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Original Article

SAMG-based human reliability analysis method in support of Level 2 PSA. Part I: Table-top eXercise experiments

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ABSTRACT

The two papers in series deal with development of a new human reliability analysis (HRA) method, SAM-L2HRA, for evaluating severe accident management (SAM) strategies utilizing portable equipment for preventing and mitigating severe accidents. The first paper, Part I, introduces technical background for developing SAM-L2HRA, including identification of task characteristics of severe accident management guidelines (SAMGs) and the critical steps of individual SAM strategies with their likelihood of human errors and decision-making associated with each strategy to be included in the SAM-L2HRA framework. Based on the identified task characteristics and context of SAMGs, an approach to Level 2 HRA based on the technical support center (TSC) SAMGs, SAM-L2HRA, is outlined. To have more elaborate basis for SAM-L2HRA, the Table-Top eXercise (TTX) experiments have been designed and conducted under postulated severe accident scenarios, and the results and insights gained from the experiments and interviews with the subjects were summarized.

1. Introduction

After the Fukushima Daiichi accident caused by the Great East Japan earthquake and ensuing tsunami, the nuclear community has been making various efforts to devise new safety systems and equipment, including passive safety systems such as the containment filtered venting system as well as active safety systems such as portable or mobile equipment, and to prepare mitigation strategies and guidelines to cope with beyond-design-basis external events (BDBEEs) with expanding emergency response organizations (EROs) and their capability [1–9]. The U.S. diverse and flexible coping strategies (FLEX) and Korean multi-barrier accident coping strategies (MACST) are the exemplary results of such efforts to mitigate the simultaneous occurrence of an extended loss of AC power (ELAP) and a loss of normal access to the ultimate heat sink (LUHS) at all units on a site [6,10]. Various types of portable or mobile equipment from FLEX or MACST such as portable generators, portable high-pressure and low-pressure pumps, portable air compressors, and portable high-capacity heat exchangers, etc. are also considered major or candidate means for preventing and mitigating severe accident phenomena in severe accident management guidelines (SAMGs) [10]. The recent review of severe accident phenomena in light water reactors highlighted new research challenges to improve existing severe accident management strategies and guidelines towards a better design and safer operation of high-power light water reactors [11].

The nuclear safety legislation in the Republic of Korea was revised in 2015, in which it establishes that the utility shall submit an accident management program (AMP) for operating nuclear power plants (NPPs) as well as new plants applying for operation permits. The AMP shall include accident conditions such as design basis accidents, multiple events or failures, beyond-design-basis natural or man-made hazards, and severe accidents. The AMP shall achieve both the prescribed deterministic and probabilistic safety goals by evaluating and assessing the plant's accident management capabilities, which are composed of strategies, equipment, and EROs [10]. Achievement of the probabilistic safety goals can be verified by performing probabilistic safety or risk assessment (PSA/PRA) for various internal and external hazards. The risk-based safety goals are specified in the revised nuclear safety legislation as follows [12].

– The prompt fatality or cancer fatality risks of the population near an NPP from the accident should not exceed 0.1 % of the sum of risks resulting from all other causes; or the equivalent performance goals for the prompt fatality and the caner fatality risks should be satisfied (e.g., core damage frequency <1.0E-5/reactor year (ry), large early release frequency <1.0E-6/ry).

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Nomenclature

AHP	analytic hierarchy process
AM	accident management
AMP	accident management program
BDBEE	beyond-design-basis external events
CABJ	computational aid-based judgment
CBDT	cause-based decision tree
CET	core exit temperature
CS	containment spray
DFC	diagnostic flow chart
DIF	decision-influencing factor
DTA	decision tree approach
ELAP	extended loss of AC power
EMBRACE	empirical data-based crew reliability assessment and cognitive error analysis method
EPRI	electric power research institute
EPRI EE HRA	EPRI external event HRA
ERO	emergency response organization
FLEX	diverse and flexible coping strategy
HCR/ORE	human cognitive reliability/operator reliability experiment
HORA	human and organizational reliability assessment
HORAAM	human and organizational reliability analysis in accident management
HRA	human reliability analysis
IDHEAS	integrated human event analysis system
K-HRA	Korean standard HRA
LSC	local safety center
LTM	long-term monitoring
LUHS	loss of normal access to ultimate heat sink
MACST	multi-barrier accident coping strategy
MCR	main control room
MERMOS	Methode d'Evaluation et de Realisation des Missions Operateurs pour la Surete
PDS-ET	plant damage state event tree
PSA	probabilistic safety assessment
PRA	probabilistic risk assessment
RCS	reactor coolant system
SAG	severe accident guideline
SAM	severe accident management
SAMG	severe accident management guidelines
SAM-L2HRA	SAMG-based level 2 HRA method
SDS	safety depressurization system
SG	steam generator
SPAR-H	standardized plant analysis risk HRA
SPDS	safety parameter display system
SRO	senior reactor operator
TERM	SAMG termination guideline
THERP	technique for human error rate prediction
TLOCCW	total loss of component cooling water
TRBJ	text rule-based judgment
TSC	technical support center
TTX	table-top exercise

– The sum of frequencies for the accident scenarios in which the amount of Cs-137 release exceeds 100 TBq should be less than 1.0E-6/ry.

In case the capability of a current AMP does not meet the risk-based safety goals, the utility should try to identify the vulnerable accident scenarios and conditions and devise possible resolutions to enhance overall plant safety until the safety goals are satisfied. The measures to improve or enhance plant safety may include equipment reliability improvement, adoption and installation of new safety systems, provision of innovative accident management (AM) strategies and measures, revision or improvement of AM procedures or guidelines, and enhancement of the EROs' capability. The effective and valid AM measures are modeled recursively into the relevant PSA models (i.e., internal or external events PSA or risk models) to see their effect on the overall risk, as shown in Fig. 1. This process is called the 'risk-based AM framework', in which human and organizational reliability assessment (HRA or HORA) techniques play an essential role in identifying and assessing the risk-significant human and organizational decisions and actions to be modeled in the risk assessment framework [13].

To date, most HRA methods and applications have been focused on Level 1 PSA scenarios and actions. Representative HRA methods include THERP [14], HCR/ORE [15,16], CBDT [15,16], SPAR-H [17], K-HRA [18], IDHEAS [19,20], EPRI EE HRA [21], and EMBRACE [22,23]. HRA methods for utilizing portable equipment such as portable generators or pumps under BDBEEs have been suggested [24–28]. In comparison to Level 1 PSA, HRA methods for Level 2 PSA (which are called 'Level 2 HRA' in this paper) are limited. HORAAM [29] and MERMOS [30] are representative ones.

This series of two papers deals with a new Level 2 HRA method, named SAM-L2HRA, with the aim to provide a framework and detailed guidance for analyzing SAMG actions, including decision-making of the technical support center (TSC) as well as use of portable equipment. The first paper of this series presents the task structure and characteristics of SAMGs and identifies critical task steps with major influencing factors that represent the context of SAMG tasks. A task analysis based on a Table-Top eXercise (TTX) is conducted to observe the process of SAMG decision-making and implementations, to identify the complex and critical steps within the overall process that lead to decisions and actions, and to estimate rough time required for completing individual guidelines of SAMGs. The second paper of this series provides a methodological framework of SAM-L2HRA.

