Development of a Multi-Unit Tsunami PSA Model for the Hanul Nuclear Power Plant Site

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Abstract: This study developed a Multi-Unit PSA (MUPSA) model to evaluate the risk of accidents induced by tsunami hazards at the Hanul Nuclear Power Plant site. To address tsunami-induced simultaneous multi-unit damage scenarios, a comprehensive "One-top" model framework was constructed to integrate all units on the site, selecting Loss of Ultimate Heat Sink (LUHS) and Station Blackout (SBO) as primary initiating events based on tsunami wave heights. The model incorporated site-specific plant configuration and design features identified through plant walkdowns, including watertight door installations and potential tsunami ingress pathways such as building openings and penetrations. In addition, the operational priorities of AAC DGs and multi-unit common cause failures (CCFs) were explicitly modeled to reflect operational constraints arising from inter-unit dependencies. The quantification results revealed that the simultaneous failure of identical water storage structures (e.g., TS-DWST) during tsunami events with wave heights of 10–13 m was the most significant contributor to the Core Damage Frequency (CDF), suggesting the need to refine conservative assumptions regarding simultaneous structural failures or re-evaluate tsunami hazard characteristics. Furthermore, RCP seal failures in specific units were identified as major risk contributors, highlighting the necessity for mitigation strategies and the potential application of mobile equipment. This study provides a technical foundation for future tsunami hazard re-evaluations and is expected to serve as an important reference for establishing regulatory review guidance for MUPSA.

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1. INTRODUCTION

Multi-Unit Probabilistic Safety Assessment (MUPSA) is a systematic approach to comprehensively analyze potential accident scenarios and quantitatively evaluate site risk by considering inter-unit dependencies or shared systems at sites where multiple nuclear power reactors are co-located [1]. Previous research outcomes regarding MUPSA have indicated that the primary factor exerting a substantial impact on multi-unit risk is a simultaneous multi-unit initiating event induced by external hazards [2, 3]. Representative external hazards capable of inducing such events include earthquakes, external flooding, typhoons, forest fires, extreme heat, extreme cold, and tsunamis. In particular, risk assessment studies have highlighted earthquakes, typhoons, and tsunamis as major external hazards requiring detailed analysis [4].

To date, domestic single-unit PSAs in the Republic of Korea have explicitly modeled and analyzed seismic events, and typhoons have been evaluated by incorporating them into Loss of Offsite Power (LOOP) events. Conversely, tsunamis have traditionally been screened out, and independent tsunami PSA models have not been developed. However, as confirmed by the Fukushima nuclear accident, tsunami-induced simultaneous damage can occur across multiple units and must be considered an external hazard with a critical impact on multi-unit risk.

To evaluate multi-unit risks from tsunamis, a site-specific tsunami PSA methodology tailored to the Hanul site was previously developed, establishing the technical foundation for the modeling framework. This paper extends that methodology to develop and implement a full-scale multi-unit tsunami PSA model. The remainder of this paper is structured as follows:

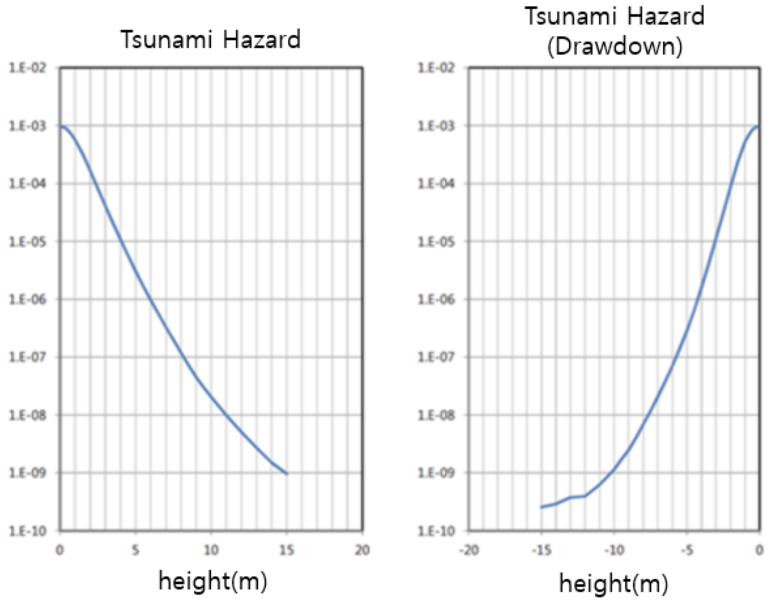
- Section 2 delineates the single-unit tsunami PSA model development, including modeling assumptions, unit-specific characteristics of the Hanul site, and design modifications for flooding protection implemented as part of the post-Fukushima action items.
- Section 3 describes the multi-unit tsunami PSA model development, focusing on the configuration of the One-top multi-unit core damage model, treatment of shared systems, incorporation of inter-unit common cause failures (CCFs), and the resulting quantification insights.
- Section 4 provides the concluding remarks and engineering insights derived from this study.

