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Original Article

Human and organizational factors for multi-unit probabilistic safety assessment: Identification and characterization for the Korean case

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ABSTRACT

Since the Fukushima Daiichi accident, there has been an emphasis on the risk resulting from multi-unit accidents. Human reliability analysis (HRA) is one of the important issues in multi-unit probabilistic safety assessment (MUPSA). Hence, there is a need to properly identify all the human and organizational factors relevant to a multi-unit incident scenario in a nuclear power plant (NPP). This study identifies and categorizes the human and organizational factors relevant to a multi-unit incident scenario of NPPs based on a review of relevant literature. These factors are then analyzed to ascertain all possible unit-to-unit interactions that need to be considered in the multi-unit HRA and the pattern of interactions. The human and organizational factors are classified into five categories: organization, work device, task, performance shaping factors, and environmental factors. The identification and classification of these factors will significantly contribute to the development of adequate strategies and guidelines for managing multi-unit accidents. This study is a necessary initial step in developing an effective HRA method for multiple NPP units in a site.

1. Introduction

Since the Fukushima Daiichi accident, risks resulting from multi-unit accidents at nuclear power plant (NPP) sites have been highlighted, and the interest in multi-unit probabilistic safety assessment (MUPSA) has significantly increased in the past few years [1]. Moreover, most of the world's NPPs operate at multi-unit sites. Specifically, reference [2] showing the distribution of the number of operating units around the world reveals that more than 68% of the world's NPP sites contained multiple units by the end of 2014.

Probabilistic safety assessment (PSA) aims at achieving completeness in identifying possible faults, deficiencies, and plant vulnerabilities. It also provides a balanced picture of the safety significance of a broad spectrum of issues, including the uncertainties of the numerical results. Any incompleteness can add to the uncertainty of the quantified results [3].

The importance of human reliability analysis (HRA), which is generally performed as part of a PSA, has continued to take on increasing importance. In 1979, the Three Mile Island accident drew attention to the importance of human factors in nuclear safety, while the Chernobyl accident in 1986 brought to the forefront the significance of management and organizational factors in nuclear safety. However, the Fukushima Daiichi accident magnified the need for an approach that views safety as an outcome of the interaction between individuals, technology, and organizations [4].

Human factors have continued to be significant contributors to the safety and reliability of complex systems. According to the literature [5], human error contributes to 90% of the safety incidents in the nuclear industry, 80% of those in the petrochemical and chemical industry, 75% of those in the naval industry, and 70% of the safety incidents in the civil aviation industry. Some failures that could be associated with human and organizational factors may have their root causes in an inadequate understanding of organizational interactions [4]. Furthermore, based on information from the Operational Performance Information System for Nuclear Power Plant (OPIS) [6], from the year 2000 to the end of the year 2017, three initiating events were caused by human errors among fourteen events that had influenced multiple units in Korean NPPs. These errors typically consider human errors during operation, management, or maintenance tasks. They do not include errors on the part of the plant designer like poor design or poor material selection for equipment. According to an International Nuclear Safety Group (INSAG) report [3], it is essential that organizational

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issues are given proper and adequate consideration within any integrated risk-informed and decision-making process, as this would maintain and improve human input to safety.

The complexity of multi-unit accidents depends greatly upon the degree of unit-to-unit interactions. These interactions may stem from the types of initiating events, the number of shared systems, or the number of shared resources [7]. Human and organizational factors are regarded as two of the key factors that can influence the unit-to-unit interaction. In order to adequately account for the risks associated with a multi-unit PRA, six main classifications of factors have been suggested which are: initiating events, shared connections, identical components, proximity dependencies, human dependencies, and organizational dependencies [8,9].

Most of the multi-unit sites in operation share significantly common operational practices, common human actions, procedural similarities, and organizational similarities. Accounting for human, inter-unit, and intra-unit dependencies was also recommended in Ref. [10]. This report opined that accounting for human actions and organizational dependencies is arguably the most important challenge in performing MUPSA.

In spite of this importance, there are several potential challenges when current HRA methods are applied to the MUPSA. For instance, current HRA methods are focused on the main control room (MCR) operation, i.e., the actions performed by MCR operators. However, in the case of multi-unit accidents, operational situations become more complicated and more organizations have to be involved in mitigating the accidents. Other constraints of the current single-unit HRA include the lack of consideration of mobile equipment, shared maintenance teams [11], and environmental factors affecting their deployment, which can ultimately affect the response times. Human and organizational factors that can affect the safety in the MUPSA have not been sufficiently identified. In addition, the current HRA is developed for single units; therefore, it does not adequately cater for multi-unit cases. To address this challenge, the first step is to properly identify those factors in multi-unit accident cases that are different from those in single-unit cases.

This study attempts to identify and characterize the human and organizational factors that need to be considered in the HRA for the MUPSA. It focuses on the inter-unit interactions of human and 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 (for example, causing radiation release, increasing complexity, and causing accessibility issues). This manuscript is organized as follows. In the second section, the approach to this study and relevant key facts are analyzed. The third section describes a model of human and organizational factors considered as related to current HRA practices. Organizational models are essential in that they can provide a clearer view of all factors involved. In the fourth section, this study suggests a model of human and organizational factors for multi-unit HRA and their interactions while highlighting the unique performance shaping factors (PSFs) and characterizing these factors. Finally, this study highlights the difference of human and organizational factors for the MUPSA (versus the single-unit case) and makes concluding remarks.

2. Categories of human and organizational factors for the MUPSA

This study identifies five categories of human and organizational factors that need to be further investigated in the MUPSA. This categorization is based on a review of the literature on multi-unit PSAs, severe accident management, and current Korean emergency response practices. Scheduled visits to Korean NPPs were also part of the information-gathering process for this work. Based on this review, this section highlights four categories of factors that can be distinguished between single- and multi-unit accidents: organizations, work device, task, and PSFs. In the following sections, detailed discussions on these categories will be presented, focusing on the difference between single- and multi-unit accidents.

2.1. Organizations

Organization represents the actors who are involved in the mitigation of accidents. It includes plant personnel, regulators, government officers, and sub-contractors in NPPs. For instance, according to the Korean emergency response plan [12], different organizations are established depending on whether an accident occurs in a single unit, two units, or over a site. Abnormal conditions need to be diagnosed and managed, and corrective actions need to be performed. Plant operations and emergency response need to be managed; information must be provided to local, state and federal authorities; and ultimately, the plant should be restored to safe conditions. Operating personnel are primarily responsible for these actions at the initial stage of any accident [13]. In Korea, a technical support center (TSC) deals with up to two units. An operational support center (OSC) can also be set up in Korean NPPs to perform maintenance, firefighting, and rescue activities and can be assigned to other duties in support of emergency operations. Local operators perform actions on the locally located and fixed equipment and, in some severe conditions, can participate to remove debris inhibiting access to mobile equipment [14]. The emergency operating facility (EOF) also provides high-level directives for the entire site. The setup of these organizations is not restrictive to the number of units involved. For example, if the severity of the accident is high in a single unit, a TSC is established to provide functions, including plant management and technical support to the reactor operating personnel located in the MCR during an emergency situation.

