Proposed Methodology to Estimate the Off-site Emergency Response Convocation Time during Multi-unit Accident Management using an Agent-Based Model

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***Keywords: Convocation Time, Emergency Response, Multi-unit Accident, Agent Based Model, PRISM-EC**

1. Introduction

The Fukushima Daiichi accident gave an important lesson to the nuclear industry that extreme external events beyond design-basis (hereinafter referred as *extreme events*) could present significant challenges to existing nuclear power plants (NPPs), even if such events are highly unlikely to occur. During extreme events (e.g. 2011 Tohoku earthquake and tsunami), NPP inter-unit dependencies (such as simultaneously occurring initiating events in multiple units, proximity of the units, and shared resources among the units) may inflict core damages to the multiple units if not properly managed. When such an event occurs, radiological emergency may be triggered with necessary procedures to mitigate and/or reduce damages from the accident.

In Korea, *Act on Physical Protection and Radiological Emergency* classifies radiological emergencies in nuclear facilities into three categories: white (alert), blue (site area emergency), and red (general emergency) [1]. This classification does not explicitly differentiate single-unit and multi-unit accidents, and timely convocation of the accident response organizations is critical for minimizing the progression of the accident, especially during the early stages. Some of the important accident response organizations that are convocated include Emergency Operations Facility (EOF), Technical Support Center (TSC), Operational Support Center (OSC), and Safety Center (SC) [2].

When a nuclear accident occurs (both single-unit and multi-unit), various organizations and emergency workers from outside the NPP site are convocated following radiological emergency plan (REP). However, managing a multi-unit accident may differ significantly from dealing with a single-unit accident because 1) more resources (including human resources) are required and 2) some of these resources may need to be shared among different units.

For example, since the Fukushima event, many countries around the world employed additional accident management strategies to utilize portable equipment (e.g. U.S. FLEX and Korean MACST) in case of an extended loss of AC power and a loss of ultimate heat sink accident. Unlike single-unit accidents where human resources may not be shared, using such a protocol during multi-unit accidents may result in shared human resources at the SC where most portable equipment will be stationed [2].

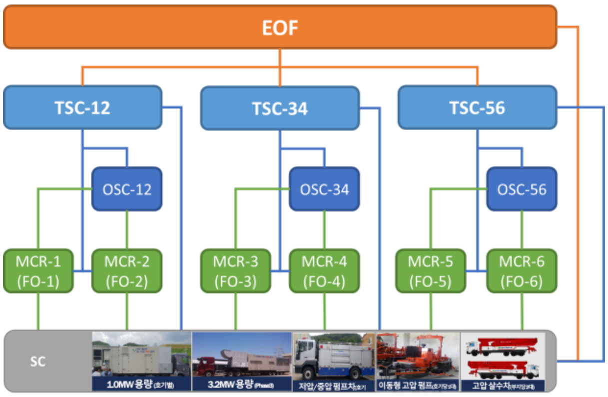

Figure 1. An example of organizational structure for radiological emergency response during multi-unit accident [2]

Therefore, for a multi-unit accident mitigation, it may become necessary to make sure that 1) all accident response organizations such as EOF and TSC are operational on time and 2) there are enough human resources to transfer, install, and operate portable equipment. Knowing distributions of convocation time will help the industry to better prepare for such an accident.

2. Emergency Response Convocation Time

In the accident management plan (AMP) and radiological emergency plan (REP), it is assumed that the aforementioned important accident response organizations will be launched after declaring radiological emergency within 1 hour and be functional within 2 hours [1]. It is also stated that the on-site workers would manage the accident (including installing portable equipment) themselves during the early stages of multi-unit accidents caused by external events, assuming off-site SC workers to transfer and install the portable equipment will not arrive on site within first few hours of the accident progression. These assumptions, however, may not hold true during extreme events.

Values of the convocation times stated in AMP and REP are what is deemed "conservative" with current expert judgement, but the chosen values for the convocation time are not tested. If these convocation times can be experimented, then the regulators and NPP companies can better determine whether the above convocation times are truly conservative or not conservative enough. If convocation time estimate distributions are available for different situations, AMP and REP may be revised to better represent the multi-unit accident management situation.

During an extreme external event beyond design-basis, such as a powerful earthquake, it will become much more difficult for the workers outside the NPP to arrive. Some workers may get injured. Some may not respond to the convocation call. Some may be late in arriving at the NPP site because they had to call all their family members to confirm everyone is safe. Electrical power outage from external events may cause loss of traffic signals and additional traffic for the off-site workers. However, these factors may not have been considered for determining convocation times stated at the AMP and REP. As a side note, factors that may impact the convocation time from Japanese case study is listed in reference [3].

All these factors can contribute to the delay or even failure to meet the convocation order. These delays and convocation failures may result in possible lack of staff for mitigation measures such as performing MACST actions for multiple units. The convocation time to arrive will differ for each worker (hence the need to find distributions instead of point estimation). Feasibility (or infeasibility) of performing mitigative actions as well as the performance time may all be affected by convocation time of the organizations and off-site workers. Thus, to better prepare for the multi-unit accidents, distributions of the off-site emergency response convocation time should be estimated.

Unfortunately, it is impossible gain experimental data for NPP operators, organizations, and off-site workers to arrive on-site during extreme external events. Therefore, simulation models may be developed to better estimate the convocation time of the necessary personnel for accident management.

