A Preliminary Site Risk Assessment for Multi-unit Nuclear Power Plants

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1. Introduction

Researches on multi-unit probabilistic safety assessment (MUPSA) are actively performed in the world. PSA is conventionally performed to estimate single unit risk. However, there are a lot of efforts to develop MUPSA methodology to estimate site risk after the Fukushima-Daiichi accident in 2011. MUPSA is a key element in site risk assessment because site risk consists of single unit risk and multi-unit risk. Single unit risk can be obtained by single unit PSA (i.e., SUPSA). Similarly, multi-unit risk can be obtained by MUPSA.

There is no standardized MUPSA methodology to date in the world. Therefore, this preliminary assessment was performed with reference to a lot of researches studied so far. Some parts were also developed directly during this study. One of the sites in Korea was selected as reference site shown in Fig. 1. It was assumed that the reference site has four units which are one WH600, one WH900, and two OPR1000. This study focused important issues in MUPSA models and analyses of site risk results.

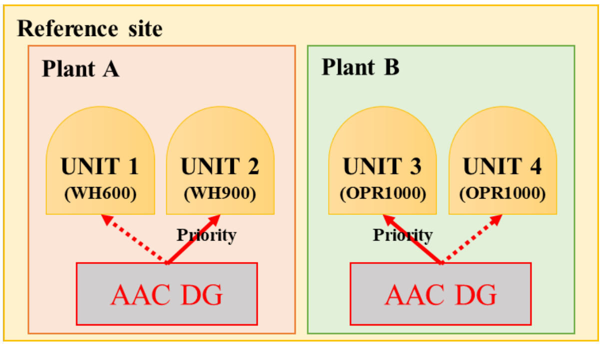

Fig. 1. Reference site with four units

2. Methodology

It is necessary to define meanings of single unit risk and multi-unit risk before detail information of the MUPSA models of this study is explained. The single unit risk means the summation of risks from accidents occurring only at one unit. The multi-unit risk means the summation of risks from accidents occurring at two or more units. This construction is used to analyze site risk, site safety goal, site QHO, etc. However, other construction is used to model single and multi-unit Level 1 PSA models. There are two types of initiating event. One is single unit initiators (SUIs), and the other is common cause initiators (CCIs) [1]. The SUIs affect only one unit, and the CCIs affect two or more units. However, core damage accident can occur in only one unit although the CCIs affect several units. This construction was utilized in single and multi-unit Level 1 PSA models. Initiating events considered in conventional Level 1 PSA, which is single unit Level 1 PSA, were assumed as the SUIs. Therefore, the CCIs were assumed as initiating events of multi-unit Level 1 PSA. These two constructions utilized in this study are shown in Fig. 2. The single unit risk from the SUIs was directly considered by already existing single unit Level 1 PSA results.

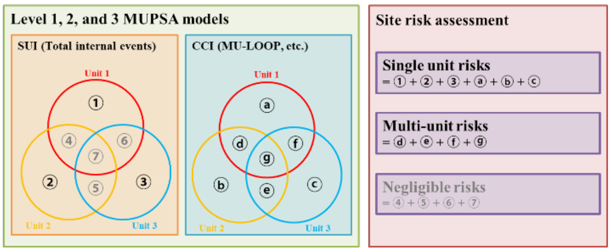

Fig. 2. Two constructions for the site risk

2.1. Multi-unit Level 1 PSA model

The following elements were considered for the multi-unit Level 1 PSA model in this study.

- Frequencies of the CCIs (MU-LOOP, MU-LOCV)
- Modeling of AAC DG sharing
- Inter unit CCF modeling
- Off-site power recovery

MU-LOOP (Multi-unit Loss Of Off-site Power) and MU-LOCV (Multi-unit Loss Of Condenser Vacuum) accidents were considered as the CCIs (multi-unit initiating events). Korea Institute of Nuclear Safety (KINS) performed investigation about multi-unit initiating events [2]. Therefore, the frequencies of MU-LOOP and MU-LOCV were obtained from Ref. 2. Also, it was assumed that the starting point of site year was the operating beginning of the first unit in the reference site.

Priority of connection order was assumed to model the AAC DG (Alternate Alternating Current Diesel Generator) sharing [3]. It was assumed that the UNIT 2 and 3 had priority of AAC DG usage by considering the locations of the AAC DGs. These are shown in Fig. 1.

Only intra unit CCF (Common Cause Failure) of same or similar SSCs was modeled in the single unit Level 1 PSA model. Therefore, inter unit CCF modeling was considered in the multi-unit Level 1 PSA model by expanding the intra unit CCF modeling. EDG (Emergency Diesel Generator), chiller, and battery were selected for the inter unit CCF modeling by using the importance analysis results of the single unit Level 1 PSA model. The inter unit CCF was modeled by using the methodology considered in Ref. 4.

