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Multi-unit risk assessment of nuclear power plants: Current status and issues

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ABSTRACT

After the Fukushima-Daiichi accident in 2011, the multi-unit risk, i.e., the risk due to several nuclear power plants (NPPs) in a site has become an important issue in several countries such as Korea, Canada, and China. However, the multi-unit risk has been discussed for a long time in the nuclear community before the Fukushima-Daiichi nuclear accident occurred. The regulatory authorities around the world and the international organizations had proposed requirements or guidelines to reduce the multi-unit risk. The concerns regarding the multi-unit risk can be summarized in the following three questions:

How much the accident of an NPP in a site affects the safety of other NPPs in the same site?

What is the total risk of a site with many NPPs?

Will the risk of the simultaneous accidents at several NPPs in a site such as the Fukushima Daiichi accident be low enough?

The multi-unit risk assessment (MURA) in an integrated framework is a practical approach to obtain the answers for the above questions. Even though there were few studies to assess the multi-unit risk before the Fukushima-Daiichi nuclear accident, there are still several issues to be resolved to perform the complete MURA. This article aims to provide an overview of the multi-unit risk issues and its assessment. We discuss the several critical issues in the current MURA to get useful insights regarding the multi-unit risk with the current state art of probabilistic safety assessment (PSA) technologies. Also, the qualitative answers for the above questions are addressed.

1. Introduction

On 11 March 2011, the Tohoku earthquake resulted in the loss of off-site power at the Fukushima-Daiichi site. All operating nuclear power plants (NPPs) in the site were shut down successfully and in the safe states as the safety systems of NPPs such as emergency diesel generators operated as designed. However, the following tsunami caused by the earthquake hit the Fukushima-Daiichi site and several NPPs in the site suffered from the station blackout. Finally, core melt occurred in three NPPs of the site (i.e., Units 1, 2 and 3), resulting in significant releases of radioactive materials into the surrounding environment.

The Fukushima-Daiichi accident is the first incident that severe accidents occurred simultaneously at several NPPs in a site, i.e., the multi-unit accident. After the Fukushima-Daiichi nuclear accident, the multi-unit risk, i.e., the risk due to multiple nuclear power plants (NPPs) in a site has become a critical issue in several countries such as Korea, Canada, China, etc. since those countries have sites with many NPPs and/or the NPPs that share the critical safety systems.

The Fukushima-Daiichi accident shows several important aspects related to the multi-unit risk, e.g., common cause initiators such as earthquake and tsunami, the interactions between NPPs in a site during accident progression [1]. Specific examples of observation are:

- The accident management framework for multi-unit accidents did not exist.
- The hydrogen explosion at Unit 1 delayed the power recovery of the adjacent Unit 2.
- The hydrogen explosion at Unit 4 was due to the hydrogen gas generated in Unit 3.

The multi-unit risk has been addressed for a long time in the nuclear community even before the Fukushima-Daiichi accident occurred. The regulatory authorities of several countries and the

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international organizations proposed requirements or guidelines to reduce the multi-unit risk. The conceptual diagram in Fig. 1 illustrates the possible results of multi-unit accidents in a site with three NPPs, Unit 1, 2 and 3. Three regions (A_1, A_2, A_3) represent the accident in each NPP, another three regions (A_{12}, A_{23}, A_{13}) represent the simultaneous accidents of two NPPs, and one region (A_{123}) represents the simultaneous accidents of all three NPPs.

The Nuclear Regulatory Commission (NRC) of the U.S.A. classifies multi-unit accidents sequences caused by single unit initiators into three sequences: restricted, cascading and propagating sequences [2]. The restricted sequences represent the sequences where the initiating events of an NPP caused a severe accident at that NPP only. The cascading sequences represent the accident sequences of an NPP that causes the severe accidents of that NPP and other NPPs in the same site, while the propagating sequences represent the accident sequences of an NPP that do not cause the severe accident of that NPP but cause the severe accidents of other NPPs. These three types of sequences make the multi-unit risk issues more complex since the cause and consequence of the accidents are not limited to a specific NPP. The cascading and propagating sequence of accidents may potentially lead to any consequences illustrated in the diagram of Fig. 1. That is, for example, an accident in Unit 1 may result in any of A_1, A_2, A_3, A_{12}, A_{23}, A_{13} or A_{123}. Furthermore, the accident progression of multi-unit accidents is significantly affected by various conditions such as the design, the staffing, the location of the site, the arrangement of units, and the population characteristics around the site.

The concerns regarding the multi-unit risk can be summarized in the following three questions:

- How much the accident of an NPP in a site affects the safety of other NPPs in the same site?
- What is the total risk of a site with many NPPs
- Will the risks of the simultaneous accidents at several NPPs in a site such as the Fukushima-Daiichi accident be low enough?

Three questions are interconnected with each other very closely. The multi-unit risk assessment (MURA) in an integrated framework is a practical approach to obtain the answers to the above questions. Even though there were several studies to assess the multi-unit risk before the Fukushima-Daiichi nuclear accident, there are still several issues to be resolved to perform the MURA completely. This article aims to provide an overview of the multi-unit risk issues and the MURA. The several critical problems in the current MURA are discussed to get useful insights regarding the multi-unit risk issue with the current state art of probabilistic safety assessment (PSA) technologies. Also, the qualitative answers for the above questions are addressed.

2. Overview of multi-unit risk issues

The multi-unit risk issues are not new ones, and the nuclear communities have historically provided essential countermeasures to cope with them. The main concern about the multi-unit sites is related to the first question, i.e., whether an accident of an NPP in a site would affect the safety of other NPPs in the same site or not. The lessons learned report for the Chernobyl accident included recommendations that address this aspect. Key recommendations of the report are related to noble gas and airborne volatiles that are propagated into other NPPs in the Chernobyl site through a shared ventilation system during the accident [3]. The current regulation system of many countries includes the requirements to cope with this problem. For example, 10CFR Part 50, Appendix A, GDC 5 of the NRC requires that "structures, systems, and components important to safety shall not be shared among nuclear power units unless it can be shown that such sharing will not significantly impact their ability to perform their safety functions, including, in the event of an accident in one unit, an orderly shutdown and cool-down of the remaining units [4]." Many countries have the similar regulatory requirements.

The nuclear community also has a concern about the increase of nuclear accident risks as the number of NPPs increase in a site or a nation, i.e., the second question. The WASH-1400 report, the first risk assessment of NPPs in 1975, already covered this problem. The

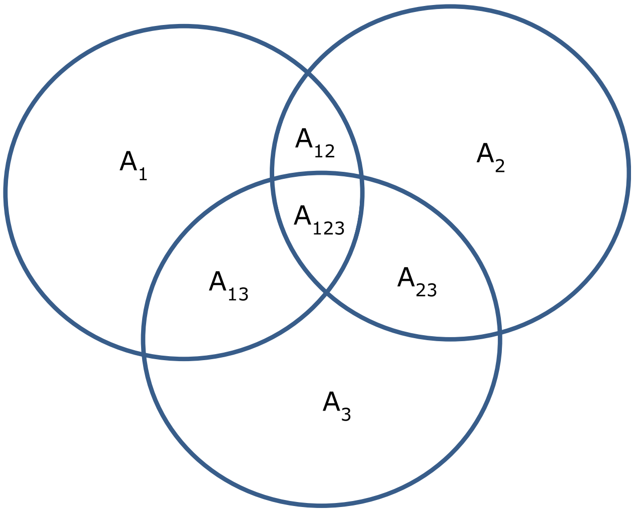

Fig. 1. Possible results of multi-unit accident for a site with 3 units.

