Transactions of the Korean Nuclear Society Autumn Meeting
Changwon, Korea, October 30-31, 2025

A Typical Cascading Level 3 MUPSA Calculation for Hanul Nuclear Power Plants

Hee Young Lee [a], Gee Man Lee [a], Seong Kyu Park[b], Woo Sik Jung [a*]
[a]*Nuclear Engineering, Sejong University, 209 Neungdong-ro, Gwanggin-gu, Seoul, Korea*
[b]*Nuclear Engineering Services & Solutions, 1305, U-Tower, Dongchendong, Yongin-shi, Kyeonggi-do, 16827, Korea*
[*]*Corresponding author: woosjung@sejong.ac.kr*

Keywords : L3 MUPSA, L2 SUPSA, Source term grouping, STC

1. Introduction

In Level 3 multi-unit probabilistic safety assessment (L3 MUPSA), the Center of Mass (COM) method is commonly employed, wherein the source terms of all reactor units are aggregated into a single multi-unit source term under the assumption that all releases originate from the same location. This simplification facilitates the direct application of conventional Level 3 single-unit PSA (L3 SUPSA) procedures. However, it may yield distorted results depending on the spatial arrangement of reactor units and the prevailing wind direction. To address this limitation, Sejong University proposed the Multiple Location (ML) method [1], which explicitly models each reactor unit at its actual geographic position. Figure 1 presents a comparison of the calculation approaches adopted in the COM and ML methods.

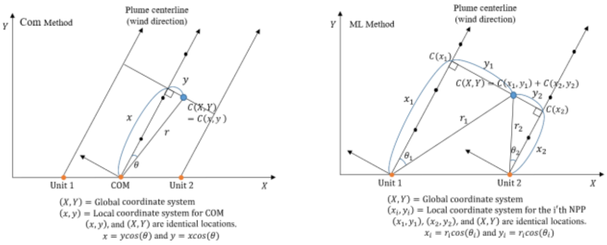


Fig. 1. Calculation of radionuclide concentrations through coordinate transformation in the COM and ML methods[1]

In L3 MUPSA, source term categories (STCs) are typically derived using the same release scale-based grouping method employed in Level 2 SUPSA. Although this approach is effective for single-unit analyses, it does not specify the release timing of each STC. As a result, most L3 MUPSA studies have adopted the simplifying assumption that all STCs are released simultaneously, irrespective of the unit or accident sequence. In reality, however, even identical initiating events may lead to different release timings due to variations in accident progression and safety system responses across units. Consequently, modeling multi-unit cascading accidents as concurrent accidents risks generating inaccurate or biased risk estimates. To overcome this limitation, Sejong University proposed a release time-based source term grouping method [2].

Building upon this, the present study introduces a Level 3 MUPSA calculation methodology for cascading accidents that integrates both the ML method and the release time-based source term grouping approach developed at Sejong University. To illustrate its application, the proposed methodology is applied to a representative two-unit cascading accident scenario.

2. Release time-based source term grouping method

In this study, the release time-based source term grouping method follows the approach proposed in a previous study [2]. Table 1 summarizes the characteristics of this method. In contrast to the conventional release scale-based grouping method, the proposed approach distinguishes release timing into two separate intervals: from the initiating event to core damage, and from core damage to containment failure.

Table I: Characteristics of each step in the release time-based source term grouping method

Category		Release time-based source term grouping method
Advantages		Enables more precise L3 MUPSA by incorporating source term release timing interval across multiple reactor units.
Disadvantages		Requires the development of new event tree headings and logic diagram classification rules to incorporate release timing.
PDSET	Time Information	Time from initiating event to core damage can be approximately estimated.
	Method	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 initiating event to core damage is used as a classification criterion.
	Method	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.
	Method	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 used as a primary classification criterion for PDS.
	Method	Further classifies STCs by incorporating release timing into the clustering variables used in the scale-based method.
Selection and Analysis of Representative STC Sequences		The same selection and analysis procedure is applied as in the scale-based method.

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

Unlike conventional L3 MUPSA approaches that rely exclusively on time-integrated calculations, this study evaluates both time-integrated and time-resolved results. A two-unit accident scenario was constructed based on the plant layout shown in Figure 2. Figure 3 compares the time-resolved and time-integrated radionuclide concentrations at Receptor 1 for both concurrent and cascading accident cases. In both cases, the magnitude of the source term released from each unit is assumed to be identical.

