Nuclear Engineering and Technology 50 (2018) 1217–1233

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Topical Issue Article

Multi-unit Level 1 probabilistic safety assessment: Approaches and their application to a six-unit nuclear power plant site

Dong-San Kim [a,*], Sang Hoon Han [a], Jin Hee Park [a], Ho-Gon Lim [a], Jung Han Kim [b]

[a] Korea Atomic Energy Research Institute, Daejeon, 34057, Republic of Korea
[b] Pusan National University, Pusan, 46241, Republic of Korea

ARTICLE INFO

Article history:
Received 22 September 2017
Received in revised form
5 December 2017
Accepted 9 January 2018
Available online 31 January 2018

Keywords:
Inter-unit Dependency
Multi-unit Core Damage Frequency
Multi-unit Probabilistic Safety Assessment
Multi-unit Probabilistic Risk Assessment
Multi-unit Risk
Site Core Damage Frequency

ABSTRACT

Following a surge of interest in multi-unit risk in the last few years, many recent studies have suggested methods for multi-unit probabilistic safety assessment (MUPSA) and addressed several related aspects. Most of the existing studies though focused on two-unit nuclear power plant (NPP) sites or used rather simplified probabilistic safety assessment (PSA) models to demonstrate the proposed approaches. When considering an NPP site with three or more units, some approaches are inapplicable or yield very conservative results. Since the number of such sites is increasing, there is a strong need to develop and validate practical approaches to the related MUPSA. This article provides several detailed approaches that are applicable to multi-unit Level 1 PSA for sites with up to six or more reactor units. To validate the approaches, a multi-unit Level 1 PSA model is developed and the site core damage frequency is estimated for each of four representative multi-unit initiators, as well as for the case of a simultaneous occurrence of independent single-unit initiators in multiple units. For this purpose, an NPP site with six identical OPR-1000 units is considered, with full-scale Level 1 PSA models for a specific OPR-1000 plant used as the base single-unit models.

1. Introduction

To date, most probabilistic safety assessments (PSAs) for nuclear power plants (NPPs) have focused on a specific “single” unit. However, as the Fukushima Daiichi nuclear accident in March 2011 highlighted the importance of considering the risks from multi-unit accidents at NPP sites, there has been a surge of interest in site risk (or multi-unit risk) in the last few years. Multi-unit risk is of particular concern in Korea as all four NPP sites—Kori, Wolsong, Hanbit, and Hanul—have six or more units.

Site risk can be obtained by summing the risk from single-unit initiators (SUIs) occurring at only one unit and the risk from multi-unit initiators (MUIs) challenging two or more units, simultaneously [1]. The initiating events covered by internal events, internal flooding, and internal fire PSAs are mostly SUIs, while MUIs are mainly caused by external hazards such as earthquakes, tsunamis, or typhoons. Here, the risk caused by SUIs can be divided into the following three categories.

- Cases in which an SUI only affects the unit where the SUI has occurred, with the other units at the site not affected.
- Cases in which an SUI also affects one or more additional units at the site.
- Cases in which independent SUIs occur in two or more units at the site simultaneously or within a short time interval [for example, a loss of offsite power (LOOP) initiator occurs in Unit 2 a few hours after a general transient occurs in Unit 1].

Among these, the first is already treated in single-unit PSAs. The second is considered to have little effect on the Korean NPPs because each unit has its own independent structures (e.g., containment building and turbine building) with very few shared systems or components. Although the risk from the third category is generally thought to be low, it is not certain that it is sufficiently low to be negligible. It is difficult to find published research that estimates the contribution to site risk from the third category, which is one of the objectives of this study.

Since the contribution to multi-unit risk from MUIs is considered dominant, most existing studies on multi-unit PSA (MUPSA) have focused on risks from MUIs. A number of studies have suggested methods for MUPSA and addressed several related aspects

* Corresponding author.
E-mail address: dongsankim@kaeri.re.kr (D.-S. Kim).

https://doi.org/10.1016/j.net.2018.01.006

[2–10]; among these, the three most recently published articles [8–10] have proposed more comprehensive approaches to MUPSA. Le Duy et al. [8] proposed some methodological options to switch a single-unit PSA model to a site-level one, illustrated with a simplified twin-unit model. Zhang et al. [9] introduced a general MUPSA framework based on the high-temperature gas-cooled reactor pebble-bed module with an integrated sequence modeling approach, and then demonstrated its applicability using a two-unit high-temperature gas-cooled reactor pebble-bed module model. Modarres et al. [10] proposed a parametric approach to address multi-unit dependencies and used a conceptual two-unit logic example to illustrate the approach.

As can be seen, most of the existing studies focused on two-unit sites and/or used rather simplified PSA models with only one or a limited number of initiating events (e.g. LOOP) to demonstrate the proposed approaches. As the number of units to be considered increases, the size and complexity of a MUPSA model also increases. Therefore, when considering three or more units, some approaches that are applicable to a MUPSA for two-unit sites can be inapplicable, such as the event tree method for accident sequence modeling, or yield very conservative results, such as the beta-factor model for inter-unit common-cause failures (CCFs).

Seeing that there are already many NPP sites with six or more operating units in several countries, including Korea, Canada, Japan, China, and India and the number of such sites is expected to increase in the near future when including the units under construction and planned for construction [11], there is a strong need to develop and validate practical approaches that are applicable to MUPSA for such multi-unit sites. For this purpose, an overall methodology and software tools for MUPSA including levels 1, 2, and 3 have been developed, which are discussed in other articles in this issue [12,13].

This study provides several detailed approaches that are applicable to a multi-unit Level 1 PSA. For validation, a multi-unit Level 1 PSA model is developed, and the site core damage frequency (CDF) is estimated for each of four representative MUIs and for the case of a simultaneous occurrence of independent SUIs in multiple units. For this purpose, an NPP site with six OPR-1000 reactor units is considered as the reference site, with full-scale Level 1 PSA models for a specific OPR-1000 plant used as the base single-unit models.

The models and quantification results from this study are further used as inputs for multi-unit Level 2 and Level 3 PSAs for the reference site, each of which is also described in this issue in study by Cho et al and Kim et al [14,15], respectively.

This study is not intended to perform a MUPSA for a specific real NPP site or identify site-specific vulnerabilities and potential for improvements. Rather, the development of MUPSA models and the estimation of site CDF performed here are intended to validate approaches that are applicable to MUPSA for sites with six or more NPP units and to gain some insight into which factors are important in MUPSA.

In this work, the terms "site CDF" and "multi-unit CDF" are differentiated; the former is defined as the frequency at which one or more units at a site experiences core damage, and the latter is defined as the frequency of multiple (two or more) units having core damage. The terms "site PSA" and "multi-unit PSA" though are used interchangeably.

The remainder of this article is organized as follows. Section 2 explains the approaches to and results of the estimation of the contribution to site CDF from a simultaneous occurrence of independent SUIs in two or more units at a site. Section 3 describes the approaches and results for estimating site CDF due to four selected MUIs. Section 4 concludes the paper and discusses the limitations of this study and future work.

2. Estimation of the contribution to site CDF from the simultaneous occurrence of independent SUIs in multiple units

The analysis in this section was performed for internal hazards including internal events, internal flooding, and internal fires. External hazards such as earthquakes and tsunamis were excluded because they are generally not considered to occur independently in each unit at the same site.

As aforementioned, an NPP site with six OPR-1000 units was considered as the reference site. For this study, the latest revisions of the at-power Level 1 PSA models (i.e., internal events, internal flood, and internal fire PSA models) for a specific OPR-1000 unit were used as the base single-unit models.

2.1. Key assumptions

This analysis is subject to the following assumptions:

- The six units at the site are identical. That is, the structures, systems, and components (SSCs) and the operating/testing/maintenance procedures are the same. Only the operators are different.
- All six units are at full power. Low-power and shutdown (LPSD) modes are not considered.
- Initiating events in each unit occur independently. In other words, there is no dependency between the units in terms of initiating events; the occurrence of an initiator in a specific unit (i.e. the initiating unit) therefore does not affect the probability that subsequent unit(s) at the same site experience an initiating event.
- The "simultaneity" of two or more initiating events is defined as the occurrence of those events within 72 h.

2.2. Calculation of the upper and lower bounds of multi-unit CDF

Multi-unit CDF due to the simultaneous occurrence of independent SUIs in two or more units varies with the level of dependency of the mitigating systems or components between units. Before CDF estimation through detailed model development, the upper and lower bounds of the multi-unit CDF were first calculated using the following respective assumptions: (1) "complete dependency" between units as the most conservative assumption and (2) "complete independence" between units as the most optimistic assumption.

In the first case, it is assumed that if independent SUIs have occurred simultaneously at two or more units and the initiating unit has experienced core damage, the subsequent unit(s) also experience(s) core damage. In contrast, the second case assumes that all events—including component failure events, human failure events and initiating events—are completely independent between the six units.

When inter-unit dependencies are completely neglected (the most optimistic case), the frequency of core damage in k unit(s) due to the simultaneous occurrence of independent SUIs in k units can be calculated using the following equation:

$$(k-unit\ CDF) = {}_6P_k \times \left[\sum_{i=1}^{n} f(IE_i) \times CCDP_i\right] \times \left[\sum_{i=1}^{n} Pr(IE_i) \times CCDP_i\right]^{k-1}, \quad (1)$$

where k is the number of units that experience core damage, n is the number of initiating events modeled in the base single-unit PSA ($n = 17$), $f(IE_i)$ is the annual frequency of a specific initiating event in a unit (the initiating unit), $Pr(IE_i)$ is the conditional probability that a specific initiating event occurs in subsequent unit(s) within 72 h after the occurrence of the initiator in the initiating unit, and $CCDP_i$ is the conditional core damage probability given the occurrence of a specific initiating event.

In this study, all possible unit permutations of initiating event occurrences were taken into account. For example, the case where a Unit 1 initiator occurs followed by a Unit 2 initiator and the case where a Unit 2 initiator occurs followed by a Unit 1 initiator are differentiated.

Here, $Pr(IE_i)$ is the probability on a per 72-hour basis, which is converted from the initiating event frequency on a per-year basis. For example, in case of a general transient (GTRN) initiating event, $f(IE_i)$ is 7.06E-01/yr and $Pr(IE_i)$ is 5.80E-03 (= 7.06E-1/yr × 72 hrs/ 8760 hrs).

In this calculation, the cases where independent SUIs have occurred simultaneously in k units but core damage has occurred in less than k units (i.e. 1, …, k-1) were not included because the CDF from those cases are negligible. For example, the frequency of core damage in two units due to the simultaneous occurrence of independent SUIs in three units is much lower than that due to the simultaneous occurrence of independent SUIs in two units.

In the assumption of complete dependency between units except for initiating events (the most conservative case), the frequency of core damage in k unit(s) due to the simultaneous occurrence of independent SUIs in k units can be calculated using the following equation:

$$(k-unit\ CDF) = {}_6P_k \times \left[\sum_{i=1}^{n} f(IE_i) \times CCDP_i\right] \times \left[\sum_{i=1}^{n} Pr(IE_i) \times 1\right]^{k-1}. \quad (2)$$

Here, $CCDP_i$ given the occurrence of any initiating event in the subsequent unit(s) is equal to 1.

