Development of a new release-time-based source-term grouping method for level 3 multi-unit probabilistic safety assessment of cascading accidents

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1. Introduction

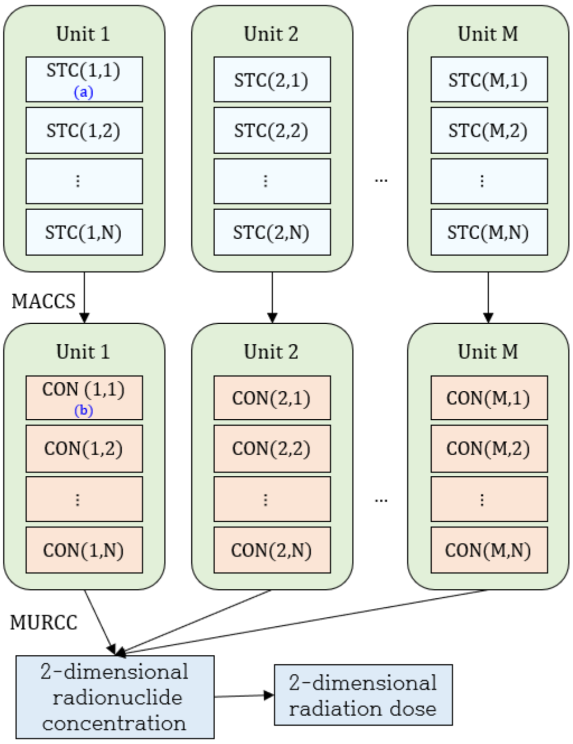
Following the Fukushima multi-unit nuclear power plant (NPP) accident in 2011, studies utilizing the level 3 (L3) multi-unit probabilistic safety assessment (MUPSA) methodology— derived from the single-unit probabilistic safety assessment (SUPSA) methodology—have been conducted to systematically evaluate the safety of multi-unit NPPs[1,2].

In Korea, studies on concurrent accidents at the Kori and Shin-Kori NPP sites were conducted using the L3 MUPSA methodologies [1,2]. However, by simplifying the plant into a single large unit at the same location (the center of mass (COM) method [1,3]), these approaches required an exponentially increasing number of source-term combinations (STCs) relative to the number of units and often overestimate or distort the risk of multi-unit accidents.

To address these limitations, Sejong University developed the multi-unit radiological consequence calculator (MURCC)[7–10]—a post-processing code based on the MELCOR Accident Consequence Code System (MACCS)[4–6]. MURCC employed the multiple location (ML) method to analyze the multi-unit accident considering the actual locations of each unit. This advancement enabled a reduction in the number of L3 MUPSA calculations required and yielded more realistic L3 MUPSA calculation results.

Recognizing that concurrent accidents are rare and that most multi-unit accidents are cascading in nature, Sejong University equipped the MURCC with features enabling L3 MUPSA of cascading accidents. Despite this innovative approach, the current L2 SUPSA methodology does not consider STCs based on release time (grouping source terms based on release time). Consequently, the existing L2 SUPSA technique is unable to offer essential inputs for the new L3 MUPSA methodology developed for analyzing cascading accidents. (see Section 3) This report introduces, for the first time, a new multi-unit source-term grouping methodology based on release time for L3 MUPSA of cascading accidents.

2. Multi-Unit Accident Assessment ML Method



(a) STC(i,j) refers to the j-th STC of the i-th unit.
(b) Radionuclide concentration along the centerline of the wind direction.

Fig. 1. Multi-Unit Accident Evaluation Procedure Using the MACCS and MURCC (Considering a Fixed Wind Direction)

The ML method combines calculated radionuclide concentrations for each unit while accounting for the actual locations of the NPP units [11]. The final dose is then computed based on the resulting combined radionuclide concentrations. This section categorizes multi-unit accident evaluation ML methods into two types: concurrent accidents and cascading accidents. Fig. 1 illustrates the computational process of the ML method for analyzing multi-unit accidents using the MACCS and MURCC. Fig. 2 illustrates the calculation procedure of the ML method for multi-unit concurrent accidents. Fig. 3 illustrates the computational procedure of the ML method for multi-unit cascading accidents.

