GAP ANALYSIS BETWEEN SINGLE-UNIT AND MULTI-UNIT PSAs FOR KOREAN NPPs

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I. INTRODUCTION

On June, 2016, the Nuclear Safety and Security Commission (NSSC) of Korea approved the construction permit for Shin-Kori Units 5 and 6. This means that a total of nine nuclear power plants (NPPs) will be operating within approximately five kilometers of one another on a single site (decommissioning of Kori unit 1 slated for 2017.) The fact that there are two metropoles located at distances of 30 kilometers to the north and southeast of the site is obviously of serious concern to the public as well as nuclear experts, particularly considering the recent Fukushima disaster. Furthermore, the simultaneous core damage at Units 1-3 and hydrogen explosion at Unit 4 spent fuel pool by inter-unit interaction in the Fukushima Daiichi Power Stations has raised a serious issue of multi-unit risk and vulnerability of NPPs to inter-unit interactions. During the licensing review process for Shin-Kori Units 5 and 6, and even for Shin-Kori Units 3 and 4 earlier, there was a heated debate as to whether multi-unit risk is adequately covered by the current regulations, or otherwise the regulations should be reinforced especially in view of the high-density nuclear power plant sites in Korea.

The interest in multi-unit PSA in Korea actually began before the Fukushima accident, with the Ministry of Science, ICT and future Planning (MSIP)'s provision of support for the R&D programs of the Korea Atomic Energy Research Institute (KAERI) to carry out fundamental researches for multi-unit PSA. Recently, as tangible results of such research have become available, Korea's nuclear utility has begun conducting a pilot multi-unit PSA on a specific site. At the same time, the NSSC launched to develop an R&D roadmap for multi-unit PSA so that multi-unit risk can be adequately addressed by the utility. It is expected that appropriate regulatory measures will be taken by the NSSC once sufficient insights are gained for the multi-unit site risk.

This paper presents a technical gap between single- and multi-unit PSAs and the particular issues in South Korea as observed in our preliminary study to assist the NSSC in developing the R&D roadmap.

II. SUMMARY OF COMMISSIONERS' CONCERNS

The NSSC has held in-depth discussions on the issues of multi-unit risk assessments, and the records of such discussions have been fully disclosed to the public. By itemizing the main issues presented in those records, the authors of this paper would like to share the Commissioners' concerns regarding multi-unit risk.

- What would happen if all units of a multi-unit power plant failed simultaneously, and released all of their radioactive sources together? Would there be any domino or cascade effect, where a single-unit failure could be propagated to other units?
- How do we define a "site"? On the east coast of Korea, there are three NPP sites, separated by distances of 50 and 150 kilometers. In the event of a major disaster, could these three NPP sites be considered as separate sites?

- Even though there is no internationally accepted methodology for evaluating multi-unit risk, the regulatory authority must adopt the most highly developed methodologies and use the most advanced technologies, as Korea is a country that could face major challenges in terms of multi-unit NPPs.

In Korea, there has been no PSA in place for dealing with multi-unit safety issues. However, the regulations in Korea prevent the propagation of damage at nuclear sites by ensuring the adequate separation of all units and minimizing the influence of external hazards by selecting the most appropriate locations for the facilities.

- Article 10 of the Nuclear Safety Act (Construction Permits) states that any person who wishes to apply for a construction permit must submit two documents to the NSSC: a preliminary safety analysis report and a radiation effects and liability document.
- Chapter 2 (Nuclear Facility Technical Standards), Section 1 (Nuclear Facility Location), Article 10 (Multi-unit Construction) of the Ministerial Ordinances on Technical Requirements Applying to Nuclear Installations (see NSSC Regulations, Vol. 13) states that facilities should be adequately separated from each other.

Furthermore, the technical advisory committee of the NSSC has responded that the construction of Shin-Kori Units 5 and 6 is in compliance with the multi-unit safety protocols of the International Atomic Energy Agency (IAEA), in consideration of the appropriateness of the locations of the facilities, positive results of the environmental impact assessment, removal of shared facilities, and installation of an alternative AC power source for individual units (Ref. 1). Nevertheless, it should be noted that a well-developed methodology is required for multi-unit risk assessment, separate from that of single-unit risk, to improve the safety levels of multi-unit nuclear installations. In particular, the Korea Institute of Nuclear Safety (KINS) has also emphasized that conducting a multi-unit PSA is crucial when adding a new unit to an existing NPP site, and that external hazards and shared facilities require appropriate countermeasures (Ref. 2).

