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Original Article

Probability subtraction method for accurate quantification of seismic multi-unit probabilistic safety assessment

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ABSTRACT

Single-unit probabilistic safety assessment (SUPSA) has complex Boolean logic equations for accident sequences. Multi-unit probabilistic safety assessment (MUPSA) model is developed by revising and combining SUPSA models in order to reflect plant state combinations (PSCs). These PSCs represent combinations of core damage and non-core damage states of nuclear power plants (NPPs). Since all these Boolean logic equations have complemented gates (not gates), it is not easy to generate exact Boolean solutions.

Delete-term approximation method (DTAM) has been widely applied for generating approximate minimal cut sets (MCSs) from the complex Boolean logic equations with complemented gates. By applying DTAM, approximate conditional core damage probability (CCDP) has been calculated in SUPSA and MUPSA. It was found that CCDP calculated by DTAM was overestimated when complemented gates have non-rare events. Especially, the CCDP overestimation drastically increases if seismic SUPSA or MUPSA has complemented gates with many non-rare events.

The objective of this study is to suggest a new quantification method named probability subtraction method (PSM) that replaces DTAM. The PSM calculates accurate CCDP even when SUPSA or MUPSA has complemented gates with many non-rare events. In this paper, the PSM is explained, and the accuracy of the PSM is validated by its applications to a few MUPSAs.

1. Introduction

1.1. Background

Numerous single unit probabilistic safety assessments (SUPSAs) have been performed since the publication of WASH-1400 [1] that was the first comprehensive PSA for nuclear power plants (NPPs). The first multi-unit probabilistic safety assessment (MUPSA) was performed to solve regulatory issues in the Unites States in early 80s [2]. Also, additional MUPSA study was performed in South Korea for the appropriate modeling of shared equipment among NPPs [3]. A comprehensive seismic MUPSA method was suggested, and its pilot application was performed [4]. It was claimed that MUPSA be treated differently from SUPSA [5].

In 2011, Fukushima accident demonstrated that concurrent multi-unit core damage could really happen [6]. In the MUPSA workshop held in Canada after Fukushima accident in 2014 [7], a number of MUPSA issues and challenges were raised and discussed. These issues and challenges can be grouped into MUPSA methodology, site-based risk metrics, site safety goal, and risk aggregation from all nuclear units and all hazards. Especially, this workshop provided an opportunity to capture up-to-date status of MUPSA methodology and practices at that time.

Recently, a number of studies and researches have been performed for realistic modeling and accurate risk calculation of MUPSA. Six groups of inter-unit dependencies were categorized [8]. These inter-unit dependencies include common cause initiators (CCIs) that simultaneously affect NPPs, inter-unit common cause failures (CCFs) for similar or identical components in NPPs, shared inter-unit connections, environmental proximity, human dependency and organizational dependency. Advanced modeling techniques with regard to the six groups of inter-unit dependencies were discussed [9]. Seismic events are recognized as the most significant CCI [4,10–12].

MUPSA models and methods have been further developed and refined in South Korea [13–16]. One typical method for the seismic

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MUPSA is to explicitly model correlated seismic failures by converting correlated seismic failures into seismic CCFs [17]. As a branch of MUPSA, Monte Carlo simulation method to calculate conditional core damage probability (CCDP) of seismic MUPSA was developed [18]. However, please note that MUPSA should be based on minimal cut sets (MCSs) for the regulatory review purpose.

In 2019, IAEA published a technical report as one of the safety report series [19], which provides comprehensive guidance for performing MUPSA. By using state-of-the-art and state-of-the-practice MUPSA knowledge and techniques, this report provides a conceptual approach for Level 1, 2 and 3 MUPSA for internal and external hazards during full power operation and low power shutdown operation. This report also provides brief guidance for risk integration in the aspect of off-site consequence and its interpretation with MUPSA. Especially, this report commented that multi-unit core damage frequency (MUCDF) is a risk for many accidents involving specific combinations of reactors. Additionally, numerous studies have been performed for MUPSA methodology and modeling. However, there has been no study for the accurate CDF or CCDP calculation of seismic MUPSA model. This is the motivation of this study.

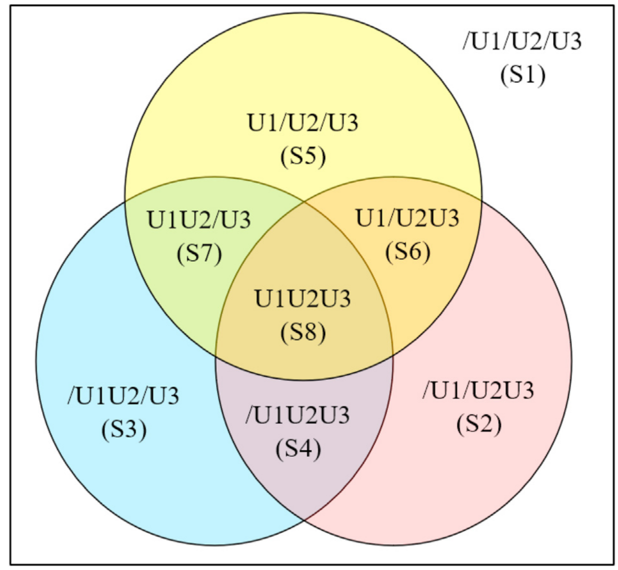


Fig. 2. Venn diagram for three-unit MUPSA.

1.2. Nomenclature

Ui	= Fault tree gate for the ith nuclear unit that is in core damage state
/Ui	= Complemented gate for the ith nuclear unit that is not in core damage state
$CCDP_{site}$	= CCDP when at least one NPP is in core damage state
$CCDP_{munit}$	= CCDP when at least two NPPs is in core damage state
p(F)	= Probability of Boolean equation F
p(X)	= Probability of basic event X
$p(F, X = 1)$	= Probability of Boolean equation F when a basic event X is true or failed
$p(F, X = 0)$	= Probability of Boolean equation F when a basic event X is false or successful

1.3. MUPSA

Fig. 1 shows plant state combinations (PSCs) in the form of event tree for three-unit MUPSA. Fig. 2 illustrates PSCs in the form of Venn diagram that is equivalent to the event tree in Fig. 1. For example, a specific PSC U1/U2U3 represents NPP state combination that U1 and U3 are in core damage state, and U2 is in non-core damage state [20].

General MUPSA procedure is as follows. (1) SUPSAs are revised for incorporating inter-unit CCIs, inter-unit CCFs, and the other inter-unit dependencies, (2) SUPSAs are combined into one MUPSA that has various PSCs as shown in Fig. 1 or Fig. 2 (3) MCSs for each PSC are generated, (4) PSC probabilities are calculated from MCSs as accurate as possible, (5) site or multi-unit CCDP is calculated from the PSC probabilities, and (6) site or multi-unit CDF is calculated by multiplying the site or multi-unit CCDP by initiating event frequency.

