Release time-based source term grouping method for level 3 multi-unit probabilistic safety assessment of cascading accidents

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ABSTRACT

Following the Fukushima Daiichi nuclear accident, research into multi-unit probabilistic safety assessment (MUPSA) has increased significantly. Currently, level 3 MUPSA (L3 MUPSA) is typically conducted using results from Level 2 single-unit PSA (L2 SUPSA), with source terms grouped based on their release scale. Consequently, the release timing of each source term remains unspecified. MUPSA is generally modeled under the assumption of simultaneous releases. However, since most multi-unit accidents occur as cascading accidents, L3 MUPSA must be performed specifically for cascading accident scenarios. To perform L3 MUPSA for cascading accident scenarios, two elements are required: (1) a release time-based source term grouping method to facilitate the determination of release timing in L2 SUPSA; and (2) a post-processing code that integrates unit-specific MELCOR Accident Consequence Code System (MACCS) calculation results while accounting for inter-unit release timing differences. Therefore, this study aims to: (1) develop a release time-based source term grouping methodology for L3 MUPSA of cascading accident scenarios; (2) establish a method for integrating unit-specific MACCS calculations that accounts for inter-unit release timing; and (3) implement a method for integrating unit-specific MACCS calculations in a MACCS post-processing code, MURCC.

Keywords: Level 3 multi-unit probabilistic safety assessment, Level 2 single-unit probabilistic safety assessment, source term grouping, Source term category (STC)

I. Introduction

Current research on level 3 multi-unit probabilistic safety assessment (L3 MUPSA) is primarily based on single-unit probabilistic safety assessment (SUPSA) frameworks [1]. While L3 MUPSA remains in its early developmental phase, studies have been conducted in several countries, including the United States [2–10], the United Kingdom [11], Japan [12], China [13], and South Korea [14–18]. However, these studies show variations in source term selection, release timing, and release location, often relying on simplified or constrained assumptions. In L3 MUPSA, a commonly adopted method, involves aggregating source terms from multiple units into a single multi-unit source term, based on the assumption that all releases originate from a common location. This simplification allows the scenario to be modeled as a single-unit accident [1,11,14]. In this study, this approach is referred to as the center of mass (COM) method. The primary advantage of the COM method is its compatibility with conventional L3 SUPSA methodologies. However, this approach may introduce distortions in the results, depending on the spatial configuration of reactor units and prevailing wind direction. To address this limitation, multi-unit accidents have been analyzed in several studies [12,13,17] by modeling each reactor unit at its actual geographic location. In this study, this modeling approach is termed the Multiple location (ML) method, with the implementation developed in a previous study [17] adopted.

In L3 MUPSA, source term categories (STCs) are derived from level 2 SUPSA (L2 SUPSA) using release scale-based grouping. However, since this grouping does not uniquely specify the release timing for each STC, the simplifying assumption that all STCs are released simultaneously in L3 MUPSA analyses have been adopted in most studies [11,12,14]. In practice, even identical initiating events can yield different release timings due to variations in accident progression and safety system responses across reactor units. Therefore, modeling multi-unit cascading accidents as concurrent accidents may lead to distorted risk estimates. While temporal offsets have been introduced in some studies [12,13], these were based on arbitrary intervals rather than actual release timings. Consequently, the outcomes of such analyses remain susceptible to potential inaccuracies.

A realistic cascading accident-based L3 MUPSA requires both a methodology and a computational framework for integrating unit-specific radionuclide concentrations based on their respective release timings. However, the MELCOR accident consequence code system (MACCS) [19-21] does not support aggregating radionuclide concentrations from multiple units with non-simultaneous releases, and scale-based STCs inherently lack the temporal resolution necessary for such analysis. Consequently, the conventional MUPSA framework is fundamentally limited in its ability to accurately model cascading accident-based L3 MUPSA scenarios.

This study aims to develop a release time-based source term grouping method that facilitates the determination of release timing, and to implement a post-processing code that integrates unit-specific MACCS calculation results while accounting for inter-unit release timing differences. These developments are motivated by the need to enable more realistic L3 MUPSA for cascading accident scenarios. Section II outlines a release time-based source term grouping method. Section III presents a methodology for integrating unit-specific MACCS simulations with temporal release data, incorporating modifications to the multi-unit radiological consequence calculator (MURCC) code. Section IV outlines the framework validation through a two-unit cascading accident scenario.

II. Release time-based source term grouping method

Fig. 1 illustrates the procedure for determining source terms in L2 SUPSA. Following core damage, the progression of the accident, from the status of key safety systems in the nuclear power plant (NPP) to potential containment failure, was analyzed using event trees and logical diagrams. Subsequently, representative accident sequences were selected for each resulting STC, with the associated radionuclide releases quantified.