For this purpose, agent-based model (ABM) is used by repeatedly simulating the call-up situation for the emergency organization's personnel. Through ABM-based PRISM-EC code, the average convocation time considering various scenarios and conditions, such as vehicle speed limits, road conditions, time of the day, and weather.

3. Application of ABM for Convocation Time Estimation

3.1. Agent-Based Model and PRISM-EC Code

Agent-based model (ABM) is a bottom-up computation model that simulates macroscopic phenomena through actions and interactions of the microscopic autonomous agents. Each agent has attributes and programmed functionalities/models that determine the values of the attributes. Each agent interacts as distinct part of simulation. Through microscopic behavior of each agents and with their interactions, macroscopic behavior of the system is observed [4].

PRISM-EC is an ABM-based model developed in NetLogo language to simulate the emergency response convocation time of the off-site workers by observing the interaction between different agents during radiological emergencies [5]. In the code, it is assumed that the moving agents use A* algorithm for path-finding to reach its desired destination (e.g. shelter for evacuees, NPP for off-site workers). In addition to evacuees and off-site workers, other modeled agents include infrastructure such as transportation, and shelter. These agents may all interact with each other through programmed models of each agent [6]. Details of the models used in PRISM-EC are listed in references [5] and [6].

3.2. Using Latin Hypercube Sampling

Difficulties exist in assuming what would be realistic values of the parameters used in the model. Easiest way to overcome this problem is to assume minimum and maximum values to use random Monte Carlo (MC) sampling. However, simple MC sampling would require tremendous number of samples (hundred-thousands to millions or more), which is not practical to use with PRISM where one set of simulation takes tens of minutes. Therefore, it is proposed to utilize Latin hypercube sampling (LHS) method to reduce the required number of samples yet still find convocation time distributions that maintain the statistical representations of the actual distribution.

Latin hypercube sampling (LHS) method is a constrained, modified sampling form of the Monte Carlo (MC) procedure. First, each examined variables are assumed of a probabilistic distribution. Then, the range of each variable is divided into equally-probable non-overlapping intervals. Next, the parameters are randomly sampled within the equally-probable divided intervals, assuring that the LHS method generates smaller number of input samples than simple random MC sampling while maintaining statistical representation of the overall distribution of the input parameters without clustering [7]. This difference between a random MC sampling method and the LHS method are shown below.

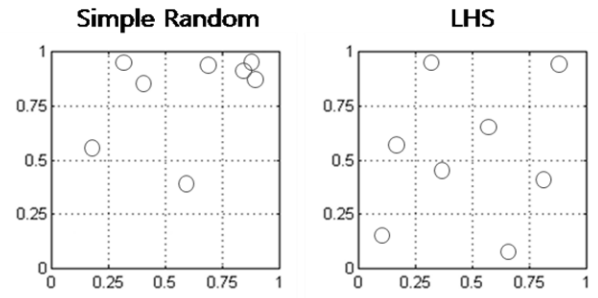

Figure 2. Example of eight samples from two different Monte Carlo methods (simple random and LHS), assuming two parameters (x and y axis) with uniform distributions

The number of suggested size of samples depend only on the statistical tolerance limits the suggested size, even without assuming any specific type of underlying probability distribution [8]. According to Roberts, sample size of over 93 was recommended for 95%/95% simulations [9]. Based on this, around 100 samples are recommended during each simulation set for estimating the off-site emergency response convocation time during multi-unit accident management using an agent-based model.

4. Future Work

For the future work, LHS be implemented into PRISM-EC model with reasonable estimations for the distributions of the parameters based on Japanese case study from reference [3]. It will be simulated for different cases, such as after earthquake or under heavy snows. Then, it will be compared with preliminary results that are simulated from small number of random sampling shown in Figure 3 and Figure 4. Once simulations with LHS are complete, there will be a better insight on the distribution of the off-site workers convocation time that may be further utilized to improve multi-unit accident response procedures.

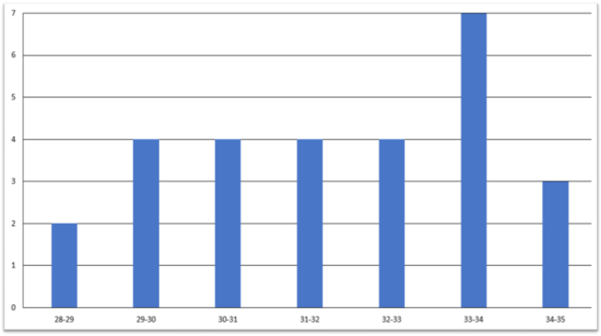

Figure 3. Preliminary result of simulated convocation time distribution using random sampling after earthquake, where x-axis is the time in minutes and y-axis is the number of sampled simulations

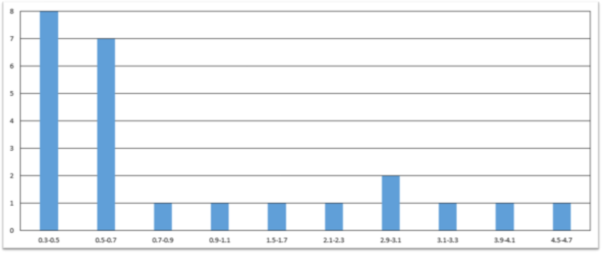

Figure 4. Preliminary result of simulated convocation time distribution using random sampling under heavy snow, where x-axis is the time in minutes and y-axis is the number of sampled simulations

Acknowledgement

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (No. 20224B10200050)

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