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Original Article

Remaining and emerging issues pertaining to the human reliability analysis of domestic nuclear power plants☆

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A B S T R A C T

Probabilistic safety assessments (PSA) have been used for several decades to visualize the risk level of commercial nuclear power plants (NPPs). Since the role of a human reliability analysis (HRA) is to provide human error probabilities for safety critical tasks to support PSA, PSA quality is strongly affected by HRA quality. Therefore, it is important to understand the underlying limitations or problems of HRA techniques. For this reason, this study conducted a survey among 14 subject matter experts who represent the HRA community of domestic Korean NPPs. As a result, five significant HRA issues were identified: (1) providing a technical basis for the K-HRA (Korean HRA) method, and developing dedicated HRA methods applicable to (2) diverse external events to support Level 1 PSA, (3) digital environments, (4) mobile equipment, and (5) severe accident management guideline tasks to support Level 2 PSA. In addition, an HRA method to support multi-unit PSA was emphasized because it plays an important role in the evaluation of site risk, which is one of the hottest current issues. It is believed that creating such a catalog of prioritized issues will be a good indication of research direction to improve HRA and therefore PSA quality.

1. Introduction

Since the publication of WASH-1400 in 1975, many countries have adopted the probabilistic safety assessment (PSA), otherwise known as the probabilistic risk assessment (PRA), as one of the primary techniques to visualize the risk levels of commericial nuclear power plants (NPPs) in a systematic manner. The US Nuclear Regulatory Commission (NRC) refers to PRA as: "The method or approach (1) provides a quantitative assessment of the identified risk in terms of scenarios that result in undesired consequences (e.g., core damage or a large early release) and their frequencies, and (2) is comprised of specific technical elements in performing the quantification [1]." According to this definition, the key to the PSA technique is to identify, as realistic as possible, a catalog of plausible scenarios with associated frequencies that can cause undesired consequences. Fig. 1 demonstrates how to develop such plausible scenarios (or event sequences) and evaluate the risk associated with the specific scenarios that lead to an undesired consequence of an arbitrary system (e.g., its shutdown).

Let us assume that the shutdown of an arbitrary system depends on the binary conditions (success or failure) of three critical components A, B, and C. This means that the total number of plausible scenarios (or event sequences) to be considered in the PSA becomes eight. Of them, any scenario that includes the functional failures of two critical components will result in the shutdown of the system, so it is possible to identify four event sequences (*#4*, *#6*, *#7*, and *#8*) of which shutdown is directly attributable. The frequency of shutdown due to, for example, *Event sequence #4* can be calcuated by multiplying the frequency of component B and C functional failures. In addition, the total shutdown risk of the given system can be

☆ Any opinions contained in this study do NOT represent official regulatory positions.

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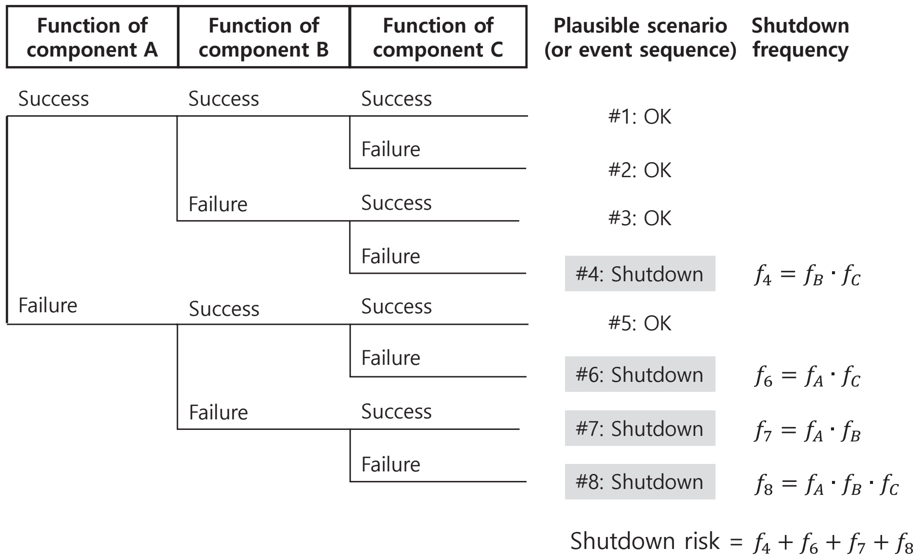

Fig. 1. Shutdown scenarios of an arbitrary system.

calculated by adding up the frequencies of all four event sequences leading to shutdown.

From this example, for the quantification of system risk, we can say that it is indispensable to assess at minimum the following two kinds of information for each critical component: (1) the frequency of a functional failure due to mechanical problems (e.g., a break of the rotating shaft, or a loss of electric power), and (2) the probability of human error resulting in a functional failure, if applicable (e.g., the omission of an action to run a required component, or the manipulation of a wrong component). This implies that the precise estimation of both mechanical failure frequencies and human error probabilities (HEPs) is essential for ensuring PSA quality. Therefore, considerable efforts have been made worldwide to estimate HEPs as precisely as possible, by applying various human reliability analysis (HRA) techniques.

It can be said that the HRA is an integral activity that seeks to evaluate the potential for, and mechanisms of, human error that may affect NPP safety. Therefore, plant-specific HRAs are required by related standards such as the ASME PRA standard [2]. Additionally, NUREG-0711 Rev. 2 emphasized the effects of advanced technology on human performance, the potential for different types of human error that may be associated with such technology, and the appropriate sources of human error data [3]. This implies that HEP estimation is not straightforward because of the wide spectrum of human actions (or tasks).

