An Approach to Human Reliability Analysis for the Multi-Unit PSA

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Abstract: Human reliability analysis (HRA) is a method for evaluating human errors and providing human error probabilities (HEPs) for the application in probabilistic safety assessment (PSA). After the Fukushima accident, HRA has been considered as one of the important issues in the multi-unit PSA. However, existing HRA methods generally focuses on the analysis of human errors in single-unit PSA, while HRA methods for the multi-unit PSA have not been established well.
This study aims to suggest an approach to the HRA for the multi-unit PSA. First, distinguished features in multi-unit HRA are briefly introduced in the perspectives of organization, task object, performance shaping factors, environmental factors, and task. Then, task analysis and qualification analysis were carried out based on the multi-unit task types. Final result of this study could be used for estimating and providing human error probabilities for the application in multi-unit PSA.

Keywords: Multi-unit PSA, Human and organizational factors, Human reliability analysis.

1. INTRODUCTION

Human reliability analysis (HRA) is a method for evaluating human errors and providing human error probabilities (HEPs) for their application in probabilistic safety assessment (PSA) [1, 2]. The main purpose of HRA in the context of the PSA is to identify, analyze, and quantify all human failure events (HFEs) represented in the logic structure of the PSA, before and during the accident, which contributes to plant risk as defined in the PSA. Up to date, many HRA methods, such as THERP (Technique for Human Error Rate Prediction) [2], ASEP (Accident Sequence Evaluation Program) [3], HCR (Human Cognitive Reliability) and CBDT (Cause-Based Decision Tree) [4], have been developed, and practically applied in a variety of complex systems such as nuclear power plants (NPPs), military systems, aircraft and chemical plants [5, 6].

After the Fukushima accident, HRA has been considered as one of the important issues in the multi-unit PSA. However, existing HRA methods generally focuses on the analysis of human errors in single-unit PSA, while HRA methods for the multi-unit PSA have not been established well. In multi-unit accidents, operational situation as well as human and organizational factors could become more complex and significant than in single-unit accidents. When an accident occurs influencing more than a unit, the organizational factors due to the formation of accident management organizations; the use of shared systems; the use of mobile equipment; and the influence of a severe accident on another unit (e.g., radiation, complexity, and accessibility) may have a crucial impact on the plant safety and the result of HRA.

This study aims to suggest an approach to the HRA for the multi-unit PSA. This approach focuses on analyzing the tasks required in the multi-unit HRA and making full use of existing HRA. First, distinguished features in multi-unit HRA were briefly introduced in the perspectives of organization, task object, performance shaping factors (PSFs), environmental factors, and task, based on the previous research [7]. Second, several task types identified in the previous study were divided into detailed task types, which reflect additional multi-unit tasks and include different task sequences. Then, task analysis was carried out based on the multi-unit task types. This task analysis considered task sequence, time window, and how the human error probabilities can be calculated on each multi-unit task type. Lastly, qualification analysis was performed on how basic error probabilities and PSFs could be treated, based on the result of task analysis.

2. PECULIAR FEATURES IN MULTI-UNIT HRA

2.1. Organization

Existing HRA methods have consider operator actions performed by MCR and local operators, while more organizations are involved in the case of multiple units. The technical support center (TSC), the emergency operating facility (EOF), the operational support center (OSC) and the sub-contractors, are additionally considered by the emergency radiation plan for Korean NPPs [8].

First, TSC is established to provide a function including plant management and technical support to the reactor operating personnel located in the main control room during emergency conditions. In Korea, a TSC deals with up to two units. Second, EOF plays a role of providing high-level directives for the entire site. Third, OSC is set up in Korean nuclear power plants to perform maintenance, firefighting, rescue activities, and can be assigned to other duties in support of emergency operation. Lastly, sub-contractors are always on hand mostly for the deployment and installation of mobile equipment and other ancillary roles during multi-unit accident cases.

2.2. Task object

Task object refers to a target on which an actor performs the task. It includes MCR board, fixed local equipment, mobile local equipment, and shared equipment. HRAs generally assign different HEPs, depending on where the task is performed. For instance, HEPs for tasks in MCRs is generally lower than for those in the local equipment because the operating condition in MCRs is more favorable to the operator. Existing HRA only includes three task objects, i.e., 1) MCR board, 2) local or fixed equipment installed at the nuclear power plant, and 3) shared equipment pooled or connected with each unit. On the other hand, multi-unit HRA additionally considers mobile equipment as a task object.

2.3. PSFs

PSFs refers to any factor that influences human performance such as experience, stress, and task complexity. Existing HRA uses a variety of PSFs for the purpose of adjusting basic HEPs on diagnosis and execution. All the PSFs currently used for existing HRA should be applicable to multi-unit HRA. However, the severity or significance level of the PSFs may be different.

2.4. Environmental factors

Environmental factors, i.e., fire, flooding, earthquake, extreme temperatures, radiation and so on, may affect local tasks such as deployment/installation & operation of mobile equipment, or execution of fixed equipment. They can cause failure of equipment, block equipment routing, limit access, or delay access to the necessary areas. They could also result in failure of buildings and structures that house or support the equipment. In addition, the habitability of areas where operator actions are needed may be affected, For instance, the radiation from the severe accident of a unit can affect the mitigating action in a neighboring unit.