2.2. Work devices

A work device refers to a target on which an actor performs a task. The work device is any equipment or device that is used by the organizations for any form of response or control during an incident. Work devices include the MCR board, fixed local equipment, mobile local equipment, and shared equipment. HRAs generally assign different human error probabilities (HEPs), depending on where the task is performed. For instance, the HEPs for tasks in MCRs is generally lower than for those involving local equipment, because the operating condition in MCRs is more favorable to the operator.

After the Fukushima accident (i.e., a multi-unit incident), mobile equipment was proposed as an important coping mechanism. For instance, Diverse and Flexible Coping Strategies (FLEX) was suggested to provide plant coping capability to prevent core damage even when there is a simultaneous extended loss of AC power and loss of normal access to the ultimate heat sink (LUHS) [15]. Meanwhile, the shared equipment in NPPs can be classified into the identical system, structure, and components (SSCs), single SSC, time-sequential, cross-connected, standby-sharing, and spare, according to the sharing type [8,16]. For example, a cross-connected system like the intake and service water systems including their pumping houses often shared between two units via cross-ties, will provide full capacity to both units while a standby sharing system like the emergency diesel generator may not have the capability to support two units simultaneously.

2.3. Task

Task characteristics depend on who performs the task (i.e., organization) and on what they perform (i.e., work device). Task refers to a set pattern of operations which alone or together with other tasks, may be used to achieve a goal [17]. The tasks of the various organizations involved in a multi-unit accident is more complex than those for a single unit. Communication among organizations becomes more complex, and there is a greater need for collaboration as the stakes become higher in a multi-unit accident. A report on the Fukushima Daiichi accident [18] pointed out that inappropriate communication between the utility and the government negatively affected the early mitigation.

Task characteristics are also influenced by the work device. While actions executed in the MCR are like pushing a button or turning a switch, the use of mobile equipment requires more subtasks, such as moving and installing equipment and implementing its function. Therefore, as the number of organizations and work devices increases, the number of task types also increases.

In addition, when the accident situation is complex, the situational awareness of the acting organizations becomes important. One of the causes of a severe accident related to the improper emergency response during the Fukushima Daiichi accident was the misdiagnosis of the state of the Unit 1 isolation condenser [19]. Therefore, appropriate situation awareness is one of the functions necessary for emergency response. Situation awareness includes the task of knowing previous and current plant states and deriving from these, predictions of the future state, which will affect decisions concerning the planning of control actions [20].

2.4. Performance shaping factors

PSFs have a central role in HRA. The HEP calculation can be separated into diagnosis and execution. The basic HEP for diagnosis and execution are adjusted using PSFs [21–23]. The final HEP is derived by summing both the diagnosis and execution HEPs. The PSFs are used to reflect time-specific and scenario-specific conditions and can be defined as any factors that influence human performance [24–26]. Typical examples include time, stress, procedure, human-machine interface (HMI)/ergonomics, workload, training/experience, complexity, fitness for duty, and work processes [27]. Other PSFs used in current HRA methodologies can be seen in Refs. [28] [29], [30], and [31].

3. Human and organizational factors for single-unit HRA with use of fixed equipment

This section describes a model of human and organizational factors in a single-unit HRA and their interactions. Fig. 1 shows a human and organizational model that is generally considered in the single-unit HRA, reflecting the operational conditions in Korea. This model also assumes only the use of fixed equipment and does not include mobile equipment.

The circles represent the actors who perform the task, whereas the curved-sided rectangles show the target object of the task. The dotted arrows show the control flow. The double-sided arrows indicate the bidirectional communication between the MCR Oper. (Operator) and the Local Oper. (Operator).

3.1. Organizations in single-unit HRA model

This model considers operator actions performed during a single shift comprising 10–12 personnel, including the MCR operators and the local operators. It assumes that the MCR operators perform diagnosis tasks. Thereafter, the necessary actions can be executed either on the MCR board by the MCR operator or on the fixed equipment by local operators.

3.2. Work devices in single-unit HRA model

The work devices in the single-unit HRA model refer to the equipment operated by the organizations and are categorized into three sub-classes: the MCR board, the local or fixed equipment installed at the NPP, and the shared equipment pooled or connected with each unit. PSA can give credit to equipment such as an AAC diesel generator or instrument air, which can be shared by two units. If necessary, the operators can connect the shared equipment for the function of one or more units. However, not all shared equipment can provide full functionality for both units at the same time.

3.3. Tasks in single-unit HRA model

Generally, there are two task types typically utilized in a single-unit HRA. In 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 the diagnosis but instructs the local operator to take action on the fixed equipment. Table 1 presents the task types considered in the single-unit HRA model. Collaboration and communication are needed for the use of the shared equipment. The local operator may control the shared equipment with directive from the MCR. This is not recognized as a separate task type because it has a process similar to task type 2.

3.4. Performance shaping factors in single-unit HRA model

The PSF considerations in this model are for organizations such as the MCR and the local operators. This reflects the current Korean nuclear industry practice. The PSFs suggested in current HRA methods, can adequately address the HEPs of these organizations for this model.

4. Human and organizational factors for multi-unit HRA

The model of human and organizational factors for the multi-unit HRA is described in this section. Fig. 2 shows such a model based on the Korean practice. It is more complex and the interactions are increased, as compared to the single-unit HRA. As in the single-unit model, the circles represent the actors who perform the tasks, the curved-edged rectangles show the target device of the task, and the dotted arrows show the control flow to the work devices. The double-sided arrows show bidirectional communication between the organizations. All the actors are affected by PSFs, and some are additionally affected by environmental factors (EFs). This is represented by the dark circle around each actor.