2. SINGLE-UNIT TSUNAMI PSA MODEL DEVELOPMENT

2.1. Tsunami Hazard and Fragility Evaluation

The tsunami accident sequence is initiated based on the tsunami hazard curve, which defines the annual exceedance frequency of tsunami wave heights. For the Hanul site, site-specific input data required for the development of a tsunami PSA model, including tsunami hazard analysis results and tsunami fragility evaluation results, were not available. Therefore, this study utilized the tsunami hazard curve and tsunami fragility analysis results presented in the regulatory research entitled “Development of Risk Assessment Technology for Extreme External Events” [1]. The tsunami hazard curve adopted in this study is shown in Figure 1.

Figure 1. Tsunami Hazard Curve



To evaluate the conditional failure probabilities of critical structures, systems, and components (SSCs) against water ingress and hydrodynamic loads, tsunami fragility parameters were mapped based on the adopted hazard profile. The major SSCs evaluated include the site breakwater, Condensate Storage Tanks (CST), Off-site power connection, and Essential Service Water (ESW) systems. These parameters are mathematically defined using a standard lognormal cumulative distribution function. The quantitative fragility parameters utilizing the median acceleration capacity (A_m) and the composite variability (β_C) are summarized in Table 1, and the resulting failure probabilities evaluated at various tsunami height intervals are presented in Table 2.

Table 1. Tsunami Fragility Evaluation Results for key SSCs

Equipment / SSC Description	Median ground acceleration capacity (A_m)[g]	Composite variability (β_C)
Site Breakwater	7.32	1.056
Condensate Storage tank (CST)	11.37	0.054
Off-site power Connection	10.64	0.221
Essential Service Water Pump (ESW)	10.8	0.1

Table 2. Failure Probability of key SSCs by Tsunami Height

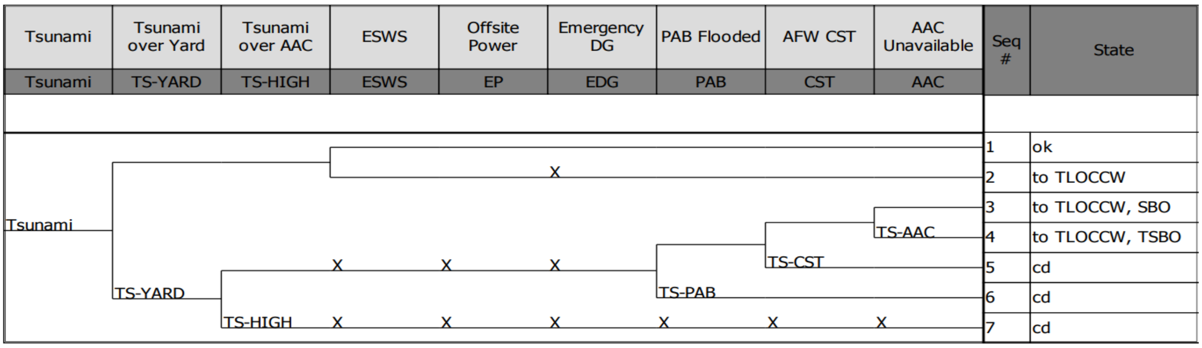
Tsunami height	Site Breakwater	Condensate Storage tank (CST)	Off-site power connection	Essential Service Water Pump (ESW)
1	2.97E-02	0.00E+00	1.86E-125	1.86E-125
2	1.10E-01	1.57E-227	4.14E-64	4.14E-64
3	1.99E-01	1.03E-134	7.27E-38	7.27E-38
4	2.84E-01	1.10E-83	1.50E-23	1.50E-23
5	3.59E-01	1.43E-52	6.75E-15	6.75E-15
6	4.25E-01	1.25E-32	2.08E-09	2.08E-09
7	4.83E-01	1.32E-19	7.24E-06	7.24E-06
8	5.34E-01	3.76E-11	1.35E-03	1.35E-03
9	5.78E-01	7.50E-06	3.41E-02	3.41E-02
10	6.16E-01	8.71E-03	2.21E-01	2.21E-01
11	6.50E-01	2.70E-01	5.73E-01	5.73E-01
12	6.80E-01	8.41E-01	8.54E-01	8.54E-01
13	7.07E-01	9.93E-01	9.68E-01	9.68E-01
14	7.30E-01	1.00E+00	9.95E-01	9.95E-01
15	7.52E-01	1.00E+00	9.99E-01	9.99E-01

2.2. Tsunami-Induced Initiating Events and Event Tree Modeling

Tsunami-induced initiating events were identified using the tsunami initiating event tree shown in Figure 2, from which SBO and LUHS were selected for detailed risk assessment. Descriptions of the event tree headings are provided below.