2.5. Task

Task relies on who performs the task (i.e., organization) and on what they perform (i.e., task object). Existing HRA typically considers two task types. As for the first type, the MCR operator makes a diagnosis and performs the necessary action on the MCR board while in the second task type the MCR operator performs diagnosis but instructs the local operator to take action on the fixed equipment. On the other hand, the task of the various organizations involved in a multi-unit accident is more complex than those for a single unit. While actions executed in the MCR are like pushing a button or turning a switch, the use of mobile equipment requires more sub-tasks such as moving and installing equipment and implementing the required function. Therefore, as the number of organizations and task objects increases, and the number of task types also increases.

In the previous research, total 8 task types are identified for the multi-unit HRA, as shown in Table 1. Task type 8 is considered as the most complex one as it involves the EOF's diagnosis and taking the final decision, a transfer of command from EOF to TSC and from TSC to the MCR, then execution of mobile equipment by local operators.

Table 1: Task categories for multi-unit HRA

No	Task Type 1		Task Type 2		Task Type 3		Task Type 4		Task Type 5		Task Type 6		Task Type 7		Task Type 8	
	Task Sequence	Actor	Task Sequence	Actor	Task Sequence	Actor	Task Sequence	Actor	Task Sequence	Actor	Task Sequence	Actor	Task Sequence	Actor	Task Sequence	Actor
1	Diagnosis	MCR	Diagnosis	MCR	Diagnosis	MCR	Diagnosis	TSC	Diagnosis	TSC	Diagnosis	TSC	Diagnosis	EOF	Diagnosis	EOF
2	Execution	MCR	Execution (Fixed Equip.)	Local Oper.	Execution (Mobile Equip.)	Local Oper.	Transfer of Command	MCR	Transfer of Command	MCR	Transfer of Command	MCR	Transfer of Command	TSC	Transfer of Command	TSC
3	–	–	–	–	–	–	Execution	MCR	Execution (Fixed Equip.)	Local Oper.	Execution (Mobile Equip.)	Local Oper.	Transfer of Command	MCR	Transfer of Command	MCR
4	–	–	–	–	–	–	–	–	–	–	–	–	Execution	MCR	Execution (Mobile Equip.)	Local Oper.

Then, four additional multi-unit tasks, i.e., decision-making on the priority of shared or mobile equipment, situation awareness, collaboration and communication, and operation of mobile equipment, were also identified and should be considered in the multi-unit task types. Following are brief explanations on the five multi-unit tasks:

- Decision-making on the priority of shared or mobile equipment: In a situation when two units require the mobile or shared equipment simultaneously and the equipment is capable of supplying the function only for one unit, the EOF or TSC should determine which unit is more severe, i.e., the priority. Therefore, this task should be considered in diagnosis part of multi-unit HRA.

- Situation awareness: Situation awareness (SA) is one of the key elements to the success of any emergency response. It is more than a simple memory check of what the operator knows or does not know. According to the Endsley's situation awareness model [9], it consists of three levels; the perception of the elements (Lv. 1 SA), comprehension of the current situation (Lv. 2 SA), and forecasting future system states (Lv. 3 SA). In the multi-unit situations that information may be missing or not available, it may take a couple of hours to deploy the mobile equipment, or there are some unexpected delays, MCR, TSC and EOF who are the subjects of diagnosis require adequate situation awareness including Lv. 1, 2 & 3 SA, for the decision making on the priority of shared or mobile equipment. Therefore, Situation awareness of those organizations needs to be explicitly reflected in the diagnosis part of multi-unit HRA.

- Collaboration and communication: Since many organizations may be involved in the mitigation of accident, collaboration and communication between organizations as well as within an organization become important to reduce the consequence of the accident. Due to the number of organizations and tasks involved, the communication becomes more complex in the multi-unit accident. This task is highly related to the diagnosis part of multi-unit HRA.

- Operation of mobile equipment: Mobile equipment such as water injection tools, portable pumps and portable diesel generators may need to be mobilized and installed at the required location during an emergency. The use of such mobile equipment requires a few sub-tasks such as Deployment, i.e., moving the mobile equipment from the storage to the installation area; Installation, i.e., connecting the power cables, hoses, and the likes to the power plant; and Execution, i.e., turning on the equipment or getting it to perform the required functions. The local operators and sub-contractors carry out these actions.

3. TASK ANALYSIS ON MULTI-UNIT TASK TYPES

This section includes the result of task analysis on the multi-unit task types. First, several task types identified in the previous study were divided into detailed task types, which reflect additional multi-unit considerations and include different task sequences. Then, task analysis was performed on the multi-unit task types.

3.1. Multi-unit task types

As mentioned in Section 2.5, five additional multi-unit tasks, i.e., decision-making on the priority of shared or mobile equipment, situation awareness, collaboration and communication, and operation of mobile equipment should be included in the identified multi-unit task types in Table 1. Operation of mobile equipment could be considered in execution part, while diagnosis part includes the others. Finally, multi-unit task types, i.e., Task type 1, 4, 6 & 8, are divided into detailed task types with a reflection of multi-unit considerations, and totally 12 multi-unit tasks are identified, as shown in Table 2. Following are simple explanations on why some of the task types are noteworthy.