Table 1 shows the ratio of the upper and lower bounds of the multi-unit CDF for each number of units experiencing core damage to six times single-unit CDF from internal events when using the base internal events at-power Level 1 PSA model. The upper and lower bounds of the multi-unit CDF were calculated by applying Eqs. (1) and (2), respectively. As the number of (core) damaged units increases, the ratio dramatically falls. This result indicates that even in the most conservative case, the contribution to site CDF from the simultaneous occurrence of SUIs in "three or more" units at the reference site is negligible (0.1% or less of six times single-unit CDF), while site CDF from the simultaneous occurrence of SUIs in "two" units (3.6% in the most conservative case) is not negligible. If a wider time interval (e.g. 7 days) between the occurrences of independent SUIs is considered, each ratio in Table 1 will increase. Even in this case, however, the contribution to site CDF from the simultaneous occurrence of SUIs in three or more units is still negligible (less than 0.6% of six times single-unit CDF).

Therefore, it is necessary to check whether the dual-unit CDF due to the simultaneous occurrence of independent SUIs in two units is actually negligible or not by developing a detailed dual-unit model which reflects the dependencies between the two units.

As with the case for internal events, the respective upper and lower bounds of the multi-unit CDF due to the simultaneous occurrence of independent internal floods as well as independent internal fires in two or more units were calculated using the base internal-flood and internal-fires at-power PSA models. Even in the most conservative cases (complete dependency), site CDF from the simultaneous occurrence of SUIs in two units was less than 1% of six times the single-unit CDF. This is because the value of $Pr(IE_i)$ in Eq. (2) is smaller by a factor of four or five than that used in the internal events PSA. The reason for the relatively high $Pr(IE_i)$ in the internal events PSA is that the GTRN initiating event frequency is very high at 7.06E-01/yr.

Accordingly, detailed assessment was performed here only for the case where independent "internal events" occurred simultaneously in two units being at-power. In other words, dual-unit CDF from the simultaneous occurrence of independent single-unit internal events was estimated by developing a detailed dual-unit model.

2.3. Development of a dual-unit CDF model

A dual-unit CDF model was developed based on the base single-unit PSA model (internal-events, at-power Level 1 model). Since this study assumes six identical units, only one unit permutation of initiating event occurrence ("Unit 1 → Unit 2") was considered.

First, a top event with an AND gate for estimating dual-unit CDF was made, and then each individual unit model was placed under the AND gate. To distinguish between the Unit 1 and Unit 2 models, each gate or basic event name was prefixed with the number 1 or 2 to represent its unit. In this model, Unit 1 was assumed as the initiating unit and Unit 2 as the subsequent unit, so each initiating event frequency in the Unit 1 model is the same as those in the base single-unit PSA model (i.e. on a per-year basis). Each initiating event frequency in the Unit 2 model was converted to a conditional probability on a per 72-hour basis.

Inter-unit dependencies were taken into account for the following three aspects: (1) SSCs shared between both units, (2) dependencies between human failure events (HFEs) in the two units, and (3) inter-unit CCFs.

Table 1
Ratio of the upper and lower bounds of the multi-unit CDF due to the simultaneous occurrence of independent initiators for each number of units with core damage to six times the single-unit CDF (when using "internal events" PSA model).

Number of units with core damage	Number of combinations (${}_6P_k$)	Ratio to six times single-unit CDF[a]	
		Most optimistic case	Most conservative case
1	6	–	–
2	30	1.1E-07	3.58E-02
3	120	9.8E-15	1.03E-03
4	360	6.5E-22	2.21E-05
5	720	2.9E-29	3.16E-07
6	720	6.4E-37	2.27E-09

CDF, core damage frequency; PSA, probabilistic safety assessment.
[a] Single-unit CDF was from the at-power "internal events" Level 1 PSA for an OPR1000 unit.

According to a recent analysis for an OPR-1000 unit [16], a very limited number of SSCs [e.g., alternative AC diesel generator (AAC DG), switchyard, and sea water] are shared between units, and among those, only the availability of the AAC DG can be affected by a multi-unit accident. In this study, it was assumed that the AAC DG is connected only to the initiating unit (Unit 1), so in case of simultaneous station blackout (SBO) in both units, it is not available to the subsequent unit (Unit 2).

Since each OPR-1000 unit has its own independent main control room (MCR) and operating crews, most HFEs included in the base single-unit PSA model are regarded as independent from those in different units, with only offsite power recovery actions considered as dependent. It was assumed here that offsite power recovery actions in both units are completely dependent; that is, if the offsite power recovery action in the initiating unit fails, the recovery action in the subsequent unit also fails regardless of the allowed time.

Inter-unit CCFs were considered only for risk-significant components, which were determined using the Fussell–Vesely (FV) importance measure. The top 50 basic events with FV importance values greater than 0.01 in the base single-unit PSA were selected as significant basic events. Table 2 shows the risk-significant CCF basic events for which inter-unit CCFs were modeled.

When the size of the common-cause component group (CCCG) is 2 or 3 in the base single-unit model, all possible combinations of inter-unit CCF events were modeled in the dual-unit model. Take for example that each unit has two trains of a containment spray (CS) system; therefore, in the dual-unit model, four CS pumps were grouped in a CCCG, and each combination of two-of-four, three-of-four, or four-of-four pumps failing due to a CCF was modeled. However, if the size of the CCCG is 4 or more in the base single-unit model, the number of combinations of inter-unit CCF events increases exponentially. Consequently, for simplicity, only the complete CCF basic event of all the components failing (i.e. eight-of-eight CCF) was added to the existing single-unit CCF model, and its probability was assumed to be 0.1 multiplied by the complete CCF probability used in the single-unit model. For example, the mean probability of eight-of-eight essential chillers failing due to an inter-unit CCF is calculated by multiplying the mean probability of four-of-four essential chillers failing due to a CCF (1.02E-05) by 0.1.

2.4. Quantification results

The quantification of accident sequence frequencies was performed using AIMS-PSA software (Rev. 1.2) [17] and the fault tree reliability evaluation expert (FTREX) quantification engine (Ver. 1.8, 64 bit) [18]. The cutoff value (or truncation limit) was determined by lowering it orders of magnitude until the dual-unit CDF converged, with a final cutoff value of 1E-19/yr used.

As a result of quantification, dual-unit CDF due to the simultaneous occurrence of independent SUIs in two specific units at the reference site was estimated to be 1.33E-11/yr (point estimate). This is the result from only one unit permutation of initiating event occurrence (Unit 1 → Unit 2). Taking into account all possible unit permutations (${}_6P_2 = 30$), dual-unit CDF was calculated to be 3.99E-10/yr, which is only 0.0025% of the sum of single-unit CDFs (i.e., six times single-unit at-power internal events CDF). It can be considered as sufficiently low to be neglected.

In terms of accident sequences, the minimal cutsets where the SBO events occurred in both units accounted for 81% of total dual-unit CDF. Specifically, the accident sequences where "after the LOOP events occurred simultaneously in both units, all five diesel generators (DGs) [four emergency diesel generators (EDGs) and a shared AAC DG] failed due to CCF and the operators also failed to recover the offsite power" accounted for about 62% of the total.

Since the contribution to site CDF was estimated to be sufficiently low, Level 2 and Level 3 PSAs were not performed for the simultaneous occurrence of independent SUIs in two or more units.

3. Estimation of site CDF due to MUIs

Among all possible initiating events that could be caused by internal and external hazards, the following four representative MUIs were selected based on the Korean NPP experience and the impact of each initiating event on an OPR-1000 plant.

- Multi-unit LOOP
- Multi-unit loss of ultimate heat sink (LOUHS)
- Multi-unit seismic events
- Multi-unit tsunami events

Among these, seismic events and tsunami events are not initiating events by themselves but hazard events [19]. In general, for any given hazard such as an earthquake, a range of hazard events are defined by creating a number of discrete intervals, each of which represents a specific level of severity of the hazard. Furthermore, a hazard event can result in multiple initiating events, each with a conditional probability of occurrence. In this study, two tsunami events and five seismic events (or seismic intervals) were

Table 2
List of CCF basic events for which inter-unit CCFs were modeled.

CCF basic events		Mean probability[a]	F-V importance[a]	Change in CCCG size
Component	Failure mode			
Diesel generator	Fail to run	1.10E-04	7.84E-02	3 → 5 [b]
Diesel generator	Fail to start	3.55E-05	5.66E-02	3 → 5 [b]
Essential chiller	Fail to run	1.02E-05	3.98E-02	4 → 8
Control element assembly	Mechanical failure	1.52E-06	1.80E-02	28 → 56
Hi-Hi containment pressure transmitter	Fail to run	2.65E-04	1.63E-02	4 → 8
Cubicle cooler for HPSI pump room	Fail to run	7.42E-05	1.60E-02	2 → 4
Containment spray (CS) pump	Fail to start	7.62E-05	1.52E-02	2 → 4
Cubicle cooler for CS pump room	Fail to run	7.42E-05	1.48E-02	2 → 4
CS heat exchanger motor-operated valve	Fail to open	6.26E-05	1.25E-02	2 → 4
Interface relay/contact in ARC	Fail to operate	4.51E-06	1.22E-02	4 → 8
Auxillary feedwater turbine steam supply valve	Fail to open	1.29E-04	1.14E-02	2 → 4
Auxillary feedwater turbine steam isolation valve	Fail to open	8.79E-05	7.78E-03	2 → 4

AAC DG, alternative AC diesel generator; CCF, common-cause failure; CCCG, common-cause component group; EDG, emergency diesel generator; PSA, probabilistic safety assessment; HPSI, high-pressure safety injection; ARC, auxiliary relay cabinet.

[a] The mean probability and F-V importance of each basic event are from the base single-unit model.

[b] In the base single-unit PSA, three DGs (two EDGs and an AAC DG) are grouped in a CCCG. In the dual-unit model, since each unit has two EDGs and the AAC DG is shared between two units, a total of five DGs are grouped in a CCCG.

taken into account, with a total of eleven seismically induced initiating events (e.g. seismic-induced LOOP) considered for each seismic event. More details are given in Sections 3.4 and 3.5. Thus, the number of MUIs included in this study is much greater than four.

For each of the above MUIs, a multi-unit Level 1 PSA model was developed using practical approaches, and the site CDF was estimated. The details of each are described in the following sections.

As mentioned before, an NPP site with six OPR-1000 units was considered as the reference site. For this analysis, the latest revisions of the at-power Level 1 PSA models (i.e., internal events, seismic, and tsunami models) for an OPR-1000 unit were used as the base single-unit models for each of the six units.

3.1. General approach

3.1.1. Key assumptions

The following are the key assumptions commonly applied to all multi-unit PSA models that were developed in this study.

- The reference site has six identical OPR-1000 units.
- All SSCs except for the DGs are identical, and their reliability data including seismic fragility are the same.
- The operators are different between units, but the operating/testing/maintenance procedures are the same, and the human error probability for a certain HFE is the same.
- All six units are at full-power operation. LPSD modes were not considered.
- A MUI challenges all six units simultaneously or nearly simultaneously, and its impact on each unit [e.g. peak ground acceleration (PGA) in seismic PSA] is the same.
- For the EDGs and AAC DGs, the current status of the Hanul and Hanbit NPP sites in which four out of six units are OPR-1000s was considered. That is, it was assumed that Units 1 and 2 have the same type of EDGs and share an AAC DG, and Units 3 through 6 have a different type of EDGs and share a different type of AAC DG.
- The adverse effects of core damage or release in one unit on the other units were not considered.
- The new set of mitigation equipment installed as part of the post-Fukushima actions in Korea (e.g. portable DGs and pumps) was not taken into account because the related reliability data were not yet available at the time of this study.

