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Suggestions on Use of Common Cause Initiating Event Frequency in Multi-unit PSA Models

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1. Introduction

In overseas countries, the IAEA (International Atomic Energy Agency) has established technical standards for multi-unit PSA (Probabilistic Safety Assessment) [1]. In Korea, operators and regulators are establishing a multi-unit PSA models and drawing conclusions

According to a reference written at the beginning of the multi-unit PSA project [2], it was expected that the frequency of events at sites with *n* units would be less than *n* times the frequency of single-unit events. This was due to the proportion of frequencies occurring due to common causes.

In addition, the frequency of initiating events for multi-unit is expected to vary depending on the inter-unit independence and common causes. This hypothesis will come to conclusion as the analysis of the multi-unit PSA model progresses.

In the meantime, it is necessary to examine how to allocate the frequency of initiating events. In the past, the frequency of initiating events was calculated by averaging the number of events occurring in all domestic nuclear power plants, and applied to the PSA models of all power plants equally. However, new issues arise to calculate frequency of initiating events for multi-unit, for example, how to count frequency of initiating events for multi-unit and how to calculate operation period for multi-unit.

In a paper published in 2016 and a report published in 2017 [3, 4], they conducted a study on how to estimate the count frequency of initiating events for multi-unit, especially in the case of LOOP (Loss Of Offsite Power) and SBO (Station Black Out). However, these references still do not say exactly what frequency should be used in the multi-unit PSA model.

The reason for this is that the frequency estimate may vary depending on how the model is constructed. In this paper, as the multi-unit PSA model appears to some progress, we discuss and present relevant comments on the initiating event allocation problem.

2. Methods and Results

2.1 Initiating Event Frequency Between Independent Plants

In this paper, the existing symbols are used as is. In addition, an initiating event that causes a single-unit event is called a SUI (Single-Unit Initiator), and an initiating event that causes an event simultaneously in two or more units is called a CCI (Common Cause Initiator) [5].

In this paper, the two plants are described as standard, but the generality will not be lost for more than that. SUI and CCI are limited to the same kind of initiating events, such as "LOOP, GTRN (General Transient), LOCV (Loss of Condenser Vacuum)" in Korea.

In other words, initiating events for only SUI, such as the LOCA (Loss of Coolant Accident), are excluded from the discussion of this paper. In addition, it is assumed that there are no multi-unit events by cascading or propagating considering the characteristics of domestic nuclear power plants and the process of creating multi-unit PSA models.

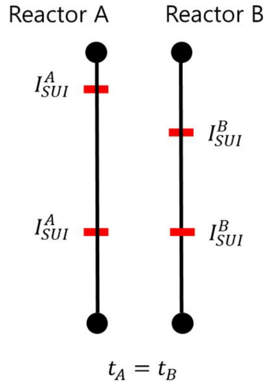

Fig.1. Flow sheets for combined cycle (only SUI)

Assume that plants A and B in a site have operated t_A, t_B years as shown in Fig. 1. However, the two plants are completely independent and have no dependencies, just like two separate nuclear power plants. Where I^A_{SUI} is the number of event occurrences in plant A and I^B_{SUI} is the number of event occurrences in plant B.

In this situation, the initiating event frequency (f'_{SUI}) based on single-unit is shown in Eq. (1). Here, RY (Reactor Year) means to a plant operating period based on a reactor, and assumes that the two reactors have the same operating period.

$$f'_{SUI} = \frac{2I^A_{SUI} + 2I^B_{SUI}}{t_A + t_B} RY^{-1} \quad (1)$$

Based on this, the site risk is calculated as in Eq. (2).

$$Risk'^{(2)}_S = f'_{SUI} \times \left[\Sigma\left(p^{(2)}_{A_i,SUI} C^{(2)}_{A_i,SUI}\right) + \Sigma(p^{(2)}_{B_i,SUI} C^{(2)}_{B_i,SUI})\right] \quad (2)$$

Where $p^{(n)}_{k_i,SUI}$ is the probability that a cut set by SUI will occur in *k* plants of *n* plants, and $C^{(n)}_{k_i,SUI}$ means the event conclusions caused by SUI in *k* plants of *n* plants.

It can be seen that the site risk is the sum of the individual risks of the two plants.