In the case of MU-LOOP, the recovery of off-site power was assumed to occur simultaneously in all affected units. The re-evaluation of the probability curve for the off-site power recovery was performed using domestic experiences of MU-LOOP [5].

2.2. Multi-unit Level 2 PSA model

All dependencies between units are considered in the multi-unit Level 1 PSA model, and accident progressions of each unit are assumed to be independent. All reactor types in the reference site are pressurized water reactor (PWR), and there are few systems shared between units. Therefore, the results of the single unit Level 2 PSA model of each unit were used without additional changes. These results include PDS (Plant Damage State), CET (Containment Event Tree), DET (Decomposition Event Tree), and STC (Source Term Category). The multi-unit Level 2 PSA modeling and quantification were performed by using the mapping table methodology considered in Ref. 6.

2.3. Multi-unit Level 3 PSA model

Most inputs of the multi-unit Level 3 PSA model were obtained by considering the single unit Level 3 PSA model. The results of the research about the Level 3 PSA inputs for the reference site were applied [7]. Multi-unit accidents could be simulated in MACCS by using the 'Multi Source Term' functions. This function can consider temporal differences in the multi-unit accidents. However, spatial differences in the multi-unit accidents can not be considered due to the limitation of MACCS. The meteorological data of the reference site in 2017 was utilized. Also, site data which includes information of population, land fraction, and so on was obtained by using MSPAR-SITE [8]. The MACCS models consider emergency phase, long-term phase, and ingestion doses in this study.

Each unit has its own STC in the multi-unit accidents. Therefore, total number of STC combinations increases exponentially as the number of units increases. The biggest problem in the multi-unit Level 3 PSA modeling is that there are a lot of STC combinations between units with core damage accidents. Therefore, the grouping methodology which groups the STCs to groups (GRPs) was utilized [9]. Applying the grouping methodology reduces the total number of off-site consequence assessments because the total number of the STC combinations is much more than that of the GRP combination. This powerful effect is shown in Fig. 3. The qualitative logic tree of the grouping methodology was applied in this study. The headings of the logic tree consider two points described below.

- Amount of radioactive materials released
- Available period for performing emergency response actions

The qualitative logic tree for OPR1000 is shown in Fig. 4. Amount of radioactive materials released is considered in the first, second, and fourth heading. Available period for performing emergency response actions is considered in the third heading. In the third heading, the STCs of containment isolation system failure were assumed to go to the 'EARLY' branch. In the fourth heading, the STCs of BMT (Basemat Melt Through) and CFBRB (Containment Failure Before Reactor Breach) were assumed to go to the 'LEAK' and 'RUPTURE' branch, respectively. Compared to OPR1000, the only difference of WH600 and WH900 is the branch criteria of the fourth heading. The containment failure modes of WH600 and WH900 are not divided into 'LEAK' and 'RUPTURE'. Therefore, the STCs of containment spray system success and failure were assumed to go to the 'LEAK' and 'RUPTURE' branch, respectively. It is needed to create representative MACCS inputs of each group considering the those of the STCs assigned after the grouping task is completed. There are five methods to create the representative MACCS inputs of each group in Ref. 9. However, the most conservative inputs of the STCs assigned were selected as the representative MACCS inputs for each group. The grouping methodology introduced in Ref. 9 is still under development and has a few of limitations. Therefore, adequate modifications about the logic tree headings and the method to create the representative MACCS inputs of each group should be considered.

