A Case study of Methodology for Common Cause Failure modeling in Multi-unit PSA model

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1. Introduction

The inter-unit dependency is considered to have a large impact on the execution of the multi-unit Probabilistic Safety Assessment (PSA). This dependency is defined as condition that several units in same site are affected by same cause, such as same initiating event, same component, human dependency, shared connection, proximity, and organizational dependency. In Korea, shared equipment is very rare because it is excluded as much as possible in the stage of plant design. But, failure of multiple components in a site due to the common cause can occur. For that reason, it is necessary to consider the common cause failure of identical components in a site. However, there are no available data to evaluate the common cause failure between components in multiple unit. Therefore, in this study, we used the methodology to model the inter-unit Common Cause Failure (CCF) between the same or similar components in multiple unit using intra-unit CCF data.

2. Methods and Results

This section briefly explains the concept of common cause failure and the alpha factor model that are basically used as CCF modeling method [1] and explains the methodology of inter-unit CCF modeling.

2.1 Common Cause failure

A common cause failure event is defined as event that two or more components fail at the same time or within a short time for any common cause. This event has a great impact on the reliability of the system because they cause simultaneous failure of components installed in a system. Common causes of failure include mechanical failure and human error when performing operation of component or maintenance. Also, several components may be simultaneously affected by environmental factors.

2.2 Basic CCF modeling

The method of modeling the CCF event in the fault tree is to model all combination of components that classified as same common cause component group (CCCG) into each basic event. For example, if there are three component A, B and C, the failure of each component including CCF can be expressed as follows.

$$P(A) = Q_A + Q_{AB} + Q_{AC} + Q_{ABC} \quad (1)$$
$$P(B) = Q_B + Q_{AB} + Q_{BC} + Q_{ABC} \quad (2)$$
$$P(C) = Q_C + Q_{AC} + Q_{BC} + Q_{ABC} \quad (3)$$

where, Q_K represents the probability of failure only for some components specified in K, and if two or more components are arranged in K, such as Q_{AB} and Q_{ABC}, it is considered as common cause failure probability (CCFP) of K.

Based on this, when there are m components in a system, the total probability of failure of a specific component can be expressed as follows.

$$Q_t^{(m)} = \sum_{k=1}^{m} {}_{m-1}C_{k-1} \cdot Q_k^{(m)} \quad (4)$$

The simplified fault tree of a component failure is modeled as follows.

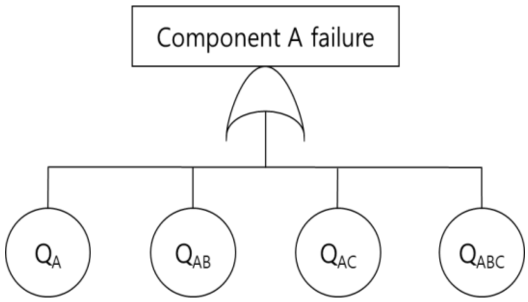

Fig. 1. The Fault tree of a component failure

To evaluate the CCFP, we investigate all component failure data that have occurred and estimate the CCF parameter to perform the analysis. The Alpha Factor Model (AFM) parameter which is generally used in PSA is defined as the ratio of the number of k-out of-m CCF events to the total number of CCF events occurring in the system and can be expressed as follows.

$$\alpha_k = \frac{n_k}{\sum_{j=1}^{m} n_j}, (1 \le k \le m) \quad (5)$$

where, n_k represents the number of events in which k out of m components existing in the system fail simultaneously.

Using these parameters, the CCFP can be calculated using the following equations in Table 1 according to the test method of the equipment.

Table I: Method to calculate CCFP

	Common Cause Failure Probability
Non-staggered Test	$Q_k^{(m)} = \frac{k}{{}_{m-1}C_{k-1}} \cdot \frac{\alpha_k}{\alpha_t} \cdot Q_t^{(m)}, (1 \le k \le m)$ (6) $\alpha_t = \sum_{k=1}^{m} k \cdot \alpha_k$ (7)
Staggered Test	$Q_k^{(m)} = \frac{1}{{}_{m-1}C_{k-1}} \cdot \alpha_k \cdot Q_t^{(m)}, (1 \le k \le m)$ (8)

Non-staggered test means testing components in the system at the same time when performing one test, and staggered test means testing components sequentially according to a specific test cycle.