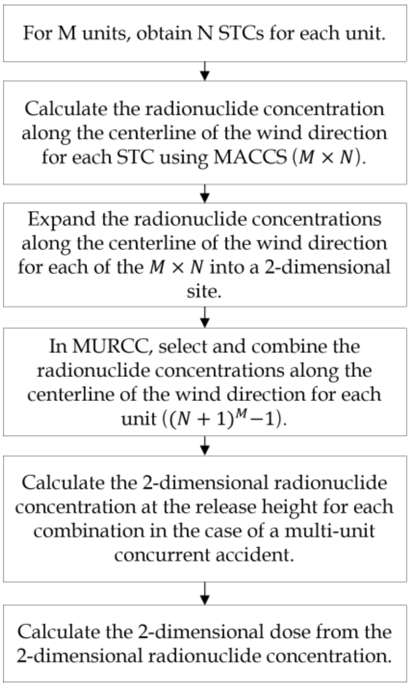


Fig. 2. Computational Procedure of the Multi-Unit Concurrent Accident ML Method (Considering a Fixed Wind Direction)

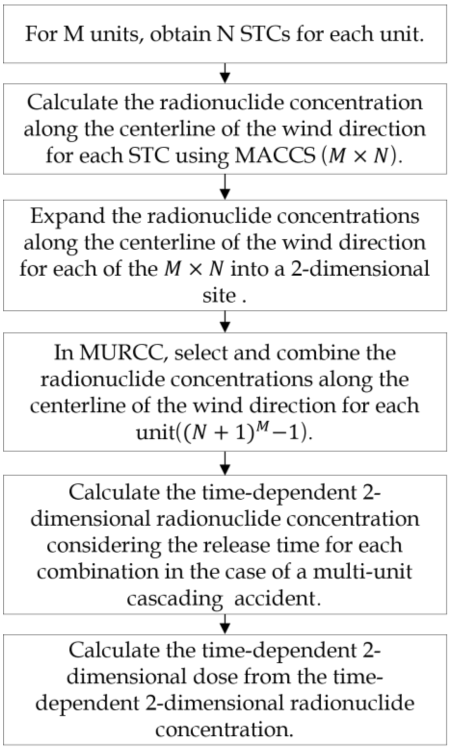


Fig. 3. Computational Procedure of the Multi-Unit Cascading Accident ML Method (Considering a Fixed Wind Direction)

3. Release-Scale-Based Source-Term Grouping

In L2 SUPSA, the source term is determined using the STC logic diagram. This process involves several steps: (1) The STC logic diagram is developed by grouping containment accident sequences from the containment event tree (CET). (2) Inputs for the CET are derived from the plant damage status logic diagram (PDSLD), while (3) inputs for the PDSLD are obtained from accident sequences included in the plant damage status event tree (PDSET). (4) The PDSET groups core damage accident sequences derived from L1 SUPSA (see Fig. 4).

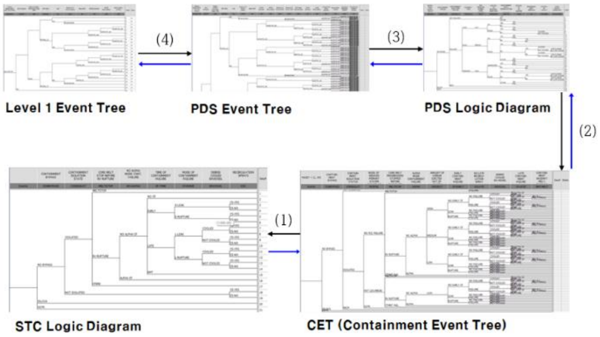


Fig. 4. Single Unit Source Term Evaluation Procedure

In the MUPSA of concurrent accidents at the Kori site [1,2], the multi-unit accident involving nine reactors was analyzed using the multi-source-term feature of the WinMACCS interface, assuming that the source terms were released simultaneously. The release position was modeled as a single point, akin to the COM method.