When an accident influencing more than one unit occurs, the TSC is responsible for the diagnosis and control of the accident for two units. The decision-making responsibility now belongs to the TSC instead of the MCR. In this case, the MCR operator's role is to perform control actions on the MCR board and to transfer the commands from the TSC to the local operators. In a multi-unit accident, the local operators may deploy mobile equipment, such as portable diesel generator and pump, with the support of subcontractors. If a severe accident occurs in one of the units or an external event (e.g., earthquake, fire, or flooding) causes a multi-unit accident, the environmental factors may affect the personnel's performance. These environmental factors could include radiation, fire, flooding, and debris from the external event. Based on the studies conducted, we identified several factors distinguishing

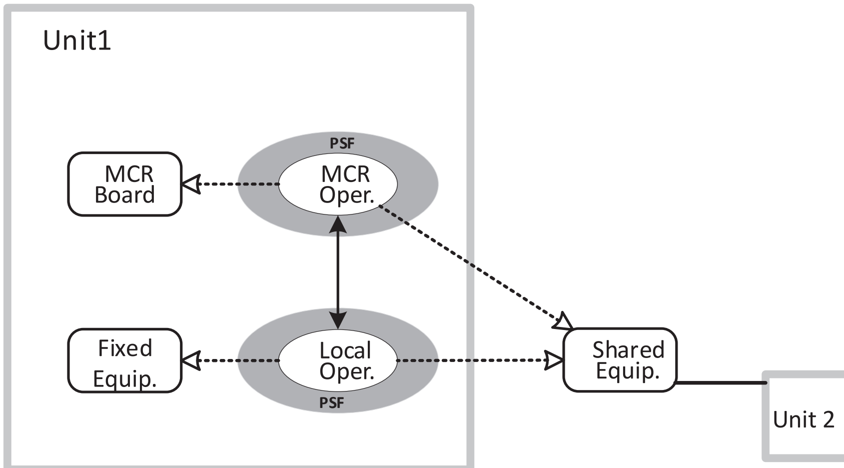

Fig. 1. Model of human and organizational factors for single-unit HRA MCR, main control room; Oper., operator; Equip., equipment; PSF, performance shaping factors.

Table 1
Task categories for single-unit HRA.

No.	Task Type 1		Task Type 2	
	Task Sequence	Actor	Task Sequence	Actor
1	Diagnosis	MCR	Diagnosis	MCR
2	Execution	MCR	Execution (Fixed Equipment)	Local Operator

*MCR, main control room.

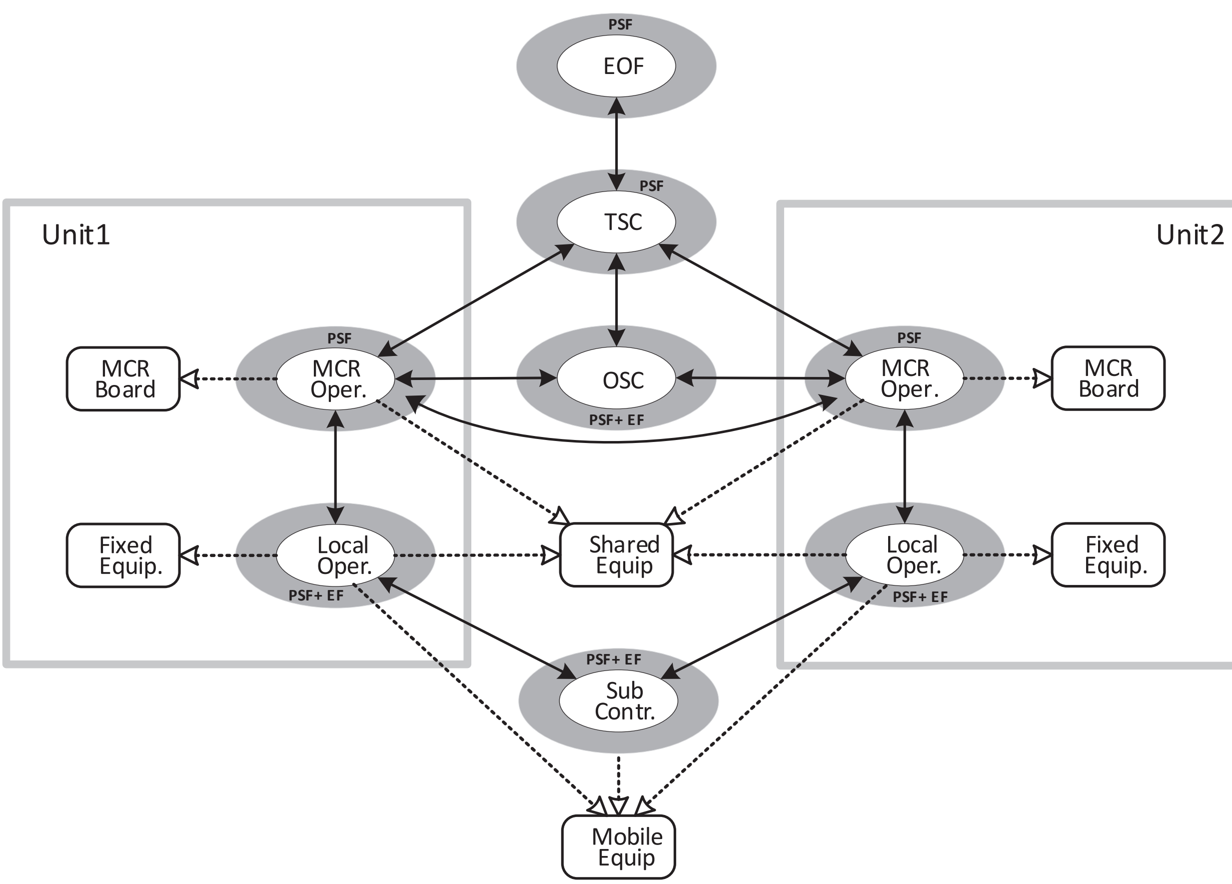

Fig. 2. Model of human and organizational factors for multi-unit HRA. EOF, emergency operating facility; TSC, technical support center; OSC, operational support center; MCR, main control room; Oper., operators; Equip., equipment; Sub Contr., sub-contractors; PSF, performance shaping factors; EF, environmental factors.