III. UNIQUE NATURE OF KOREAN MULTI-UNIT NPPs

II.A. Challenges of Emergency Response

The most serious challenge facing Korean NPPs is the high-density populations located near the plant sites. Kori units 1 to 4 and Shin-Kori units 1 and 2 are located along the same administrative boundary (Busan), and Shin-Kori units 3 and 4 are operating on the next boundary (Ulsan), situated along the northeast side of a small river, as shown in Figure 1 (left). Shin-Kori units 5 and 6 are currently under construction on the boundary with Ulsan. Figure 1 (right) shows the location of the nearby metropoles of Busan and Ulsan.

Fig. 1. Layout of the Kori site (left) and location of nearby metropoles (right)

Even though the legal requirements for the current nuclear site are well satisfied, in the event of an accident, the emergency response, including evacuation and/or relocation, will be crucial. This is essentially the same for single-unit sites. In the case of a multi-unit accident, however, it is obvious that the amount of source terms will be higher. Considering that the impact on human life and the environment could occur in a nonlinear fashion, it is of great importance to have an effective emergency response system in place.

II.B. Variety of Accident Scenarios

Traditionally, a PSA, say for Unit 1 in a 3-unit site, was performed for Unit 1 primarily focusing on this unit alone with little attention to the condition of other units. In some PSAs conducted lately, LOOP (Loss of Off-site Power) initiating events are divided into single-unit LOOP and multi-unit LOOP. In the case of multi-unit LOOP, the availability of the AAC diesel generator is calculated taking into account the possibility that it might not be available to Unit 1 since it is used by other units.

Unit 1 PSA was mostly carried out thus far without paying attention to the operational states of other units. In other words, some of the Unit 1 accident sequences might also lead to the accident sequences at Unit 2, Unit 3, or both of Units 2 and 3. These sequences are shown in dotted arrows in Figure 2. As far as the risk evaluation is limited to Unit 1 alone, these propagating sequences may not need to be separately identified since it will require considerable additional analysis in connection with the states of other units.

However, in order to more adequately evaluate the Unit 1 risk, those accident sequences that are initiated in Unit 2 or 3, but propagated to Unit 1 (i.e., the four bold arrows in Figure 2) should be identified. In order to identify those sequences propagating from other units to Unit 1, the tasks that need to be conducted basically include the following:

- Objective: Identify the accident sequences originating in Unit 2 or 3 that could propagate to Unit 1 under certain circumstances. The annual frequencies of these accident sequences should be added to the Unit 1 risk, which was evaluated without due consideration of the other units.
- Assumption: Units 1, 2, and 3 are different types of NPPs, and thus, the accident sequences for these units are not symmetrical.
- Analysis Method: (a) Define the normal operational conditions of each unit over one year in consideration of the organizational policy (e.g., power operation, hot shutdown, cold shutdown, and refueling); and b) in consideration of the operational conditions, identify the initiating events and accident sequences originating in Unit 2 or 3 that have the potential to propagate to Unit 1, resulting in fuel damage in and/or radiological release by Unit 1.

Note that the accident sequences which will get started in Unit 2 or 3 might cause an accident in Unit 1 while Unit 1 is in power operation or shutdown. If such an accident propagation happens while Unit 1 is in power operation, then those sequences from other units should be added to the Unit 1 PSA for power operation mode. If such an accident propagation happens while Unit 1 is in shutdown mode, then those sequences from other units should be added to the Unit 1 PSA for shutdown mode. Since the results of a single-unit PSA are typically used as a part of the decision making process in evaluating the nuclear power plant risk, it is important to develop a methodology for identifying those missing risk elements from a site risk perspective.

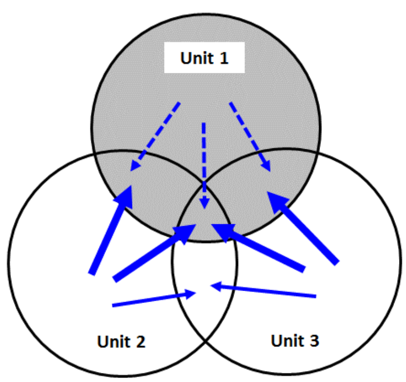

Fig. 2. Accident sequences propagating from other units

As outlined above, Korean NPPs have unique features. For instance, the reactors shown in Figure 1 are of five different reactor types: Westinghouse 587 MWe, 650 MWe, and 950 MWe, OPR-1000, and APR-1400. Furthermore, Shin-Kori units 3 and 4 and Shin-Kori units 5 and 6 are considered to be identical reactors, but as there are minor design differences between the units, they are not actually identical. Therefore, it seems unreasonable to establish multi-unit PSA models based on the assumption that the reactors are identical, which was the usual approach in previous pilot studies.