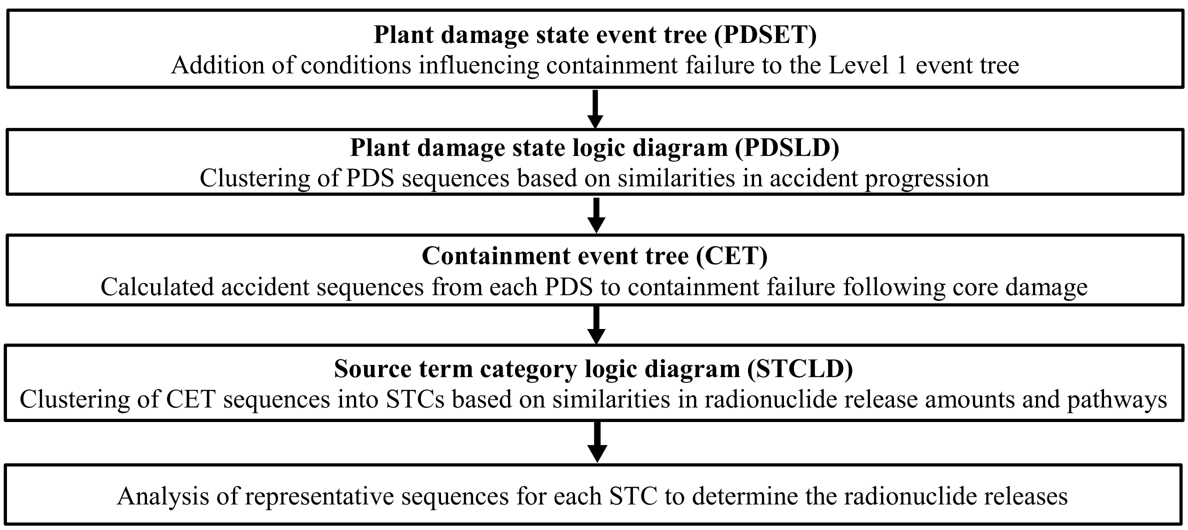


FIGURE 1. Procedure for level 2 single-unit probabilistic safety assessment
Abbreviations: PDSET, Plant Damage State Event Tree; PDSLD, Plant Damage State Logic Diagram; CET, Containment Event Tree; STCLD, Source Term Category Logic Diagram; PDS, Plant Damage State; STC, Source Term Category.

Table 1 presents a comparison of the conventional release scale-based source term grouping method [22] and the release time-based source term grouping approach developed in this study. In the release scale-based source term grouping method, only the interval between core damage and containment failure was considered, followed by the release of radioactive materials. However, in realistic multi-unit cascading accident scenarios, the timing of core damage can vary across reactor units. Therefore, defining a reference time and distinguishing between the time from the initiating event to core damage and the interval from core damage to containment failure are essential. In the release time-based source term grouping method, the source term release timing was classified into three groups (Table 2). Table 1 summarizes the methods used for assessing the time from the initiating event to core damage (T1) and from core damage to containment failure (T2).

TABLE I. Comparison of release scale-based and release time-based source term grouping methods

Category		Release scale-based source term grouping method [22]	Release time-based source term grouping method
Advantages		Utilizes established methodologies, eliminating the need to develop new analytical frameworks.	Enables more precise L3 MUPSA by incorporating source term release timing interval across multiple reactor units.
Disadvantages		Cannot identify the release timing of the source term for each unit, limiting the accuracy of multi-unit analysis.	Requires the development of new event tree headings and logic diagram classification rules to incorporate release timing.
PDSET	Time Information	Difficult to estimate the time from the initiating event to core damage.	Time from initiating event to core damage can be approximately estimated.
	Method	The Level 1 event tree does not account for systems affecting building performance post-core damage. → Develop a PDSET incorporating critical systems for analyzing accident progression.	1) Supplement time information by refining the release scale-based method. 2) Use specific event tree headings indicating event initiation timing. 3) When timing is unclear (e.g., due to operational malfunctions), group minimal cut sets by occurrence time to estimate timing.
PDSLD	Time Information	Time from the initiating event to core damage is not used as a classification criterion for PDS.	Time from initiating event to core damage is used as a classification criterion.
	Method	Clustering variables include system status, system-dependent parameters, initiating event types, and key event timings (e.g., power recovery).	PDS classification incorporates time as an additional clustering variable alongside existing ones.
CET	Time Information	Time from core damage to source term release can be approximately estimated.	Time from core damage to source term release can be approximately estimated.
	Method	1) Analyze reactor building behaviors, including building conditions and failure types. → Reflect severe accident phenomena, accident progression paths, and operator actions affecting containment failure and source term evaluation. 2) Incorporate complex and detailed elements in decomposition event trees, supplementing the CET.	1) Incorporate time-related information into the conditions used in the scale-based method. 2) Account for variations in release timing based on the containment failure mechanism, necessitating more detailed event tree headings. 3) Classify source terms released after a delay as delayed releases, while applying a single release timing if timing differences are insignificant for assessment.
STCLD	Time Information	Time from core damage to source term release is not used as a primary classification criterion for PDS.	Time from core damage to source term release is used as a primary classification criterion for PDS.
	Method	1) In the CET, accident sequences with similar containment degradation and fission product release characteristics are grouped into STCs. 2) For a multi-unit analysis, single-unit STC characteristics such as population-weighted early fatality risk, collective dose, release scale, and containment failure mode are stored in a database. STC data for each unit are retrieved and integrated to estimate the characteristics of STC combinations, which are then used as headings in a logic diagram.	Further classifies STCs by incorporating release timing into the clustering variables used in the scale-based method.
Selection and Analysis of Representative STC Sequences		For each STC, the sequence with the highest frequency or most severe release characteristics is selected as the representative case, while severe accident analysis is performed.	The same selection and analysis procedure is applied as in the scale-based method.

