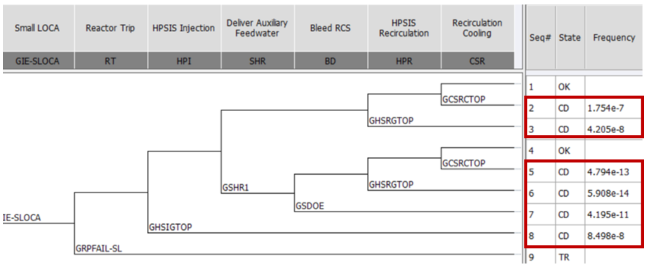
This section applied the framework to the two target initiating events of the OPR-1000 as a case study: loss of feedwater (LOFW) and small loss of coolant accident (SLOCA). By following the five-step methodology, risk profiles were generated for these events using F-C curves. The results enabled an intuitive comparison of the risks associated with different initiating events.

2.1 Accident scenarios identification

Fig. 2 illustrates event trees for LOFW and SLOCA from the level 1 PSA of the OPR-1000. The total core damage frequency (CDF) for LOFW is 6.845 × 10^{-9}, while that for SLOCA is 3.007 × 10^{-7}, showing that SLOCA has a much higher CDF than LOFW.



(a)LOFW



(b) SBLOCA

Fig. 2. OPR-1000 level 1 PSA ET of LOFW and SBLOCA

2.2 Source term analysis

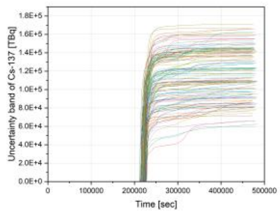
A severe accident analysis was performed for the accident sequences identified in the previous step using MAAP5.05, a code developed by Fauske & Associates, LLC (FAI) and licensed by the Electric Power Research Institute (EPRI). The Cs-137 release amounts and release start times for each sequence are presented in Table I.

Table I. Source term analysis results of LOFW and SLOCA accident sequences.

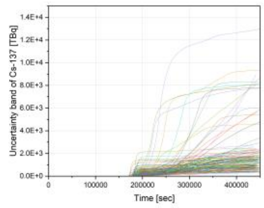
Accident sequences \ Event		Start time [hr]	Release amount [TBq]
LOFW	03	60.69	76,461
	04	52.95	991
	05	46.89	321
	06	50.86	9,562
SLOCA	02	41.85	18,101
	03	42.77	10,380
	05	52.52	88,910
	06	46.59	6,391
	07	49.07	8,561
	08	54.78	8,538

2.3 Uncertainty analysis

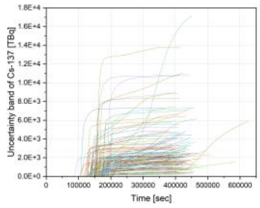
An uncertainty analysis was performed for LOFW and SBLOCA accident sequences using MAAP5.05, a code developed by Fauske & Associates, LLC (FAI) and licensed by the Electric Power Research Institute (EPRI). A total of 124 simulations were carried out for 10 core damage sequences. Figs. 3 and 4 illustrate the uncertainty range of Cs-137 release for each sequence.



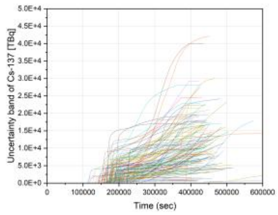
a) LOFW03



b) LOFW04

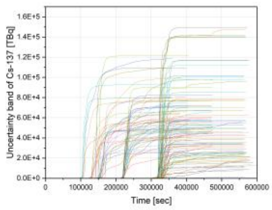


c) LOFW05

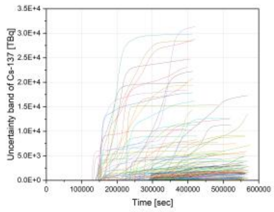


d) LOFW06

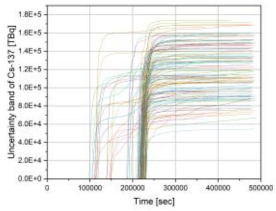
Fig. 3. Uncertainty band of Cs-137 release of LOFW core damage scenarios



