Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 17-18, 2018

An Application of the Cascading Assessment Methodology for Evaluating Multi-Unit Risk

Wonjong Song, Sunghyun Park, and Moosung Jae*
Department of Nuclear Engineering, Hanyang University, Seoul, 04763, Korea
**Corresponding author: jae@hanyang.ac.kr*

1. Introduction

A lot of researches have been conducted on how to estimate multi-unit site risk in many countries including Korea. Many multi-unit Probabilistic Safety Assessment(PSA) methodologies have been proposed because multi-unit PSA must be performed to estimate site risk. Specifically, researches on multi-unit PSA are being actively carried out in Korea with a high density of nuclear power plants(NPPs).

Most of the researches on the proposed multi-unit PSA methodology are about multi-unit Level 1 PSA [1,2,3]. However, Level 3 PSA should be performed to ultimately estimate site risk.

Therefore, the multi-unit Level 3 PSA methodology proposed by D. W. Hudson et al. was applied to hypothetical site consisting of three units [4,5]. The methodology estimates multi-unit accident risks through combinations of several representative accident scenarios (The Hudson's methodology is called 'the methodology' in the rest of this paper). This research will provide an insight that will help to develop a new multi-unit Level 3 PSA methodology.

2. Methods and Results

Multi-unit accident risks were estimated for the hypothetical site consisting of WH600 and WH900 reactor types in this research. The hypothetical site is shown in Fig. 1. In the methodology, multi-unit accident risks were estimated for identical reactor types (Peach Bottom and Surry NPP). The methodology was extended to estimate the hypothetical site risk with three different reactor types, and many factors were assumed.

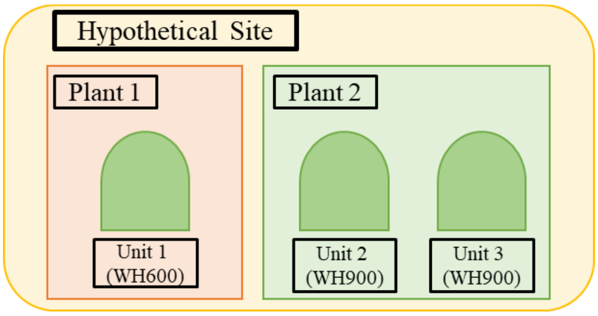

Fig. 1. Hypothetical multi-unit site

2.1. Multi-unit Accident Sequences

Multi-unit accident sequences can be caused by single-unit initiators(SUIs) and common-cause initiators(CCIs) [6]. The CCIs are initiators that affect multiple units mainly due to natural disasters (e.g. earthquake, several weather). On the other hand, the SUIs are initiators that affect single unit (e.g. internal events, internal fires, and internal floods). The SUI can be categorized into restricted, cascading, and propagating sequences. The restricted sequences limit an accident to the unit with the SUI. However, if other units are affected, the SUI becomes the cascading and propagating sequences. The difference between the cascading and propagating sequences is whether the accident occurs in the unit with SUI. This classification is shown in Fig. 2. Only the cascading sequences were considered in this research.