During L2 SUPSA, accident sequences from the CET were grouped into STCs based on containment integrity issues and similarities in fission product release characteristics. Consequently, the duration from the initial event to source-term release was not adequately incorporated within the STCs. However, by leveraging the core damage time data included in the PDSET and the time to containment failure following core damage reflected by the CET, the release time of a single-unit source term following the initial event can be roughly estimated.

Accurate L3 MUPSA requires analyses of staggered multi-unit accidents, which necessitates information on the release times of multi-unit source terms, particularly when analyzing cascading accidents using the MURCC. Therefore, developing a multi-unit source-term grouping methodology that considers the release times of source terms is crucial. To address this need, (1) the PDSET and CET must be updated to include more precise information that can help determine the release times of source terms. (2) Classification rules in the PDSLD and STC logic diagram must be developed to more distinctly differentiate the release times of source terms. However, updating the L2 SUPSA model to include source-term release-time information may significantly increase the number of source terms to be analyzed. Hence, creating an appropriate logic for grouping and simplifying source terms while ensuring no significant discrepancies in offsite consequences represent essential steps.

4. Release-Time-Based Source-Term Grouping Method

The proposed multi-unit source-term grouping method is developed with a focus on key multi-unit accidents, such as seismic events and station blackouts. This is in accordance with the intended primary application of this method in multi-unit offsite consequence assessments. Furthermore, in this context, the release timing of a single-unit source term is considered relative to a common reference point based on the timing of the initial multi-unit accident, rather than the timings of specific events such as core damage or reactor vessel failure.

$$p(N-STC) = \sum i \sum j \, [p(N-CET_{ij}) \times p(N-PDS_{jk})] \quad (1)$$

where the terms have the following meanings:

- $p(N-STC)$: Frequency of a specific STC N in a single unit.
- $p(N-CET_{ij})$: Probability of accident sequence i, classified under a specific STC N, corresponding to the j-th position in the sequence of containment failure times.
- $p(N-PDS_{jk})$: Frequency of an accident sequence in the PDSLD branching to accident sequence i, classified under a specific STC N, corresponding to the k-th position in the sequence of core damage times.

Notably, the term $\mathrm{p(N-CET_{ik})}$ can be classified and evaluated using the single-unit CET, while the term $\mathrm{p(N-PDS_{jk})}$ can be classified and examined using the PDSET. Specifically, $\mathrm{p(N-PDS_{jk})}$ can be computed by evaluating core damage times derived from the PDSET, while $\mathrm{p(N-CET_{ik})}$ can be computed by evaluating containment failure times following core damage derived from the CET.

4.1 Method for Core-Damage-Time Classification

Core damage time points included in PDSETs with the same L1 core damage sequence are identical. To explain the core-damage-time classification method, we consider the PDSET created for a plant blackout accident caused by the failure of its emergency diesel generator after a station blackout scenario. Fig. 5 illustrates a simplified version of this PDSET.

For instance, in Accident Sequence 6 depicted in Fig. 5, core damage occurs owing to the failure of the safety injection for feed (SIF) header. This SIF header failure follows the failure of the maintain secondary heat removal (MSHR) header. Assuming that the MSHR header failure occurs approximately 8 h after the initial event, as evidenced by the depletion time of the secondary feedwater source, the SIF header failure can be estimated to occur approximately 9 h after the initial event. Hence, core damage in this case occurs approximately 10 h after the initial event. Thus, the earliest core damage time can be determined as 10 h following the initial event. Similar to Accident Sequence 6, in Accident Sequence 23 depicted in Fig. 5, core damage also results from SIF header failure. However, in this sequence, the SIF header failure follows the successful recover AC power late header, occurring approximately 3 h after the initial event. Thus, core damage in this case occurs approximately 4 h after the initial event. Thus, 4 h after the initial event can be determined as the earliest time at which core damage can occur.