In MUPSA, site CCDP represents conditional probability that at least one NPP is in core damage state following an initiating event. Similarly, multi-unit CCDP is conditional probability that at least two NPPs are in core damage state after an initiating event. The site and multi-unit CCDPs are the summation of specific PSC probabilities as shown in Eq. (1) and Eq. (2), respectively.

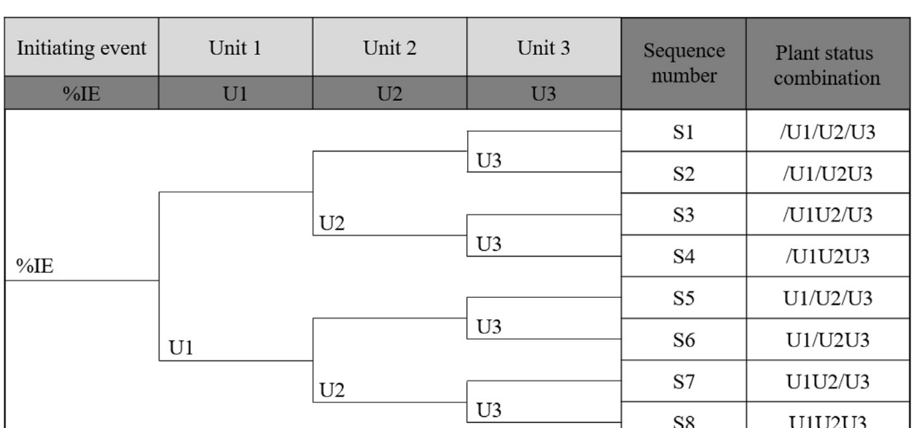


Fig. 1. Event tree for three-unit MUPSA.

$$\begin{aligned}CCDP_{site} &= p(U1/U2/U3) + p(/U1U2/U3) + p(/U1/U2U3) \\ &+ p(U1U2/U3) + p(U1/U2U3) + p(/U1U2U3) \\ &+ p(U1U2U3)\end{aligned} \quad (1)$$

$$\begin{aligned}CCDP_{munit} &= p(U1U2/U3) + p(U1/U2U3) + p(/U1U2U3) \\ &+ p(U1U2U3)\end{aligned} \quad (2)$$

Here, Eq. (1) and Eq. (2) have seven and four PSCs, respectively. Each PSC has a combination of NPPs in core damage state or non-core damage state. Normal gates U1, U2, and U3 represent NPPs in core damage state, and complemented gates/U1,/U2, and/U3 represent NPPs in non-core damage state.

1.4. Objective and paper structure

Usually, MCSs for PSC such as U1U2/U3 are generated by using delete-term approximation method (DTAM, see Section 2.1). This DTAM is acceptable only for SUPSA or MUPSA that has rare events. If SUPSA or MUPSA has many non-rare events, the use of DTAM results in unacceptably overestimated site or multi-unit CCDP (see Section 2.1 and Section 4). Therefore, appropriate method should be developed for calculating accurate PSC probabilities and CCDPs. In order to accomplish this objective, this paper suggests a new probability subtraction method (PSM). This PSM replaces DTAM, and it calculates much more accurate PSC probabilities and CCDPs than DTAM.

DTAM and its disadvantage are illustrated in detail in Section 2. The PSM for MUPSA is explained in Section 3. Applications of PSM to simple MUPSAs and actual MUPSAs are described in Section 4.

2. MCS generation and probability calculation

2.1. MCS generation

One accident sequence in SUPSA or one PSC in MUPSA is a Boolean combination of normal gate(s) and complemented gate(s) as shown in Eq. (3). In the whole paper, Boolean combination denotes Boolean sum or Boolean multiplication. Here, A, B, C and D are independent basic events.

$$\begin{aligned}F &= U1/U2 \\ U1 &= AB + AC + BD \\ U2 &= D\end{aligned} \quad (3)$$

MCSs are calculated by the traditional Boolean algebra in Eq. (4). The two MCSs in Eq. (4) can be disjointed for calculating exact MCS probability by using sum of disjoint product (SDP) method [21,22] as Eq. (5) (see Eq. (A.1)). Since the two Boolean terms in the right-hand side of Eq. (5) are mutually exclusive, p(AB /D)+ p(A /BC /D) is an exact probability of F.

$$F = U1/U2 = (AB + AC + BD)/D = AB/D + AC/D \quad (4)$$

$$\begin{aligned}F &= AB/D + /(AB/D)\, AC/D = AB/D + (/A + /B + D)AC/D \\ &= AB/D + A/BC/D\end{aligned} \quad (5)$$

Please note that the exact probability calculation from Eq. (3) to Eq. (5) is possible only for very small fault tree that has a small number of basic events. In order to solve medium-size fault tree, exact solution generation algorithms have been developed that are mainly based on the Shannon decomposition [23]. Some applications of Shannon decomposition are the truth table method [24] and binary decision diagram (BDD) method [25–28]. They are different encoding methods of the identical Shannon decomposition. Among many computer codes, popular tools in the PSA industry are direct probability calculator (DPC) [29], Aralia [30], and Fault Tree Reliability Evaluation eXpert (FTREX) [31]. FTREX can generate either MCSs or BDDs from fault trees. However, there is no tool that can generate exact solution for huge fault tree in SUPSA or MUPSA that has more than thousands of basic events.

DTAM [32] is designed to generate approximate MCSs for Boolean equation that has complemented gate(s) such as U1/U2. DTAM deletes nonsense MCSs instead of generating exact solutions as illustrated in the following example for Eq. (3).

First, MCSs of U1 and U2 in Eq. (3) are generated. Second, MCSs of U1 are tested with U1/U2. The first MCS BD is deleted since it makes F false. The other MCSs AB and AC are preserved since they do not make F false.

$$\begin{aligned}F(B = D = true) &= U1/U2 = true/true = false \\ F(A = B = true) &= U1/U2 = true/indefinite = indefinite \\ F(A = C = true) &= U1/U2 = true/indefinite = indefinite\end{aligned} \quad (6)$$

Finally, MCSs AB and AC are chosen as final MCSs of F = U1/U2 by DTAM.

$$F \sim DTAM(U1, U2) = AB + AC \quad (7)$$

The two MCSs in Eq. (7) can be disjointed by the SDP method for exact MCS probability calculation. Here, the two Boolean terms in the right-hand side of Eq. (8) are mutually exclusive.

$$\begin{aligned}F &\sim DTAM(U1, U2) = AB + AC = AB + /(AB)AC \\ &= AB + (/A + /B)AC = AB + A/BC\end{aligned} \quad (8)$$