- **TS-YARD (Site Elevation of 10 m):** For tsunami wave heights below 10 m, only LUHS is considered as the initiating event. However, for tsunami wave height between 10 m and 13 m, both LUHS and SBO are simultaneously considered due to the partial flooding of yard structures.
- **TS-HIGH (Tsunami Wave Height ≥ 13 m):** For tsunami wave heights exceeding 13 m, all major safety-related structures and systems are assumed to be completely submerged, resulting directly in core damage.
- **Essential Service Water (ESW) System:** The ESW system is assumed to be completely lost if the breakwater or intake structures sustain physical damage from the tsunami impact.
- **Emergency Diesel Generators (EDGs):** In accordance with system functional dependencies, the EDGs are assumed to become unavailable following the loss of the ESW system due to the loss of the cooling water supply required for EDG operation.
- **Primary Auxiliary Building (PAB) & Alternate AC Diesel Generator (AAC-DG):** Both the PAB and the AAC-DG building are assumed to be flooded and unavailable when the tsunami wave height reaches or exceeds 13 m.
- **Condensate Storage Tank (CST):** For tsunami wave heights between 10 and 13m, the tsunami-induced failure probability of the CST is explicitly modeled to reflect the potential loss of secondary cooling water inventory.

Figure 2. Tsunami-Induced Initiating Event Tree



The tsunami PSA model was developed using the full-power internal events MPAS model as the baseline. The event trees associated with the selected initiating events were modified to incorporate the effects of tsunami-induced system and component failures. The availability of mitigating systems was modeled as a function of tsunami wave height, and mitigation functions lost due to inundation were removed from the accident progression logic. The resulting unit-specific tsunami event tree models are provided in Figures 3 and 4.

Figure 3. LUHS Event Tree for Shin-Hanul Unit 1 and 2

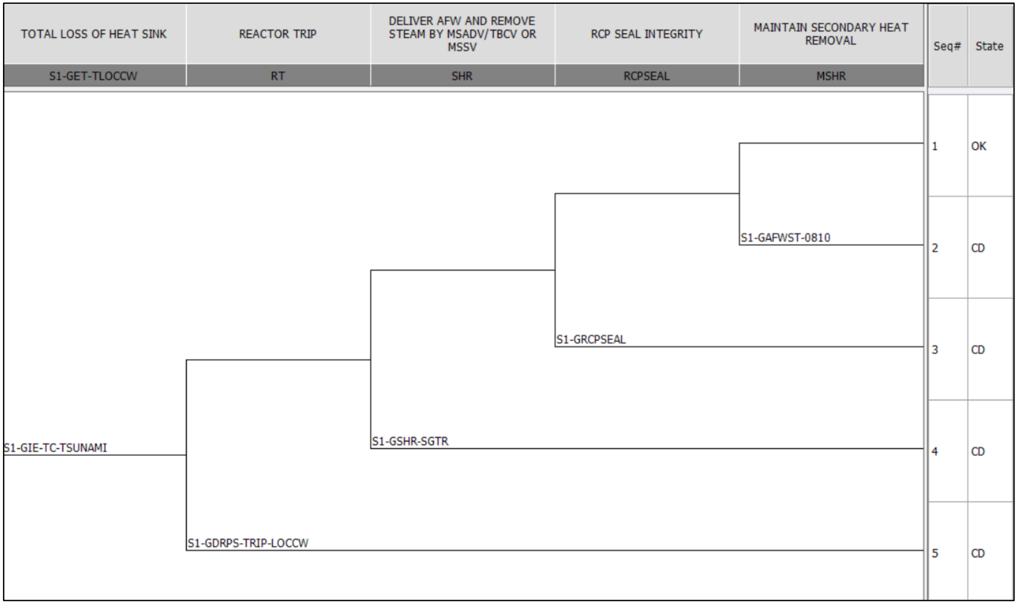
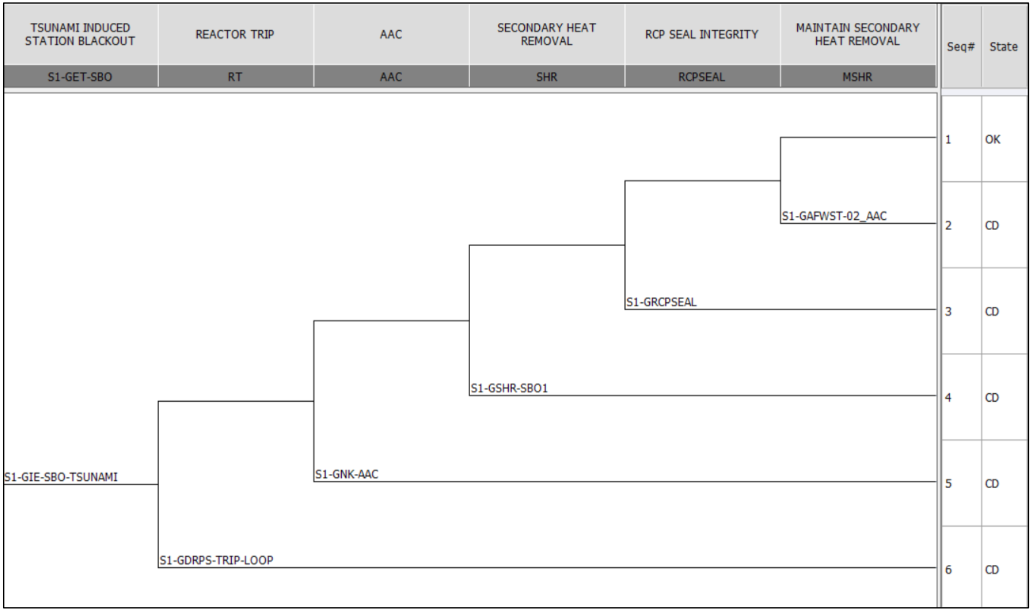