2.3 Multi-unit CCF modeling

Currently, there are many available data for the intra-unit CCF internationally. However, since CCF in multiple unit in a same site has not been investigated, a separate method should be considered to calculate inter-unit CCFP.

From the point of view of the multi-unit PSA, it can be assumed that the intra-unit CCF includes failure of not only the components in the single unit but also the other components as shown in Figure 2. Therefore, it is assumed that inter-unit CCF can be calculated using the intra-unit CCF data.

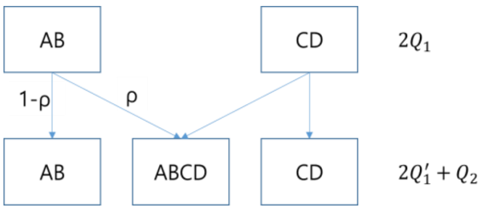

Fig. 2. The concept of inter-unit CCF modeling

There are many difficulties to consider all CCFs in multiple units. Therefore, in the same manner as in the method developed by Korea Atomic Energy Research Institute (KAERI) [2], the intra-unit CCF event are modeled in the same way as single-unit PSA and the inter-unit CCF data are evaluated by multiplying intra-unit CCF data where all components in a single unit are fail by the fraction of inter-unit CCF calculated using inter-unit correlation coefficient (r) and unit-specific parameter (ρ).

The unit-specific parameter is assumed to be $(0.5)^m$ depending on the number of CCCG (m). The inter-unit correlation coefficient is calculated using the dependency tree that added a factor of maintenance to the tree developed by KAERI [2], as shown below. The value of each sequence is calculated using the dependency considered in human reliability analysis (HRA) [3].

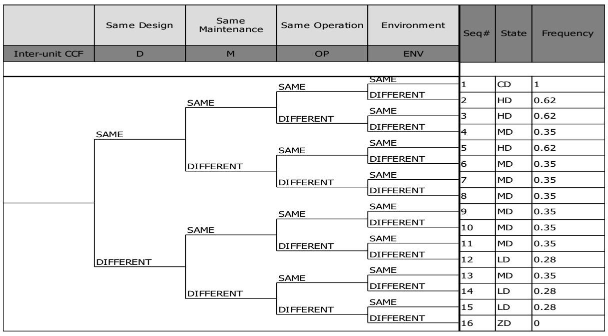

Fig. 3. Inter-unit dependency tree

The fraction of inter-unit CCF is calculated by the following method.

The inter-unit dependency rate (R) can be calculated as follows using the values obtained above.

$$R_I = r_I \rho^{u-1}, (1 \le u \le n) \quad (9)$$

where, I represents any possible combinations among units within a site, and u is the number of units considered in I.

In order to calculate the fraction of inter-unit CCF (f), the CCF fraction of all combinations including I and other units should exclude in R_I as follows, because R_I includes the failure in other units without I.

$$f_I = R_I - \sum f(\mathit{Cutsets\ including\ I\ and\ other\ units}) \quad (10)$$

The final inter-unit CCF data is calculated by combining the inter-unit CCF fractions and intra-unit CCF event that all component in a unit fail obtained in the single-unit PSA.

$$Q_I = Q_{\text{All in single unit}} \cdot f_I \quad (11)$$

2.4 Case study

To apply the above method, we performed multi-unit PSA with 4 units (1 of WH600, 1 of WH900, 2 of OPR1000).

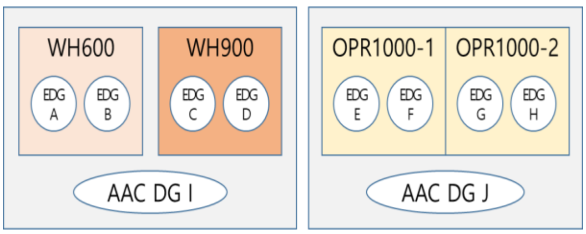

Fig. 4. The conceptive plant design of 4 units

There are two emergency diesel generators (EDG) for each unit. And, one alternate AC diesel generator (AAC DG) is shared by WH600 and WH900. Another AAC

DG can supply emergency power to one of the two OPR1000 units. As an initiating event, we considered multi-unit Loss of Offsite Power (LOOP) and assumed event frequency to be 1. To simplify the accident sequence, only EDG and AAC DG are considered in case of loss of off-site power, and it is assumed that if the power supply through the above component is successful, core damage does not occur.