The composition of this first paper is as follows. Section 2 introduces the basic structure of SAMGs and describes key characteristics and task contexts of SAMGs, including the strategies and actions that deploy portable equipment. Section 3 establishes a basic framework for developing SAM-L2HRA, and outlines the planning and preparation of TTX experiments for anticipated severe accident scenarios. Section 4 lists major findings obtained from the experiments, summarizes time information associated with conducting SAMGs, and provides the results of pairwise comparison of the relative complexity between evaluation rules for negative impacts, which will be used in the methodology of the second paper. Finally, Section 5 concludes this study.

2. Characteristics of SAMG tasks and contexts

2.1. Structure of SAMGs

The structure of SAMGs of the reference plant is basically like the Westinghouse-type reactor SAMGs [31]. The SAMGs are largely composed of the main control room (MCR) SAMG and the TSC SAMG. The MCR SAMG is divided into two parts: the initial emergency actions before the TSC is operational, and the follow-up actions after the TSC is operational. The TSC SAMG, which is used by the TSC after it becomes operational, is composed of several elements including a diagnostic flow chart (DFC), severe accident guidelines (SAGs), and long-term monitoring (LTM) and termination guidance. The basic structure and composition of the TSC SAMG are shown in Fig. 2. Once the TSC is organized by emergency call according to the emergency action level, the authority of leadership for the NPP accident control shifts from the

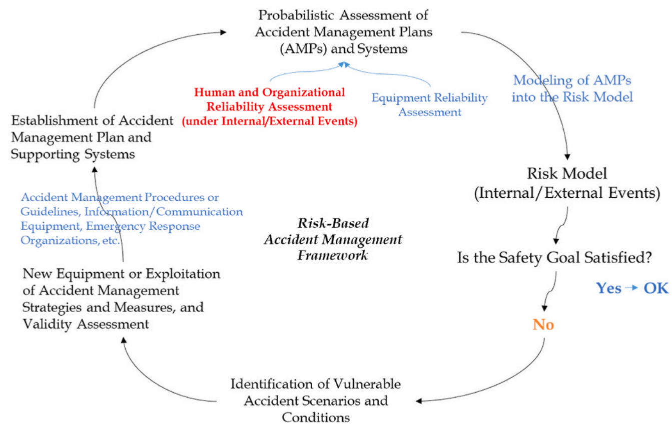

Fig. 1. Risk-based accident management framework and the role of human and organizational factors, reproduced from Kim and Cho [13].

MCR to the TSC. The TSC then takes control of the mitigation of NPP accidents, makes required decisions, and gives orders to the MCR and local safety center (LSC)[1] to implement a SAM strategy as well as to monitor and observe plant status and accident conditions.

The DFC is used to assist the TSC in diagnosing the plant conditions and selecting the appropriate SAGs that need to be implemented depending on plant conditions. It provides a comprehensive overview of the accident control and mitigation guidelines as well as the critical plant parameters that need to be continually monitored and controlled during the severe accident progression.

If any critical plant parameter does not meet the predefined criteria, the TSC is directed to the corresponding SAG in which decision-making on whether to implement the given strategy and the implementation itself of the strategy once its need has been determined are done. In particular, if any of the severe challenge parameters such as fission products (FPs) release, containment pressure, or containment hydrogen exceeds the predefined severe challenge setpoints, then all actions being performed are immediately suspended and an associate severe challenge mitigation guideline should be used to deal with the severe challenge accident conditions.

SAGs include specific severe accident management (SAM) guidelines or strategies for preventing or mitigating severe accident phenomena. Such SAM strategies include Injection into the steam generators (SGs), Depressurization of the reactor coolant system (RCS), Injection into the RCS, injection into the containment, reduction and control of FPs release, control of containment conditions, reduction and control of containment hydrogen, etc. Among the SAGs, the candidate guidelines expected to employ portable equipment as a means for accident mitigation are SAG-01 (Injection into the SGs), SAG-03 (Injection into the RCS), SAG-04 (Injection into the Containment), SAG-05 (Reduction or Control of FP Release), and SAG-06 (Control of Containment Conditions).

The LTM guideline is used for monitoring all the long-term concerns associated with the implemented strategies. If there are unsatisfied conditions of plant parameters from long-term concerns, then the TSC assesses whether a strategy currently in use is still valid for managing the accident progression and evaluates alternative strategies.

If all the critical safety parameters such as CET, FP release, containment pressure, containment hydrogen, and the spent fuel pool water level are maintained and controlled at safe and stable conditions for the long-term, then the SAMG termination (TERM) guideline is used to provide the TSC with important information for judging the termination of all SAM strategies and considering other recovery measures.

[1] The local safety center (LSC) is called off when portable or mobile equipment is required to implement mitigation strategies in response to an accident scenario such as ELAP.

2.2. SAMG task characteristics and contexts

The basic operation method of implementing the TSC SAMG is to enter an individual SAG to determine and implement the accident mitigation measures that could terminate the progression of a severe accident or mitigate the consequences of severe accident phenomena in case the criteria for safe and stable conditions of specific plant safety parameters are not satisfied in accordance with the DFC. For the priority between the strategies associated with the plant safety parameters and the ones associated with the containment severe challenge parameters, implementation of the guidelines for mitigating the containment severe challenge parameters takes precedence. After entering an individual SAG, the TSC determines the availability of the required systems or equipment, makes a decision on the strategy, and implements the strategy once it is determined. Most of SAGs, while differing in detailed contents, fundamentally consist of the following sub tasks, as represented in Fig. 3.

- T1: Identify the available means for implementing a strategy.
- T2: Identify the positive effects as well as negative impacts of a given strategy, and evaluate the actions to mitigate the negative impacts if they exist. Make a decision on whether to implement the strategy or not after comparing the positive and negative effects in association with the strategy.
- T3: Determine the preferred pathway for implementing the strategy and the associated limitations.
- T4: Direct the implementation staff (i.e., MCR crew or LSC personnel) to implement the selected strategy with limitations.
- T5: Verify the strategy implementation and determine if additional mitigative actions are necessary.
- T6: Monitor the long-term concerns and take appropriate countermeasures.

From the perspective of human reliability of a particular SAM strategy, important actions are those in the above-described fundamental tasks as well as the judgments required at each critical parameter of the DFC, with the potential for human errors and the likelihood of decision-making during the performance of the steps contributing to the overall success or failure probability of the SAM strategy. In addition, strategy implementation should be achieved or completed within the time allowed for the strategy to prevent a specific severe accident or phenomenon. Thus, the human reliability analysis of SAMG tasks requires an analysis of human error potential or decision-making likelihood as well as an analysis of the time information, namely time available and time required.