Figure 4. SBO Event Tree for Shin-Hanul Unit 1 and 2



2.3. Incorporation of Site Walkdown Results

To reflect unit-specific characteristics of the Hanul site and evaluate the impacts of tsunami hazards, site walkdowns were conducted for Hanul Units 1-6 and Shin-Hanul Units 1 and 2. The walkdowns focused on SSCs considered in the tsunami PSA, design modifications implemented following the Fukushima accident, including flood protection features such as watertight doors, and potential tsunami ingress pathways into major plant buildings.

First, the walkdowns assessed vital SSCs required for post-tsunami accident mitigation, including the essential service water intake structures, main transformers, condensate storage tanks, and TS-DWST. Based on the walkdown results, unit-specific modeling assumptions were developed as follows:

- **Auxiliary Feedwater Storage Tanks (AFST) in Units 1 and 2:** Unlike other standardized units where condensate or auxiliary feedwater tanks are exposed to external flooding hazards, the walkdown confirmed that the AFSTs for Hanul Units 1 and 2 are located indoors within robust auxiliary buildings. This design feature provides protection against direct tsunami wave impacts and was therefore modeled as not susceptible to tsunami-induced flooding damage.
- **Submerged Intake System in Shin-Hanul Units 1–4:** The walkdown confirmed that Shin-Hanul Units 1 and 2 employ a submerged intake structure without an offshore breakwater, in contrast to the other Hanul units, where the intake structures are located behind offshore breakwaters. Because site walkdowns could not be performed for Shin-Hanul Units 3 and 4, which are currently under construction, the same submerged intake configuration as that of Shin-Hanul Units 1 and 2 was assumed. This design difference results in a distinct tsunami vulnerability mechanism. For Hanul Units 1–6, tsunami-induced damage to the breakwater and the subsequent impact of debris on the intake structures were considered in the evaluation of ESW failure. In contrast, such breakwater failure scenarios are not applicable to Shin-Hanul Units 1–4 due to the absence of a breakwater. Accordingly, the tsunami fragility of the submerged intake structure was explicitly incorporated into the quantification of the LUHS initiating event frequency.

Second, design modifications implemented after the Fukushima accident were also reviewed and verified through document reviews and site inspections. To enhance plant protection against flooding caused by extreme tsunami events, seismically qualified watertight doors and modular flood barriers were installed at building openings housing emergency power systems and major safety-related equipment. The walkdowns confirmed that these design modifications had been fully implemented in the plant.

The review further confirmed that access openings to structures housing major safety-related equipment were protected by watertight doors. In addition, HVAC openings and louvers located within 3 m of the site grade were equipped with flood protection barriers, whereas openings located more than 3 m above the site grade were not protected. Because flood protection measures were only credited up to the evaluated inundation conditions, tsunami wave heights exceeding 13 m were conservatively assumed to result in extensive flooding of safety-related structures and equipment, leading directly to core damage.