- Task type 1 & 4: Task type 1 and 4 are divided into two task types by the shared equipment operation. Task type 1-1 and 4-1 do not include any additional multi-unit tasks and correspond to the scope of existing HRA. On the other hand, diagnosis of Task type 1-2 and 4-2 not only include decision making on priority of the use shared equipment, but also situation awareness. Those tasks highly affect task sequences in comparison with Task type 1-1 and 4-1.

- Task type 6 & 8: The number of available mobile equipment distinguished Task type 6 and 8 into two task types. Task type 6-1 and 8-1 have conditions where the number of mobile equipment is available more than one per unit, therefore, additional multi-unit tasks in the diagnosis are not required. However, in the case of Task type 6-2 and 8-2, decision making on priority of mobile equipment and situation awareness are necessary in the diagnosis, because the number of mobile equipment is less than the number of unit.

Table 2: Multi-unit task types with additional considerations

Task type	Detailed task type	Actor (Diagnosis)	Additional multi-unit considerations of diagnosis				Actor (Execution)	Additional multi-unit considerations of execution			
			Decision making on priority of shared system	Decision making on priority of mobile equipment	Situation awareness	Complex communication and collaboration between different organizations		Local operation	Shared equipment operation	Mobile equipment operation	Consideration of environment factors
1	1-1	MCR	No	No	No	No	MCR (MCR board)	No	No	No	No
	1-2	MCR	Yes	No	Yes	MCR-MCR	MCR (Shared eq.)	No	Yes	No	No
2	-	MCR	No	No	No	No	LOCAL (Fixed eq.)	Yes	No	No	Yes
`3	-	MCR	No	No	No	No	LOCAL (Mobile eq.)	No	No	Yes	Yes
4	4-1	TSC	No	No	No	TSC-MCR	MCR (MCR board)	No	No	No	No
	4-2	TSC	Yes	No	Yes	TSC-MCRs	MCR (Shared eq.)	No	Yes	No	No
5	-	TSC	No	No	No	TSC-MCR	LOCAL (Fixed eq.)	Yes	No	No	Yes
6	6-1	TSC	No	No (More than 1 available per unit)	No	TSC-MCR	LOCAL (Mobile eq.)	No	No	Yes	Yes
	6-2	TSC	No	Yes (Less than 1 availa ble per unit)	Yes	TSC-MCRs	LOCAL (Mobile eq.)	No	No	Yes	Yes
7	-	EOF	Yes	No	Yes	EOF-TSCs	MCR (Shared eq.)	No	Yes	No	No
8	8-1	EOF	No	No (More than 1 available per unit)	No	EOF-TSC	LOCAL (Mobile eq.)	No	No	Yes	Yes
	8-2	EOF	No	Yes (Less than 1 availa ble per unit)	Yes	EOF-TSCs-	LOCAL (Mobile eq.)	No	No	Yes	Yes

3.2. Task analysis on the multi-unit task types

Task analysis is the process of collecting task-related information necessary for performing HRA on the human failure events that require detailed analysis. Basically, all the detailed information related to the task is included in the task analysis with the overall situation information of the task and the factors influencing the error occurrence. For the task analysis of HRA, a variety of different task analysis techniques are used. Representatively, hierarchical task analysis and HRA event tree analysis are used in the process of identifying detailed task sequences, and timeline analysis identifies related time information. Lastly, the results of task analysis can be used as a direct input in the quantitative analysis or as a technical basis for the input.

For task analysis on the multi-unit task types represented in Table 2, first, task sequence of each multi-unit task type is analyzed using HRA event tree analysis used in THERP method [2]. Then, time information, i.e., the time windows for such as diagnosis and execution, is estimated based on the analyzed results. Time window refers to the time that the task should be completed to maintain the state of the plant successfully. Lastly, how the human error probabilities can be calculated on each multi-unit task type is treated based on the result of the time window and the HRA event tree analysis.

3.2.1 HRA event tree analysis on the multi-unit tasks

HRA event tree analysis was performed on the 12 multi-unit task types in Table 2. Representatively, Task type 1-1 and 8-2 which are respectively the simplest and the most complex HRA event trees on the multi-unit task types are described in this paper.

Task type 1-1 consists of diagnosis and execution by MCR, which are included in the scope of existing HRA. Figure 1 shows the event tree of Task type 1-1, and Table 3 represents information of the branch in Figure 1. On the other hand, Task type 8-2 has more complex sub-tasks with communication processes in comparison with Task type 1-1. Figure 2 represents the event tree of Task type 8-2, and Table 4 shows information of the branch in Figure 2.

Task type 8-2 largely classified into three regions; diagnosis by EOF, transfer of command by MCR and execution by sub-contractors and local operators. First, diagnosis by EOF includes two sub-tasks, i.e., complex communication and collaboration with TSCs, and determination of which unit requires the use of mobile equipment within a site. Additionally, latter sub-task requires Lv. 1, 2, 3 situation awareness.

Second, transfer of command consists of communication steps on the result of diagnosis from EOF to TSC and from TSC to MCR, and meta-diagnosis by MCR. Meta-diagnosis refers to repeated diagnosis on the already diagnosed results. When the sub-organization, i.e., MCR, receives the result of diagnosis from the parent-organization, such as TSC, they should diagnose and determine the required action or command according to the steps in procedures. This kind of task corresponds to the meta-diagnosis. In addition, consideration of meta-diagnosis depends on the task characteristics. For example, ‘Feed and bleed operation’ by MCR requires multiple steps for the execution, so therefore, meta-diagnosis by MCR should be considered for performing this task. On the other hand, for simple tasks such as opening values or starting pumps consideration of meta-diagnosis is not necessary. Operation of shared and mobile equipment also may not require meta-diagnosis by MCR. MCR does not play an important role in those tasks but perform a few steps in procedures.