From the judgment at each critical parameter of the DFC through strategy selection and implementation to the verification and monitoring of the implementation and long-term concerns, necessary

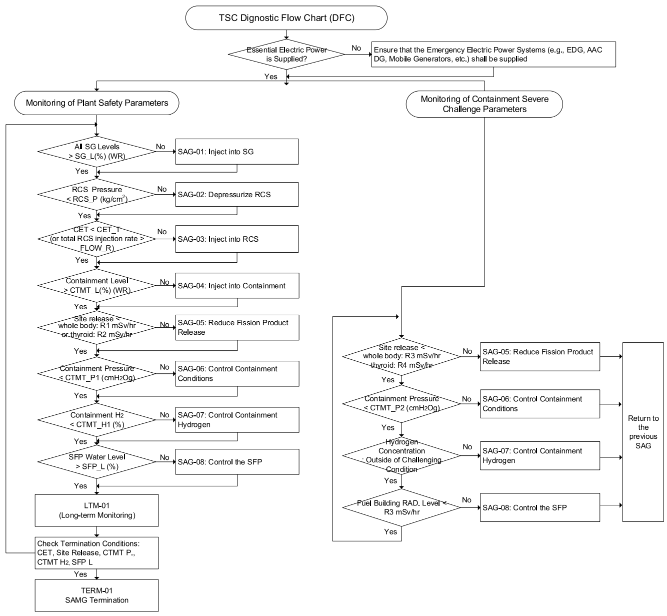

Fig. 2. The overall structure of TSC SAMGs of the reference plant, reproduced from Kim and Cho [13].

cognitive functions and activities are defined as shown in Fig. 4. Descriptions on the necessary cognitive functions and activities and potential error modes for each critical action steps are listed as follows.

- DFC: Making a judgment on whether to enter the relevant SAG in DFC

The DFC are basically designed to determine whether or not to enter an individual SAG based on a single plant parameter or an alternative variable, therefore the task of judgment is relatively simple on condition that the reliability of the instrumentation of plant parameters is secured. In this perspective, the overall reliability of this stage depends on the degree of reliability of the instrumentation associated with critical plant parameters at the time of judgment for entry into the individual SAG and the reliability of the crew or TSC staff in judging the criteria based on the observation of critical plant parameters. The degree of reliability of the instrumentation needs to be verified in the entire phases of strategy evaluation and implementation.

- T1: Identify the available means for implementing a strategy

In the T1 step, information gathering and system state identification activities are carried out to gain an overall understanding of the availability of the means (systems, paths, and resources) to implement the appropriate accident management strategy and to eventually derive the available means for the strategy implementation. Overall system status information can be obtained through the safety parameter display system (SPDS) installed in the TSC, obtained from the MCR, or depending on the circumstances, collected through LSC personnel. Because the SPDS can provide most of the information needed to perform SAMGs, if the SPDS is available, the TSC will basically acquire most of the necessary information through the SPDS, or from the MCR if the SPDS is not available. Information delivery over satellite phones are possible if communication facilities and resources such as safety-grade satellite phones are established between the TSC, MCR and LSC when the SPDS is not available. If no satellite phones are available, information delivery between the EROs must be done in a direct, oral manner (e.g., face-to-face communication). However, in situations where no communication means such as satellite phones are available, communication capabilities will be significantly degraded, making it difficult to reliably ensure the implementation of the SAMG strategies that require continuous monitoring and control. Furthermore, if the strategy using portable or mobile equipment are employed in a severe accident situation when most of fixed safety systems are lost, it will be more difficult to successfully implement the strategy in the event of loss of communication with local personnel.

Considering the above, the method we are proposing assumes a scenario condition in which communication facilities are available, and assumes a probability of failure of 1.0 in situations in which communication is lost. If detailed reliability assessment is required even for the situation in which communication is lost, experiments and data collection of SAMG implementations, under scenario conditions in which communication is completely lost, would be needed to verify the feasibility of the ERO's activities.

- T2: Identify the positive and negative effects of the strategy and decide on its implementation

The T2 step includes consideration of possible negative effects of implementing a particular strategy. As SAMG tasks, unlike EOPs, are requested in a severe accident situation, almost all strategies involve negative impacts. But depending on the given severe accident scenario, there may be differences in the degree of negative effects. At this stage, the TSC makes a decision on whether or not to implement the strategy using the available means identified in T1, by identifying the potential for all possible negative effects, evaluating the mitigative actions to mitigate the effects if any, and then comparing the positive and negative effects of implementing the strategy.

The cognitive functions of phase T2 may require high levels of cognitive activities depending on the situations. The overall positive effects associated with the strategy as well as the specific negative effects that may arise should be identified while assessing the feasibility of mitigating the negative effects. The degree of negative effects with the feasibility of mitigative measures is compared with the consequences that may progress if the strategy is not implemented. This process requires various levels of cognitive activities, such as information gathering to evaluate the likelihood of negative effects, understanding of the phenomena associated with negative effects, evaluating the likelihood of negative effects, comparing the positive effects with the negative effects, and finally, decision-making on the strategy implementation.

A Level 2 HRA method dealing with SAMG tasks should adequately address the likelihood of the strategy decision-making, which is

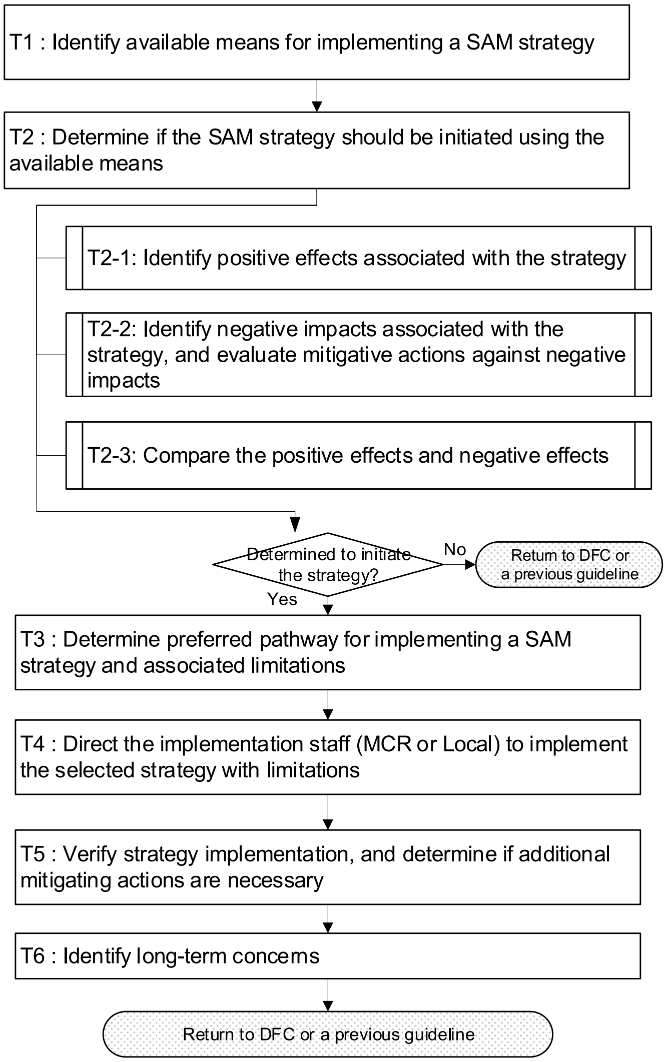

Fig. 3. Basic structure of an individual SAG.

associated with the decision on whether or not to implement the SAMG strategy. The method should represent how decisions are made based on what particular information such as decision-influencing factors (DIFs) and criteria and how the likelihood of strategy decision-making is under given scenario conditions. The SAM-L2HRA method suggests a simplified decision tree approach (DTA) based on the insights and results from our previous study on the application of fuzzy theory to the estimation of decision-making likelihood of a SAM strategy when evaluation of its positive and negative effects needs to be made [32]. The main reason why we adopt the DTA instead of the fuzzy model-based approach is that the fuzzy model-based approach requires specific fuzzy rules and membership functions that should be obtained from actual TSC staff of particular NPPs to be applicable to a specific plant, which may require a large amount of resources and time. The DTA method adopted in this study uses the same DIFs as the fuzzy theory-based applications but simplifies the description levels of the DIFs and operationalize the judgmental criteria.

