Dependency Analysis of Human Failures in Multi-unit Scenarios: Types and Evaluation Method

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Abstract: Dependency between human failure events (HFEs) is often analyzed as a part of the conventional human reliability analysis (HRA) process for nuclear power plants (NPPs). Many regulators have suggested that the probabilistic risk assessment (PRA) should address the dependency between HFEs. In this study, we investigate the characteristics of multi-unit human failure dependency based on about 800 combinations of HFEs derived from realistic multi-unit cutsets in the multi-unit research project. From 2017 to 2021, the authors participated in a project to develop a multi-unit PSA model for regulatory use. Eventually, the model was developed for nine nuclear power plants at the Kori site in Korea. The human error probability (HEP) and dependency were analyzed using the multi-unit HFE dependency evaluation method. A set of multi-units HFE dependency evaluation elements and their evaluation criteria have been utilized in the HRA practice for NPPs. The result of this work will be used to re-validate and modify the recently developed multi-unit HFE dependency analysis method for qualitative analysis.

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1. INTRODUCTION

To date, most probabilistic safety assessments (PSAs) for nuclear power plants (NPPs) have focused on a "single" unit [1]. However, many events, the Fukushima Daiichi NPP accident clearly demonstrated that multi-unit accidents can occur. Existing PSA models might not adequately evaluate the total risk involved at a multi-unit site [2]. The multi-unit risk, i.e., the risk due to multiple NPPs in a site, has become a critical issue in the United States, Japan, Korea, Canada, and France that build multiple units at a site [3,4].

Human reliability analysis (HRA), which is generally performed as part of a PSA, has continued to take on increasing importance [5]. Generally, HRA aims to identify the potential types of human errors for each task, understand which factors might trigger them, and proposes solutions to reduce human errors. Through the HRA, safety engineers can enhance human-centered and error-tolerant design to make high-risk systems inherently suited to operation by humans. To reduce the accidents linked with human errors, they have been extensively utilized in various industries, including nuclear, aerospace, chemical, healthcare, and other safety-critical industries.

Dependency between human failure events (HFEs), specifically defined as the degree to which one erroneous action can impact subsequent actions, has been a fixture in many HRA methods for forty years. Appropriate dependency analysis is thus mandatory to avoid underestimation of the risk and to ensure a realistic risk profile from the PSA results. The basic assumption of dependency is that the probability of a secondary task failure is higher if an operator fails on the primary task. The conditional human error probability (CHEP) of a task given failure on the preceding task results from the dependence assessment in HRA. According to NUREG-1792 [6], it is necessary to quantitatively account for dependencies among post-initiator HFEs in an accident sequence in the PSA model by the joint probability used for human error probabilities (HEPs).

One of the most widely used dependence assessment methods in HRA is the technique for human error rate prediction (THERP) [7]. THERP provides implicit guidelines on assessing dependence among subtasks with five categories: zero dependence (ZD), low dependence (LD), moderate dependence (MD), high dependence (HD), and complete dependence (CD). The conceptual dependency level now recognized in THERP dependency has been incorporated into many HRA methodologies that employ the same technical basis. Various methods have been developed regarding the assessment of dependence between HFEs in HRA, including accident sequence evaluation program (ASEP) /THERP [8], Standardized plant analysis risk-HRA method (SPAR-H) [9], EPRI HRA method [6,10], Korean standard nuclear power-human reliability analysis (K-HRA) [11], and DEPEND-HRA [12].

As can be seen, most of the existing HRA dependency methods focused on the PSA model of individual units of NPPs [13]. The multi-unit (MU) PSA may not be handled using the current single-unit (SU) HRA dependency method. The current HRA methods assess dependencies in the one shift that includes the main control room (MCR) operators and the local operators. In MU accidents, emergency response organizations (EROs) such as technical support center (TSC), operational support center (OSC), and emergency operating facility (EOF), can be established to make decision-makings and manipulations [14]. In this regard, some researchers indicate that the complexity of MU accidents considerably depends on the degree of unit-to-unit interactions, and human and organizational factors are regarded as the critical factors that can influence the unit-to-unit interactions [2,13,15]. However, very limited methods of MU HFEs dependency analyses method are available [16].