Lastly, execution by sub-contractors and local operators include three sub-tasks, i.e., communication with MCR, deployment and installment of mobile equipment by sub-contractors, and operation of mobile equipment by local operators.

Figure 1: HRA event tree of Task type 1-1

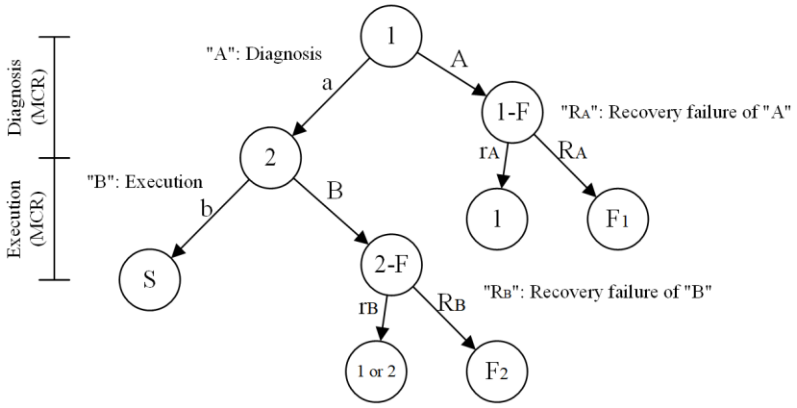


Table 3: Branch explanation of HRA event tree for Task type 1-1

Sub-tasks	Potential performance	Notation in HRA event tree
Diagnosis	Success in diagnosis	a
	Failure in diagnosis	A
	Success in recovery of A	r_A
	Failure in recovery of A	R_A
Execution	Success in execution	b
	Failure in execution	B
	Success in recovery of B	r_B
	Failure in recovery of B	R_B