For example, Chang and Lois stated that: “In PRA, important human tasks that could prevent or mitigate undesired consequences are identified in event sequence. An important responsibility in HRA analysis is to estimante the failure probability for these tasks. The tasks cover human actions during all major hazards (e.g., internal events, floods, fires, and seismic events) with a wide range of complexity.” Accordingly, a variety of HRA methods have been proposed over multiple decades in order to properly estimate HEPs for human actions conducted in diverse contexts. Fig. 2 depicts the lineage of representative HRA methods applied over the last five decades in the nuclear industry, as of 2018.

As can be seen from Fig. 2, however, such a large number of different HRA methods indicates that the calculation of an HEP is very sensitive to its context or purpose. In other words, in terms of quantifying HEPs, there is no single, comprehensive method applicable to all contexts in which human operators should conduct required tasks. It is therefore inevitable that various limitations hamper HRA practitioners to properly model or incorporate actual contexts human operators may face [4–7].

In order to properly address these limitations, one of the initial responses is to identify a catalog containing important issues to be resolved. Such a catalog would clarify specific issues with associated significance and urgency, thereby indicating not only effective ways to resolve the issues but also their priority.

For this reason, this study proposes a catalog of HRA issues in domestic Korean NPPs based on a survey of 14 subject matter experts (SMEs) from six different organizations who have worked as HRA method developers, practitioners, and regulators. At first, the SMEs suggested a total of 39 remaining and emerging HRA issues; many focused on similar contents though, so they were regrouped into 19 common issues belonging to six categories. After that, the SMEs rated the urgency and importance of each common issue and as a result, five significant HRA issues were identified that should be resolved to enhance HRA quality.

The structure of this paper is organized as follows. First, the methodology used to identify the catalog of key HRA issues is provided in Section 2. Section 3 gives detailed explanations about the individual HRA issues, having diverse backgrounds and requirements. Section 4 details an additional key issue to be addressed, regarding HRA development for multi-unit sites. Finally, in Section 5, the limitations and significance of this study are discussed, along with the status of on-going research dealing with key HRA issues.

2. Methodology

As briefly mentioned in the Introduction, this study conducted a survey of key HRA issues that should be resolved at least from the perspective of domestic Korean PSA. Fig. 3 depicts the overall process implemented in this study, with the purpose to identify a catalog of key HRA issues.

As can be seen from Fig. 3, the first step was to collect a group of SMEs who have sufficient knowledge or experience with respect to the HRA of domestic NPPs. In this light, a total of 14 SMEs were invited from six distinctive affiliations, including a research institute, regulatory body, utility and its contractors (for convenience, the term *review group* will be used to represent the group of SMEs

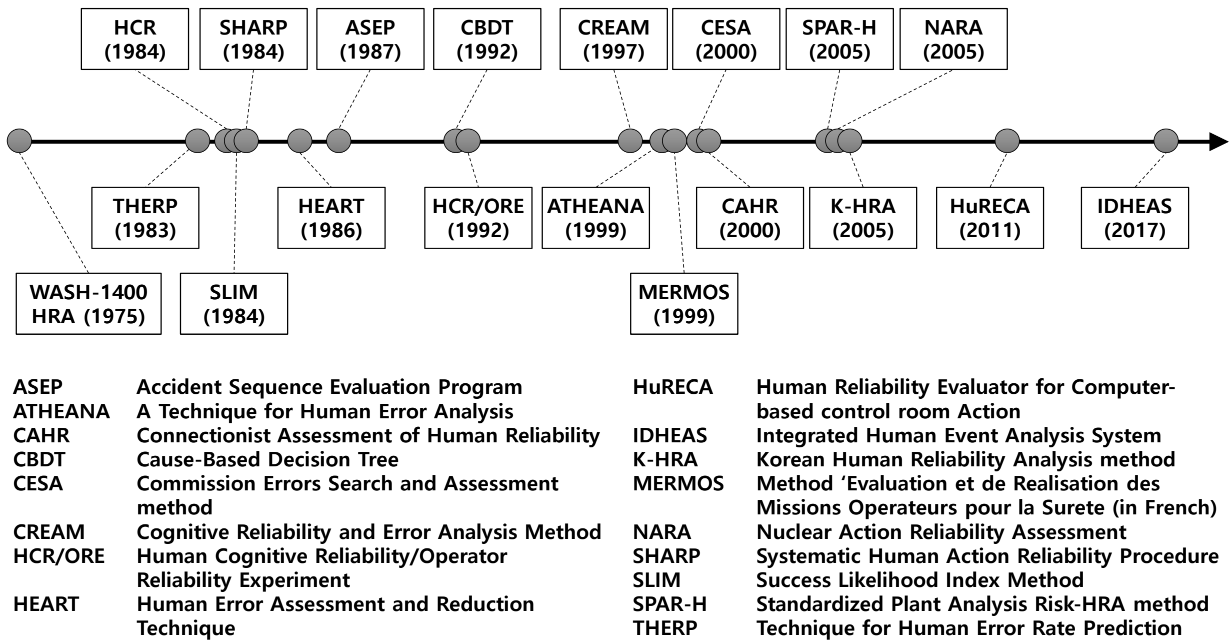

Fig. 2. Lineage of typical HRA methods applied to the nuclear industry.