This paper aims to identify the characteristics of MU HRA dependency based on a practical experience of MU PSA and HRA. The paper includes the following remaining sections. Section 2 introduces the elements of existing dependency analysis methods for determining the level of dependency. Section 3 describes the human and organizational factors considered in the MU accident scenario. This section also describes the various types of HFE dependency interactions that may potentially occur in the MU accident, and Section 4 outlines our conclusions.

2. ELEMETNS OF SINGLE-UNIT HRA DEPENDENCY METHODS

Several SU dependency methods have been proposed to evaluate and quantify the dependency level between HFEs. Those include THERP [7], ASEP [8], SPAR-H [9], EPRI HRA [9], K-HRA [11], and DEPEND-HRA [12]. Table 1 shows the comparison of elements suggested by the methods for determining the level of dependency.

As shown in the table, the elements generally considered in the methods are the similarity of crew, stress, timing of cues, similarity of cues, and similarity of location. On the other hand, THERP method suggests the functional relatedness, while EPRI HRA method uses the adequacy of manpower. DEPEND-HRA applies the complexity of execution for the element. In addition, THERP and EPRI HRA suggest that if there is any succeeded action between HFEs, the dependency level should be adjusted.

Table 1. Principal HRA Dependency Elements in Single-unit HRA Methods.

	THERP [6]	ASEP [7]	SPAR-H [8]	K-HRA [11]	DEPEND-HRA [12]	EPRI HRA [9]
Similarity of crew		X	X	X	X	X
Timing of cue demand	X	X	X	X		X
Interval time of sequential action				X	X	X
Stress	X			X	X	X
The similarity of cue (for cognitive)			X	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
Complexity of execution					X	

3. CHARACTERISTIC IDENTIFICATION OF MULTI-UNIT HRA DEPENDENCY

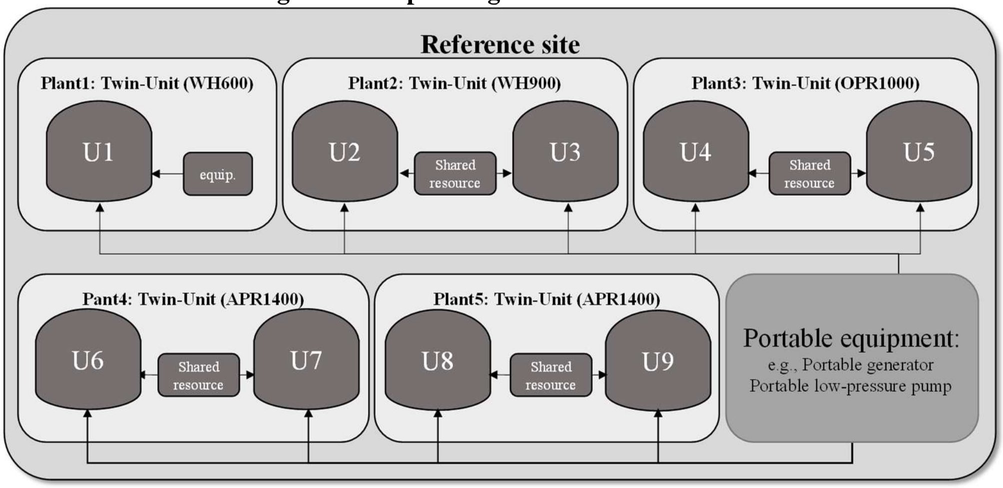
3.1. Method

To identify the characteristics of MU dependency, this study reviewed 818 MU cutsets derived for the MU PSA model. Then, it presented five characteristics of MU cutsets in terms of dependency analysis distinguished from the SU cutsets. A cutset includes a combination of the minimum number of events required for the top event to be reached.

The Multi-Unit Risk Research Group (MURRG) conducted research to complete the development of a MU PSA model from 2017 to 2021 with the support of Korean regulation body. The MURRG developed SU PSA models and integrated them to develop a MU PSA model [1,17]. This MUPSA model includes internal and external initiating events, and at-power (AP) and low power-shutdown (LPSD) modes. In addition, the MU PSA model considers the portable equipment in the case of loss of ultimate heat sink (LOUHS) or extended loss of all alternating current power (ELAP).