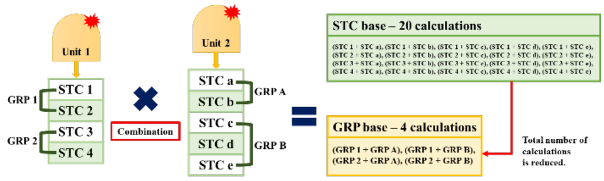

Fig. 3. Effects of the grouping methodology

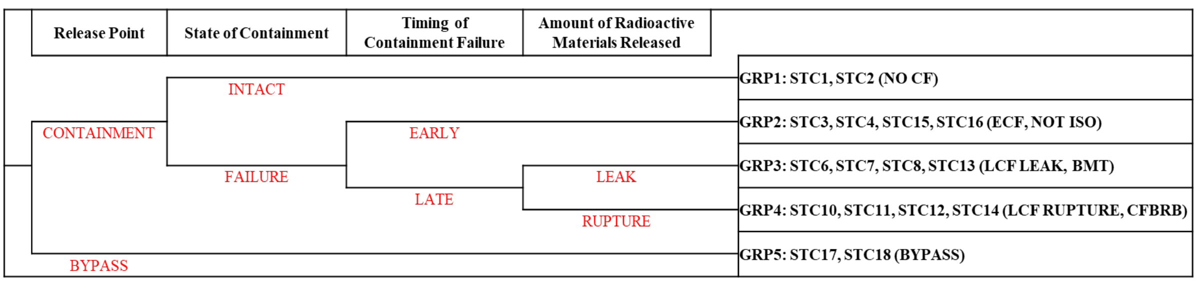

Fig. 4. Qualitative logic tree of OPR1000

3. Results and Discussions

Around 20,000 accident scenarios were resulted from the quantification of the multi-unit Level 2 PSA model based on the multi-unit Level 1 PSA model when the cut off value was 1.0E-15/yr. The total number of the STC combinations which should be calculated was around 1,400 among the total accident scenarios. However, the total number of the GRP combinations which should be calculated was around 450 by using the grouping methodology. Two types of risk were estimated which are early and latent cancer fatality individual risk. Radii of 5 and 26km were considered to estimate the early and latent cancer fatality individual risk, respectively. These radii were selected by considering PAZ (Precautionary Action Zone) and UPZ (Urgent Protective Action Planning Zone) which are utilized in domestic radioactive emergency plan.

3.1. Point estimates of the reference site risk

Point estimates of the single and multi-unit risk obtained in this study are shown in Table I. All early and latent cancer fatality individual risks in Table I are expressed as a percentage of each column summation. And, the numbers in front of MU-LOOP and MU-LOCV indicate the number of units with core damage accidents. The SUI risks were obtained in the already existing SUPSA models, and the CCI risks were obtained from the results of the MUPSA models developed in this study.

The SUI risks are dominant among the single unit risks for the early and latent cancer fatality. The CCI risks of the 1 MU-LOOP case are larger than those of the 1 MU-LOCV case. In the CCI risks of the 1 MU-LOOP case, the risks of the UNIT 3 and 4 are different although the two units are identical reactor type. The risk of the UNIT 4 are larger than that of the UNIT3 because the UNIT 3 has the priority of AAC DG connection order.

The risks of the 2 MU-LOOP case are dominant among the multi-unit risks for the early and latent cancer fatality. Accident scenarios of 3 MU-LOCV and 4 MU-LOCV were not resulted from the quantification because they had very low frequencies. Also, the frequencies of the MU-LOOP accidents were larger than those of the MU-LOCV accidents. In the risks of the 2 MU-LOOP case, the risks of the accidents with units which have same AAC DG sharing are very dominant (UNIT 1+UNIT 2 and UNIT 3+UNIT 4). If the UNIT 2 and 3 are utilizing the AAC DG, the UNIT 1 and 4 can not utilize that. Therefore, the risks of the first and last unit combination of the 2 MU-LOOP case are very high.

3.2. Risk profiles of the reference site

The early and latent cancer fatality individual risk profiles are shown in Fig. 5. Also, the risk profile of the Seabrook MUPSA results is shown in Fig. 5 for comparison [10]. The contribution of the single unit risk is dominant when the consequence (x-axis) is small. However, the contribution of the multi-unit risk increases as the consequence increases. This tendency of this study is consistent with the results of the Seabrook MUPSA.

3.3. Discussions

The trends of the frequency, consequence, and risk according to the increase of the number of units with core damage accidents are shown in Fig. 6. Both the SUI and CCI accidents are included in the 1 unit case. Summation was used for the frequency and risk, and average was used for the consequence. The fatality probabilities, which is the population weighted risk result of MACCS, were used for the consequence. The frequency decreases exponentially as the number of units with core damage accidents increases. The consequence increases weakly as the number of units with core damage accidents increases. Conclusively, the risk decreases exponentially as the number of units with core damage accidents increases. The trend of the risk is similar that of the frequency because the effect of the decrease in frequency is much greater.