In some cases, the failure of the header related to core damage does not occur simultaneously with the operational demand but rather due to an in-service failure during operation. In such cases, the core damage time in the respective accident sequence may be delayed compared to the earliest time identified using the method described above. Since the specific time of in-service failure cannot be defined, the failure time must be grouped for application. That is, it is necessary to group and define the minimal cut set that includes in-service failures related to the header failure based on their impact on the results of the offsite consequence analysis. For

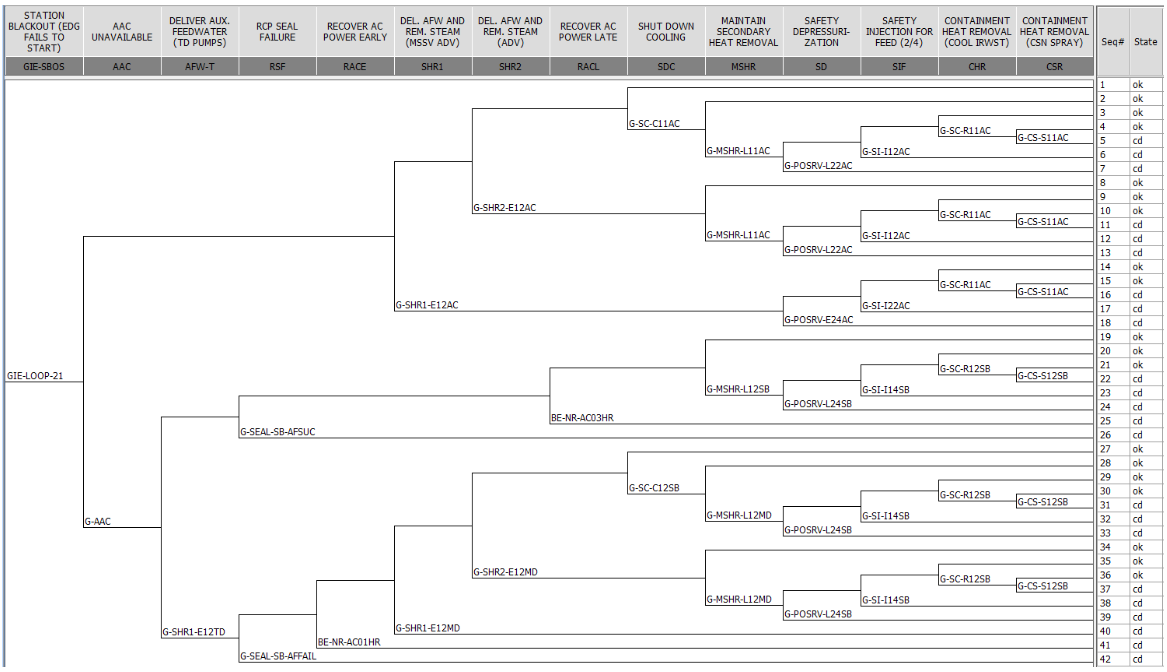


Fig. 5. Event Tree of a Plant Blackout Accident Caused by an Emergency Diesel Generator Failure

example, if at least 8 hours are required to implement offsite protective actions such as evacuating residents, the time of the SIF header failure can be categorized as either before or after 8 hours of system operation. The probability of failure before 8 hours can be calculated through a review of the minimal cut set for the respective accident sequence.

4.2 Method for Classifying the Time from Core Damage to Source-Term Release

The time from core damage to source-term release refers to the interval between the occurrence of core damage and the point at which the containment structure is breached. In single-unit source-term analysis, source-term release is modeled considering design-basis leakage even when the containment structure is intact. However, in multi-unit offsite consequence analysis, the impact of source-term release on the final results of scenarios with intact containment structures is negligible.

To explain the method for determining the time of source-term release induced by containment damage following core damage, we use a highly simplified CET developed for a typical domestic pressurized water reactor as an example. Fig. 6 illustrates this CET.

Leveraging the method described in Section 4.1, the interval from core damage to source-term release can be grouped using the CET. Notably, each header in the CET represents the occurrence time of a major severe accident phenomenon. Furthermore, for some headers, the start time of the corresponding event can be determined. For instance, Accident Sequence 97, depicted in Fig. 6, represents a high-temperature-induced steam generator tube rupture (SGTR) event resulting from a severe accident. Generally, in a high-pressure-induced severe accident scenario, a high-temperature-induced SGTR event occurs approximately 1 h following core damage. Therefore, the interval between core damage and source-term release for Accident Sequence 97 can be determined as 1 h.