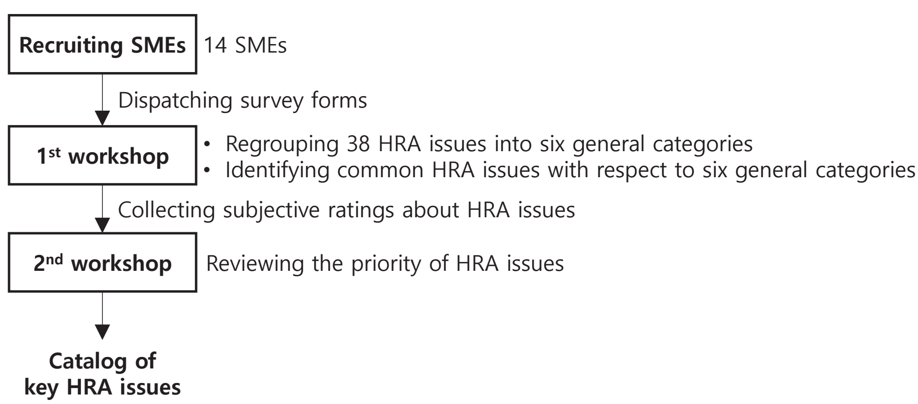

Fig. 3. Overall process to identify a catalog of key HRA issues.

hereafter). After the establishment of this review group, survey forms were sent to the SMEs asking them to freely raise the HRA issues that need to be considered to either enhance HRA quality (remaining issues), or to resolve novel problems (emerging issues) from the viewpoint of regulation.

The SMEs initially proposed a total of 39 HRA issues, several of which were very similar or largely overlapped in terms of their contents. Thus, the first of two workshops was held in order to properly organize them into several categories. In this workshop, the SMEs intensively discussed the details of each HRA issue with associated contents, and agreed to regroup the 39 HRA issues into six general categories: (1) a technical basis for the K-HRA (Korean HRA) method, (2) an HRA method for dealing with diverse external events, such as earthquakes or flooding, (3) an HRA method applicable to a digital main control room (MCR) environment, (4) an HRA method for supporting both the modeling of FLEX (diverse and flexible coping) strategy and Level 2 PSA, (5) an HRA method for supporting multi-unit PSA, and (6) HRA cross-cutting issues. Table 1 shows these six general categories with the associated number of HRA issues collected from the first workshop.

In addition, the review group discussed the commonality of several HRA issues. For example, as can be seen from Table 1, the SMEs originally suggested a total of 14 remaining or emerging issues that can be included in the sixth general category (*HRA cross-cutting issue*). However, since the contents of several issues belonging to this category largely overlap with each other, it was possible to regroup them into nine common issues: (1) securing an HRA database reflecting the characteristics of domestic Korean operators, (2) providing a technical basis for generic HRA issues, including the dependencies of human operators and the

Table 1
Initial catalog of the HRA issues from the first workshop.

Category ID	Category	Number[a]
1	Technical basis of the K-HRA method	2
2	HRA for diverse external events	7
3	HRA for digital environment	9
4	HRA for FLEX and Level 2 PSA	5
5	HRA for multi-unit PSA	2
6	HRA cross-cutting issues	14
Total		39

[a] The number of HRA issues included in each category.

Table 2
Refined catalog of the 19 common HRA issues.

Category ID	Issue ID	Common issue
1	1–1	Providing a technical basis of the K-HRA method for the application of a low-power and shut-down condition
2	2–1	Developing an HRA method applicable to diverse external events including earthquake, fire, flooding and other external events (supporting Level 1 PSA)
	2–2	Securing HRA data reflecting the characteristics of human operators under diverse external events
3	3–1	Developing an HRA method applicable to a digital environment
	3–2	Securing HRA data reflecting the features of a digital environment (e.g., nominal HEPs and PSF multipliers with respect to a digital MCR)
4	4–1	Developing an HRA method reflecting the performance of human operators in establishing mobile equipment to cope with ELAP* and LOUHS** events
	4–2	Securing HRA data reflecting the characteristics of human performance under ELAP and LOUHS events
	4–3	Developing an HRA method considering the nature of tasks included in SAMGs***
	4–4	Securing HRA data reflecting the characteristics of human performance under severe accident conditions
5	5–1	Developing an HRA method supporting multi-unit PSA
6	6–1	Securing a domestic HRA database
	6–2	Providing a technical basis for generic HRA issues
	6–3	Identifying the applicability of a full-scope simulator to enhance HRA quality
	6–4	Providing practical ways to reduce the variability among HRA practitioners
	6–5	Developing a dynamic HRA method
	6–6	Validating the allowable times used in HRAs
	6–7	Providing practical ways to incorporate organizational factors into HRAs
	6–8	Developing a standardized HRA method
	6–9	Developing an HRA tool

*ELAP: Extended loss of AC power **LOUHS: Loss of ultimate heat sink ***SAMG: Severe accident management guideline.

determination of performance shaping factor (PSF) multipliers, (3) identifying the applicability of a full-scope simulator to enhance HRA quality, (4) providing pracitcal ways to reduce variability among HRA practitioners, (5) developing a dynamic HRA method, (6) validating the allowable times used in HRAs, (7) providing practical ways to incorporate organizational factors into HRAs, (8) developing a standardized HRA method applicable to the full scope of PSA (i.e., Levels 1, 2 and 3), and (9) developing an HRA tool similar to EPRI's (Electric Power Research Institute) HRA calculator.

Similarly, although the SMEs raised nine original issues belonging to the third general category (*HRA for digital environment*), they could be regrouped into two common issues: (1) developing an HRA method applicable to a digital envrionment (e.g., a digital MCR), and (2) securing HRA data reflecting the features of a digital environment (e.g., nominal HEPs and PSF multipliers with respect to the digital MCR). In this way, HRA issues included in the remaining categories were also revisited. Table 2 summarizes the refined catalog of 19 common issues associated with six general categories.