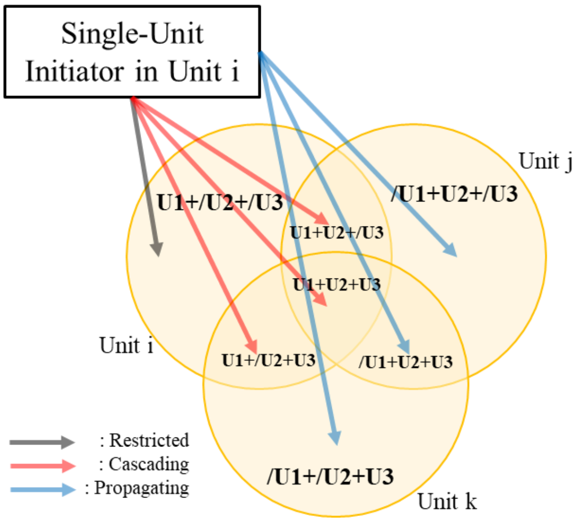

Fig.2. Multi-unit sequences from SUIs

2.2. Reference STC Selection

Only the single-unit accident scenarios considered in the State-of-the-Art Reactor Consequence Analysis(SOARCA) Project were used to estimate multi-unit accident risks in the methodology. However, accident sequences can be categorized into different source term categories(STCs) starting from a same initiating event. Therefore, combinations of STCs rather than combinations of accident sequences were considered in this research. Representative STCs of the Unit 1, Unit 2, and Unit 3 considered by the below criteria are shown in Table I [7,8]. The STCs with higher frequency were selected among the STCs satisfying the criteria.

i) Containment failure accidents (except for containment isolation failure and Basemat Melt-Through)

ii) Bypass accidents (ISLOCA or SGTR)

Table I. Reference STCs for Unit 1, 2, and 3

Unit 1	Unit 2 and 3 (identical)
STC 11: Late Containment Failure	STC 3: Early Containment Failure
STC 13: Containment Failure Before Reactor Breach	STC 13: Containment Failure Before Reactor Breach
STC 17: SGTR	STC 17: SGTR

In point of view for conditional consequence distributions, it was assumed that the representative STCs represent other accident sequences that did not modeled.

2.3. Single-unit Accident Risks

Single-unit accident risks are estimated using frequencies and conditional consequences of the representative STCs in the methodology, because the SOARCA Project did not perform conditional consequence analysis for all accident sequence scenarios. However, single-unit accident risks of each unit were estimated by performing conditional consequence analysis of all STCs in this research.

2.4 Multi-unit Accident Risks

The methodology was used to estimate multi-unit accident risks. Specifically, more assumptions were added because of the increased number of units and the reactor types. This process flow is shown in Fig. 3. "k" in the subscripts for the following paragraphs indicates to the term applied to estimations of three-unit accident scenarios.

2.4.1. Multi-unit Accident Scenario Frequencies

Multi-unit accident scenario frequencies were estimated using Eq. (1).

$$F_{ijk}^{m} = F_i^s \times \beta \times \left(\frac{F_j^s}{\sum_j F_j^s}\right) \times \left(\frac{F_k^s}{\sum_k F_k^s}\right) \qquad (1)$$

F_{ijk}^{m} is mean multi-unit accident scenario frequency. The index i is used for reference unit, while the index j and k are used for co-located units. F_i^s means frequency of i STC for reference unit, and $\left(\frac{F_j^s}{\sum_j F_j^s}\right)$ means fraction of j STC frequency among the representative STCs for co-located unit. $\left(\frac{F_k^s}{\sum_k F_k^s}\right)$ means fraction of k STC frequency among the representative STCs for the other co-located unit. β means global conditional probability of an accident occurring in the co-located units and reflect dependency between the units. β between each unit was assumed as follows.

i) Between Unit 2 and 3: 0.1
ii) Between Unit 1 and 2(or 3): 0.01
iii) Between Unit 1, 2, and 3: 0.001 (three-unit accident)

These dependencies are reasonable to be derived by analyzing accident reports as researched in [7]. Because all three units can be the reference unit, F_{ijk}^{m} was calculated considering this.

2.4.2. Multi-unit Accident Scenario Consequences

Conditional multi-unit accident consequences were estimated using the MACCS 3.10 version according to each STC combination. The population-weighted risk resulted from the MACCS was used as risk metrics. For simplicity, emergency response was not considered, and consequences were estimated up to EARLY module.

