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HRA Dependency Analysis for Multi-unit Human Failure Events

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1. Introduction

After the accident at the Fukushima Daiichi nuclear power plant (NPP), the importance of multi-unit probabilistic safety assessment (MUPSA) has been increasing. Especially, Korea has a higher urgency to evaluate its risk because the NPPs and population density are at the highest level globally [1]. Accordingly, human reliability analysis (HRA), which is conducted as a part of probabilistic safety assessment (PSA), also gains increasing importance. Moreover, in the multi-unit event, interactions between units, organizations, and human failure events (HFEs) are more influential on the accident.

Yet, most of the HRA dependency analysis methods such as technique for human error rate prediction (THERP) [2], accident sequence evaluation program (ASEP) [3], standardized plant analysis risk-HRA (SPAR-H) [4], Fire HRA (NUREG-1921) [5] focused on the single-unit (SU) PSA model. Considering the characteristics of multi-unit (MU) accident scenarios, dependency analysis methods for the SU PSA may not handle the MU accident scenarios [6]. In case of MU accident scenarios, several characteristics should be considered such as (1) using shared equipment between several units, (2) prioritizing the equipment and personnel in charge, (3) establishment of the emergency response organizations (i.e., technical support center (TSC) and emergency operations facility (EOF)), and (4) delays of human actions due to the radiation release from adjacent units.

In this light, this study introduces an HRA dependency analysis method for MU HFEs, based on the authors' previous works. First, this study introduces an decision tree for determining the level of dependency. Then, it characterizes the types of HRA dependencies in the multi-unit scenarios. Finally, a case study for the dependency analysis will be presented.

2. Developing MU HFE dependency analysis method

There are several SU dependency analysis methods suggested in an effort to evaluate the dependency level between HFEs. In the authors' previous study [7], five SU dependency analysis methods including THERP [2], ASEP [3], SPAR-H [4], Fire HRA [5], and K-HRA [8] were reviewed. The comparison of dependency elements used to determine the level of dependency is presented in Table I. Those elements could be summarized into five elements, i.e., similarity of crew, timing of cue demand, stress, the similarity of cue, and the similarity of location.

Table I. HRA dependency elements in SU HRA methods [9].

	THERP	ASEP	SPAR-H	Fire HRA	K-HRA
Similarity of crew		X	X	X	X
Timing of cue demand	X	X	X	X	X
Interval time of sequential action				X	X
Stress	X			X	X
The similarity of cue (for cognitive)			X	X	X
The similarity of decision-making rule or state (for cognitive)	X				X
The similarity of location	X	X	X	X	X
Functional relatedness	X				
Preceding succeeded action	X			X	
Adequate manpower				X	

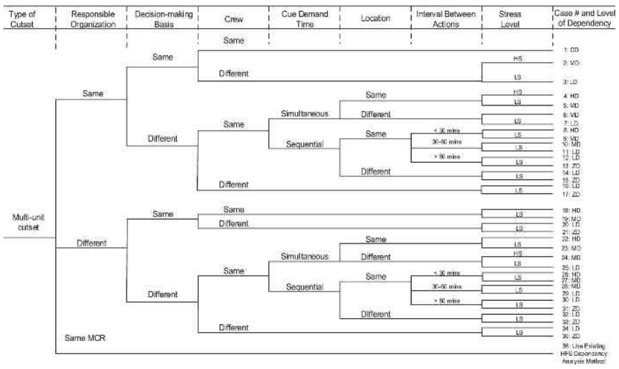

Fig 1. MU HFE dependency analysis tree [7]

Based on these elements, the authors' previous study suggested a MU HFE dependency decision tree as shown in Fig. 1. [7].

3. Characterization of MU dependency types

This study identified the characteristics of MU HFE dependency based on the practical experiences in Multi-

Unit Risk Research Group (MURRG). The MURRG conducted research for developing a MU PSA model from 2017 to 2021 with the support of Korean nuclear regulatory body. To derive the characteristics of MU HFE dependency, a total of 818 MU cutsets derived from the MU PSA model were reviewed.

The reference site of MU PSA model consists of nine units (i.e., one Westinghouse 2-loop, 600 MWe reactor (WH600, U1), two Westinghouse 3-loop, 900 MWe reactors (WH900, U2 and U3), two optimized power reactors (OPR1000, U4 and U5), and four advanced power reactors (APR1400, U6 to U9) [10, 11]. Twin-units share identical designs and are located in close proximity to each other. They also share alternative alternating current diesel generators (AAC DG) and instrument air (IA).

After reviewing 818 MU cutsets, this study identified 5 characteristics of dependency in the MU HFEs distinguished from the SU PSA, as follows.

3.1 A MU cutset can include HFEs under different operation modes

This characteristic indicates that in a MU PSA cutset, HFEs can be considered under various operational modes, which is not feasible in a SU cutset. Even when dealing with the same initiating event, a cutset can include HFEs in different operation modes, e.g., one HFE at power in a unit and one at the low power in another unit. This characteristic is applicable to 337 out of 818 cutsets.

3.2 A MU cutset can include two or more initiating events

This characteristic indicates that in a MU PSA cutset, it is possible to include HFEs from multiple initiating events. When two or more initiating events occur across units, it can lead to different accident scenarios for each unit. This characteristic is applicable to 391 out of 818 cutsets.

3.3 The MU HFE dependency analysis should consider the involvement of emergency response organizations (EROs)

The emergency response organizations (EROs) such as TSC or EOF are established within an hour after the issuance of a radiation emergency. In Korea, a TSC controls two units while an EOF controls the whole site. This indicates that the decisions made by EROs can affect multiple units. This characteristic is applicable to 189 out of 818 cutsets.