3.1.2. Procedure for estimating site CDF due to each MUI

The site CDF due to each MUI was estimated using the following steps:

1) Estimation of the multi-unit initiating event frequency on a per site-year basis.
2) Construction of a single-top fault tree logic for the site CDF model.
3) Development of each individual unit model based on the base single-unit model, and integration of each unit model into the top logic.
4) Modification of the single-top fault tree considering inter-unit dependencies.
5) Quantification of the accident sequence frequencies.

As in a single-unit PSA, the frequency of each MUI was estimated using different approaches according to their characteristics. For internal events (e.g. multi-unit LOOP), the frequency distribution is generally obtained from plant-specific or generic industry data. For extremely rare initiating events (e.g. multi-unit loss of ultimate heat sink), the frequency can be estimated by engineering judgment [19]. For external events such as seismic and tsunami events, the frequency is generally based on a site-specific probabilistic hazard analysis.

Fig. 1 shows an example of the single-top fault tree structure for estimating the site CDF of a six-unit site. The top event corresponds to core damage in at least one of the six units, which includes all cases where one to six of the six units at the site experience core damage. To distinguish between these cases easily in analyzing the quantification results, tag events such as “#1UNIT”, “#2UNITS”, … , “#6UNITS” were added.

Each individual unit model is based on the base single-unit PSA model in the form of a single-top fault tree, with modifications made before integration into the top logic for the site CDF model as follows.

- Fault tree logics unrelated to the initiator being analyzed were deleted; hence, only the logics related to the initiator remained. This reduces the size of each unit model.
- Each individual unit model was constructed so that each accident sequence includes its plant damage state information to make it easier to link with multi-unit Level 2 PSA.
- To evaluate the conditional core damage probability (CCDP) given the occurrence of an initiator, only the frequency of the initiator being analyzed was set to 1, with the other initiating events set to “False.”
- Each unit model was distinguished by changing the names of all gates and basic events included in the base single-unit LOOP model. Basically, each gate or basic event name was prefixed with the number representing its unit: 1, 2, 3, 4, 5, or 6 (e.g. “1GIE-LOOP”). Regarding the initiator, the same basic event was applied equally to all six unit models without distinguishing between units, because it was assumed in this study that the MUIs challenge all six units simultaneously.

Inter-unit dependencies were taken into account for the following five aspects: (1) common-cause initiating events, (2) SSCs shared between multiple units, (3) dependencies between HFEs in different units, (4) inter-unit CCFs, and (5) inter-unit seismic correlation.

As previously mentioned, the dependency of a common-cause initiating event was addressed by modeling it as the one and only initiator (one basic event) in the site CDF model for the initiator.

In terms of shared SSCs, as described in Section 2.3, only AAC DG availability can be affected by a multi-unit accident in OPR-1000 plants. In this study, it was assumed that Units 1 and 2 share an AAC DG, and Units 3 through 6 share another AAC DG. Since current emergency operating procedures do not describe the priorities for shared components, including the AAC DG, it was assumed that for each AAC DG, the priority was given in the order of Unit 1 → Unit 2 and of Unit 3 → Unit 4 → Unit 5 → Unit 6. The fault trees related to the AAC DGs were modified considering these assumptions [20]. That is, for the cases where SBO events simultaneously occur in two or more units, as the AAC DG is connected only to the unit with the highest priority (e.g. Unit 3), it is not available to the other unit(s) with lower priorities (e.g., Units 4, 5, and 6). Switching its connection from one unit to another was not considered. Fig. 2 shows an example of the modified fault tree logic for the AAC DG used by Unit 6. As shown in this figure, when an SBO event occurs in Unit 3, 4, or 5, the AAC DG is not available for Unit 6.

As also discussed in Section 2.3, each OPR-1000 unit is controlled by its own operating crews in separate MCRs, and hence operator actions performed in the MCRs are regarded as independent from those in different units. As most HFEs included in the

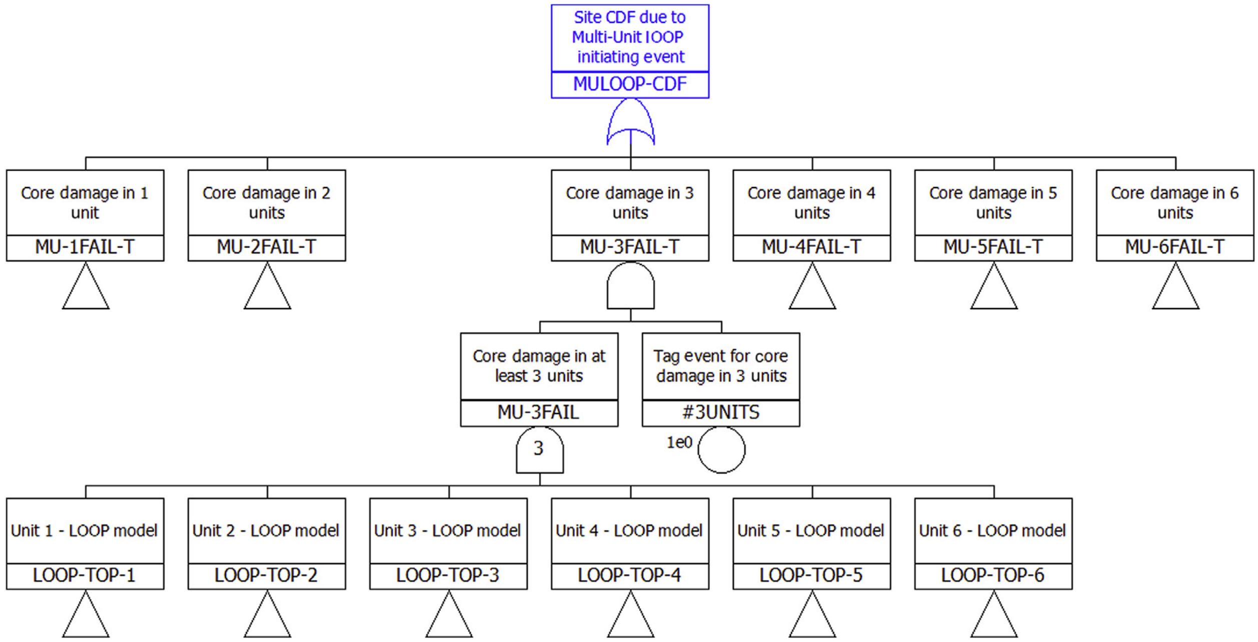

Fig. 1. Example of a single-top fault tree logic for estimating the site CDF of a six-unit site considering a multi-unit LOOP initiating event.
CDF, core damage frequency; LOOP, loss of offsite power.

base single-unit PSA model occur in the MCR, it was assumed for those HFEs that there is no dependency between units, and the basic event name for each HFE with no inter-unit dependency was prefixed with a number representing its unit. However, offsite power recovery actions were treated as dependent because multiple units share a switchyard or grid.

Inter-unit CCFs were modeled only for risk-significant components, which were selected based on the FV importance measure. Basically, a component was regarded as risk significant if at least one of the basic events involving its failure (random or common-cause failure) had an FV importance value of 0.01 or more in the base single-unit model, which contains only the logics related to

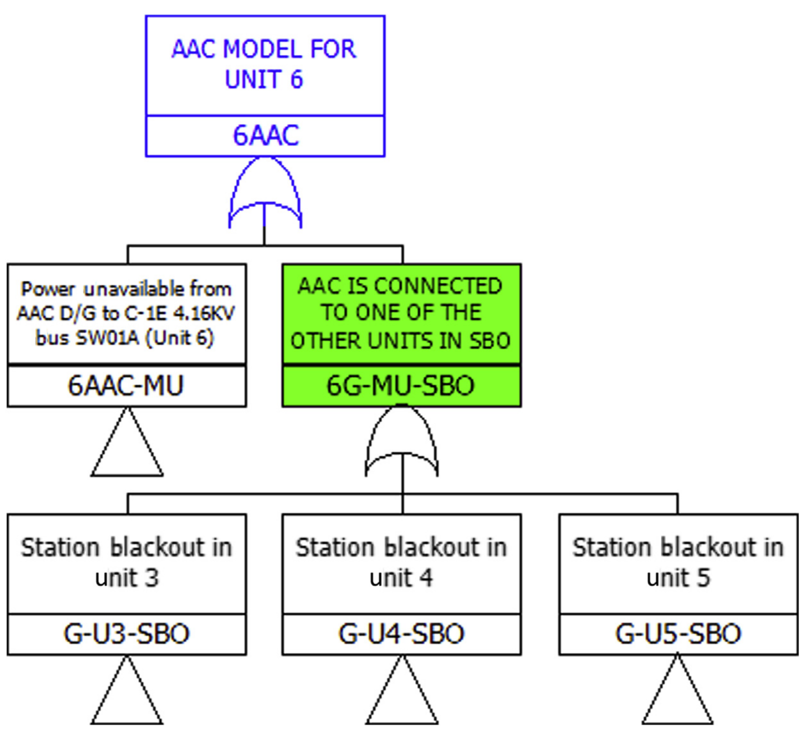

Fig. 2. Example of a modified fault tree logic for the AAC DG used in Unit 6.
AAC DG, alternative AC diesel generator.

the initiating event being analyzed. For each selected component type except for the DGs, all the components of the six units were grouped into a CCCG, and all possible CCF basic events were modeled because it was assumed that all SSCs other than the DGs are the same across units. For calculating inter-unit CCF basic event probabilities, generic data (alpha factors from NUREG/CR-5497 [21]) was used as in the base single-unit PSA. However, since inter-unit CCFs for six units are considered in this study, it was often the case that the CCCG size was greater than the maximum size for which NUREG/CR-5497 provides alpha factors. Hence, the corresponding impact vectors were first estimated using the mapping up technique [22], and then the alpha factors were calculated. In addition, a staggered testing scheme was assumed in the calculations of the probabilities of inter-unit CCF basic events.

For multi-unit seismic PSA, inter-unit seismic correlation was considered for seismically induced initiating events and risk-significant fragility basic events. Details are described in Section 3.4.

3.1.3. CDF quantification methods

The quantification of accident sequence frequencies was performed using AIMS-PSA software (rev. 1.2) [17] and the FTREX quantification engine (ver. 1.8, 64 bit) [18]. In addition, SiTER (splitter and integrator for total estimation of site risk) was used to find and delete nonsense or duplicate cutsets (see [13] for details). The cutoff value (or truncation limit) for the quantification of each model was determined by lowering it orders of magnitude until the total CCDP converged.

Cutset-based quantification using the rare event approximation or the min cut upper bound can significantly overestimate site CCDP when the model has numerous high-probability basic events (e.g. a seismic PSA model). Therefore, in this case, quantification was performed using fault tree top event probability evaluation using Monte Carlo simulation (FTeMC) (see [13] for details).

For each multi-unit PSA model, the site CCDP given the occurrence of the initiator being analyzed was first estimated, and then the site CDF was calculated by multiplying the site CCDP by the initiating event frequency.

