

Human reliability analysis of the pre-deployment strategy for portable equipment and evaluation of its effectiveness

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1. Introduction

After the Fukushima Daiichi accident, new accident coping strategies using portable equipment have adopted to increase safety of nuclear power plants. U.S. adopted diverse and flexible coping strategies (FLEX) and Korea adopted multi-barrier accident coping strategy (MACST). Since the coping strategies are risk-significant and humans play an important role in performing the strategies, the importance of human reliability analysis (HRA) is emphasized in safety assessment. In most HRA methodologies, timing factor is considered to be a significant contributor to human error because cognitive researches have demonstrated that time pressure affects human performance. Integrated human event analysis system (IDHEAS) defines human failure mode resulting from time uncertainties in the time available and time required [1]. Technique for human error rate prediction (THERP) utilizes time-reliability curve to estimate diagnosis error probability [2]. K-HRA also utilizes the time-reliability curve and define other factors as functions of time available [3].

In Korea, nuclear power plants have multi units and multi-unit probabilistic safety assessment (MUPSA) has been performed to identify their impacts on safety. The MU-PSA considers extreme hazard conditions which affect multiple units simultaneously. In these conditions, the time available for human actions is severely limited and thus, the human error probability (HEP) involving portable equipment increases. Due to the severe conditions, pre-deployment of portable equipment is considered to reduce time required to perform adequate human actions.

A seismic induced loss of off-site power (LOOP) and the following extended loss of all AC power (ELAP) is one of primary targets for the coping strategy using portable equipment due to its risk significance. When an ELAP occurs, the DC battery system supplies power to essential safety systems. However, the Battery capacity varies depending on the plant design and its associated coping strategy. Consequently, the time available for human actions and the subsequent effectiveness of pre-deployment strategy differ due to the plant characteristics.

This study analyzes HEPs of coping strategy, which adopts pre-deployment of portable equipment, and assesses its effectiveness depending on the time available for human actions.

2. Human reliability analysis

In the K-HRA methodology, human actions are decomposed into two sub-tasks: diagnosis and execution. The HEP for each sub-task is defined as the product of nominal HEP and performance shaping factors (PSFs), and a recovery failure probability is additionally considered for execution. To address time-constrained conditions, the nominal diagnosis error probability is derived from a time-reliability curve. In addition, diagnosis PSF has a time multiplication factor and recovery failure probability is discretized according to the time available for recovery.

On the other hand, operating portable equipment requires coordination and communication among multiple teams. In particular, multi-unit events can occur under extreme hazard conditions and multiple teams are involved in the coping strategies. For instance, the main control room (MCR) operator requests the technical support center (TSC) to transport and install portable equipment, and the TSC relays the request to the local safety center headquarter. However, most HRA methodologies including K-HRA do not focus on inter-team communication error probability. In contrast, IDHEAS defines inter-team collaborative activities as one of the cognitive failure modes, and it proposes the HEP of inter-team coordination along with associated performance influencing factors. Therefore, this study adopts the estimation process in IDHEAS for the inter-team communication failure probability. Since the failure modes are treated as independent events, the HEP is calculated as follows:

$$(1) \quad HEP = 1 - (1 - P_{diag})(1 - P_{exe})(1 - P_{com})$$

In practice, the portable equipment is normally stored at an equipment storage facility and requires local safety center operators for operation. Conversely, under a pre-deployment strategy, the equipment is staged near the nuclear power plant and requires only local operators belonging to the MCR shift. In this case, the inter-team coordination is not necessary to perform the strategy, and thus the communication errors among the teams can be considered negligible. Consequently, this study assumes the inter-team communication probability as zero for the pre-deployment strategy.