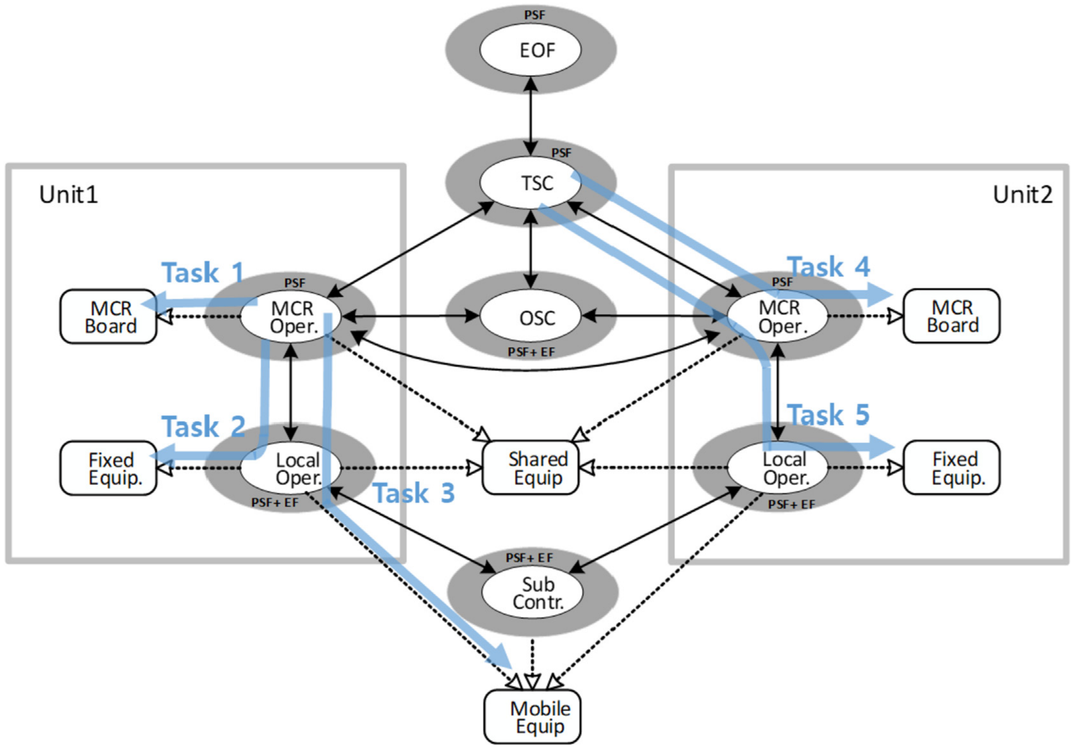

Fig. 3. Model of multi-unit human and organizational factors showing task types 1, 2, 3, 4, and 5. EOF, emergency operating facility; TSC, technical support center; OSC, operational support center; MCR, main control room; Oper., operators; Equip., equipment; Sub Contr., sub-contractors; PSF, performance shaping factors; EF, environmental factors.

a multi-unit HRA from a single-unit HRA, including organizations, work devices, PSFs, and environmental factors.

Based on the human and organizational model in Fig. 3 and the current emergency response plan in Korea, this study identifies and characterizes human and organizational factors that should be considered in a multi-unit HRA.

4.1. Organizations for multi-unit HRA

An organization in a multi-unit HRA refers to all the persons or group of persons that have one or more functions to mitigate an accident in a multi-unit scenario. More organizations are involved in the case of a multi-unit facility compared to a single-unit facility. In the case of Korean NPPs, six organizations are involved in a multi-unit facility, and they are described as follows:

4.1.1. Technical support center (TSC)

The TSC is an onsite facility located close to the control room that provides plant management and technical support to the reactor operating personnel located in the MCR during emergency conditions. The TSC is responsible for two NPP units and is the primary communication center for the plants during an emergency.

4.1.2. Operational support center (OSC)

The Operating support center (OSC) provides the engineering support for chemical, electrical, mechanical and instrumentation and control systems. The OSC also performs maintenance, fire-fighting, and rescue activities. There are bidirectional communications between the OSC and the MCR and between the OSC and the TSC so that the personnel reporting to the OSC can also support the emergency operations.

4.1.3. Main control room (MCR)

Licensed reactor operators and the senior reactor operator staff the MCR, which is the onsite facility for operating the NPP. The senior reactor operator is designated as the shift supervisor. Until the TSC is established, the MCR is responsible for diagnosing and mitigating abnormal conditions, performing or directing corrective measures, and providing plant status information to higher authorities, among other duties.

4.1.4. Local operators and sub-contractors

Local operators perform required actions on locally located fixed and mobile equipment. If the TSC or MCR personnel decides to use mobile equipment, sub-contractor staff will join the deployment and installation of such equipment. They may also participate to remove debris limiting the accessibility of mobile equipment to be deployed during an emergency, among other ancillary duties.

4.1.5. Emergency operating facility (EOF)

The EOF is a facility located outside the NPP site that provides plant management and technical support to both the TSC and reactor-operating personnel located in the MCR during emergency conditions. The EOF is responsible for making important top-level decisions regarding the course of action during incidents involving more than two NPP units. The EOF makes final decisions regarding the priority of deploying mobile equipment, especially when multiple plants require the equipment simultaneously. It is also responsible for communicating with local government officials, the police, the fire service, the military, and all relevant agencies in the case of emergency. The EOF contains the teams for radiological evaluation and public relations, among others.

4.2. Work devices for multi-unit HRA

The work devices for a multi-unit HRA can be categorized into four sub-classes: MCR board, local or fixed equipment, shared equipment, and mobile equipment. Typical examples of fixed equipment, shared equipment, and mobile equipment are an auxiliary feedwater pump, instrument air system, and mobile diesel generator, respectively. Notice that many organizational factors have been added to the multi-unit HRA model, as compared to the single-unit HRA model. Whereas, in terms of work devices, only one is added (mobile equipment) in the multi-unit HRA model. Nonetheless, the impact of this one work device on the other factors is quite large from human and organizational perspectives.

Mobile equipment could be considered as the last option in mitigation strategies for severe accidents; when they fail to function or are inhibited by EFs, the accident will not be arrested promptly. Further discussion on mobile equipment is made in Section 4.3.3.

4.3. Task characteristics in multi-unit HRA

The increase in organizations and therefore work devices has, therefore, lead to more complicated task characteristics for the multi-unit HRA, as compared to those of single units. This study has identified five task characteristics for the multi-unit HRA, described in detail in the following subsections.

4.3.1. Task types

The definition of task types depends on the complexity of communication between the organizations and the nature of the jobs carried out by the various actors (see Table 2). This means that the task type can be different when the actors, the work device, or the communication path changes. Nine task types have been identified. Only two of these task types (Types 1 and 2) are applied to the single-unit HRA, whereas, all the nine task types are worth considering for the multi-unit HRA. The current single-unit HRAs in Korea do not give credit to emergency response organizations like the TSC/EOF. One complex task type that is likely in a multi-unit HRA is Type 6, wherein the diagnosis is carried out by the TSC, which communicates such information to the MCR. The MCR operators then relay information accordingly to the actor.

In Task Type 1, the diagnosis is made in the MCR, and the MCR operator executes the necessary action on the MCR board. In Task Type 2, the MCR makes a diagnosis but gives directive for the local operator to implement necessary action on fixed equipment in the NPP. Similarly, the MCR makes the diagnosis in Task Type 3, but, in this case, the local operator takes action on one of the mobile equipment in the NPP site. As for Task Type 4, the diagnosis is performed by the TSC, while the MCR is tasked with taking the mitigating action on the MCR board. Task Types 5 and 6 are alike in that the TSC carries out the diagnosis and transfers command to the MCR. The difference lies in the fact that the local operator only acts on fixed equipment in Task Type 5 while acting on mobile equipment in Task Type 6. Notably, in Task Type 6, there has to be collaboration between a local operator and sub-contractors.