Based on the aforementioned 19 common issues, each SME was then asked to provide subjective rating scores with respect to two evaluation dimensions: the urgency and importance of each common issue. Fig. 4 shows the part of the survey form dispatched to SMEs, and Table 3 summarizes the criteria of the subjective ratings with the associated scales used in this survey.

As can be seen from Table 3, each criterion for the subjective ratings consists of three scales, *High*, *Medium* and *Low*. In the case of *Urgency*, which refers to the criticality of the resolution timing of a given common issue, *High* denotes the need to unravel the issue within the next three years, while *Medium* and *Low* are those to be addressed in the next three to seven years and seven to ten years, respectively.

Similar to the subjective scales of *Urgency*, those of *Importance* are also threefold but with different meanings. For example, *High* denotes an issue that is directly relevant to a safety or operatonal license that could result in the modification of HEP values included in a PSA model. In contrast, *Low* denotes an issue that is negligible in terms of safety or operatonal licensing, and *Medium* implies that the issue lies in between *Low* and *High*.

Although each issue has its own ratings in terms of *Urgency* and *Importance*, it was still difficult to distinguish a list of key issues because of the qualitative nature of the subjective rating scales. A second workshop was therefore held in order to select a number of significant HRA issues from the refined 19 issues summarized in Table 2. To facilitate discussion, the priority of each refined issue was characterized by assigning specific numbers to the *Urgency* and *Importance* scale: 3, 2, and 1 for *High*, *Medium*, and *Low*, respectively. All refined issues were then ranked by aggregating the averaged *Urgency* and *Importance* scores; Table 4 summarizes the priority scores of the 19 refined issues. Section 3 provides detailed explanations about the significant HRA issues as determined by high priority scores.

3. Significant HRA issues

Based on Table 4, it was possible to pick out several common issues possessing high priority scores from different viewpoints. It should be noted that, for convenience, the term *significant HRA issues* will be used hereafter for those having high priority scores. In terms of each evaluation dimension, a cut-off value of 2.7 was applied to identify such significance; this value was determined by SMEs during the second workshop. It should be noted that this cut-off value was determined from the 90th percentile value of priority scores for each evaluation dimension. That is, despite being a rule of thumb, it is reasonable to judge an HRA issue to be significant if its prority score exceeds the 90th percentile of priority scores collected for each evaluation dimension. This percentile was calculated to be 2.7 for Urgency and 2.8 for Importance; therefore, 2.7 was

Category ID	Issue ID	Issue description	Urgency	Importance
1	1-1	Providing a technical basis of the K-HRA method for the application of a low-power and shut-down condition	High/Medium/Low	High/Medium/Low
2	2-1	Developing an HRA method applicable to diverse external events including earthquake, fire, flooding and other external events (supporting Level 1 PSA)	High/Medium/Low	High/Medium/Low
	2-2	Securing HRA data reflecting the characteristics of human operators under diverse external events	High/Medium/Low	High/Medium/Low
3	3-1	Developing an HRA method applicable to a digital environment	High/Medium/Low	High/Medium/Low
	3-2	Securing HRA data reflecting the features of a digital environment (e.g., nominal HEPs and PSF multipliers with respect to a digital MCR)	High/Medium/Low	High/Medium/Low

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Fig. 4. Part of the survey form to collect subjective scores for each HRA issue.

Table 3
Subjective rating criteria with associated scales.

Criterion	Scale	Meaning
Urgency	High	Short-term issue
	Medium	Mid-term issue
	Low	Long-term issue
Importance	High	Directly related to safety or operational licence issues
	Medium	Indirectly related to safety or operational license issues
	Low	Irrelevant to either safety or operational licence issues

Table 4
Summary of priority scores for the 19 refined issues.

Category ID	Issue ID	Urgency[a]	Importance[a]	Priority score
1	1–1	2.6	2.8	5.4
2	2–1	2.7	2.9	5.6
	2–2	2.3	2.5	4.8
3	3–1	2.7	2.8	5.5
	3–2	2.4	2.6	5.0
4	4–1	2.9	2.8	5.7
	4–2	2.5	2.5	5.0
	4–3	2.7	2.8	5.5
	4–4	2.3	2.4	4.7
5	5–1	2.5	1.9	4.4
6	6–1	1.9	2.3	4.2
	6–2	2.1	2.1	4.2
	6–3	1.9	2.3	4.2
	6–4	2.1	2.3	4.4
	6–5	1.3	1.3	2.6
	6–6	2.1	2.4	4.5
	6–7	2.0	2.3	4.3
	6–8	2.0	1.9	3.9
	6–9	1.6	1.4	3.0

[a] Averaged score based on the subjective ratings of the 14 SMEs.

suggested as the cut-off value of each dimension with SMEs agreement. This means that, for a common issue of which the sum of the priority scores for *Urgency* and *Importance* is greater than 5.4, it should be classified as a significant HRA issue.

It should be noted that even when the average score of either *Urgency* or *Importance* was less than 2.7, a refined issue could be marked as significant if the sum of both average scores was greater than 5.4. For example, in the case of the refined issue *Providing a technical basis of the K-HRA method for the application of a low-power and shut-down condition (*Issue ID 1-1*)*, although the SMEs scored its *Urgency* as 2.6, this issue was classified as significant because its *Importance* was rated 2.8 (i.e., 2.8 + 2.6 = 5.4).

As a result, five significant HRA issues were distinguished, as listed in Table 5. More detailed explanations about each significant HRA issue are given in the following sections.