Numerous headers in the CET represent the occurrence times of specific severe accident phenomena and can be determined relative to the core damage point. However, for some headers, such as CF-LATE, the interval between core damage and containment damage can vary based on the failure mechanism of the containment. For instance, if containment damage occurs owing to hydrogen combustion (hydrogen explosion), the containment structure may be breached approximately 8 h following reactor vessel failure. Conversely, containment failure induced by over-pressures from steam or non-condensable gases may occur approximately 72 h after core damage. When the interval between core damage and containment damage varies within a single CET header, the CET and associated event trees may need to be revised to enable accurate classification. However, from the perspective of offsite consequence analysis, the timing of source-term release is not anticipated to significantly impact the final results, except in cases leading to substantial early releases.

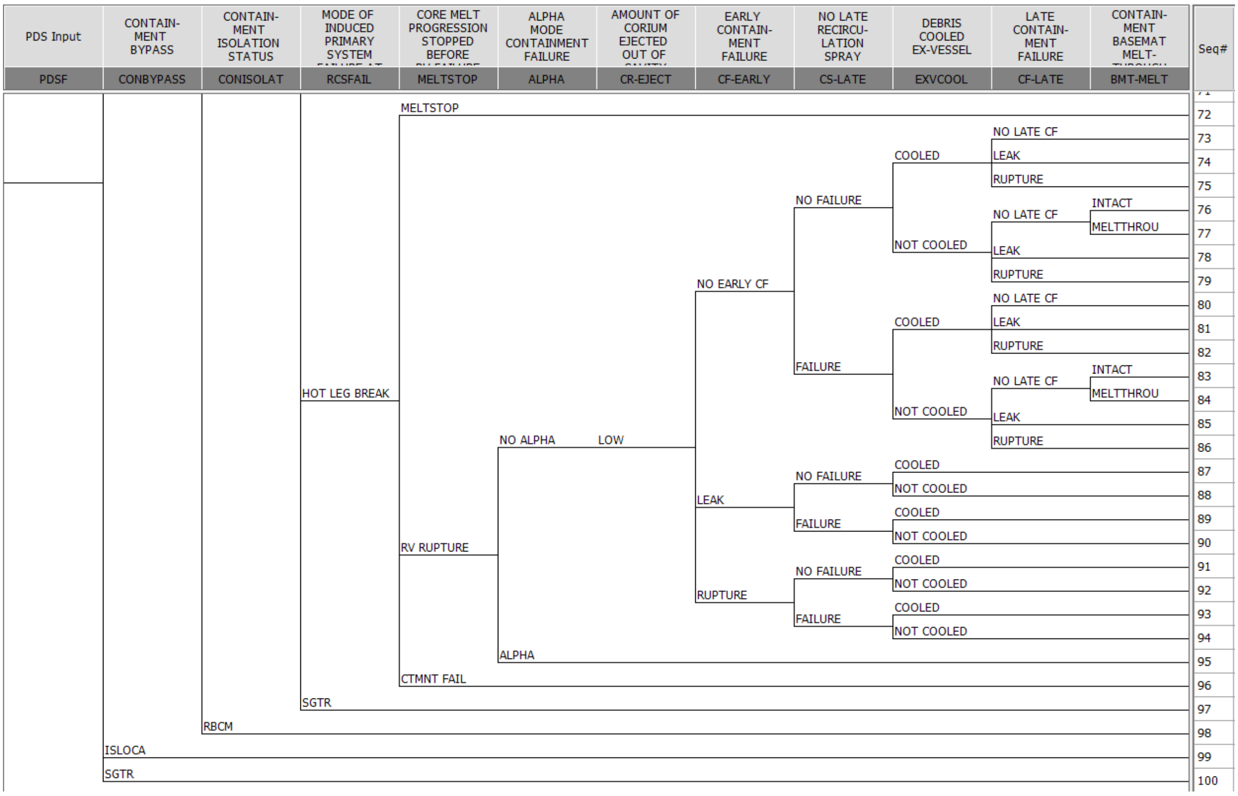


Fig. 6. Typical Containment Event Tree for a Pressurized Water Reactor Nuclear Power Plant