3.2. Estimation of site CDF due to a multi-unit LOOP initiating event

3.2.1. Estimation of multi-unit LOOP initiating event frequency

Multi-unit LOOP initiating event frequency was estimated based on the Korean nuclear operating experience. Table 3 summarizes the LOOP events that occurred in Korean NPPs through the end of 2016. A total of 10 site-level LOOP events (fifteen plant-level LOOPs) occurred, which can be classified into the following three categories:

- Events that affected all units at the site.
- Events that affected two but not all units at the site.
- Events that affected only one unit at the site.

Among the 10 LOOP events, there were two that affected all units at the site, one event that affected two units but not all units at the site, and seven events that occurred at one unit (i.e. single-unit LOOPs). Therefore, in this study, three LOOP initiating events were considered: six-unit LOOP, dual-unit LOOP, and single-unit LOOP. Although a six-unit LOOP event has never occurred in Korea, the two events affecting all units at the site were regarded as six-unit LOOP events. As can be seen in Table 3, all three multi-unit LOOP events occurred before 1998, and since then only single-unit LOOPs have occurred. It is therefore likely that there is a decreasing trend in the frequency of multi-unit LOOP events and an increasing trend in the frequency of single-unit LOOPs over time. A time-trend analysis was not performed in this study however, and hence all LOOP events were used to estimate the frequency of each LOOP initiating event category.

For a multi-unit PSA, it is most convenient to measure initiating event frequencies on a per site-year basis, not on a per reactor-year basis [3]. As shown in Table 4, a total of 131.1 site-years were obtained by summing the operating years of the four NPP sites in Korea during the period 1978–2016. Shin-Kori and Shin-Wolsong site-years were incorporated into Kori and Wolsong site-years, respectively.

The mean frequency and distribution of each LOOP initiating event category, as shown in Table 5, were estimated by a Bayesian update of the Jeffreys noninformative prior with Korean industry data.

3.2.2. Development of the site CDF model for multi-unit LOOP

Basically, the site CDF model for a multi-unit LOOP was developed using the methods described in Section 3.1.

Fig. 3 shows an example of site CDF model development for a six-unit LOOP initiating event using the base single-unit LOOP model, which includes only the LOOP-related fault tree logics. As mentioned in Section 3.1.2, each individual unit model (Units 1 through 6) was developed by first making some modifications to the base model and then incorporating it into the single-top logic to estimate site CDF due to the multi-unit LOOP initiator. The site CDF model for the dual-unit LOOP initiating event was developed in a similar way, but with only two individual unit models (Units 1 and 2) used. For estimating site CDF due to the single-unit LOOP initiating event, the base single-unit LOOP model was used.

For dependencies between HFEs, it was assumed that there was no dependency between operation actions in different units, except for offsite power recovery actions. In case of offsite power recovery, "complete dependency" between units was assumed because a multi-unit LOOP event challenging all six units is likely to be weather- or grid-related. Therefore, for offsite power recovery, the same basic event was applied equally to all six unit models without distinguishing between units.

For inter-unit CCFs, only the CCFs of the DGs (EDGs and AAC DGs) were considered because the minimal cutsets involving failure(s) of DG(s) account for about 96% of total CDF resulting from the LOOP event in the base single-unit internal events PSA model. According to Section 3.1.1, two different CCCGs were considered: one group for the five DGs in Units 1 and 2 and another group for the nine DGs in Units 3 through 6. For each CCCG, all CCF basic events were modeled.

3.2.3. Reevaluation of nonrecovery probabilities of offsite power

Another important issue is to determine the probability of not recovering offsite power to a safety bus at various times following the initiation of LOOP. In the base single-unit PSA model, the nonrecovery probabilities were estimated using Korean nuclear industry data from the period 1978–2016. Among 15 plant-level LOOP events that occurred during a critical or shutdown operation, eight events were related to multi-unit LOOP and the other seven were single-unit LOOP events.

Because the offsite power restoration times of multi-unit LOOP events (avg. 6.5 h) are much longer than those of single-unit LOOP events (avg. 1.1 h), the probability of exceedance versus duration curves were generated separately for single-unit and multi-unit LOOPs in this study. Both lognormal and Weibull curve fits were generated for each category; as the former demonstrated a better fit to the data, lognormal curves were used. In addition, no significant differences existed between the critical operation and shutdown operation data, so curves were generated combining the data for both operations. In this study, each curve was

Table 3
LOOP events that occurred in Korean NPPs during the period 1978–2016.

No.	Unit(s)	Date	Operation mode	Cause	Restoration time (min)	LOOP category[a]	Remarks
1	Kori 3/4	8/28/1986	Shutdown at-Power	Typhoon	465	Weather-related	2 out of 4 units at the site
2	Kori 1/2 Kori 3/4	7/16/1987 7/17/1987	At-power At-power	Typhoon Typhoon	480 576	Weather-related	4 out of 4 units at the site
3	Hanul 1/2	1/1/1997	At-power	Heavy snow	28	Weather-related	2 out of 2 units at the site
4	Kori 2	9/27/1998	At-power	Component failure	30	Plant-centered	1 out of 4 units at the site
5	Wolsong 2	6/19/2004	Shutdown	Human error	233	Plant-centered	1 out of 4 units at the site
6	Hanbit 5	11/29/2006	Shutdown	Component failure	26	Plant-centered	1 out of 6 units at the site
7	Wolsong 2	9/3/2009	Shutdown	Human error	83	Plant-centered	1 out of 4 units at the site
8	Hanbit 5	12/29/2010	Shutdown	Human error	21	Plant-centered	1 out of 6 units at the site
9	Kori 3[b]	4/19/2011	Shutdown	Human error	50	Plant-centered	1 out of 4 units at the site
10	Kori 1	2/9/2012	Shutdown	Human error	12	Plant-centered	1 out of 4 units at the site

LOOP, loss of offsite power; NPP, nuclear power plant.
[a] Categories of LOOP events: plant-centered, switchyard-centered, grid-related, and weather-related [23].
[b] Although the LOOP event occurred in both Units 3 and 4, Unit 4 continued critical operation without reactor trip.

Table 4
Site-years of each Korean NPP site during the period 1978–2016.

Site	Start date of commercial operation	Site-years[a] (~2016.12)
Kori[b]	1978-4-29	38.7
Hanul	1988-9-10	28.3
Hanbit	1986-8-25	30.4
Wolsong[b]	1983-4-22	33.7
Sum		131.1

LOOP, loss of offsite power; NPP, nuclear power plant.
[a] Operation modes (at-power or shutdown) of each unit at the site are not considered.
[b] Kori and Wolsong sites include Shin-Kori and Shin-Wolsong units, respectively.

generated using a similar process with that used in NUREG/CR-6890 [23]. For example, a lognormal curve for multi-unit LOOPs was generated by fitting the offsite power restoration times for multi-unit LOOPs to the lognormal density function, and then the probability of not recovering offsite power within a given duration (e.g. 2 h) was calculated by one minus its cumulative distribution function.

Fig. 4 and Table 6 show the results of the lognormal fits to the offsite power restoration times. For 7 h and 15 h—the most risk significant durations in the base single-unit PSA model—the probabilities of exceedance increased by a factor of about 2 compared to the probabilities used in the base single-unit model. This result is not surprising because all three multi-unit LOOP events in Table 3 were caused by severe weather conditions such as typhoons or heavy snow. This is consistent with US data where weather-related LOOP durations were much longer than durations of other LOOP categories [23].

In this study, the probabilities for multi-unit LOOP in Table 6 (e.g., 3.24E-01 for the probability that the operator fails to recover offsite power within 7 h) were used to estimate the site CDF due to multi-unit LOOP initiating events (i.e., six-unit LOOP and dual-unit LOOP), while the probabilities for single-unit LOOP were used to estimate the site CDF due to a single-unit LOOP initiating event.

3.2.4. Quantification results

Table 7 shows the results of estimating site CDF due to the three categories of LOOP initiating events. The mean site CDF was about 6.93E-06 per site-year. The frequency of core damage in only one unit contributes 92.9% of site CDF, followed by the frequency of core damage in only two units (6.5%), and the frequency

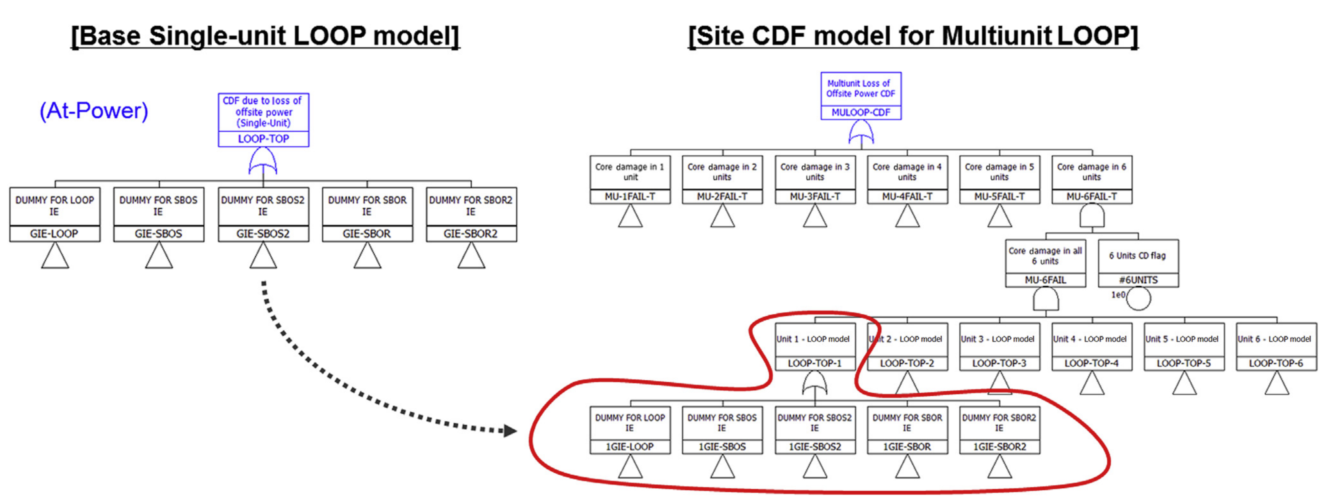

Fig. 3. Example of site CDF model development for a six-unit LOOP initiating event. CDF,core damage frequency; LOOP, loss of offsite power.

Table 5
LOOP initiating event data and frequency distribution.

LOOP initiating event category	Num. of events	Site-year	Frequency (/site-year)			
			MLE[b]	Gamma distribution		
				Mean[c]	α	β
Six-unit LOOP[a]	2	131.1	1.53E-02	1.91E-02	2.5	131.1
Dual-unit LOOP	1	131.1	7.63E-03	1.14E-02	1.5	131.1
Single-unit LOOP	7	131.1	5.34E-02	5.72E-02	7.5	131.1

LOOP, loss of offsite power.
[a] Among the ten LOOP events, two events that affected all units at the site when the events occurred were considered to fall into this category.
[b] MLE (maximum likelihood estimate) = (number of events)/131.1 site-year.
[c] Mean of the Gamma distribution = (number of events + 0.5)/131.1 site-year (Bayesian update of the Jeffreys noninformative prior).

of core damage in three units (0.6%). The frequency of core damage in four or more units is negligible. In these results, the CCDP given the single-unit LOOP initiating event (7.43E-06) decreased by a factor of about five compared with that in the single-unit PSA because risk-significant probabilities of not recovering offsite power were reduced by more than an order of magnitude, as shown in Table 6.