3. MULTI-UNIT TSUNAMI PSA MODEL EXPANSION AND QUANTIFICATION

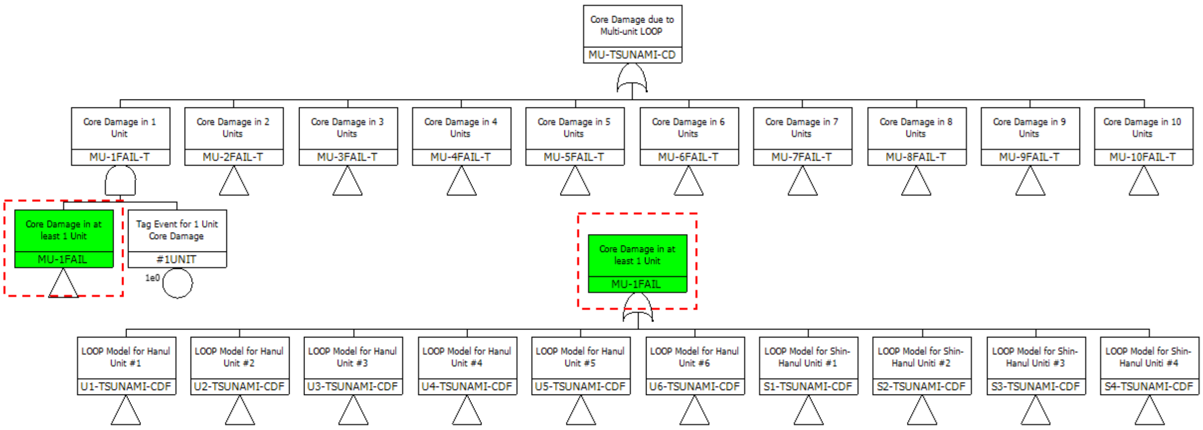
3.1. One-Top Multi-Unit Model Configuration

To systematically evaluate multi-unit risk at the Hanul site, this study developed a MUPSA model tailored for the Hanul site. The model consists of a site-level top logic (One-Top model), unit-specific core damage models, and inter-unit dependency models representing shared vulnerabilities and common-cause impacts among units.

To evaluate site-level risk, an integrated top event, designated as *MU-TSUNAMI-CD*, was established to quantify the site-wide multi-unit core damage frequency induced by tsunami hazards. This overarching top event represents all possible combinations of tsunami-induced core damage occurrences across the ten units at the Hanul site, ranging from core damage in a single unit to simultaneous core damage in multiple units up to all ten units.

To facilitate the straightforward interpretation of the quantification results, a set of designated dummy events—labeled as #1UNIT, #2UNIT, ..., up to #10UNIT—was introduced into the respective logical branches of the fault tree. These dummy events do not affect the quantitative results but provide a clear means to identify, classify, and aggregate accident sequences and minimal cutsets according to the specific number of units experiencing core damage. The overall top logic structure of the multi-unit tsunami PSA model is illustrated in Figure 5.

Figure 5. Top Logic Configuration of the Master Multi-Unit Tsunami Core Damage Fault Tree



3.2. Inter-Unit Dependency and Multi-Unit Common Cause Failure Modeling

To integrate the individual unit tsunami PSA models into a unified multi-unit framework, a systematic component identification scheme was developed. Unique unit identifiers were appended to all unit-specific events to preserve logical independence among units, while shared systems and components were assigned common identifiers reflecting their cross-unit dependencies.

For example, unit-specific events associated with Hanul Units 1 and 2 were designated using the identifiers U1 and U2, respectively. Shared systems serving both units were assigned the identifier A1 to distinguish them from unit-specific components. The alternate AC diesel generator, which is shared between Hanul Units 1 and 2, was therefore modeled using the A1 identifier. This identification scheme enabled the integration of individual unit models into a unified multi-unit PSA model while preserving the distinction between unit-specific and shared equipment. Examples of the resulting model structure are presented in Figures 6 and 7.