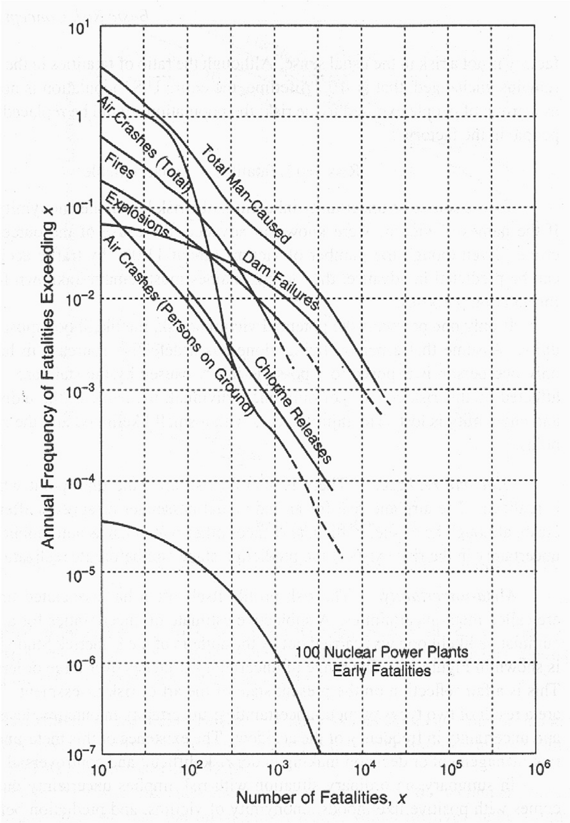

Fig. 2. Results of WASH-1400.

result of WASH-1400 is shown in Fig. 2 [5]. In WASH-1400, the authors assumed that 100 NPPs might be operated in the U.S.A. by about 1980, so they compared the total risk due to 100 NPPs to other man-caused risks.

The International Atomic Energy Agency (IAEA) also has similar concerns on the multi-unit risk. In 1999, the IAEA proposed the probabilistic safety objectives for existing and new NPPs. The IAEA recommends improving the safety of new NPPs to 10 times higher than that of the existing NPPs [6]. The requirements for new NPPs can have an effect of limiting the increased risk from adding new NPPs into a society. The IAEA proposed the safety goals by as shown below:

- For existing NPPs
  - ■ Core Damage Frequency (CDF): less than 1.0E-4/year
  - ■ Large Early Release Frequency (LERF): less than 1.0E-5/year
- For new NPPs
  - ■ CDF: less than 1.0E-5/year
  - ■ LERF: less than 1.0E-6/year

The simultaneous accidents at multiple NPPs in a site are another important issue, i.e., the third question. The current regulation system of many countries also includes some requirements to manage this issue. For example, 10 CFR 100.11(b) of the NRC requires that “if the reactors are interconnected to the extent that an accident in one reactor could affect the safety of operation of any other, the size of the exclusion area, low population zone, and population center distance shall be based on the assumption that all interconnected reactors emit their postulated fission product releases simultaneously [7].” Also, several MURAs were performed to address this issue before the Fukushima-Daiichi accident [8–10].

Up to now, we have reviewed the current regulatory requirements or guidelines to cope with the multi-unit risk. Actually, before the Fukushima-Daiichi accident, the multi-unit risk is not a significant concern of the nuclear community. The NRC raised the multi-unit safety issue after the TMI-2 accident. However, this issue was subsequently dropped at the Commission's direction in TMI Action Plan [11]. SECY-82-1B states that nts or guidelines to cope with the multi-unit risk. Actually, before the Fukushima-Daiichi accident, the multi-unit risk is not a significant concern of the nuclear community. Ts [12].”

However, after the Fukushima-Daiichi accident, the multi-unit risk has become a critical issue in several countries such as Korea, Canada, China, etc. On the other hand, some countries do not have a significant interest in the multi-unit risk issue even after the Fukushima-Daiichi accident. It is because various factors such as the design of NPPs, the location and number of NPPs in a site, population distribution, natural environments around a site significantly affect the importance of the multi-unit risk.

One of the most critical factors that affect the multi-unit risk is the design related to the shared safety systems among NPPs in a site. In Canada, several CANDU NPPs in a site share a vacuum building [13]. The vacuum building can be used to relieve the high pressure of a reactor building when an accident to the primary reactor system or heat transport system occurs. If the severe accidents occur at multiple CANDU NPPs simultaneously in a site where the vacuum building is shared, this site might have a high multi-unit risk. Several CANDU NPPs in a site also share the main control room (MCR). If the shared MCR is contaminated due to an accident of an NPP in a site, then the operations of all NPPs which share the same MCR are affected no matter other NPPs are in normal conditions or accident conditions.

The locations of each NPP in a site might be another important factor affecting the multi-unit risk. For example, works to restore the electric power for the Fukushima-Daiichi Unit 2 was stopped due to the hydrogen explosion at the adjacent Unit 1. The Fukushima-Daiichi Unit 5 and 6 are located at the higher level than Units 1, 2, 3 and 4. So they could survive from the tsunami. The total number of NPPs in a site is another factor. Several countries have the nuclear sites with many NPPs, e.g., seven NPPs are in operation in Qinshan site in China and Kashiwazaki-Kariwa site in Japan, respectively. There are eight units in the Kori site in Korea, and in the Bruce and Pickering sites in Canada. Most sites of the U.S.A. have less than or equal to two units in a site. The population densities around the sites in Korea and many European countries are much higher than those of sites in the U.S.A.

In the U.S.A, the multi-unit core damage accident had been proposed as a candidate topic of the NRC's generic safety issue before the Fukushima-Daiichi accident. During the screening process of this topic, the Fukushima-Daiichi accident occurred, and the importance of better understanding and quantification of the multi-unit risk was emphasized. However, the results of the conservative evaluation showed that the multi-unit risk is low and the screening panel concluded that the interim regulatory actions are not warranted. The screening panel recommends that this issue exit the Generic Issue Program because of the estimates of low-risk significance and because it requires longer-term efforts to develop the tools to fully and accurately quantify the multi-unit risk [14]. However, above decision of the NRC is based on the U.S.A. specific conditions, e.g., most sites of the U.S.A. have less than or equal to two units in a site and the population densities around the sites are not high in most cases. On the contrary, the multi-unit risk becomes a critical issue in several countries such as Korea and Canada since such countries have several factors that enlarge the multi-unit risk of sites of their countries.

Therefore when we address the multi-unit risk, we need to consider various factors carefully. The MURA in an integrated framework is a practical approach to estimate the effects of those factors systematically. Many countries and international organizations started and are performing research for the MURA again after the Fukushima-Daiichi accident to estimate the effects of country and site-specific issues of their multi-unit sites [15–29]. In the next section, we review the studies on the MURA in detail.

3. Progress and current status of multi-unit risk assessment

There were several studies on the MURA before the Fukushima Daiichi accident and several new studies on the MURA are on-going in many countries after the accident. In this section, we review several important studies on the MURA.

A pioneering study on the MURA was the Seabrook risk assessment performed in the early 1980s [8]. It was an integrated Level 3 PSA (Probabilistic Safety Assessment) of the planned two-unit Seabrook site in the U.S.A. Although the construction and operation of only one unit were actually achieved, the original design called for the limited sharing of systems. PSA included full scope treatment of internal and external hazards and plant operating states. The Seabrook PSA estimated the multi-unit risk from the single-unit risk model (i.e., Level 1/2/3 PSA model) through the application of the multi-unit event tree. This PSA proposed the concept of inter-unit common cause failure (CCF) to quantify the effects of the multi-unit initiators (MUI). The events that affect the multiple units simultaneously are called the MUIs. The results of Seabrook PSA are summarized in Tables 1 and 2.

In the late 1990s, single-unit PSAs were performed for the Byron and Braidwood sites with each having two units [9]. In contrast to the Seabrook NPP, the two units of each site have many shared support systems such as service water system and co-located equipment in a common structure, e.g., the auxiliary building.

Table 1
Result of seabrook PSA (1/2).