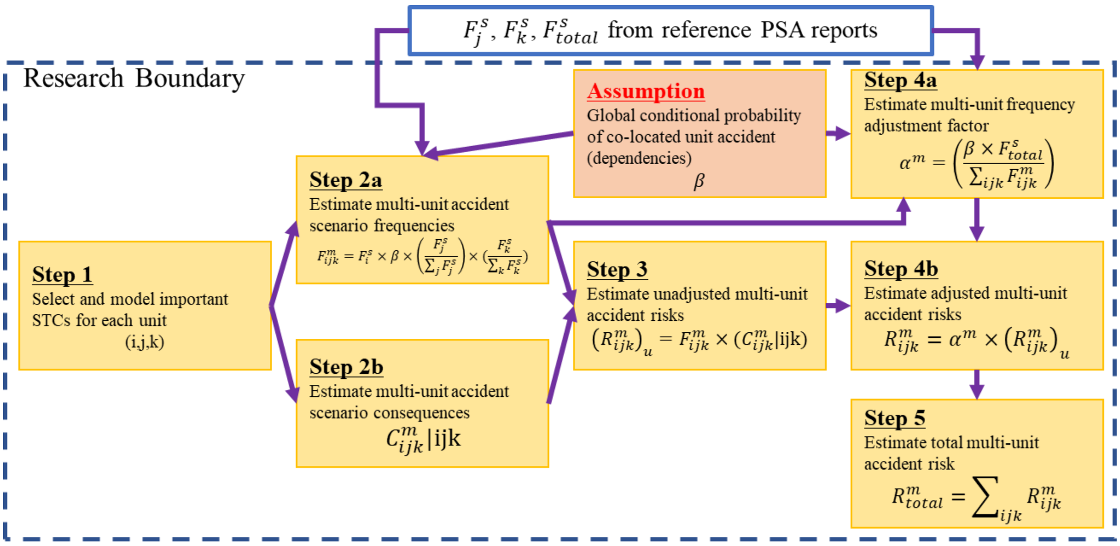

Fig. 3. Process flow of estimating multi-unit accident risks

Through the SOARCA Project and various recent researches, input parameters reflecting the domestic situation were investigated and used for the MACCS [8,9]. Also, multiple source term function was utilized to simulate two-or three-unit accident assuming concurrent accident condition (time offset=0). Multi-unit accident risks are estimated by using Eq. (2).

$$\left(R_{ijk}^{m}\right)_{u} = F_{ijk}^{m} \times \left(C_{ijk}^{m} \middle| \text{ijk}\right) \qquad (2)$$

$\left(R_{ijk}^{m}\right)_{u}$ means an unadjusted multi-unit accident risk. Also, C_{ijk}^{m} means conditional consequence when i, j, and k STC occur at the same time.

2.4.3. Multi-unit Frequency Adjustment Factor

The methodology does not take into all accident scenarios, so there is a necessity to adjust frequencies. This is solved through the estimation of adjustment factor calculated by Eq. (3).

$$\alpha^{m} = \left(\frac{\beta \times F_{total}^{s}}{\sum_{ijk} F_{ijk}^{m}}\right) \qquad (3)$$

α^{m} means global frequency adjustment factor that can be used for all combinations of STCs. $\beta \times F_{total}^{s}$ means multi-unit accident frequency and simply estimated by multiplying single-unit core damage frequency(CDF) by β in the methodology. The reason for this assumption is that there is no integrated multi-unit Level 1 PSA model. Therefore, the average CDF of considered units was applied similarly to the methodology in this research. This is a very strong assumption and should be replaced by reasonable values in future research. Also, β should be applied differently according to each STC combination, so that more realistic evaluation would be possible.

2.4.4. Adjusted Multi-unit Accident Risks

Using the frequency adjustment factor calculated in 2.4.3., adjusted multi-unit accident risk is estimated by Eq. (4).

$$R_{ijk}^{m} = \alpha^{m} \times \left(R_{ijk}^{m}\right)_{u} \qquad (4)$$

2.4.5. Total Multi-unit Accident Risk

Total multi-unit accident risk is estimated by Eq. (5) by summing the adjusted multi-unit accident risks for each STC combination.