Figure 6. Model Configuration Example with Unit-Specific Identifiers

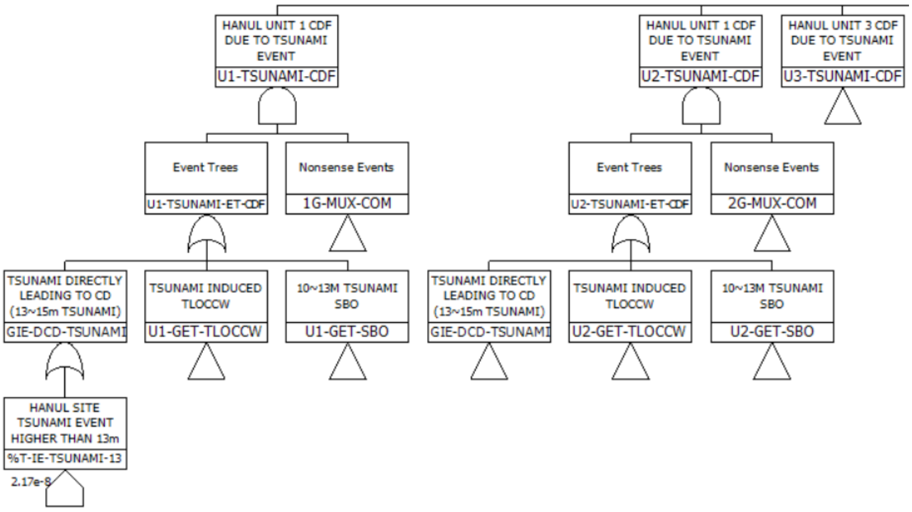
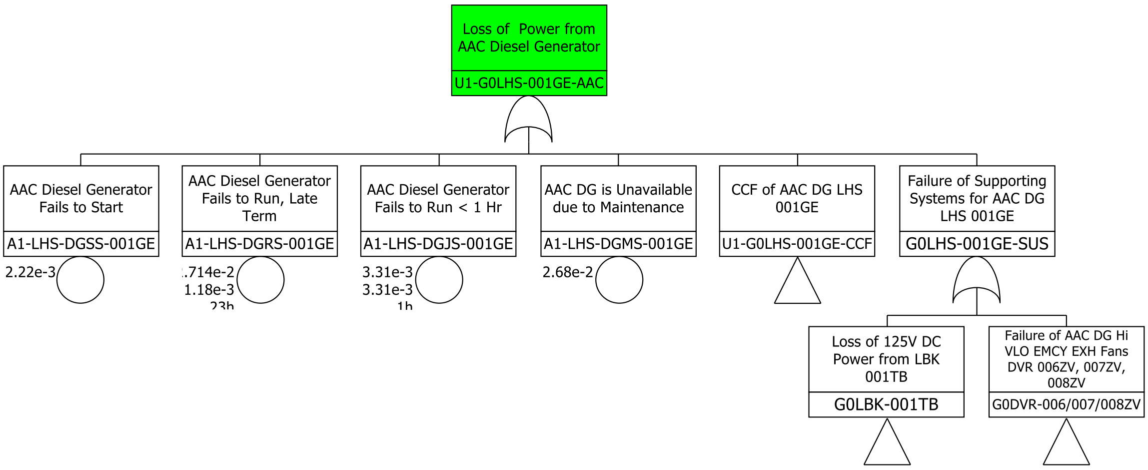


Figure 7. Model Configuration Example with Shared System Designators

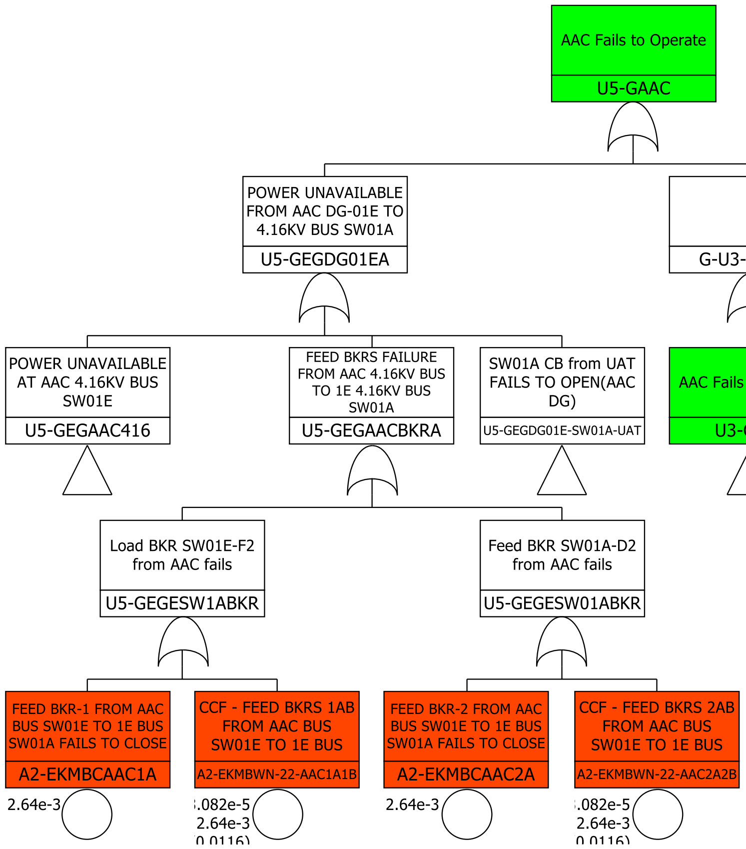


3.2.1. Operational Priority Logic for Shared Systems and Components

The modeling of shared systems explicitly incorporates the physical and operational availability constraints of the AAC DGs deployed across the site. At the Hanul site, one AAC DG is shared between Units 1 and 2, another AAC DG is shared among Units 3–6, and one between Shin-Hanul Units 1 and 2, while Shin-Hanul Units 3 and 4 are each equipped with an independent dedicated AAC DG. To address resource contention, a strict operational priority logic was applied within the multi-unit fault tree. Specifically, if SBO conditions occur simultaneously in Units 1 and 2, the shared AAC DG is credited to Unit 1 and cannot be credited to Unit 2. For the AAC DG shared among the four units from Unit 3 to Unit 6, the priority is sequentially allocated in the order of Units 3, 4, 5, and 6.

