Development of a Tsunami PSA bounding analysis model for the Hanul Site

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ABSTRACT

This study developed a Tsunami PSA bounding analysis model to evaluate the risk of nuclear power plant accidents caused by tsunamis at the Hanul site. The study reviewed tsunami hazard analysis and fragility analysis results applicable to the Hanul site, performed tsunami-induced accident sequence analysis, and developed a base model with conservative assumptions. Additionally, a sensitivity analysis model incorporating on-site inspection findings was developed to evaluate the effects of post-Fukushima measures, such as watertight door installations. A comparison of quantification results for each unit showed differences in Core Damage Frequency (CDF) due to variations in the Reactor Coolant Pump (RCP) Seal models, the configuration of water sources for secondary heat removal, and differences in the ESW Intake Structure. This study is expected to provide a technical basis for the future development of tsunami PSA review guidelines.

Keywords: Tsunami PSA Bounding Analysis Model, Multi-unit Nuclear Power Plant, Hanul Site, MPAS Model

I. Introduction

In Korea, most nuclear power plants are co-located at sites with six or more units, resulting in a relatively higher risk of multi-unit accidents compared to other countries. Consequently, during the construction licensing phase of Shin-Kori Units 5 and 6, multi-unit PSA emerged as a key regulatory concern. In response, a pilot multi-unit PSA model was developed for the Kori site. However, due to the distinct geographical and technological characteristics of the Hanul site, the direct application of the Kori based model is limited.

The Hanul site hosts multiple reactor types with varying design features, including Framatome-type reactors, and is located on Korea's eastern coastline, where the assessment of natural external hazards such as tsunamis is essential. In line with recent efforts to enhance nuclear safety and strengthen regulatory oversight, the need for developing regulatory-grade PSA models that reflect reactor-specific characteristics has grown. Accordingly, a Tsunami PSA bounding analysis model for the Hanul site was developed, based on the full-power internal event MPAS model which was originally intended for regulatory verification.

The developed model includes a simplified Tsunami PSA bounding analysis base model constructed under conservative assumptions using site-specific tsunami hazard data. Furthermore, a Tsunami PSA bounding analysis sensitivity model was implemented to assess the effects of post-Fukushima design modifications, such as the installation of watertight doors and flood protection walls, which were introduced to improve flood resilience.

II. Tsunami PSA Methodology

The development procedure for the tsunami PSA model is similar to that of the seismic PSA model, and the general procedure for performing a tsunami PSA is shown in Figure 1 [1]. The tsunami PSA bounding analysis model consists of technical elements including tsunami hazard analysis, tsunami fragility analysis, and tsunami accident sequence analysis.

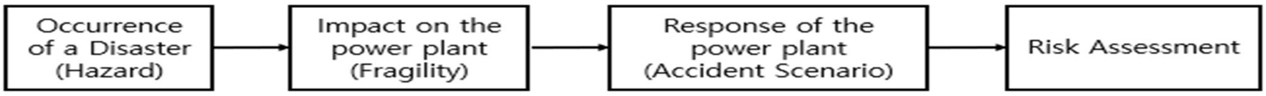

FIGURE 1. Procedure of Tsunami PSA

II.A. Applicability Review of Tsunami Hazard Assessment

Due to the absence of site-specific input data for tsunami hazard analysis at the Hanul site, existing tsunami hazard results applicable to the site were reviewed. The tsunami hazard curve developed in a previous multi-unit PSA study [1] for the Hanul site was adopted for this analysis, as shown in Figure 2.

The tsunami hazard assessment is defined based on the tsunami wave height and its corresponding exceedance frequency. The hazard curve presented in the previous study [1] was developed using a tsunami seismic hazard logic tree approach in conjunction with a tsunami propagation analysis code. In the logic tree, various tsunami-generating seismic sources were modeled probabilistically by considering parameters such as maximum potential magnitude, recurrence intervals, and associated wave heights. Each branch of the logic tree was weighted, and the resulting tsunami heights were calculated through numerical propagation simulations for each scenario.

