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Original Article

Development of a human reliability analysis (HRA) guide for qualitative analysis with emphasis on narratives and models for tasks in extreme conditions

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A B S T R A C T

Probabilistic risk assessment (PRA) has improved its elemental technologies used for assessing external events since the Fukushima Daiichi Nuclear Power Station Accident in 2011. HRA needs to be improved for analyzing tasks performed under extreme conditions (e.g., different actors responding to external events or performing operations using portable mitigation equipment). To make these improvements, it is essential to understand plant-specific and scenario-specific conditions that affect human performance.

The Nuclear Risk Research Center (NRRC) of the Central Research Institute of Electric Power Industry (CRIEPI) has developed an HRA guide that compiles qualitative analysis methods for collecting plant-specific and scenario-specific conditions that affect human performance into "narratives," reflecting the latest research trends, and models for analysis of tasks under extreme conditions.

1. Background

In probabilistic risk assessment (PRA) used for safety improvement assessment of nuclear power plants, various latest findings are reflected, and improvement of assessment methods and refinement of data have been made. In a PRA, when an operator or worker performs a task, an event in which "the purpose of the task cannot be achieved" or "the task fails to be completed" should be considered as human failure events (HFE). HRA consists of qualitative analysis which organizes information such as the effects of failure, and quantification methods which creates human error probabilities (HEPs) based on data obtained from qualitative analysis.

A variety of quantification methods have been developed for HRA in various countries since the THERP (Technique for Human Error Rate Prediction) method, which model errors in the execution of procedural steps, was introduced into PRA by the NRC in its "Human Reliability Analysis Handbook [1]" in 1983. However, human behavior is not a simple accidental occurrence of errors. the results vary greatly according to various influencing factors, such as the effect of situational factors on cognition and behavior and the stress imposed by time pressure as well as the characteristics of individuals. Therefore, results also differ depending on the quantification method.

In order to conduct a more realistic HRA, the importance has been emphasized in recent years of the process of qualitative analysis that collects plant-specific and scenario-specific situations affecting human performance in accident scenarios.

Nuclear Risk Research Center (NRRC) of the Central Research Institute of Electric Power Industry (CRIEPI) felt it was important to establish a qualitative analysis method in order to stabilize HRA evaluation results, so the NRRC HRA guide [2] detailing HRA narrative collection and analysis methods was developed.

2. Need for HRA advancement in Japan

Japanese NPPs are promoting advancement of PRA models for use in "voluntary safety improvement evaluations" and for Reactor Oversight Process (ROP) program of the new regulatory inspection system.

The voluntary safety improvement assessments by utilities are required to be submitted within 6 months after a periodic

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Table 1
Table of contents of the HRA Guide for Qualitative Analysis with Emphasis on Narratives.

Main text	【Appendix】 HRA models and know-how for tasks under extreme conditions
1.Overview of the Guide	Appendix A. Cognition Task
1.1 Scope of Application	(i) How to Select Quantification Methods
1.2 Structure of the Guide	(ii) Determining the Standard Error "σ" of the Lognormal Distribution
2. Relation with AESJ Standards and HRA Team Formation	Appendix B. Execution Task: THERP method
2.1 Relation with AESJ Standards	(i) Procedures for Calculating HEPs of Execution Tasks
2.2 HRA Team Formation	(ii) Example of Collecting/Compiling Narrative of Execution Tasks
3. Concept of the Qualitative Analysis with Emphasis on Narratives	(iii) Example of Rephrasing the Table of Estimated HEPs Based on the Japanese Situation (iv) Example of Rephrasing the Table of Estimate HEP Based on the On-Site Operation/Work
3.1 Necessity of Narratives	(v) Example of Evaluation Methods for Stress Levels
3.2 What are "Qualitative Analyses with Emphasis on Narratives?"	(vi) Evaluation Methods for Dependence and Error Recovery Effects (vii) Evaluation Method for Learning Effects of Repetitive Work
3.3 Format for Organizing Narratives	
4. Collecting and Compiling Narrative	
4.1 Task Structure Information	
4.2 Time Progression Information	
4.3 Performance Shaping Factors (PSF) Information	
5. Idea of HRA under extreme condition	**Appendix C. Reception and Transmission of Command, Report, and Note**
5.1 New Method to Organize Task Structure Information and Time Progression Information	(i) Evaluation example of reception (ii) Evaluation example of transmission
5.2 Setting Status and Environmental Conditions	**【Evaluation examples】 HRA models and know-how used** I. F &B operation of the PWR
5.3 Deviation Scenarios	{Application example for Appendix A-(i), B-(i), (ii), (iii), (v), and (vi)}
5.4 Failures of Annunciators/ Instrumentation	II. Example of Evaluation: Use of Mobile Equipment {Application example for Appendix all items}
5.5 Resilience	III. Example of Special Evaluation [Watertight Door Inadvertently Left Open in Evacuation from the Building]
5.6 Safety Culture and Organizational Factors	{Application example for Appendix A-(i), B-(iv) and (v)}