As illustrated in Eq. (9), if basic events B and D are rare events, the probability p(AB) + p(A /BC) in Eq. (8) is very close to p(AB /D) + p(A /BC /D) in Eq. (5). However, if they are non-rare events, the probability p(AB) + p(A /BC) is much bigger than p(AB /D) + p(A /BC /D). This example shows that DTAM results can be highly overestimated when the Boolean logic has non-rare events. Similar overestimation has been frequently reported in seismic SUPSA and MUPSA that have many complemented gates and non-rare events.

$$\begin{aligned}&p(AB) + p(A/BC) > p(AB/D) + p(A/BC/D), \text{ if } p(B) = p(D) = 0.001 \\ &p(AB) + p(A/BC) \gg p(AB/D) + p(A/BC/D), \text{ if } p(B) = p(D) = 0.5\end{aligned} \quad (9)$$

Table 1 shows the level of overestimation with regard to various basic event probabilities. As listed in Table 1, if MCSs are generated by DTAM, the overestimation error drastically increases as basic

Table 1
Probability p(F) calculated by Exact method and DTAM.

Event probability[a]	Exact method[b]	DTAM[c]	Error[d]
0.01	1.97E-04	1.99E-04	1.0%
0.10	1.71E-02	1.90E-02	11.1%
0.50	1.88E-01	3.75E-01	100.0%
0.90	8.91E-02	8.91E-01	900.0%

[a] p(A) = p(B) = p(C) = p(D).
[b] p(F) = p(AB/D) + p(A/BC/D) (see Eq. (5)).
[c] p(F) ~ p(AB) + p(A/BC) (see Eq. (8)).
[d] 100*(c-b)/b.

event probabilities increase even though MCS probabilities are calculated by SDP method. Thus, DTAM is an acceptable method only for SUPSA or MUPSA that has only rare events. However, the use of DTAM should be avoided for SUPSA or MUPSA that has a number of non-rare events.

2.2. MCS probability calculation

Probability calculation with given MCSs can be classified into two groups (see Appendix A) [32]. First, exact probability can be calculated by SDP method by converting MCSs into SDPs (see Eq. (A.1)), BDD method by converting MCSs into a BDD (see Eq. (A.2)), and inclusion-exclusion method (see Eq. (A.3)). Although these three methods require huge computational memory, BDD method consumes relatively less memory. So, the BDD method is applicable to calculate accurate MCS probability in SUPSA or MUPSA. Available BDD tool is Advanced Cutset Upper Bound Estimator (ACUBE) [33]. Second, approximate MCS probability can be calculated by min cut upper bound (MCUB) method (see Eq. (A.5)) and rare event approximation (REA) method (see Eq. (A.6)).

3. MUPSA quantification methods

3.1. DTAM in MUPSA

As explained in Section 2, it is impossible to generate exact Boolean solutions from the large PSC fault tree. So, approximate MCSs are generated from PSCs by DTAM as Eq. (10).

$$\begin{aligned}
&U1/U2/U3 = U1/(U2+U3) \sim DTAM(U1, U2+U3)\\
&/U1U2/U3 = U2/(U1+U3) \sim DTAM(U2, U1+U3)\\
&/U1/U2U3 = U3/(U1+U2) \sim DTAM(U3, U1+U2)\\
&U1U2/U3 = U1U2/U3 \sim DTAM(U1U2, U3)\\
&U1/U2U3 = U1U3/U2 \sim DTAM(U1U3, U2)\\
&/U1U2U3 = U2U3/U1 \sim DTAM(U2U3, U1)
\end{aligned} \tag{10}$$

The probability equations for each PSC are listed in Table 2. As illustrated in Section 2, it is well known that the approximate MCSs generated by DTAM can result in unacceptably overestimated probabilities. If basic events in complemented gates are rare events, this overestimation may be negligible. However, since there are many non-rare events in complemented gates in seismic SUPSA or MUPSA, the probability overestimation is inevitable when applying DTAM. Therefore, the use of DTAM should be limited only for the internal event SUPSA or MUPSA with rare events.

Table 2
PSC probabilities by DTAM.

PSC[a,b]	PSC probabilities by DTAM[c]
U1/U2/U3	p(DTAM(U1, U2+U3))
/U1U2/U3	p(DTAM(U2, U1+U3))
/U1/U2U3	p(DTAM(U3, U1+U2))
U1U2/U3	p(DTAM(U1U2, U3))
U1/U2U3	p(DTAM(U1U3, U2))
/U1U2U3	p(DTAM(U2U3, U1))
U1U2U3	p(U1U2U3)

[a] Ui means i'th NPP is in core damage state.
[b] /Ui means i'th NPP is in non-core damage state.
[c] See Eq. (7).

3.2. Probability subtraction method (PSM)

General PSM equations for N nuclear units are described in Appendix B. In this Section, PSM is illustrated with three nuclear units for the clearer explanation.

NPP core damage combinations in three-unit MUPSA, U1, U2, U3, U1U2, U1U3, U2U3, and U1U2U3 can be expanded into Boolean equations as Eq. (11).

$$\begin{aligned}
&U1 = U1(U2+/U2)(U3+/U3) = U1(U2U3+/U2U3+U2/U3+/U2/U3)\\
&U2 = U2(U1+/U1)(U3+/U3) = U2(U1U3+/U1U3+U1/U3+/U1/U3)\\
&U3 = U3(U1+/U1)(U3+/U3) = U3(U1U2+/U1U2+U1/U2+/U1/U2)\\
&U1U2 = U1U2(U3+/U3) = U1U2U3+U1U2/U3\\
&U1U3 = U1U3(U2+/U2) = U1U2U3+U1/U2U3\\
&U2U3 = U2U3(U1+/U1) = U1U2U3+/U1U2U3\\
&U1U2U3 = U1U2U3
\end{aligned} \tag{11}$$

By using these expanded Boolean equations, PSC probabilities are calculated by successive subtraction from the last to the first equation in Eq. (12). In other words, the PSC probabilities are successively calculated from the inner to the outer PSC probabilities in Venn diagram of Fig. 2. When an outer PSC probability is calculated, the overlapped inner PSC probabilities are subtracted from one of p(U1), p(U2), p(U3), p(U1U2), p(U1U3), and p(U2U3).

$$\begin{aligned}
&p(U1/U2/U3) = p(U1) - p(U1U2/U3) - p(U1/U2U3) - p(U1U2U3)\\
&p(/U1U2/U3) = p(U2) - p(U1U2/U3) - p(/U1U2U3) - p(U1U2U3)\\
&p(/U1/U2U3) = p(U3) - p(U1/U2U3) - p(/U1U2U3) - p(U1U2U3)\\
&p(U1U2/U3) = p(U1U2) - p(U1U2U3)\\
&p(U1/U2U3) = p(U1U3) - p(U1U2U3)\\
&p(/U1U2U3) = p(U2U3) - p(U1U2U3)\\
&p(U1U2U3) = p(U1U2U3)
\end{aligned} \tag{12}$$