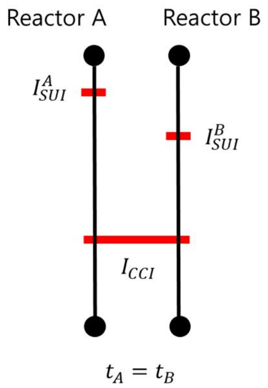

Fig.2. Flow sheets for combined cycle (SUI & CCI)

Fig. 2 assumes that, unlike the situation in Fig. 1, assumes that one initiating event affects all units and there are no dependencies. At this time, if the frequency of initiating events by SUI and CCI are calculated, Eq. (3) and (4) are respectively. SY (Site Year) means the period of operation of a nuclear plant on a site basis.

$$f_{SUI} = \frac{I_{SUI}^{A}+I_{SUI}^{B}}{t_A+t_B}\ \mathrm{RY}^{-1} \quad (3)$$

$$f_{CCI} = \frac{I_{CCI}}{t_A}\ \mathrm{SY}^{-1} \quad (4)$$

Where I_{CCI} is the number of occurrences by CCI. If SY is based on the first operated plant in a site, the relationship shown in Eq. (5) is established.

$$RY^{-1} = n * SY^{-1} \quad (5)$$

Where n in a site means the number of power plants. As a result, if $I_{SUI}^{A} = I_{SUI}^{B} = I,\ I_{CCI} = 2\mathrm{I}$, the relationship same with Eq. (6).

$$f'_{SUI} = f_{SUI} + f_{CCI} \quad (6)$$

Eq. (6) shows that for some assumptions, the frequency of initiating events for single-unit model and the frequency of initiating events for multi-unit model is constant.

SUI, CCI and site risk are expressed as Eq. (7), (8) and (9).

$$Risk_{S,SUI}^{(2)} = f_{SUI} \times \left[\sum(p_{A_i,SUI}^{(2)} C_{A_i,SUI}^{(2)}) + \sum(p_{B_i,SUI}^{(2)} C_{B_i,SUI}^{(2)})\right] \quad (7)$$

$$Risk_{S,CCI}^{(2)} = f_{CCI} \times \left[\left[\sum\left(p_{A_i,CCI}^{(2)} C_{A_i,CCI}^{(2)}\right) + \sum\left(p_{B_i,CCI}^{(2)} C_{B_i,CCI}^{(2)}\right)\right] + \sum\sum g\left(p_{A_i,CCI}^{(2)} p_{B_i,CCI}^{(2)}\right) h\left(C_{A_i,CCI}^{(2)} C_{B_i,CCI}^{(2)}\right)\right] \quad (8)$$

$$Risk_{S}^{(2)} = Risk_{S,SUI}^{(2)} + Risk_{S,CCI}^{(2)} \quad (9)$$

Eq. (7) is the risk when an initiating event occurs that affects only a single-unit. Eq. (8) describes a case where a single core damage or both units become core damages when an initiating event affects multi-unit occurs. The last term in Eq. (8) is the case where two power plants are accidentally damaged at the same time, which assumes that the value is very small and does not show a significant impact [6].

Eq. (2) and (9) show the site risk differences in Fig. 1 and 2 in the absence of dependencies.

2.2 Initiating Event Frequency Between Dependent Plants

This section describes the case where there are dependencies between plants. In fact, there are inter-unit dependencies in the case of multi-unit. Looking at the current implementation of the multi-unit PSA model, the cut sets derived from the multi-unit PSA model are obtained from only one unit core damage cut set to *n* unit core damage cut sets. It is necessary to discuss what frequency of initiating event should be applied to each of these cut sets.

In the case of single-unit core damage shown in Eq. (8), it is calculated to exclude the multi-unit element. Therefore, in the single-unit event scenario in Eq. (7) and in the multi-unit event scenario in Eq. (8), the terms in which core damage occurs only in the single-unit should be the same.