As a representative example of this inter-unit dependency, the logic model for Hanul Unit 6 is structured such that if a SBO occurs in any single unit among Units 3, 4, or 5, the shared AAC DG is completely credited to the higher-priority units, rendering it unavailable for Unit 6. This realistic operational restriction ensures that mitigation credits are not double-counted across multiple units during multi-unit accident scenarios. The logic configuration reflecting this four-unit shared AAC DG dependency is presented in Figure 8.

Figure 8. Model Configuration Example for AAC DG Dependencies Shared Across Four Units



3.2.2. Modeling of Inter-Unit Dependencies, Shared Systems, and Common-Cause Failures

The inter-unit CCF modeling was not applied indiscriminately to all components; instead, it selectively targeted safety-related components with a Fussell-Vesely (F-V) importance measure of 0.005 or higher derived from the single-unit full-power tsunami PSA. Consequently, the auxiliary feedwater system turbine-driven pumps and the AAC DGs were selected as the target component groups. Rather than grouping all identical target components across the entire 10-unit site into a single Common Cause Component Group (CCCG), the CCF groups were partitioned based on reactor types. To determine the basic event probabilities for the multi-unit CCF configurations, CCF multipliers were calculated by applying the mapping-up methodology to the single-unit alpha-factor parameters provided in NUREG/CR-5497 [5, 6].

Furthermore, for key outdoor storage structures located in the yard area—specifically the TS-DWST, TS-CSTA, TS-CSTB, and TS-RWT supporting eight units (excluding Hanul Units 1 and 2)—it was assumed that identical structures experience potentially similar hydrodynamic impacts within the 10–13 m tsunami wave height range. Therefore, these eight identical storage tanks were modeled with a complete, perfect logical dependency. This was accomplished by assigning identical basic event names without appending unit-specific identifiers, meaning that a severe tsunami triggers a simultaneous failure across all eight units based on the conditional failure probability derived from the single-unit hazard analysis.

3.3. Quantitative Results and Risk Insights

The developed multi-unit tsunami PSA model was quantified using a PSA quantification tool to evaluate the integrated risk profile of the Hanul site and identify dominant contributors to multi-unit core damage risk. The analysis was performed using the tsunami hazard curves and fragility results developed in the precursor regulatory research [1]. Through quantification of the MU-TSUNAMI-CD top event, multi-unit core damage frequencies and their corresponding minimal cutsets were generated. The dominant cutsets identified from the quantification results are summarized in Table 3.

The importance analysis indicated that the conditional failure of the TS-DWST under tsunami wave heights in the range of 10 m to 13 m is the dominant contributor to the multi-unit core damage frequency. Because the TS-DWST provides the inventory required to support long-term secondary-side heat removal, its failure can lead to the loss of secondary cooling capability and contribute to concurrent core damage sequences. The dominant minimal cutset corresponds to a tsunami-induced LUHS event followed by successful reactor trip, initial secondary cooling, and maintenance of Reactor Coolant Pump (RCP) seal integrity. However, failure of the TS-DWST during the mission time associated with maintaining long-term secondary heat removal ultimately results in the loss of secondary cooling capability and leads to concurrent core damage in Hanul Units 3, 4, 5, and 6, as identified by the presence of the #4UNIT dummy event.

It should be noted that the current analysis includes a conservative assumption regarding TS-DWST failures. In the present model, the TS-DWSTs associated with the applicable units are represented by a single shared failure event. Consequently, failure of the TS-DWST is assumed to result in the simultaneous loss of the corresponding water inventory for all affected units. This assumption was adopted to conservatively account for potential common impacts of tsunami hazards on the water supply function. In reality, tsunami effects may vary across the site depending on local inundation conditions, plant layout, structural protection features, and shielding effects. Therefore, a more detailed site-specific assessment of tsunami-induced damage to individual TS-DWSTs may reduce the degree of inter-unit dependency and lead to different estimates of multi-unit core damage frequency.