4.3 Method for Grouping Multi-Unit Source Term Based on Release Time

To group multi-unit source terms effectively, the timing of source-term release for individual units—which is essential for this grouping—can be determined using the methods outlined in Sections 4.1 and 4.2. For greater precision, revisions to the PDSET and PDSLD can help clarify core damage timing, while updates to the CET and STC logic diagram can help better define the period from core damage to containment failure.

The timing of source-term release can be expressed as the sum of the time interval between the initial event and core damage (T_{CD}) and the interval between core damage and containment failure (T_{CF}). Hence, the single-unit source-term release time (T_{REL}) can be defined as $T_{CD} + T_{CF}$. T_{REL} can then be grouped based on its impact on the results of the offsite consequence analysis.

Key tasks and considerations for multi-unit source-term grouping include the following: (1) Grouping the source terms of individual units based on existing information on source-term scale and release timing determined by the methodology presented in this document. (2) Determining combinations of source terms for multi-unit evaluations and analyzing their frequencies.

In the context of multi-unit source-term grouping, any source term released following the release of the first unit's source term and after a defined period (such as evacuation time) must be classified as a late-release source term. This implies that, once a source term is released from a specific unit, the implementation of evacuation measures will be completed within some time. Hence, any subsequent source-term releases—regardless of their classification as early or late releases in single-unit analysis—must be categorized as late-release source terms during multi-unit source-term grouping.

4.4 Application Instance of the Release-Time-Based Source-Term Grouping Method

The applicability of the release-time-based multi-unit source-term grouping method, as described in Sections 4.1–4.3, is demonstrated through an example. This verification is conducted using a highly simplified L1 PSA event tree and a containment event tree.

Fig. 7 and Fig. 8 present the simplified L1 PSA event tree and containment event tree, respectively.

4.4.1 Classifying Core Damage Time

Table I outlines specific criteria for determining the earliest core damage time points for the accident sequences displayed in Fig. 7.

Table I: Criteria for Classifying the Earliest Core Damage Times of Various Accident Sequences

Core Damage Accident Sequences	Initial Core Damage Time
Accident sequences related to containment heat removal (CSR) failure	More than 24 h (Based on the results of thermal-hydraulic analysis, a unique analysis is needed for each unit)
Accident sequences related to main secondary heat removal (MSHR) failure	More than 10 h (Time until depletion of secondary-side feedwater (8 h) + time until core damage (2 h))
Accident sequences that do not rely on the success of specific auxiliary systems	2 h (Time from event occurrence to core damage)

Table II summarizes the results obtained after applying the abovementioned criteria to classify the earliest core damage times for the accident sequences illustrated in Fig. 7.