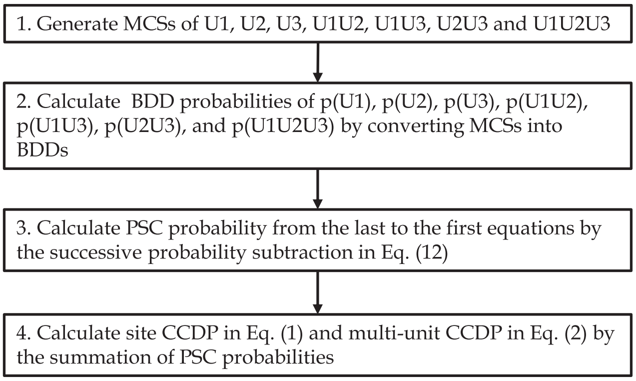


Fig. 3. PSM procedure for three-unit MUPSA.

Table 3
Comparison of four MUPSA calculation methods.

Methods	Solution generation	Probability calculation
Exact method	PSC FT into BDD	PSC probability by BDD
Method 1	PSC FT into MCSs by DTAM	PSC probability by MCUB
Method 2	PSC FT into MCSs by DTAM	MCS conversion into BDD PSC probability by BDD
PSM	UFT to UMCSs	UMCS conversion into UBDD UBDD probability PSC probability by Eq. (12)

FT is a fault tree.
UFT is a fault tree for U1, U2, U3, U1U2, etc.
UMCSs are MCSs for U1, U2, U3, U1U2, etc.
UBDD is a BDD for U1, U2, U3, U1U2, etc.

The procedure for calculating PSC probabilities in Eq. (12) is depicted in Fig. 3. First, MCSs for core damage combinations of U1, U2, U3, U1U2, U1U3, U2U3, and U1U2U3 are generated. Second, accurate probabilities of p(U1), p(U2), p(U3), p(U1U2), p(U1U3), p(U2U3), and p(U1U2U3) are calculated by converting MCSs into BDDs. Third, PSC probabilities in the left-hand side of Eq. (12) are calculated from the last to the first equation by the successive probability subtraction. Here, pre-calculated probabilities are subtracted from p(U1), p(U2), p(U3), p(U1U2), p(U1U3), or p(U2U3). Then, the site CCDP in Eq. (1) is calculated by the summation of all the PSC probabilities in Eq. (12), and multi-unit CCDP in Eq. (2) is calculated by the summation of the last four PSC probabilities in Eq. (12).

For example, the third PSC probability of p(/U1/U2U3) in Eq. (12) is calculated by subtracting pre-calculated PSC probabilities p(U1/U2U3), p(/U1U2U3), and p(U1U2U3) from p(U3). As illustrated in the previous paragraphs, accurate PSC probabilities can be calculated by PSM that is not affected by non-rare events, since PSM does not employ any complemented gates. In this way, the probability overestimation by DTAM can be avoided. So, much more accurate PSC probabilities can be calculated by PSM than by DTAM. This results in accurate site and multi-unit CCDP calculations.

3.3. Inclusion-exclusion method (IEM)

General IEM equations for N nuclear units are described in Appendix B. In this Section, IEM is illustrated with three nuclear units for the clearer explanation.

PSC probabilities can be calculated by IEM that uses summation and subtractions of p(U1), p(U2), p(U3), p(U1U2), p(U1U3), p(U2U3), and p(U1U2U3) as shown in Eq. (13). Calculated PSC probabilities by IEM are exactly the same as those by PSM.

$$
\begin{aligned}
&p(U1/U2/U3) = p(U1) - p(U1U2) - p(U1U3) + p(U1U2U3)\\
&p(/U1U2/U3) = p(U2) - p(U1U2) - p(U2U3) + p(U1U2U3)\\
&p(/U1/U2U3) = p(U3) - p(U1U3) - p(U2U3) + p(U1U2U3)\\
&p(U1U2/U3) = p(U1U2) - p(U1U2U3)\\
&p(U1/U2U3) = p(U1U3) - p(U1U2U3)\\
&p(/U1U2U3) = p(U2U3) - p(U1U2U3)\\
&p(U1U2U3) = p(U1U2U3)
\end{aligned}
\tag{13}
$$

It can be easily shown that the equations of Eq. (12) and Eq. (13) are basically identical. If the IEM equations in Eq. (13) are inserted into the PSM equations in Eq. (12), PSM equations result in IEM equations.

3.4. Comparison between PSM and IEM

The difficulty or burden for the formulation and calculation of PSM and IEM in Eq. (12) and Eq. (13) seems to be similar. However, as explained in Appendix B, the IEM equations become very complex as the number of plants increases. For example, each term in the right-hand-side of the IEM equations in Appendix B has plus or minus sign. Furthermore, the coefficients of each term in the right-hand-side of the IEM equations change according to the combination of core damage states. For example, Kori nuclear site in South Korea has nine nuclear units. On the other hand, as explained in Appendix B, PSM equations are easily formulated regardless of the number of nuclear units.

Therefore, the development of IEM algorithm or tool is much more difficult than that of PSM. So, if many NPPs exist in MUPSA, PSM in Eq. (12) is recommended instead of IEM in Eq. (13) since successive subtraction of pre-calculated PSC probabilities is much easier than adding and subtracting complex combination probabilities.

3.5. Importance measures for MUPSA

The calculation of importance measures is essential to get meaningful risk insight from MUPSA. Typical importance measures are marginal importance factor (MIF), critical importance factor (CIF), risk reduction worth (RRW), and risk achievement worth (RAW) [34]. Here, MIF is identical to Birnbaum Importance measure, and CIF is identical to Fussell-Vesely (FV) importance measure. All the importance measures can be calculated with probabilities of p(X), p(F), p(F, X = 1), and p(F,X = 0). Here, X is a basic event, and F is a Boolean equation.

