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Review Article

Analysis of the technical status of multiunit risk assessment in nuclear power plants

Changkyung Seong [a], Gyunyoung Heo [a, *], Sejin Baek [a], Ji Woong Yoon [b], Man Cheol Kim [c]

[a] Department of Nuclear Engineering, Kyung Hee University, 1732 Deogyeong-daero, Giheung-gu, Yongin-si, Gyeonggi-do, 17104, Republic of Korea
[b] Department of Public Administration, Kyung Hee University, 26 Kyunghee-daero, Dongdaemun-gu, Seoul, 02447, Republic of Korea
[c] School of Energy Systems Engineering, Chung-Ang University, 84 Heukseok-ro Dongjak-gu, Seoul, 06974, Republic of Korea

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ABSTRACT

Since the Fukushima Daiichi nuclear disaster, concern and worry about multiunit accidents have been increasing. Korea has a higher urgency to evaluate its site risk because its number of nuclear power plants (NPPs) and population density are higher than those in other countries. Since the 1980s, technical documents have been published on multiunit probabilistic safety assessment (PSA), but the Fukushima accident accelerated research on multiunit PSA. It is therefore necessary to summarize the present situation and draw implications for further research. This article reviews journal and conference papers on multiunit or site risk evaluation published between 2011 and 2016. The contents of the reviewed literature are classified as research status, initiators, and methodologies representing dependencies, and the insights and conclusions are consolidated. As of 2017, the regulatory authority and nuclear power utility have launched a full-scale project to assess multiunit risk in Korea. This article provides comprehensive reference materials on the necessary enabling technology for subsequent studies of multiunit or site risk assessment.

1. Introduction

Multiple nuclear power plants (NPPs) are often located together for technical and economic reasons. In Korea, 25 NPPs are operating at four sites. As of the end of 2016, Shin-Hanul Units 1 and 2 were waiting for an operating license, and if they are added, a total of eight NPPs will be operational at the Hanul site. In addition, 10 NPPs (including Kori Unit 1 scheduled to be closed in 2017) will be located at the Kori site after the operating license for Shin-Kori Units 3 and 4 and the construction permit for Shin-Kori Units 5 and 6 are approved. Locating several units on a single site provides economic benefits and eases in using resources for normal operation and accident mitigation, but it can lead to unpredictable results when a catastrophic event affects multiple units, as seen with the Fukushima Daiichi NPPs. In particular, the Fukushima accident has focused deserved attention on the dangers of region-wide or multiple external events, such as an earthquake and tsunami.

Setting a target value for a quantitative indicator is a process of social consensus and should be discussed separately, but calculating the quantitative indicator itself is a technical issue. However, because a methodology for evaluating multiunit or site risk has not been sufficiently established worldwide, site safety metrics and regulatory review standards have not been established.

Currently, the quantitative risk for individual NPPs is analyzed using a probabilistic safety assessment (PSA), but it is not appropriate to analyze multiunit risk by simply adding the risks of individual NPPs. For example, to qualitatively guess the frequency and consequence of accidents, which is required to calculate the multiunit risk, two identical plants A and B on the site are simply assumed. As shown in Fig. 1, accident frequency can be expressed as the sum of the frequencies of two single units and their common accidents. In other words, the frequency of accidents on a site decreases as the dependency between units increases. It is expected that the projected consequences of an accident will also vary according to the conditions. Fig. 2 shows the expected patterns of the consequences. When an accident occurs in two units within a short time interval, twice the amount of radioactive material will be released, and the consequences will double. However, if we assume a situation exceeding a threshold threatening human health, the

* Corresponding author.
E-mail addresses: ckdrud1718@khu.ac.kr (C. Seong), gheo@khu.ac.kr (G. Heo), sejin.baek@khu.ac.kr (S. Baek), jiwoongy@khu.ac.kr (J.W. Yoon), charleskim@cau.ac.kr (M.C. Kim).

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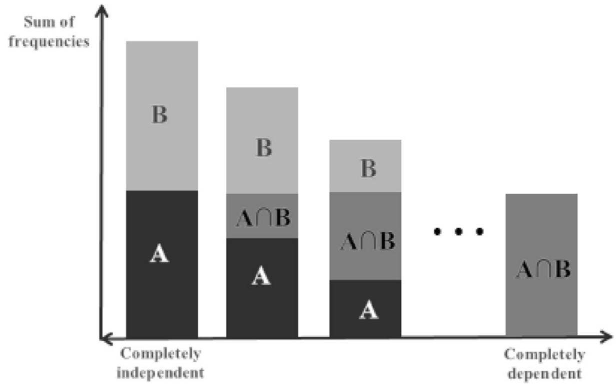

Fig. 1. Frequency of multiunit accidents (1).