Meanwhile, the various operation modes of each entity on a site (e.g., reactor, spent fuel pool) at a specific moment are also of concern. For example, the authors conducted a simple Monte Carlo simulation to calculate a steady-state combination of operational modes in which all six NPPs are in operation, taking into consideration the nuclear utility's typical overhaul plan. It was found that the fraction of full-power operation for all plants was around 43 percent; that of the shutdown for one unit was 42 percent, and for two units, it was 14 percent. Based on this result, it can be concluded that multi-unit PSA models combining full-power and low-power/shutdown operational modes, as mentioned above, need to be created. Concerning the issues of the low-power/shutdown operational mode, the contribution from spent fuel pools needs to be taken into account as well. Another factor that requires consideration is the fact that the Wolsong NPP site features dry cask storage, and other sites may install interim dry casks in the future. This may serve to complicate the analysis further.

II.C. Less Concerned about SSCs, More Concerned about Nature

There are three situations that can lead to multi-unit events: a) an internal event in a certain unit that propagates to the other units, where it initiates new events (referred to as "Propagation" in Table 1), b) events in both units that occur simultaneously but independently, and c) a single event that has a common effect on both units (referred to as "Common" in Table 1).

Sometimes, the sharing of systems, structures, and components (SSCs) among NPPs is necessary, due to engineering constraints. Although not all domestic NPPs were observed, it was found that the safety issues related to the sharing of SSCs were negligible. It was confirmed that the instrument air, power supply (switch yard, etc.), and seawater intake systems were the only shared facilities that could influence accident management. Moreover, it was found that the amount of shared SSCs is decreasing as new NPPs are constructed. Therefore, it seems reasonable to conclude that an internal event in a single unit is very unlikely to propagate to other units, meaning that the accident management required for internal events of a single unit is not influenced by events in the others.

Meanwhile "nature" serves as a multi-unit initiator; here, "nature" refers to external events and human errors. The following is a summary of the types of events that have occurred at NPPs in South Korea. The types of multi-unit events listed in Table 1 are not official classifications, but have been classified by the authors based on the known history of the events.

TABLE I. Multi-unit events in Korea

Site/Unit	Cause	Classification
Site A 3, 4	Typhoon	Common
Site A 1, 2	Grounding	Common
Site A 1,2,3,4	Typhoon	Common
Site B 1, 2	Grounding	Common
Site B 1, 2	Heavy Snow	Common
Site B 1, 2	Marine organism	Common
Site B 1, 2	Marine organism	Common
Site B 1, 2	Forest fire	Propagation
Site B 1, 2	Marine organism	Common
Site B 1, 2	Marine organism	Common
Site C 5, 6	Grounding	Propagation
Site A 1, 2	Typhoon	Common
Site B 1, 2	Marine organism	Common
Site A 3, 4	Component fault	Propagation
Site A 1, 2	Lightning	Common
Site A 3, 4	Human error	Propagation

According to the event reports provided by KINS (Ref. 3), most of the initiators of multi-unit events were triggered by external events, particularly, typhoons and marine organisms. Although earthquakes occur relatively infrequently in Korea and have small magnitudes, their threat should not be underestimated, especially as they are practically impossible to predict in a timely manner. Korea's NPPs are equipped with automatic reactor shutdown systems that are initiated when an earthquake event exceeding a certain threshold occurs, but there has so far been no earthquake strong enough to trigger the system. Typhoons, on the other hand, are quite predictable, leading many to believe that they are not critical events. However, there have been cases where reactors have been unexpectedly shutdown due to typhoons. Characterized by strong winds and heavy rain, typhoons have been increasing in terms of both strength and frequency. Considering the nature of complex disasters, external events should be considered the most important factor in multi-unit accident analysis.

Another significant contributor is human-induced events, which are less influential than the general external events in terms of area and scope. Nonetheless, mistakes made by NPP personnel while working on power supply systems are likely to initiate multi-unit events.

III. TECHNICAL ISSUES OF MULTI-UNIT PSAs

In order to identify the technical issues associated with multi-unit PSAs, the authors examined materials from international and domestic journals, conferences, and technical reports, and classified them into several categories. The results are shown in TABLE II. Two points should be noted: the literature was limited to materials that had been published after 2011, and this paper focused only on the issues of multi-unit PSAs, where possible. Many of these issues are the same as those of single-unit PSAs, so we attempted to narrow them down for ease of understanding.