Importance measures to $CCDP_{munit}$ can be calculated with p(X), CCDPmunit(X), CCDPmunit(X = 1), and CCDPmunit(X = 0) as Eq. (14). Similarly, importance measures to $CCDP_{site}$ can be calculated with p(X), CCDPsite(X), CCDPsite(X = 1), and CCDPsite(X = 0).

$$\begin{aligned}
&CCDPmunit(X) = p(U1U2/U3) + p(U1/U2U3) + p(/U1U2U3) + p(U1U2U3)\\
&CCDPmunit(X = 1) = p(U1U2/U3,\ X = 1) + p(U1/U2U3, X = 1) + p(/U1U2U3,\ X = 1) + p(U1U2U3, X = 1)\\
&CCDPmunit(X = 0) = p(U1U2/U3,\ X = 0) + p(U1/U2U3, X = 0) + p(/U1U2U3,\ X = 0) + p(U1U2U3, X = 0)
\end{aligned} \tag{14}$$

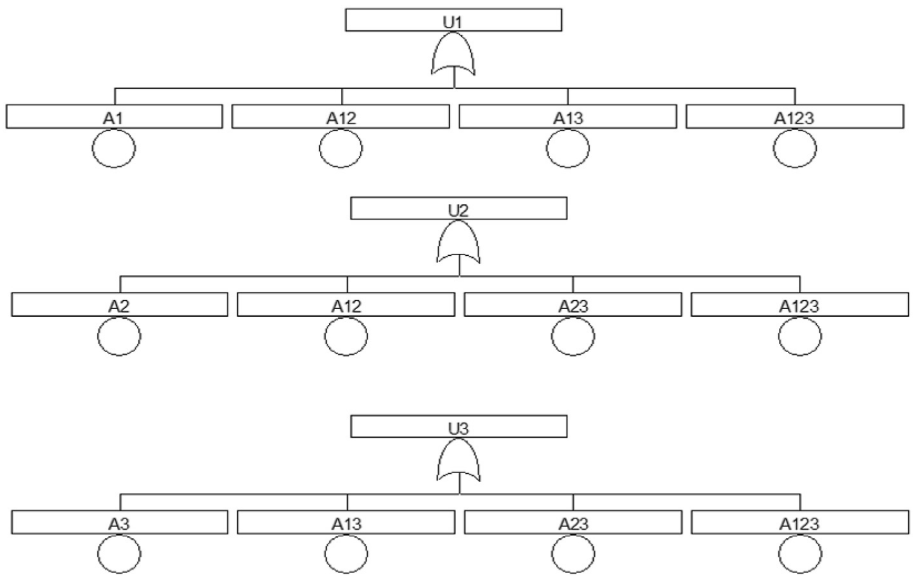


Fig. 4. Three simple SUPSAs for MUPSA.

Table 4
Probabilities for a simple MUPSA with all rare events

PSC(a)	Exact method(b)	Method 1(c)	Error(d)	Method 2(e)	Error(f)	PSM(g)	Error(h)
U1/U2/U3	9.94E-04	1.00E-03	0.60%	1.00E-03	0.60%	9.94E-04	0.00%
/U1U2/U3	9.94E-04	1.00E-03	0.60%	1.00E-03	0.60%	9.94E-04	0.00%
/U1/U2U3	9.94E-04	1.00E-03	0.60%	1.00E-03	0.60%	9.94E-04	0.00%
U1U2/U3	9.97E-04	1.00E-03	0.30%	1.00E-03	0.40%	9.97E-04	0.00%
U1/U2U3	9.97E-04	1.00E-03	0.30%	1.00E-03	0.40%	9.97E-04	0.00%
/U1U2U3	9.97E-04	1.00E-03	0.30%	1.00E-03	0.40%	9.97E-04	0.00%
U1U2U3	1.01E-03	1.01E-03	0.00%	1.01E-03	0.00%	1.01E-03	0.00%
Site CCDP	6.98E-03	7.01E-03	0.43%	7.01E-03	0.43%	6.98E-03	0.00%
Multi-unit CCDP	4.00E-03	4.01E-03	0.25%	4.01E-03	0.25%	4.00E-03	0.00%

(a) Each basic event probability 0.001 (see Fig. 4).
(b) BDD method after fault tree conversion into BDD for each PSC.
(d) 100*((c)-(b))/(b).
(f) 100*((e)-(b))/(b).
(h) 100*((g)-(b))/(b).

4. PSM applications

In order to demonstrate the strength of PSM over the other methods, the four methods in Table 3 are applied to (1) simple MUPSA that has all rare events in Section 4.1, (2) simple MUPSA that has all non-rare events in Section 4.1, (3) actual loss of off-site power (LOOP) MUPSA that has rare events in Section 4.2, and (4) actual seismic MUPSA that has many non-rare events in Section 4.3. Furthermore, PSM application to SUPSA is also discussed in Section 4.4. In Section 4.1 to Section 4.3, PSC probabilities, site CCDPs, and multi-unit CCDPs are calculated by the four methods in Table 3, and the calculated probabilities are compared and discussed.

As listed in Table 3, (1) Exact method converts a PSC fault tree into a BDD, and calculates BDD probability that is a PSC probability. (2) Method 1 converts a PSC fault tree into MCSs by DTAM, and calculates MCUB probability that is a PSC probability. (3) Method 2 converts a PSC fault tree into MCSs by DTAM, converts MCSs into a BDD, and calculates BDD probability that is a PSC probability. (4) PSM converts core damage combination fault tree into MCSs, converts MCSs into a BDD, calculates BDD probability, and performs probability subtraction. Here, core damage combination denotes U1, U2, U3, U1U2, etc.

4.1. Simple MUPSA

For the application of Exact method, Method 1, Method 2 and PSM, each PSC fault tree is constructed by using simple SUPSA fault trees in Fig. 4. They have shared basic events that represent inter-unit dependency.

Table 5
Probabilities for a simple MUPSA with all non-rare events

PSC(a)	Exact method(b)	Method 1(c)	Error(d)	Method 2(e)	Error(f)	PSM(g)	Error(h)
U1/U2/U3	5.24E-02	2.00E-01	281.7%	2.00E-01	281.7%	5.24E-02	0.0%
/U1U2/U3	5.24E-02	2.00E-01	281.7%	2.00E-01	281.7%	5.24E-02	0.0%
/U1/U2U3	5.24E-02	2.00E-01	281.7%	2.00E-01	281.7%	5.24E-02	0.0%
U1U2/U3	9.50E-02	2.32E-01	144.2%	2.32E-01	144.2%	9.50E-02	0.0%
U1/U2U3	9.50E-02	2.32E-01	144.2%	2.32E-01	144.2%	9.50E-02	0.0%
/U1U2U3	9.50E-02	2.32E-01	144.2%	2.32E-01	144.2%	9.50E-02	0.0%
U1U2U3	3.48E-01	3.79E-01	8.9%	3.48E-01	0.0%	3.48E-01	0.0%
Site CCDP	7.90E-01	1.68E+00	112.7%	1.64E+00	107.6%	7.90E-01	0.0%
Multi-unit CCDP	6.33E-01	1.08E+00	70.6%	1.04E+00	64.3%	6.33E-01	0.0%

(a) Each basic event probability 0.2 (see Fig. 4).
(b) BDD method after fault tree conversion into BDD for each PSC.
(d) 100*((c)-(b))/(b).
(f) 100*((e)-(b))/(b).
(h) 100*((g)-(b))/(b).