Model Type	Risk Metric	Core Damage Frequency Uncertainty Distribution			
		Mean Value	5%	50%	95%
Single Reactor PRA	CDF Per reactor year	2.3×10^{-4}	6.9×10^{-5}	1.8×10^{-4}	5.4×10^{-4}
Integrated Site PRA of both Units	Single reactor CDF Per site year	4.0×10^{-4}	1.2×10^{-4}	3.1×10^{-4}	9.4×10^{-4}
	Dual reactor CDF Per site year	3.2×10^{-5}	1.1×10^{-6}	1.5×10^{-5}	1.2×10^{-4}
	Total reactor CDF Per site year	4.3×10^{-4}	1.40×10^{-4}	3.4×10^{-4}	1.0×10^{-3}

Table 2
Result of seabrook PSA (2/2).

Initiating Event	Dual Unit Site CDF (Per Site Year)	% of Total
Seismic Events	2.80E-05	88%
Loss of Offsite Power	2.80E-06	9%
External Flooding	1.60E-06	5%
Truck Crash into Transmission Lines	1.00E-07	0.3%
Total	3.20E-05	100%

The PSAs included the integrated Level 1 PSAs of two units for internal events and internal floods at full power. This PSA explicitly modeled the dual-unit dependencies related to the shared systems and flagged all sequences and cut-sets involving two-unit accidents. The results are summarized in Fig. 3.

In 2007, T. Hakada developed a seismic PSA method for a multi-unit site and applied the developed method to an imaginary site with 5 units [10]. The results showed that the mean CDF per site-year is 2.3E-5/yr., and the mean number of damaged units is 1.66 which can be interpreted as that single NPP accidents are more common incidents. In Korea, several studies on the multi-unit risk have been performed including the modeling method of the shared component between two units for the PSA and a proposal for the safety goal for a multi-unit site [30,31].

Although there were several useful studies performed from the early 1980s to the mid-2000s including the above studies, the nuclear community did not pay notable attention to the multi-unit risk before the Fukushima-Daiichi accident. However, after the Fukushima-Daiichi accident, the multi-unit risk becomes a critical issue in several countries. After the Fukushima-Daiichi accident, the Canadian regulatory body made the regulatory requirements that request to assess the multi-unit risk [32]. It was the first regulatory requirement on the MURA in the world. Other countries are also trying to establish the regulatory requirement on the MURA as well.

Currently, many research efforts are on-going regarding the multi-unit risk such as the studies being performed by France, China and India, etc. [16–18]. Also, the NRC is performing research

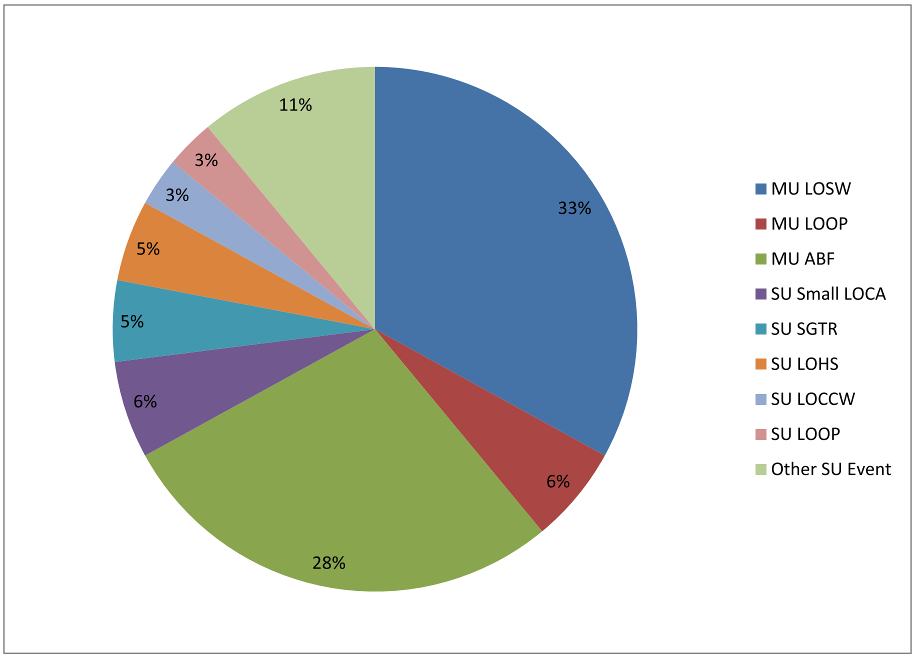

Fig. 3. Results of Byron & Braidwood PSA. (MU: Multi-unit, SU: Single unit, LOSW: Loss of Service Water, ABF: Aux. Building Flooding, LOCA: Loss of Coolant Accident, SGTR: Steam Generator Tube Rupture, LOHS: Loss of Heat Sink, LOCCW: Loss of Component Cooling Water).

Table 3
Results of estimating site CDF due to LOOP initiating events.

LOOP initiating event category	IE frequency (/site-yr)	CCDP	CDF (/site-yr)	CDF for each number of units with core damage					
				1 unit	2 units	3 units	4 units	5 units	6 units
Six-unit LOOP	1.91E-02	2.81E-04	5.36E-06	4.93E-06	3.80E-07	4.07E-08	2.87E-09	ε[a]	ε[a]
Dual-unit LOOP	1.14E-02	1.00E-04	1.15E-06	1.08E-06	6.80E-08	N/A	N/A	N/A	N/A
Single-unit LOOP	5.72E-02	7.43E-06	4.25E-07	4.25E-07	N/A	N/A	N/A	N/A	N/A
Sum	8.77E-02	–	6.93E-06	6.44E-06	4.48E-07	4.07E-08	2.87E-09	ε	ε
%	–	–	100.0%	92.9%	6.5%	0.6%	0.04%	ε	ε

[a] Minimal cut sets for core damage in 5 or 6 units were truncated. (*CCDP cutoff value = 1E-12).

on the MURA as part of the NRC Level 3 PRA project [19]. Korea Atomic Energy Research Institute (KAERI) has also developed a MURA method and a framework [20–25]. The developed method and framework are applied to a site with six NPPs. The characteristics of this research effort are summarized below:

- Identifications of MUIs including external events
- Development of methods for the multi-unit Level 1/2/3 PSA
- Development of software tools that can build and quantify the vast multi-unit PSA model
- Validation of the methods and software tools by their application to a six-unit NPP site

The details of the developed framework can be found in references [22–25]. Key results of this work are shown in Table 3 and Fig. 4 [23].

The international organization such as the IAEA and OECD/NEA (Nuclear Energy Agency) organized international cooperation works regarding the MURA after the Fukushima Daiichi accident. The IAEA is performing research on the multi-unit PSA and risk aggregation [26] and a coordinated research project on the PSA benchmarks for multi-unit/multi-reactor sites [27]. The working group on risk (WGRISK) of OECD/NEA started activity to collect information on whether and how member countries are addressing multi-unit (multi-source) issues in the PSA [28]. Even though there is various on-going research on the MURA, there are still many issues to be resolved in the MURA. OECD/NEA organized an international workshop regarding the multi-unit risk. In the workshop which was held in 2014 in Canada, the technical issues and challenges of the MURA were collected and discussed as shown in Table 4 [33].

4. Important issues regarding the multi-unit risk assessment

As we can see in Table 4, there are various issues to be resolved for the complete MURA. Most issues of Table 4 are related to the characteristics of the MURA, i.e., (1) enormous consequences of the accident, (2) extremely low frequencies of major MUIs such as huge external events and (3) various accident scenarios.

In the nuclear community, two types of approaches have been used in the safety assessment: (1) the conservative approach and (2) the realistic approach. The basic approach used in the risk assessment of NPPs is the realistic one. However, it seems that, in many cases, the conservative approaches are inevitable to resolve several issues in Table 4 such as the assessment of the inter-unit CCF. However, if the conservative approaches are overly used in the MURA, the results of the MURA become unrealistic one for any use.

Under the present situation, we have to note that the primary objective of performing the MURA is not to derive the quantitative value of the multi-unit risk but to find insights that enable us to reduce the multi-unit risk through programs such as the site accident management. If we focus the primary objective of the MURA, we can find some practical ways to assess the multi-unit risk with the current state of art PSA technology.