- T3: Determine preferred pathway for implementing the strategy and the associated limitations

Based on the available means, the T3 step selects the systems and paths that will best facilitate the strategy implementation and identifies various limitations to consider when carrying out the strategy. Selection of the systems and routes to be used shall be prioritized by the reliability and effectiveness of the available facilities, so if fixed safety system equipment are available, such systems will be selected first, and if no fixed safety system equipment are available, mobile/portable equipment will be selected. Limitations identified at this stage include precautions to be taken when implementing the strategy (e.g., actions to mitigate negative impacts), plant conditions that are required for a strategy to be implemented, and actions that need to secure sufficient resources, and so on.

Most severe accident scenarios, except for accident sequences involving human error, happen due to the multiple losses of fixed safety systems. In other words, under SAMG conditions, fixed safety systems that are used to implement particular strategies are often all lost or only partially available. Therefore, the selection of the systems and routes for implementing the strategy required at this stage is not considered to be a high cognitive burden, and the identification of the limitations itself is considered to be moderate because guidelines to identify the limitations are described in the SAG. Thus, in this study, the T3 and T4 phases are integrated and evaluated in a single quantitative stage.

- T4: Direct the implementation staff (MCR crew or LSC personnel) to implement the selected strategy with limitations

In the T4 step, information about the strategy implementation measures (systems and paths), limitations related to the implementation of the strategy, mitigative actions related to the negative effects, and special monitoring variables are delivered to the MCR. If the strategy can be achieved by MCR actions, the MCR crew alone performs the tasks, but if the tasks require local or field activities such as those using mobile/portable equipment, the LSC under the supervision of the MCR performs the tasks via coordination and communication. In the case of on-site accident management measures using mobile/portable equipment, close cooperation between the MCR and LSC is required, with communication generally made via satellite phones or mobile phones. Compared to the information delivery activities between the TSC and MCR, each in an indoor environment where SAMG documents can be cross-checked, the information delivery activities to the LSC located in an outdoor environment where SAMG documents are relatively difficult to refer to have vulnerabilities that can produce uncertain and untimely communication results. Under these circumstances, the MCR should communicate to the LSC the precautions (limitations and mitigative actions) to be taken in implementing the strategy while simultaneously communicating to the LSC about the equipment and flow paths for implementing the strategy, and the LSC should keep all these things in their mind even under the situations where the SAMG documentation may not be directly available. Of course, not all limitations and mitigative actions need to be communicated initially, and a distinction between the initial precautions and the appropriate monitoring during implementation of the strategy can provide an efficient and effective communication strategy. Once the method of implementation and limitations for the strategy are delivered, the LSC implements the SAM strategy using mobile/portable equipment. It is also important to note that even if a specific limitation (e.g., maintain the SG injection flowrate below a certain value) has been delivered from the MCR to the LSC, there may be no clear indication to observe the limitation (e.g., an accurate indication for SG injection flowrate) at the local area, therefore actual monitoring (i.e., verification of injection flowrate) should be performed by the MCR. In other words, after the MCR delivers required instructions correctly to the LSC using satellite phones including major limitations and mitigative actions and the LSC initiates the strategy implementation measures using mobile/portable equipment, if there is a problem with the LSC actions, immediate feedback must be made through the same communications means. To derive such feedback, during the implementation of the strategy, the MCR constantly checks whether the limitations are adequately met and whether additional measures are necessary, and delivers information and instructions to the LSC.

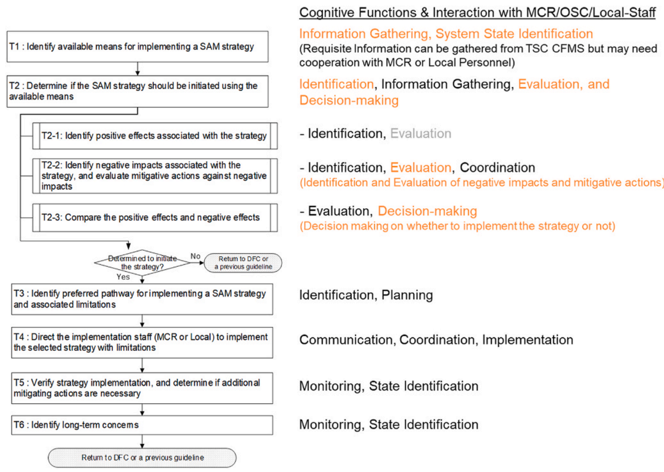

Fig. 4. Cognitive functions and interactions involved in the critical steps of a SAG.

In this study, in order to incorporate the level of task complexity between the MCR and LSC when implementing SAM strategies using mobile/portable equipment into the estimation of human reliability, SAMG-based TTX experiments were first conducted by several experts in SAMGs under postulated accident scenarios, and after those experiments, the experts participated in quantitative pair-wise comparisons about the perceived level of complexity between the MCR actions only and the coordinated MCR and LSC actions. The outline and results of the TTX experiments and pair-wise comparisons between the MCR actions only and the coordinated MCR - LSC actions are described in Section 3, and a quantification method for the T3 and T4 action steps using the results are presented in Section 4.

- T5: Verify the strategy implementation and determine if additional mitigative actions are necessary

The T5 step is to verify the effectiveness of the strategy after implementation. If any negative effects are observed during the implementation, the candidate measures to mitigate the negative effects are evaluated and appropriate measures among candidates are directed to the MCR. Currently, a list of plant parameters to be monitored is available for checking the effectiveness of each SAG, and relevant information is also provided to identify any negative effects. In order to perform this task, both the TSC and MCR must perform monitoring activities individually, with appropriate information delivery activities required between the two entities. Since the information required at this step is used for monitoring the late phase of the accident progression and management, the availability/reliability associated with the instrumentation should be assessed from different point of time other than the time at the entry to each SAG.

A more realistic risk model should reflect the potential accident progression associated with the occurrence of negative impacts and intervention of the ERO to mitigate those impacts. However, since current Level 2 PSA technology has a limitation for a detailed modeling of negative effects and human interventions, this study only considers the potential for error recovery of the initial implementation error through the verification of the effectiveness of the strategy. Therefore, in this step, it is necessary to analyze the availability of the essential information for error detection and to identify when signals or information are presented for error detection.