In the representative two-unit cascading accident scenario, the final time-integrated radionuclide concentrations remain identical irrespective of release timing; however, the temporal distribution of radiation doses differs depending on when each release occurs. Therefore, accurate assessment of multi-unit cascading accidents—particularly for applications such as public evacuation planning—requires unit-specific, time-dependent release rates together with the corresponding time-resolved radionuclide concentrations and radiation doses at each receptor. Furthermore, as shown in the left-hand graph, even if a concurrent accident is assumed, the actual arrival time of source terms at a receptor can differ depending on the geographic locations of the units and the prevailing wind direction. Such differences cannot be captured by the COM Method. Thus, multi-unit accident scenarios must be analyzed using the ML method, which accounts for the actual positions of the reactor units.

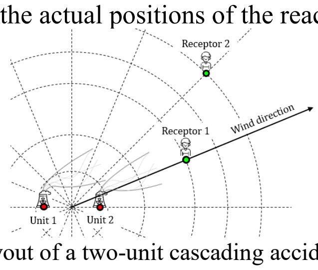


Fig. 2. Site layout of a two-unit cascading accident scenario

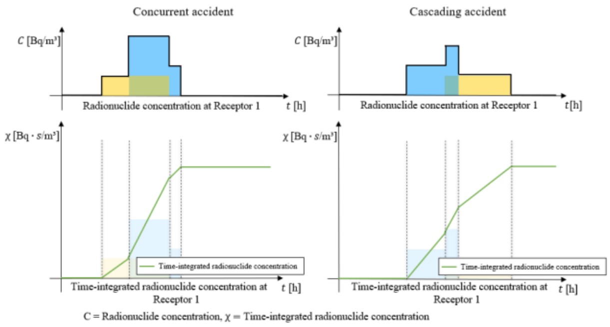


Fig. 3. Time-integrated radionuclide concentrations for a two-unit cascading accident scenario

This study conducted L3 MUPSA for cascading accidents using the MACCS [3,4,5] code and its post-processing tool, MURCC [1]. Figure 4 illustrates the computational procedure for conducting L3 MUPSA of a cascading accident involving two reactor units, based on the combined use of MACCS and MURCC.

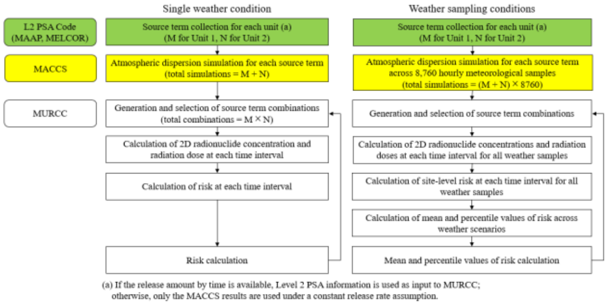


Fig. 4. Computational procedure for conducting L3 MUPSA for a cascading accident involving two reactor units.

4. Application of the proposed L3 MUPSA methodology

4.1 Multi-unit cascading accident scenario on the East Coast of Korea

To demonstrate the proposed methodology, a hypothetical multi-unit accident scenario was developed for the Hanul and Shin-Hanul nuclear power plants located on the East Coast of Korea. The maximum core fission product inventory of the APR1400 reactor type was used as the basis, with the inventories of the FRA900 and OPR1000 reactors assumed to be 0.64 and 0.71 times that of the APR1400, respectively. For simplification, a two-unit accident scenario was assumed.

Based on the plant damage state event tree (PDSET) and the containment event tree (CET) from the Level 2 SUPSA for a single-unit APR1400 accident, twenty source term categories (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 results for Shin-Hanul Units 1 and 2 (APR1400 reactors) as the reference. Owing to the lack of detailed time-dependent release data, a constant release fraction was assumed over two intervals: 0–24 hours and 24–72 hours after the initiation of release.

An accident impact analysis was conducted for STC 6 and STC 20 over 120 hours, assuming a wind speed of 3 m/s and a receptor located 10 km downwind along the plume centerline at ground level. The results indicated that, for STC 6, the cumulative effective dose was 5.464 mSv during the first 24 hours and 0.1244 mSv during the subsequent 48 hours. For STC 20, the corresponding values were 0.1382 mSv and 9.153 μSv, respectively. These results demonstrate that the total release associated with STC 20 is approximately 1/38th of that associated with STC 6, underscoring the substantial difference in release magnitude between the LER and LLR models.