Table 6
LOOP MUPSA with rare events.

Gates	28,524
Basic events	9578
Complemented gates	190
Complemented events	0

PSC and CCDP probabilities calculated by the four methods are in Table 4 and Table 5 with basic event probabilities 0.001 and 0.2, respectively.

As shown in Table 4, the overestimations of PSC probabilities, site CCDP, and multi-unit CCDP are less than one percent. So, any methods can be used for simple MUPSA with rare events. As listed in Table 5, PSC probabilities and CCDPs are drastically overestimated by Method 1 and Method 2. However, PSC probabilities and CCDPs calculated by PSM are identical to the results by Exact method. This implies that the application of PSM is more appropriate than Method 1 or Method 2 for MUPSA with non-rare events in complemented gates.

Table 7
Probabilities for LOOP MUPSA

PSC	Method 1(a)	Error(b)	Method 2(c)	Error(d)	PSM(e)
U1/U2/U3	7.25E-05	3.4%	7.11E-05	1.4%	7.01E-05
/U1U2/U3	7.35E-05	3.5%	7.20E-05	1.4%	7.10E-05
/U1/U2U3	3.86E-05	9.0%	3.84E-05	8.5%	3.54E-05
U1U2/U3	5.71E-05	5.9%	5.66E-05	5.0%	5.39E-05
U1/U2U3	2.01E-07	18.9%	2.00E-07	18.3%	1.69E-07
/U1U2U3	2.01E-07	18.9%	2.00E-07	18.3%	1.69E-07
U1U2U3	2.68E-06	0.8%	2.66E-06	0.0%	2.66E-06
Site CCDP	2.45E-04	5.2%	2.41E-04	3.4%	2.33E-04
Multi-unit CCDP	6.02E-05	5.8%	5.97E-05	4.7%	5.69E-05

(b) 100*((a)-(e))/(e).
(d) 100*((c)-(e))/(e).

Table 8
Seismic MUPSA with non-rare events.

Gates	45,154
Basic events	9817
Complemented gates	185
Complemented events	0
Non-rare events ($p > 0.05$)[a]	106
Non-rare seismic failures	11

[a] Non-rare events include random failures, human failure events and seismic failures.

4.2. LOOP MUPSA

Method 1, Method 2, and PSM are applied to actual LOOP MUPSA that has three NPPs. Two NPPs are twin units that have identical design, and the other unit is differently designed. The LOOP is multi-unit CCI that affects all three NPPs. This MUPSA has inter-unit CCFs for the identical components such as emergency diesel generators and essential chillers between twin units. The sizes of MUPSA gates and events are listed in Table 6. Since the size of MUPSA is not very small, Exact method cannot be applicable to this MUPSA.

PSC probabilities, site CCDP, and multi-unit CCDP are calculated and compared for LOOP MUPSA in Table 7. The overestimations of the site CCDP calculated by Method 1 and Method 2 are 5.2% and 3.4%, respectively. The overestimations of multi-unit CCDPs by Method 1 and Method 2 are 5.8% and 4.7%, respectively. As a conclusion of this application, DTAM is acceptable for internal event MUPSA. However, PSM is recommended for more accurate calculation of MUPSA.

4.3. Seismic MUPSA

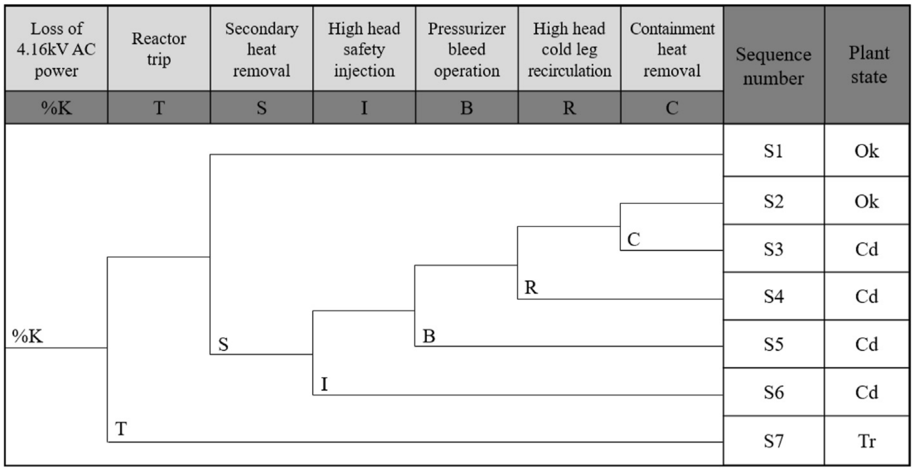
Method 1, Method 2, and PSM are applied to the actual seismic MUPSA for the identical NPPs of LOOP MUPSA with seismic acceleration of 0.7 g. As usual seismic SUPSA, seismic failures of the identical structures, systems, and components (SSCs) between the identical NPPs are assumed to be fully correlated. The inter-unit CCFs are the same as the LOOP MUPSA. The sizes of MUPSA gates and events are listed in Table 8. Please note that Exact method cannot be applicable to this huge size of MUPSA.

As shown in Table 9, the overestimations of the site CCDP by Method 1 and Method 2 are 265.2% and 238.1%, respectively. The overestimations of the multi-unit CCDP by Method 1 and Method 2 are 73.8% and 49.1%, respectively. In addition, since many PSC

Table 9
Probabilities for seismic MUPSA.

PSC	Method 1[a]	Error[b]	Method 2[c]	Error[d]	PSM[e]
U1/U2/U3	5.76E-01	37,061.3%	5.63E-01	36,222.6%	1.55E-03
/U1U2/U3	5.76E-01	37,061.3%	5.63E-01	36,222.6%	1.55E-03
/U1/U2U3	1.60E-01	155.6%	1.59E-01	154.0%	6.26E-02
U1U2/U3	5.73E-01	22.4%	5.60E-01	19.7%	4.68E-01
U1/U2U3	1.35E-01	20,354.5%	9.30E-02	13,990.9%	6.60E-04
/U1U2U3	1.35E-01	20,354.5%	9.30E-02	13,990.9%	6.60E-04
U1U2U3	1.34E-01	45.2%	9.23E-02	0.0%	9.23E-02
Site CCDP	2.29E+00	265.2%	2.12E+00	238.1%	6.27E-01
Multi-unit CCDP	9.77E-01	73.8%	8.38E-01	49.1%	5.62E-01

[b] 100*(a-e)/e.
[d] 100*(c-e)/e.