In addition, tsunami-induced loss of component cooling water, combined with subsequent degradation of RCP seal performance, was identified as the second most significant contributor to site risk. In particular, Hanul Units 1 and 2 exhibit relatively higher conditional frequencies for core damage sequences initiated by RCP seal failures. This finding suggests that additional risk reduction may be achieved through engineering improvements to the RCP seal design, such as the adoption of enhanced high-temperature-resistant seal packages that reduce the likelihood of seal leakage or seal loss-of-coolant accidents under severe external flooding conditions.

Overall, the preliminary results indicate that tsunami-induced risk is not negligible compared with other external hazards considered in PSA studies. Consequently, if future refined analyses continue to identify significant risk contributions from tsunami hazards, further refinement of site-specific tsunami hazard characterization and fragility evaluations may be warranted. The methodology developed in this study provides a technical basis for future multi-unit tsunami PSA applications and may support the development of regulatory guidance for multi-unit PSA evaluations.

Table 3. Dominant Minimal Cutsets for the Multi-Unit Tsunami PSA Model

NO	BE#1	BE#2	BE#3	BE#4	BE#5
1	%IE-LUHS	TS-DWST	#4UNITS		
2	%IE-LUHS	U2-SEAL	#1UNIT		
3	%IE-LUHS	U1-SEAL	#1UNIT		
4	%IE-LUHS	TS-DWST	U2-SEAL	#5UNITS	
5	%IE-LUHS	TS-DWST	U1-SEAL	#5UNITS	
6	%IE-LUHS	U1-SEAL	U2-SEAL	#2UNITS	
7	%IE-LUHS	TS-DWST	U1-SEAL	U2-SEAL	#6UNITS
8	%IE-SBO	TS-DWST	#4UNITS		
9	%IE-LUHS	U3-AFTPR01BA	U3-AFTPR02AB	#1UNIT	
10	%IE-LUHS	U4-AFTPR01BA	U4-AFTPR02AB	#1UNIT	
11	%IE-LUHS	U5-AFTPR01BA	U5-AFTPR02AB	#1UNIT	
12	%IE-LUHS	U6-AFTPR01BA	U6-AFTPR02AB	#1UNIT	
13	%IE-SBO	U2-SEAL	#1UNIT		
14	%IE-SBO	U1-SEAL	#1UNIT		
15	%T-IE-TSUNAMI-13	#10UNITS			

4. CONCLUSION

This study established a site-specific multi-unit tsunami Probabilistic Safety Assessment (PSA) model for the Hanul site. To reflect plant responses to tsunami flooding, tsunami-induced initiating events were defined for different tsunami wave height ranges.

For tsunami wave heights between 5 and 10 m, an LUHS sequence was modeled by adapting the total loss of component cooling water fault trees from the MPAS internal event frameworks. The initiating event frequency was determined by multiplying the tsunami hazard frequency by the average failure probability of the breakwater. For Shin-Hanul Units 1–4, which have a breakwaterless intake structure, Essential Service Water (ESW) pump failure probabilities were applied instead.

For tsunami wave heights between 10 and 13 m, an SBO sequence combined with LUHS was implemented to model the inundation of main transformers when the tsunami wave height exceeds the site elevation. The frequency was calculated as the sum of the hazard frequencies within this wave height range. For tsunami heights exceeding 13 m, direct core damage sequences were assumed due to the total unavailability of vital safety systems, including the PAB and the AAC DG.

The realism of the model was enhanced by incorporating site walkdown insights, including post-Fukushima design modifications such as watertight doors and flood barrier configurations.
The integrated One-Top multi-unit model successfully incorporated shared system configurations through the operational priority logic of the AAC DG, multi-unit CCF structures, and fully correlated failures of identical outdoor storage tanks (e.g., *TS-DWST*). The quantification results indicated that the simultaneous failure of identical outdoor storage tanks under tsunami wave heights of 10–13 m is the dominant contributor to the site-wide core damage frequency. The dominance of this cutset suggests that either the tsunami hazard characterization or the assumption of complete correlation among identical outdoor storage tanks may be conservative. Therefore, future work should focus on re-evaluating the tsunami hazard curves or limiting structural co-failures to localized boundaries, such as a twin-unit configuration.

Additionally, the high risk-significance of RCP seal failures at Hanul Units 1 and 2 indicates a need for engineering modifications, such as replacing existing legacy seals with improved high-temperature-resistant packages, to reduce seal LOCA probabilities. Although mobile mitigation equipment was conservatively excluded from the baseline quantification, evaluating the practical applicability of these mobile systems may provide an effective risk reduction measure.

The methodology developed in this study provides a technical basis for future multi-unit tsunami PSA applications and supports the development of regulatory guidance for multi-unit PSA evaluations.

Acknowledgements

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