Abbreviations: PDSET, Plant Damage State Event Tree; PDS, Plant Damage State; PDSLD, Plant Damage State Logic Diagram; CET, Containment Event Tree; STC, Source Term Category; STCLD, Source Term Category Logic Diagram; L3 MUPSA, Level 3 Multi-Unit Probabilistic Safety Assessment.

TABLE II. Definitions and calculations method for T1, T2, and T

Variable	Definition	Calculation method
T1	Time interval from the initiating event to core damage	Determined using the PDSET
T2	Time interval from core damage to containment failure	Determined using the CET
T	Total time from the initiating event to the release of radioactive materials	Calculated as the sum of T1 and T2

Abbreviations: PDSET, Plant Damage State Event Tree; CET, Containment Event Tree.

III. Calculation method for cascading accidents in Level 3 multi-unit probabilistic safety assessment

In this study, L3 MUPSA for cascading accidents was performed using the MACCS code and its post-processing tool, MURCC. Fig. 2 illustrates the computational procedure used for conducting L3 MUPSA in a cascading accident scenario involving two reactor units. Source terms for each unit were derived from L2 PSA tools, yielding M source terms for Unit 1 and N for Unit 2. The MACCS code was used to conduct $M + N$ atmospheric dispersion simulations, while MURCC was used to generate $M \times N$ combinations of source terms. MACCS outputs time-integrated air concentrations and atmospheric dispersion parameters (sigma-y, sigma-z) along the plume centerline at specified distances from the release point, based on user-defined input. Using these 1D outputs, 2D time-integrated air concentrations at ground level can be calculated [17].

The total amount of radioactive material released and the duration of the release are provided as inputs to MACCS, and the release rate is derived from these input values. MURCC applies the proportional relationship between the release amount and the time-integrated radionuclide concentration to calculate 2D time-resolved ground-level radionuclide concentrations at specified intervals. This calculation derives 2D time-resolved ground-level radionuclide concentrations at specified intervals based on the previously calculated 2D time-integrated air concentrations and the time-dependent release rate or release amount. Subsequently, MURCC evaluates radiation doses using the equations presented in Table 3 [23], while risk calculations are performed using the same equations [19] as those employed in MACCS.

Under weather sampling conditions, 8,760 hourly meteorological samples were incorporated in L3 MUPSA. MACCS was used to perform dispersion calculations for each sample, and MURCC was used to calculate radionuclide concentrations, radiation doses, and corresponding risks. The final results are expressed as the mean and percentile values of the estimated risk.