Figs. 3 and 4 show the suggested models of human and organizational factors for multi-unit HRA, indicating the task types and communication paths. Task Type 7 involves the EOF making the diagnosis or making the final decision as to the response pattern based on the information available. There is a transfer of command from the EOF to the TSC, and from the TSC to the MCR operator who executes the required action on the MCR board. Task Type 8 follows the same pattern as in Type 7, except that the MCR

Table 2
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 Type 9	
	Task Sequence	Actor	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	Diagnosis	EOF
2	Execution	MCR	Execution (Fixed Equip.)	Local Oper.	Execution (Mobile Equip.)	Local Oper.	Execution	MCR	Transfer of Command	MCR	Transfer of Command	MCR	Transfer of Command	TSC	Transfer of Command	TSC	Transfer of Command	TSC
3	–	–	–	–	–	–	–	–	Execution (Fixed Equip.)	Local Oper.	Execution (Mobile Equip.)	Local Oper.	Execution	MCR	Transfer of Command	MCR	Transfer of Command	MCR
4	–	–	–	–	–	–	–	–	–	–	–	–	–	–	Execution (Fixed Equip.)	Local Oper.	Execution (Mobile Equip.)	Local Oper.

† MCR, main control room; Equip., equipment; Oper., operators; TSC, technical support center; EOF, emergency operating facility.

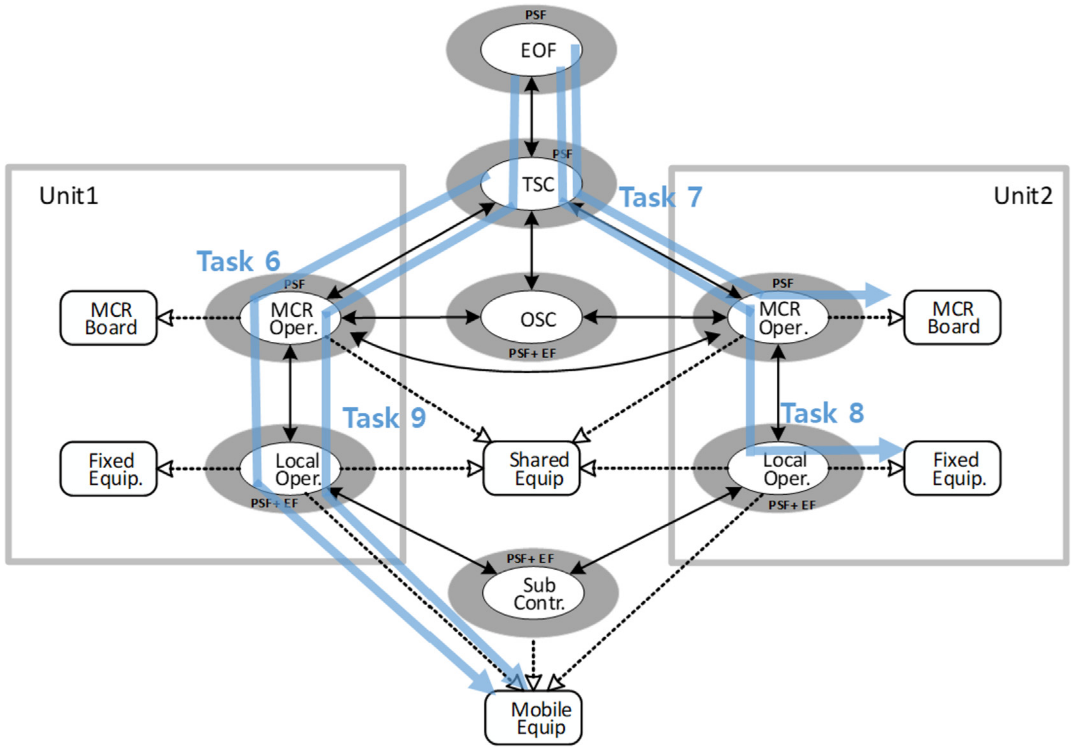

Fig. 4. Model of multi-unit human and organizational factors showing task types 6, 7, 8, and 9. EOF, emergency operating facility; TSC, technical support center; OSC, operational support center; MCR, main control room; Oper., operators; Equip., equipment; Sub Contr., sub-contractors; PSF, performance shaping factors; EF, environmental factors.

gives a directive to the local operator, who implements the needed action on fixed equipment in the NPP.

The most complex task type is Type 9. In this case, the diagnosis decisions are made by the EOF and transfer of execution command occurs twice: firstly, between the EOF and the TSC, and, secondly, between the TSC and the MCR. The local operator or the subcontractor executes the task.

Human error event trees can provide a pathway for the quantification of HEPs. The individual subtasks or steps in the tasks form the branches of the human error event trees. Fig. 5 shows the error modes in human error event trees for a complex task, corresponding to Task Type 9.

Each of the task elements is treated as either a success or a failure. “F” represents a failure to implement the subtask, while “Fx” (where “x” is a number) represents an irreversible failure in implementing a subtask, with the number(s) representing the task stage(s). A notation like “1, 2, 3, 4, 5, 6, or 7” indicates that recovery could be made to any of the listed stages, 1, 2, 3, 4, 5, 6, or 7. The same goes for similar notations, while “S” represents the success of the entire task. Table 3 shows details of the notations used.

It must be noted that the TSC and the EOF only determine the high-level strategies, while the MCR operators determine the detailed tasks or actions. After these strategies are transferred to the MCR, communication is also required between the MCR and local operators for the operation of fixed, shared, or mobile equipment.

4.3.2. Collaboration and communication

Since many organizations may be involved in accident mitigation, collaboration and communication between as well as within the organizations become important to reduce the consequences of the accident. As discussed in Section 2, the Fukushima NPP accident involved instances of inadequate communications among the relevant organizations. Due to the number of organizations and tasks involved, communication becomes more complex, as shown in the multi-unit HRA models. Therefore, the risk of inadequate communication, improper communication, or even a total communication failure may become higher. However, this does not imply that this additional risk will negatively affect the overall aim of mitigating the accident as that is beyond the scope of this paper and in fact may not be so.