- T6: Long-term monitoring and actions

The last step of all SAGs consists of monitoring and actions related to the long-term issues associated with the strategy implementation. From a long-term perspective of accident management and progression, modeling of the plausible severe accident phenomena and associate countermeasures against those phenomena in this phase are desirable, but the technical limitations of current Level 2 PSA make it difficult to reflect. The actions associated with this phase are excluded from the scope of study.

The above results including cognitive function analysis, objectives and characteristics of each critical action step, as well as the error analysis items provide the basis for the qualitative and quantitative analyses of the SAM-L2HRA method, detailed in Section 4.

3. Technical approach to SAM-L2HRA and SAMG table-top eXercise (TTX) experiments

3.1. Technical approach to SAM-L2HRA

3.1.1. The approach to failure probability quantification of a SAMG task

This section presents a methodological approach to Level 2 HRA based on the characteristics of SAMG tasks and context.

The implementation of the SAMG tasks or strategies has the purpose of preventing or mitigating the various phenomena that occur in the course of a severe accident. The tasks are performed within a limited allowable time related to the mitigation and termination of the phenomena, and there may occur errors or wrong decision-making during a series of cognitive processes such as information gathering, situation assessment, evaluation and decision-making, strategy implementation, and confirmation of effectiveness associated with the implementation. In particular, the major characteristics that can appear in a severe accident situation and the related SAMG task is the negative impact that a specific strategy can generate in connection with a specific scenario situation.

Reflecting these SAMG task characteristics, this study uses two quantification approaches to estimate the failure probability of a SAMG task: (1) a time-based approach for failure analysis, (2) a task-based approach for error potential and decision-making likelihood. The basic direction of each approach is briefly described below.

First, while the basic concept and method of time-based reliability assessment has already been suggested in other previous HRA studies [16,19,22,23], our study in the time-based approach deals with the issue of phenomenological uncertainty that must be dealt with in a severe accident situation. It also proposes a way to integrate the distribution of various time elements that must be considered in the SAMG situation, namely, the time required for completing each SAG, the time required for the LSC in their composition and deploying, installing and operating portable equipment, and the time required to confirm effectiveness after implementing the strategy. The detailed information on time required and time available for the case study is composed of the data obtained from the SAMG TTX experiments, the phenomenological data from the severe accident analysis code, and the data from the validation results of the stress tests conducted at domestic NPPs in preparation for extreme events. Since the TTX experiments were conducted in a very limited environment under postulated accident scenarios, it is expected that the results and observations derived from this experiment may more or less differ from the responses in an actual severe accident situation. The current experiment though is thought to be most suitable at this time when considering the full-scope plant simulator does not have the capability to simulate severe accidents. Although it may differ from an actual situation, it is judged that the response patterns and the time required for a severe accident in general can be confirmed.

Next, the task-based approach for error potential and decision-making likelihood provides error analysis and quantitative assessment methods that consider the characteristics of the critical task steps of each SAG. The critical task steps include judgment related to entering a SAG from the DFC, identification of system availability (T1) related to strategy implementation, evaluation of negative impacts and decision-making on a strategy implementation (T2), implementation of a determined strategy (T3, T4), and verification of a strategy implementation (T5, T6). Qualitative and quantitative analysis methods for each critical task step are provided in Section 4. Among the critical task steps, the 'evaluation of negative impacts and decision-making on a strategy implementation' and the 'implementation of a determined strategy, especially using portable equipment, which are conducted based on coordination and cooperation between the TSC-MCR-LSC organizations' require a new method beyond simply applying existing HRA methods.

For the decision-making likelihood analysis, a preliminary study using fuzzy theory was conducted to estimate the likelihood of decision-making on implementation of a SAM strategy under existence of negative impacts [32]. Four decision-making influencing factors such as 'likelihood of negative impacts,' 'evaluation complexity of negative impacts,' 'implementation feasibility of mitigative actions,' and 'decision burden from the complexity of mitigative actions' are used for decision-making likelihood estimation using the fuzzy rule base and individual membership functions. Based on this preliminary study and using the same influencing factors, this study provides a more simplified decision tree-based method for practical use in Level 2 HRA, which is introduced in Section 4.

For comparison of the relative complexity between judgmental tasks for the evaluation of the potential for negative impacts used in the DTA and for comparison of the relative complexity between in-MCR tasks and ex-MCR tasks using portable equipment for reliability assessment of tasks to implement a strategy using portable equipment based on coordination and cooperation between the TSC-MCR-LSC organizations, a questionnaire survey was conducted by the participants after their TTX experiment on SAMG tasks. The results of the SAMG TTX experiment and questionnaire are dealt with in Section 4.

3.1.2. The essential information resulted from the TTX experiment for qualitative and quantitative assessment of a SAMG task

The SAMG TTX experiment was conducted to obtain qualitative and quantitative information on the SAMG performance and to gain methodological insights for developing Level 2 HRA method. Through the SAMG TTX experiment, the following essential information was obtained. This information is necessary for both time-based and task-based analysis approaches.

First, we observed and confirmed a general way of TSC SAMG conductance under hypothetical severe accident scenario conditions. The scope of TSC SAMG conductance identified through the TTX experiment includes all the guidelines such as the DFC and individual SAGs, in which detailed steps involve the activities such as information gathering, situation assessment, decision-making, implementation of a strategy, monitoring of the strategy implementation and long-term concerns, and returning to the DFC or progressing to the next guideline, etc.

Second, time information was gathered such as the time for initial preparation for starting the TSC SAMG and entering the DFC, the time required for completing each SAG, the time required for each task step within an individual SAG, and the time required from the initiation of a strategy implementation to confirmation of the effectiveness, and so on. As stated above, these results were derived from limited experimental conditions and may differ from the actual progress of a severe accident. Despite this, the results can still be used as base data or rough estimates when applying HRA in the future as approximate ranges of the time required and for identifying the rationale and background of the time information.

Third, from the SAMG TTX experiment and consultation with the participants after the experiment, unique characteristics of the decision-making in association with some strategies were identified. In relation to a specific strategy, it was found that, rather than blindly following the conditions for entering the SAG as given in the DFC, decision was suspended until they recognize an actual necessity for implementing the strategy by continuously monitoring the given situation and observing the trends. Moreover, it could be identified that decision-making of the SAG-1 strategy, which may induce radioactive release, cannot be made by the TSC alone, but requires consultation with the emergency operation facility (EOF).

Fourth, after the SAMG TTX experiment, a qualitative and quantitative survey was conducted on the burden of strategic decision-making. Additionally, a comparison of the relative complexity between judgmental tasks for evaluating the potential for negative impacts and a relative complexity of the strategy implementation using portable equipment compared to the MCR control tasks were evaluated. These results are used in the DTA-based decision-making likelihood estimation and the reliability estimation of the tasks using portable equipment based on coordination and cooperation between multiple organizations (i.e., TSC-MCR-LSC organizations), respectively.

Section 3.2 describes the process of planning and preparation of SAMG TTX experiments, and Section 4 summarizes the results and insights from the experiments. Based on these, the second paper of this series ones introduces the qualitative and quantitative analysis method, SAM-L2HRA, for SAMG-based accident management strategies, and presents an illustration of the step-by-step application of SAM-L2HRA to the RCS injection strategy using a portable pump.

