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Original Article

Study on multi-unit level 3 PSA to understand a characteristics of risk in a multi-unit context

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ABSTRACT

Since the Fukushima Daiichi accident in 2011, concerns for the safety of multi-unit Nuclear Power Plant (NPP) sites have risen. This is because more than 70% of NPP sites are multi-unit sites that have two or more NPP units and a multi-unit accident occurred for the first time. After this accident, Probability Safety Assessment (PSA) has been considered in many countries as one of the tools to quantitatively assess the safety for multi-unit NPP sites. One of the biggest concerns for a multi-unit accident such as Fukushima is that the consequences (health and economic) will be significantly higher than in the case of a single-unit accident. However, many studies on multi-unit PSA have focused on Level 1 & 2 PSA, and there are many challenges in terms of public acceptance due to various speculations without an engineering background. In this study, two kinds of multi-unit Level 3 PSA for multi-unit site have been carried out. The first case was the estimation of multi-unit risk with conservative assumptions to investigate the margin between multi-unit risk and QHO, and the other was to identify the effect of time delays in releases between NPP units on the same site. Through these two kinds of assessments, we aimed at investigating the level of multi-unit risk and understanding the characteristics of risk in a multi-unit context.

1. Introduction

Since the Fukushima Daiichi accident in 2011, concerns for the safety of multi-unit Nuclear Power Plant (NPP) sites has risen. This is because more than 70% of NPP sites are multi-unit sites that have two or more NPP units, and a multi-unit accident occurred for the first time. After this accident, Probability Safety Assessment (PSA) was considered in many countries as one of the tools to quantitatively assess the safety for multi-unit NPP sites. However, there is no systematic methodology for multi-unit NPP sites, as the technical improvements in the PSA area have been carried out on single units. Accordingly, many research projects are being carried out in the IAEA and OECD/NEA as well as many countries operating NPPs. In South Korea, in particular, public concerns for the safety of NPP sites is relatively high. This is because Korea has four NPP sites, and each site has more than six units that are operating or under construction. Also, one of the fundamental reasons for this concern is that the population density around the NPP site is higher than that of other countries by Korea's geographical characteristics. Upon this background, Korean utilities, government, and research institutes, as in other countries, are considering PSA as one of the tools to address safety-related issues on NPP sites, and are carrying out research projects to develop a methodology for a multi-unit PSA.

The biggest concern regarding a multi-unit accident, such as Fukushima, is that the consequences (health or economic) caused by such an accident will be significantly higher than in the case of a single-unit accident. However, in terms of the risk expressed by multiplication of frequency and consequences as given by the following equation, it is not appropriate to judge safety only by its consequences.

$$Risk = Probability(or\ \ Freqeuncy) \times \ \ Consequence$$

Currently, there are many challenges in terms of public acceptance due to various speculations without an engineering background despite that safety-related research for multi-unit sites is being carried out. For this reason, we performed two kinds of multi-unit Level 3 PSA for a multi-unit site. The first case was the estimation of multi-unit risk to investigate the margin between multi-unit risk and QHO. For this, we evaluated the consequences of a

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reference site that has nine NPP units and ultimately estimated multi-unit risk using the results of a Level 3 PSA. The other case was to identify the effect of time delays in releases between NPP units on the same site. If the amount of release to the environment increases, risk also increases due to the increase of exposure. Moreover, if it is released simultaneously from all units, the situation is expected to be more serious. On the other hand, if there is a delay time between the releases of each unit, the consequences may be lower than that of simultaneous release because there is potential to decrease the total exposure to the public. We therefore performed a multi-unit Level 3 PSA considering the release time delays between two NPP units. Through these two kinds of assessments, we aimed at investigating the level of multi-unit risk and understanding characteristics of risk in a multi-unit context.

1.1. Multi-unit PSA in South Korea

The Fukushima accident has caused many changes in the safety assessment area for NPPs. In the PSA area, there are also many discussions on the methodology, scope, and so on. The existing PSA (or single-unit PSA) identifies initiating events that may occur, and performs an assessment for identified initiating events for a single-unit NPP. This is carried out based on the assumption that other units around the target unit are safe. Through the Fukushima accident, however, it was shown that multi-units on the same site can be affected by a single hazard, and the need to develop a methodology considering multi-unit accidents was highlighted. PSA for a multi-unit accident (or multi-unit NPP site) has been carried out on a limited basis before the Fukushima accident. However, it did not receive much attention because of its low frequency and lack of realism. For this reason, the maturity of the technique for a multi-unit PSA is lower than that of the existing PSA for single units and many research projects are actively being carried out in the world.

In the case of Korea, more than six units have been operated on the same site due to the geographical characteristics. Table 1 shows the status of operation and construction units of each site. In the case of the Kori site, a maximum of nine units will be operated on the same site after the completion of the construction for new units. Since the number of units on a single site is higher than that of other countries, concerns about multi-unit accidents are rising steadily.

The first research project related with a multi-unit PSA in Korea was performed by KAERI from 2012 to 2017. This project included the development of a multi-unit PSA methodology and application to a pilot site that has six identical units [1–3]. Currently, KAERI has carried out a follow-up project to improve the methodology. In 2016, KHNP has launched a multi-unit PSA project aimed at the development of a methodology and applied it to a pilot site that has nine NPP units because the safety of the NPP site was raised as one of the important issues during the license process for newly built units. KHNP project consists of two phases, first phase so called preliminary phase was done in June 2018 [4–6]. The final phase will be finished by June 2020. A preliminary phase focused on developing an overall framework for a multi-unit PSA and a model integrating nine units on the pilot site, and Table 2 shows the scope of the KHNP project.