Figure 2: HRA event tree of Task type 8-2

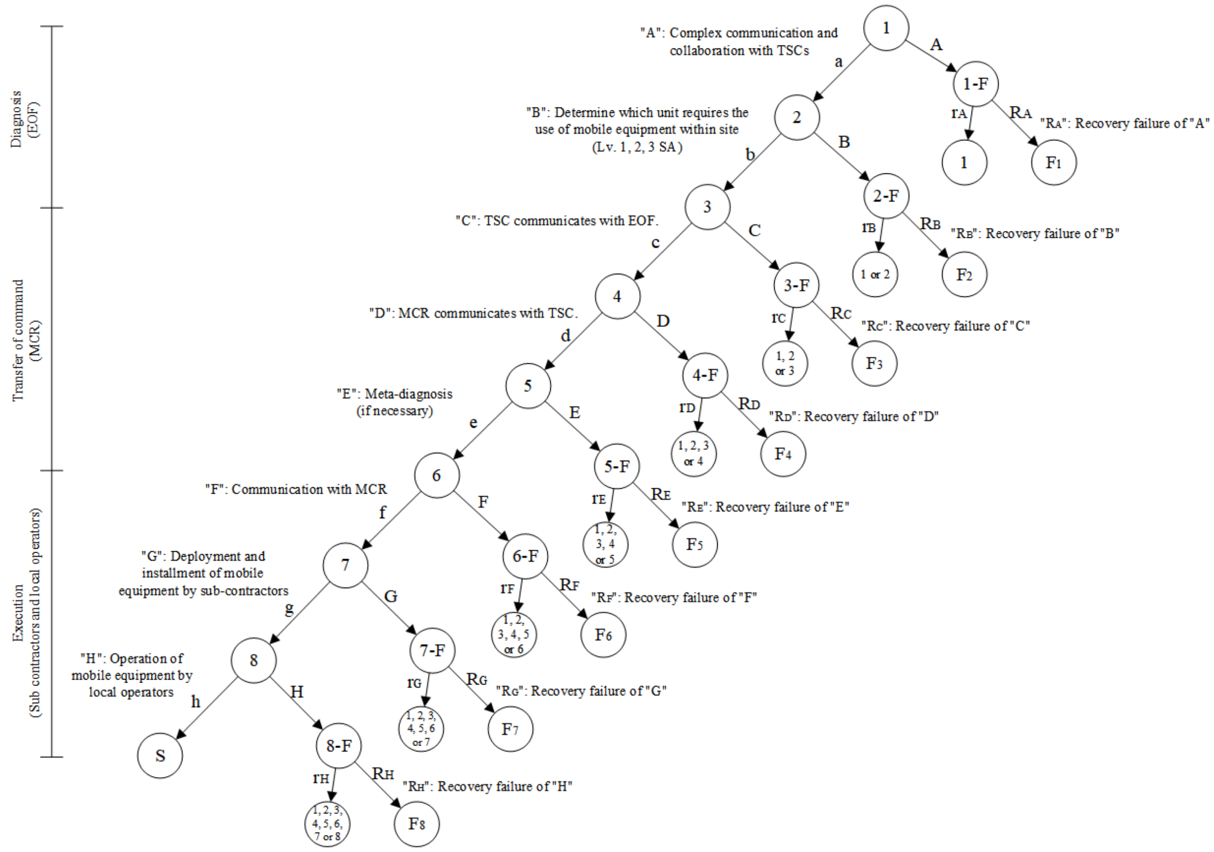


Table 4: Branch explanation of HRA event tree for Task type 8-2

Sub-tasks	Potential performance	Notation in HRA event tree	Sub-tasks	Potential performance	Notation in HRA event tree
1. Complex communication and collaboration with TSCs	Success in complex communication and collaboration	a	5. Meta-diagnosis by MCR	Success in meta-diagnosis	e
	Failure in complex communication and collaboration	A		Failure in meta-diagnosis	E
	Success in recovery of A	r_A		Success in recovery of E	r_E
	Failure in recovery of A	R_A		Failure in recovery of E	R_E
2. Priority determination	Success in priority determination	b	6. Communication with MCR	Success in communication	f
	Failure in priority determination	B		Failure in communication	F
	Success in recovery of B	r_B		Success in recovery of F	r_F
	Failure in recovery of B	R_B		Failure in recovery of F	R_F
3. Communication with EOF	Success in communication	c	7. Deployment and installment by sub-contractors	Success in deployment and installment	g
	Failure in communication	C		Failure in deployment and installment	G
	Success in recovery of C	r_C		Success in recovery of G	r_G
	Failure in recovery of C	R_C		Failure in recovery of G	R_G
4. Communication with TSC	Success in communication	d	8. Operation of mobile eq. by local operators	Success in operation	h
	Failure in communication	D		Failure in operation	H
	Success in recovery of D	r_D		Success in recovery of H	r_H
	Failure in recovery of D	R_D		Failure in recovery of H	R_H

As a result of HRA event tree analysis, Table 5 summarizes sub-tasks required on the 12 multi-unit task types, according to the diagnosis, transfer of command, and execution.

Table 5: Summary of sub-tasks required on the 12 multi-unit task types

Task types	Diagnosis	Transfer of command	Execution
Task type 1-1	• Diagnosis	-	• Execution
Task type 1-2	• Complex communication & collaboration between first and second MCR sharing the equipment • Determination of which unit requires the use of the shared system (Lv. 1, 2, 3 SA)	-	• Communication with the second MCR (if necessary) • Connect shared equipment from the second unit (if necessary) • Connect shared equipment to the first unit
Task type 2	• Diagnosis	-	• Communication with MCR • Access and operation of fixed equipment
Task type 3	• Diagnosis	-	• Communication with MCR • Deployment and installment of mobile equipment by sub-contractors • Operation of mobile equipment by local operators
Task type 4-1	• Diagnosis	• Communication with TSC • Meta-diagnosis	• Execution
Task type 4-2	• Complex communication & collaboration • Determination of which unit requires the use of the shared system (Lv. 1, 2, 3 SA)	• Communication with TSC • Meta-diagnosis (if necessary)	• Communication with the second MCR (if necessary) • Connect shared equipment from the second unit (if necessary) • Connect shared equipment to the first unit
Task type 5	• Diagnosis	• Communication with TSC • Meta-diagnosis	• Communication with MCR • Access and operation of fixed equipment
Task type 6-1	• Diagnosis	• Communication with TSC • Meta-diagnosis (if necessary)	• Communication with MCR • Deployment and installment of mobile equipment by sub-contractors • Operation of mobile equipment by local operators
Task type 6-2	• Complex communication & collaboration • Determination of which unit requires the use of the mobile equipment (Lv. 1, 2, 3 SA)	• Communication with TSC • Meta-diagnosis (if necessary)	• Communication with MCR • Deployment and installment of mobile equipment by sub-contractors • Operation of mobile equipment by local operators
Task type 7	• Complex communication & collaboration	• Communication with EOF • Communication with TSC	• Communication with the second MCR (if necessary)

	• Determination of which unit requires the use of shared system (Lv. 1, 2, 3 SA)	• Meta-diagnosis (if necessary)	• Connect shared equipment from the second unit (if necessary) • Connect shared equipment to the first unit
Task type 8-1	• Diagnosis	• Communication with EOF • Communication with TSC • Meta-diagnosis (if necessary)	• Communication with MCR • Deployment and installment of mobile equipment by sub-contractors • Operation of mobile equipment by local operators
Task type 8-2	• Complex communication & collaboration • Determination of which unit requires the use of the mobile equipment (Lv. 1, 2, 3 SA)	• Communication with EOF • Communication with TSC • Meta-diagnosis (if necessary)	• Communication with MCR • Deployment and installment of mobile equipment by sub-contractors • Operation of mobile equipment by local operators

3.2.2 Time window analysis on the multi-unit tasks

Time window analysis was carried out on 12 multi-unit task types in Table 2. It is assumed that the time required for communication is negligibly small compared to the execution time of other tasks. For example, communication time between the organizations may be much smaller than the time for deployment and installment of mobile equipment. As in Section 3.2.1, the result of time window analysis on Task type 1-1 and 8-2 are representatively provided in this paper.