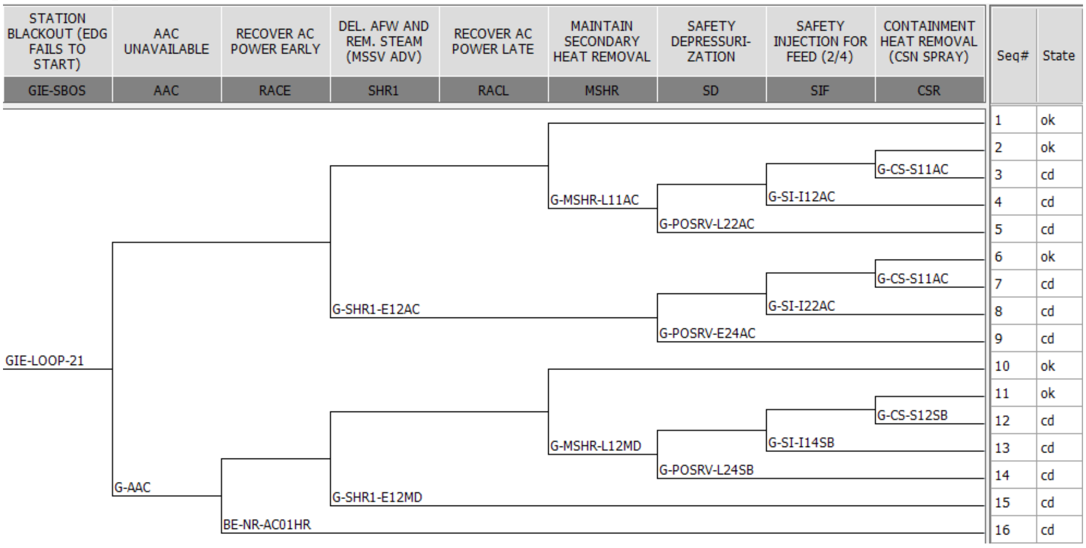


Fig. 7. Simplified L1 Event Tree

Table II: Results of Earliest Core Damage Time Classification of Several Core Damage Accident Sequences

Core Damage Accident Sequence	Initial Core Damage Time (*n* h after the initial event occurrence)
03	24 h
04	10 h
05	10 h
07	24 h
08	2 h
09	2 h
12	24 h
13	10 h
14	10 h
15	2 h
16	2 h

4.4.2 Classifying the Time from Core Damage to Source Term Release

Table III details the criteria for classifying the times from core damage to containment failure in the accident sequences displayed in Fig. 8.

Table III: Criteria for Classifying the Earliest Containment Failure Times of Various Containment Event Tree Accident Sequences

Containment Damage Accident Sequences	Initial Containment Damage Time
When branching to "NOT ISOLATED" under the containment isolation failure (CONISOLAT) header	0 h (Source term release occurs immediately after core damage)
When branching to "SGTR" under the primary system break (RCSFAIL) header	1 h (Period from core damage to steam generator tube rupture)
When branching to "ALPHA" under the alpha mode containment failure (ALPHA) header	1 h (Period from core damage to reactor vessel steam explosion)
When branching to "RUPTURE" under the early containment failure (CF-EARLY) header	3 h (Period from core damage to reactor vessel failure, plus 1 h)
Remaining containment accident sequences	More than 24 h (Time of containment failure caused by overpressure)

Table IV details the results obtained after applying the aforementioned criteria to classify the earliest containment failure times of the accident sequences depicted in Fig. 8 after core damage. Before this classification, Accident Sequences 29 and 30, which are not associated with major multi-unit accident-initiating events (such as seismic events or multi-unit station blackout events), were excluded from consideration to enhance the efficiency of the multi-unit source-term grouping analysis. Furthermore, to simplify the final multi-unit source-term grouping, accident sequences with intact containment structures were also excluded.