Taking a closer look at the results for the six-unit LOOP, the minimal cutsets (accident scenarios) where “two or more DGs failed due to a common cause and the recovery of offsite power also failed” account for 43.7% of site CDF (5.36E-06/site-yr) and 99.4% of multi-unit CDF, which is the frequency of core damage in two or more units (4.24E-07/site-yr). In terms of basic event importance, failures of recovering offsite power by operators within 15 h and within 7 h are the highest with FV values of 0.535 and 0.310, respectively, followed by the unavailability of the AAC DG due to testing or maintenance, AAC DG failure to run, and AAC DG connection failure by the operator. The FV importance value of each DG CCF basic event is relatively low (at most 0.011) because all possible CCF combinations were modeled.

It is important to note that the separation of LOOP duration curves for single- and multi-unit LOOP events had a considerable impact on site CDF due to a multi-unit LOOP (six-unit and two-unit LOOP in this study). The separation itself increased site CDF by about 70% compared to the case where the LOOP events were not separated. Also, the contribution of multi-unit CDF (i.e. core damage in two or more units) to site CDF increased from 4.3% to 7.1% when the LOOP duration curves were separated.

Table 6
Probability of not recovering offsite power at various times.

Duration (hr)	Single-unit LOOPs	Multi-unit LOOPs	All LOOPs[a]
1	3.60E-01	8.83E-01	6.52E-01
2	1.58E-01	7.27E-01	4.67E-01
3	8.38E-02	6.03E-01	3.59E-01
4	4.97E-02	5.07E-01	2.89E-01
5	3.18E-02	4.32E-01	2.39E-01
6	2.14E-02	3.72E-01	2.02E-01
7	1.51E-02	3.24E-01	1.74E-01
8	1.09E-02	2.85E-01	1.51E-01
9	8.14E-03	2.52E-01	1.33E-01
10	6.20E-03	2.24E-01	1.18E-01
11	4.81E-03	2.01E-01	1.06E-01
12	3.79E-03	1.81E-01	9.54E-02
13	3.03E-03	1.63E-01	8.65E-02
14	2.45E-03	1.48E-01	7.88E-02
15	2.00E-03	1.35E-01	7.21E-02
16	1.65E-03	1.24E-01	6.62E-02
17	1.37E-03	1.14E-01	6.10E-02
18	1.15E-03	1.05E-01	5.65E-02
19	9.74E-04	9.65E-02	5.24E-02
20	8.29E-04	8.93E-02	4.87E-02

LOOPs, loss of offsite powers, PSA, probabilistic safety assessment.
[a] Probabilities used in the base single-unit PSA model.

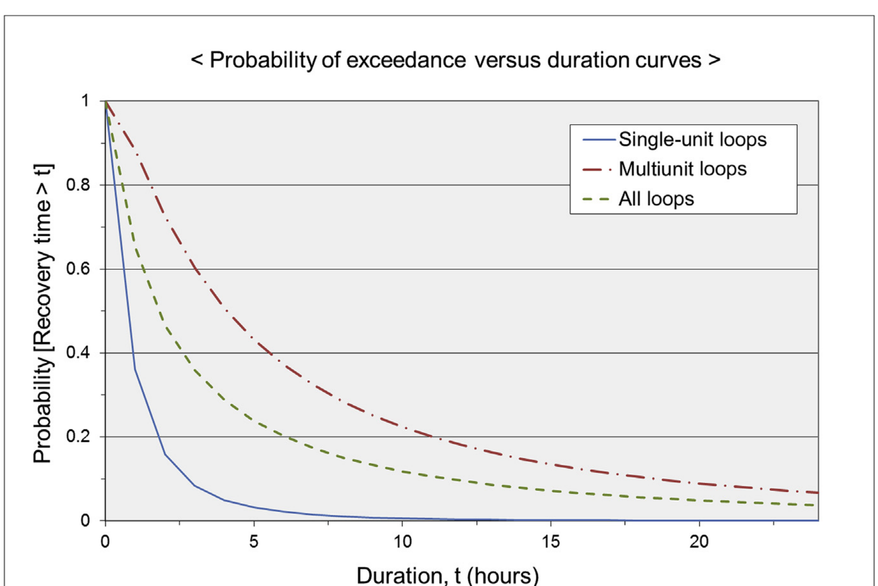

Fig. 4. Probability of exceedance versus duration curves for single-unit, multi-unit, and all LOOPs.
LOOP, loss of offsite power.

Table 7
Results of estimating site CDF due to LOOP initiating events.

LOOP initiating event category	Initiating event frequency (site-yr)	CCDP	CDF (site-yr)	CDF for each number of units with core damage					
				1 unit	2 units	3 units	4 units	5 units	6 units
Six-unit LOOP	1.91E-02	2.81E-04	5.36E-06	4.93E-06	3.80E-07	4.07E-08	2.87E-09	ε[a]	ε[a]
Dual-unit LOOP	1.14E-02	1.00E-04	1.15E-06	1.08E-06	6.80E-08	N/A	N/A	N/A	N/A
Single-unit LOOP	5.72E-02	7.43E-06	4.25E-07	4.25E-07	N/A	N/A	N/A	N/A	N/A
Sum	8.77E-02	–	6.93E-06	6.44E-06	4.48E-07	4.07E-08	2.87E-09	ε	ε
%	–	–	100.0%	92.9%	6.5%	0.6%	0.04%	ε	ε

CCDP, conditional core damage probability; CDF, core damage frequency; LOOPs, loss of offsite powers.
[a] Minimal cutsets for core damage in 5 or 6 units were truncated. (CCDP cutoff value = 1E-12).

3.3. Estimation of site CDF due to a multi-unit LOUHS initiating event

3.3.1. Estimation of multi-unit LOUHS frequency

In this study, a multi-unit LOUHS initiating event is defined as a total loss of component cooling water (TLOCCW) event occurring simultaneously in all six units. Since the probability of simultaneous TLOCCW in six units caused by internal factors (e.g. CCF of all CCW pumps) is extremely low, it was assumed to occur due to external factors, such as a large amount of marine organisms or garbage in the sea water shared by all six units.

Unlike the multi-unit LOOP initiating event, a multi-unit LOUHS (even a single-unit LOUHS) has never occurred in the Korean nuclear industry. In this case, its frequency distribution can be obtained by a Bayesian update of Jeffreys noninformative prior with industry data (i.e. "zero" events during the period), and the resulting mean frequency is 3.81E-03 per site-year (= 0.5/131.1 site-yr). However, since this frequency is higher by a factor of about 20 than the single-unit TLOCCW frequency (2.12E-04 per reactor calendar year) used for the base single-unit PSA, it is inadequate to be used.

Consequently, multi-unit LOUHS frequency was assumed to be 1/10 of the single-unit TLOCCW frequency by engineering judgment. This means that one of 10 TLOCCW initiating events was assumed to affect all six units at the site. Therefore, 2.12E-05/site-yr was used as the mean frequency of the multi-unit (six-unit) LOUHS initiating event. The frequency of LOUHS in less than six units was not considered in this study.

3.3.2. Development of the site CDF model for multi-unit LOUHS

The site CDF model for multi-unit LOUHS was developed in the same way as the model for multi-unit LOOP.

In case of a TLOCCW event, it is possible to supply offsite power through unit or standby auxiliary transformers, unlike in LOOP events, and thus the conditional probability of the LOOP given a TLOCCW is very low. For this reason, the availabilities of the AAC DGs have very little effect on the quantification result, and so the sharing of AAC DGs between units was not taken into account in the site CDF model for multi-unit LOUHS.

Further, there is no need to recover offsite power in a TLOCCW event; therefore, all HFEs included in the site CDF model for multi-unit LOUHS (e.g., "engineered safety feature (ESF) switchgear room and inverter room cooling recovery") were assumed to have no inter-unit dependency.

Inter-unit CCFs were modeled for the three types of components that have FV importance values of 0.01 or higher in the base single-unit LOUHS model: turbine-driven auxiliary feedwater (AFW) pumps, AFW turbine steam supply valves, and AFW turbine steam isolation valves. For each component type, a total of twelve components (two redundant trains in each unit) were grouped into one CCCG, and all possible CCF basic events were modeled. A total of 4,083 ($= 2^{12} - 12 - 1$) CCF basic events were modeled for each CCCG.

The CCF multiplier values needed to calculate inter-unit CCF basic event probabilities were calculated using the alpha factors for each component type, with staggered testing schemes assumed for all the component types. Since NUREG/CR-5497 [21] does not include alpha factors for a CCCG of twelve, the impact vectors for a CCCG of this size were first estimated using the mapping up technique followed by alpha-factor calculation. In particular, as the impact vectors in NUREG/CR-5497 are all zero for the failure mode "turbine-driven AFW pumps fail to start", the impact vectors for "pooled turbine-driven pumps fail to start" in NUREG/CR-5497 (2012 update) [24] were used instead.

3.3.3. Quantification results

Table 8 summarizes the results of estimating site CDF due to the multi-unit LOUHS initiator (six-unit LOUHS). Mean site CDF was about 3.02E-07 per site-year. The frequency of core damage in only one unit contributes 98.0% of site CDF, followed by the frequency of core damage in two units (1.7%). The frequency of core damage in three or more units is negligible at less than 1%.

In terms of minimal cutsets, the cutsets in which "operators fail to recover the ESF switchgear room and/or inverter room cooling" or "reactor coolant pump (RCP) seal LOCA occurs" after the initiation of the multi-unit LOUHS account for about 80% of site CDF.

In terms of basic event importance (FV), "operators fail to recover the ESF switchgear room and/or inverter room cooling" and "RCP seal LOCA occurs" events are the highest at 0.11 and 0.02 (0.65 and 0.12 summing over all six units), respectively, followed by the intraunit CCFs of two trains of AFW turbine steam supply valves in the same unit and of two trains of AFW turbine steam isolation valves in the same unit.

3.4. Estimation of site CDF due to multi-unit seismic events

3.4.1. Seismic event frequency

In this study, the frequency of seismic events was based on the resulting seismic hazard curves from a probabilistic seismic hazard analysis for the Hanul NPP site [25]. The hazard curves (15^{th} percentile, median, mean, and 85^{th} percentile) are in the form of annual frequencies of exceedance of various levels of ground motion (PGA).

In the single-unit seismic PSA, the mean hazard curve was divided into five discrete intervals, or ground motion ranges, with a seismic PSA model developed for each. Table 9 shows the mean frequency of seismic events and the representative magnitude for each seismic interval.

As previously mentioned, it was assumed that a seismic event occurs concurrently in all six units at the site and its impact on each unit (i.e. PGA) is the same, so the frequencies in Table 9 were also used for the multi-unit seismic PSA.

3.4.2. Development of the site CDF model for multi-unit seismic events

As with the models for multi-unit LOOP and multi-unit LOUHS, the site CDF model for multi-unit seismic events was developed using the methods described in Section 3.1: each individual unit model was developed by making modifications to the base single-

Table 8
Results of estimating site CDF due to multi-unit LOUHS.

Number of units with core damage	Multi-unit LOUHS IE frequency (site-yr)	Conditional core damage probability (CCDP)	CDF (site-yr)	%
1	2.12E-05	1.40E-02	2.96E-07	98.0%
2	2.12E-05	2.35E-04	4.98E-09	1.7%
3	2.12E-05	4.38E-05	9.28E-10	0.3%
4	2.12E-05	8.05E-06	1.71E-10	0.1%
5	2.12E-05	9.25E-07	1.96E-11	0.0%
6	2.12E-05	6.55E-08	1.39E-12	0.0%
Sum	–	1.42E-02	3.02E-07	100.0%

CDF, core damage frequency.

unit seismic PSA model and then incorporated into the single-top logic for estimating site CDF due to multi-unit seismic events. Here, respective site CDF models were developed for each seismic interval.