3.4 The MU HFE dependency analysis should consider the limitation of shared resources

In the context of a multi-unit scenario, certain resources must be shared among the units. These resources may include systems like mobile equipment and a shared alternate diesel generator, as well as manpower, such as the personnel responsible for transporting and installing the mobile equipment or maintenance personnel. Consequently, the shared equipment may not be available if the shared resource is currently in use in other units. This characteristic is applicable to 4 out of 818 cutsets.

3.5 An HFE can be affected by multiple preceding actions

An HFE in a MU cutset can be interacted by several preceding actions, even, actions from other units. This characteristic was observed in MU cutsets most frequently. Performing a MU dependency analysis requires a thorough consideration of all potential interactions between actions, which demands more effort compared to a SU analysis. This characteristic is applicable to 493 out of 818 cutsets.

4. Case study: application of the MU HFE dependency analysis tree

This section presents an example of the dependency analysis by using the suggested method. Fig. 2 shows the accident scenario. This scenario corresponds to the MUHFE dependency characteristics presented in Sections 3.1, 3.3, and 3.5. The scenario of the event is as follows: In Unit 4, prior to the initiating event, the maintenance personnel mistakenly did not recover the functionality of the safety injection (SI) valve after maintenance (U4-WOOPUHS-1049A). Upon the occurrence of the loss of offsite power (LOOP) event, Unit 4 underwent a successful trip. However, one of the two emergency diesel generators (EDGs) failed to initiate, i.e., U4-EGDGR01B. Consequently, the pressure within the primary loop increases due to an existing imbalance between the primary and secondary loops. To mitigate the pressure rise, a power-operated relief valve (PORV) is automatically activated, subsequently relieving the elevated pressure in the primary loop. The steam generators effectively dissipates the residual heat present in the reactor coolant system (RCS). Despite this, operators fail to transfer the water source from the auxiliary feedwater storage tank (AFWST) to the condensate storage tank (CST). Subsequent to this, the operator successfully engaged the PORV for feed and bleed (F&B) operation; however, due to an error in the maintenance crew (U4-WOOPUHS-1049A), the safety injection (SI) failed to operate as intended. Consequently, U4's condition progressed towards potential core damage.

The scenario in Unit 5 is outlined as follows: Unit 5 is undergoing an overhaul. Upon the occurrence of a LOOP, the shutdown cooling (SDC) pump was stopped. In response, the operator initiates manual activation of the backup SDC pump. However, this standby pump fails (U5-RSOPH-LPP05). Following this, the operator's attempt to start the safety injection (SI) pump to provide water (U5-FBOPH-LPP05) is also unsuccessful. As a result, the unit undergoes core damage. This multi-unit scenario is illustrated in Fig.2

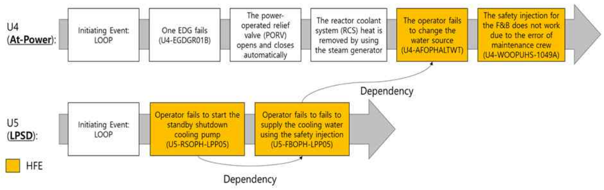

Fig. 2. The MU accident scenario for the case study [9]

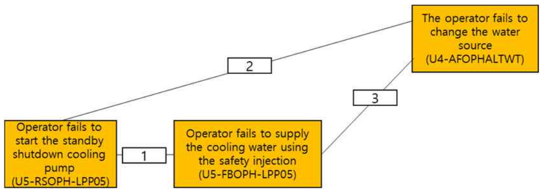

Fig. 3. Dependencies between the HFEs

As shown in Fig. 3, a total of 3 interactions between the HFEs must be considered in the MU accident scenario. The dependencies of these interactions then were applied to the MU HFE dependency analysis tree presented in Fig. 1. Among the three interactions, two interactions between the HFEs were able to be evaluated using the MU HFE dependency analysis tree (i.e., Interactions #2 and #3). Interaction #1 was not applicable to MU HFE dependency analysis tree since both actions were conducted by same MCR. Thus, the dependency of interaction #1 was evaluated as low dependency (LD) using the SPAR-H method.

Interactions #2 and #3 were applicable to the MU HFE dependency analysis tree. Using the suggested tree, *responsible organization* was evaluated as different since the decisions for HFE #1 and HFE #2 were made by MCR operators in U5 while HFE #3 were made by TSC. *Decision-making basis* was evaluated as different since the procedures and parameters that affect decision-making for HFE #1, #2, and #3 were different. The *crew* that takes actions based on the recommendation of the *responsible organization* were different. Finally, *stress* was evaluated as high because the operators need to progress to functional restoration or emergency contingency action procedures. Based on this, the dependencies of interaction #2 and #3 were evaluated as LD (i.e., case # 34 in Fig. 1).

Basic human error probabilities (BHEPs) of U5-RSOPH-LPP05 (HEP #1), HEP of U5-FBOPH-LPP05 (HEP #2), and HEP of U4-AFOPHALTWT (HEP #3) can be estimated as 7.68E-04, 1.02E-03, and 1.02E-03, respectively. When we apply the determined dependency levels, the joint HEP of three HFEs can calculated as 2.00E-06.

5. Conclusion

This study suggested an HRA dependency analysis method for MU HFEs. This study introduced an decision tree for determining the level of dependency and the unique characteristics of dependencies in the multi-unit cutsets.

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