In Table 4, various issues are summarized according to the technical areas such as the selection of the initiating events, accident sequence modeling, etc. However, in this section, we discuss the issues from another point of view rather than technical areas. We discuss the issues related to the following three categories since the issues belong to these categories are the critical issues in performing the complete MURA with the current state of art PSA technology:

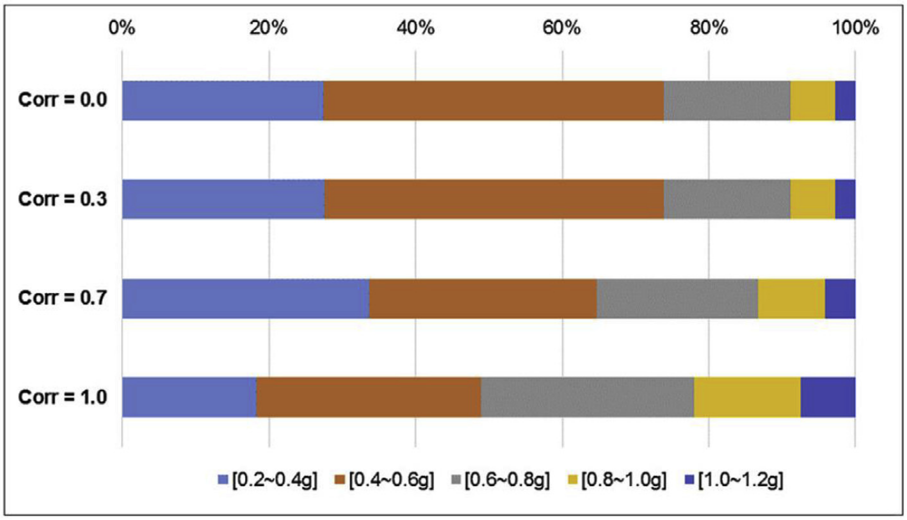

Fig. 4. Distribution of the percentage of site CDF. at each seismic hazard interval according to interunit seismic correlation.

- The Scope of the MURA,
- Conservatism in the MURA, and
- Consensus related Issues.

4.1. THE scope of MURA

There are two issues related to the scope of the MURA. The first one is the number of NPPs to be included in a MURA. The second one is the level of PSA for the MURA.

4.1.1. THE physical scope of MURA

The MURAs performed in the U.S.A. only cover two units in a site [8,9]. Other studies in other countries such as Japan and Korea analyzed sites with more than two units [10,20]. However, the scope to be analyzed in the MURA is not well-defined yet. There are several factors related to the physical scope of the MURA.

The first factor to be considered is the locations of NPPs in a site. For instance, NPPs in a site may be located nearby of each other, or the distance between NPPs in a site may be very long. In the Fukushima-Daiichi accident, the hydrogen explosion at Unit 1 affected Unit 2 since they are located closely with each other. In the Kori site in Korea, the distances between some NPPs are more than several kilometers. The elevation of NPPs in a site may be different with each other. Units 5 and 6 in the Fukushima-Daiichi site could survive from the tsunami because they are located at the higher elevation comparing to Unit 1, 2, 3 and 4. In such cases, we should define the appropriate scope of the MURA considering such site-specific geometrical characteristics.

There can be a case that several sites face the same challenges. For example, the external hazards that may cause the multi-unit problems could be a large scale, and multiple sites in the same region could be challenged by the same external event as in the Fukushima Daiichi accident. In 2011, fourteen NPPs at four sites, i.e., the Fukushima-Daiichi (six NPPs), Fukushima-Daini (four NPPs), Onagawa (three NPPs) and Tokai (one NPP) sites of Japan experienced the similar challenges at the same time. Political (country) borders may not limit the extent of regional proximity. During the Northeast Blackout in 2003, thirty NPPs in the U.S.A. and Canada were either tripped or experienced significant transients during regional grid power outage.

The second factor is the structure of operating organizations. There can be a case that each NPP in a site can have independent organizations in charge of the operation and accident management of each NPP. In such cases, the accident management process may be different in each NPP even though the NPPs are located at the same site.

The physical scope of the MURA should be determined considering the above factors. However, the MURA in an integrated framework for fourteen NPPs at four sites in Japan is impossible and unnecessary. The MURA is based on the PSA for a single NPP, at least initially. So, the scope of the MURA needs to be minimized. The MURA model to cover the site or sites can be built from small MURA models. For example, the MURA for a region with several nuclear sites can be developed based on the site-specific MURA models in that region. This approach enables us to address the MURA in a site, and then to address the MURA for a broader scope.

4.1.2. THE PSA scope of MURA

Before the Fukushima-Daiichi accident, the Level 1 PSA (CDF) and the limited Level 2 PSA (LERF) were the scopes of typical PSAs around the world. In other words, before the Fukushima-Daiichi accident, the main outcomes of the PSA were the CDF and LERF. The CDF and LERF are used in many countries as the surrogates to check whether the safety goal of an NPP is met or not [34]. After the Fukushima-Daiichi accident, many MURA research tries to include the Level 3 PSA [19,20].

However, there are various reasons that only the CDF and LERF were used rather than using the quantitative risk values derived from the Level 3 PSA. One of the reasons is that the CDF and LERF provide us with enough information to reduce the risk of an NPP.

It is expected that to assess the consequences of multi-unit accidents is much more difficult than to assess the frequencies of multi-unit accidents. We may need the conservative assumptions and simplification to cope with the various factors related to the multi-unit Level 3 PSA. If we use overly conservative approaches, we might get an unrealistic multi-unit risk profile.

Therefore, it is reasonable to focus on the Level 1 and Level 2 PSA for the CFF (Containment Failure Frequency) estimations, rather than the full scope multi-unit Level 3 PSA. If we focus on the frequency rather than the consequence of multi-unit accidents, we can avoid many problems related to the analysis scope and the model sizes of the MURA (We discuss the problem related to the model size in subsection 4.2.4). From the result of Level 1 and Level 2 PSA, we can still get valuable insights for managing the site risk, i.e., to prevent the core damages and containment failures of multiple units.

4.2. Conservatism

Previously, we mentioned the effects of conservatism on the MURA. There are many issues of the MURA related to the conservatism. We discuss such issues in this subsection. Maybe the conservative approach is inevitable to handle various issues in Table 4 such as the inter-unit CCF, the combined hazards of the external events. The problem is how to minimize the adverse effects of the conservative approach to be used in the MURA.

4.2.1. Conservatism due to the simplification

The conservative approach is widely used in many areas in the risk and safety analysis of NPPs. The conservative approach is a useful tool to handle complex and uncertain issues in many cases. The NRC performed a conservative scoping analysis for the multi-unit risk by simplifying the problem. The following equation is derived and applied to a site with two NPPs. The results are shown in Table 6 [2].

$$R^{(n)}_S < n\, R_{\text{single-unit, CCI}} + n^2\, R_{\text{single-unit, SUI}}$$

- $R^{(n)}_S$: Site Risk with “n” NPPs
- CCI (Common-Cause Initiators): Initiators that simultaneously challenge all of the units at the site. CCIs include initiators that are caused by external hazards (e.g., earthquakes, severe weather, etc.).
- SUI (Single-Unit Initiators): Initiators that occur at one unit. SUIs generally include initiators caused by internal hazards such as internal events, internal floods, and internal fires. SUIs may cause multi-unit accidents due to cross-unit dependencies such as shared support systems, spatial interactions (e.g., internal flood and internal fire propagation pathways), common cause failures, or shared operator actions.
- $R_{\text{single-unit, CCI}}$: Risk of an NPP due to CCI
- $R_{\text{single-unit, SUI}}$: Risk of an NPP due to SUI

According to the results of scoping analysis, the NRC concludes that the multi-unit risk is not a serious concern in the U.S.A. This result might be acceptable in the U.S.A. since there are thirty-two sites with two NPPs and three sites with three NPPs in the U.S.A

Table 4
Technical issues and challenges in multi-unit risk assessment.