In the single-unit seismic PSA, a total of 11 seismically induced initiating events (e.g. seismic-induced large LOCA) are modeled. When considering multiple units, different initiating events in each unit can be induced by a seismic event, such as a seismic-induced large LOCA in Unit 1 and seismic-induced LOOP in Unit 2. In general, however, PSA software does not allow for the simultaneous occurrence of two or more initiating events. To address this problem, as can be seen in Fig. 5, the seismic event itself at each interval (e.g. 0.3*g* seismic event) was modeled as the only initiating event, and all 11 seismic-induced initiating events in the single-unit seismic PSA model were changed to basic events, each with an associated conditional probability of occurrence given the seismic event.

In the seismic PSA, no credit was given to the AAC DG because it is a nonsafety (Non-1E) component. Moreover, offsite power recovery actions were also not credited because significant damage to the grid or switchyard was assumed.

Therefore, inter-unit dependencies were taken into account for the following types of events: (1) all seismically induced initiating events (eleven basic events for each unit) and (2) seismically induced fragility basic events with FV importance values greater than 0.01 in the base single-unit seismic PSA model (e.g., EDGs, condensate storage tanks, essential chillers, and C-1E 125V DC bus). Inter-unit dependencies of nonseismically induced failures were not considered because their important values are insignificant in the single-unit seismic PSA.

Inter-unit CCF basic events (CCCG size = 6) were modeled for each of the seismically induced initiating events and risk-significant fragility basic events. However, for those with a mean probability high enough that its sixth power was greater than the 6-out-of-6 CCF probability, inter-unit CCFs were not modeled because this can contribute to an underestimation of site CDF.

Inter-unit dependencies were not applied to the associated SSC failures (e.g., reactor building, RCPs, steam generators, piping, and heat exchangers) for seismically induced initiating events, but to the probability itself, or in other words, the conditional probability of occurrence given the seismic event at a specific interval. Figs. 6 and 7 show examples of six-unit CCF models for seismically induced initiating events and fragility events, respectively. The fault tree logic in Fig. 6 includes all possible combinations of seismic-induced reactor building failure initiating events for Unit 1: a basic event for independent seismic-induced reactor building failure only in Unit 1 and 31 seismic CCF basic events (2-of-6, 3-of-6, 4-of-6, 5-of-6, and 6-of-6 units) including reactor building failure in Unit 1. For each of the other units (Units 2 to 6), a fault tree logic with the same structure and size was modeled.

In contrast with nonseismically induced CCFs, it is difficult to find either plant-specific or generic data for seismically induced CCFs. Therefore, in single-unit seismic PSAs, a binary approach is typically used for seismic fragility correlation [26]. For example, a correlation of 1 (full correlation) is assumed for identical and redundant components on the same building elevation, and a correlation of zero (no correlation) is assumed for all the other components. However, in case of multi-unit seismic PSAs, using the binary approach can significantly overestimate or underestimate site CDF.

To calculate seismically induced inter-unit CCF basic event probabilities, all failure probabilities of the same components in all six units (i.e. 6-out-of-6 CCF probability) were first calculated for each seismic hazard bin by using a computational code that takes the median values and standard deviations of the response and capacity of the component and the inter-unit seismic correlation as input [27]. An example of the results is presented in Table 10. It shows how the simultaneous failure (structural failure) probability of the EDGs in all six units changes as the inter-unit seismic correlation increases from 0 to 1 for each seismic hazard range.

In Table 10, the probabilities for a correlation coefficient of 1 are the same as those used for the single-unit seismic PSA model (i.e., seismically induced structural failure probabilities of both EDGs in a single unit), and the probabilities for a correlation coefficient of 0 are equal to the sixth power of those used in the single-unit seismic PSA model. When an inter-unit correlation of 0 or 1 is assumed, seismically induced inter-unit CCFs do not need to be modeled. For other inter-unit correlations, such as 0.3, a CCF alpha factor (α_6) representing the ratio of 6-out-of-6 CCF to total failures can be obtained by dividing the probability for the assumed correlation (e.g. 3.90E-09 at 0.2–0.4*g*) by the probability for the correlation of 1 (ex. 1.04E-03 at 0.2–0.4*g*).

However, from these results, only one CCF alpha factor, α_6, can be obtained. Therefore, the other alpha factors (α_1, α_2, α_3, α_4, α_5) were estimated in the order of α_5 to α_1 by applying the ratio between alpha factors for generic demand CCF distribution in NUREG/CR-5497 [21]. Since the sum of alpha factors should be equal to 1, if $\sum_{n=k}^{6}\alpha_n$ (the sum of α_k to α_6) is larger than 1, then $(1-\sum_{n=k+1}^{6}\alpha_n)$ was assigned to α_k. Moreover, if $\sum_{n=k+1}^{6}\alpha_n$ has already reached 1, a nominal value of 1.0E-04, which is sufficiently low not to change the sum, was assigned to α_k. Table 11 shows an example of the alpha factor estimation results for EDG structural failure when an inter-unit seismic correlation of 0.3 was assumed.

Table 9
Mean frequency of seismic events in each seismic interval.

Seismic intervals (g[a])	Mean frequency (/yr)	Representative magnitude (g)
0.2–0.4	1.35E-04	0.3
0.4–0.6	2.13E-05	0.5
0.6–0.8	6.31E-06	0.7
0.8–1.0	2.22E-06	0.9
1.0–1.2	1.01E-06	1.1

[a] g: peak ground acceleration (PGA).

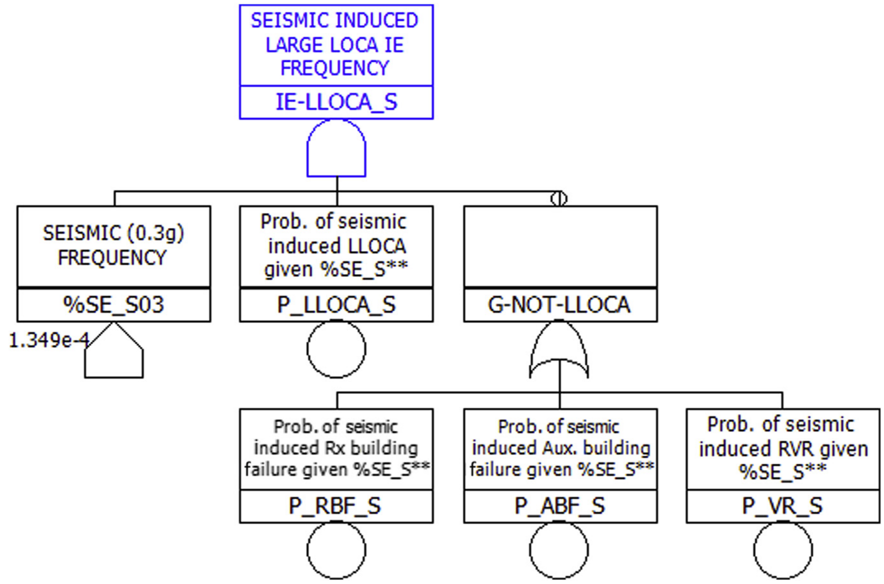

Fig. 5. Example of a revised model for a seismic-induced initiating event.
ABF: auxiliary building failure; RBF: reactor building failure; LLOCA: large loss of coolant accident; SE: seismic.

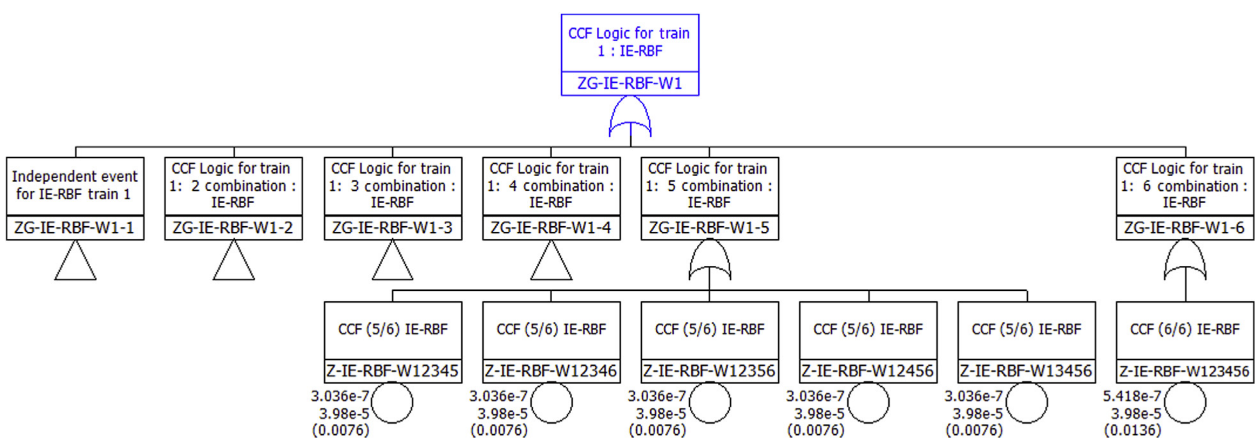

Fig. 6. Example of a six-unit CCF model for a seismically induced initiating event (reactor building failure in Unit 1). IE-RBF: seismically induced reactor building failure initiating event.
CCF, common-cause failure.

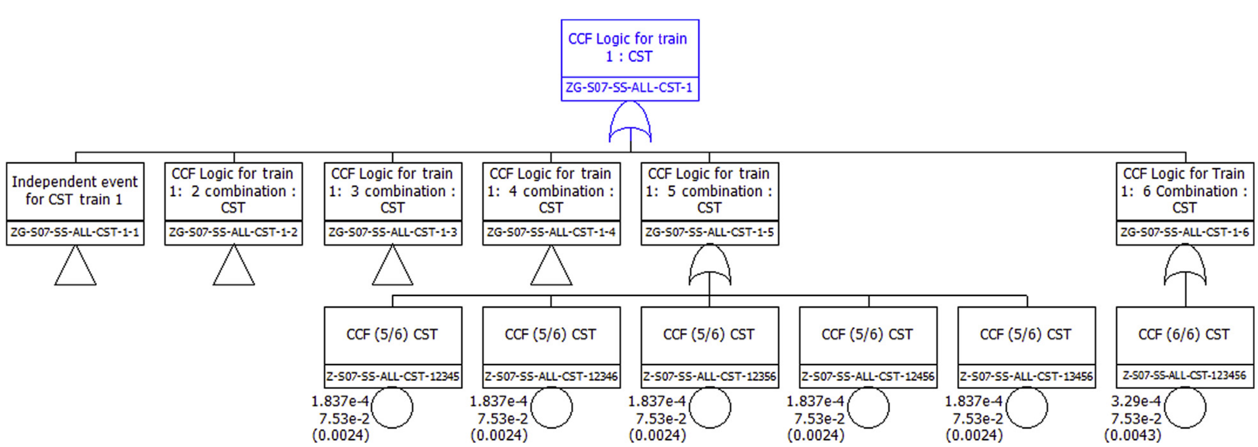

Fig. 7. Example of a six-unit CCF model for a seismically induced fragility event (condensate storage tank in Unit 1).
CCF, common-cause failure.