3.1. Providing a technical basis of the K-HRA method

Several different HRA methods have been employed in PSAs for domestic Korean NPPs, with typical examples including HCR/ORE (Human Cognitive Reliability/Operator Reliability Experiment), ASEP (Accident Sequence Evaluation Program), and THERP (Technique for Human Error Rate Prediction). Because PSA results are significantly influenced by HRA results, such variation existing in HRA methods weakens any comparison of risk metrics. This leads to the necessity of standardization in terms of a comprehensive HRA method, and from this necessity, the K-HRA method was proposed.

Developed by the Korea Atomic Energy Research Institute (KAERI) with cooperation from the Korea Electric Power Corporation Engineering & Construction Company (KEPCO E&C) in 2005, the K-HRA method is largely based on the process of ASEP HRA. The majority of efforts during its development focused on standardizing the HRA process and clarifying the input data used for estimating HEPs. In other words, the main purpose of the K-HRA method is to minimize the variation of HRA results due to different HRA practitioners, as well as to strengthen its technical adequacy compared to previous HRA methods. Therefore, during development, its technical adequacy was investigated based on the PSA models of different NPPs, such as an OPR1000 (Optimized Power Reactor 1000 MWe) and Westinghouse 3-loop pressurized water reactor.

Over three years from 2013 to 2015, both at-power and low power and shutdown (LPSD) PSAs were carried out for all domestic Korean NPPs. In order to make these PSA results more consistent, the K-HRA method was commonly used for calculating all related HEPs, which was a good opportunity to test its adequacy as well as feasibility. In this regard, a Framatome NPP was selected as a pilot plant for the adequacy evaluation of the HRA results for post-initiator human failure events (HFEs) with the K-HRA method in at-power and LPSD conditions.

The adequacy of the HRA results, including HEP estimations, was scrutinized with the consideration of important PSFs pertaining to the performance of diagnostic as well as execution HFEs in the at-power and LPSD conditions. In addition, an extensive review of HRA reports was conducted in parallel [8–13]. Consequently, a catalog of PSFs to be used for evaluating the adequacy of the K-HRA results was selected.

Through discussions about the LPSD HRA results regarding the PSFs that play an important role in quantifying HEPs, several insights were derived as below.

- Generally, LPSD HRA results are well explained by the PSFs considered important.
- K-HRA methodology provides a tool to differentiate HFEs of which tasks are essentially the same but performed in completely different accident contexts. It provides a PSF of *mainstream tasks in accident context* to reflect them.
- Recovery potential by shift change needs to be considered in the K-HRA method.

Table 5
Catalog of significant HRA issues.

Issue ID	Significant HRA issue	Priority score
1–1	Providing a technical basis of the K-HRA method	5.4
2–1	Developing an HRA method for diverse external events	5.6
3–1	Developing an HRA method for a digital environment	5.5
4–1	Developing an HRA method for mobile equipment	5.7
4–3	Developing an HRA method for SAMG tasks	5.5

- For tasks performed in the field, there is a tendency for high HEPs even with sufficient available time.

If these abovementioned insights can be properly reflected, it is believed that the K-HRA method will become more consistent and robust for both at-power and LPSD conditions. In addition, the importance of several PSFs can be distinguished between internal and external event PSAs; for example, instrument availability for cue, workload, quality of working environment, and accessibility PSFs are critical for external event PSAs but not for internal event PSAs. Therefore, in order to use the K-HRA method as a comprehensive tool for supporting all scopes of PSA, it is necessary to revise the K-HRA method with a technical basis so that it can fully incorporate additional PSFs into the quantification of HEPs.

3.2. Developing an HRA method for diverse external events

The next significant issue relates to an HRA method applicable to Level 1 PSA for diverse external events including earthquake, fire, flooding, tsunami, and typhoon. Indeed, increased attention to NPP risk due to diverse external events has followed the Fukushima accident on March 11, 2011.

For existing earthquake, fire, and flooding HRAs of domestic Korean NPPs, HEPs have been simply considered as 5 to 10 times higher than those calculated in internal event HRAs. However, HEPs for external events can exceed such a 10-times limit depending on the characteristics of the external events; one existing study shows that, at a preliminary HEP analysis stage, HEPs for a seismic event can be 2 to 30 times of those for the internal event HRA [14].

Unfortunately, at present, there is no domestic HRA method for external events with a firm technical basis. Accordingly, an HRA method applicable to diverse external events needs to be developed, which can consider various unique task contexts expected from external events (e.g. cue availability, response time, manpower, stress, and training). A number of technical challenges should therefore be resolved, such as: (1) the definition of HFEs, (2) a systematic procedure for screening analyses, and (3) an explicit method to be used for detailed analyses.

One plausible solution is to develop an HRA method for external events based on the framework of the K-HRA method, which secures consistency with HRA results of internal events. In addition, since the K-HRA method already provides detailed guidelines that could resolve the first abovementioned technical issue (e.g., how to distinguish important tasks included in an HFE), associated rationales could be directly (or indirectly) used in external event contexts. In parallel with HRA method development, research for collecting HRA data that reflects the characteristics of human operators under diverse external events is needed to obtain the technical underpinnings of an HRA applicable to external events.

3.3. Developing an HRA method for a digital environment

As the fruit of long research for a Korean next-generation NPP, the APR1400 (Advanced Power Reactor 1400 MWe) started its commercial operation in 2015. One major feature is its MCR design, which differs from conventional analog control rooms based on an extensive use of computers, such as a computerized procedure system (CPS), soft controls, information flat panel displays (IFPDs), and large display panels (LDPs). However, it is expected that the installation of these new systems may affect the characteristics of HFEs and associated HEPs (e.g., the increase of HEPs due to an excessive number of secondary tasks resulting from information navigation using the IFPDs).