(a) Ok denotes NPP is in non-core damage state.
(b) Cd denotes NPP is in core damage state.
(c) Tr denotes S7 is transferred to another event tree

Fig. 5. Event tree for SUPSA.

probabilities are greatly overestimated, the site CCDP is greater than one by Method 1 and Method 2. Therefore, the use of PSM is recommended instead of DTAM for seismic MUPSA with non-rare events in complemented gates.

4.4. SUPSA event tree sequences

Fig. 5 shows a typical event tree in SUPSA. The accident sequence S5 has CCDP Boolean logic combination of / T*S*/ I*B. This sequence has failed safety functions S and B, and successful safety functions T and I.

Since the accident sequence S5 has Boolean combination of failed and successful safety functions, the CCDP for S5 can be calculated by DTAM in Eq. (15) or by PSM in Eq. (16). Since PSM is a much more accurate probability calculation method than DTAM, the use of PSM is recommended for SUPSA with non-rare events in complemented gates.

$$p(S5) \sim p(DTAM(S * B, T + I)) \tag{15}$$

$$p(S5) = p(S*B) - p(S*B*(T + I)) \tag{16}$$

5. Conclusions

In this study, currently available DTAM is explained, newly suggested PSM is described, and DTAM and PSM are applied to MUPSAs in order to illustrate strength of PSM over DTAM. These application results can be summarized as follows.

1. Since the probability of a complemented rare event is close to one, the complemented event can be ignored by DTAM. Thus, both DTAM and PSM calculate similar probabilities for SUPSA and MUPSA with rare events in complemented gates.
2. Since the probability of a complemented non-rare event is much smaller than one, the complemented event cannot be ignored by DTAM. If the complemented non-rare event is ignored by DTAM, overestimated probabilities of accident sequences and PSCs are calculated in SUPSA and MUPSA with non-rare events in complemented gates.
3. Since PSM does not use complemented gates and performs the probability subtraction, accurate probabilities of accident sequences and PSCs are calculated for SUPSA and MUPSA with non-rare events in complemented gates.
4. In this study, the strength of PSM was demonstrated by comparing the point estimate results of PSM over DTAM, such as seismic CCDP or CDF. It is believed that the similar conclusions can be drawn by the uncertainty calculations of PSM and DTAM.

Therefore, it is recommended that PSM be used for the accurate probability calculation in SUPSA and MUPSA that have many non-rare events in complemented gates.

As a further study, the comparison of PSM and DTAM point estimate calculation and uncertainty analysis is recommended for MUPSA model that has correlated seismic failures or seismic CCFs. Please note that a new method [17] to convert correlated seismic failures into seismic CCFs was already developed by the authors of this study. This method makes it possible to convert correlated seismic failures into seismic CCFs, insert seismic CCFs into a seismic fault tree, and calculate MCSs that have seismic CCFs.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. MCS Probability Calculation Methods

Exact probability of MCSs can be calculated by SDP method [21,22] as Eq. (A.1). Here, C_1, C_2, C_3, and C_4 denote MCSs.

$$P_{SDP} = p(C_1) + p(/C_1 C_2) + p(/C_1\,/C_2 C_3) + p(/C_1\,/C_2\,/C_3 C_4) + \ldots \tag{A.1}$$

Exact probability of a fault tree or MCSs can be calculated by BDD algorithm [25,30]. A BDD is a nested structure of binary Boolean equations in Eq. (A.2). If a BDD is generated from a fault tree or MCSs, exact probability can be calculated. BDD algorithm was originally developed to generate a BDD from a fault tree.

$$\begin{aligned} F &= XF(X=\text{true}) + /XF(X=\text{false}) \\ p(F) &= p(X)p(F(X=\text{true})) + p(/X)p(F(X=\text{false})) \end{aligned} \tag{A.2}$$

When a fault tree is small, it can be directly converted into a BDD. If a fault tree is not small, the conversion from a fault tree into a BDD frequently fails. In this case, MCSs are generated from the fault tree by using dedicated tools such as FTREX [31]. Here, DTAM is inevitably used for solving Boolean logic that has complemented gates. Then, MCSs are converted into a BDD for the accurate MCS probability calculation by dedicated tools such as ACUBE [33]. Please note that the probability overestimation from DTAM cannot be overcome, although the MCSs are converted into a BDD.

Exact probability with MCSs can also be calculated by IEM [32] as Eq. (A.3). Here, C_i, C_j, and C_k denote MCSs.

$$P_{IEM} = \sum_i p(C_i) - \sum_{i \neq j} p(C_iC_j) + \sum_{i \neq j \neq k} p(C_iC_jC_k) \pm \ldots \tag{A.3}$$

The approximate IEM is in Eq. (A.4). If any C_i and C_j do not share identical basic events, Eq. (A.3) and Eq. (A.4) are identical since $p(C_iC_j) = p(C_i)p(C_j)$. If MCSs C_i and C_j share identical basic events, Eq. (A.4) is an upper bound of Eq. (A.3) since $p(C_iC_j) > p(C_i)p(C_j)$.

$$P_{AIEM} = \sum_i p(C_i) - \sum_{i \neq j} p(C_i)p(C_j) + \sum_{i \neq j \neq k} p(C_i)p(C_j)p(C_k) \pm \ldots \tag{A.4}$$

Approximate probability with MCSs can be calculated by MCUB method [32]. MCUB method in Eq. (A.5) is identical to Eq. (A.4). The calculation of Eq. (A.5) is much easier than Eq. (A.4) [32]. If any C_i and C_j do not share identical basic event, Eq. (A.5) and Eq. (A.3) are identical.

$$P_{MCUB} = 1 - \prod_i (1 - p(C_i)) \tag{A.5}$$

Approximate probability with MCSs can also be calculated by REA method [32]. REA method ignores all terms except for the first one in the right-hand side of Eq. (A.3). REA method calculates overestimated MCS probability when MCSs have no complemented events.

$$P_{REA} = \sum_i p(C_i) \tag{A.6}$$

Appendix B. General PSM and IEM Equations for N Nuclear Units

Probability equations in Eq. (B.4) and Eq. (B.5) can be derived by using Boolean and probability equations in Eq. (B.1), Eq. (B.2), and Eq. (B.3).

$$A + B = /AB + A/B + AB \tag{B.1}$$

$$A + B + C = /A/BC + /AB/C + A/B/C + /ABC + A/BC + AB/C + ABC \tag{B.2}$$

$$p(/AB) = p(B) - p(AB) \tag{B.3}$$

$$\begin{aligned} p(/A/BC) &= p(C) - p((A+B)C) = p(C) - p(/ABC) \\ &\quad - p(A/BC) - p(ABC) \end{aligned} \tag{B.4}$$

$$\begin{aligned} p(/A/B/CD) &= p(D) - p((A+B+C)D) = p(D) \\ &\quad - p(/A/BCD) - p(/AB/CD) - p(A/B/CD) \\ &\quad - p(/ABCD) - p(A/BCD) - p(AB/CD) - p(ABCD) \end{aligned} \tag{B.5}$$