Figure 3 shows time window of Task type 1-1. It consists of 'T_{Delay}', '$T_{Diagnosis}$', '$T_{Execution}$', and 'T_{SW}'. 'T_{Delay}' refers to the delay time by alarm or disturbance noted. '$T_{Diagnosis}$' and '$T_{Execution}$' mean the time window of diagnosis and execution time, respectively. 'T_{SW}' represents time available to complete diagnosis and action before plant condition becomes an irreversible state, and it is calculated by the equation (1) below:

$$T_{SW} = T_{Delay} + T_{Diagnosis} + T_{Execution} \quad (1)$$

Figure 3: Time window of Task type 1-1

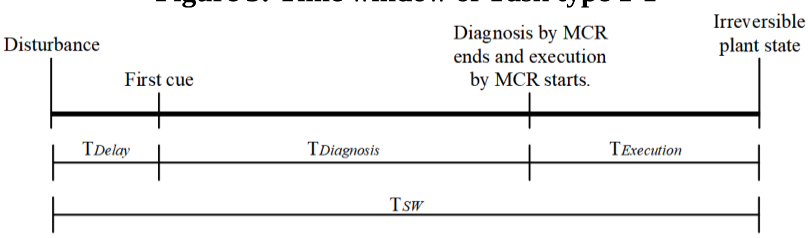
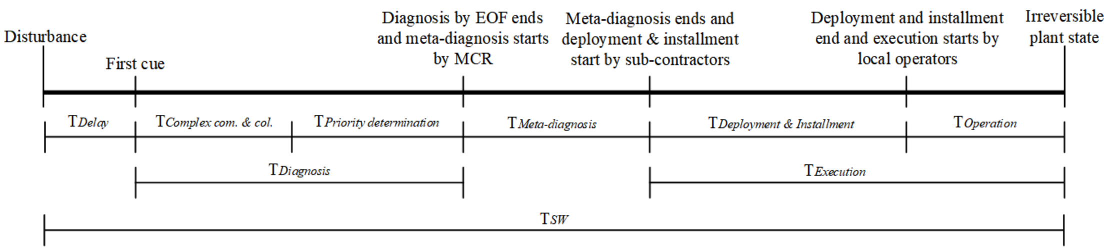


Figure 4 represents time window of Task type 8-2. 'T_{SW}' is calculated by the equation (2) below:

$$T_{SW} = T_{Delay} + T_{Complex\ com.\ \&\ Col} + T_{Priority\ determination} + T_{Meta\text{-}diagnosis} + T_{Deployment\ and\ installment} + T_{Operation} \quad (2)$$

Figure 4: Time window of Task type 8-2



As a result of time window analysis, Table 6 summarizes the time windows of the 12 multi-unit task types.

Table 6: Time windows on the multi-unit tasks

Task types	Time window
1-1	$T_{sw} = T_{Delay} + T_{Diagnosis} + T_{Execution}$
1-2	$T_{sw} = T_{Delay} + T_{\text{Complex com. \& Col}} + T_{\text{Priority determination}} + T_{Connection1} + T_{Connection2}$
2	$T_{sw} = T_{Delay} + T_{Diagnosis} + T_{Access} + T_{Operation}$
3	$T_{sw} = T_{Delay} + T_{Diagnosis} + T_{\text{Deployment \& Installment}} + T_{Operation}$
4-1	$T_{sw} = T_{Delay} + T_{Diagnosis} + T_{\text{Meta-diagnosis}} + T_{Execution}$
4-2	$T_{sw} = T_{Delay} + T_{\text{Complex com. \& Col}} + T_{\text{Priority determination}} + T_{\text{Meta-diagnosis}} + T_{Connection1} + T_{Connection2}$
5	$T_{sw} = T_{Delay} + T_{Diagnosis} + T_{\text{Meta-diagnosis}} + T_{Access} + T_{Operation}$
6-1	$T_{sw} = T_{Delay} + T_{Diagnosis} + T_{\text{Meta-diagnosis}} + T_{\text{Deployment \& Installment}} + T_{Operation}$
6-2	$T_{sw} = T_{Delay} + T_{\text{Complex com. \& Col}} + T_{\text{Priority determination}} + T_{\text{Meta-diagnosis}} + T_{\text{Deployment and installment}} + T_{Operation}$
7	$T_{sw} = T_{Delay} + T_{Diagnosis} + T_{\text{Meta-diagnosis}} + T_{Execution}$
8-1	$T_{sw} = T_{Delay} + T_{Diagnosis} + T_{\text{Meta-diagnosis}} + T_{\text{Deployment \& Installment}} + T_{Operation}$
8-2	$T_{sw} = T_{Delay} + T_{\text{Complex com. \& Col}} + T_{\text{Priority determination}} + T_{\text{Meta-diagnosis}} + T_{\text{Deployment and installment}} + T_{Operation}$

3.2.3 Calculation of human error probabilities

This section includes how the human error probabilities can be calculated on each multi-unit task type based on the result of the time window and the HRA event tree analysis. Table 7 shows a summary of approach to calculate human error probabilities on the multi-unit tasks.