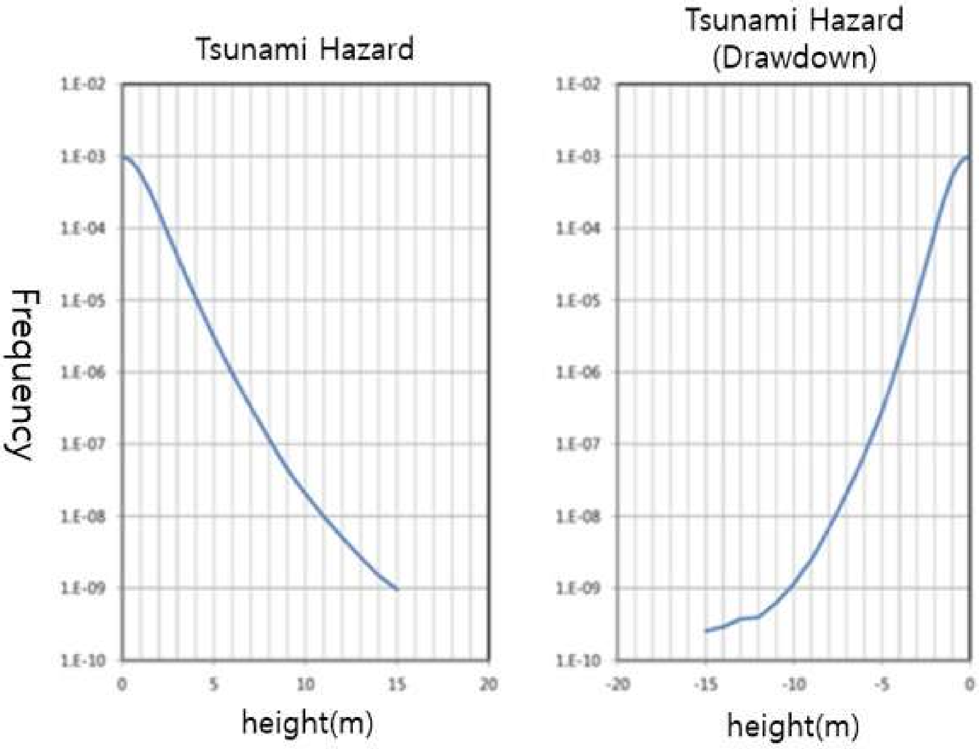

FIGURE 2. Tsunami Hazard Curve

II.B. Applicability Review of Tsunami Fragility Assessment

Tsunami fragility analysis is conducted to evaluate the probability of failure of safety-related structures, systems, and components (SSCs) as a function of tsunami intensity parameters. The SSCs that can impact either initiating event frequency or accident mitigation capability were selected for tsunami PSA fragility evaluation. The selection of target SSCs was performed in consultation with system analysis experts.

In this study, the fragility data were adopted from the results presented in a previous multi-unit PSA study [1], and are summarized in Table 1. The failure probabilities were computed using a lognormal cumulative distribution function, based on the median capacity (*Am*) and logarithmic standard deviation (*βC*) for each SSC with respect to tsunami wave height. The resulting damage probabilities calculated from the fragility curves are provided in Table 2.

TABLE 1. Tsunami Fragility of Key Structures and Equipment in Nuclear Power Plants

Equipment	Am	βC
Break water	7.32	1.056
CST	11.37	0.054
Offsite power	10.64	0.221
ESW	10.8	0.1

TABLE 2. Damage probability of major equipment by elevation

Tsunami height	Breakwater	CST	Offsite power	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

II.C. Accident Sequence Analysis Induced by Tsunami

The accident sequence analysis evaluates potential accident scenarios based on the damage status of critical safety-related SSCs affected by tsunami wave height. Initiating event trees were developed for different tsunami height intervals, and Total Loss of Component Cooling Water (TLOCCW) and Station Blackout (SBO) were identified as representative initiating events. The tsunami-induced initiating event tree is illustrated in Figure 3 [1].

- **TS-YARD**: Tsunami impact evaluated at yard level. For tsunami wave heights ≤10 meters (site elevation reference), only TLOCCW is considered. For wave heights >10 meters, both TLOCCW and SBO are considered.
- **TS-HIGH**: If the tsunami height exceeds 13 meters, core damage is assumed due to flooding of the Alternate AC Diesel Generator (AAC DG), failure of the Condensate Storage Tank (CST), and flooding of the Primary Auxiliary Building (PAB).