shutdown inspection has been conducted at the end of a nuclear plant 13-month operation.

The following is to be reported.

- ➢ Compliance with safety regulations
- ➢ Voluntary measures for improving safety
- ➢ Investigation and analysis of such measures
  - ✓ Compliance with industry standards, and IAEA safety standards (SSG -25, etc.)
  - ✓ Internal Event PRA (Level 1, Level 2)
  - ✓ External Event PRA (Level 1, Level 2)
  - ✓ Safety margin evaluation (stress test)
- ➢ Comprehensive evaluation

Of the above, the items included in an Internal Event PRA and External Event PRA are aimed, as much as possible, at reflecting severe accident countermeasures in the PRA model and introducing the latest knowledge with the goal of producing the best PRA evaluation. The immediate targets of External Event PRA are the seismic events and tsunami. In these PRAs, human error events (HFE) occur in different situations and have a significant impact on core damage frequency (CDF).

The implementation of HRA in Japan was based solely on the results of an analysis of Internal Event Level 1 PRA which was conducted by PRA analysts using the THERP method. However, it was necessary to conduct Level 2 PRA evaluations for External Event PRA (particularly for seismic events and tsunami) as soon as possible so that the data may be used for voluntary safety improvement evaluations. Each nuclear power plant in Japan decided to adopt the EPRI HRA Calculator ® as the quantification method. As a result, CBDTM and HCR/ORE were used as evaluation methods employing a more detailed decision tree based on evaluation using the THERP time reliability curve for cognition failure. On the other hand, execution failure is evaluated using THERP in the HRA Calculator ®.

As a result, the following issues and considerations emerged with respect to HRA in Japan.

A) In order to reduce variability in results among HRA assessors, a qualitative analysis process for generating input data as well as implementation methods would be consolidated into an HRA guide.
B) Current quantification tools are insufficient for HRA required for External Event PRA and Level 2 PRA, so consideration would be given to the development of quantification methods.

NRRC began developing an HRA guide to address these issues in 2016. The qualitative analysis concept presented in NUREG -2199 [3] was adopted as the method for conducting qualitative analysis to address A). As for B), we decided to examine the PRA case in a pilot study of actual seismic PRA and tsunami PRA.

3. Concept of qualitative analysis emphasizing the narrative

In the Halden Reactor Project, multiple HRA groups calculated HEPs for tasks necessary to handle an internal event and differences in HRA results were discussed among those groups (NUREG-2127) [4]. The results showed that the HEPs differed by two to three orders of magnitude, even for the same task, depending upon the quantification method used as well as among groups using the same method. This suggested that it is necessary in HRA to identify a realistic context for qualitative analyses, which thus points out the importance of developing a narrative representing how tasks in an accident scenario are affected by various factors, such as plant conditions (speed of