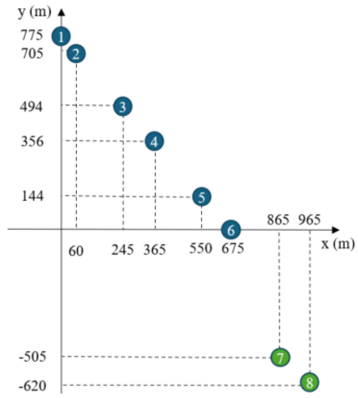


Fig. 4. Site layout of Hanul and Shin-Hanul NPPs

Table II: Characteristics of each step in the release time-based source term grouping method

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

Table III: Selection of representative STCs

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

Table IV: Release fractions by STC (Following the initiation of off-site release)

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

4.2 Comparison of time-integrated calculation results for multi-unit accident scenarios

The computational domain was defined as –3000 m to 3000 m along both the x- and y-axes. A wind speed of 2 m/s was assumed, and two wind directions—southeast and northeast—were considered. The reactor units are arranged along a negatively sloped line at an angle of approximately 49° from the x-axis. When the wind direction is aligned with this line, the contributions from individual units overlap, leading to an increased dose. Therefore, the wind directions associated with the maximum and minimum doses were selected for analysis. Effective doses were calculated in accordance with ICRP-60 and evaluated as cumulative values over a 120-hour period, considering the typical 4-day early phase specified by the Protective Action Guides (PAGs) together with the completion of both LER and LLR releases.

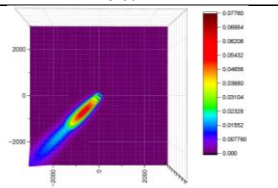
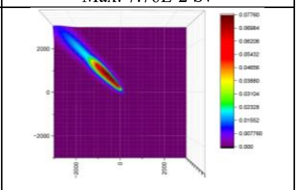
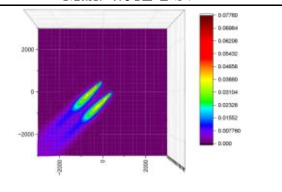
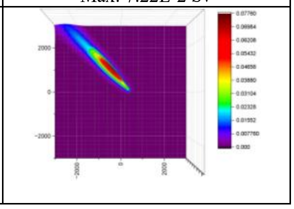
The comparative analysis of two-unit accident scenarios was performed by accounting for inter-unit distance, differences in source terms, and differences in source term release timing.

4.2.1. Inter-unit distance difference

Table V: Combinations for Analyzing Inter-Unit Distance Differences

Case ID	Unit 1	Unit 2	Unit 1 Source Term	Unit 2 Source Term
U34-LL	U3	U4	LLR	LLR
U36-LL	U3	U6	LLR	LLR

Table VI: Cumulative effective dose by wind direction for Case U34-LL and U36-LL

U34-LL(Distance: 182.9m)	
Northeast wind Max: 5.59E-2 Sv	Southeast wind Max: 7.76E-2 Sv
	
U36-LL(Distance: 182.9m)	
Northeast wind Max: 4.01E-2 Sv	Southeast wind Max: 7.22E-2 Sv
	