Figure 1 shows the reference site that the MU PSA model is based on. The site includes nine units i.e., one Westinghouse 2-loop, 600 MWe reactor (WH600, called U1 later), two Westinghouse 3-loop 900 MWe reactors (WH900, called U2 and U3), two optimized power reactors (OPR1000, called U4 and U5), and four advanced power reactors (APR1400, called U6 to U9) [18,19]. Twin units have the same design and are located closely. It shares alternative alternating current diesel generators (AAC DG) and instrument air (IA).

Figure 1. Simple Diagram of Reference Site.



3.2. Characteristics of Dependency in the Multi-unit HFE

This section describes the characteristics of dependency between MU HFEs.

1) A cutset can contain HFEs in different operation modes.

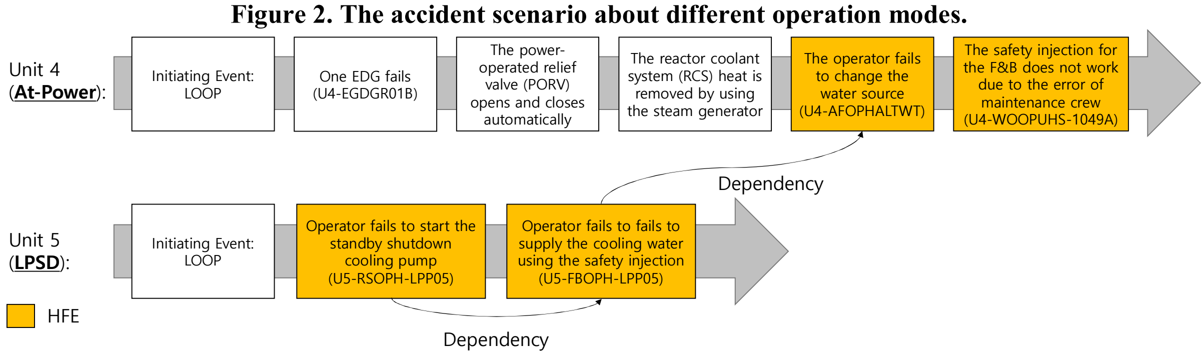
A MU PSA cutset can include HFEs under different operation modes, which is impossible in a single unit cutset. Figure 2 shows an example of a cutset that contains HFEs in different operation modes in the MU loss of offsite power (LOOP) event. This characteristic accounts for 337 cutsets among 818 ones.

In this example, as shown in Figure 2, U4 is under at-power mode while U5 is in the low-power-shut-down (LPSD) mode. When the LOOP event occurs, U4 is successfully tripped, but EDG fails, i.e., U4-EGDGR01B. Then, the pressure of the primary loop is increased due to unbalance between the primary and secondary loops. To reduce this, the power-operated relief valve (PORV) opens and closes automatically. The remaining heat in the reactor coolant system (RCS) is removed using the steam generator. However, the operator fails to change the water source from the auxiliary feedwater storage tank to the condensate storage tank, i.e., U4-AFOPHALTWT. Then, the operator successfully opens the PORV for the feed and bleed (F&B) operation, but the safety injection for the F&B does not work due to the error of the maintenance crew (U4-WOOPUHS-1049A). Thus, the U4 leads to the core damage.

The U5 is under the overhaul, i.e., LPSD condition. When the LOOP occurs, the shutdown cooling stops. Here, the operator is supposed to start the standby shutdown cooling pump manually, but fails (U5-RSOPH-LPP05). Next, the operator fails to supply the cooling water by using the safety injection pump (U5-FBOPH-LPP05). Consequently, the core undergoes damage.

Figure 2 shows the accident sequence in two units. In this case, generally, the dependency between the actions in the same unit is considered. In the example, the dependency between U5-RSOPH-LPP05 and U5-FBOPH-LPP05 in U5 is stronger than between any of these actions and the actions in U4. The MURRG project addressed the dependency between the actions as shown in Figure 2. The second tasks in each unit have dependency on the preceding actions in its unit. In addition, to evaluate the interaction between units, the dependency between U4-AFOPHALTWT and U5-FBOPH-LPP05 was assessed because this interaction was evaluated as the strongest in all possible dependencies between two units.