In fact, many existing studies [15–17] have stressed that the change in task environment may possibly impact the performance of human operators, including HEPs. Therefore, a huge amount of effort has been spent to develop an HRA method based on the unique characteristics of a digital MCR [18]. Nevertheless, no HRA method has been widely accepted for treating the digital MCR environment until today; rather, existing HRA methods that do not properly consider these characteristics are still being used.

The domestic nuclear industry also perfomed an HRA of the APR1400 using existing methods, with research including expert consultation to reflect several features of the plant. It is essential that HRA method development and the associated HEP data reflect all features of the APR1400. Nevertheless, current efforts in the nuclear industry are insufficient to clearly resolve all HRA issues for the APR1400, as technical HRA issues still remain.

For example, the HRA of the first APR1400 unit was conducted using THERP, which was not originally intended for use with a digital MCR. Several technical questions were consequently raised during such application. The first question relates to the estimation of HEPs for decision-making tasks. As already mentioned, the use of new systems in digital MCRs means that the way of accessing or gathering information is quite different from conventional MCRs. However, the THERP method provides a time reliability correlation (TRC) curve that was not verified for a digital environment. Accordingly, it is necessary to clarify whether or not the TRC curve can be used for estimating the HEPs of decision-making tasks.

The second technical question concerns HEP quantification for execution tasks. One of the significant design features in terms of operational behaviors is that human operators have to manipulate equipment or components through soft controls. The adoption of soft controls, however, inevitably requires human operators to perform secondary tasks (or interface management tasks), such as screen navigation to perform primary tasks (e.g., stop a pump or close a valve). The THERP method though does not consider the effect of soft controls on the variation of HEPs. It is therefore highly questionable if the THERP method can be directly applicable to the estimation of HEPs for execution tasks in a digital MCR.

The third technical question considers the catalog of PSFs for a digital MCR. Most existing HRA methods share similar PSFs that can affect HEPs under specific task environments. However, if human operators have to use novel systems not encountered in conventional MCRs (e.g., CPS or IFPDs), it is natural to expect that other PSFs should be explicitly incorporated during HEP quantification.

The last technical question relates to the technical underpinnings of HEP values. For example, the THERP method provides many tables that include diverse HEP values with respect to specific human error modes (e.g., selection of a wrong switch). The problem is that those human error modes and associated HEP values were not derived from a digital environment. That is, it is again questionable whether the THERP method can cover the whole spectrum of human error modes observable in a digital MCR. In the case of an identical human error mode, it is additionally uncertain whether or not the THERP HEP values are directly applicable to a digital MCR.

3.4. Developing an HRA method for mobile equipment

After the Fukushima accident, various countermeasures called *Post Fukushima Action Items* have been established in most countries, which are necessary for preventing or mitigating the consequences of Fukushima-like accidents. In Korea, the Korea Hydro and Nuclear Power company (KHNP) has been implementing 49 Post Fukushima Action Items for all domestic Korean NPPs, derived from intensive safety investigations. One of the most important action items is related to the use of mobilie equipment, such as movable power generators or pumps, as alternative equipment when the functions of cooling or injection fail.

Table 6
Comparing PSA scope based on the new SAMP legislation.

Mode	Initiating event	Level 1	Level 2	Level 3
At-power operation	Internal event Internal flooding, fire, earthquake	NPPs both in operation and under construction		NPPs under construction
LPSD operation	Internal event Internal flooding, fire, earthquake	NPPs in operation and under construction[a]	NPPs under construction[a]	N/A

[a] Extended scope due to the new legislation of SAMP.

With respect to regulations, a number of important environmental changes in 2016 followed from the new Severe Accident Management Plan (SAMP) legislation. This requires both the extension of PSA scope (Table 6) and the enforcement of safety performance goals (Table 7). For example, according to this new law, KHNP should additionally conduct LPSD Level 1 PSA for all NPPs in operation, while NPPs under construction should receive not only LPSD Level 1 PSA but also LPSD Level 2 PSA. Based on these PSA results, it is mandatory that the risk level of all domestic NPPs satisfies the stricter safety performance goals in the new SAMP legislation.

To satisfy these environmental changes, it is necessary to reflect mobile equipment in PSA models. This strongly indicates that existing PSA models including HRA models should be largely revised so that they can properly express the effect of mobile equipment installations on the reduction of risk levels for NPPs both in operation and under construction. However, there is no mature HRA method that allows HRA practitioners to estimate the HEPs of critical tasks that should be considered during the installation of mobile equipment. Even though there are HRA methods suggested by the Nuclear Energy Institute for FLEX equipment, and FLEX Supporting Guidance in the US [19] and the Canadian Nuclear Safety Commission for emergency movable equipment procedures [20]; it seems that they are still in a premature state compared to existing HRA methods supporting Level 1 PSA. Moreover, since the PSA results of all domestic Korean NPPs should be submitted by June 2019 according to the SAMP legislation, this issue should be resolved as early as possible.

3.5. Developing an HRA method for SAMG tasks

The last issue emphasized by the SMEs is the development of an HRA method that will allow HRA practitioners to properly model a series of critical tasks (or HFEs) to be conducted under severe accident conditions. As shown in Table 6, the scope of HRAs in domestic Korean NPPs is largely focused on how to support Level 1 PSA that concerns the occurrence of core damage due to various kinds of internal events, such as a loss of coolant accident (LOCA) or steam generator tube rupture (SGTR). However, since the Fukushima accident, many countries have started to think about how to enhance NPP safety even after core damage has occurred. Unfortunately, it is widely perceived that existing HRA methods supporting Level 1 PSA cannot be directly used for modeling critical tasks to be conducted for mitigating the consequences of core damage (for convenience, the term *SAMG tasks* will be used hereafter). Some technical challenges in modeling SAMG tasks are as follows [21–23].