3.2. Planning and preparation of the SAMG TTX

As described in Chapter 2, the development of Level 2 HRA method requires specific information such as 1) the practice of usage of SAMGs under given accident scenarios, 2) the characteristics of cognitive activities (e.g., decision-making) required of the emergency response organizations (EROs) such as TSC staff and MCR crew responsible for the various tasks, and 3) the time required to perform required task or to complete a SAG. However, until now, there is a lack of such basic information and understanding in terms of SAMG situations and tasks both domestically and internationally. Therefore, before suggesting a Level 2 HRA method, this study investigated the usage or operation method of SAMGs and the processes and characteristics of the cognitive activities required to perform various SAMG tasks, and conducted a TTX under hypothetical severe accident scenarios to estimate the time required to perform SAMG tasks. After the experiment, two surveys were conducted to investigate the relative complexity among the judgmental tasks for the identification and evaluation of negative impacts and the relative complexity between in-MCR tasks and ex-MCR tasks requiring coordination between EROs when employing portable equipment.

Five subjects who had sufficient knowledge and experience in SAMGs participated in the TTX experiment. They took the role of an SAMG evaluator and decision-maker at the same time, with all the requisite information such as dynamic accident progression with physical parameters needed for judging entry conditions of individual SAGs provided in advance. Information of the five subjects is as follows.

- Subject-1: SAMG developer who participated in the SAMG development and verification for various plant types with more than 20 years of experience in nuclear safety and severe accident analysis.
- Subject-2: Shift supervisor (currently) of an MCR crew with SRO certification and more than 20 years of experience in operating NPPs.
- Subject-3: Retired shift supervisor of an MCR crew with SRO certification and more than 20 years of experience in operating NPPs. Also an instructor at a nuclear training center who ran operator training programs for the operation of NPPs based on EOPs and SAMGs.
- Subject-4: Retired shift supervisor of an MCR crew with SRO certification and more than 20 years of experience in operating NPPs. Also an instructor at a nuclear training center who ran operator training programs for the operation of NPPs based on EOPs and SAMGs.
- Subject-5: Retired senior reactor operator with SRO certification who participated as a TSC member during the radiation emergency drill at NPPs.

Because the TTX experiment is an indirect experiment that does not use a full-scope simulator, plant-specific dynamic information such as changes of plant physical parameters along accident progression under a simulated scenario is required to be prepared in advance. Based on the MAAP5.0 accident analysis code, this study obtained the dynamic behaviors of the critical plant parameters under a postulated accident scenario along with the expected SAMG performance paths and associated system status. To make it easy for the experiment participator to obtain required plant parameters at an appropriate time, especially after the implementation of a SAMG strategy, the points of changes for the major plant parameters are marked off on the trend graph of each parameter. In addition, prior to the experiment, a preliminary experiment has been performed to identify any unexpected difficulties or obstacles during the experiment. As shown in Fig. 5, the accident sequences used in this experiment were the eighth and tenth sequences of the plant damage state event tree (PDS-ET) of a total loss of component cooling water (TLOCCW) in the primary system.

In Fig. 5, both the eighth and tenth sequences in the PDS-ET represent the loss of secondary heat removal function. Under the same loss of secondary heat removal, the eighth sequence represents the case when the RCS depressurization using the safety depressurization system (SDS) has been successfully implemented, whereas the tenth sequence the case when there is no attempt for RCS depressurization or a failure in the SDS itself occurs. In addition, it is assumed that in the entire TLOCCW sequences all the HPSI pumps, LPSI pumps, and containment spray (CS) pumps would eventually fail due to the loss of equipment room cooling capability as resulting from the TLOCCW. In reality, these safety systems would work to some extent after a demand signal is initiated. Due to this reason, it is assumed that the operators could have the potential to initiate feed and bleed (F&B) operation using the SDS valves at an early stage of event progression.

The severe accident scenarios used in this experiment can be classified as "RCS low pressure scenario" (PDS-ET eighth sequence) and "RCS high pressure scenario" (PDS-ET tenth sequence), and each of the scenarios is characterized by the following event progression.

- Scenario-1 (RCS low pressure scenario): RCP and reactor trip due to TLOCCW - > Loss of all SG feedwater including main and auxiliary feedwater - > RCS depressurization for safety injection - > Loss of HPSI/LPSI/CS [but with passive safety injection tank (SIT) injection] - > Core uncovery and degradation due to the eventual loss of reactor coolant - > Reaching the SAMG entry condition (i.e., CET >650 °C)
- Scenario-2 (RCS high pressure scenario): RCP and reactor trip due to TLOCCW - > Loss of all SG feedwater including main and auxiliary feedwater - > No RCS depressurization by intention or due to equipment failure - > Core uncovery and degradation due to continual evaporation of reactor coolant and release into the containment - > Reaching the SAMG entry condition (i.e., CET >650 °C)

The SAGs expected to be performed in each scenario are as follows.

- SAGs in Scenario-1 (RCS low pressure scenario): SAG-1 (SG injection), SAG-3 (RCS injection), SAG-4 (Containment injection), and SAG-6 (Containment condition control).
- SAGs in Scenario-2 (RCS high pressure scenario): SAG-1 (SG injection), SAG-2 (RCS depressurization), SAG-3 (RCS injection), SAG-4 (Containment injection), and SAG-6 (Containment condition control).

In the above scenarios, all SAGs except SAG-2 (RCS depressurization) may include the use of portable equipment, and this study added a strategy using portable equipment to the existing SAMGs.

4. Results and discussion

4.1. Major findings from the SAMG TTX

Subjects-1 and -2 participated in Scenario-1 (RCS low pressure scenario), and Subjects-3, -4, and -5 participated in Scenario-2 (RCS high pressure scenario). All system status information and plant dynamic parameters needed for SAMG performance were obtained in advance based on MAAP5.0. Whenever a subject required specific information,

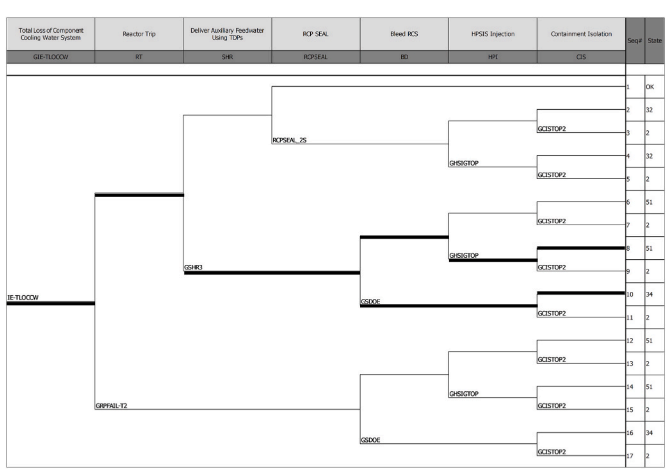

Fig. 5. TLOCCW PDS-ET accident sequences used in the SAMG TTX experiment.

the experimenter provided the real-time status of the parameters according to the scenario progression with time and strategy implementation.