Using the previous equations, general PSM equations for PSC probabilities $p(/Uj\prod_{i\neq j}^{N}Ui)$, $p(/Uj/Uk\prod_{i\neq j\neq k}^{N}Ui)$, and $p(/Uj/Uk/Ul\prod_{i\neq j\neq k\neq l}^{N}Ui)$ can be formulated as Eq. (B.6), Eq. (B.7), and Eq. (B.8). First, core damage combination probabilities $p(\prod_{i=1}^{N}Ui)$, $p(\prod_{i\neq j}^{N}UiUj)$, $p(\prod_{i\neq j\neq k}^{N}UiUjUk)$, and $p(\prod_{i\neq j\neq k\neq l}^{N}UiUjUkUl)$ are calculated. Then, all the PSC probabilities are successively calculated by PSM as Eq. (B.6), Eq. (B.7), and Eq. (B.8). The PSC probabilities are probabilities of individual pieces of Venn diagram for N nuclear units (see Fig. 2). These PSC probabilities are successively calculated from inner to outer direction in the Venn diagram. When an outer PSC probability is calculated, the overlapped inner PSC probabilities are successively subtracted. Thus, this PSM can be easily implemented in a computer code.

$$p\left(/Uj\prod_{i\neq j}^{N}Ui\right) = p\left(\prod_{i\neq j}^{N}Ui\right) - p\left(Uj\prod_{i\neq j}^{N}Ui\right) = p\left(\prod_{i\neq j}^{N}Ui\right) - p\left(\prod_{i=1}^{N}Ui\right) \tag{B.6}$$

$$\begin{aligned} p\left(/Uj/Uk\prod_{i\neq j\neq k}^{N}Ui\right) &= p\left(/(Uj+Uk)\prod_{i\neq j\neq k}^{N}Ui\right) = p\left(\prod_{i\neq j\neq k}^{N}Ui\right) - p\left((Uj+Uk)\prod_{i\neq j\neq k}^{N}Ui\right) = p\left(\prod_{i\neq j\neq k}^{N}Ui\right) \\ &\quad - p\left(/UjUk\prod_{i\neq j\neq k}^{N}Ui\right) - p\left(Uj/Uk\prod_{i\neq j\neq k}^{N}Ui\right) - p\left(UjUk\prod_{i\neq j\neq k}^{N}Ui\right) = p\left(\prod_{i\neq j\neq k}^{N}Ui\right) - p\left(/Uj\prod_{i\neq j}^{N}Ui\right) \\ &\quad - p\left(/Uk\prod_{i\neq k}^{N}Ui\right) - p\left(\prod_{i}^{N}Ui\right) \end{aligned} \tag{B.7}$$

$$\begin{aligned} p\left(/Uj/Uk/Ul\prod_{i\neq j\neq k\neq l}^{N}Ui\right) &= p\left(/(Uj+Uk+Ul)\prod_{i\neq j\neq k\neq l}^{N}Ui\right) = p\left(\prod_{i\neq j\neq k\neq l}^{N}Ui\right) - p\left(/Uj/Uk\prod_{i\neq j\neq k}^{N}Ui\right) \\ &\quad - p\left(/Uj/Ul\prod_{i\neq j\neq l}^{N}Ui\right) - p\left(/Uk/Ul\prod_{i\neq k\neq l}^{N}Ui\right) - p\left(/Uj\prod_{i\neq j}^{N}Ui\right) \\ &\quad - p\left(/Uk\prod_{i\neq k}^{N}Ui\right) - p\left(/Ul\prod_{i\neq l}^{N}Ui\right) - p\left(\prod_{i}^{N}Ui\right) \end{aligned} \tag{B.8}$$

General IEM equations for $p(/Uj\prod_{i\neq j}^{N}Ui)$, $p(/Uj\,/Uk\prod_{i\neq j\neq k}^{N}Ui)$, and $p(/Uj\,/Uk\,/Ul\prod_{i\neq j\neq k\neq l}^{N}Ui)$ can be formulated as Eq. (B.9), Eq. (B.10), and Eq. (B.11) where probability equations $p(A+B) = p(A)+p(B) - p(AB)$ and $p(A+B+C) = p(A) + p(B) + p(C) - p(AB) - p(AC) - p(BC) + p(ABC)$ are employed. As shown in these equations, the sign of each term in the right-hand-side of the IEM equations changes according to the number of core-damaged nuclear units. Thus, this IEM cannot be easily implemented in a computer code when there are many nuclear units. For example, Kori nuclear site in South Korea has nine nuclear units.

$$p\left(/Uj\prod_{i\neq j}^{N}Ui\right) = p\left(\prod_{i\neq j}^{N}Ui\right) - p\left(Uj\prod_{i\neq j}^{N}Ui\right) \tag{B.9}$$

$$\begin{aligned} p\left(/Uj\,/Uk\prod_{i\neq j\neq k}^{N}Ui\right) &= p\left(/(Uj+Uk)\prod_{i\neq j\neq k}^{N}Ui\right) = p\left(\prod_{i\neq j\neq k}^{N}Ui\right) - p\left((Uj+Uk)\prod_{i\neq j\neq k}^{N}Ui\right) \\ &= p\left(\prod_{i\neq j\neq k}^{N}Ui\right) - p\left(Uj\prod_{i\neq j\neq k}^{N}Ui\right) - p\left(Uk\prod_{i\neq j\neq k}^{N}Ui\right) + p\left(UjUk\prod_{i\neq j\neq k}^{N}Ui\right) \end{aligned} \tag{B.10}$$

$$\begin{aligned} p\left(/Uj\,/Uk\,/Ul\prod_{i\neq j\neq k\neq l}^{N}Ui\right) &= p\left(/(Uj+Uk+Ul)\prod_{i\neq j\neq k\neq l}^{N}Ui\right) = p\left(\prod_{i\neq j\neq k\neq l}^{N}Ui\right) \\ &-p\left(Uj\prod_{i\neq j\neq k\neq l}^{N}Ui\right) - p\left(Uk\prod_{i\neq j\neq k\neq l}^{N}Ui\right) - p\left(Ul\prod_{i\neq j\neq k\neq l}^{N}Ui\right) \\ &+p\left(UjUk\prod_{i\neq j\neq k\neq l}^{N}Ui\right) + p\left(UjUl\prod_{i\neq j\neq k\neq l}^{N}Ui\right) \\ &+p\left(UkUl\prod_{i\neq j\neq k\neq l}^{N}Ui\right) - p\left(UjUkUl\prod_{i\neq j\neq k\neq l}^{N}Ui\right) \end{aligned} \tag{B.11}$$

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