- Shift of decision-making responsibilities from control room operators to the technical support center
- Insufficient or inaccurate information to be used for decision-making
- Use of SAMGs that have entirely different intentions, contents, and formats compared to those of emergency operating procedures (EOPs)
- Decision-making that involves trade-offs between choices with no equivalent *success path* or obvious *better path*

It should be noted that several technical issues in modeling SAMG tasks could be soundly resolved based on existing techniques or research results. For example, the first technical challenge deals with the cooperation of diverse organizations, widely scrutinized in other industries as *group decision-making* and *distributed group decision-making*. In addition, since most existing HRA methods consider the effect of insufficient (or inaccurate) information on HEPs, it is anticipated that the second technical issue could be managed during their estimation to some extent.

Unfortunately, it is expected that the modeling of SAMG tasks would be the most difficult aspect of estimating HEPs under severe accident conditions. In general, SAMGs consist of many severe accident guidelines (SAGs) [24–26, 32, 33]; for example, if the water level of a steam generator (SG) is less than a certain setpoint (e.g., 85%), then it is recommended to perform a series of SAMG tasks described in SAG-01, of which the title is *Water injection into SGs*. However, the contents and formats of SAMG tasks do not clarify *what should be done* and *how to do it*. Instead, they provide multiple alternatives for mitigating the consequence of a given condition (e.g., low SG water level), which are followed by the evaluation (or prediction) of an on-going situation. This means that not only verbatim compliance to SAMG tasks is required but also *no action* (i.e., do not perform any tasks in SAGs if they seem less effective for coping with the on-going situation) should be seriously considered [27]. Accordingly, existing HRA methods are not directly applicable to the estimation of HEPs with respect to SAMG tasks, because they were developed under the assumption of strict compliance of prescribed tasks (i.e., EOPs). In order to properly resolve this techical issue, therefore, it is necessary to develop an HRA method that supports the estimation of HEPs based on the modeling of SAMG tasks.

4. HRA method for multi-unit PSA

Although the necessity of a multi-unit related HRA method was not selected as a significant HRA issue in Table 5, its importance is increasing because such modeling is crucial not only in multi-unit PSA model development but also for evaluating the safety performance goals as summarized in Table 7 [28–30]. Multi-unit related HRA issues are associated with human and

Table 7
Safety performance goals specified in the new SAMP legislation.

Safety performance goal	NPPs in operation	NPPs under construction
CDF*	<1.0E-04/yr	<1.0E-05/yr
LERF**	<1.0E-05/yr	<1.0E-06/yr
Frequency of Cs-137***	<1.0E-06/yr	

*Core damage frequency.
**Large early release frequency.
***Sum of all frequencies for event sequences that are supposed to release Cs-137 over 100 TBq

organizational factors that could arise from multi-unit interactions at the same site during an accident progression. The issues can be largely divided into two cases: the first being where one or more preceding units experience severe accident(s) or release radioactive materials, and the second being where multiple units at the same site experience extreme hazards that require site-level accident management interventions.

Issues from the first case are to identify and assess the potentials that: (1) the effect units experiencing severe accident(s) or release of radioactive materials may have on the capability of emergency response, and (2) human and organizational performance at the other units which are normally operating or under normal control at an emergency situation. Specific examples are as follows.

- If one or more units are undergoing severe accidents resulting in the release of radioactive or hazardous materials, human operators working in other units (i.e., units that are normally operating or responding to a normally controlled emergency situation) may experience higher stress or degraded performance due to psychological fear. In addition, human operators in the normally operating units are expected to determine manual reactor shutdown.
- If one or more units are releasing radioactive and hazardous materials, it may affect the long-term habitability of the MCRs as well as the performance of local emergency personnel working in other units. Therefore, the effects of the radiation level on the operating crew, their tasks, and local personnel activity need to be reassessed. In addition, it is required to evaluate whether it is possible for off-site emergency response staff and personnel to enter the site and join the on-site emergency response organization to cope with long-term accident response.

Issues from the second case include the need for assessing the situational awareness and decision-making capability of the site-level emergency response organization, and for performing realistic analyses to evaluate whether required emergency staff or personnel are sufficiently supplied to local emergency activities. Detailed examples are as follows.

- *Multi-unit situational awareness of the site-level emergency response organization*: When multiple units at the same site are experiencing extreme hazards that require site-level accident management interventions, it is necessary to adequately assess the situation for individual reactor units and spent fuel pools to make correct and prompt decisions for site-level accident management. Especially, in case of limited human and equipment resources, it is of utmost importance to adequately evaluate the status of individual reactors and spent fuel pools because required staff and equipment should be deployed along their priority.
- *Multi-unit staffing analysis*: Multi-unit staffing analyses are necessary in situations requiring multiple personnel, including intra- and inter-team coordination, especially for local activities utilizing mobile equipment. In such analyses, demand vs. availability for staff and personnel at the site should be appraised in a predictive way as an accident progresses, and the command and control flow between higher-level and lower-level emergency response organizations should be properly evaluated with realistic postulation.

5. Discussion and conclusion

From the point of view of enhancing NPP safety, one of the prerequisites is to precisely identify potential causes that may result in undesired consequences. In this regard, PSA results (e.g., minimal cutsets) are valuable because they allow us to systematically investigate a large number of likely paths leading to undesired consequences. This means that the quality of HRA results is essential for accurately assessing the safety of NPPs based on PSA. To this end, the first step is to distinguish the specific HRA issues to be resolved for improving HRA quality.