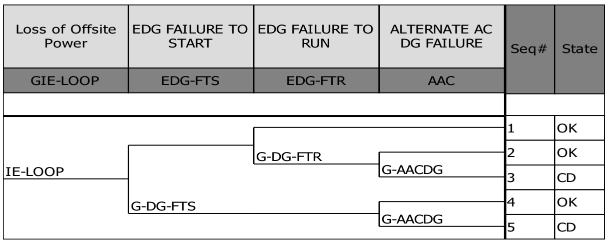

Fig. 5. The simplified LOOP event tree

The LOOP model for each unit was developed according to the Figure 5, and top logic was constructed like the following fault tree to model the multi-unit accident scenario.

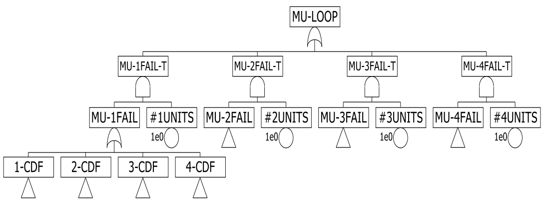

Fig. 6. The top logic of multi-unit PSA model

In EDG and AAC DG fault trees, only the failure of the equipment was considered except failure of supporting system. The equipment failure rate is based on the data presented in NUREG/CR-6928(2007) [4], since the plant-specific data is not available. And two EDGs and a AACDG are classified as one CCCG because those components have similarity in equipment feature such as component design. The CCF data uses the values given in NUREG/CR-5496(2007) [5] and CCF events including AAC DG are calculated by reflecting the similarity derived from Figure 3.

Table II: The component data of an EDG failure

Event	Description	Data
EGDGS	EDG fails to start	7.43×10^{-3}/d
EGDGR	EDG fails to run	8.48×10^{-4}/hr
EGDGW	CCF of EDG demand failure	2/3 CCF factor-4.84×10^{-3} 3/3 CCF factor-3.65×10^{-3}
EGDGK	CCF of EDG running failure	2/3 CCF factor-5.35×10^{-3} 3/3 CCF factor-5.42×10^{-3}

2.5 Results

To derive the inter-unit CCF data, the inter-unit correlation must first be investigated. First, we searched component information (equipment design, maintenance, operation, etc.) by each unit and classified the correlation as follows by reflecting it on the developed dependency tree.

Table III: The inter-unit correlation between 4 units

	1	2	3	4	A1	A2
1	S/S/S/S	D/D/S/S	D/D/S/D	D/D/S/D	D/S/D/S	D/D/D/D
2	D/D/S/S	S/S/S/S	D/D/S/D	D/D/S/D	D/D/D/S	D/D/D/D
3	D/D/S/D	D/D/S/D	S/S/S/S	S/S/S/S	D/D/D/D	S/S/D/S
4	D/D/S/D	D/D/S/D	S/S/S/S	S/S/S/S	D/D/D/D	S/S/D/S
A1	D/S/D/S	D/D/D/S	D/D/D/D	D/D/D/D	S/S/S/S	D/D/S/D
A2	D/D/D/D	D/D/D/D	S/S/D/S	S/S/D/S	D/D/S/D	S/S/S/S

Note) 1: WH600, 2: WH900, 3: OPR1000-1, 4: OPR1000-2, A1: AAC DG I, A2: AACDG J, D: Different, S: Same

To calculate the inter-unit dependency rate, inter-unit correlation coefficients were evaluated using Table 3. Inter-unit correlation coefficients for 3 or more units were classified by comparing the results in Table 3. For example, r_{123} was classified to D/D/S/D because the factor of operation was only same when the correlations of 1-1, 1-2, and 1-3 were compared. For the unit-specific parameter, $(0.5)^2$ is applied considering only two EDGs in case that AAC DG is not included, and when the AAC DG is included, $(0.5)^3$ is applied. The calculated inter-unit dependency rates are summarized in Table 4.