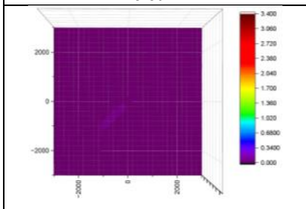
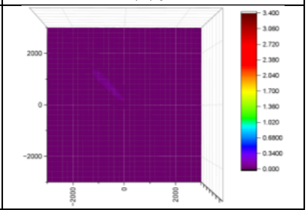
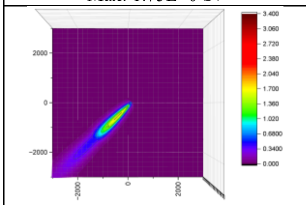
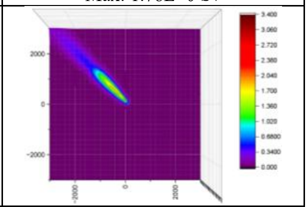
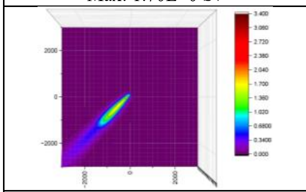
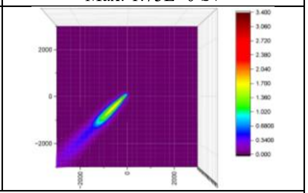
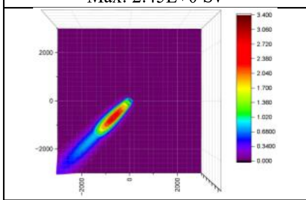
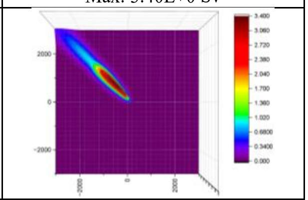
The results of the cases in Table 5 are summarized in Table 6. It is observed that the cumulative effective dose for U34-LL, which corresponds to a shorter inter-source distance, is higher than that for U36-LL, which has a longer inter-source distance. This suggests that the assumption adopted in the conventional L3 SUPSA methodology—that all source terms are released from the same location—may lead to an overestimation of risk. Accordingly, it is more appropriate to apply the ML method, which accounts for the actual spatial configuration of reactor units, in order to achieve a more realistic assessment.

4.2.2. Source term differences

Table VII: Combinations for Analyzing Inter-Unit Source term Differences

Case ID	Unit 1	Unit 2	Unit 1 Source Term	Unit 2 Source Term
U34-LL	U3	U4	LLR	LLR
U34-LE	U3	U4	LLR	LER
U34-EL	U3	U4	LER	LLR
U34-EE	U3	U4	LER	LER

Table VIII: Cumulative effective dose by wind direction for Case U34-LL, U34-LE, U34-EL and U34-EE

U34-LL(Distance: 182.9m)	
Northeast wind Max: 5.59E-2 Sv	Southeast wind Max: 7.76E-2 Sv
	
U34-LE(Distance: 182.9m)	
Northeast wind Max: 1.75E+0 Sv	Southeast wind Max: 1.78E+0 Sv
	
U34-EL(Distance: 182.9m)	
Northeast wind Max: 1.70E+0 Sv	Southeast wind Max: 1.73E+0 Sv
	
U34-EE(Distance: 182.9m)	
Northeast wind Max: 2.45E+0 Sv	Southeast wind Max: 3.40E+0 Sv
	

To examine the differences associated with source terms, the results of the calculations for the cases in Table 7 are presented in Table 8. A comparison of the cumulative effective doses for U34-LL and U34-EE indicates that the LER source term yields a significantly higher cumulative effective dose than the LLR source term. Because the magnitude of the LLR source term is substantially smaller than that of the LER source term, the differences in cumulative effective dose between southeasterly and northeasterly wind directions in U34-LE and U34-EL are smaller than those observed in U34-LL and U34-EE.

4.3 Comparison of time-resolved calculation results for multi-unit accident scenarios

In cases where different source terms are released, such as U34-LE and U34-EL, a time lag occurs between the releases. Regardless of whether the releases are assumed to occur simultaneously or their actual release timings are considered, the resulting time-integrated radionuclide concentrations and cumulative doses remain similar. Therefore, distinguishing between these scenarios requires the evaluation of radionuclide concentrations and radiation doses at specific time intervals.

To investigate the difference between the conventional assumption that all source terms are released simultaneously and the case where an actual time lag is considered, two scenarios were analyzed: (i) the actual Cascading U34-EL case, in which the LER and LLR source terms are released with a time lag, and (ii) the Concurrent U34-EL case, in which the LLR was assumed to be released simultaneously with the LER. The computational conditions were identical to those described in Section 4.2, with the receptor assumed to be located at (–1000 m, 1000 m) under southeasterly wind conditions. Radionuclide concentration graphs at 1-h intervals and time-integrated radionuclide concentration graphs were produced, and the results are presented in Figures 6.

When examining the time-integrated radionuclide concentrations after a certain degree of release completion, the actual U34-EL and the hypothetical concurrent case appear nearly identical. However, the 1-hour interval concentration graphs reveal differences between the two cases. In this scenario, the effect of the LLR source term is relatively small due to its much smaller scale compared to the LER source term. Nevertheless, cases in which the source term magnitudes are not significantly different must also be considered, and for off-site consequence assessments at specific time intervals or for evacuation modeling, it is essential to accurately evaluate even relatively minor contributions.