Table 1
Status of NPP sites in Korea.

Site	Number of units			
	Operation	Under Construction	Plan	Total
Kori	7	1	2	10
Hanul	6	2	2	10
Hanbit	6	–	–	6
Wolsung	6	–	–	6

2. Development of multi-unit level 3 PSA models

In this chapter, we describe considerations and assumptions used in the development of multi-unit Level 3 PSA models. For performing the Level 3 PSA, we used MACCS 2 code developed by U.S. NRC [7], and developed two multi-unit Level 3 PSA models. The first model (Case 1) is for estimating multi-unit risk, and the other (Case 2) is for evaluating the effect of release time delay between NPP units. In addition, each model has a sub-model for sensitivity study to investigate the effect of the radiological emergency response plan such as evacuation. To use multi-unit core damage frequencies of the KHNP project for estimating multi-unit risk, we assumed a reference site that has nine NPP units. As for the base input of MACCS2, we used *Appendix C* of NUREG/CR-6613[7]. In addition, site-specific data such as population and weather was developed based on the reference site.

2.1. Source term category for generating multi-unit STC

One of the important technical issues for performing a multi-unit PSA is the exponential increase in the number of combinations of accidents as the number of units rises. This is the same for source term evaluation. Even if the same type of nuclear power plants are located at the same site, there are various combinations of source terms. Furthermore, in the case of actual sites considered in the KHNP project, the number of combinations will increase further because there are three types of NPP. For this reason, a multi-unit Level 3 PSA considering all these combinations is expected to have many limitations at the current technology level. In this study, we assumed the same Source Term Category (STC) in all of the units. In other words, the same inventory and release to the environment were assumed regardless of the reactor types and actual core inventories. In MACCS2 code, we modeled the multiple STC by modifying the total core inventory and release fraction of radioactive materials to the environment. If there are n units on the same site, the total inventory of n units will be modified by a scaling factor of MACC2 code and the release fraction will be expressed by multiplying the release fraction of a single unit by the number of damaged units divided by the total number of units in the site. In the case of the NPP site considered in this study, nine times the inventory of APR-1400 was modeled as the total inventory, and releases of multiple units were modeled by multiplying 2/9, 3/9, …, 9/9 by the release fraction of STC that was assumed as the representative STC. For conservative assessment, we used early containment failure sequence as representative STC.

2.2. Modeling of radiation emergency plan in multi-unit level 3 PSA

2.2.1. Radiological emergency response plan of reference site

The Radiological Emergency Planning Zone (EPZ) can be defined as an area that establishes the proactive actions such as sheltering and evacuation for the public in the event of a NPP accident. Generally, the EPZ is classified into the Precautionary Action Zone (PAZ) and the Urgent Protective action planning Zone (UPZ). IAEA defines the PAZ as 3 ~ 5 km and UPZ as 20–30 km, and recommends that they be flexibly scoped according to the state of each country such as the characteristics of the facilities and geographical conditions. Table 3 shows the status of the PAZ and UPZ. In the case of Korea, the PAZ is within 3~5 km, and the UPZ is within 20–30 km. The PAZ is the area within which arrangements should be made to implement precautionary urgent protective actions before or shortly after a major release with the aim of preventing or reducing

Table 2
Scope of KHNP multi-unit PSA research project.

Operating Mode	Multi-Unit Initiators	Estimating Methods of IEF	Scope of PSA
All Operating Modes	Loss of Off-site Power (due to typhoon, heavy snow) General Transient (due to typhoon, lightning, sharing system) Loss of Circulating Water (due to marine lives)	Based on Operating Experiences	Level 1 (Core Damage Frequency) & Level 2 (Large Early Release Frequency)
	Seismic Event	Based on Hazard Analysis	

Table 3
Status of radiological emergency planning zone.

Country	PAZ (km)	UPZ (km)
USA	3.2–8	16
France	5	10
China	3–5	7–10
Korea	3–5	20–30
Japan	5	30
IAEA	3–5	5–30

the occurrence of severe deterministic effects. The UPZ is area where preparations are made to promptly shelter or evacuate in place, and urgent protective actions are implemented based on the basis of the results of monitoring within a few hours following a release [8].

Radiological emergency alarm of Korea is divided into three levels: facility (white), site area (blue), and general (red). Protective actions for the public are actively started with a general alarm. When a general alarm goes off, local governments implement actions to protect the public. These activities are differently carried out in the PAZ and UPZ. In case of the PAZ, all public inside the PAZ evacuate to the outside of the EPZ (20–30 km) with a general alarm. On the other hand, the protective actions from the outside of the PAZ to the inside of the UPZ are differently implemented depending on the expected dose in each sector of the UPZ. In the initial phase of a general alarm, the expected dose of each sector inside the UPZ is estimated using computer code. Using these results, protective actions such as sheltering or evacuation for the public are decided according to the basis shown in Table 4. That is, if the expected dose of a certain sector is estimated from 10 mSv to 50 mSv, sheltering will be recommended to the public in that sector. If the dose in sectors is expected to exceed 50 mSv, the public in those sectors will evacuate to the outside of the UPZ. Fig. 1 briefly summarizes the radiological emergency response plan of the reference site.