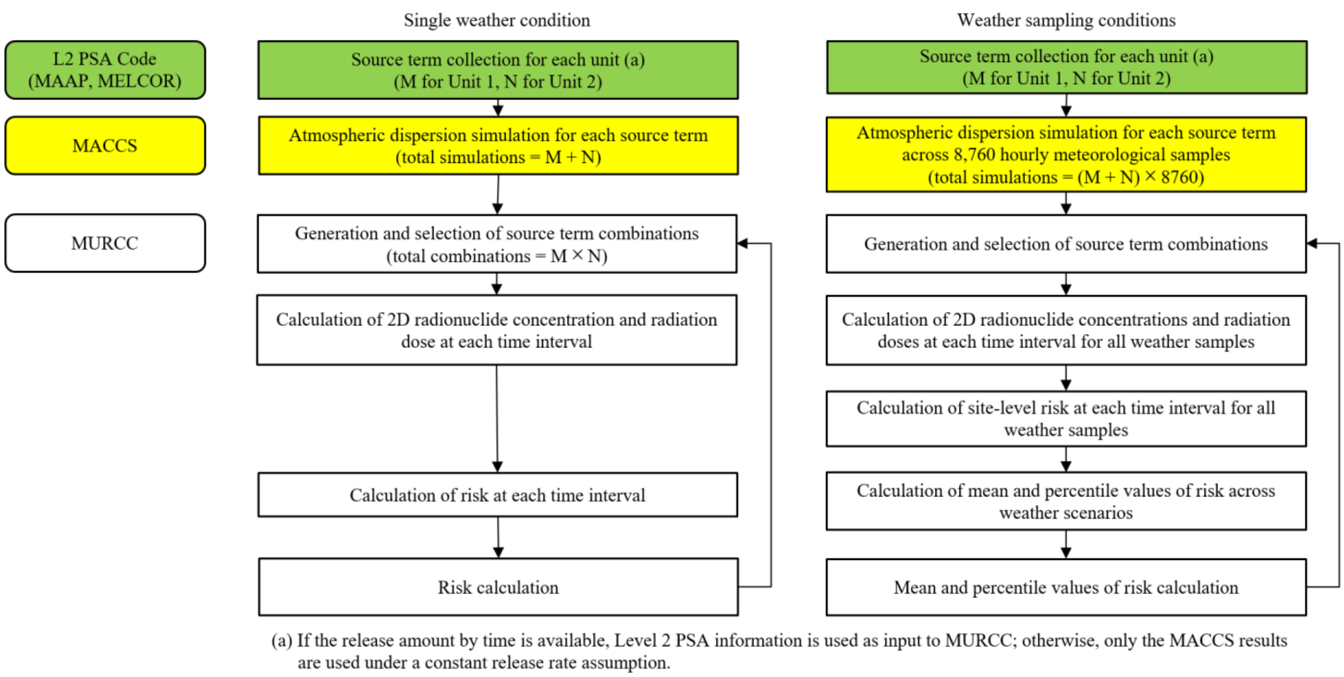


FIGURE 2. Computational procedure for conducting L3 MUPSA for a cascading accident involving two reactor units.

TABLE III. Equations used in MURCC for radiation dose calculation [23]

Cloudshine	$D(x,y) = \sum_{n=1}^{N} \chi_n(x,0,H) \times DC_{cs,n} \times FCDCF(x,y)$	D [Sv], χ [Bq·s/m^3], DC [(Sv/Bq) / (s/m^3)], FCDCF [dimensionless],
Groundshine	$D(x,y) = \sum_{n=1}^{N} C_n(x,y,0) \times DC_{gs,n} \times Time$	D [Sv], C [Bq/m^2], DC [(Sv/Bq) / (s/m^2)], Time [s]
Cloud Inhalation	$D(x,y) = \sum_{n=1}^{N} \chi_n(x,y,0) \times DC_{ih,n} \times BR$	D [Sv], χ [Bq·s/m^3], DC [Sv/Bq], BR [m^3/s]

In contrast to the conventional L3 MUPSA approaches that rely solely on time-integrated calculations of radionuclide concentrations and radiation doses, both time-integrated and time-resolved concentrations were computed in this study. In a cascading accident scenario involving two reactor units (Fig. 3), radioactive materials were released from Unit 1 and Unit 2 at different times. Subsequently, these materials were transported downwind, sequentially passing through Receptor 1 and Receptor 2. The two graphs on the right side of Fig. 3 show the time-integrated radionuclide concentration for the cascading accident involving two reactor units and, for comparison, the time-integrated radionuclide concentration calculated by assuming that the cascading accident occurs concurrently. These time-integrated concentrations are identical in both graphs because the time-integrated values are determined by integrating the radionuclide concentration over time, i.e., by calculating the area under the concentration–time curve. Therefore, if the measurement is taken after both source terms have been fully released, the time-integrated radionuclide concentration remains the same regardless of the release timing from the two units. However, in practice, the radiation dose received at each time interval varies depending on the timing of the radioactive releases. To accurately assess multi-unit cascading accidents, particularly when considering evacuation of the public, time-resolved dose information is essential. This approach requires time-dependent release rates from each unit and the corresponding time-resolved radionuclide concentrations and radiation doses at each receptor calculated.

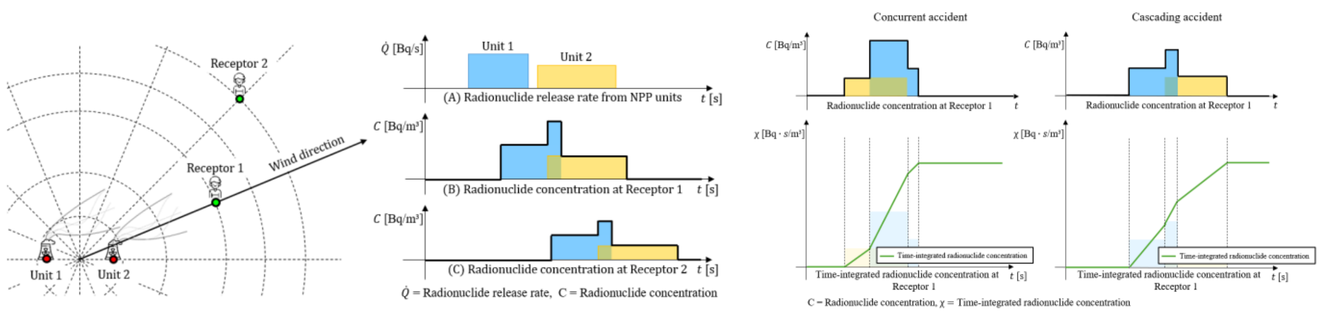


FIGURE 3. Time-resolved and time-integrated radionuclide concentrations for a two-unit cascading accident scenario

IV. Application of the proposed L3 MUPSA methodology to a multi-unit cascading accident scenario

IV.A. Multi-unit cascading accident scenario on the East Coast of Korea

To demonstrate the proposed L3 MUPSA methodology, a hypothetical multi-unit accident scenario was developed for the Hanul and Shin-Hanul NPPs on the East Coast of Korea. Reactor-specific information (Table 4) was obtained from Korea Hydro & Nuclear Power (KHNP), while Fig. 4 illustrates the corresponding site layout. In this study, the maximum fission product inventory of the APR1400 reactor type was used as the reference source term. Given that the site comprises different reactor types, the source terms were scaled accordingly: the inventories for the FRA900 and OPR1000 reactor types were assumed to be 0.64 and 0.71 times that of the APR1400, respectively.