This study prioritized such HRA issues through 14 SMEs who have sufficient experience with the HRAs of domestic Korean NPPs. The five significant HRA issues emphasized by SMEs are: (1) providing a technical basis for the K-HRA (Korean HRA) method, and developing dedicated HRA methods applicable to (2) diverse external events to support Level 1 PSA, (3) digital environments, (4) mobile equipment, and (5) severe accident management guideline tasks to support Level 2 PSA. A further issue, developing an HRA method for multi-unit PSA, was also deemed important.

It is true that the underlying limitation of this study is a lack of theoretical underpinning in extracting the subjective opinions from SMEs. That is, the priority scores of each HRA issue were determined through a simple aggregation of average scores with respect to two rating dimensions (*Urgency* and *Importance*). In addition, the two cut-off values (2.7 and 5.5) used to classify HRA issues as significant were chosen based on SME consensus. This implies that, in terms of such subjective opinion extraction, reliability is still uncertain.

Nevertheless, the result of this study is still insightful because of the wide spectrum of SMEs that participated in the collection of HRA issues. The SMEs represented four different positions (namely, a research institute, regulatory body, utility and its subcontractors), which compose all stakeholders in conducting HRAs of domestic Korean NPPs. This strongly implies that the quality of HRA (or PSA) can be drastically enhanced, if the abovementioned issues are able to be soundly resolved. In this vein, Table 8 summarizes potential resolutions with respect to each significant HRA issues.

For example, in order to provide a technical basis of the K-HRA method (Issue 1), one promising measure would be the collection of HRA data from a full-scope simulator allowing confirmation of the appropriateness of the rules and assumptions involved [34]. If this data collection can be conducted in parallel with a workshop of

Table 8
Promising resolutions with respect to significant HRA issues.

Significant HRA issue	Promsing resolution
Technical basis of the K-HRA method	Collecting simulator-based data to provide appropriate rationales, in tandem with domestic workshops with SMEs and HRA practitioners
HRA method for diverse external events	Capturing the effect of the nature of external events (e.g., fragility) on the performance of human operators
HRA method for a digital environment	Developing a novel HRA method that encompasses digital features affecting the performance of human operators
HRA method for mobile equipment	Incorporating the characteristics of installations and operations related to mobile equipment
HRA method for SAMG tasks	Developing a novel HRA method to model the performance of team-decision making tasks being described in SAMGs
HRA metnod for supporting multi-unit PSA	Combining the insights and experience related to HRA methods for eveternal events, mobile equipment and SAMG tasks

SMEs and HRA practitioners, it is highly expected that more concrete rationales can be secured.

In the case of an HRA method applicable to diverse external events, it is possible to revise existing HRA methods through capturing the effect of external events on the performance of human operators. To this end, it seems inevitable to organize an internal collaboration activity that will facilitate the collection of a sufficient amount of experience and knowledge about external events with rare frequencies.

In contrast, it is also necessary to put available resources to the development of novel HRA methods, especially for a digital environment and SAMG tasks. For example, except for HuRECA and MERMOS (refer to Fig. 2), Porthin et al. emphasized that it is rare to find an HRA method applicable to a digital environment [18]. Similarly, Park et al. stated that it is highly questionable to use existing HRA methods to evaluate HEPs under severe accident conditions because of the entirely different nature of decision-making tasks included in SAMGs [31]. Finally, in terms of an HRA method for supporting multi-unit PSA, it is necessary to effectively combine insights and experience about several HRA methods (i.e., HRA methods for external events, mobile equipment, and SAMG tasks) because of the large spectrum of initiating events being considered in multi-unit PSA.

In this regard, it would be meaningful to stress that research projects dealing with the third, fourth, and fifth significant HRA issues have been initiated by KAERI and the Central Research Institute (CRI) of KHNP. Reflecting the third issue (*Developing an HRA method for a digital environment*), for example, KAERI launched a project funded by the Korean government in January 2017 with the main purpose to develop an HRA method that can properly reflect the characteristics of a digital MCR. This project will be finished by the end of 2019, and its primary product is a detailed HRA method to estimate the HEPs of HFEs in a digital MCR.

Further, CRI has also contracted a preemptive project with KAERI in December 2017 with the aim to collect HEPs observable from a digital MCR. By December 2018, a huge amount of data (including audio-visual records and process parameter logs) will be gathered from a full-scope simulator, which is a replica of the digital MCR installed in domestic Korean NPPs. Based on these data, this project will be finished by June 2019 with a catalog of HEP values actually derived from observations of a digital MCR.

Another urgent project for domestic Korean NPPs has also been started by KAERI in January 2017, with the main objective to develop an HRA method for supporting Level 2 PSA. This government-funded project consists of two phases with dedicated outcomes. The first phase, scheduled to finish by December 2018, will draft an HRA method for estimating the HEP of critical tasks that are involved in the installation of mobile equipment and components, such as movable power generators and pumps. The second phase will propose a guideline that allows HRA practitioners to estimate the HEPs of SAMG tasks by December 2019. It is should be noted that the outcomes of the first and second phase are closely related to the fourth and fifth significant HRA issues, respectively.

It is true that the catalog of significant HRA issues identified in this study is a preliminary version. However, the implications of this catalog are quite positive, as the tangible result represents the first consensus of domestic HRA practitioners. Accordingly, it is believed that this catalog will be a good starting point to come up with further detailed countermeasures for enhancing the quality of HRA results, such as KAERI's project for developing a digital HRA method and CRI's project for collecting HEP data from a full-scope digital MCR simulator. This expectation will become more evident if HRA stakeholders continue their effort to elaborate this catalog in the future.

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