Figure 2. The accident scenario about different operation modes.



2) A cutset can include two or more initiating events.

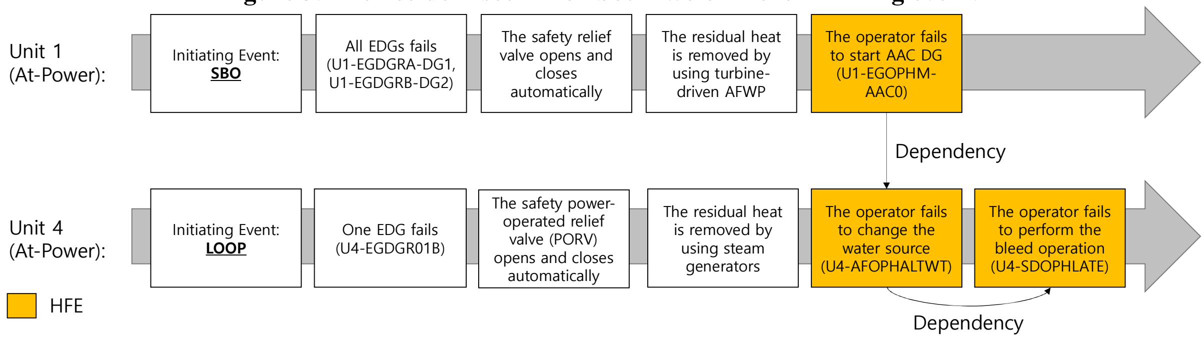
A MU PSA cutset can contain HFEs from two or more initiating events that are not possible in a SU cutset. Figure 3 presents an example of a cutset containing HFEs of multiple initiating events at power operation mode. This characteristic accounts for 391 cutsets among 818 ones.

For example, as seen in Figure 3, U1 is at power operation mode in the station black out (SBO) event. In the U1, the reactor is successfully tripped, but two EDGs fail (U1-EGDGRA-DG1, U1-EGDGRB-DG2). Then, the safety relief valve is automatically opened to relieve the pressure unbalance between the primary and secondary loops. The RCS heat is removed by using the turbine-driven auxiliary feedwater pump (AFWP). For NPP safety, the operator wants to supply the power using AAC DG, but fails to start AAC DG (U1-EGOPHM-AAC0). This leads to the core damage since offsite power is not recovered within 11.6 hours. Therefore, U1 leads to the core damage.

The LOOP event of U4 occurs, the reactor is successfully tripped, and one EDG fails, i.e., U4-EGDGR01B. Then, the pressure of the primary loop is increased because of unbalance between the primary loop and the secondary loop. For this reason, the PORV opens and closes automatically. The RCS heat is removed by using the steam generator. However, the operator fails to change the water source from the auxiliary feedwater storage tank to the condensate storage tank, i.e., U4-AFOPHALTWT. Moreover, the operator fails to perform the bleed operation using PORVs (U4-SDOPHLATE). Thus, U4 leads to the core damage.

Figure 3 shows the accident sequence in two units. In this case, the interaction between the units is not so strong that the dependency between the actions in U4 is considered primarily. Then, to evaluate the interaction between the units, the dependency between U1-EGOPHM-AAC0 and U4-AFOPHALTWT was assessed. In this dependency, U1-EGOPHM-AAC0 was regarded as the preceding action because it was performed early in the scenario.

Figure 3. The accident scenario about two or more initiating event.



3) The MU dependency analysis should consider the involvement of emergency response organizations.