- **ESWS** (Essential Service Water System): ESWS is Considered the most vulnerable system; loss of ESW is assumed when the breakwater is overtopped or damaged.
- **EP**: Offsite Power is assumed to be lost when tsunami waves reach the site grade level (10 m), resulting in submergence of switchyard transformers.
- **EDG**: Emergency Diesel Generator is assumed to be inoperable due to ESWS failure during a tsunami.
- **PAB**: Flooding potential is considered for mitigation systems; assumed to be inundated for tsunami heights ≥13 meters.
- **CST** (Condensate Storage Tank): Damage probability is evaluated as a function of tsunami height.
- **AAC** (Alternate AC Diesel Generator): Damage status is considered based on tsunami height.

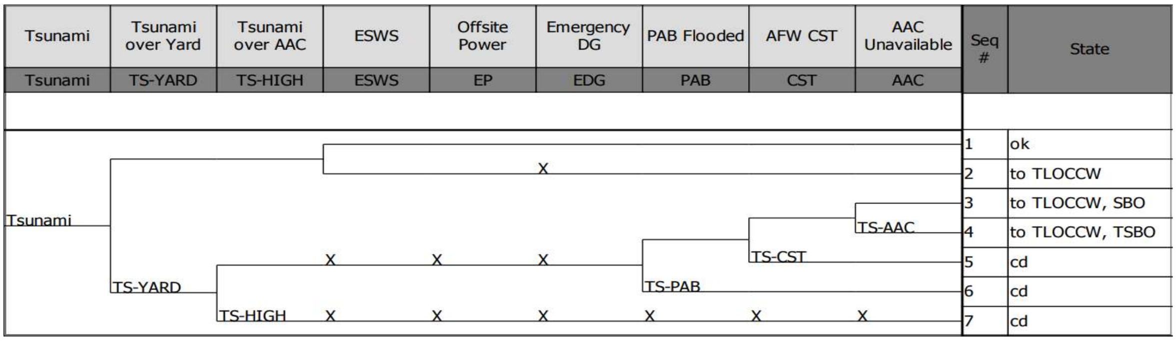

FIGURE 3. Tsunami-Induced initiating Event Tree

Ⅲ. Model Development

Ⅲ.A. Reference Site

A model was developed for representative reactor types at the Hanul site, including Framatome, OPR1000, and APR1400.

Ⅲ.B. Tsunami PSA bounding analysis base model

Due to the limited availability of data, the Tsunami PSA bounding analysis base model was constructed using conservative assumptions to account for inherent uncertainties. The base model was developed under a conservative assumption that a tsunami over 10 meters in height infiltrates the building through exterior doors, resulting in flooding of the mitigation systems. The base model excludes tsunami wave heights between 1 and 4 meters from the analysis, as the damage probability of the Essential Service Water System (ESWS) within this range is considered negligible. For tsunami wave heights ranging from 5 to 10 meters, the model evaluates scenarios considering TLOCCW. Tsunami wave heights exceeding 10 meters are modeled with the assumption of direct core damage.

III.B.1. Development of the Event Tree and Fault Tree (Base model)

The event tree for TLOCCW caused by tsunami wave heights between 5 and 10 meters is presented in Figure 4. The fault tree utilized the full-power internal events MPAS (Multi-purpose Probabilistic Analysis of Safety) model, where failure of the ESWS and Circulating Water System (CWS) due to TLOCCW was incorporated into the fault tree using the SIMA file. The SIMA file is a tool designed to modify fault tree data, logical structures, and configuration flags in PSA models. The initiating event frequency of TLOCCW (GIE-TC-TSUNAMI) was calculated by multiplying the sum of tsunami occurrence frequencies within the 5 to 10 meter range by the breakwater damage probability. The breakwater damage probability for 5 to 10 meter tsunami (0.39) was obtained by dividing the sum of the products of breakwater failure probabilities at each tsunami height and their respective occurrence frequencies by the occurrence frequency of 5-meter tsunami. The initiating event frequency for tsunami exceeding 10 meters (%T-IE-TSUNAMI-HG) was computed as the sum of the occurrence frequencies of tsunami exceeding 10 meters. For quantification, the Tsunami PSA Bounding analysis base model developed a core damage fault logic, which is illustrated in Figure 5.