To simplify the analysis, a multi-unit accident scenario involving two reactor units was assumed. Based on the plant damage state event tree (PDSET) and containment event tree (CET) from the L2 SUPSA for a single-unit APR1400 accident, 20 STCs were identified. Among these, STC 6 and STC 20 were selected as representative source terms for the large early release (LER) and large late release (LLR) models, respectively, using the PSA for Shin-Hanul Units 1 and 2 as the basis. Table 5 and 6 summarize the details of each STC and their associated release fractions following the initiation of off-site release, respectively. Owing to the lack of detailed time-dependent release fractions data, a constant release fraction was assumed to occur at a constant rate within two defined intervals: from 0 h to 24 h and from 24 h to 72 h after the initiation of release.

Table 7 presents the combinations of accident units and source terms selected for the analysis to examine the differences based on the key parameters for multi-unit accidents, which will be further discussed in Sections IV.B and IV.C under the given conditions. To enable a clear comparison, the combinations were determined so that in each case, only one parameter (reactor type, inter-unit distance, or source term type) varies, while the others remain constant. Although all cases listed in Table 7 were evaluated, only representative cases that best illustrate the differences for each key parameter are presented in this paper.

To evaluate the release characteristics of radioactive materials, an accident impact analysis was conducted for the selected source terms (STC 6 and STC 20). For each source term, the calculation was performed from the onset of the accident up to 120 hours, considering the release timing and the transport time for radionuclides from the release point to the emergency planning zone (EPZ) boundary. It was assumed that the source term is released in two phases: a predetermined fraction is released uniformly during the first 24 hours following the initiation of the release, and the remaining fraction is released uniformly over the subsequent 48 hours. A wind speed of 3 m/s was assumed, and the receptor was assumed to be located 10 km downwind from the release point along the centerline at ground level. The analysis results showed that, for STC 6, the cumulative effective dose during the first 24 hours following the initiation of the release was 5.464 mSv, while the cumulative effective dose during the subsequent 48 hours was 0.1244 mSv. For STC 20, the cumulative effective dose during the first 24 hours after the release was 0.1382 mSv, and 9.153 µSv during the following 48-hour period. These results confirm that the total release from STC 20 is approximately 1/38 of that from STC 6.

TABLE IV. Reactor unit specifications for the Hanul and Shin-Hanul NPPs

Unit number	Unit	Commercial Operation Date	Reactor Type	Capacity(MW)
1	Hanul Unit 1	1988.09.10	FRA900	950
2	Hanul Unit 2	1989.09.30	FRA900	950
3	Hanul Unit 3	1998.08.11	OPR1000	1000
4	Hanul Unit 4	1999.12.31	OPR1000	1000
5	Hanul Unit 5	2004.07.29	OPR1000	1000
6	Hanul Unit 6	2005.04.22	OPR1000	1000
7	Shin-Hanul Unit 1	2022.12.07	APR1400	1400
8	Shin-Hanul Unit 2	2024.04.05	APR1400	1400

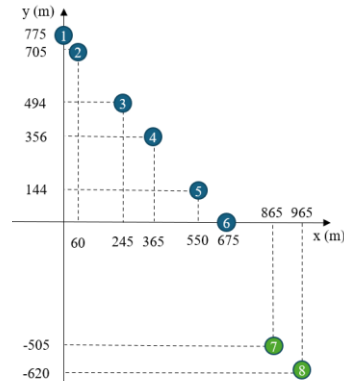


FIGURE 4. Site layout of Hanul and Shin-Hanul NPPs

TABLE V. Selection of representative STCs

CF model	Representative STC	Remark	Source Term Release Timing	Remark
LER	STC-06	Failure of CIS in SBO scenario; failure of Containment Spray	2 h after accident initiation	Core damage (assumed TDP failure)
LLR	STC-20	CIS integrity maintained in SBO scenario; failure of Containment Spray	38 h after accident initiation	Damage caused by RPV over-pressurization (conservative assumption)

Abbreviations: CF, Containment Failure; STC, Source Term Category; LER, Large Early Release; LLR, Large Late Release; CIS, Containment Isolation System; SBO, Station Black Out; TDP, Turbine-Driven Pump; RPV, Reactor Pressure Vessel.

TABLE VI. Release fractions by STC (Following the initiation of off-site release)

STC	Release Time (h)		Noble Gas	I	Cs	Te	Sr	Ru	Ba	La	Ce
	Start	End									
6	1.8	25.8	9.53E-01	1.25E-02	2.02E-02	2.25E-02	2.91E-03	1.39E-03	7.25E-03	1.99E-04	4.23E-03
	1.8	73.8	9.98E-01	1.28E-02	2.02E-02	2.37E-02	2.91E-03	1.39E-03	7.25E-03	1.41E-04	4.26E-03
20	37.9	61.9	5.24E-01	2.18E-03	3.45E-04	1.18E-03	2.04E-05	1.93E-06	1.64E-05	2.30E-07	2.66E-05
	37.9	109.9	5.91E-01	2.48E-03	3.96E-04	1.74E-03	2.05E-05	1.93E-06	1.65E-05	2.41E-07	3.51E-05