2.2.2. Modeling approaches of radiological emergency response plan

It is difficult to model the radiological emergency response plan of the reference site using the modeling functions for the radiological emergency response in MACCS2 code because MACCS2 code was developed based on the characteristics of U.S. NPPs. In response, we modeled protective actions at the level applicable to MACCS2 code. As mentioned above, when a general alarm goes off, people living within the PAZ immediately evacuate to the outside of the EPZ and people who live within the UPZ conditionally evacuate if the dose is expected to exceed 50 mSv. To simulate this, we used dose-dependent relocation, which is one of the MACCS2 functions. For this function, if the dose in the region exceeds the user-defined relocation threshold dose, the people in that region will be relocated at the time entered by users after the first plume arrives at that distance. Using this function, we developed base models for two cases, and the dose criterion was set to 50 mSv according to Table 4. It is noted that the relocation function we used in MACCS2 code was used to roughly model the evacuation and is different from the definition of relocation in Table 4. The time needed to evacuation was assumed as 3 h. Dose-dependent relocation used in the base model is operated by the arrival of a plume regardless of release timing of radioactive material and alarm time. This is different from the actual emergency response plan, and it will produce relatively conservative results. Therefore, in the sub-model for the sensitivity study, we modeled immediate evacuation within the PAZ according to the emergency response plan. To apply it to the Level 3 PSA model, it is necessary to consider various information such as release timing of radioactive material to the environment, alarm time point, evacuation preparation time, and so on. This information can be defined from Level 2 PSA results and the emergency response plan of the reference site. While there is clear information, there is also information that must be assumed. In the case of the alarm time point, various conditions to issue the alarms have to be satisfied. However, it is difficult to estimate the time for all conditions from the results of Level 1 and 2 PSA, although it is possible to estimate the time satisfying some conditions related with the reactor core from a thermo-hydraulic analysis for an accident sequence. We hence assumed the accident scenario including large early release. In PSA Application Guide [9], "Early" was defined as 4 h after the failure of reactor vessel. For a conservative assessment, we assumed 4 h after an occurrence of initiating event. Assumptions and considerations used in the sub-model are as follows.

- General alarm time point: we conservatively assumed 1 h after an initiating event based on the conditions to issue the alarms in radiological emergency response plan.
- Delay time of the recommendation for protective actions to the public: if a general alarm goes off, local government recommends protective actions such as sheltering and evacuation to the public. The emergency response plan of the reference site specifies a delay time between a general alarm and the recommendation for the protective actions as a maximum of 15 min.
- Start time of protective actions: we assumed 1.25 h (1 h +15 min) after an initiating event.

Table 4
Protection actions by dose in Korea.

Protective Action	Generic Intervention Level	Remarks
Sheltering	10 mSv	No more than 2 days
Evacuation	50 mSv	No more than 1 week
Distribution of medicines for protecting the thyroid gland	100 mGy	
Temporary relocation	30 mSv in first month 10 mSv in a subsequent month	1 month is assumed to be 30 days
Permanent resettlement	1 Sv in Lifetime	Lifetime is assumed to be 70 years

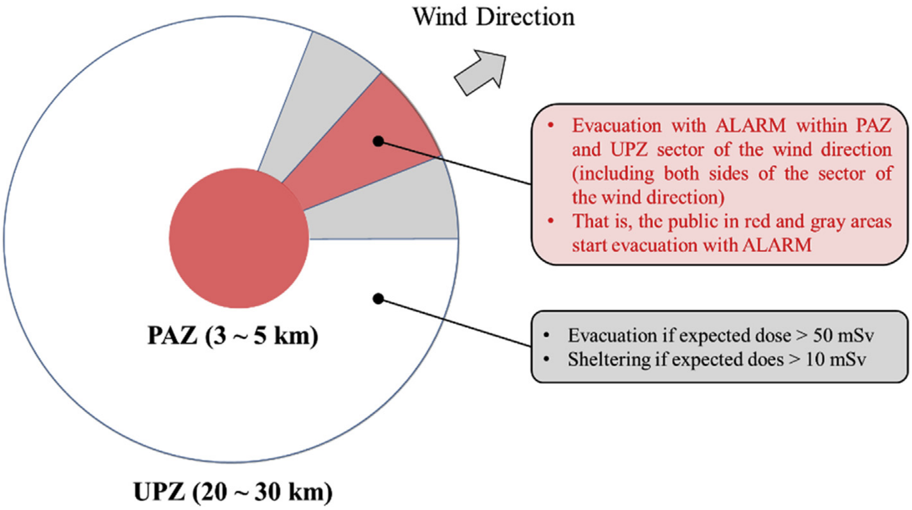

Fig. 1. Radioactive emergency response plan by dose.

- Evacuation preparation time: this means the time required to initiate actual movement to the outside of the EPZ after the evacuation recommendation. An ETE report published by KHNP Central Research Institute (CRI) [10] estimated the evacuation preparation time from 15 min to 2 h. In this study, we assumed 2 h conservatively.

Fig. 2 shows the main time point of the accident sequence and radiological emergency plan applied to the sub-model.

In the sub-model, we assumed two public categories within the PAZ based on Appendix C of [7]. The first is the group who is evacuating outside the EPZ according to the evacuation recommendation from local government and they are assumed as 95% of the total population. The other is the group who does not respond to the evacuation recommendation and they are assumed as 5% of the total population inside the PAZ. Fig. 3 shows the pattern of protective actions within the PAZ and UPZ in the sub-model for the sensitivity study.