Technical Area	Technical Issues and Challenges
MUPSA infrastructure	- Lack of experience and guidance for performing MUPSA; small body of existing case studies in MUPSA. - Lack of existing deterministic safety analyses of multi-unit accidents to support MUPSA. - Need to revisit and re-analyze the international operating experience for lessons to be learned from significant events and accidents for MUPSA insights; many examples of such events discussed at workshop.
Selection of initiating events	- Many single-unit PSA-initiating events (e.g., loss of off-site power, loss of heat sink, external events) challenge multiple units. - Need to delineate single-unit/facility and multi-unit/facility events. - Most external events involve multi-unit challenges. - Extent of shared systems increases the importance of some internal initiating events (e.g., support system faults).
Accident sequence modeling	- Need to delineate single and multi-unit accident sequences. - Need to account for multi-unit common cause and causal dependencies, including functional, human and spatial dependencies; MUPSA models more than just a set of single-reactor PSA models. - Need to consider adverse impacts of single reactor/facility accident on other units, thus creating additional multi-unit accident scenarios. - Need to consider how operator actions may be adversely affected by multi-unit interactions. - Need to consider the timing of releases from different units. - Need to consider how radiological contamination of the site may inhibit operator actions and accident management measures. - Need to consider new end states involving multi-unit accidents and interactions, including the effects of combined and correlated hazards. Problem of proliferation of multi-unit combinations for sites with three or more reactor units. - Limitations of static PSA modeling approaches may require a re evaluation of dynamic PSA approaches.
Accident sequence quantification and site based risk metrics	- Need for additional risk metrics beyond CDF and LERF to fully express the risk profile of a multi-unit site. - Need to change frequency basis from events per reactor year to events per site year to capture risks from non-reactor sources and multi-unit accidents. - Lack of surrogate frequency-based risk metrics for spent fuel accidents; temporal variations in the radiological hazard in spent fuel storage. - Need to delineate CCF models and supporting data analysis to address inter-unit and intra-unit CCFs. - Need to improve human reliability models and analyses to address performance-shaping factors unique to multi-unit accidents. - Need to rethink the selection of mission times and consider extending beyond 24 h. - Need to address variations in site response to the same earthquake and correlation among component fragilities in the MUPSA context - Current issues in single-reactor PSA with proliferation of scenarios, impact of conservatism and difficulties in achieving realistic fire PSA results will be compounded in the multi-unit PSA context. - Current issues in single-reactor Level 2 PSA with treatment of human actions during implementation of Severe Accident Management Guidelines (SAMGs) and prioritization of emergency response measures will be even more difficult in the MUPSA context.
Accident progression and source term characterization	- Existing severe accident models that are limited to single-reactor accidents will have to be enhanced to treat multi-unit and fuel storage accidents - Need to define new release categories that adequately describe the releases from multi-unit accidents; this includes release magnitudes, energies, and timing from reactor units, spent fuel storage and other radiological sources
Evaluation of radiological consequences	- Consequence models need to consider how to model releases from multi-unit and multi-facility accidents; this includes consideration of different points of release from the plant, possible differences in time of release and release energies for plume rise considerations. - Method of decoupling consequence models from inventories needs revision for spent fuel accidents
Site-based safety goals, risk integration and interpretation	- Method of aggregating risk contributions across different reactor units and facilities, single- and multi-unit and facility accidents, hazard groups and operating states with due regard to differences in level of realism/conservatism, level of detail in modeling, and uncertainty treatment. - Methods for comparing calculated risks against existing and new site-based safety goals. - Question of whether safety goals should be quantitative or qualitative, supported by quantitative safety design objectives. - Lack of multi-unit site-based acceptance criteria for evaluating the integrated risks from a multi-unit site PSA. - Need for more international consensus on approach to safety goals and use of such goals to interpret PSA results.

[35]. However, the simplification based on the conservatism might result in unrealistic conclusions. For instance, if the above equation is applied to a site with many NPPs, e.g., ten NPPs, the result from the above simple equation would be too conservative and unrealistic.

This example shows the strength and weakness of the simplification. In many cases, the simplification of the problem is a powerful tool to achieve the desired objective. However, in some cases, such an approach cannot be used since its results are too conservative. Therefore the simplification should be minimized as possible as we can. Also, we should be cautious in using the simplification approach if we have to use it for the MURA.

4.2.2. Conservatism due to the lack of knowledge

There are some issues related to the MURA that we do not have enough knowledge or methodologies to handle the issues. One of them is the inter-unit dependency between units due to various reasons.

A typical example is an inter-unit CCF caused by the external hazard events or operational aspects across the multiple units. The external hazards can cause the inter-unit CCF. For instance, if an earthquake strikes a site with multiple units and the same equipment is installed at NPPs in the site, there could be inter-unit CCFs. Up to now, we do not have enough knowledge to handle this issue. At present, the expert judgment is the essential part to assess the effects of the inter-unit CCF even though there are some methods proposed to resolve this issue [35,36].

The inter-unit CCF due to an earthquake is a critical issue in the MURA. The current approaches proposed to handle the inter-unit CCF due to the earthquake are very conservative. They assume that the same types of components at different NPPs in a site experience the same seismic accelerations and fail due to the CCF mechanisms. However, in the real world, the observed seismic accelerations are different at NPP unit in a site as shown in Table 7 [37]. We may need to use different seismic response spectrums for each unit in a site. Therefore, it seems that the current approaches

Table 5
Multi-unit licensee event report classifications from 2000 to 2011.

Classification	Percentage of Total
Initiating Event	6.63%
Definite	3.83%
Conditional	2.81%
Shared Connection	32.40%
Single	26.79%
Time Sequential	1.28%
Standby	4.34%
Identical component	8.16%
Proximity	4.59%
Human	3.83%
Pre-event	3.57%
Post-event	0.26%
Organizational	44.39%

to handle the inter-unit CCF due to the earthquake are too conservative.

So, to avoid the excessive conservatism found in the current approach for estimating the inter-unit CCF due to an earthquake it would be better to perform the sensitivity analysis as the Seabrook PSA [8].

The operational aspect can cause another type of inter-unit dependency. For instance, if there are any mistakes in the procedures that are used across the multiple NPPs in a site or across similar NPPs at several sites, those procedures might result in same problems in many NPPs where the same procedures are used. Suzanne Schroer analyzed all Licensee Event Reports (LERs) submitted to the NRC from 2000 to 2011 [38]. The results are shown in Table 5. About 9% of LERs may be linked to multi-unit problems. It is identified that the most common link between multiple units is the organizational dependencies, i.e., 44% of the 392 multi-unit LERs. The problems related to the procedures might be handled in the present PSA framework. However, there are no agreed or standardized methods to assess the organizational aspects into the PSA, up to now. So when we interpret the results of the MURA, the organizational element should be considered separately.

4.2.3. *Conservatism due to the uncertainty*

There are many factors related to the uncertainties in the risk assessment of an NPP such as the severe accident phenomena, etc. There is another important source of the uncertainty from the MURA perspective, i.e., the hazards of the external events. The primary candidates of MUI are the external events, e.g., seismic events as shown in previous studies [8,10,20]. We also think that the large external event would be the major causes of the multi-unit accident. However, it is difficult to assess the hazard of large external events. The hazard curves related to such external events have substantial uncertainty. It means the multi-unit risk based on those hazard curves will have considerable uncertainty as well. For example, after the Fukushima-Daiichi accident, there were serious discussions regarding the credibility of the tsunami hazard assessed by the TEPCO (Tokyo Electric Power Co.). The TEPCO determined that the result of the tsunami hazard assessment was not acceptable due to uncertainty [37], but others insisted that the TEPCO should have done something to cope with the anticipated tsunami level [39].