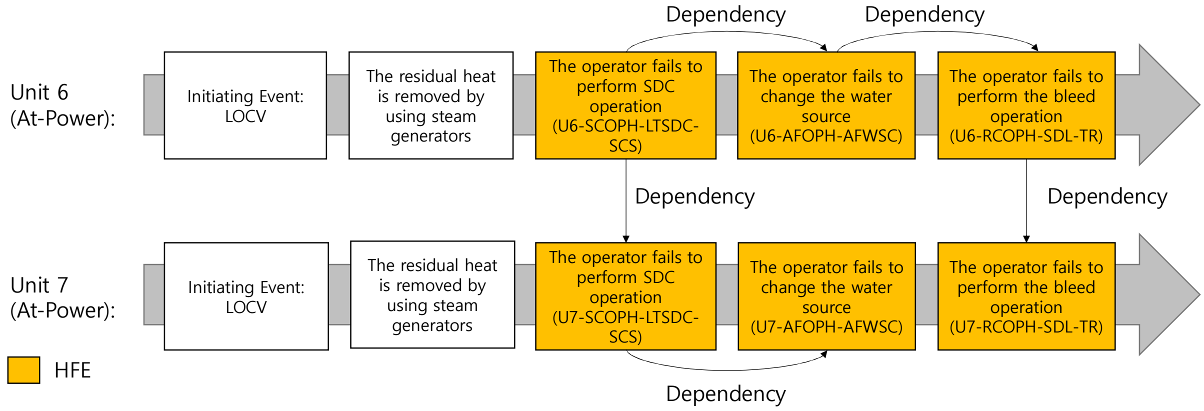
EROs such as TSC and EOF should be established in the event that has potential to release the radiation out of the NPP. In Korea, those EROs should be established within one hour after announcing the radiation emergency. The dependency analysis needs to consider two perspectives. First, those EROs cover multiple units. For instance, in Korea, the TSC covers two units while the EOF controls the entire site which includes four to six units. Therefore, the decision making of a single ERO may influence multiple units. Second, the decision of HFEs in the same unit can be made by different personnel. In Korea, once the ERO is established, the authority of decision making is transferred from the MCR operators to the ERO. Therefore, an action within one hour after the initiating event may be performed by the MCR operators and the other action past one hour may be decided by the TSC. This characteristic accounts for 189 cutsets among 818 ones.

In the example of Figure 4, the cutsets in U6 and U7 are basically identical. In the loss of condensate vacuum (LOCV), the reactors trip automatically and the residual heat is removed through the steam generators. However, the operators fail to perform the shutdown cooling (SDC) (U6-SCOPH-LTSDC-SCS and U7-SCOPH-LTSDC-SCS). Then, they also fail to change the water source to the steam generators (U6-AFOPH-AFWSC and U7-AFOPH-AFWSC). In addition, they fail to perform the F&B operation (U6-RCOPH-SDL-TR and U7-RCOPH-SDL-TR). Consequently, two reactors lead to the core damage.

In the cutset of each unit, the first actions, i.e., U6-SCOPH-LTSDC-SCS and U7-SCOPH-LTSDC-SCS, are performed by the MCR operators. On the other hand, the second and third actions (U6-AFOPH-AFWSC and U6-RCOPH-SDL-TR for U6, and U7-AFOPH-AFWSC and U7-RCOPH-SDL-TR for U7) are all decided by a single TSC because those actions are performed after one hour since the initiating event and those units are managed by one TSC.

The MURRG project addressed the dependency between the first and second actions in the cutset of each unit. However, interestingly, the dependency between the F&B operations, i.e., U6-RCOPH-SDL-TR and U7-RCOPH-SDL-TR, was considered because the actions were decided by the TSC and then the interaction was evaluated to be strong.

Figure 4. The accident scenario that ERO take over the decision-making of MCR operators in twin units.



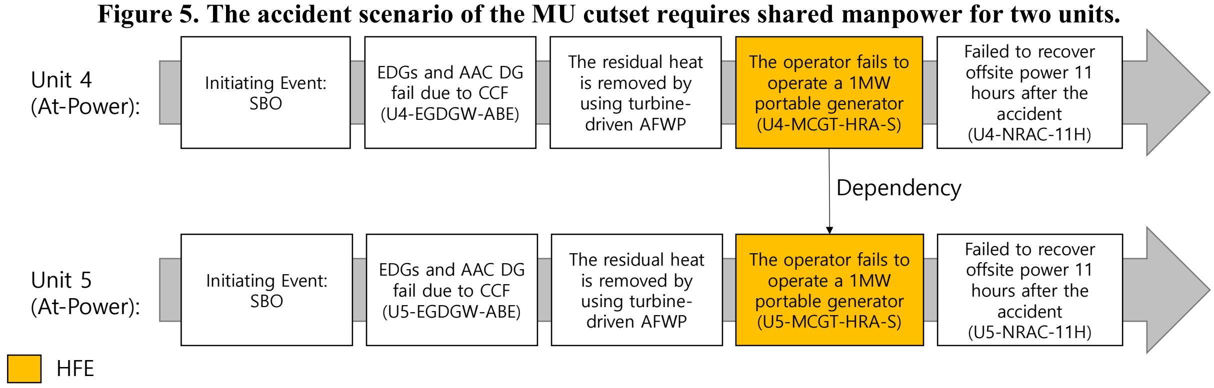
4) The dependency analysis should consider the limitation of shared resources.