TABLE VII. Analyzed STC combinations

Case ID	Unit 1	Unit 2	Unit 1 Source Term	Unit 2 Source Term	Case ID	Unit 1	Unit 2	Unit 1 Source Term	Unit 2 Source Term
U12-LL	U1	U2	LLR	LLR	U78-LL	U7	U8	LLR	LLR
U36-LL	U3	U6	LLR	LLR	U12-EE	U1	U2	LER	LER
U34-LL	U3	U4	LLR	LLR	U36-EE	U3	U6	LER	LER
U12-EL	U1	U2	LER	LLR	U34-EE	U3	U4	LER	LER

U36-EL	U3	U6	LER	LLR	U78-EL	U7	U8	LER	LLR
U34-EL	U3	U4	LER	LLR	U78-EE	U7	U8	LER	LER

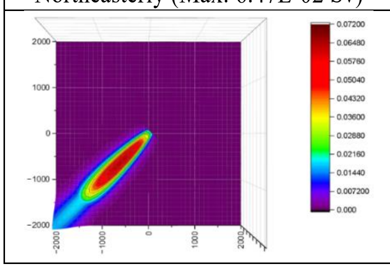
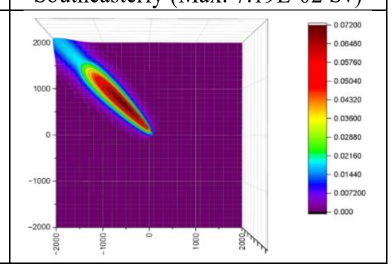
IV.B. Comparison of time-integrated calculation results for multi-unit accident scenarios

IV.B.1. Multi-unit layout and wind direction

In Case U12-LL, the wind direction producing the greatest radiological impact was identified. The computational domain was defined as a square region extending from –2000 m to 2000 m along both the x-axis and y-axis. A uniform wind speed of 2 m/s was assumed. The radiation dose was evaluated as the cumulative effective dose over a 120-hour period following initiation, based on the ICRP-60 dose coefficients.

The lowest cumulative effective doses were observed under southwesterly and northeasterly wind conditions, while the highest occurred under northwesterly and southeasterly winds. The two units are located along a line with a negative slope, forming an angle of approximately 49° with the x-axis. When the wind direction aligns with this axis, the contributions from both units are assumed to overlap significantly, resulting in higher cumulative effective dose. Therefore, the closer the wind direction is to the line connecting the two units, the higher the resulting radionuclide concentration.

TABLE VIII. Cumulative effective dose by wind direction for Case U12-LL

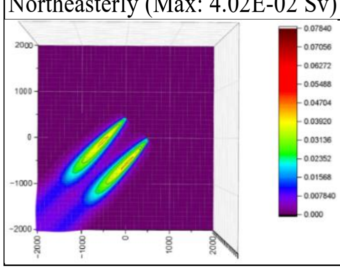
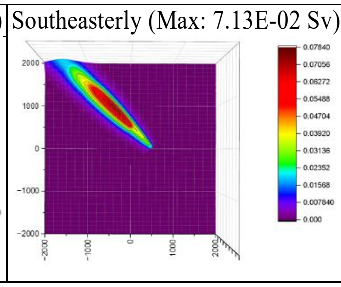
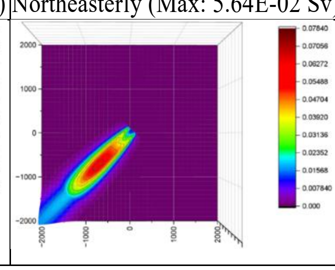
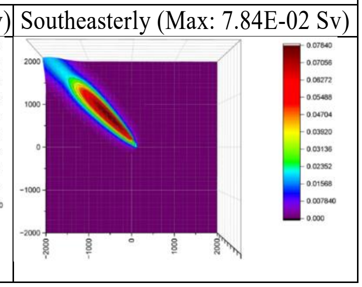
Northeasterly (Max: 6.47E-02 Sv)	Southeasterly (Max: 7.19E-02 Sv)
	

IV.B.2. Inter-unit distance

To analyze the relationship between inter-unit distance and the cumulative effective dose, simulations were performed for Cases U36-LL and U34-LL under southeasterly and northeasterly wind directions. The simulation conditions were consistent with those outlined in Section IV.B.1.

Table 9 shows that Case U36-LL, which has a greater inter-unit distance, results in a lower cumulative effective dose compared to Case U34-LL, where the units are more closely spaced. This suggests that, under identical accident scenarios and wind directions, a greater inter-unit distance leads to a lower cumulative effective dose. As mentioned in the introduction, placing all source terms at a common location for compatibility with conventional L3 SUPSA methodologies may lead to overestimation of results, particularly when the inter-unit distance is large. Therefore, modeling multiple units as co-located at a single point using the conventional COM method can overestimate radionuclide concentrations. To address this issue, multi-unit accidents should be assessed using the ML method [17], which accounts for the actual spatial configuration of reactor units.