The more difficult issue related to the external events is the combined hazard. As well known, the Fukushima-Daiichi accident occurred due to the combined effects of the earthquake and after-effect tsunami that sequentially struck the Fukushima-Daiichi site. There can be many different combinations of external events. Several kinds of basic research on this topic are currently underway [40,41]. However, it is challenging to assess the impacts of the various combined hazards. Even though we may assess the combined hazards, it could have substantial uncertainty. Such large

Table 6
Result of NRC scoping risk estimate.

Plant	CCIs Seismic ^{R}Single-unit,*CCI*	SUIs Internal Events	 Internal Fires	 Total ^{R}Single-unit,*SUI*	Bounding Site Risk $R_s^{(2)}$
Individual Early Fatality Risk (0–1 miles)					
Peach Bottom	1.6E-6/ry^{3}	4.7E-11/ry	4.8E-10/ry	5.3E-10/ry	3.2E-6/sy^{b}
Surry	1.8E-7/ry	1.6E-8/ry	6.3E-10/ry	1.7E-8/ry	4.3E-7/sy
Individual Latent Cancer Fatality Risk (0–10 miles)					
Plant	CCIs Seismic ^{R}Single-unit,*CCI*	SUIs Internal Events	Internal Fires	Total ^{R}Single-unit,*SUI*	Bounding Site Risk $R_s^{(2)}$
Peach Bottom	1.6E-6/ry	4.3E-10/ry	2.4E-9/ry	2.8E-9/ry	3.2E-6/sy
Surry	3.1E-8/ry	1.7E-9/ry	1.2E-10/ry	1.8E-9/ry	6.9E-8/sy

Table 7
Observed seismic acceleration at Fukushima Daiichi NPS and Fukushima Daini NPS.

Observation Point (Lowest Basement of Reactor Buildings)		Observed Data Maximum Response Acceleration (gal) Horizontal (North-South)	 Horizontal (East-West)	 Vertical	Maximum Response Acceleration Against Design-Basis Ground Motion (gal) Horizontal (North-South)	 Horizontal (East-West)	 Vertical
Fukushima Daiichi	Unit 1	460	447	258	487	489	412
	Unit 2	348	550	302	441	438	420
	Unit 3	322	507	231	449	441	429
	Unit 4	281	319	200	447	445	422
	Unit 5	311	548	256	452	452	427
	Unit 6	298	444	244	445	448	415
Fukushima Daini	Unit 1	254	230	305	434	434	512
	Unit 2	243	196	232	428	429	504
	Unit 3	277	216	208	428	430	504
	Unit 4	210	205	288	415	415	504

uncertainty related to the external events might produce unrealistic results of the MURA.

Under this situation, we need to find insights for the site risk management related to the external events. For this, we think that the estimation of the multi-unit CCDP (Conditional Core Damage Probability) for important hazards may be enough. For example, the multi-unit CCDP for the specific ground acceleration values may give reasonable insights to reduce the multi-unit risk due to the earthquake.

4.2.4. Conservatism due to the limit of current PSA tools

Let's assume that the simultaneous accidents occur at ten multiple units in a site, and if each unit has fifty accident sequences, there could be 50^10 different combinations of the accident sequences at the site level. In such a case, it is impossible to analyze each accident sequence in detail. Also, the consequences of multi-unit accidents can vary over wide ranges according to the number of NPPs in which accidents occur, the release amount of radioactive materials, the release time and duration from NPPs, and the weather condition of the site, the population around the site, etc. These various factors affect the consequences of the MURA and result in the huge number of different combinations of accident conditions. It means that the size of the MURA model will be enormous. The current PSA tools (computer codes) widely used in many countries cannot handle such large PSA models.

So as mentioned in subsection 4.1.2, it would be better to confine the PSA scope of the MURA to the Level 1 and 2 PSA until the reasonable Level 3 PSA framework for the MURA is developed. Then we can avoid many parts of the problems described above. We may get the insights related to the consequential aspects of a multi-unit accident from case studies for the typical accident scenarios to enhance the emergency preparedness for multi-unit accidents. There are on-going studies related to this problem as in Refs. [24,25]. However, it seems we need more time to get the realistic risk profile of the multi-unit risk based on the multi-unit Level 3 PSA.

4.3. Consensus

How safe is safe enough? It is a question that the nuclear community has been looking for an answer for a long time. The safety goal for an NPP is one type of answer to this question. At present, the safety goal in most countries is defined not for a site level but for a unit level.

This issue is already discussed when the safety goal was defined in the U.S.A. The multi-unit safety goal became an issue when the NRC introduced the safety goal into the regulatory framework of the U.S.A. in the mid-80's. At that time, there were arguments that the proposed individual and societal numerical guidelines should be applied on a per-site basis. However, this approach could result in a kind of bias, i.e., the different requirements for a unit in a multi-unit site and a unit in a single unit site. The NRC decided not to impose a regulatory bias against multi-unit sites. Therefore, the quantitative health objectives are applied at the unit level, not at the site level [42].

However, in several countries, a more explicit definition of the safety goal became an important issue after the Fukushima-Daiichi accident. There are two issues regarding the safety goal for a multi-unit site. One is the measures of the safety goal for a multi-unit site, and another is the quantitative values associated with the safety goal for a multi-unit site.

There are some research efforts regarding the measures for the safety goal for a multi-unit site [31,43]. These researches tried to define the new measures for the safety level of a site such as a site CDF. However, there are no measures for the safety goal of a multi-unit site that are accepted universally in the international nuclear community yet. Even if we derive the technical definition of the safety goal for a multi-unit site that is internationally accepted, we still have a problem regarding the quantitative criteria of a multi-unit safety goal.

A key concern about the multiple units is the increased risk of a site as the number of unit increases in a site. As mentioned earlier, the IAEA suggested that new NPPs should have ten times higher level of safety comparing to the safety level of existing NPPs [6]. If we adopt this approach, the risk due to NPPs converges to some values as shown in Fig. 5. Fig. 5 shows the changes of a risk level of a site as the number of NPPs increase in that site. We assume that the LERFs of Generation I, II and III NPP are 1.0E-4/yr., 1.0E-5/yr., and 1.0E-6/yr., respectively. The issue is whether or not the public or society can accept the final resulting value with that site.

Fig. 6 shows another aspect of the safety goal for a multi-unit site. The multi-unit risk is changed continuously as old NPPs are retired. The multi-unit risk is reduced drastically as the old NPPs are shut down permanently. We assumed that one old NPP of Generation I NPPs would be stopped if one new NPP of Generation II starts its operation. We also assume that one old NPP of Generation II NPPs is stopped if one new NPP of Generation III NPPs starts its operation. As we can see in Figs. 5 and 6, the multi-unit risk is dominated by the older NPPs with high risks. From this aspect, we can find ways to manage the site risk level. By controlling the permanent shutdown and the operation of new NPPs, we can achieve the site risk level to what we want to keep.

5. Discussions and conclusions

After the Fukushima-Daiichi accident, the multi-unit risk has become an important issue in several countries. We summarize the concerns regarding the multi-unit risk into the following three questions:

- How much the accident of an NPP in a site affects the safety of other NPPs in the same site?
- What is the total risk of a site with many NPPs?
- Will the risks of the simultaneous accidents at several NPPs in a site such as the Fukushima Daiichi accident be low enough?

The MURA in an integrated framework is a practical approach to obtain the answers for above questions. At present, various studies on the MURA are on-going in many countries. However, there are still several issues to be resolved to perform the complete MURA. In this paper, we give an overview of the history and current status regarding the multi-unit risk issue. We also review several critical issues of the MURA and suggest several ways to get useful insights to reduce the multi-unit risk with the current state art of PSA technologies. In this section, based on the reviews on the MURA studies performed up to now and previous discussions, we would like to give qualitative answers to the above three questions.