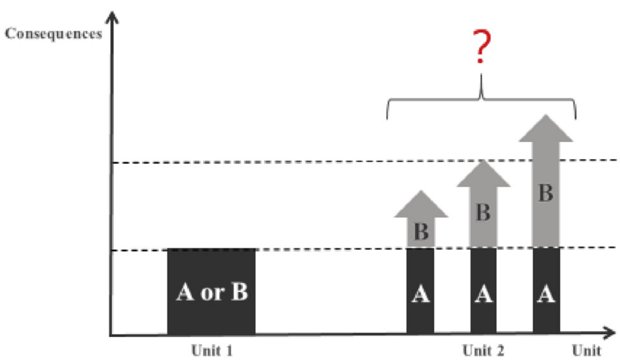

Fig. 2. Consequences of multiunit accidents.

consequences could be more than double, which could open a debate about the appropriate health or economic objectives. Meanwhile, if evacuation and emergency preparedness plans are working perfectly, the consequences will reach only a certain limit that is less than double of the amount in one reactor regardless of the increase in radioactive source terms. In conclusion, the risk represented by the product of the frequency and the consequences remains ambiguous, as shown in Fig. 3.

To obtain realistic multiunit risks, it is necessary to evaluate the dependency of every component in the PSA, such as initiators, mitigating systems, accident sequences, and emergency preparedness. The situation becomes even more complicated if the

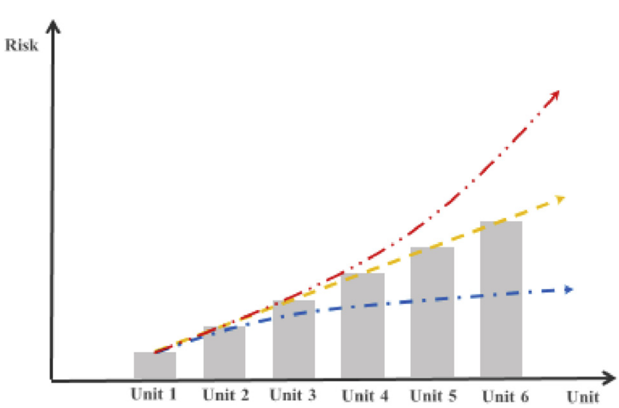

Fig. 3. Expected multiunit risk represented by frequency × consequences.

assessment takes into account a complex disaster that acts as a common initiator affecting multiple NPPs at the same time. It is well known that the uncertainty becomes larger as the level of the PSA increases. It is, therefore, obvious that interunit dependency under internal or particularly external initiators amplifies uncertainty and complicates interpretation.

Since the Fukushima accident, interest in multiunit accidents has increased significantly; in Korea, the number of NPPs per site and the population density around each plant area are relatively high. Therefore, the urgency and importance of evaluating multiunit risk are significantly higher in Korea than in other countries, and debates occur about the methods and criteria for dealing with multiunit and site risk assessments.

To provide a comprehensive reference on the enabling techniques necessary for subsequent studies, we reviewed and summarized journal and conference papers on multiunit and/or site risk assessments. The contents of the reviewed references are classified by technical status into the following categories: (1) research status, (2) risk metric or safety goal, (3) qualitative risk assessment, (4) quantitative risk assessment, (5) initiating event or initiator, (6) dependency data analysis, and (7) human reliability. We drew insights and summarized our conclusions.

2. Analysis of technical status

2.1. Overview

This study investigated the main technical elements and research status of multiunit and site risk assessment. For this purpose, we analyzed the journal and conference papers published from 2011 to 2016 on multiunit PSA. The articles we reviewed focused on multiunit and/or site risk; we deliberately excluded general PSA issues. In cases of multiple publications with the same content, we selected and analyzed the latest one. Technical elements are divided into the seven aforementioned categories. It should be noted that many publications cover several categories; therefore, the seven categories are not completely mutually exclusive. However, we attempted to reorganize the PSA technical elements systematically using definitions in the standards of the IAEA-TECDOC-1804 or ASME PRA standard [1,2]. For instance, in terms of International Atomic Energy Agency standards, "model integration and Level 1 PSA quantification" and "dependent failure analysis" are strongly related to categories (3) and (4), and "initiating event" and "hazard event" belong to category (5). Category (6) includes "data analysis" and category (7) is matched with "human reliability analysis (HRA)." A simple summary and statistics for the reviewed publications are shown in Table 1.

At present, there is no fully agreed upon methodology for multiunit PSA, and various studies of multiunit risk are ongoing. Several institutes are publishing their current research status and future studies. We also highlighted risk metrics and safety goals as they fit the multiunit situation. Generally speaking, the conventional surrogate risk metrics, such as core damage frequency (CDF) and large early release frequency (LERF), need to be

Table 1
Summary of the references reviewed.

Category	References	Number of articles
(1) Research status	[6–9]	4
(2) Risk metric or safety goal	[10–13]	4
(3) Qualitative risk assessment	[14–18]	5
(4) Quantitative risk assessment	[19–26]	8
(5) Initiating event or initiator	[27–33]	7
(6) Dependency data analysis	[34,35]	2
(7) Human reliability	[36]	1

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