Table IV: The summary of inter-unit dependency rate

Event	Branch	r	R	Event	Branch	r	R
R_1	S/S/S/S	1.0	1.0	R_{1A1}	D/S/D/S	0.35	3.50×10^{-1}
R_2	S/S/S/S	1.0	1.0	R_{2A1}	D/D/D/S	0.28	2.80×10^{-1}
R_3	S/S/S/S	1.0	1.0	R_{3A2}	S/S/D/S	0.62	6.20×10^{-1}
R_4	S/S/S/S	1.0	1.0	R_{4A2}	S/S/D/S	0.62	6.20×10^{-1}
R_{12}	D/D/S/S	0.35	8.75×10^{-2}	R_{12A1}	D/D/D/S	0.28	3.50×10^{-2}
R_{13}	D/D/S/D	0.28	7.00×10^{-2}	R_{34A2}	S/S/D/S	0.62	7.75×10^{-2}
R_{14}	D/D/S/D	0.28	7.00×10^{-2}	R_{13A12}	D/D/D/D	-	-
R_{23}	D/D/S/D	0.28	7.00×10^{-2}	R_{14A12}	D/D/D/D	-	-
R_{24}	D/D/S/D	0.28	7.00×10^{-2}	R_{23A12}	D/D/D/D	-	-
R_{34}	S/S/S/S	1.0	2.50×10^{-1}	R_{24A12}	D/D/D/D	-	-
R_{123}	D/D/S/D	0.28	1.75×10^{-2}	R_{123A12}	D/D/D/D	-	-
R_{124}	D/D/S/D	0.28	1.75×10^{-2}	R_{124A12}	D/D/D/D	-	-
R_{134}	D/D/S/D	0.28	1.75×10^{-2}	R_{134A12}	D/D/D/D	-	-
R_{234}	D/D/S/D	0.28	1.75×10^{-2}	R_{234A12}	D/D/D/D	-	-
R_{1234}	D/D/S/D	0.28	4.37×10^{-3}	$R_{1234A12}$	D/D/D/D	-	-

The fraction of inter-unit CCF was calculated using the inter-unit dependency rate obtained above.

Table V: The fraction of inter-unit CCF(1/2)

Event	Equation	Value
f_1	R_1-Σf(12,13,14,123,124,134,1234)	8.21×10^{-1}
f_2	R_2-Σf(12,23,24,123,124,234,1234)	8.21×10^{-1}
f_3	R_3-Σf(13,23,34,123,134,234,1234)	6.59×10^{-1}
f_4	R_4-Σf(14,24,34,124,134,234,1234)	6.59×10^{-1}
f_{12}	R_{12}-Σf(123,124,1234)	5.68×10^{-2}
f_{13}	R_{13}-Σf(123,134,1234)	3.93×10^{-2}
f_{14}	R_{14}-Σf(124,134,1234)	3.93×10^{-2}
f_{23}	R_{23}-Σf(123,234,1234)	3.93×10^{-2}
f_{24}	R_{24}-Σf(124,234,1234)	3.93×10^{-2}
f_{34}	R_{34}-Σf(134,234,1234)	2.19×10^{-1}
f_{123}	$R_{123}-f_{1234}$	1.31×10^{-2}
f_{124}	$R_{124}-f_{1234}$	1.31×10^{-2}
f_{134}	$R_{134}-f_{1234}$	1.31×10^{-2}
f_{234}	$R_{234}-f_{1234}$	1.31×10^{-2}
f_{1234}	R_{1234}	4.37×10^{-3}

Table V: The fraction of inter-unit CCF(2/2)

Event	Equation	Value
f_{1A1}	R_{1A1}-f_{12A1}	3.15×10^{-1}
f_{2A1}	R_{2A1}-f_{12A1}	2.45×10^{-1}
f_{3A2}	R_{3A2}-f_{34A2}	5.42×10^{-1}
f_{4A2}	R_{4A2}-f_{34A2}	5.42×10^{-1}
f_{12A1}	R_{12A1}	3.50×10^{-2}
f_{34A2}	R_{34A2}	7.75×10^{-2}

2/3 CCF factor is used for CCF which contains EDGs only as base data for inter-unit CCF factor, and 3/3 CCF factor is used in case that AAC DG is included. The final inter-unit CCF factors are shown in Table 6.