We think there is no general answer to the first question even though we have several regulatory requirements to minimize the effects of the accident at an NPP to other NPPs in the same site. Such effects depend upon various factors such as the shared system, the location of NPP in a site, and so on. However, we can qualitatively estimate the degree of impact by reviewing such factors for each site. For examples, if NPPs in a site do not share the critical safety system, and the distance between NPPs is long enough, then the effects of the accident in an NPP to other NPPs in the same site would not be significant. However, we need the site-specific MURA to get the quantitative answer to this question.

The results of Seabrook multi-unit PSA shows that the site risk is less than the sum of individual units' risk as shown in Table 1. One

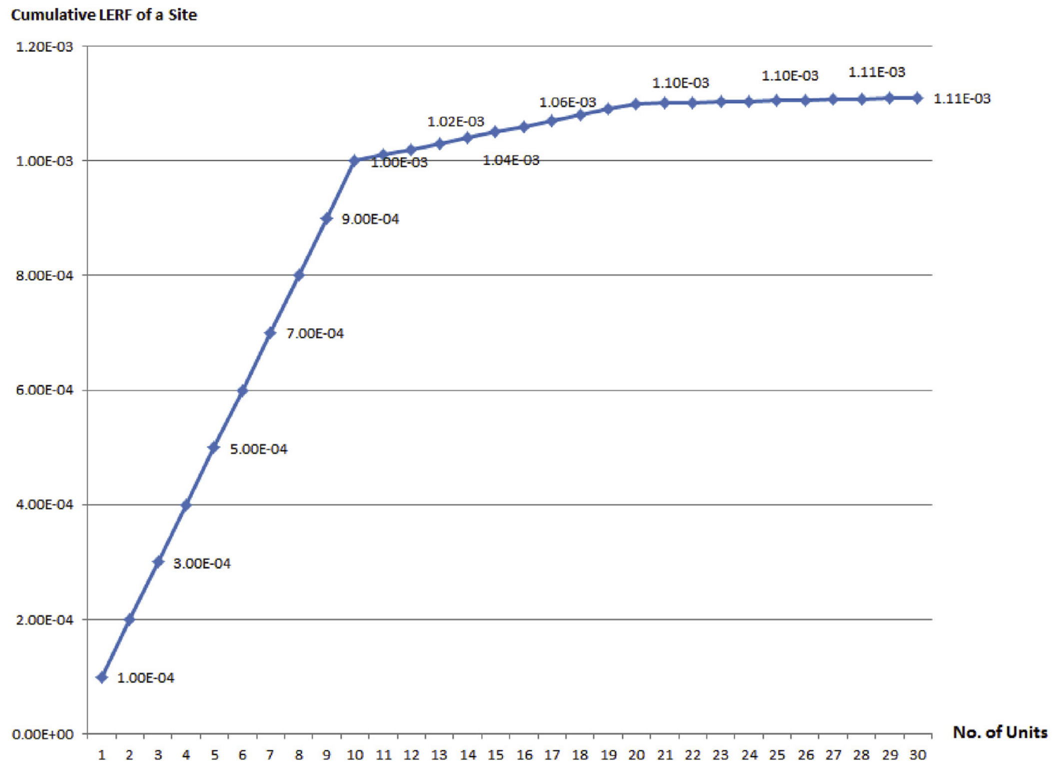

Fig. 5. Changes of multi-unit risk in a site as new NPPs start operation.

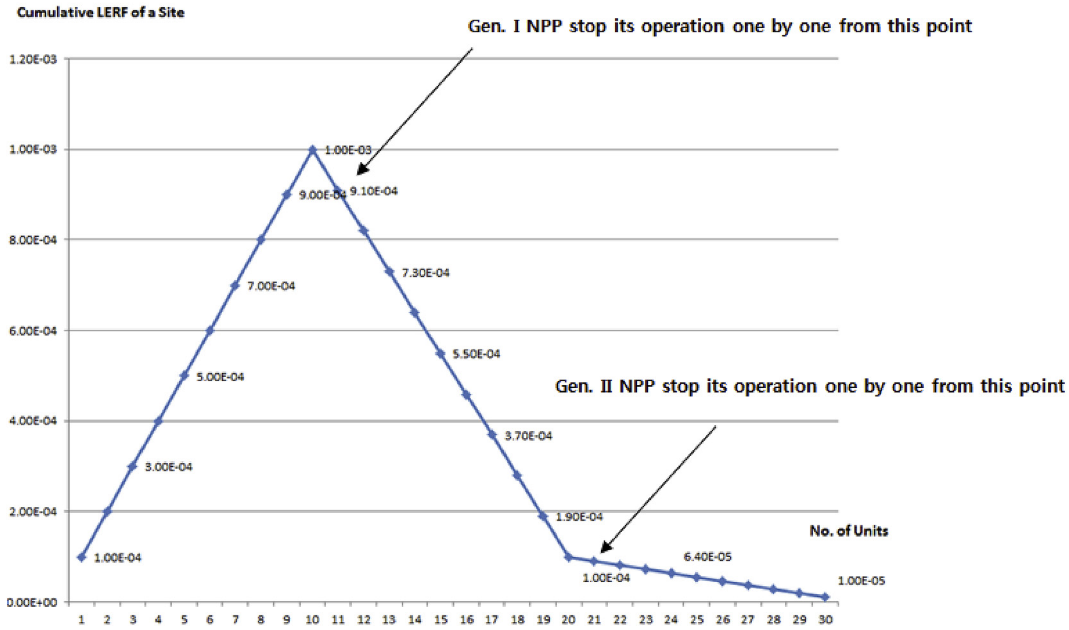

Fig. 6. Changes of Multi-Unit Risk in a Site as Old NPPs stopped.

study insisted that the multi-unit risk can be reduced through mutual supports among NPPs in a site [10]. However, another study indicates a possibility that the site risk might be larger than the sum of individual units' risk [44]. However, in principle, the total site risk is dominated by the sum of the individual units' risk as shown in Table 1. Therefore, the total site risk depends upon the number of NPPs in a site and the safety level of each NPP as explained in Section 4.3 with Figs. 5 and 6. So if we manage the number of NPPs in a site and the safety level of each NPP, we can control the site risk as we want.

We can drive the answer for the third question from the above discussions regarding the first and the second questions. We do not have a general answer to the third question as well. We may need the site-specific MURA to get the quantitative answer to this question. However, we think that the large external hazards or the combined external hazards are the primary candidates for the MUI as in the Fukushima-Daiichi accident. The Tohoku earthquake is the strongest one ever measured in Japan. However, the earthquake itself did not cause the multi-unit accident. So it is expected that the size of the external or combined hazards that can cause the multi-unit accident should be huge. The occurring frequency of such huge external or combined hazards would be extremely low. So it is reasonable that the frequencies of multi-unit accidents are also very low, and the multi-unit risk due to the simultaneous accidents is low as well.

As mentioned earlier, the multi-unit risk has become an important issue in several countries, and various studies on the MURA are on-going. We still have many issues to be resolved for the complete MURA. However, we have ways to find valuable insights for managing the site risk, i.e., to prevent the core damages and containment failures of multiple units if we focus on the site risk management rather than the value of the site risk itself.

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References

[1] Y.A.N.G. Joon-Eon, Fukushima Dai-ichi accident: lessoned learned from the risk perspective, Nuclear Engineering and Technology 46 (1) (Feb. 2014).

[2] A. Stutzke, Scoping estimates of multiunit accident risk, in: Proceedings of Probabilistic Safety Assessment and Management (PSAM 12), June 2014 (Honolulu, Hawaii).

[3] U.S. Nuclear Regulatory Commission, Resolution of Generic Safety Issues: Task CH2: Design (NUREG-0933), Washington, D.C, 2011.

[4] U.S. Nuclear Regulatory Commission, Code of Federal Regulations, 10 CFR 50, Appendix a – General Design Criteria for Nuclear Power Plants.

[5] U.S. Nuclear Regulatory Commission, Reactor Safety Study – an Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants (WASH-1400), Washington, D.C, 1975.