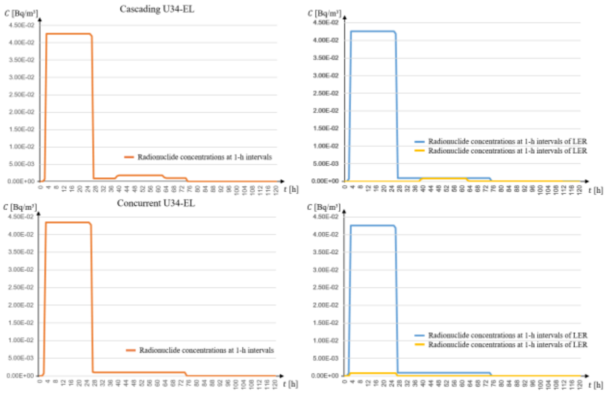


Fig. 5. Radionuclide Concentrations at Receptor for Cascading U34-EL vs. Concurrent U34-EL (SE Wind)

5. Conclusions

In this study, a release time-based source term grouping method was proposed, and a hypothetical two-unit accident scenario on the East Coast of Korea was analyzed using the MURCC code, which was enhanced to perform L3 MUPSA by accounting for inter-unit release timing differences. The results highlight several key findings.

First, even in concurrent accident scenarios, depending on the arrangement of reactor units and weather conditions, receptors located at different positions may experience staggered exposure to source terms. To accurately capture this effect, calculations must reflect the ML method rather than the COM Method.

Second, the distinction between conservative and best-estimate evaluations must be carefully addressed. For conservative estimates, assuming concurrent accidents is acceptable regardless of evacuation timing, as this provides bounding results. In best-estimate analyses, concurrent accident assumptions may also be acceptable when evacuation is not explicitly considered. When evacuation is taken into account, however, the situation changes: evacuation of the public may begin after the release of a single source term, reducing subsequent exposure from later releases. If all source terms are instead assumed to be released simultaneously, this effect cannot be reflected, and public radiation exposure may be overestimated. Therefore, to ensure accurate L3 MUPSA results, the actual release timing of each source term should be incorporated into the analysis rather than assuming simultaneous releases.

When the difference in release scale between source terms is substantial, the contribution of the smaller source term may not be apparent in the overall results. Nonetheless, in off-site consequence assessments conducted at specific time intervals or in analyses that incorporate evacuation modeling, even relatively minor contributions must be evaluated with precision.

The proposed methodology requires further refinement before being applied to real-world multi-unit cascading accident scenarios. These limitations have been identified as subjects for future research.

ACKNOWLEDGMENTS

This work was supported by the Nuclear Safety Research Program through the Korea Foundation Of Nuclear Safety(KoFONS) using the financial resource granted by the Nuclear Safety and Security Commission(NSSC) of the Republic of Korea. (RS-2022-KN067010 and RS-2021-KN050610)

REFERENCES

[1] W. S. Jung, H. R. Lee, J. R. Kim, G. M. Lee, Development of MURCC code for the efficient multi-unit level 3 probabilistic safety assessment, Nucl. Eng. Technol. 52(10) 2221–2229, 2020.

[2] H. Y. Lee, G. M. Lee, W.S. Jung, S. K. Park, Development of a new release-time-based source-term grouping method for level 3 multi-unit probabilistic safety assessment of cascading accidents, Transactions of the Korean Nuclear Society Autumn Meeting, Changwon, Korea, October 24-25, 2024

[3] Chanin, D., Young, M. L., Randall, J., Jamali, K., Code manual for MACCS2: Volume 1, User's guide, NUREG/CR-6613, SAND97-0594, U.S. NRC, 1998.

[4] McFadden, K., Bixler, N. E., Lee Eubanks, Haaker R., WinMACCS, a MACCS2 interface for calculating health and economic consequences from accidental release of radioactive materials into the atmosphere: User's guide and reference manual for WinMACCS version 3, U.S. NRC, 2009.

[5] Sandia National Laboratories, MACCS, https://maccs.sandia.gov/maccs.aspx.