4.3.3. Installation of mobile equipment

Mobile equipment, such as water injection pumps, portable pumps, and portable diesel generators may need to be mobilized to and installed at required locations during an emergency. Since the Fukushima NPP accident, the use of mobile equipment on-site has been increased to enhance defense-in-depth capabilities. Representative examples, especially as used in Korea, are portable pumps and portable diesel generators. The use of such mobile equipment requires a few subtasks 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 like to the power plant; and Execution, i.e., turning on the equipment or getting it to perform the required functions. The local operators and subcontractors carry out these actions.

Current HRA methodologies apply the time window, which is the time available for the operator to perform his/her duties, for quantification. The time window is the time within which the job must be completed to successfully maintain the state of the plant. For Task Types 1 and 9 (involving the use of mobile equipment), the system time window (*TSW*), which is available to the operators, can be calculated as in Equations (1) and (2), respectively. The system time window (Tsw) is used here in the context of human reliability analysis i.e. with more emphasis on the operator actions. The Tsw value may be derived from thermodynamics of the system, or some

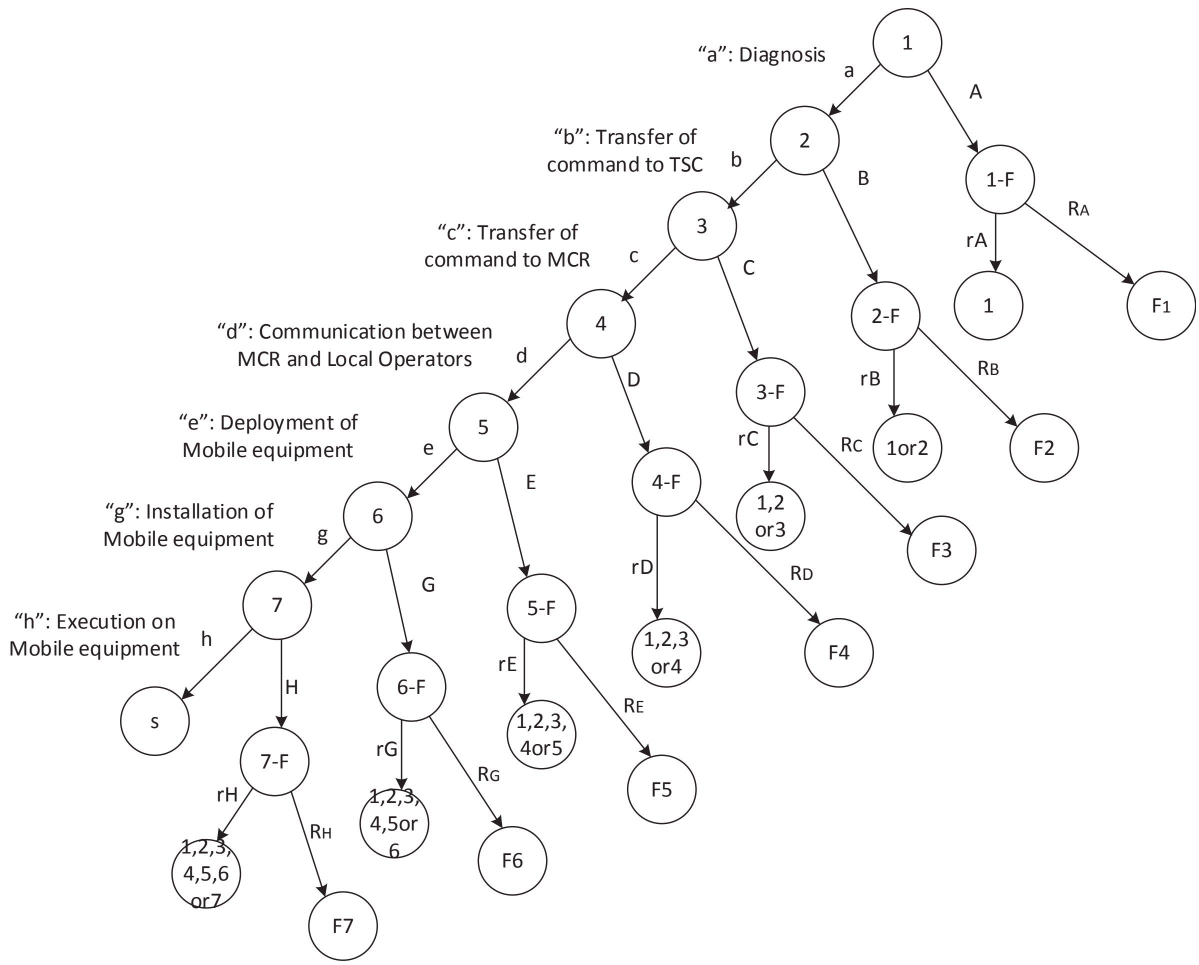

Fig. 5. Human error event tree showing the error modes of Task Type 9.

Table 3
Key to Task Type 9 HRA event tree.

Subtasks	Potential performance	Notation
Diagnosis	Success in diagnosis	a
	Failure in diagnosis	A
	Success in the recovery of A	rA
	Failure in the recovery of A	RA
Transfer of Command	Success in the transfer of command to TSC	b
	Failure in the transfer of command to TSC	B
	Success in the recovery of B	rB
	Failure in the recovery of B	RB
	Success in the transfer of command to MCR	c
	Failure in the transfer of command to MCR	C
	Success in the recovery of C	rC
	Failure in the recovery of C	RC
Communications to Facilitators	Success in communication between MCR and local operators	d
	Failure in communication between MCR and local operators	D
	Success in the recovery of D	rD
	Failure in the recovery of D	RD
Deployment	Success in deployment of Mobile equipment	e
	Failure in deployment of Mobile equipment	E
	Success in the recovery of E	rE
	Failure in the recovery of E	RE
Installation	Success in the installation of Mobile equipment	g
	Failure in the installation of Mobile equipment	G
	Success in the recovery of G	rG
	Failure in the recovery of G	RG
Execution	Success in execution on Mobile equipment	h
	Failure in execution on Mobile equipment	H
	Success in the recovery of H	rH
	Failure in the recovery of H	RH

deterministic safety analysis. The right hand side of the equation is to show all tasks that must be completed within the given system time window. A detailed task analysis is needed to determine the time required for the modelled human actions. The use of equation (1) in the HRA for MUPSA is in a case of a common cause failure in two or more units which only require the MCR in those units to diagnose and execute on their respective MCR boards.

$$T_{Sw} = T_{Delay} + T_{Diagnosis} + T_{Execution} \tag{1}$$

$$T_{Sw} = T_{Delay} + T_{Diagnosis} + T_{Transfer\ 1} + T_{Transfer\ 2} + T_{Deployment} + T_{Installation} + T_{Execution} \tag{2}$$

Figs. 6 and 7 illustrate the system time window and tasks from when a disturbance that potentially disrupts the stable plant state begins to when the execution of the action is complete. Figs. 6 and 7 are based on Task Types 1 and 9, respectively, which were also introduced in previous sections. Fig. 7 corresponds to scenarios involving more than two units and requiring the installation of mobile equipment. Table 4 shows the time window considerations for all the task types already identified in previous sections.