Table VI: The final CCF factors of multi-unit PSA model

CCF	Factor (demand)	Factor (running)	Remark
AB	3.97×10^{-3}	4.39×10^{-3}	2/3 CCF factor×f_1
CD	3.97×10^{-3}	4.39×10^{-3}	2/3 CCF factor×f_2
EF	3.19×10^{-3}	3.52×10^{-3}	2/3 CCF factor×f_3
GH	3.19×10^{-3}	3.52×10^{-3}	2/3 CCF factor×f_4
ABCD	2.75×10^{-4}	3.04×10^{-4}	2/3 CCF factor×f_{12}
ABEF	1.91×10^{-4}	2.11×10^{-4}	2/3 CCF factor×f_{13}
ABGH	1.91×10^{-4}	2.11×10^{-4}	2/3 CCF factor×f_{14}
CDEF	1.91×10^{-4}	2.11×10^{-4}	2/3 CCF factor×f_{23}
CDGH	1.91×10^{-4}	2.11×10^{-4}	2/3 CCF factor×f_{24}
EFGH	1.06×10^{-3}	1.17×10^{-3}	2/3 CCF factor×f_{34}
ABCDEF	6.35×10^{-5}	7.02×10^{-5}	2/3 CCF factor×f_{123}
ABCDGH	6.35×10^{-5}	7.02×10^{-5}	2/3 CCF factor×f_{124}
ABEFGH	6.35×10^{-5}	7.02×10^{-5}	2/3 CCF factor×f_{134}
CDEFGH	6.35×10^{-5}	7.02×10^{-5}	2/3 CCF factor×f_{234}
ABCDEFGH	2.12×10^{-5}	2.34×10^{-5}	2/3 CCF factor×f_{1234}
ABI	1.15×10^{-3}	1.71×10^{-3}	3/3 CCF factor×f_{1A1}
CDI	8.94×10^{-4}	1.33×10^{-3}	3/3 CCF factor×f_{2A1}
EFJ	1.98×10^{-3}	2.94×10^{-3}	3/3 CCF factor×f_{3A2}
GHJ	1.98×10^{-3}	2.94×10^{-3}	3/3 CCF factor×f_{4A2}
ABCDI	1.28×10^{-4}	1.90×10^{-4}	3/3 CCF factor×f_{12A1}
EFGHJ	2.83×10^{-4}	4.20×10^{-4}	3/3 CCF factor×f_{34A2}
AI/BI	1.69×10^{-3}	1.87×10^{-3}	2/3 CCF factor×r_{1A1}
CI/DI	1.36×10^{-3}	1.50×10^{-3}	2/3 CCF factor×r_{2A1}
EJ/FJ	3.00×10^{-3}	3.32×10^{-3}	2/3 CCF factor×r_{3A2}
GJ/HJ	3.00×10^{-3}	3.32×10^{-3}	2/3 CCF factor×r_{4A2}
IJ	3.22×10^{-3}	4.34×10^{-3}	2/3 CCF factor×r_{A12}

As a result of quantification (Cutoff=1.0×10^{-15}), the total CDF was calculated to be 3.75×10^{-4}/yr when the inter-unit CCF was not considered, and 3.58×10^{-4}/yr with inter-unit CCF. Even though the total CDF of second case was decreased compared to that of first case, the percentage of multi-unit core damage frequency increases from 0.09% to 4.78%, as shown in Table 7.

Table VII: The result of multi-unit PSA model

# of Core Damage	Base(/yr)	w/ Inter-unit CCF(/yr)
1 unit	3.75×10^{-4}	3.41×10^{-4}
2 units	3.40×10^{-7}	1.71×10^{-5}
3 units	5.11×10^{-11}	9.58×10^{-9}
4 units	-	6.46×10^{-10}
Total(/yr)	3.75×10^{-4}	3.58×10^{-4}

3. Conclusions

In this report, we perform the case study using the methodology of inter-unit CCF modeling, which is important in multi-unit PSA. In this methodology, inter-unit CCF data was derived by using the existing intra-unit CCF data and inter-unit correlation coefficient. A dependency tree was developed to determine the inter-unit correlation coefficient, and the inter-unit dependency rate was calculated in combination with the unit-specific parameters. The inter-unit CCF fractions was evaluated by subtract the CCF fraction of all combinations including I and other units from R_I. The final inter-unit CCF data is calculated by combining the inter-unit CCF fractions and intra-unit CCF event that all component in a unit fail obtained in the single-unit PSA. As a result of the quantification with inter-unit CCF, the total CDF was decreased compared to that of the original model, but the percentage of the multi-unit core damage frequency was increased from 0.09% to 4.78%.

Since there is no available data that can handle inter-unit CCF until now, it is expected that this methodology can be used to model inter-unit CCF in multi-unit PSA.

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