The main observations obtained from the experiment and the items to be reflected in the L2SAM-HRA method are summarized as follows.

- More than two SAGs should not proceed at the same time. In other words, after the decision-making and implementation of one SAG, the next SAG should only proceed after identifying the results and effectiveness (including negative impacts) of the first strategy. However, there are exceptions where a certain SAG is used as a measure to mitigate the negative impacts of other specific SAGs.
- The time required to perform a SAG may vary depending on the degree of task complexity and activity, where it takes approximately 10–30 min from entering a SAG to the decision on the strategy implementation. (The time estimated here is based on the TTX experiment. Because information is collected and evaluated through many information channels in a real severe accident, this time may vary). The time to implement a strategy after decision-making should consider the time required for implementation both in the MCR and on-site after instructing/delivering the implementation method and limitations to the actual performer (MCR operator or field operator). The time to complete a strategy is at least when the result (or effect) of the implemented strategy begins to appear on the indicators. In a severe accident situation, because the SG level and the core level could fall below the measurable range of the indicators, it is necessary to wait until the minimum level at which an indication appears is recovered.
- The following are the characteristics of the decision-making and task performance identified in the given scenarios.
  - Although SAG-1 (SG injection) decision-making requires the consideration of negative impacts such as thermal shock and creep rupture due to SG depressurization and feeding into SGs using a portable pump, most subjects decided to implement SG injection by following the mitigation measures suggested by SAMG (e.g., limiting the injection flow rate for the first several minutes). Therefore, this strategy requires additional consideration of the mitigation measures to mitigate the negative impacts of the SG injection to recover the SG level, where the negative impacts may vary depending on the success or failure of the mitigation measures. In addition, communication with the EOF is necessary in real situations as this strategy is related to the release of radioactive material.
  - On the other hand, in Scenario-2, SAG-1 suggests to consider RCS depressurization as a mitigation measure in SAG-2 to reduce or eliminate the creep rupture caused by the pressure difference between the RCS and SG. However, in SAG-1, only one subject performed this action, while the other two subjects intended to decide after observing the effect of the SG injection.
  - In SAG-4 (Containment injection), half of the subjects were found to be reluctant to decide on containment spray, considering the negative impacts such as possible damage to the equipment inside the containment caused by the spray. They suggested that it is necessary to continuously monitor the status of both core cooling and containment conditions (e.g., pressure and temperature) at the same time to check whether the core is gradually deteriorated and the containment pressure is threatening the integrity of the containment.
  - Similar to SAG-4, the subjects in SAG-6 (Containment condition control) suggested that it is necessary to continuously monitor the status of both core cooling and containment conditions because the containment spray may cause damage to the equipment inside the containment. In addition, when there was a risk of exceeding the maximum water level of the containment after implementing the spray strategy using a portable pump, the subjects were found to have difficulty in deciding on whether to continue the spraying or not.

4.2. Time analysis of SAMGs from the SAMG TTX

The time required for each SAG was derived through the TTX experiment. The time data is the time required for the guidelines including information gathering, situation assessment, decision-making, instruction delivery, and effectiveness confirmation of each SAG excluding implementation activities using portable equipment on-site. Table 1 summarizes the time required for each SAG. The sigma (lognormal) value in the last column was calculated for use in estimating the distribution of time required applying lognormal distribution. 'DFC from Entry' indicates the time required from SAMG entry, through performing an initial status check, to the identification of SAG-1 entry using the DFC. Because SAG-6 has similar contents as SAG-4 and has already been evaluated in SAG-4, the time required for SAG-6 is relatively short.

As shown in Table 1, the time required varies by subjects according to their approach to the guidelines. After checking the values of plant variables at a point, some subjects ignored the reconfirmation of the same plant variables in the subsequent situations, while some subjects proceeded with reconfirmation of the variables at every situation. As seen in Table 1, because Subject-1 carefully read and evaluated the details of every step in the guidelines, he took relatively longer than the other subjects. For example, for judgement of potential negative impacts, he carefully checked every items of the necessary information, by hand calculation when necessary, to evaluate the feasibility and effectiveness of each mitigation measures.

4.3. Pairwise comparison of the relative complexity between evaluation rules for negative impacts

After the SAMG TTX experiment by five subjects, a quantitative pairwise comparison between the types of evaluation rules for judging negative impacts was conducted to ultimately derive human error probability of failure to correctly identify the plausible negative impacts. To do so, a survey was conducted after the experiment to obtain the relative complexity or difficulty of each rule to determine negative impacts, based on a pairwise comparison suggested by the analytic hierarchy process (AHP) technique [33].

4.3.1. Classification of evaluation rules for judging negative impacts

Review of the entire evaluations rules for judging negative impacts lead us to categorize the rules into two groups largely: (1) Text rule-

Table 1
Time required by each subject to perform each SAG (unit: minutes).

	Subject_1	Subject_2	Subject_3	Subject_4	Subject_5	Mean	SD	Sigma (Lognormal)
DFC from Entry	6.3	8.8	6.4	8.1	8.7	8.8	–	–
SAG-1	27.5	18.2	11.9	17.3	8.5	19	7.94	0.43
SAG-2			12.2	20.3	1.1	14	7.21	0.51
SAG-3	52.8	16.5	14.5	19.5	7.5	23	17.51	0.72
SAG-4	21.5	14.8	10.7	4.4	4.4	10.8	7.19	0.75
SAG-6	5.1	3.0	6.5	12.9	6.2	6.4	3.78	0.49

based judgment (TRBJ) that uses only prescribed text rules for judgment of negative impacts, and (2) computational aid-based judgment (CABJ) that uses computational aids such as figures or tables with or without text rules for judging negative impacts. From the complexity point of view, there are three types of TRBJ and four types of CABJ. The characteristics of each type are summarized as follows:

- TRBJ-1: Judgment of current state based on a single variable,
- TRBJ-2: Judgment of current state based on multiple variables,
- TRBJ-3: Judgment of current state and anticipated trends based on multiple variables,
- CABJ-1: Judgment of current state based on computational aids,
- CABJ-2: Judgment of current state based on computational aids and text rules,
- CABJ-3: Judgment of current state and anticipated trends based on computational aids,
- CABJ-4: Judgment of current state and anticipated trends based on computational aids and text rules.

Examples for some selected types of evaluations rules are given as follows.

An example of TRBJ-3 is the evaluation rule for judging the possibility of the SG tube creep rupture that may be caused by the initiation of SG depressurization for feeding into a low water level SG, which appears in SAG-1. The rule suggests to consider the negative impact based on the current status of the SG level and the RCS pressure as well as on the anticipated trend of SG pressure.

An example of CABJ-1 is the evaluation rule for judging the possibility of the containment severe challenge that may be caused by hydrogen combustion, which appears in SAG-6. The rule suggests to consider the possibility of the containment severe challenge based on the identification of current status of containment pressure and hydrogen concentration which are provided by computational aids.