Applying the symmetry between power plants A and B, the single-unit core damage can be expressed as Eq. (10).

$$\sum(p_{A_i,SUI}^{(2)} C_{A_i,SUI}^{(2)}) = \sum(p_{B_i,SUI}^{(2)} C_{B_i,SUI}^{(2)}) \quad (10)$$

If the sum of each cut set is expressed in one term and the symmetry allows, Eq. (7) to be expressed as Eq. (11), in addition, the Eq. (8) can be represented as Equation (12), considering the characteristics of the dependencies for multi-unit scenarios.

$$Risk_{S,SUI}^{(2)} = 2f_{SUI} \times (p_{1,SUI}^{(2)} C_{1,SUI}^{(2)}) \quad (11)$$

$$Risk_{S,CCI}^{(2)} = f_{CCI} \times \left[\left[\sum\left(p_{A_i,CCI}^{(2)} C_{A_i,CCI}^{(2)}\right) + \sum\left(p_{B_i,CCI}^{(2)} C_{B_i,CCI}^{(2)}\right)\right] + \sum\sum g\left(p_{A_i,CCI}^{(2)} p_{B_i,CCI}^{(2)}\right) h\left(C_{A_i,CCI}^{(2)} C_{B_i,CCI}^{(2)}\right) + \sum\left(p_{AB_i,CCI}^{(2)} C_{AB_i,CCI}^{(2)}\right)\right] \approx f_{CCI} \times \left[2(p_{1,CCI}^{(2)} C_{1,CCI}^{(2)}) + (p_{2,CCI}^{(2)} C_{2,CCI}^{(2)})\right] \quad (12)$$

Eq. (12), unlike Eq. (8), adds a term for dependent simultaneous core damage. Independent simultaneous core damages were omitted because they were previously considered to be insignificant.

The site risk of Eq. (9) can be summarized as Eq. (13) by considering the dependencies.

$$\begin{aligned} Risk_S^{(2)} &= Risk_{S,SUI}^{(2)} + Risk_{S,CCI}^{(2)} \\ &= 2f_{SUI} \times \left(p_{1,SUI}^{(2)} C_{1,SUI}^{(2)}\right) \\ &+ f_{CCI} \times \left[2\left(p_{1,CCI}^{(2)} C_{1,CCI}^{(2)}\right) + \left(p_{2,CCI}^{(2)} C_{2,CCI}^{(2)}\right)\right] \end{aligned} \quad (13)$$

Core damage of a single-unit is expected to be constant irrespective of SUI and CCI, which can be expressed as Eq. (14).

$$p_{1,SUI}^{(2)} C_{1,SUI}^{(2)} = p_{1,CCI}^{(2)} C_{1,CCI}^{(2)} \quad (14)$$

As a result, Eq. (13) can be expressed as the site risk Eq. (15) of the two units considering the dependency.

$$\begin{aligned} Risk_S^{(2)} &= 2(f_{SUI} + f_{CCI}) \times p_{1,SUI}^{(2)} C_{1,SUI}^{(2)} \\ &+ f_{CCI} \times p_{2,CCI}^{(2)} C_{2,CCI}^{(2)} = 2f'_{SUI} \times p_{1,SUI}^{(2)} C_{1,SUI}^{(2)} \\ &+ f_{CCI} \times p_{2,CCI}^{(2)} C_{2,CCI}^{(2)} \end{aligned} \quad (15)$$

To summarize the meaning of Eq. (15) is as follows.

- Even if the actual periods of operation between reactors in a site are different, RY is applied based on plants that have operated longer.
- The same concept applies to SY.
- For risks caused by SUI, cut set ($p_{1,SUI}^{(2)} C_{1,SUI}^{(2)}$) which excludes the effect of inter-unit derived from risks caused by CCI, is used.
- In this case, the initiating event applies the frequency of initiating events of a single-unit (f'_{SUI}) that is used previously.
- In the multi-unit model, the frequency of initiating events (f_{CCI}) based on SY is applied to the cut set where simultaneous failures occur.
- In case of f_{CCI}, it can be determined through various logic and judgment. In this case, f_{SUI} is calculated using the calculated f_{CCI} as an input value.

3. Further Discussions

Chapter 3 describes the assumptions applied to the equation in Chapter 2 and other topics that may be discussed.

3.1 Site specific vs. National Average

In general PSA, when calculating f'_{SUI}, general data or overall experience data of Korea are averaged. In order to maintain consistency in this view, it is reasonable to use the national average for f_{CCI}. In the case of CCI, site dependence is very large, but initiating events such as LOOP, which are currently being focused on the multi-unit model, already use the above data even though they know that site dependence is large.