2.2.3. Multi-unit level 3 PSA model considering release time delay

Health effects (or consequences) increase depending on exposure of an individual by the release of radioactive materials. In a multi-unit accident, there is a possibility to have significant differences in exposure of individuals depending on the simultaneous release or delayed release. For a simple example, assuming releases from two units, if the second unit releases radioactive materials to the environment 6 h later after the first release, exposure may vary due to changes in wind direction between the first and second release. However, it is difficult to consider such delay time due to the characteristics of the PSA producing an annual average as a result. That is, core damage and release in multiple units are assessed to occur at the same time if a failure of the same equipment or operator actions occur by the same multi-unit initiating events. In an actual situation, however, there are differences in the accident progression time although the accident sequence in the PSA is the same with the failure of safety systems and operator actions. In particular, failure to run is one of the main elements to cause a time interval of accident sequences between multiple units. For example, there is a cooling pump that must be operated for 24 h to mitigate core damage in the PSA model. If a multi-unit initiating event occurs at two identical units (unit A and B), cooling pumps of both units can fail after 10 h and 5 h operation, respectively. In this case, if it is assumed that accident progressions to containment failure are the same in both units, there is a 5 h difference between the release time points of both units. In addition, the phenomena of a severe accident after core damage have many uncertainties. Even if the same severe accident phenomena such as hydrogen explosion occur at multiple units, the time and progression duration of the phenomena may not be the same. Given all of these considerations, there may be differences in the release timing of each unit to the

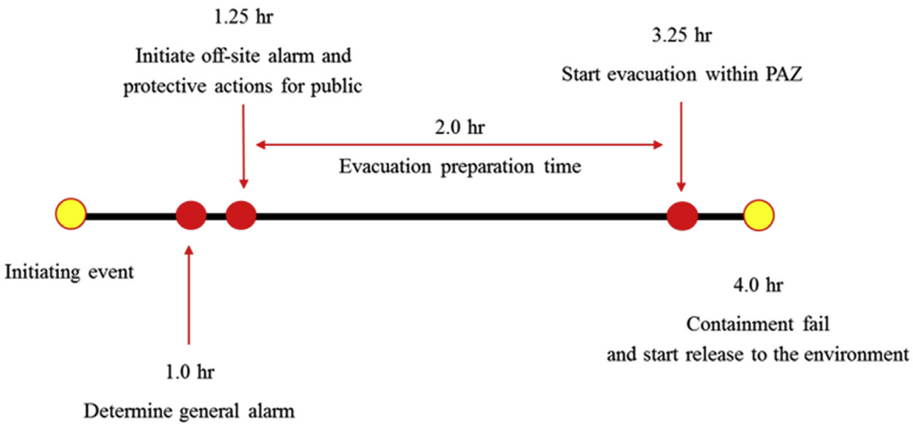

Fig. 2. Time point of accident sequence with radiological emergency response plan.

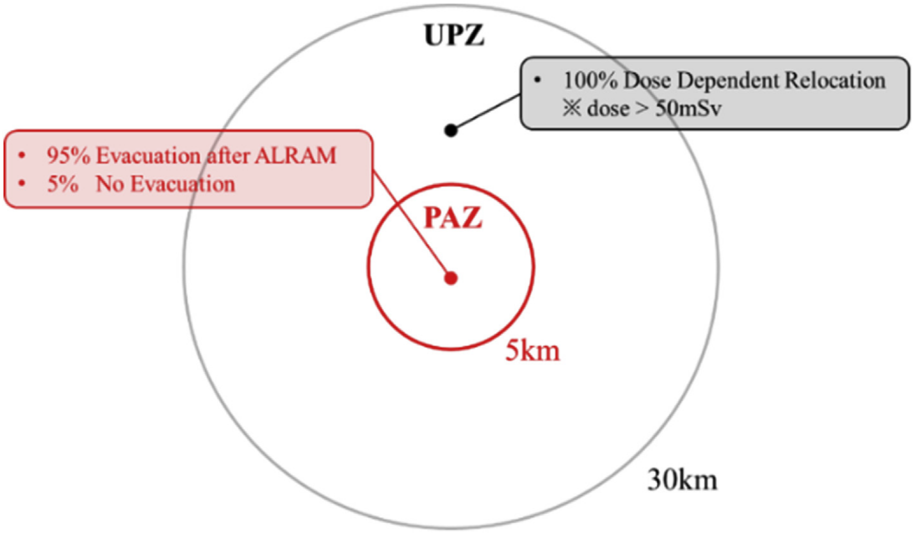

Fig. 3. Protective actions within PAZ and UPZ in sub-model for sensitivity study.

environment. As mentioned above, it is difficult to determine the time interval between units in the current PSA practice. We therefore assumed two identical units and considered the release time interval between the first release and the next release as 2, 4, 6, 12, and 24 h. Fig. 4 shows the time table of the sub-model for assessing the effect of the release time interval.

3. Results

3.1. Results of multi-unit risk assessment

In this assessment, we considered nine NPP units and assessed two models, as mentioned in chapter 3. Individual early fatality risk within 1 mile of the NPP site boundary and individual latent cancer fatality risk within 10 miles were estimated. Assuming that all units had the same source term category regardless of reactor types, as mentioned in section 3.1, we do not perform an additional multi-unit Level 2 PSA to produce multi-unit STC and its frequencies. We thus conservatively assumed that containment failure occurs if core damage occurs. That is, the release frequency of a multi-unit STC is the same as the core damage frequency. We used the preliminary results of the KHNP multi-unit project for multi-unit LOOP as the frequency of the multi-unit STC, and detailed information such as methodology and assumptions used in the KHNP project can be found in our previous studies [4–6]. Figs. 5 and 6 show the results of the multi-unit risk assessment. The red line in each figure denotes Quantitative Health Objectives (QHO) requirements established by NRC [11]. Despite conservative assumptions that the frequency of the multi-unit STC was equal to that of multi-unit core damage, the results were assessed to meet QHO requirements. Latent cancer fatality risk has a sufficient margin for the QHO requirement, while early fatality risk has a relatively small margin. Considering that many core damage sequences progress to No Containment Failure (NOCF) sequence in the actual Level 2 PSA, margins between multi-unit risk and QHO will increase significantly if the release frequencies of the multi-unit STC are properly evaluated by the multi-unit Level 2 PSA.