Table 10
Example of simultaneous failure probability of the same SSCs in all six units according to inter-unit seismic correlation coefficients by seismic hazard intervals (EDG structural failure: $A_m = 1.1g$, $\beta_R = 0.25$, $\beta_U = 0.34$).

Seismic intervals (g)	Inter-unit seismic correlation coefficient					
	0.0	0.3	0.5	0.7	0.9	1.0
0.2–0.4	1.26E-18	3.90E-09	5.66E-07	1.35E-05	1.64E-04	1.04E-03
0.4–0.6	8.64E-10	2.89E-05	3.92E-04	2.25E-03	9.66E-03	3.09E-02
0.6–0.8	8.23E-06	1.93E-03	8.78E-03	2.54E-02	6.48E-02	1.42E-01
0.8–1.0	1.02E-03	1.99E-02	5.01E-02	9.85E-02	1.82E-01	3.17E-01
1.0–1.2	1.56E-02	8.07E-02	1.43E-01	2.23E-01	3.35E-01	5.00E-01

EDG, emergency diesel generator; SSC, structures, systems, and component.

3.4.3. Quantification results

Since the multi-unit seismic PSA model has numerous high-probability fragility events, cutset-based quantification using AIMS-PSA and FTREX significantly overestimated site CCDP. Therefore, quantification of the multi-unit seismic PSA model was performed using FTeMC, which is based on Monte Carlo simulations, with 10^6 samples for each quantification. Therefore, for each seismic hazard interval, only the site CDF was obtained without the minimal cutsets.

Considering the difficulty to find a feasible way to calculate the inter-unit seismic correlation coefficient, site CDF was estimated and results were compared for four correlation coefficients: 0, 0.3, 0.7, and 1.0.

Fig. 8 shows the distribution of the number of units with core damage according to inter-unit correlation coefficients for each seismic hazard interval. The following trends can be found in this figure:

- At a certain seismic hazard interval (0.2–0.4g), as the inter-unit correlation coefficient increases, the site CDF itself decreases whereas the number of damaged units increases, particularly the proportion of “all six units.”
- When a specific inter-unit correlation coefficient is assumed (e.g. 0.3), as the seismic magnitude (PGA) increases, the number of damaged units increases.
- The inter-unit correlation coefficient of 0.3 has very little impact on the results as compared to those when no correlation is assumed, especially at lower PGA levels.

Fig. 9 shows how the ratio of the site CDF at each seismic interval to the total sum varies by inter-unit correlation coefficient. As the inter-unit seismic correlation increases, the ratio of site CDF at higher PGA levels (0.6g or greater) also increases.

Table 11
Example of alpha factor estimation results for seismically induced inter-unit CCF models (EDG structural failure with an inter-unit correlation coefficient of 0.3).

Alpha factors for generic demand CCF[a]		Alpha factors for each seismic hazard interval				
		0.2–0.4g	0.4–0.6g	0.6–0.8g	0.8–1.0g	1.0–1.2g
α_1	0.969765	0.999909	0.977358	0.671358	1.00E-04[b]	1.00E-04
α_2	1.26E-02	3.79E-05	9.45E-03	1.37E-01	1.18E-01	1.00E-04
α_3	7.19E-03	2.16E-05	5.39E-03	7.83E-02	3.61E-01	1.00E-04
α_4	5.64E-03	1.69E-05	4.23E-03	6.14E-02	2.83E-01	3.87E-01
α_5	3.50E-03	1.05E-05	2.63E-03	3.81E-02	1.76E-01	4.52E-01
α_6	1.25E-03	3.76E-06	9.38E-04	1.36E-02	6.27E-02	1.61E-01

CCF, common-cause failure; CCCG, common-cause component group; EDG, emergency diesel generator.
[a] NUREG/CR-5497 (2007 Update), generic demand CCF distribution, alpha factor means for CCCG = 6.
[b] If the sum of alpha factors below reaches 1, 1.0E-04 was assigned.

3.5. Estimation of site CDF due to multi-unit tsunami events

3.5.1. Tsunami event frequency

In this study, the frequency of tsunami events was based on tsunami hazard curves from a probabilistic tsunami hazard analysis for the Hanul NPP site [25]. The hazard curves are in the form of annual frequencies for exceeding specified values of the maximum wave (run-up) or minimum wave (drawdown) height caused by a tsunami.

In the single-unit tsunami PSA, two tsunami events are considered as initiating events: a tsunami of 5 to <10 m (%TS-L), and a tsunami of 10 m or higher (%TS-H). This follows the ground level of the Hanul site being about 10 m. Tsunami events with maximum run-up heights of less than 5 m and tsunami drawdown events were screened out because the related adverse effects on plant operation are negligible. The frequency of %TS-L is 2.40E-05/yr, and the frequency of %TS-H is 1.60E-07/yr.

For the multi-unit tsunami PSA, it was assumed that the ground levels of the six units were the same (10 m), which means that when a tsunami initiating event occurs at the site, its impact on each unit is the same. Therefore, the above frequencies of the two tsunami initiating events were also used in the multi-unit seismic PSA.

3.5.2. Development of the site CDF model for multi-unit tsunami events

As with the other models explained above, the site CDF model for multi-unit tsunami events was developed using the methods described in Section 3.1. Each individual unit model was developed by making modifications to the base single-unit tsunami PSA model and then incorporated into the single-top logic for estimating site CDF due to multi-unit tsunami events.

As mentioned in Section 3.1.2, to deal with the two shared AAC DGs between the six units, related fault trees were modified so that the priority of each AAC DG is given in the order of Unit 1 → Unit 2 and of Unit 3 → Unit 4 → Unit 5 → Unit 6.

Since it was assumed that the ground levels on which the same SSCs of the six units are located were the same, their tsunami fragilities are fully correlated. In other words, the probability that all the same SSCs in all six units will fail simultaneously due to a tsunami is equal to the tsunami-induced failure probability of the SSC used in the single-unit tsunami PSA. Therefore, for tsunami-induced fragility events (e.g., tsunami-induced failure of the essential service water system (ESWS), or the primary auxiliary building (PAB) being flooded given %TS-H), the same basic events were applied equally to all six unit models without distinguishing the individual units.

Moreover, for the HFEs additionally modeled in the tsunami PSA (e.g., “operators fail to refill the condensate storage tank”), “complete dependency” between the six units was assumed; hence, the same basic events were applied to each individual unit model. For

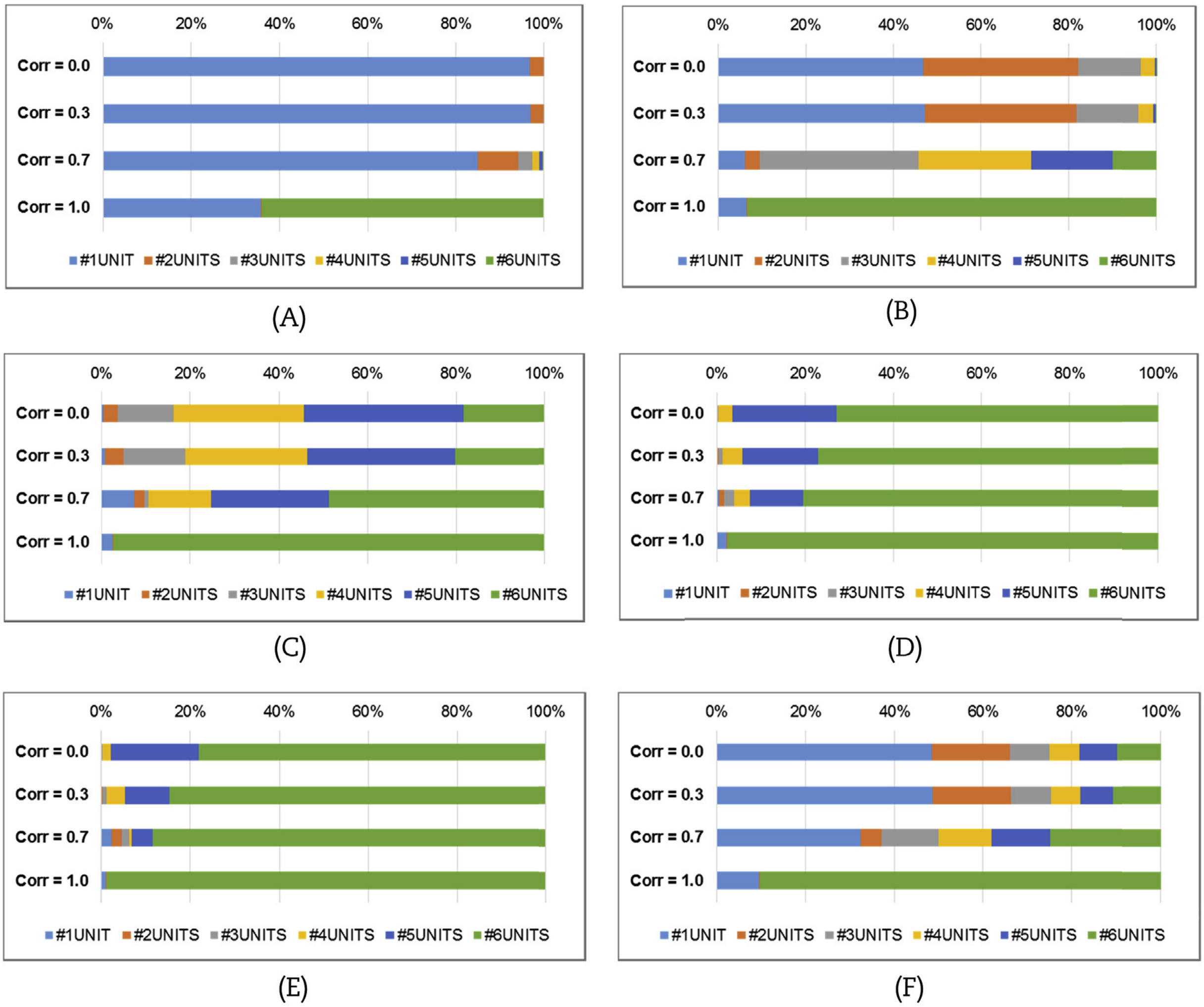

Fig. 8. Distribution of the number of core damage units according to inter-unit seismic correlation for each seismic hazard interval. (A) Seismic hazard interval: 0.2~0.4g. (B) Seismic hazard interval: 0.4~0.6g. (C) Seismic hazard interval: 0.6~0.8g. (D) Seismic hazard interval: 0.8~1.0g. (E) Seismic hazard interval: 1.0~1.2g. (F) Sum: 0.2~1.2g.

other HFEs, "zero dependency" between units was assumed. As with the site CDF model for multi-unit LOUHS, offsite power recovery actions were not modeled because offsite power is not lost in %TS-L, and the recovery actions were not credited in %TS-H since the main transformer and unit or standby auxiliary transformers were all assumed to be flooded.