4.3.4. Decision-making and priority of shared equipment

In the case of a multi-unit accident, decisions have to be made about the deployment of mobile equipment and prioritization as to which unit should utilize the shared equipment. In a situation when two units require the mobile equipment to be deployed simultaneously and the equipment is capable of supplying the function only for one unit, the TSC should determine which unit is more severe, i.e., the priority of deployment. Decision-making is significant here because sometimes the shared or mobile equipment cannot provide full functionality for multiple units at the same time. Moreover, the emergency operating procedures and abnormal operating procedures provide symptom based guidance to the operating organizations but the severe accident management guidelines (SAMGs) provide a more general guidance. Therefore, in implementing the SAMGs which are less prescriptive, the responsible organization has to decide among the competing priorities.

Decisions may also have to be made in a multi-unit scenario regarding the prioritization for the use of shared redundant equipment (classified as spare shared systems) that are not yet installed but are available to replace failed equipment. Such decisions will require situation awareness.

4.3.5. Situation awareness

Appropriate situation awareness is one of the key elements to the success of any emergency response. The MCR, TSC, EOF, and local operators should be able to recognize the current situation of the plant and monitor and control the changes throughout the states of a rapidly changing NPP. This is called ‘situation awareness’. Therefore, situation awareness is more than a simple memory check of what the operator knows or does not know. Situation awareness is considered a part of information processing, such as cognition, decision-making, and performance, frequently influenced by the personality of the individual, the task, and system factors [32]. Endsley’s situation awareness model [33] comprises levels 1, 2, and 3, which are: perception of the elements, comprehension of the current situation, and forecasting future system states, respectively.

In the first level, there is no processing of the data being perceived. These data depend on several factors, such as the task being performed, the goal of the operator, and experience. In the second level, the operator develops an interpretation of the data being perceived. This is also influenced by the individual’s goals, experiences, and biases regarding the situation. In the third level, a prediction of the future plant state is made based on the situational data from levels one and two and on experience. Thereafter, decisions are made, and the necessary actions are implemented.

An instance of where situation awareness becomes important is when the EOF, TSC, or operating personnel does not access all the information necessary for the decision-making, i.e., information may be missing or not available, but the EOF, TSC or operator has to make a decision. As such, this relates to levels 1 and 2 of situation awareness. Another instance is where it may take a couple of hours to deploy the mobile equipment, or there are some unexpected delays. The TSC or MCR must then be able to project the possible future state for the use of mobile equipment and decide on the deployment in advance. This relates to Level 3 of situation awareness.

4.4. Environmental factors as PSFs for the multi-unit HRA

The PSFs currently used in single-unit HRA seem to be applicable to the multi-unit HRA. However, the PSFs can be more impactful in a multi-unit accident because the tasks in the multi-unit accident are typically more complex than in the single-unit accident. In addition, the current procedures for the single-unit scenario may not be comprehensive enough to deal with a multi-unit scenario.

EFs, i.e., fire, flooding, earthquake, extreme temperatures, radiation, and so on, may affect the use of mobile equipment. Inundation of the plant with salt and moisture during extreme typhoons, gales, or blizzards are common severe conditions that lead to degradation in multiple units. The EFs can cause failure of equipment, block equipment routing, limit access, or delay access to the necessary areas. They could also result in the 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 a severe accident in a unit can affect the mitigating action in a neighboring unit.

EFs have been included alongside the PSF on the model of human and organizational factors for the multi-unit HRA. This is

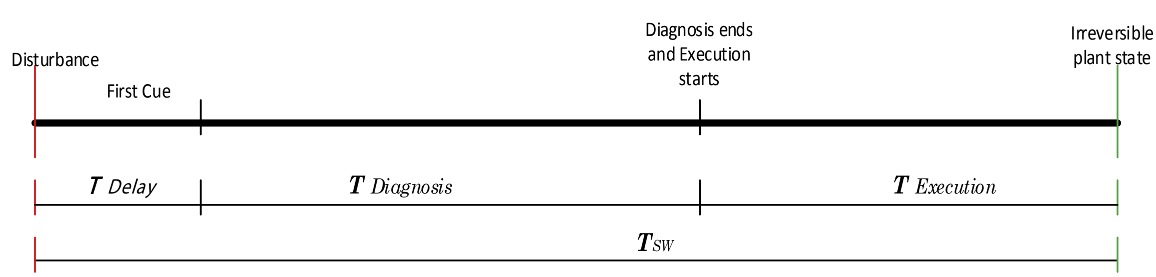

Fig. 6. Time window for Task Type 1.

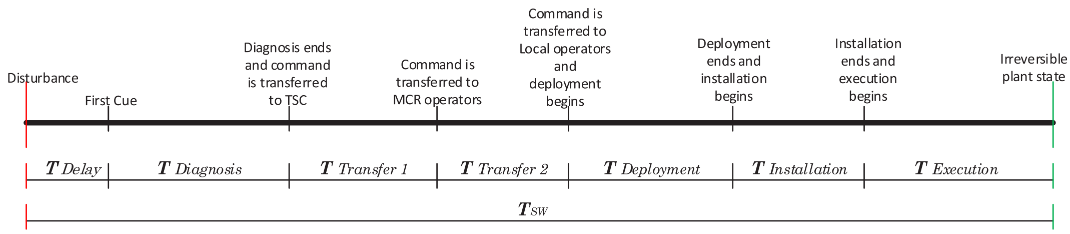

Fig. 7. Time window for Task Type 9.

Table 4
Time window considerations based on task types.

Task Type	Time Window
1	Diagnosis + Execution
2	Diagnosis + Execution
3	Diagnosis + Deployment + Installation + Execution
4	Diagnosis + Transfer of Command + Execution
5	Diagnosis + Transfer of Command + Execution
6	Diagnosis + Transfer of Command + Deployment + Installation + Execution
7	Diagnosis + Transfer of Command 1 + Transfer of Command 2 + Execution
8	Diagnosis + Transfer of Command 1 + Transfer of Command 2 + Execution
9	Diagnosis + Transfer of Command 1 + Transfer of Command 2 + Deployment + Installation + Execution

because the authors are convinced that EFs should be considered as new PSFs in the multi-unit HRA. The supposedly extraneous effect of EFs on human performance is more likely and severe in the multi-unit scenario, especially as related to the deployment of mobile equipment. EFs could affect the performance of the OSC, local operators or sub-contractors, as they are all involved in the deployment of mobile equipment. For example, when there is large amount of debris on the pathway of cables or mobile equipment, this would delay or possibly obstruct the work of such organizations. This may even result in an additional task for the organizations (i.e. removing the debris). Hence, an excellent way to consider them will be as PSFs in human error analysis for multi-unit HRA and each environmental factor should be considered as a separate PSF. The effect of each environmental factor can hence be analyzed.