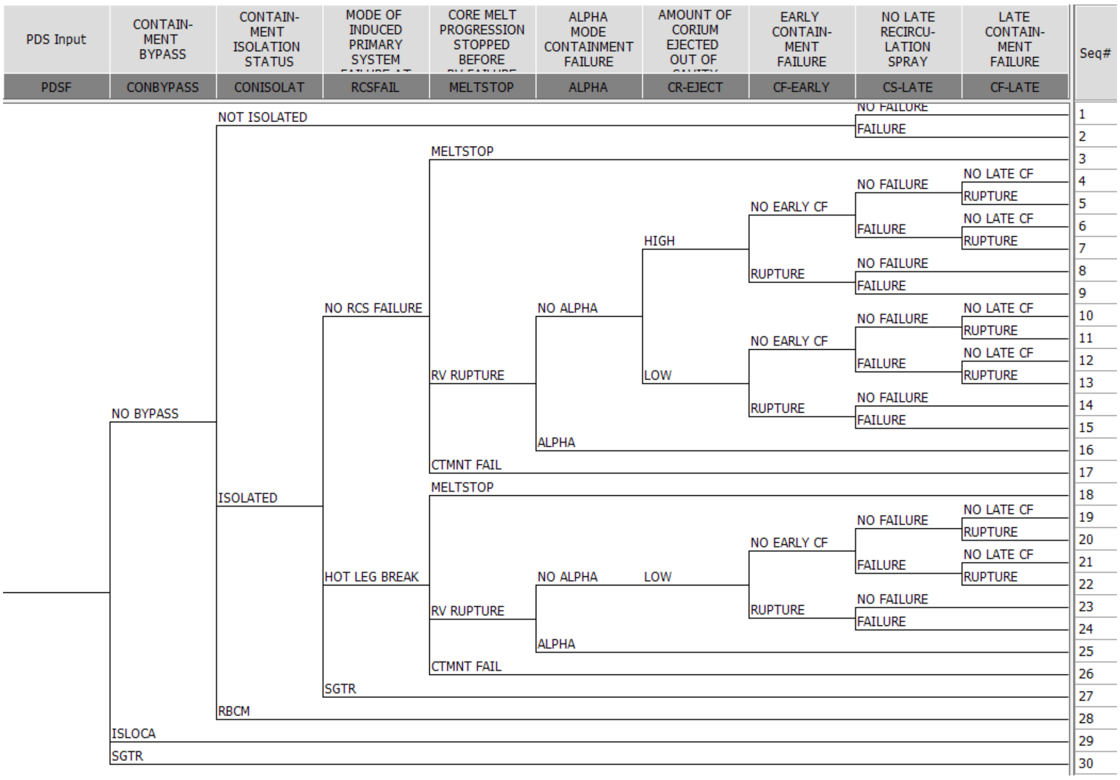


Fig. 8. Simplified Containment Event Tree

Table IV: Results of Earliest Containment Failure Time Classification for Several Containment Event Tree Accident Sequences

Containment Damage Accident Sequence	Initial Containment Damage Time (*n* h after core damage occurrence)
02	0 h
03	0 h
05	24 h
07	24 h
08	3 h
09	3 h
11	24 h
13	24 h
14	3 h
15	3 h
16	2 h
17	24 h
20	24 h
22	24 h
23	3 h
24	3 h
25	2 h
26	24 h
27	0 h
28	24 h

As discussed previously, in the CET, the failure of the containment structure occurs no earlier than 24 h after the initial core damage, except in scenarios classified as cascading accidents within the STC logic diagram. Furthermore, the CET accident sequences categorized under the STC logic diagram are associated with a specific time point. Therefore, barring the late containment failure instance occurring after 24 h of core damage, all other scenarios are grouped and assigned a single time point. In other words, if the timing of late containment failure does not significantly impact the off-site consequence analysis results, considering a single time point of "after 24 h of core damage" is feasible. Furthermore, when integrating CET sequences with similar source-term scales for late containment damage, the number of multi-unit source-term combinations under analysis can be substantially reduced. Moreover, in all CET sequences classified under the STC logic diagram, off-site release begins within 4 h of core damage.

This implies that off-site emergency responses are not considered for these CET sequences. Consequently, if the source-term scale is similar for these CET sequences, they can be grouped together for analysis, which can further reduce the number of multi-unit STCs. In practice, the grouping of late containment damage and CET sequences classified under the STC logic diagram can be assessed using the classification criteria established through source-term analysis and the level of detail required by the multi-unit off-site consequence analysis.

5. Conclusions

The current version of the L2 SUPSA methodology fails to provide inputs required by the L3 MUPSA methodology developed by Sejong University for analyzing cascading accidents. This is because L2 SUPSA relies on STCs based on release scale rather than release time. To address this, the current study introduces a new multi-unit source-term grouping methodology based on the release time of source terms.

This release-time-based source-term grouping technique is anticipated to reflect the differences in the release times of STCs, leading to more realistic multi-unit off-site impact assessment results. This approach is also anticipated to significantly improve initial response efforts in multi-unit accidents. Hence, the widespread adoption of this method has the potential to enhance the accuracy of L3 MUPSA worldwide.

Future studies must validate and refine the proposed methodology by applying and evaluating it based on the L2 SUPSA event trees and CETs of actual multi-unit initial events at NPPs. We plan to apply this methodology to analyze accidents at the Hanul and Shin Hanul PP sites.

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