3.2 Definition of Site Year

It is appropriate to see SY as a kind of external event effect that has a common effect on the entire site. Therefore, it is desirable to define SY from the beginning of the first operating point to the present. In other words, from the first operation of the unit, all currently operating power plants are considered to be operating.

This can be conservative because the numerator will be large in terms of counting long-term in calculating the frequency of initiating event for multi-unit. On the other hand, because the period is maximized, the denominator may be larger, leading to optimistic results. As there is no official data on the common cause frequency of initiating events for multi-unit, this is a technical issue to be solved.

3.3 Counting of CCIs

For two units discussed in Chapter 2, CCI can also be counted for events affecting two plants. On the other hand, if there are *n* units, there is an issue of whether CCI should be counted by the number of plants. For example, if we create a multi-unit PSA model for *n* power plants, a cut set is derived from the combination of *1 to n* power plants. In this case, f_{SUI} can be used for cut set for only one power plant.

However, in the case of f_{CCI}, it is necessary to consider applying it to a cut set represented by a combination of *2 to n-1* power plants since it represents the frequency of initiating events where all power plants in the site are simultaneously affected.

Theoretically, the frequency of initiating events should be reassessed by the number of plants, but considering the domestic situation and the availability of data, it is realistic to apply the CCI frequency of two plants and the CCI frequency affecting all plants.

Otherwise, from a conservative point of view, we suggest a method that finds all the initiating events affecting two or more power plants and applies them to *2 to n-1* cut sets in common.

3.4 Aggregation of Core Damage Frequencies

The discussion in Chapter 2 focuses on risk, assuming the implementation of Level 3. This section examines the core damage frequency represented by the combination of different numbers of power plants.

Except for the event conclusions part in Eq. (15), it remains the same as (16) if only the probability of events remains. Where SCDF is the core damage frequency in a site.

$$SCDF \neq 2f'_{SUI} \times p_{1,SUI}^{(2)} + f_{CCI} \times p_{2,CCI}^{(2)} \quad (16)$$

Intuitively, it would be unreasonable to simply eliminate the event conclusions, as the SUI and CCI events will be different.

If we can estimate the ratio of SUI event conclusions to CCI event conclusions, we can suggest to use of the correction factor for f_{CCI}, which is shown in Eq. (17).

$$SCDF \approx 2f'_{SUI} \times p^{(2)}_{1,SUI} + f_{CCI} \times \mathrm{k} \times p^{(2)}_{2,CCI} \quad (17)$$

Where k is a constant that can be approximated to satisfy $C^{(2)}_{2,CCI} = \mathrm{k} \times C^{(2)}_{1,SUI}$. Here, the event conclusions of a single-unit assume symmetry according to the unit, otherwise a weight is required accordingly.

This approximation will be possible only if there is enough information on the event conclusions. Since this indicator weights multi-unit event scenarios as the event conclusions, it is more reasonable as a surrogate metric than a simple frequency-based SCDF.

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3.5 Comparison between single-unit risk and multi-unit risk

It is one of the final conclusions of the multi-unit PSA, and it is an indicator of the ratio of the difference in risks between the construction of the multi-unit in a site with or without independence. In that sense, if we compare risks on a ratio scale, Eq. (18) is suggested.

$$r^{dep}_{ind} = \frac{r_{dep}}{r_{ind}} \quad (18)$$

Where r_{dep} is the risk when existing multi-unit in a site and there are inter-unit dependencies, r_{dep} is the risk when existing multi-unit in a site and there are no inter-unit dependencies.

Alternatively, the above measures could be applied using the ratio to SCDF without using risk.

4. Conclusions

In this paper, we reviewed some of the issues related to the allocation of initiating events and suggested a solution for constructing a multi-unit PSA model.

The issue of assigning the frequency of initiating event depends on how to construct the multi-unit PSA model. The current characteristics of the domestic model will make all units into one model, so we suggested and discussed a method for allocating the frequency of initiating events corresponding these characteristics.

However, since there are no examples of numerical values for the frequency of initiating events for multi-unit, a continuous of studies such as technology establishment, expert judgment, and statistical processing are needed.

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