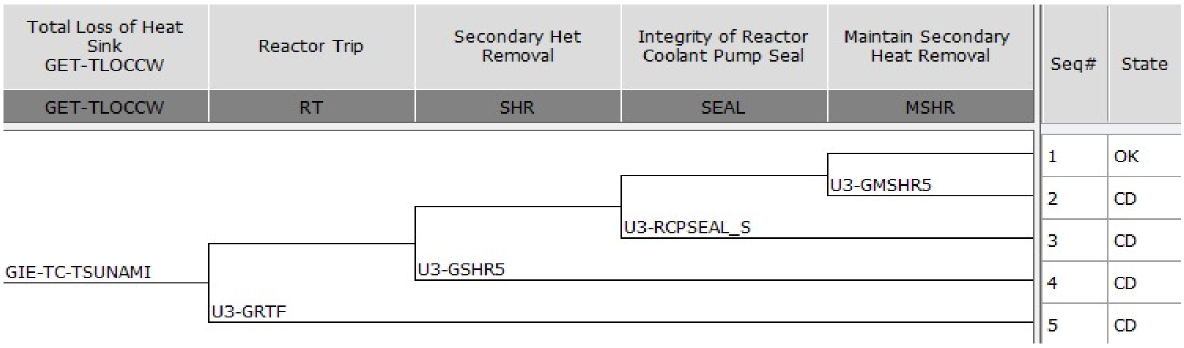

FIGURE 4. Tsunami-Induced TLOCCW Event Tree

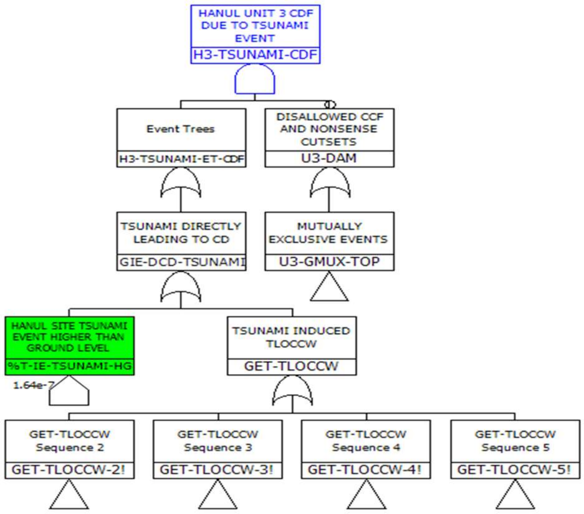

FIGURE 5. Core Damage Top-Logic (Base model)

III.C. Tsunami PSA bounding analysis sensitivity model

The Tsunami PSA bounding analysis sensitivity model was developed to incorporate the results of an on-site inspection at the Hanul site and to perform additional analyses for tsunami wave heights between 10 and 13 meters. The on-site inspection confirmed the installation of seismic-resistant watertight doors on all access points of relevant structures to protect key safety equipment against flooding caused by tsunamis. Additionally, HVAC openings susceptible to tsunami ingress were verified to be located at elevations exceeding 3 meters above site grade. Accordingly, the analysis assumed no tsunami ingress into the PAB and Secondary Auxiliary Building (SAB) for tsunami heights up to 13 meters. As an exception, the ESWS, identified as the most vulnerable component, was assumed to be unavailable during tsunamis exceeding 10 meters. The damage probabilities of major SSCs for each tsunami wave height are summarized in Table 3.

TABLE 3. Damage Probability of Structure, System, and Component by Tsunami Wave Height

SSC	Value	Explanation
ESWS	3.9E-01	Average Probability of Damage to the Primary Component Coolant Water System Due to tsunamis ranging from 5 to 10 meters
	1.0	Assuming damage from a tsunami of over 10 meters
CST	2.2E-01	Probability of damage to Condensate Storage Tanks due to tsunamis between 10 and 13 meters
DWST	2.2E-01	Probability of damage to Demineralized Storage Tanks due to tsunamis between 10 and 13 meters
AAC DG	0.0	The damage probability is not considered for tsunamis with wave heights below 13 meters.
	1.0	The assumption is made that damage occurs for tsunamis exceeding 13 meters

III.C.1. Development of the Event Tree and Fault Tree (Sensitivity model)