5. Discussion

Table 5 shows a summary of the five categories that depict the major differences between a single-unit HRA with credit only to fixed equipment and multi-unit HRA. Only the MCR and local operators are given credit as organizations for the current single-unit HRA, but four other organizations are identified for the multi-unit case. The TSC may only have a major role in the dual-unit case, but the responsibility for decision-making must be handed to the EOF should it involve more than two units. The OSC and sub-contractors are always on hand, mostly for the deployment and installation of mobile equipment and other ancillary roles during multi-unit accident cases.

Nine possible task types are identified for multi-units as opposed to only two task types for single units. A single-unit HRA only considers the collaboration and communication between the MCR and a local operator or between the MCR in one unit and the MCR in another unit. Whereas, the collaboration and communication in a multi-unit HRA are more complex because there are many organizations involved. The mobile equipment is recognized as an important work device for the multi-unit HRA. Installation (by the sub-contractor) and operation (by the local operator) of mobile equipment is solely considered in the multi-unit HRA.

Although some of these factors are applicable to the single unit cases, the single unit HRA in Korea does not currently consider such factors as; complex communications among organizations (i.e., TSC, OSC, and EOF), decision making priorities (especially for the use and installation of shared or mobile equipment), and environmental factors (especially those that hamper the deployment or use of mobile equipment) in human error analysis. Similarly, situation awareness is not explicitly considered in the current single-unit

Table 5
Comparison of human and organizational factors in single-unit HRA with credit only to fixed equipment and multi-unit HRA.

Category		Single-Unit HRA	Multi-Unit HRA
Organization		MCR, Local Operator	MCR, Local Operator, TSC, EOF, OSC, Sub-contractor
Work device		MCR Board, Fixed Equipment (non-shared), Shared Equipment (fixed)	MCR Board, Fixed Equipment (non-shared), Shared Equipment, Mobile Equipment
Task	Task Type	Task Types 1 and 2	Nine task types
	Collaboration and Communication	MCR–Local, MCR (Unit 1)–MCR (Unit 2)	Complex communication and collaboration occur
	Installation of Mobile Equipment	Conventionally not credited	Installation of Mobile Equipment: sub-contractor, Operation of Mobile Equipment: local operator
	Decision-making on Priority of Shared/Mobile Equipment	Not Applicable	A standard and guideline for priorities for the use of shared/mobile equipment are required.
	Situation Awareness	Not explicitly considered in the current HRA	Situation awareness needs to be explicitly considered due to the insufficient information and necessity for situation prediction.
PSFs		Applicable	The same PSFs are applicable, but the significance level of the PSFs can be different.
Environment Factors		Conventionally not credited	The impact of radiation, debris from natural disaster, etc. needs to be considered.

HRA, this should be unambiguously included for the multi-unit HRA. This is because the lack thereof could lead to more severe consequences, as compared to a single-unit case. Likewise, the prioritization of shared/mobile equipment is only necessary for the multi-unit HRA. Therefore, a standard guideline for the prioritization of shared or mobile equipment needs to be developed.

All the PSFs currently used for the single-unit HRA should be applicable to the multi-unit HRA. However, the severity or significance level of the PSFs may be different. EFs are not considered in single-unit HRA, but they can be critically impactful to human and organizational factors, as has been seen in past multi-unit accidents. Hence, it is recommended that these EFs to be considered as new PSFs in multi-unit HRAs, especially as they affect the use of mobile equipment. A seismic event is also an environmental factor that can cause the failure of equipment and even the building or structures that house the equipment. These should be considered in the fault tree analysis of the plant PSA and not the HRA.

Other factors that are involved in multi-unit HRAs as human and organizational factors include the relationship with the regulatory body, the government, and the international community. However, these factors are not treated in this write-up, because they are not unique to the multi-unit HRA.

HEP estimation in the current HRA considers only diagnosis and execution, but it has been shown that transfer of command is also a key factor in multi-unit conditions. As such, it is recommended that considerations should also be given to the transfer of command (communication), deployment, and installation in the multi-unit HRA. The separate analysis of communication task between actors in different rooms is suggested. The communication errors can also be considered within the framework of the transfer of command between separate actors. The time windows for performing tasks in multi-unit cases are also different from those of single-unit cases. This should also be given the required attention in the multi-unit HRA. Consideration of these factors will make the HRA for multi-units more comprehensive.

6. Conclusion

This study has provided a summary of the work conducted to date, with a view to developing a comprehensive HRA model for multi-unit sites. A review of the relevant literature concerning the multi-unit PSAs, severe accidents, and the Korean nuclear power industry's emergency response practice was performed. The lessons learned from the Fukushima incident were similarly taken into consideration.

First, this study identified and characterized the human and organizational factors for the multi-unit HRA. A model for the human and organizational factors for a multi-unit HRA was developed and discussed in detail. These factors are described in five categories: organization, work device, task characteristics, PSFs, and EFs. The various organizations include the EOF, TSC, OSC, MCR operators, local operators, and sub-contractors.

Second, the importance of situation awareness in decision-making, with regard to the prioritization of mobile or shared equipment was underlined. Third, all the various task considerations for the multi-unit HRA and their complexity were identified and discussed. Nine task types were identified, modeled, and analyzed for a multi-unit HRA, including the use of human error event trees. A comparison of the human and organizational factors for single-unit and multi-unit HRA was performed to highlight similarities and areas for consideration in the multi-unit HRA.

Finally, the importance of EFs in the deployment of mobile equipment was emphasized. This study recommends the inclusion of EFs such as fire, flooding, high winds, and radiation as PSFs in the multi-unit HRA. Further work on this subject should consider how to include these factors as PSFs in a contemporary site-wide HRA.

The result of this work is an essential input to developing a comprehensive multi-unit HRA method. However, the generalization of the model described in Fig. 2 is somewhat difficult as it is mostly based on the Korean operations although it may be modified for application in other countries who may have to consider their peculiar conditions. It will play an important role in improving the regulatory requirements pertaining to human and organizational factors for multi-unit sites. This work can also aid the upgrading of support mechanisms for decision-making in severe accident management involving multiple NPPs.

Conflicts of interest

The authors have no conflicts of interest to declare.

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