

Literature Survey on Technical Issues and Insights of Multi-Unit PSA

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1. Introduction

The conventional PSA (Probabilistic Safety Assessment) has focused on the risk of single-unit, however, there are more than two units at a site in the Republic of Korea. The need consider the risk impact in case of multi-unit in a single site increased after the accident at Fukushima Daiichi in March 2011. This means that we have to consider the single-unit initiators impacting the other units and the simultaneous accidents of the multi-unit on the same site. Particularly, this kind of technical concern is serious in case of the Republic of Korea where multi-units had to be located in high-density population area due to geographical features.

The Nuclear Safety and Security Commission (NSSC) in the Republic of Korea has been trying to identify the state of the art of international and domestic regulations and techniques on multi-unit risk assessment and planning the road map for the safety researches.

However, we have to say that finding a common accepted methodology along with safety criteria for multi-unit PSA was not an easy task up to now.

This paper summarizes and analyzes related international and domestic journals' papers, conferences' papers and reports about the multi-unit PSA classifying categories with themes to understand the technical tendency of multi-unit PSA. In addition, some insights that were obtained from this classification have been arranged too.

The literatures in this paper are limited to those which were published during and after 2011.

2. Descriptive Statistics: Classification

Since 2011 up to now, about the 100 papers associated with multi-unit PSA are selected from literatures by using the keywords such as "nuclear power plant accident", "risk", "multi-unit", "external event" and so on. We classified the papers with year-based, country-based and topic-based and summarized the main contents that can be related to multi-unit PSA. The collected international and domestic journals papers, conferences papers and reports were 27, 51 and 26, respectively. However, reports were excluded from the classifications due to the low significance as statistic and also the reports are surveyed only by the language of Korean and English.

2.1 Year-based Classification

The number of journals and conferences published from 2011 is shown in the Table 1. The conferences papers which have addressed relatively fast tendency of the issue are more published than the journals. Most of the papers were published in 2014; three years after Fukushima accident. Although reports are not addressed in the Table 1, we found out that many related reports have been published domestically when the government project for multi-unit PSA was started in earnest on 2015.

Table 1. Statistic of Year-based Classification

Year	Journals	Conferences
2011	2	1
2012	1	7
2013	4	10
2014	9	18
2015	4	12
2016	7	3
Total	27	51

2.2 Country-based Classification

The attention of multi-unit PSA has been issued globally after the accident at Fukushima Daiichi. Thus, the countries which don't have a severe problem about multi-unit also present various opinions for the multi-unit PSA.

The U.S.A had already conducted tasks about multi-unit PSA such as Seabrook PSA [1], Modular HTGR PSAs and Bryon/Braidwood PSA for Risk-informed Tech. Spec. Evaluation and so on before 2011[2]. Likewise, we concluded the U.S.A that have outstanding capability for the multi-unit PSA is currently in the top level with pacesetting technique. Not limited to U.S.A the Republic of Korea which has urgent multi-unit problem published many papers, and the Europe contributed to the multi-unit PSA, too. Although, Canada which has urgent multi-unit problem due to many of shared connections has not published many of official papers, it published many proceedings performed by the workshops with experts. [3]

The number of journals and conferences published in the last 6 years are shown in the Table 2. The country

classification standard was done regarding the affiliated institute of corresponding author and the publications of the multinational experts are classified as etcetera.

Table 2. Statistic of Country-based Classification

Country	Journals	Conferences
Canada	1	2
U.S.A	4	17
EU	7	12
South Korea	4	14
Japan	2	0
China	2	2
India	4	0
Hong Kong	0	1
Taiwan	2	0
UAE	1	1
etc. (IAEA)	0	2
Total	27	51

2.3 Topic-based Classification

The technical problem confined by the multi-unit PSA could be classified as initiating event and dependency [4]. In this paper, we subdivided initiating event into event classification, internal event and external event and dependency into scenario modeling, common cause failure (CCF), off-site consequence and human error. Furthermore, publications of overall multi-unit PSA status report and quantitative metric were divided separately. The result is shown in the Table 3.

Among all of the initiating events, the number of papers of external event such as an earthquake, tsunami and typhoon were the most. While the number of papers related to scenario modeling were the most in term of dependency.

Table 3. Statistic of Topic-based Classification

Classification		Journals	Conferences
Initiating Event	Event Classification	1	6
	Internal Event	0	1
	External Event	6	15
Dependency	Scenario modeling	12	7
	CCF	4	3
	Off-site Consequence	0	2
	Human Error	0	3
etc	Status Report	3	7
	Quantitative Metric	1	7
Total		27	51

3. Technical Issues and Insights

The papers associated with the multi-unit PSA were classified into 3 themes in section 2.

In this section, we arranged the technical issues and insights of the representative journals and conferences of each as a topic-based classification. Thus, we could find that research situation was different based on the topics. Among 7 items of topic-based classification except for status report and quantitative metric, the researches focused on dealing with event classification, external event and scenario modeling that have been studied briskly. However, we could identify the lack of research in the cases of internal event, CCF and off-site consequence.

The reason of this situation maybe came from the relative priority of the event classification which can be considered as a cornerstone of the multi-unit PSA, the external event was introduced because of Fukushima Daiichi accident, and the scenario modeling was required to set up a methodology. But, it doesn't seem to be enough supplements for the CCF, off-site consequence and human error that were pointed out due to their high uncertainties. Following is the summarized contents of the representative papers for each topic-based classification.