3. Timeline analysis

Timeline analysis is an essential part to estimate HEP. The time window is typically composed of delay time, diagnosis time, execution time, and time margin. The delay time refers to the time required for the operators to recognize a cue following an initiating event. When the seismic event occurs, the operators can recognize the cue immediately, and thus the delay time can be considered negligible. In the case of strategies using portable equipment, the execution time can be decomposed into transportation time, installation time, and operation time. In the EPRI analysis, the execution time of portable pump is estimated as 80 minutes [4]. Thus, the execution time of portable equipment including installation and operation is conservatively assumed to be 90 minutes in this study. For the pre-deployment strategy, the time that the field operators access pre-deployed equipment is required instead of the transportation time of portable equipment. In addition, the execution time is reduced when the pre-deployment strategy is adopted because the human actions for execution is simplified. Consequently, the time required for execution is assumed to be 60 minutes in this study. Furthermore, although the time margin represents uncertainties in the timeline analysis, this uncertainty is substantially reduced due to the simplified adequate human actions. Thus, the time margin is excluded in the time window of pre-deployment strategy in this study. Figure 1 shows the results from timeline analysis of the conventional coping strategy using portable equipment with and without the pre-deployment.

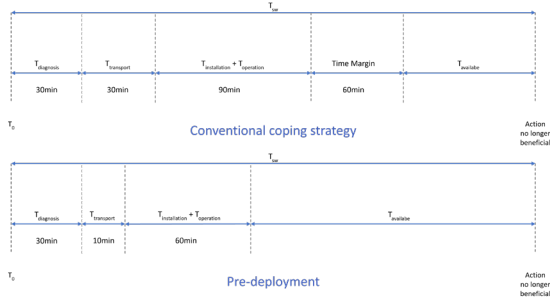


Fig. 1. Timeline analysis for coping strategies

On the other hand, during the early stage of beyond design basis external events, there might be a lack of human resources required to execute the coping strategies using portable equipment, particularly outside of regular working hours. In practice, the off-site workers are convoked following emergency response protocols. Kang et al. estimated the time distribution from the convocation to installation of portable equipment based on a Monte-Carlo agent-based model [5]. The estimation divides magnitude of the earthquake into four bins: 0.1-0.2g, 0.2-0.3g, 0.3-0.5g, and 0.5-1.0g. Events exceeding 1.0g of peak ground acceleration are too extreme to perform any human actions; thus, the HEP is assumed to be 1. According the estimated convocation time

distributions, the execution time is extended in the coping strategy without pre-deployment.

4. Results

In the ELAP scenario, the portable generator is generally used in the early stage of coping strategy. Thus, the HEP of operating the portable generator is estimated based on the HRA methodology and the timeline analysis. Since the HEP and the effectiveness of pre-deployment are affected by the system time window (T_{sw}), three representative time windows are analyzed considering the plant designs and coping strategies: 2 hours, 4 hours, and 8 hours. Table I shows the improvement rate of HEP due to the pre-deployment strategy compared to the conventional coping strategy. Since the pre-deployment strategy extend the time available for human actions, the effectiveness is increased as the system time window decreases. It is noted that the improvements stem not only the increased system time window but also the reduction of communication error. In particular, in the case of 8 hour system time window, the communication error probability is comparable to the time effect of pre-deployment.

Table I: Human error probability improvement rate

	System time window		
	2HRs	4HRs	8HRs
Int	97.05%	64.20%	45.14%
G1	95.42%	55.47%	35.48%
G2	95.42%	55.47%	35.48%
G3	95.42%	87.92%	37.95%
G4	95.42%	97.17%	37.95%

5. Conclusion

This study evaluates the effectiveness of pre-deployment strategy in the context of multi-unit PSA. The K-HRA methodology and the timeline analysis are applied to an ELAP scenario involving the deployment of a portable generator, and the HEP is estimated for three representative system time windows. To consider the extreme conditions of external hazard, convocation time of off-site workers is incorporated into the timeline analysis. As a result, the pre-deployment strategy is significantly effective when the system time window is limited, and the effectiveness is decreased as the system time window increases. In addition, because portable equipment operations require coordination among multiple teams, inter-team communication error is considered as an additional contributor using IDHEAS methodology. It is noted that the communication error probability is comparable to the effectiveness of pre-deployment with a sufficient the system time window. However, because the communication error is estimated using different HRA methodology, HRA of inter-team

coordination consistent with the K-HRA should be developed and the effectiveness of pre-deployment should then be evaluated. This result is expected to contribute to the decision-making regarding implementing the pre-deployment strategy, especially when a site features multiple units.

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