In the multi-unit scenario, some resources need to be shared. The resource can be systems such as mobile equipment and shared alternate diesel generator, or man-power such as the personnel who transport and install the mobile equipment. Therefore, the share equipment cannot be available if they are being used in other units. This characteristic accounts for 4 cutsets among 818 ones.

Figure 5 shows an example of MU SBO, in which U4 and U5 require 1 MW mobile diesel generators. In Korea, a 1 MW diesel generator is prepared for each unit. Therefore, the diesel generator does not need be shared. However, the personnel to transport and install the equipment are not sufficient enough to work for two units at the same time.

The MURRG project assumed that the personnel applied the mobile diesel generator to a unit that had a higher priority. Therefore, the installation of equipment was performed sequentially on the second unit. The dependency analysis separated the timeline of actions and regarded those actions as sequential ones.

Figure 5. The accident scenario of the MU cutset requires shared manpower for two units.



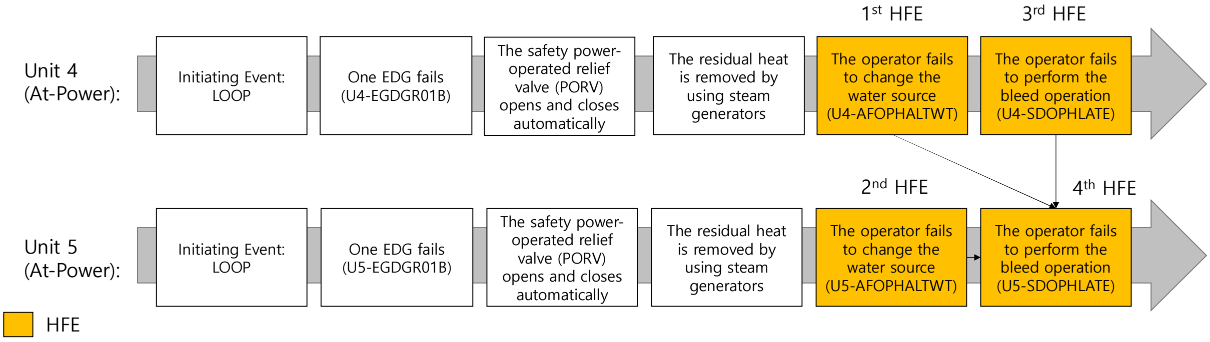
5) An HFE can be affected by multiple preceding actions. Inter-unit dependency should be considered.

In the multi-unit cutset, an HFE can be affected by multiple preceding actions, even by actions from another unit. This characteristic was found frequently in the MURRG project. The multi-unit dependency analysis should consider all the possible interaction between the actions, which requires more efforts than the single unit analysis.

Figure 6 shows an example of the MU LOOP event. In this example, the reactor is successfully tripped, and one EDG fails (U4-EGDGR01B and U5-EGDGR01B). The pressure control successfully prevents the pressurizer safety valve from being stuck open. The steam generator is used to remove heat from the reactor. However, the operator fails to change the AFWT source and thus fails to remove heat for a long time (U4-AFOPHALTWT and U5-AFOPHALTWT). The operator also fails to perform the F&B operation (U4-SDOPHLATE and U5-SDOPHLATE). Thus, the U4 and U5 lead to the core damage.

Let's consider the action U5-SDOPHLATE. This action can be influenced by three actions. First, it can be affected by U5-AFOPHALTWT because this is the preceding action in the same unit. In addition, it can be also affected by the actions performed in U4 because the same TSC makes the decisions for the actions. The MURRG project analyzed all the three potential dependencies and applied the strongest dependency, i.e., interaction to U4-SDOPHLATE.