■ Event Classification

- The causes of the dependency in a nuclear power plant are initiating events, shared connections, identical components, proximity dependencies, human dependencies, organizational dependencies and so on. And with this, the initiating events can be classified again with the multi-unit point of view. It can be classified to Definite and Conditional that influence certainly and only in the particular condition to the multi-unit, respectively. And these events such as LOOP (Loss of Off-site Power) accident and SGTR (Steam Generator Tube Rupture) accident, respectively. The analyzed result of event reported in LER (Large Early Release) can show us that the 7 % of the ratio caused by initiating events, 34 % by shared connections and 41 % by organizational dependencies [5].

■ Internal Event

- CDF (Core Damage Frequency) is increased about 5~9 % when the dual-unit LOOP is considered in the existing single-unit PSA model [6]. In the case of multi-unit event caused by internal event is usually not treated severely.
- The calculation of LOOP frequency considering the impact of the multi-unit and the composition of LOOP event tree for the dual-unit on the site [7].

■ External Event

- The external events include natural disasters. In addition, among of these external events, seismic event, the causes of the SBO (Station Black-Out) and LOCA (Loss of Coolant Accident) is the biggest impacting factor for the multi-unit.
- On a multi-unit site, a seismic event can produce a multi-unit accident due to the independent combinations of component failures and seismically correlated failures. Unless the small number of shared structure on the Seabrook station, it is important that the level of contribution to the multi-unit event caused by an external event. [1][8]
- The analysis about the earthquake and tsunami considering the multi-unit is performed. Using the correlation of inter-unit, inter-structure, geology and so on, the seismic response is analyzed and also the correlation of the independent, conditional dependent and completely dependent is used to calculate the CDF into the site unit [9].

■ Scenario Modeling

- The definition of the site CDF was obtained using Boolean algebra and the methodology of the scenario modelling of the Define, Conditional, internal and external events was suggested. And with this, the site CDF for the 4 reactor unit was calculated. The result of the calculation showed that the ratio of the external event is increased and earthquake influences considerably when the reactor units are increased on a site [10].
- A multi-unit PSA is conducted by LOOP accident sequence modelling which was analyzed by multi-branch node, phased evolution method, multi-unit fault tree and so on in the HTGR (High-Temperature Gas cooled Reactor). However, they used RC (Large) frequency as an evaluation indicator instead of the general CDF or LERF[11].

■ CCF (Common Cause Failure)

- If the current single-unit safety level is not changed, the integrated risk in a site of the multi-unit will be increased due to the increase of the risk of the public resided in the area nearby the site. And the technical factors (quantification of integrated risk, consideration of unavailability and teamwork for the human reliability etc.) are existed to apply the ASME PRA to the multi-unit as a methodology. The risk is increasing when the common components of inter-unit is getting bigger [12].
- The potentiality between the reactor and SFP (Spent Fuel Pool) is also existed in a single-unit site. In addition, the possibility of risk is

increased in a multi-unit site which has common components [13].

- The CCF evaluated by a single-unit based is many but, the CCF research based on the multi-unit is judged in insufficiency.

■ Off-site Consequence

- The release categories and PDS (Plant Damage State) have to be included for accident sequences involving one and more units at the site. And accident progression for different core damage scenarios and interactions among the units has to be considered. In addition, if it is applicable, dependency of the inter-stations A and B should be considered, too [14].
- U.S Nuclear Regulatory Commission (NRC) calculated the risk of multi-unit on a site to solve the problems for the multi-unit PSA. The result performed with an assumption that identical and consequence of inter-unit are proportional to the number of reactor-units, showed us that the multi-unit risk is n times or n^2 times bigger than the single-unit risk schematically and conservatively [15].

■ Human Error

- The research of multi-unit PSA considering a human error is conducted for the double-unit on a site. The upgraded PSA model considering dependencies was suggested. To improve the multi-unit PSA, the simple summation of CDF of double-unit and CDF considering the double-unit accidents at the same time were used [16].

■ Status Report

- The current CANDU PSA results (CDF&LRF) are calculated by a single-unit based. Risk at the site level cannot yield simply by multiplying CDF by the number of units. The Canadian Nuclear Safety Commission (CNSC) has been working on developing site-base safety goals and making whole-site PSA for Pickering station that would be completed in 2017 [14].
- New risk metrics (Site based) which needed to capture the risk profiles for integrated site safety assessments are being developed as a part of the IAEA Working Area eight safety reports being developed to provide guidance for future site safety risk assessments [17].
- Site based risk metrics should be used in risk-informed decision making. Prevention and mitigation of multi-unit accidents need to be addressed in deterministic safety principles. And the safety significance of shared systems and structures, and application of GDC 5 need to be reconsidered in the context of the multi-unit safety assessment [18].

■ Quantitative Metric

- Suggesting Site CDF or Site LERF conceptually. And the current single-unit based frequency should be expressed to site based frequency suggestion is proposed [9].

4. Conclusions

This paper investigated the technical trend of the multi-unit PSA as collecting of the international and domestic journals' papers, conferences papers and reports, and analyzing them. Upon the literature survey, a few statistics, technical issues, and insights were summarized. Both of the fundamental and practical researches need to find a globally accepted methodology to calculate and determine quantitative objectives for a multi-unit PSA. We want to expect that this paper can be shared to understand the current status of multi-unit PSA.

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