3.2. Results of multi-unit level 3 PSA considering the release time delay

Figs. 7 and 8 show results of population weighted individual early fatality risk within 1 mile of the NPP site boundary and latent cancer fatality risk within 10 miles of the NPP site boundary. Early fatality risk decreased by about 50% even if the time delay was only 2 h. At 2 h delay, latent cancer fatality was equal to or increased

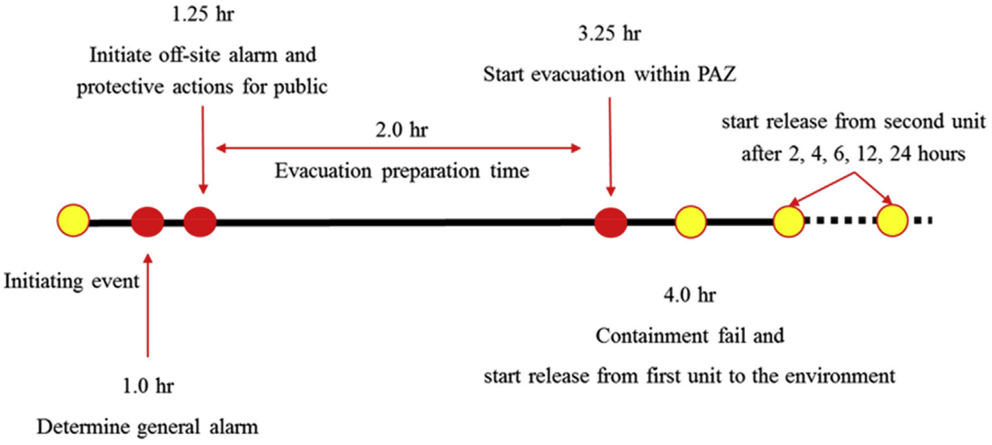

Fig. 4. Time point of accident sequence with release time interval.

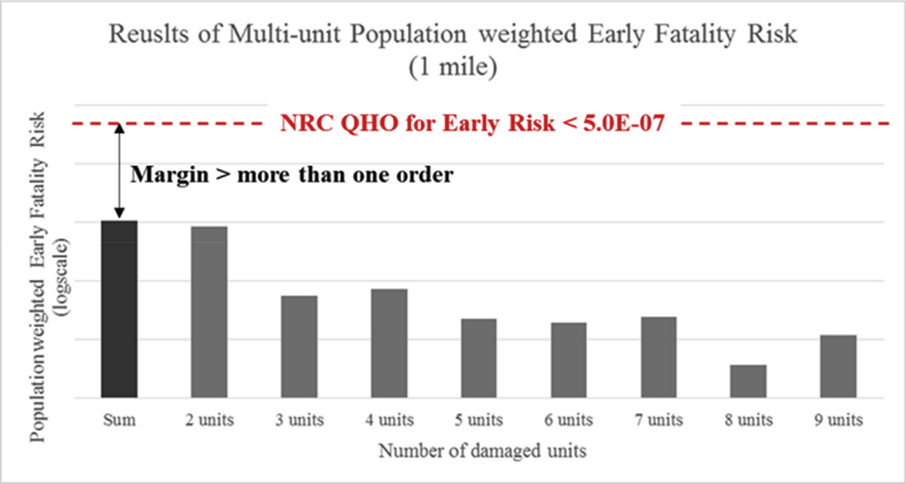

Fig. 5. Multi-unit individual early fatality risk (1 mile).

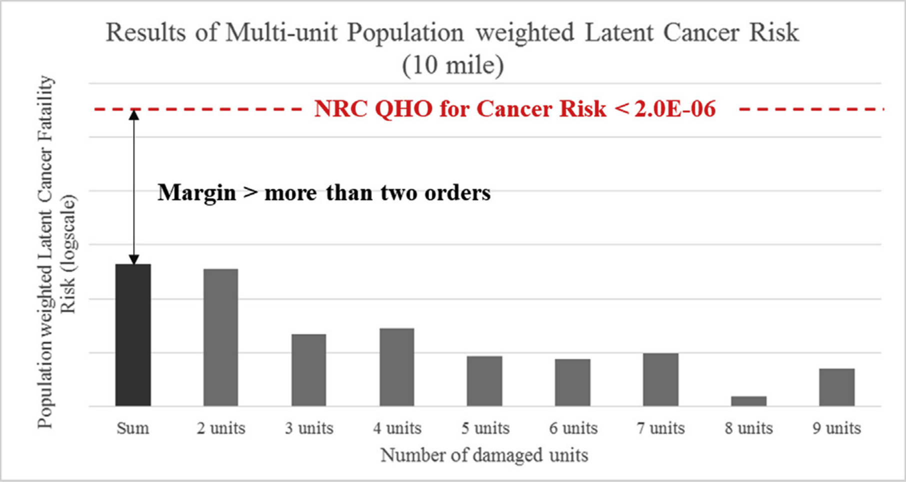

Fig. 6. Multi-unit individual latent cancer fatality risk (10 miles).