Figure 6. The accident scenario of the MU cutset includes multiple preceding HFEs in one HFE.



4. CONCLUSION

This study introduced the characteristics of MU HRA dependency from the practical examples. This study reviewed more than 800 cutsets from the MURRG project which the authors participated in. Then, the characteristics distinguished from the single unit HRA were identified and discussed. The method to determine the dependency level and quantify the effect of dependency will be studied in the following study.

Acknowledgments

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References

[1] D. S. Kim, S. H. Han, J. H. Park, H. G. Lim, and J. H. Kim. "*Multi-unit Level 1 probabilistic safety assessment: Approaches and their application to a six-unit nuclear power plant site*", Nuclear Engineering and Technology, vol. 50, pp. 1217–1233, (2018).
[2] S. St Germain, R. Boring, G. Banaseanu, Y. Akl, and H. Chatri. "*Multi-Unit Considerations for Human Reliability Analysis*," in PSAM Topical Conference 2017, pp. 7–9, (2017).
[3] T. Zhou, M. Modarres, and E. L. Droguett. "*Multi-unit nuclear power plant probabilistic risk assessment: A comprehensive survey*" Reliability Engineering and System Safety, vol. 213, (2021).
[4] CNSC, "*Summary Report of the International Workshop on Multi-Unit Probabilistic Safety Assessment*," CNSC, 2015, Ottawa.
[5] M. A. Ramos, R. Patriarca, and N. Paltrinieri. "*The social structure of 70 years of literature on Human Reliability*", Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability, pp. 1-12, (2021).
[6] S. C. S. Lewis, "*EPRI/NRC-RES Fire Human Reliability Analysis Guidelines*," NRC, 2012, California.

[7] A. D. Swain and H. E. Guttmann, "*Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications - Final Report*," NRC, 1983, U.S.Washington.
[8] A. D. Swain, "*Accident Sequence Evaluation Program Human Reliability Analysis Procedure*," NRC, 1987, California.
[9] D. Gertman, H. Blackman, J. Marble, J. Byers, and C. Smith, "*The SPAR-H Human Reliability Analysis Method*," NRC, 2005, U.S.Washington.
[10] Parry GW, "*An Approach to the Analysis of Operator Actions in Probabilistic Risk Assessment*," EPRI, 1992, California.
[11] J. Wondea, "*Development of A Standard Method for Human Reliability Analysis (HRA) of Nuclear Power Plants*," KAERI, 2005, Daejeon (Korean).
[12] M. Čepin. "*DEPEND-HRA-A method for consideration of dependency in human reliability analysis*", Reliability Engineering and System Safety, vol. 93, pp. 1452–1460, (2007).
[13] A. M. Arigi, G. Kim, J. Park, and J. Kim. "*Human and organizational factors for multi-unit probabilistic safety assessment: Identification and characterization for the Korean case*", Nuclear Engineering and Technology, vol. 51, pp. 104–115, (2019).
[14] KNS, "*Analysis of Fukushima Nuclear Power Plant Accident*," KNS, 2013, Daejeon (Korean).
[15] J. Park, A. M. Arigi, and J. Kim. "*Treatment of human and organizational factors for multi-unit HRA: Application of SPAR-H method*", Annals of Nuclear Energy, vol. 132, pp. 656–678, (2019).
[16] A. M. Arigi, G. Park, and J. Kim. "*Dependency analysis method for human failure events in multi-unit probabilistic safety assessments*", Reliability Engineering and System Safety, vol. 203, (2020).
[17] J. E. Yang. "*Multi-unit risk assessment of nuclear power plants: Current status and issues*", Nuclear Engineering and Technology, vol. 50, pp. 1199–1209, (2018).
[18] K. Son et al. "*Development of Level 1 Internal Event Single-unit PSA Models for Multi-unit Risk Profiles*", 2021 International Topical Meeting on Probabilistic Safety Assessment and Analysis (PSA 2021), pp. 944–952, (2021).
[19] J. S. Kim et al. "*Modeling portable equipment in probabilistic safety assessment of nuclear power plants*", 2021 International Topical Meeting on Probabilistic Safety Assessment and Analysis (PSA 2021), pp. 592–600, (2021).