TABLE IX. Cumulative effective dose by wind direction for Cases U36-LL and U34-LL

U36-LL		U34-LL	
Northeasterly (Max: 4.02E-02 Sv)	Southeasterly (Max: 7.13E-02 Sv)	Northeasterly (Max: 5.64E-02 Sv)	Southeasterly (Max: 7.84E-02 Sv)
			

IV.B.3. Effect of source term differences

To examine the effect of source term differences between LLR and LER, cumulative effective doses for Cases U12-LL and U12-EE were calculated. In both cases, all conditions were kept identical except for the applied source term. A comparison of the cumulative effective doses from Table 8 (U12-LL) and Table 10 (U12-EE) indicates that the LER source term yields a significantly higher cumulative effective dose than the LLR source term.

The cumulative effective dose for Case U12-EL, involving both LLR and LER source terms, was calculated. All other conditions were identical to those for Case U12-LL and U12-EE, except for the source terms. Table 11 presents the results. In U12-EL, the difference in cumulative effective doses between southeasterly and northeasterly wind directions was smaller than in U12-EE, primarily due to the significantly lower scale of the LLR source term than that of the LER source term.

TABLE X. Cumulative effective dose by wind direction for Case U12-EE

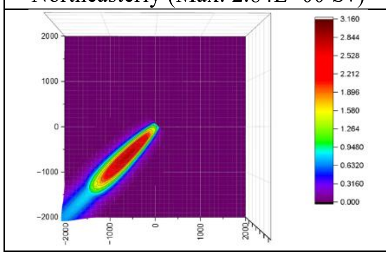
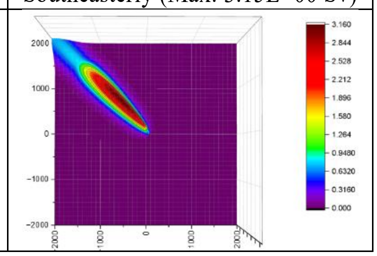
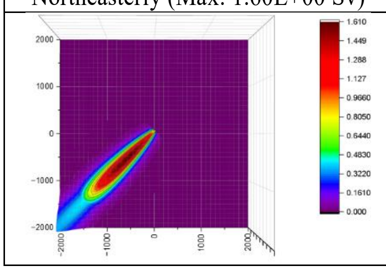
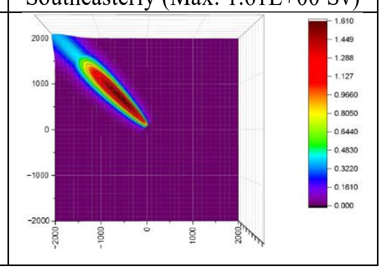
Northeasterly (Max: 2.84E+00 Sv)	Southeasterly (Max: 3.15E+00 Sv)
	

TABLE XI. Cumulative effective dose by wind direction for Case U12-EL

Northeasterly (Max: 1.60E+00 Sv)	Southeasterly (Max: 1.61E+00 Sv)
	

IV.C. Comparison of time-resolved calculation results for multi-unit accident scenarios

As previously discussed (Section IV.B.3), when different source terms are released in a scenario such as U12-EL, a time lag occurs between the releases. Once both source terms have been fully released, the time-integrated radionuclide concentrations and cumulative doses become similar for both concurrent and cascading accident scenarios. Therefore, distinguishing between these scenarios requires calculating radionuclide concentrations and radiation doses at specific time intervals.

Under southeasterly wind conditions at 2 m/s, radionuclide concentration was calculated for Case U36-EL. The computational domain was defined as a square region extending from –2000 m to 2000 m along both the x-axis and y-axis. The receptor was assumed to be located at (–500 m, 500 m). Considering the assumption that the release fraction is constant within two release periods (from 0 to 24 hours and from 24 to 72 hours after the initiation of release) radionuclide concentrations were calculated at 2-h intervals to balance temporal resolution with computational efficiency. Fig. 5 illustrates the radionuclide concentrations at 2-h intervals and the time-integrated radionuclide concentration results. The time-integrated radionuclide concentration previously discussed (Section III) represent the cumulative levels of radionuclides released from all multi-unit source terms up to the calculation time. Therefore, if both source terms are released within the evaluation period, the time-integrated concentration remains similar regardless of the release timing. Consequently, when the scales of the two source terms are identical, the time-integrated radionuclide concentrations will be equivalent for both concurrent and cascading accident scenarios.

However, Fig. 5 illustrates that the radionuclide concentrations at each time interval vary depending on the release timing of each source term. Based on these data, to assess the effective dose corresponding to the timing of each source term release, radiation doses for Case U36-EL were calculated for the 4–6 h and 40–42 h intervals under southeasterly and northeasterly wind conditions. The results are presented in Table 12.

Owing to the significant difference in scale between the LER and LLR source terms, the effect of the LLR source term is relatively small. In multi-unit accident scenarios, when the release scales differ significantly between units, the contribution from the unit with the smaller source term is relatively minor in the results. However, for off-site consequence assessments at specific time intervals or when incorporating evacuation modeling, accurately evaluating even relatively minor contributions is essential.