The technical issues of multi-unit PSAs can be classified under initiating events and dependency. The authors subdivided initiating events into event classifications, internal events, and external events, and dependency into scenario modeling, common cause failures (CCF), off-site consequences, and human error. Furthermore, the publications of overall multi-unit PSA status reports and quantitative metrics are divided as well.

TABLE II. Classification of research

Classification		Journals	Conferences
Initiating Events	Classifications	1	6
	Internal Events	0	1
	External Events	6	15
Dependency	Scenario Modeling	12	7
	Common Cause Failures	4	3
	Offsite Consequences	0	2
	Human Error	0	3
Other	PSA Status	3	7
	Quantitative Measures	1	7
Total		27	51

- Initiating Events

The classification of initiating events that lead to a series of incidents, as well as the analysis of their frequency, is crucial. Regarding initiating events, a number of papers have dealt with external events, such as earthquakes, tsunamis, and typhoons. External events pose the same technical challenges as those of single-unit analysis. For example, in calculating frequency, there is a tendency to estimate hazard curves conservatively, due to the high uncertainty involved, leading to the override of internal event cut sets in risk aggregation. In the case of complex disasters, it is necessary to develop the combined hazard and fragility curves of two or more simultaneous events. Furthermore, the analysis of external incidents goes beyond the scope of general nuclear engineering—as it incorporates multiple viewpoints from various fields of study, including geoscience, geology, meteorology, oceanography, climatology, and structural engineering—which makes technical sophistication all the more challenging.

- Dependency

Many technical issues related to multi-unit safety arise from the high degree of inter-unit dependency. Considering that total risk is defined as the multiplication of the severity of possible consequences with the likelihood of their occurrence, inter-unit dependency will have the following outcomes.

Normally, in an independent event, the probability of simultaneous multi-unit failures is almost zero; however, high levels of inter-unit dependency serve to reduce isolation, eventually increasing the likelihood of detrimental events. For instance, the likelihood of seismic events will be the same regardless of single- or multi-units while they have a direct impact on all units together such that the risk is likely to be increased. Inter-unit dependencies also heavily influence the severity of core damage, due to the non-linear impact of radiation sources, domino effects, and inter-unit CCFs.

From a technical point of view, inter-unit dependency issues include the classification of multi-unit initiating events, scenario analyses, inter-unit CCFs, staff/organization dependencies, emergency preparedness, and so on. Inter-unit dependencies increase the quantity of computing workload at an exponential rate. This is likely why such a large number of papers address the issue of scenario modeling. The calculation of common cause component group (CCCG) for multi-units may result in calculation deluge. it will likely take quite some time to find a realistic solution to this problem, as there is no proper parametric method for addressing the CCCG shared among six to ten NPPs.

As mentioned earlier, external events should be the main initiator, and the inter-unit CCF of external events should have significant impact. If the inter-unit CCF is estimated to be too weak or too strong, it will be much more difficult to find realistic results. In the event of a seismic event, international collaboration is required, particularly for Korea, where earthquakes are quite rare.

Inter-unit CCF is not only a matter of hardware. In the event of a single-unit accident, staffs may be shared among units, which is a significant advantage. In the event of a multi-unit accident, however, personnel support from outside may be necessary. In addition, accessibility to the site would be hampered, making it difficult to ascertain whether accident management could be conducted properly within the site. This calls for increased support for research on human and organization reliability analyses for multi-unit accidents.

VII. CONCLUSIONS

In Korea, the legislation that has made PSAs compulsory as a means of preventing and mitigating severe accidents nearly two decades after the Nuclear Safety Policy Statement of 1994 and the Severe Accident Policy Enactment in 2001 certainly seems like a step in the right direction in terms of nuclear safety. However, there is a general consensus that even the single-unit PSA requires much improvement in order for such legislation to serve as an adequate regulatory measure. The nuclear utility and regulators are required to conduct sufficient, realistic, and objective risk assessments in order to meet the rapidly increasing demand for multi-unit PSAs. At the same time, they are striving to achieve matching levels of technological development.

The technical issues associated with multi-unit PSAs that were not mentioned in this paper are essentially the same as those of their single-unit counterparts; therefore, reinforcing the basic infrastructure of PSAs in general will help resolve such technical issues of multi-unit PSAs. This is described in detail in the cited work published by the Korea Nuclear Society (Ref. 4). It is obvious that the results of a single PSA from a certain point in time cannot be used as the standard quantitative indicator for the entire unit; ensuring that the quality of PSAs can be increased through continuous improvement is therefore crucial. Whether such technical grounds would require a new legal system or deeper understanding of the stakeholders within the existing system is a question that remains to be answered.

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