[6] IAEA, Basic Safety Principles for Nuclear Power Plants, 75-INSAG-3 Rev. 1, INSAG-12, 1999.

[7] U.S. Nuclear Regulatory Commission, Code of Federal Regulations, 10 CFR 100.11, Determination of Exclusion Area, Low Population Zone, and Population Centre Distance.

[8] Pickard Lowe, Garrick, Inc, Seabrook Station Probabilistic Safety Assessment – Section 13.3 Risk of Two Unit Station, Prepared for Public Service Company of New Hampshire, PLG-0300, 1983.

[9] K.N. Fleming, Application of probabilistic risk assessment to multi-unit sites, in: Presented to the National Academy of Sciences Fukushima Committee, June 24, 2013.

[10] T. Hakata, Seismic PSA method for multiple nuclear power plants in a site, Reliab. Eng. Syst. Saf. 92 (2007) 883–894.

[11] U.S. Nuclear Regulatory Commission, NRC Action Plan Developed as a Result of the TMI-2 Accident (NUREG-0660), Washington, D.C, 1980.

[12] U.S. Nuclear Regulatory Commission, Proposed Commission Policy Statement on Severe Accidents and Related Views on Nuclear Reactor Regulation, SECY-82-1B, Washington, D.C, 1982.

[13] C.W. Carthew, F.A. Knautz, G.T. Chan, The design of the vacuum building for pickering generating station, Nucl. Eng. Des. 23 (2) (November 1972).

[14] S.D. Weerakkody, Results of screening of proposed generic issue PRE-GI-0001, in: Multiunit Core Damage Events,” Memorandum, 2013.

[15] Changkyung Seong, Gyunyoung Heo, Sejin Baek, Ji Woong Yoon, Man Cheol Kim, Analysis of the technical status of multiunit risk assessment in nuclear power plants, Nuclear Engineering and Technology 50 (2018).

[16] T.D. Le Duy, D. Vasseur, E. Serdet, Probabilistic safety assessment of twin-unit nuclear sites: methodological elements, Reliab. Eng. Syst. Saf. 145 (2016) 250–261.

[17] S. Zhang, J. Tong, J. Zhao, An integrated modeling approach for event sequence development in multi-unit probabilistic risk assessment, Reliab. Eng. Syst. Saf. 155 (2016) 147–159.

[18] C.S. Kumar, V. Hassija, K. Velusamy, V. Balasubramaniyan, Integrated risk assessment for multi-unit NPP sites – a comparison, Nucl. Eng. Des. 293 (2015) 53–62.

[19] US NRC, Research Activities FY 2018-2020, NUREG-1925, Rev, vol. 4, 2018.

[20] Joon-Eon Yang, Development of Site Risk Assessment and Management Technology Including Extreme External Events, KAERI/RR-4225/2016, Korea Atomic Energy Research Institute, 2017.

[21] H.-G. Lim, D.-S. Kim, S.H. Han, J.-E. Yang, Development of logical structure for multi-unit probabilistic safety assessment, Nucl. Eng. Technol. 50 (2018) 1210–1216.

[22] S.H. Han, K. Oh, H.-G. Lim, J.-E. Yang, AIMS-MUPSA software package for multi-unit PSA, Nucl. Eng. Technol. 50 (2018) 1255–1265.

[23] D.-S. Kim, S.H. Han, J.H. Park, H.-G. Lim, J.H. Kim, Multi-unit Level 1 probabilistic safety assessment: Approaches and their application to a six-unit nuclear power plant site, Nucl. Eng. Technol. 50 (2018) 1217–1233.

[24] J. Cho, S.H. Han, D.-S. Kim, H.-G. Lim, Multi-unit Level 2 probabilistic safety assessment: Approaches and their application to a six-unit nuclear power plant site, Nucl. Eng. Technol. 50 (2018) 1234–1245.

[25] S.-Y. Kim, Y.H. Jung, S.H. Han, S.-J. Han, H.-G. Lim, Multi-unit Level 3 probabilistic safety assessment: Approaches and their application to a six-unit nuclear power plant site, Nucl. Eng. Technol. 50 (2018) 1246–1254.

[26] IAEA International Workshop on the Safety of Multi-unit Nuclear Power Plant Sites against External Natural Hazards, Mumbai, India, October 17–19, 2012.

[27] Shahen Poghosyan, Ovidiu Coman, IAEA activities on multi-unit PSA and risk aggregation, in: International Workshop on Status of Site Level PSA (Including Multi-unit PSA) Development, Munich, July 2018.

[28] Matthias Krause, IAEA coordinated research project on PSA benchmarks for multi-unit/multi-reactor sites, in: International Workshop on Status of Site Level PSA (Including Multi-unit PSA) Development, Munich, July 2018.

[29] Smain Yalaoui, Akl Yolande, WGRISK Site-level PSA Project: Status Update and Preliminary Insights for the Risk Aggregation Focus Area, PSA 2017, Pittsburgh, PA, September 24-28, 2017.

[30] W.S. Jung, Joon-Eo E. Yang, J. Ha, A new method to evaluate alternate AC power source effects in multi-unit nuclear power plants, Reliab. Eng. Syst. Saf. 82 (2003) 165–172.

[31] J.J. Ha, Safety goals - for A unit or site?, in: 2001 ANS Winter Meeting, USA, 2001.

[32] Canadian Nuclear Safety Commission, Regulatory Document REGDOC 2.4.2, Probabilistic Safety Assessment for Nuclear Power Plants, 2014.

[33] Canadian Nuclear Safety Commission, in: Summary Report of the International Workshop on Multi-unit Probabilistic Safety Assessment, 2014.

[34] Lisa Bengtsson, Jan-Erik Holmberg, Jukka Rossi, Michael Knochenhauer, Probabilistic Safety Goals for Nuclear Power Plants, Phases 2-4/Final Report, 2011. Report number: 2010:35 ISSN: 2000-0456.

[35] M.D. Muhlheim, G.F. Flanagan, W.P. Poore III, Initiating Events for Multi-reactor Plant Sites (ORNL/TM-2014/533), Oak Ridge National Laboratory, Oak Ridge, TN, 2014.

[36] Keisuke Kondo1, Toshio Teragaki1, Hiroshi Abe, Development of Multi-unit Seismic Response Correlation and Level 1 Seismic PRA Model, SMiRT-23, Manchester, United Kingdom - August 10-14, 2015.

[37] Fukushima Nuclear Accident Analysis Report, Tokyo Electric Power Company, Inc., 2012. June 20.

[38] S. Schroer, M. Modarres, An event classification schema for evaluating site risk in a multi-unit nuclear power plant probabilistic risk assessment, Reliab. Eng. Syst. Saf. 117 (2013) 40–51.

[39] M. James, Acton and Mark Hibbs, Why Fukushima Was Preventable, The Carnegie Papers, Nuclear Policy, March 2012.

[40] Jung Han Kim, Min Kyu Kim, In-Kil Choi, Daegi Hahm, Preliminary research on the quantification of failure frequency by multi-hazard, in: Transactions of the Korean Nuclear Society Autumn Meeting, Gyeongju, Korea, October 26-27, 2017.

[41] Yasushi Okano, Hidemasa Yamano, Study on combination hazard curve of forest fire with lightning and strong wind, in: Asian Symposium on Risk Assessment and Management 2017, PACIFICO Yokohama, Yokohama, Japan, 13 - 15, November 2017.

[42] U.S. Nuclear Regulatory Commission, Safety Goals for Nuclear Power Plant Operation, (NUREG-0880), Rev. 1, for Comment, Washington, D.C, 1983.

[43] Mohammad Modarres, Probabilistic risk assessment of multi-unit nuclear power plant sites: advances and implication on the safety goals, in: Seminar Presentation, Ohio State University, Department of Mechanical and Aerospace Engineering, 2016.

[44] Mohammad Modarres, Some misconceptions about multi-unit PSAs, in: International Workshop on Status of Site Level PSA, Munich, Germany, 2018.