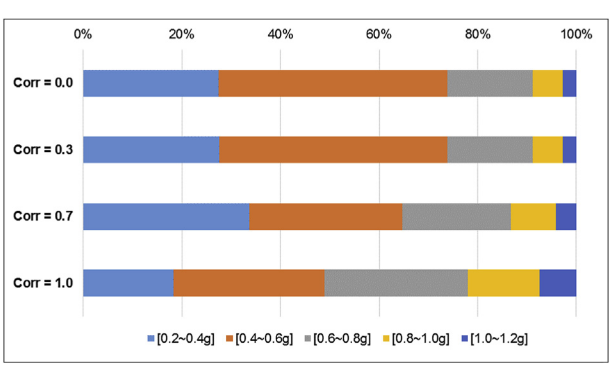

Fig. 9. Distribution of the percentage of site CDF at each seismic hazard interval according to inter-unit seismic correlation.
CDF, core damage frequency.

In the base single-unit tsunami PSA model, basic events with an FV importance value of 0.01 or more are tsunami-induced SSC fragility events or HFEs, which have already been discussed above. Therefore, inter-unit CCFs were modeled for the three types of components with an FV importance value of 1.5E-03 or higher in the base single-unit tsunami PSA model: AFW pumps, AFW turbine steam supply valves, and AFW turbine steam isolation valves. These are the same as the components considered in the site CDF model for multi-unit LOUHS. For each component type, a total of 12 components (two redundant trains in each unit) were grouped into one CCCG, and all possible CCF basic events (2-out-of-12, 3-out-of-12, ..., 12-out-of-12 CCF) were modeled. The same CCF basic event probabilities as in the site CDF model for multi-unit LOUHS were used.

3.5.3. *Quantification results*

Table 12 summarizes the results of estimating site CDF due to the multi-unit tsunami events. The mean site CDF is about 3.16E-07 per site-year. The frequency of core damage in only one unit and in all six units accounts for about 42% and 56% of mean site CDF, respectively. On the other hand, the frequency of core damage in two to five units is relatively very low. This indicates that if a tsunami event occurs at a site and it causes core damage to at least one unit, the number of damaged units is one or six in most cases.

Table 12
Results of estimating site CDF due to multi-unit tsunami events.

Number of units with core damage	CDF due to each initiator		Sum of CDF (/yr)	%
	%TS-L (5 to <10m)	%TS-H (>=10m)		
1	1.31E-07	6.63E-10	1.31E-07	41.6%
2	2.03E-09	4.16E-12	2.03E-09	0.6%
3	3.62E-10	2.46E-13	3.62E-10	0.1%
4	6.50E-11	4.92E-09	4.99E-09	1.6%
5	7.50E-12	7.24E-10	7.31E-10	0.2%
6	0.00E+00	1.76E-07	1.76E-07	55.8%
Sum	1.33E-07	1.83E-07	3.16E-07	100.0%
%	42.2%	57.8%	100.0%	-

CDF, core damage frequency; %TS-L, a tsunami of 5 to < 10 m; %TS-H, a tsunami of 10 m or higher.

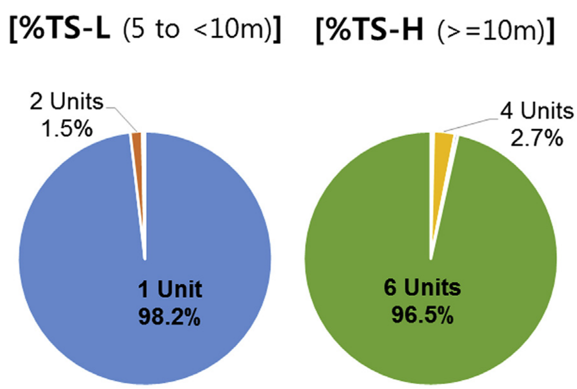

Fig. 10. Distribution of the numbers of core damage units for each tsunami event. %TS-L, a tsunami of 5 to < 10 m; %TS-H, a tsunami of 10 m or higher.

Looking closely at the distribution of the numbers of core damage units for each tsunami initiating event, as shown in Fig. 10, the frequency of core damage in only one unit contributed about 98% of the site CDF due to %TS-L, while the frequency of core damage in all six units accounted for about 97% in case of %TS-H.

In terms of minimal cutsets, the cutset “the PAB is flooded after the initiation of a tsunami of 10 m or higher (%TS-H) and as a result core damage occurs in all six units” accounted for 23% of site CDF, which is the most frequent. Next, the cutset “all safety systems are damaged by a tsunami exceeding 12 m and consequently core damage occurs in all six units” accounted for 12% of site CDF, followed by each of the cutsets with “the ESWS of one unit is damaged after the initiation of %TS-L, and operators fail to recover ESF switchgear room and inverter room cooling, and hence core damage occurs in the unit” contributing 4.5% of site CDF.

In terms of basic event importance (FV), the event with the ESWS being damaged given the occurrence of %TS-L was the highest at 0.424, followed by the event with the PAB being flooded by %TS-H at 0.233; the event of condensate storage tank (CST) failure at 0.185; and the event where operators fail to refill the CST at 0.148.

4. Conclusions and discussion

4.1. Conclusions

In this article, practical approaches that are applicable to multi-unit Level 1 PSAs for sites with up to six or more NPP units were proposed. Several of them, such as those in Sections 2 and 3.1, can be commonly used for all types of multi-unit initiating events, including simultaneous occurrences of independent SUIs. Other approaches are specific to a certain type of initiating event, like seismic events.

To validate the approaches, a multi-unit Level 1 PSA model was developed, and site CDF was estimated for each of four representative MUIs, as well as for the case of the simultaneous occurrence of independent SUIs in multiple units. An NPP site with six identical OPR-1000 units was considered as the reference site, and the full-scale Level 1 PSA models for a specific OPR-1000 plant were used as the base single-unit models.

Although the proposed approaches were applied to a six-unit NPP site in this study, most of the approaches can also be used in MUPSA for a wide range of multi-unit sites, from two-unit sites to sites with even 10 or more units.

The main results of this study are summarized as follows.

- The contribution to site CDF from the simultaneous occurrence of independent SUIs in two or more units at the reference site was sufficiently low to be neglected.
- In case of the three categories of LOOP initiating events, the frequency of core damage in only one unit contributed 92.9% of site CDF, while the frequency of core damage in two or more units accounted for 7.1%. Furthermore, the separation of LOOP duration curves for single-unit and multi-unit LOOP events had a considerable impact on the probabilities of not recovering offsite power, which significantly increased site CDF due to multi-unit LOOP initiating events as well as the contribution to site CDF from multi-unit CDF (i.e. core damage in two or more units).
- In case of a multi-unit LOUHS initiating event, the frequency of core damage in only one unit contributed 98.0% of site CDF, while the frequency of core damage in two or more units accounted for only 2.0%. The primary reason for the relatively small contribution of multi-unit CDF is that in the base single-unit model including only the LOUHS-related logics, the most risk-significant basic event (“operators fail to recover ESF switchgear room and inverter room cooling”), with an FV of 0.684 is considered as completely independent between units.
- In case of multi-unit seismic events, site CDF was estimated for four cases according to inter-unit seismic correlation coefficient (0, 0.3, 0.7, and 1.0), and the results were compared. The following trends were found:
  - At a certain seismic hazard interval, as the inter-unit seismic correlation increased, the number of damaged units also increased whereas the site CDF itself decreased.
  - Given a specific inter-unit seismic correlation, as the seismic magnitude (PGA) increased, the number of damaged units also increased.
  - The inter-unit seismic correlation of 0.3 had very little impact on the results compared to those from a correlation of 0, especially at lower PGA levels.

- The contribution to site CDF from relatively high-magnitude seismic intervals (0.6g or greater) increased as the inter-unit seismic correlation increased.

- In case of multi-unit tsunami events, the number of damaged units depended primarily on the maximum run-up height of the tsunami. When the height was lower than the ground level of the site (5 to < 10 m), the frequency of core damage in only one unit contributed 98%, while the frequency of core damage in all six units accounted for 97% in case of a tsunami exceeding the ground level (10 m or higher).

4.2. Limitations and future work

A number of assumptions were made in this study to simplify the model development and CDF estimation (see Sections 2.1 and 3.1). Therefore, the following related limitations will be addressed in our future work.

- While the reference site here was assumed to have six identical units, many actual NPP sites have multiple units of different types or models [11]. For example, the Kori NPP site in Korea has three different types of operating units: three Westinghouse (WH-F), two OPR-1000, and one APR-1400. Although most of the proposed approaches in this study can also be used in MUPSA for such sites with nonidentical units, additional aspects may have to be considered, and it may be more complicated to treat inter-unit dependencies (a crucial element of MUPSA).
- All six units were assumed to be in operation at full power, as LPSD modes were not considered. If both at-power and LPSD operation modes are considered, numerous combinations of plant operational states (POSs) for each unit also need to be considered, because each unit may be in a different POS at the time of an MUI. The fraction of time spent in each selected POS combination should then be obtained [28].
- Multi-unit initiating events were assumed to affect multiple units simultaneously, with the time interval between the occurrences in each unit not taken into account. However, in reality, this is often not the case. For example, if a dual-unit LOOP initiating event occurs and then transfers into a dual-unit SBO event due to all the EDGs failing, there can be a time delay between the different onsets of SBO in each unit. In this case, the AAC DG shared between the two units can be connected to the unit experiencing the SBO first, and then to the other unit after. Consideration of such dynamic aspects of multi-unit accident scenarios is usually expected to reduce site CDF.
- Cascading effects of core damage or release resulting from an SUI in one unit on the other units were not considered. As discussed in Section 1, such effects are expected to be very limited in the Korean NPP sites under consideration here, where each unit has its own independent structures with very few shared SSCs. However, if there is a release of radioactive material from one unit and the site is contaminated, the adverse effects on the mitigation capabilities (in particular, the human actions taken outside the control room and accident management) of the other units at the site need to be considered [28].
- Mitigation equipment installed as part of the post-Fukushima actions, for example portable DGs and pumps, was not considered. If these components are credited in MUPSA, site CDF will surely be reduced. Therefore, there is a strong need for further research on the reliability of these components and related human actions.
- For inter-unit CCFs, all possible CCF basic events were modeled, and the mapping up technique was used to obtain the impact vectors for large CCCG sizes. Accident sequence quantification using AIMS-PSA and FTREX successfully resulted in minimal cutsets for each multi-unit PSA model used in this study. However, the inclusion of all possible CCF basic events for CCCGs of larger sizes results in a model too large to be quantified and also makes CCF parameter estimation more complicated. Moreover, it is known that the mapping up technique works well when the CCCG sizes are close to each other, for example mapping from a CCCG of size 2 to size 3 or 4 [29]. Therefore, a more practical approach to inter-unit CCF modeling and parameter estimation should be developed.
- Since quantification of the multi-unit seismic PSA model was performed using the FTeMC, which is based on Monte Carlo simulations, only the site CDF was obtained without minimal cutsets. Software improvement or development is needed to obtain minimal cutsets from such PSA models with numerous high-probability basic events while avoiding significant overestimation.
- Inter-unit seismic correlation was defined at the plant level, not the SSC level. In other words, if an inter-unit correlation of 0.3 was assumed, the inter-unit correlation of each SSC in the model was considered the same. In addition, the inter-unit correlation was assumed to be the same regardless of the distance between each pair of units—in other words, the correlations between Units 1 and 2 and between Units 1 and 6 were the same. Although some existing studies have proposed methods for estimating CDF considering inter-unit seismic correlation [6], there is still much room for improvement.

Conflicts of interest

All authors have no conflicts of interest to declare.

Acknowledgments

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT: Ministry of Science and ICT) (No. 2017M2A8A4015287).

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