$$R_{total}^{m} = \sum_{ijk} R_{ijk}^{m} \qquad (5)$$

2.5 Results

Two figure of merits(FOMs) were calculated to compare the total multi-unit accident risk estimated with quantitative health objectives(QHOs) in the methodology. However, there are no official QHOs in Korea, so total multi-unit accident risk estimated was simply compared to total single-unit accident risk. The total single-unit accident risk was simply calculated by summing the risks of the Unit 1, 2, and 3. This is possible when core damage events of each unit are mutually exclusive. However, this is a very strong assumption because there is obvious dependency between each unit. More accurate total single-unit accident risk will be needed in the future research. The total multi-unit accident risk estimated in this research is the result of considering only the cascading multi-unit sequences due to the SUIs. Therefore, this research results are not total multi-unit accident risk considering all multi-unit accidents.

The MACCS was utilized to estimate conditional multi-unit accident consequences in 2.4.2. The population-weighted risks were calculated for early fatality(EF) case and latent cancer fatality(LCF) case. According to the amendment of domestic radiation Emergency Planning Zone(EPZ), the EF was calculated for 5km radius from NPP considering the Precaution Action Zone(PAZ). Also, the LCF was calculated for 30km radius from NPP considering the Urgent Protective Action Planning Zone(UPZ) [10].

Multi-unit accidents were categorized into four cases as follows.

i) Case 1: Unit 1 + Unit 2
ii) Case 2: Unit 1 + Unit 3
iii) Case 3: Unit 2 + Unit 3
iv) Case 4: Unit 1 + Unit 2 + Unit 3

Total multi-unit accident risk was estimated by including each case in several ways. The FOM was calculated by dividing total multi-unit accident risk by total single-unit accident risk and is shown in Fig. 4. The purpose of this research is not to estimate accurate risk but to study trends, so the FOM values on the y-axis are not shown.

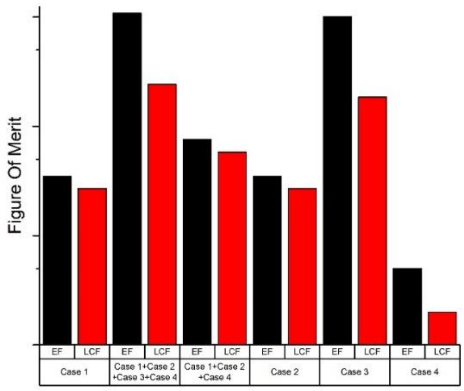

Fig. 4. Results of FOM (EF: Early Fatality, LCF: Latent Cancer Fatality)

The results of Fig. 4 show that the EF is more sensitivity than the LCF. This is because of the threshold dose in the EF. The possibility of exceeding the threshold dose increases due to the increased amount of radioactive materials in multi-unit accidents. The Case 3 also showed a great variation in the EF. This is because the thermal power of the Unit 3 and 4 is nearly twice as much as that of the Unit 1, and the amount of radioactive materials emitted is large.

The result of the Unit 3 and 4 were much greater than those of the Unit 1 comparing the calculated conditional single-unit accident consequences in the research. In addition, the ratio of total frequency of the representative STCs to the sum of all STCs for the Unit 3(or 4) was smaller than that of the Unit 1. Therefore, it was judged that the representative STCs for the Unit 3(or 4) did not sufficiently represent the other scenarios which were not considered.

3. Conclusions

The methodology was used to simply estimate multi-unit accident risk initiated from the SUIs in this research. The methodology was extended to estimate the hypothetical multi-unit site consisting of three unit with different reactor types. Therefore, a lot of factors were assumed in this research, among which very strong assumptions exist. Additionally, there are limitations in considering only internal events and not considering all possible combinations of STCs. Thus, it is difficult to conclude that the result of this research is an accurate multi-unit accident risk. However, the results of this research will contribute to establishing a developed multi-unit Level 3 PSA methodology where it is not possible to model all multi-unit accident scenarios.

Acknowledgement

This work was supported by the Nuclear Safety Research Program through the Korea Foundation Of Nuclear Safety (KOFONS), granted financial resource from the Multi-Unit Risk Research Group (MURRG), Republic of Korea (No. 1705001)

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