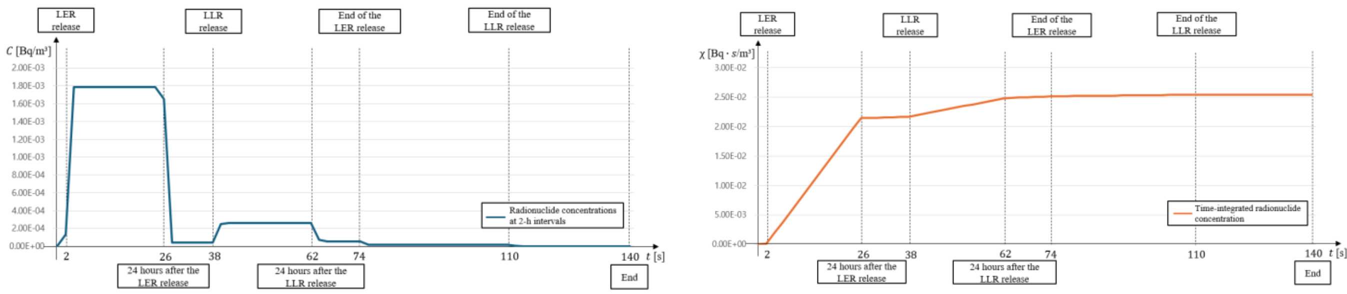
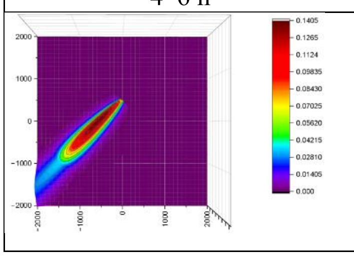
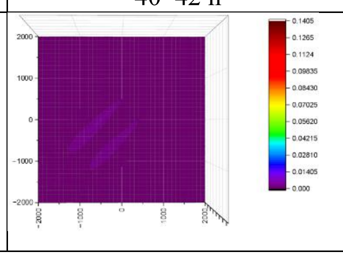
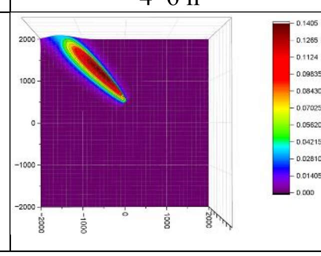
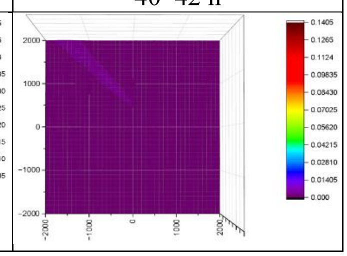


FIGURE 5. Radionuclide concentrations at 2-h intervals and time-integrated radionuclide concentration at the receptor location (–500 m, 500 m) for Case U36-EL

TABLE XII. Effective dose at each time interval by wind direction for Case U36-EL

Northeasterly		Southeasterly	
4–6 h	40–42 h	4–6 h	40–42 h
			

V. Conclusions

In this study, a release time-based source term grouping method is proposed, and MURCC is enhanced to integrate unit-specific calculations by accounting for inter-unit release timing differences in the MUPSA of cascading accidents. The methodology was applied to a hypothetical two-unit accident scenario on the East Coast of Korea.

In time-integrated calculations of released radionuclides, cascading and concurrent accident scenarios yield similar results once all source terms are fully released. In contrast, time-resolved calculations consistently reveal differences between the two scenarios, as the staggered release in cascading accidents distributes radionuclide concentrations and radiation doses over time. In a multi-unit cascading accident scenario, evacuation of the public may begin after the release of a single source term. Under these conditions, radiation exposure to the population remains lower in the cascading accident than in the concurrent accident. To ensure accurate L3 MUPSA results, the analysis should incorporate the actual release timing of each unit, rather than assuming concurrent releases. In multi-unit accident scenarios with significant differences in release scale between units, the effects of the smaller source term may not be observable. However, when off-site consequence assessments are conducted at specific time intervals or when evacuation modeling is incorporated, even minor contributions require precise evaluation.

Table 13 summarizes the additional research required to support the implementation of the release time-based source term grouping method. The proposed methodology requires further refinement before application to real-world multi-unit cascading accident scenarios. These limitations are identified for future investigation.

TABLE XIII. Additional research needs for the release time-based source term grouping method

Procedure in L2 PSA	**Additional research needs for the release time-based source term grouping method**
PDSET	1) Revise event tree headings to reflect the timing of key events more accurately.

	2) Develop a method to determine the time from the initiating event to core damage with greater precision.
PDSLD	1) Establish classification rules that more clearly distinguish timing differences. 2) Since incorporating time from the initiating event to core damage as a classification criterion may significantly increase the number of PDSs, develop a logic-based approach to reduce this complexity, such as grouping PDSs that result in similar off-site consequences.
CET	Revise event tree headings to reflect the timing related to source term release more accurately.
STCLD	1) Establish classification rules that differentiate source term release timing. 2) Since incorporating release timing as a classification criterion may significantly increase the number of STCs, develop a logic-based approach to reduce complexity, such as grouping STCs with similar off-site consequences.

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