Table 7: Calculation of human error probabilities on the multi-unit tasks

Task types	Human error probabilities
1-1	HEP(Diagnosis)+HEP(Execution)
1-2	HEP(Complex communication & collaboration)+HEP(Priority determination)+HEP(Communication)+HEP(Connection of shared system by unit 2)+HEP(Connection of shared system by unit 1)
2	HEP(Diagnosis)+HEP(Communication)+HEP(Access and operation)
3	HEP(Diagnosis)+HEP(Communication)+HEP(Deployment and installment)+HEP(Operation)
4-1	HEP(Diagnosis)+HEP(Communication)+HEP(Meta-diagnosis)+HEP(Execution)
4-2	HEP(Complex communication & collaboration)+HEP(Priority determination)+HEP(Communication)+HEP(Meta-diagnosis)+HEP(Communication)+HEP(Connection of shared system by unit 2)+HEP(Connection of shared system by unit 1)
5	HEP(Diagnosis)+HEP(Communication)+HEP(Meta-diagnosis)+HEP(Communication)+HEP(Access and operation)
6-1	HEP(Diagnosis)+HEP(Communication)+HEP(Meta-diagnosis)+HEP(Communication)+HEP(Deployment and installment + Operation)
6-2	HEP(Complex communication & collaboration)+HEP(Priority determination)+HEP(Communication)+HEP(Meta-diagnosis) +HEP(Communication)+HEP(Deployment and installment)+HEP(Operation)
6	HEP(Complex communication & collaboration)+HEP(Priority determination)+HEP(Communication)+ HEP(Communication) +HEP(Meta-diagnosis)+HEP(Communication)+HEP(Connection of shared system by unit 2) +HEP(Connection of shared system by unit 1)
8-1	HEP(Diagnosis)+HEP(Communication)+HEP(Communication)+HEP(Meta-diagnosis)+HEP(Communication)+ HEP (Deployment and installment)+HEP(Operation)
8-2	HEP(Complex communication & collaboration)+HEP(Priority determination)+HEP(Communication)+ HEP(Communication) +HEP(Meta-diagnosis)+HEP(Communication)+HEP(Deployment and installment)+HEP (Operation)

4. QUALITATIVE ANALYSIS

This section describes the result of qualification analysis on how basic error probabilities and PSFs could be treated for the sub-tasks identified in the HRA event tree analysis. Representatively, Task type 1-1 and 8-2 which are respectively the simplest and the most complex multi-unit task types are introduced in this paper.

For the qualitative analysis, applicability in the scope of existing HRA was evaluated for the sub-tasks in each task type. For example, in the case of shared system operation, it consists of three sub-tasks, i.e.,

1) communication with the second MCR, 2) connection of shared equipment from the second unit, and 3) connection of shared equipment to the first unit. The formal sub-task, i.e., communication with the second MCR has not been considered in the scope of existing HRA, while second and third sub-tasks are the actions which are generally calculated in execution part in the existing HRA. First of all, sub-tasks considered in the scope of existing HRA are distinguished, then how the basic error probabilities and PSFs could be assumed for each sub-task are not covered in existing HRA.

4.1. Task type 1-1

Task type 1-1 consists of diagnosis and execution, which are fully included in the scope of existing HRA. Therefore, basic HEPs and PSFs of those sub-tasks could be assumed as considered in the existing HRA.

4.2. Task type 8-2

Task sequence of Task type 8-2 represents that EOF diagnoses the use of mobile equipment with complex communication & collaboration between EOF and TSCs, diagnosed result by EOF is transferred from EOF to TSC and from TSC to MCR, MCR performs meta-diagnosis on the result of diagnosis, MCR contacts with local operators, sub-contractors deploy and install the mobile equipment, then finally, local operators operate mobile equipment. It includes 8 sub-tasks, i.e., 1) complex communication & collaboration, 2) determination which unit requires the use of mobile equipment, 3) communication with EOF by TSC, 4) communication with TSC by MCR, 5) meta-diagnosis by MCR, 6) communication with MCR by local operators, 7) deployment and installment of mobile equipment by sub-contractors, and 8) operation of mobile equipment by local operators.

4.2.1 Complex communication & collaboration

Complex communication & collaboration is not considered in the existing HRA. Based on the literature survey, Lee, Ha and Seong [10] developed CREAM-based communication error analysis method (CEAM) for nuclear power plant operators' communication. According to this research, it suggests several communication failure types; 1) message is sent to the wrong place or person, 2) message transmission is inadequate, 3) message production is inadequate, 4) message content is wrong, 5) message content is inappropriate for the receiver, 6) message is sent at the wrong time, 7) message is not sent at all, and 8) message content is inconsistent content with other information. After the adequate error failure types are identified and selected for the communication and collaboration, then corresponding basic HEPs should be estimated. CEAM method also includes basic HEPs on each error failure type.

Some of PSFs, such as organization, working conditions, equipment, procedures, workload, available time, time of day, expertise level, crew, collaboration quality, can affect communication errors, as mentioned in CEAM method.

4.2.2 Determination which unit requires the use of mobile equipment

The determination of which unit requires the use of mobile equipment cannot be calculated by existing HRA. This sub-task includes not only Lv. 1, 2 SA, but also 3 SA. Actually, some of the diagnosis tasks in existing HRA contain Lv. 1, 2 SA. Although, it is not explicitly mentioned about whether the task requires situation awareness or not. When Lv. 3 SA is additionally considered, basic HEP may be estimated as having higher error probability than only including Lv. 1 & 2. Therefore, basic HEP of this sub-task should be modified as a higher value in comparison with the task considered in existing HRA. For this sub-task, i.e., determination of which unit requires the use of mobile equipment, the upper bound of basic HEPs can be assumed by multiplying nominal basic HEPs and their error factors.