The sensitivity model evaluation for tsunami wave heights between 5 and 10 meters was conducted identically to the base model. However, to assess the impact of watertight door installation implemented as a post-Fukushima countermeasure, the effects of tsunamis between 10 and 13 meters were additionally evaluated. For tsunamis within the 10 to 13-meter range, SBO was considered as an initiating event, and the tsunami-induced SBO event tree for the power plant is presented in Figure 6. The impacts on TLOCCW and SBO due to tsunamis in this range were incorporated into the fault tree using SIMA files. Furthermore, damage probabilities were considered for tanks used as secondary heat removal water sources under 10 to 13-meter tsunamis conditions. The initiating event frequency for SBO was calculated as the cumulative occurrence frequency of tsunamis between 10 and 13 meters, while tsunamis exceeding 13 meters were assumed to cause direct core damage. In the Tsunami PSA bounding analysis sensitivity model, core damage fault logic was developed to support the quantification process, as illustrated in Figure 7.

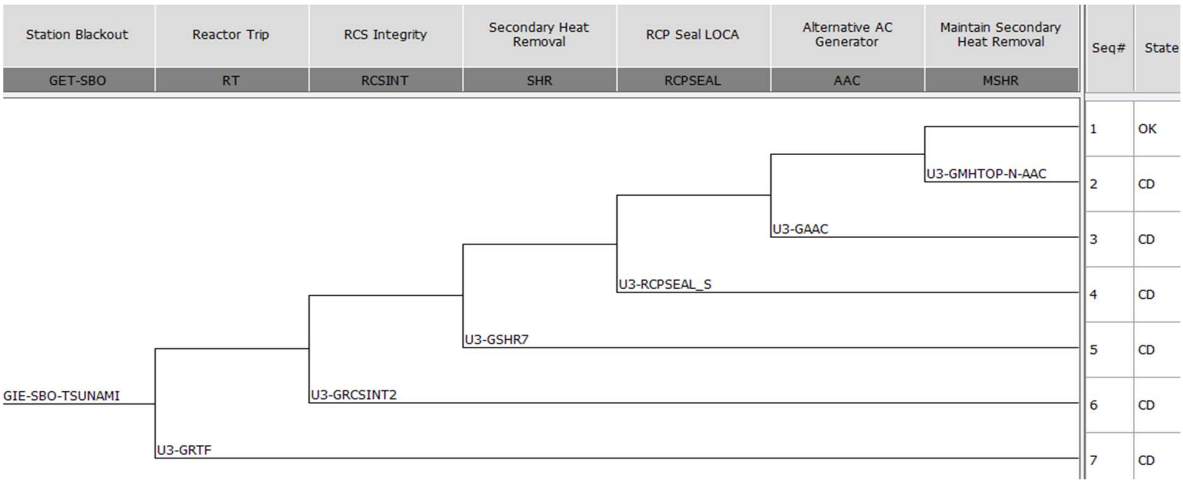

FIGURE 6. Tsunami-Induced SBO Event Tree

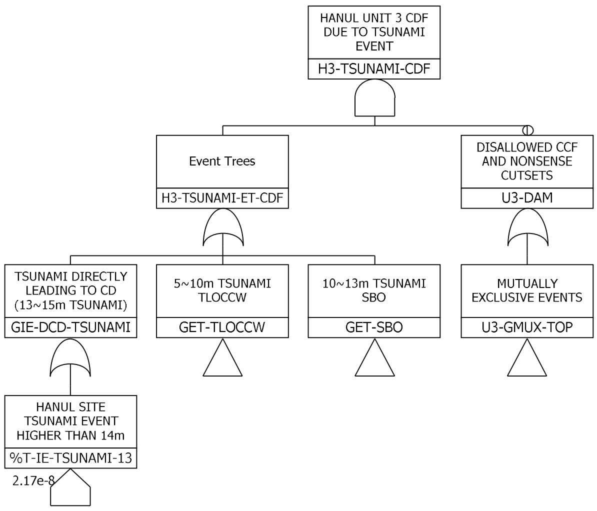

FIGURE 7. Core Damage Top-Logic (Sensitivity model)