An example of CABJ-3 is the evaluation rule for judging the possibility of the containment flooding due to the containment spray, which appears in SAG-4 and SAG-6. The rule suggests to consider the containment flooding based on the identification of current status of the containment water level via computational aids and the estimation of the required time to reach the maximum flooding level considering the current injection rate.

4.3.2. Quantitative evaluation of the relative complexity between the rules for negative impacts and estimation of associated HEPs

The relative complexity between the evaluation rules for judging negative impacts was compared systematically using the AHP pairwise comparison. Table 2 shows the results between the types of evaluation rules, provided by 5 subjects from the TTX participants. The comparison included a relative comparison between the types both within TRBJ and within CABJ as well, and a relative comparison between TRBJ-2, which is a representative of TRBJ, and CABJ-1, a representative CABJ. This relative comparison of the complexity makes the derivation of HEP for each of evaluation rules for failure of correctly identifying a negative impact, by multiplying an anchoring HEP for an evaluation rule by a relative weight. This study used TRBJ-2 for the anchoring HEP because TRBJ-2 is the most representative rule in SAMGs which can be used for effective comparison with other evaluation rules, as TRBJ-1 is judged to be too simple to be compared with other complicated rules such as computational aids.

The CBDT method, one of the EPRI HRA methods, was used for calculating the base HEP of TRBJ-2, with consideration of judgement error due to the rule complexity (i.e., logical rules such as AND, OR, or both) as well as an error of omission. The CBDT method consists of 8 decision trees. Each decision tree provides human error potential (probabilities) associated with specific human error mechanism, as follows: Pca: availability of information, Pcb: failure of attention, Pcc: misread/miscommunicate data, Pcd: information misleading, Pce: skip a step in procedure, Pcf: misinterpret Instructions, Pcg: misinterpret decision logic, and Pch: deliberate violation. Only an error of omission was considered for TRBJ-1 because of its simple rule. In addition to an initial error, the potential for error recovery was reflected with consideration

Table 2
Quantitative evaluation of the relative complexity between evaluation rules for negative impacts.

Subjects	Relative Weight within TRBJ			Relative Weight within CABJ				Relative Weight between TRBJ and CABJ	
	TRBJ-1	TRBJ-2	TRBJ-3	CABJ-1	CABJ-2	CABJ-3	CABJ-4	TRBJ-2	CABJ-1
Expert-1	0.103	0.257	0.640	0.072	0.196	0.196	0.536	0.333	0.667
Expert-2	0.103	0.257	0.640	0.096	0.131	0.293	0.481	0.75	0.25
Expert-3	0.116	0.199	0.685	0.077	0.199	0.199	0.524	0.25	0.75
Expert-4	0.089	0.216	0.695	0.074	0.105	0.320	0.502	0.667	0.333
Expert-5	0.069	0.277	0.653	0.086	0.183	0.204	0.527	0.167	0.833
Mean	0.096	0.241	0.663	0.081	0.163	0.242	0.514	0.433	0.567
Relative Weight based on TRBJ-2		1.000	2.747	1.307	2.628	3.912	8.296		
		1	**3**	**1**	**3**	**4**	**8**		

Table 3
HEPs for judgement errors associated with negative impacts.

Evaluation Rules for Judging Negative Impacts	Basic HEP (BHEP; No Recovery)	Basis for BHEP	Recovered BHEP (HD; BHEPx0.5)
TRBJ-1: Judgment of current state based on a single variable	3.0E-03	CBDT Pce (c)[a]	1.5E-03
TRBJ-2: Judgment of current state based on multiple variables	3.4E-02	CBDT Pce (c) + Pcg (h)	1.7E-02
TRBJ-3: Judgment of current state and anticipated trends based on multiple variables	9.6E-02	CBDT Pce (c) + 3[a]Pcg (h)	4.8E-02
CABJ-1: Judgment of current state based on computational aids	3.4E-02	CBDT Pce (c) + Pcg (h)	1.7E-02
CABJ-2: Judgment of current state based on computational aids and text rules	9.6E-02	CBDT Pce (c) + 3[a]Pcg (h)	4.8E-02
CABJ-3: Judgment of current state and anticipated trends based on computational aids	1.3E-01	CBDT Pce (c) + 4[a]Pcg (h)	6.4E-02
CABJ-4: Judgment of current state and anticipated trends based on computational aids and text rules	2.5E-01	CBDT Pce (c) + 8[a]Pcg (h)	1.3E-01

[a] In the CBDT Pce Tree, the last heading, 'Placekeeping Aids', does not actually exist in the SAMGs, but it is assumed that TSC will be checking each item of negative impacts in a careful way considering importance of the potential for negative impacts.

of the possibility of checking by the other TSC members. According to THERP [14], the level of dependency within an operating team is estimated to be a 'moderate (MD)' under a normal operating condition, but this may increase under high stress conditions. It is also stated that an operating team may have a high dependency (HD) level under situations where there is a high authority person within an organization or there is high confidence between members, or when faced in an emergency response situation. Considering these factors, our method applied HD for a dependency between an initial judgment error and an error of recovery, which results in 0.5 for a recovery failure probability (RFP) that redundant TSC members fail to detect and recover an initial judgment error of the strategy evaluator.

The HEP values associated with judgment errors for negative impacts are provided in Table 3, and these HEPs are used in the decision tree-based probability evaluation method in Step 3: SAM Strategy Decision-Making Likelihood Assessment of the SAM-L2HRA method in Section 4.

5. Concluding remarks

As a preliminary step to develop a human reliability analysis method for SAMG-based tasks, the basic structure of SAMGs was first identified. Then, the critical steps of each SAG and individual SAM strategy were delineated along with the likelihood of human errors and decision-making associated with each strategy. Based on the identified task characteristics and context of SAMGs, an approach to Level 2 HRA based on TSC SAMG is outlined, i.e., SAM-L2HRA. In addition, SAMG-TTX experiments have been conducted to acquire more practical information such as usage of SAMGs, time required for completion of individual SAGs, and post-experiment questionnaire surveys from the participants.

Through the TTX experiments and participants' survey and interviews, we drew following findings:

(1) While there are common ways of conducting SAMGs through the DFC and SAGs, individual SAGs (or strategies) of SAMGs have its own set of task characteristics. These characteristics need to be reflected when applying the SAM-L2HRA method, which will be introduced in the second paper, to an actual accident scenario.
(2) A set of time required for completing individual SAGs is obtained. The time required for each SAG includes several critical steps such as identifying system status, making strategy decisions including evaluation of negative impacts, and verifying the effectiveness and potential negative impacts of the strategy after implementation. This time information can be utilized when applying the time-based reliability estimation part of the SAM-L2HRA method.
(3) We categorized the types of negative impact judgment rules related to SAMG strategy decision-making and derived error probability values for each type of judgment rule. These probabilities will be utilized in the development of DTA for estimating decision probability of strategy implementation in the second paper.

Based on the above findings from this study, the SAM-L2HRA method will be presented in the second paper.

CRediT authorship contribution statement

Jaewhan Kim: Writing – original draft, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Jaehyun Cho:** Writing – review & editing, Investigation, Data curation. **Sooyong Park:** Formal analysis, Data curation. **Jinkyun Park:** Writing – review & editing, Project administration, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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