PSFs in this task should reflect specific situation or condition that this task is required. First, existing HRA methods only consider diagnosis by MCR. In the case of this sub-task, it is performed by EOF, which cannot be evaluated as having the same working condition as the MCR. EOF normally includes more organization members, has less training/experience, and their information is limited in comparison with MCR. Therefore, when the diagnosis is carried out by the other organizations, i.e., TSC or EOF, their characteristics should be reflected in the PSFs. Second, when the severe accident occurs, the personnel in EOF may have more burdens, and some of PSFs, such as stress, workload, and complexity may be negatively affected by that situation. This situation information should be considered while assigning the PSF values.

4.2.3 Communication with EOF by TSC and with TSC by MCR

This sub-task refers to communication errors occurred during the transfer of command from EOF to TSC or from TSC to MCR, and it is also not considered in the existing HRA. It could be evaluated by CEAM, which is introduced in Section 4.2.1. However, it may estimate much lower basic human error probability than complex communication and collaboration introduced in Section 4.2.1.

4.2.4 Meta-diagnosis by MCR

Meta-diagnosis is related to the execution using procedures. Basic HEP of meta-diagnosis could be estimated by Table 20-7 of THERP method, which includes estimated probabilities of instruction when use of written procedure is specified [2]. In the case of PSFs in meta-diagnosis, same scope of PSFs evaluated in existing HRA are assumed.

4.2.5 Communication with MCR by local operators

This communication follows the method in Section 4.2.3.

4.2.6 Deployment and installment of mobile equipment by sub-contractors

Deployment and installment of mobile equipment by sub-contractors means moving the mobile equipment from the storage to the installation area, and connecting the power cables, hoses, and the likes to the power plant. In this case, connecting the power cables or hoses is the human actions which affect the success of the corresponding task, and it could be assumed as the task considered in the existing HRA. Therefore, basic HEP of this task does not require additional modification in comparison with existing HRA.

Environmental factors should be considered as one of the PSFs. This task may be highly affected by environmental factors. They can cause failure of equipment, block equipment routing, limit access, or delay access to the necessary areas. In addition, environmental factors may give more negative effects on some of PSFs which are easily affected by environmental factors, such as workload, stress/stressors, and task complexity.

4.2.7 Operation of mobile equipment by local operators

Operation of mobile equipment refers to turning on the equipment or getting it to perform the required functions by local operators. This task could be assumed as the local action for fixed equipment, which is covered in the scope of existing HRA.

Environmental factors are also considered as PSF, as same as the task, i.e., deployment and installment of mobile equipment. Habitability of areas where operator actions are needed may be affected by environmental factors. Environmental factors may also give more negative effects on some of PSFs such as workload, stress/stressors, and task complexity.

5. CONCLUSION

This study aims to suggest an approach to the HRA for the multi-unit PSA. This approach focused on analyzing the tasks required in the multi-unit HRA and making full use of existing HRA. First, the distinguished features in multi-unit HRA were briefly introduced in the perspectives of organization, task object, PSFs, environmental factors, and task. Then, task analysis and qualification analysis were carried out based on the multi-unit task types, which reflect additional multi-unit considerations and include different task sequences. Even if quantification analysis for calculating human error probability is not provided in this paper, it will be developed in the near future. The final result of this study could be used for estimating and providing human error probabilities for the application in multi-unit PSA.

Acknowledgments

This work was supported by the Nuclear Safety Research Program through the Korea Foundation of Nuclear Safety (KoFONS), using the financial resource granted by the Nuclear Safety and Security Commission (NSSC) of the Republic of Korea. (No. 1705001).

References

[1] P. Pyy. “Human reliability analysis methods for probabilistic safety assessment”, VTT PUBLICATIONS, 4(2): p. 2, (2000).
[2] A.D. Swain and H.E. Guttmann. “Handbook of human-reliability analysis with emphasis on nuclear power plant applications”, Final report, Sandia National Labs., Albuquerque, NM (USA), (1983).
[3] A. Swain. “Accident Sequence Evaluation Program Human Reliability Analysis Procedure”, NUREG/CR-4772, (1987).
[4] G. Parry et al. “An approach to the analysis of operator actions in probabilistic risk assessment”, EPRI Report TR-100259, (1992).
[5] A.D. Swain. “Human reliability analysis: Need, status, trends and limitations”, Reliability Engineering & System Safety, 29(3): p. 301-313, (1990).
[6] Y. Kim, J. Park and W. Jung. “A classification scheme of erroneous behaviors for human error probability estimations based on simulator data”, Reliability Engineering & System Safety, 163: p. 1-13, (2017).
[7] J. Kim and G. Kim. “Identification of Human and Organizational Factors for the Multi-Unit PSA”, Asian Symposium on Risk Assessment and Management (ASRAM2017), (2017).
[8] KHNP. “Radiation Emergency Plan”, (2015).
[9] M. R. Endsley. “Toward a theory of situation awareness in dynamic systems”, Human factors, 37(1): p. 32-64, (1995).
[10] Lee, S.M., J.S. Ha, and P.H. Seong, CREAM-based communication error analysis method (CEAM) for nuclear power plant operators’ communication. Journal of Loss Prevention in the Process Industries, 2011. 24(1): p. 90-97.