IV. Result

Models reflecting unit-specific characteristics were developed for the representative reactor types at the Hanul site, and the quantification results are presented in Table 4. The results are compared based on the CDF of the Hanul Units 3 and 4 base model, and the reduction rate is demonstrated by comparing the CDF values between the base model and sensitivity model for each unit. Differences in CDF among units are primarily attributed to variations in the Reactor Coolant Pump (RCP) Seal models, which are illustrated in Figure 8. For Sin Hanul Units 1 and 2, the ESW Intake Structure differs from other units by having a pump well configuration; therefore, the breakwater damage probability was excluded and only the ESWS damage probability was applied when calculating TLOCCW frequencies. Additionally, the greater reduction rate in the sensitivity model is due to the increased number of available water sources during Secondary heat removal (SHR) or Maintained Secondary Heat Removal (MSHR) states.

The quantification results indicated that differences in CDF were primarily attributed to variations in the RCP seal model, the number of available water sources for SHR/MSHR, the presence of flood barriers, and the configuration of the ESW intake structure. Among these factors, the RCP seal model had the greatest impact on the CDF. This is attributed to the fact that in tsunami-induced TLOCCW and SBO scenarios, an RCP seal LOCA was assumed to lead directly to core damage. Therefore, the RCP seal model plays a critical role in determining the CDF, and mitigation strategies to reduce RCP seal failure probability should be considered, particularly for Hanul Units 1 and 2.

TABLE 4. Tsunami PSA Bounding Analysis Model Quantification

HU12 (Framatome) CDF			HU34 (OPR-1000) CDF			SHU12 (APR-1400) CDF		
Base model	Sensitivity model	Reduction rate	Base model	Sensitivity model	Reduction rate	Base model	Sensitivity model	Reduction rate
939.1%	899.0%	4.3%	100.0%	63.3%	36.7%	71.5%	14.6%	79.5%

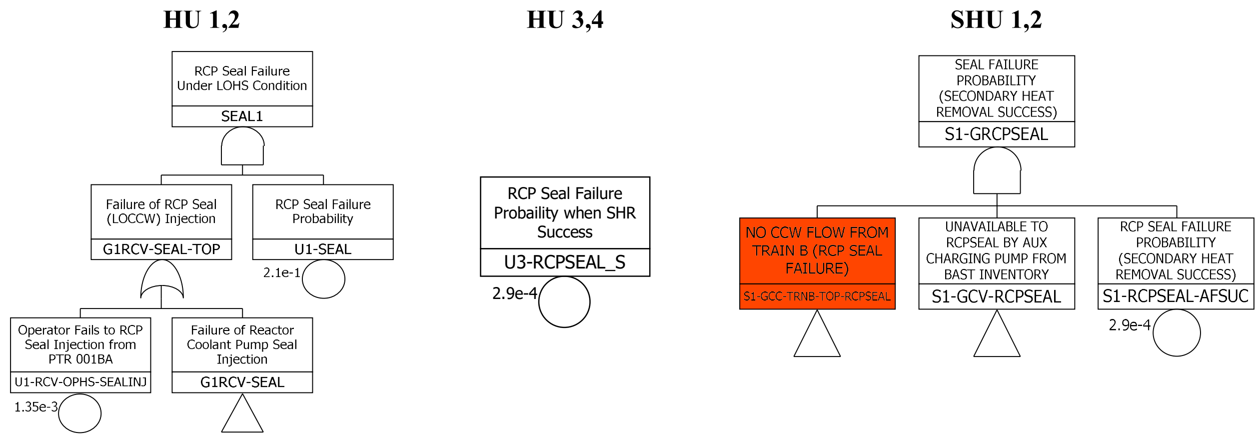

FIGURE 8. RCP Seal model for each unit

V. CONCLUSIONS

This study developed a tsunami PSA bounding analysis methodology for representative reactor designs at the Hanul site and established a single-unit tsunami PSA bounding model based on a regulatory verification model. The developed tsunami PSA bounding analysis models, incorporating design-specific characteristics, identified factors influencing differences in quantification results and core damage frequency among reactor types. Additionally, a sensitivity model reflecting the impact of watertight door installations—implemented as a post-Fukushima measure—was developed to evaluate the reduction in CDF. The findings of this study are expected to provide a technical foundation for the future development of single-unit tsunami PSA review guidelines.

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