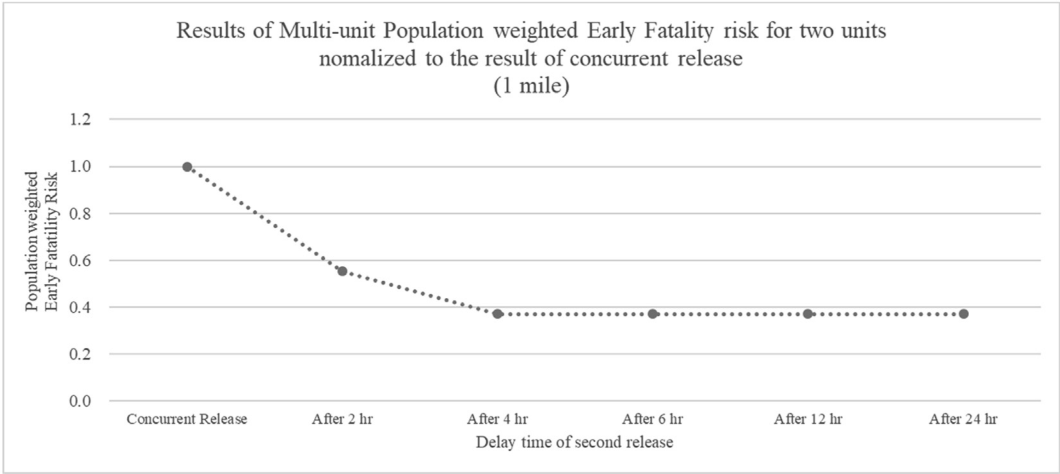

Fig. 7. Consequences of individual early fatality considering release time delay.

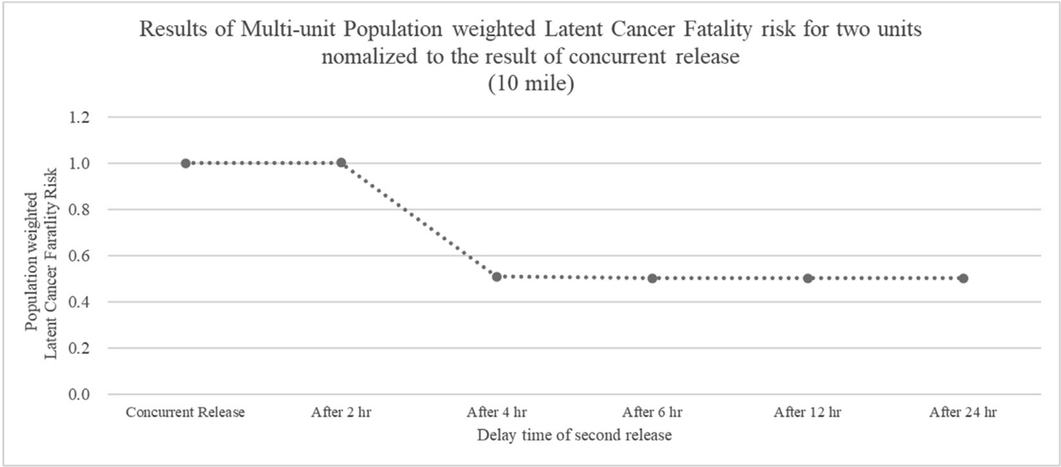

Fig. 8. Consequences of individual latent cancer fatality considering release time delay.

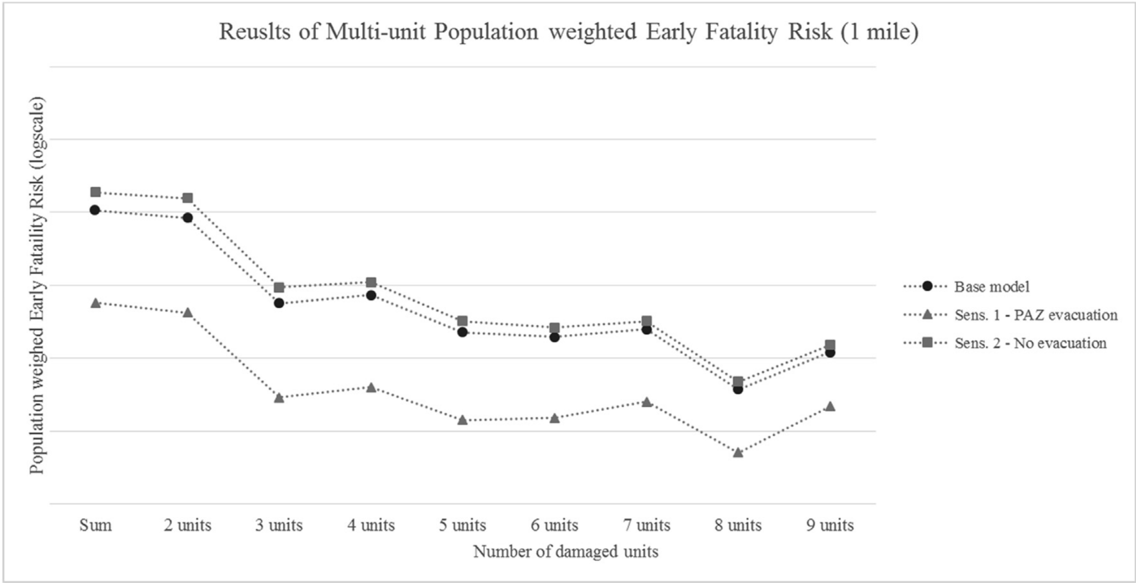

Fig. 9. Results of sensitivity study – multi-unit individual early fatality risk (1 mile).

compared to concurrent release. This is because cancer fatality increased due to the change of wind direction and the decrease of exposure by conducting relocation. As mentioned in section 3.2, we used dose-dependent relocation to model the evacuation. In this study, the delay time (delay time here means that the public in a region where a radiological plume has arrived is not exposed to radioactive materials after this duration) for evacuation after the arrival of the radioactive plume was assumed to be 3 h. This reduced the exposure from the second release compared to that of concurrent release and ultimately reduced exposure to below the threshold dose resulting in early fatality. This is the reason that the result was equal to or increased at 2 h delay. All consequences of both early and latent cancer fatality were the same from 4 h delay. The reason for this is similar to the explanation of the result of 2 h delay. As mentioned above, in code calculation, it is assumed that all the public exposed to first release have completed relocation to the outside EPZ after 3 h. This means that the second release after 4 h does not affect the public in terms of risk. It is noted that results can be different depending on the delay time for evacuation.