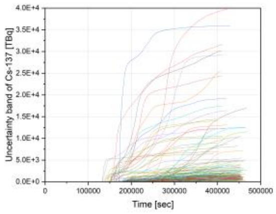
a) SBLOCA02



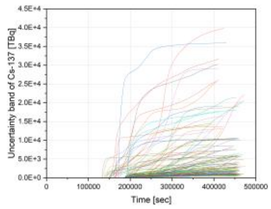
b) SBLOCA03



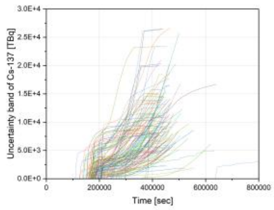
c) SBLOCA05



d) SBLOCA06



e) SBLOCA07



f) SBLOCA08

Fig. 4. Uncertainty band of Cs-137 release of SBLOCA core damage scenarios

2.4 Consequence quantification

In the fourth step of the case study, the consequences of each accident sequences were quantified using Eq. (1), with the environmental adjustment coefficient (k_{env}) set to 1 [hr/TBq]. Fig. 5 presents the quantified consequences for each accident sequence, illustrating the minimum and maximum values, the interquartile range (25th to 75th percentiles), and the mean and median values. This comprehensive visualization provides insight into the distribution and trends of accident impacts across different sequences. The results indicate that among the LOFW accident sequences, LOFW-03 has the most severe consequences, while SLOCA-02 and SLOCA-05 exhibit the highest consequences among the SLOCA sequences.

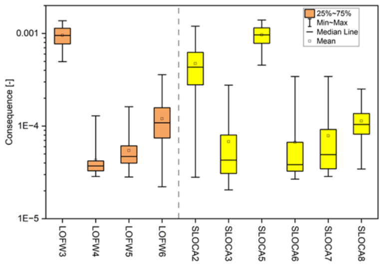
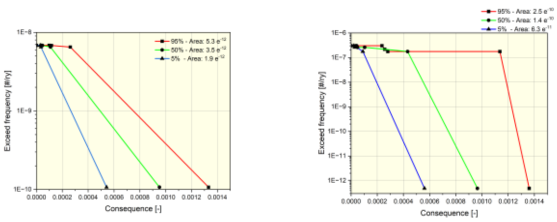


Fig. 4. Minimum and maximum values, 25–75% range, mean, and median of the quantified accident consequences of the accident sequences

2.5. Development of risk profiles

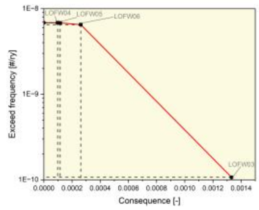
After quantifying accident consequences, risk is visualized using F-C curves, which intuitively represent NPP accident risks. In these curves, the x-axis denotes accident consequences, while the y-axis indicates the exceed frequency. A larger area under the F-C curve signifies a higher overall risk.

Fig. 5 shows F-C curves for LOFW and SLOCA. The red, green, and blue lines correspond to the 95th percentile, median, and 5th percentile of accident consequences. For LOFW, the areas under the F-C curves at the 95th percentile, median, and 5th percentile are 5.3×10^{-12}, 3.5×10^{-12}, and 1.9×10^{-12}, respectively, while for SLOCA, they are 2.5×10^{-10}, 1.4×10^{-10}, and 6.3×10^{-11}, indicating the risk of SLOCA significantly higher. Fig. 6 further confirms that the 95th percentile risk of SLOCA is approximately 50 times greater than LOFW, highlighting its substantially higher risk level.

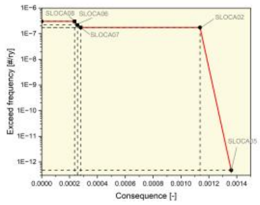


a) LOFW b) SLOCA

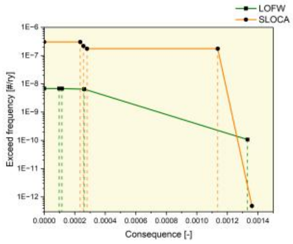
Fig. 5. F-C curves for LOFW and SLOCA



a) LOFW



b) SLOCA



c) LOFW vs. SLOCA

Fig. 6. Comparison of the 95th percentile F-C curves for LOFW and SLOCA

5. Conclusion

This study introduced a framework for developing risk profiles of accident sequences by leveraging source term analysis and establishing a correlation between source terms and consequences. By employing a simplified correlation, the framework eliminates the need for complex offsite consequence analysis codes, making it a versatile and efficient tool for risk assessments across various reactor types. This approach is particularly valuable for improving risk communication and optimizing the design of SMRs and Gen IV reactors.

To demonstrate its applicability, the framework was implemented in the OPR-1000 by constructing risk profiles for LOFW and SLOCA sequences. The results revealed that SLOCA presents a significantly higher risk than LOFW, as reflected in an F-C curve area more than 50 times larger.

Although the case study confirmed the framework's potential for risk assessment, the correlation requires further validation due to its reliance on a limited dataset and simplified assumptions. Future research should incorporate a broader dataset and additional offsite consequence simulations to enhance the robustness of the regression analysis and refine the correlation equation.

6. Acknowledgment

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