Table I: Percentage results of the single and multi-unit risk

Single unit risk				Multi-unit risk			
Type	Unit	EF [%]	LF [%]	Type	Unit Combination	EF [%]	LF [%]
SUI	UNIT 1	13.65	37.37	2 MU-LOOP	UNIT 1+2	1.68	14.45
	UNIT 2	3.01	20.37		UNIT 1+3	0.01	0.02
	UNIT 3	33.04	17.26		UNIT 1+4	0.09	0.19
	UNIT 4	33.04	17.26		UNIT 2+3	0.01	0.02
1 MU-LOOP	UNIT 1	1.39	1.73		UNIT 2+4	0.09	0.18
	UNIT 2	1.13	1.68		UNIT 3+4	97.85	84.79
	UNIT 3	5.83	1.61	2 MU-LOCV	UNIT 3+4	0.25	0.32
	UNIT 4	7.36	2.09	3 MU-LOOP	UNIT 1+2+3	0.00	0.00
1 MU-LOCV	UNIT 1	0.01	0.05		UNIT 1+2+4	0.00	0.01
	UNIT 2	0.00	0.01		UNIT 1+3+4	0.01	0.01
	UNIT 3	0.79	0.29		UNIT 2+3+4	0.01	0.01
	UNIT 4	0.75	0.29	4 MU-LOOP	UNIT 1+2+3+4	0.00	0.00

*EF: Early fatality individual risk, LF: Latent cancer fatality individual risk

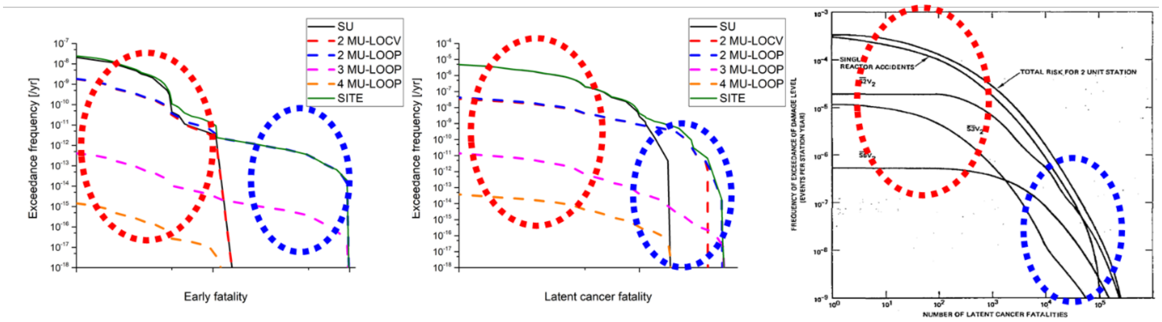

Fig. 5. Comparison of the risk profiles between this study (left and middle) and the Seabrook MUPSA (right)

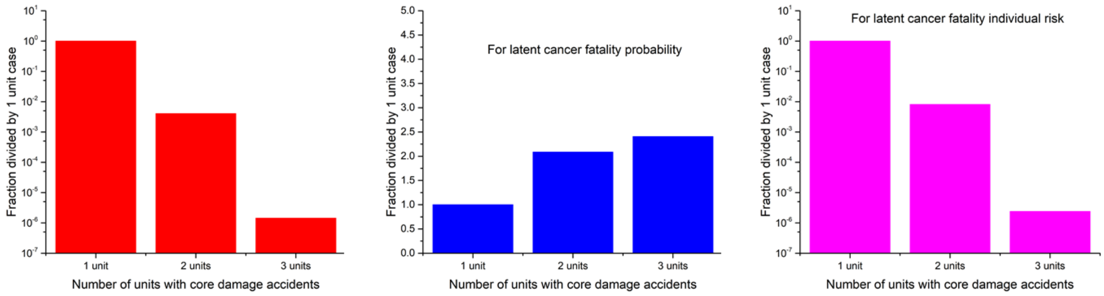

Fig. 6. Trends of the frequency (left), the consequence (middle), and the risk (right)

4. Conclusions

Preliminary site risk assessment of the reference site was performed in this study. The site risk consists of the single and multi-unit risk. Therefore, the MUPSA should be considered in the site risk assessment. MU-LOOP and MU-LOCV accident were considered as the multi-unit initiating events which are the CCIs. Priority of AAC DG connection order and inter unit CCF modeling were considered in the multi-unit Level 1 PSA models. The mapping table methodology was utilized in the multi-unit Level 2 PSA modeling. The grouping methodology was utilized in the multi-unit Level 3 PSA modeling. Based on these modeling results, all elements of the single and multi-unit risk were estimated for the site risk assessment. It was confirmed that the priority of AAC DG connection order and the inter-unit CCF modeling were important. The consistency between the results of this study and those of the Seabrook MUPSA was confirmed by comparing the risk profiles. Also, it was confirmed that the trend of the risk is very similar to that of the frequency because the decrease in the frequency is much larger than the increase in the consequence. The MUPSA methodology in this study should be further developed. However, the insights from the results of this study will contribute greatly to the development of the site risk assessment methodology.

Acknowledgement

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