3.3. *Results of sensitivity study*

A sensitivity study was performed to investigate the effects of protective actions for the public. We developed two kinds of models for the sensitivity study. The first (Sensitivity 1) considers immediate evacuation within the PAZ, as mentioned in 3.2.2, and the other (Sensitivity 2) considers no protective actions. Figs. 9 and 10 show a comparison of Case 1 between the base model and sensitivity models. Insights from the sensitivity study for Case 1 are as follows.

- Early fatality risk in Sensitivity 1 model was reduced more than one order compared to that of the base model. This is because the exposure of the public from the radioactive plume decreased significantly in the early stages of the accident by conducting immediate evacuation.
- In the Sensitivity 1 model, we applied immediate evacuation to the public who lives within 0 km–5 km, and this led to a reduction in the result for latent cancer fatality risk. However, the population within PAZ was relatively small compared to the

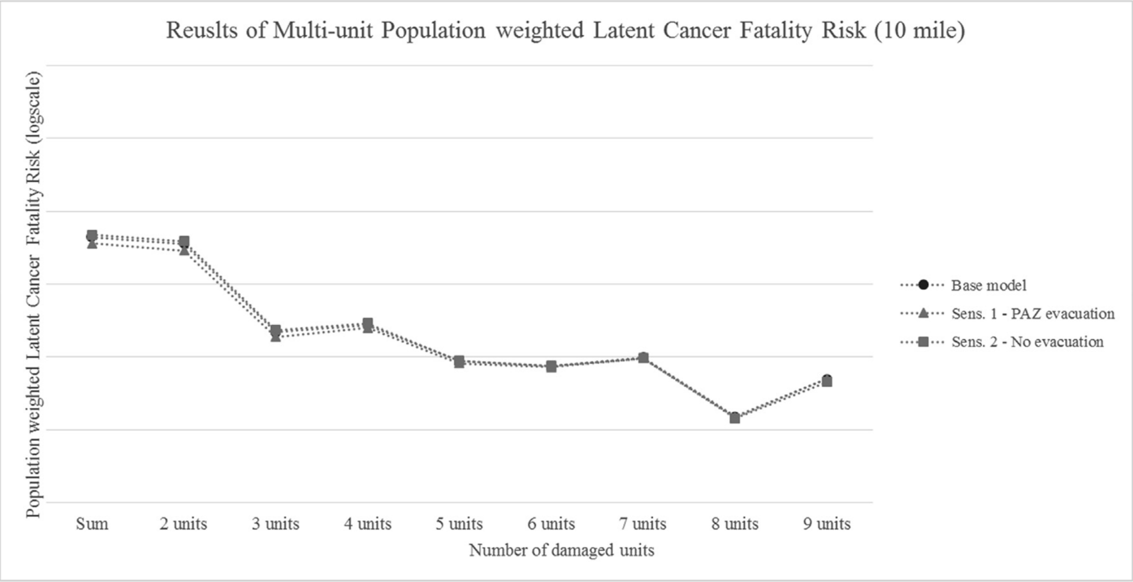

Fig. 10. Results of sensitivity study – multi-unit individual latent cancer fatality risk (10 miles).

total population considered in the calculation for latent cancer fatality risk. Therefore, immediate evacuation within the PAZ did not have a significant impact on the results of latent cancer fatality risk for the public who live within 10 miles (approximately 16 km).

- In the case of the Sensitivity 2 model, the results of both early and latent cancer fatality risk increase slightly compared to that of the base model. This means that the protective action modeled in the base model was conservative.

Figs. 11 and 12 show a comparison of Case 2 between the base model and sensitivity models. Insights from the sensitivity study for Case 2 are as follows.

- Similar with Case 1, the results of the sensitivity 1 model for both early fatality and latent cancer fatality decreased compared with that of the base model. In particular, consequences of early fatality were greatly reduced.
- In the case of the sensitivity 2 model, results of several delay times increased compared to that of concurrent release. This resulted from a change in wind direction between the first and second release. Because the sensitivity 2 model does not consider protective actions such as evacuation, the public around the NPP site remains in their homes or companies even if an accident occurs. As such, changes in wind direction could result in an increase in the population exposed to the radioactive plume in areas larger than that of concurrent release.
- However, delayed release of the sensitivity 2 model does not cause an increase in consequences in some cases. This is dependent on the population in the area affected by the second release.

4. Conclusions and discussions

4.1. Conclusions

In this study, we performed a multi-unit Level 3 PSA for a reference site that has nine NPP units and ultimately estimated multi-unit risk. In addition, the effect of the release time interval between NPP units on the same site was also investigated. It is

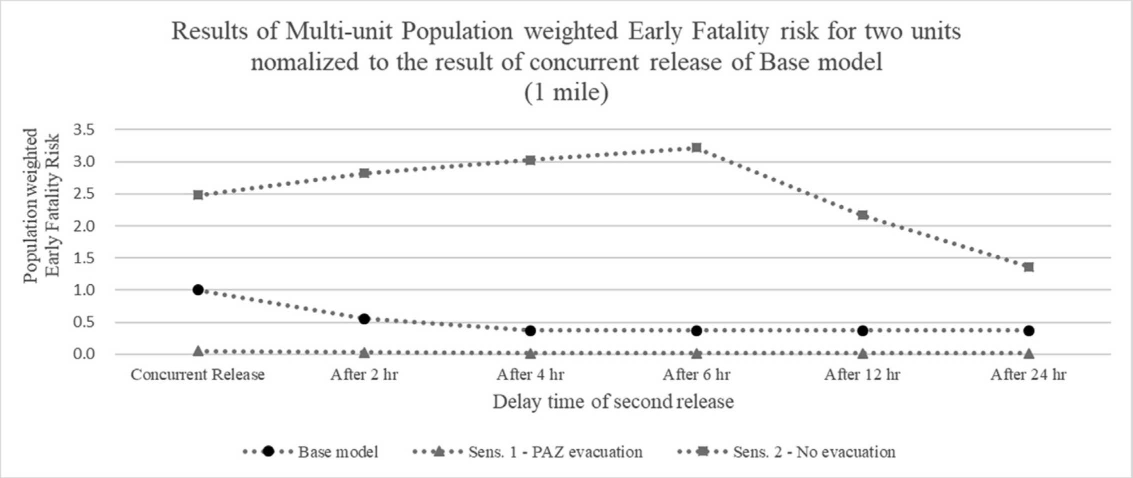

Fig. 11. Results of sensitivity study – multi-unit individual early fatality risk (1 mile) for two units.

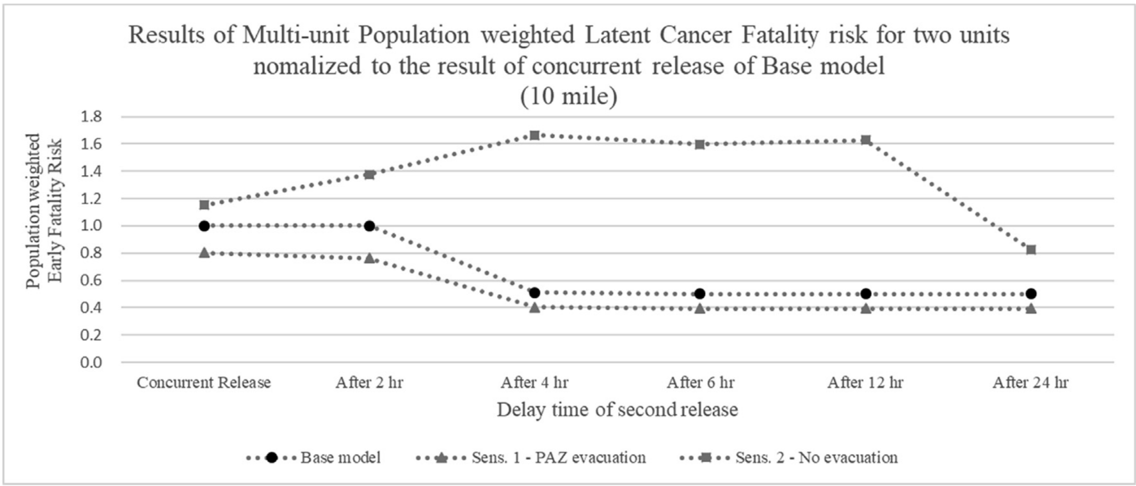

Fig. 12. Results of sensitivity study – multi-unit individual latent cancer fatality risk (10 miles) for two units.

noted that this study was carried out to identify the characteristics of the Level 3 PSA in terms of a multi-unit context and is not an assessment of an actual site in Korea.

The insights from this study are summarized as follows:

- Although many conservative assumptions have been used to estimate multi-unit risk, there is a sufficient margin between multi-unit risk and QHO. This is because the consequences of a multi-unit accident are larger than those of a single unit accident but their frequencies are relatively low.
- If a delay time between releases of radioactive materials to the environment of damaged units exists, there is a possibility that the consequences will be reduced compared to that of concurrent release. This is dependent on the radiological emergency response plan.
- If protective actions such as evacuation of the public near the NPP are properly carried out in the early stage of the accident, consequences can be significantly reduced, particularly the consequence of early fatality.

4.2. Limitations and further study

The multi-unit Level 3 PSA in this study was carried out with limited information such as multi-unit STCs and its frequencies as studies on multi-unit PSA are currently being conducted. A number of conservative assumptions were hence used as mentioned above. The limitations that should be addressed in further studies are as follows.

- In this study, the results do not cover all STC combinations of accident sequences because we did not perform a multi-unit Level 2 PSA. This may overestimate or underestimate the consequences.
- Frequency of multi-unit STC was assumed to be the same with multi-unit core damage frequency. Generally, the portion of early release sequences has less than 10% of a core damage sequence, and most core damage sequences progress to a no containment sequence. If the frequencies of a multi-unit STC are properly evaluated, multi-unit risk will be decreased because the representative STC used in this study is one of the early release sequences.
- The release point of multi-unit STC was assumed to be in a single point. In the case of the reference site, the distance between the first unit and last unit is more 2 km. If multiple release points are modeled, the consequences will be changed.
- Many assumptions to model protective actions for the public, including evacuation pathway, time point of alarm, and so on, were used

In addition to the limitations mentioned above, there are many others. To resolve these limitations, many studies should be carried out in the future.

Declaration of competing interest

All authors declare there is no conflicts of interest.

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