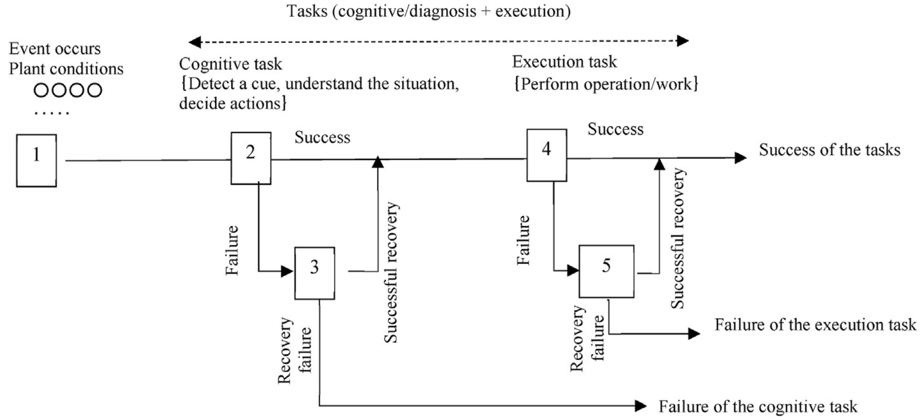

Fig. 1. CRD (Crew Response Diagram) [2] (Modified Figs. 4–3 of NUREG-2199 [3]).

accident progression, equipment availability, etc.), operational procedures including cognition, and human-machine interfaces. As a result of this suggestion, guidelines were recently published in the US detailing methods for developing narratives for qualitative analysis independent of HRA team experience and skill [3,5,6]. In referencing these documents, NRRC follows the concept outlined in NUREG-2199 [3] for the qualitative analysis process and creates an HRA guide for description, which is easy for Japanese utility users to understand.

In the HRA guide, the term "narrative" is defined as information concerning the background of human performance (e.g. physical environment and temporal restrictions) including cognition and diagnosis (e.g. understanding plant status, determining what to do).

In order to stipulate more specifically the concept of the qualitative analysis in NUREG-2199 [3], the NRRC defined narrative as comprising the following three pieces of information.

- **Task structure information:** Task structure information is defined in diagramming the process from cue occurrence, which prompts a realization of the need for human action tasks, through cognition/diagnosis and execution as well as recovery in cases of error.
- **Time progression information:** Time progression information is the entire time starting from initiating event occurrence through the time allowing the task to be performed and is understood to be the time delay until the cue is noticed, cognitive/diagnosis time, execution time, and the margin of time based upon the result of these.
- **Performance shaping factor (PSF) information:** An assessment is made of content relating to the understanding of factors, such as plant-specific and scenario-specific situations, that affect the failure probability of each act of cognition/diagnosis or task execution, as well as the procedure manuals, etc., and these are organized in accordance with the quantification method.

The following sections describe the three types of narrative information collection.

4. HRA guide for qualitative analysis with emphasis on narratives

Table 1 shows the principal headings in the table of contents of the HRA guide on narrative for qualitative analysis, which the NRRC created. The NRRC examined the application of HRA guide to HRA under extreme conditions. As an example, a trial application was carried out with the operation of mobile equipment, but it was found that there were several problems with quantification. An expanded method of quantification to address these issues is summarized in the appendix of the HRA guide as an example of a proposal, and an evaluation example is prepared as an appendix.

The following provides an outline of information which needs to be collected to develop a narrative.

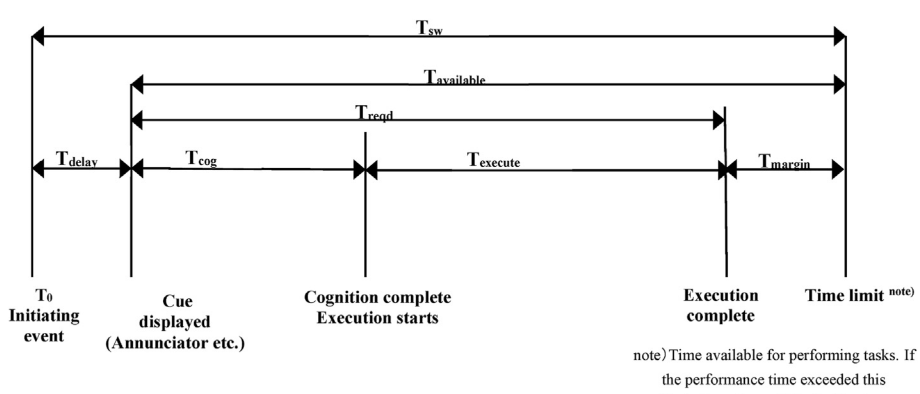

Fig. 2. Time progression diagram [2] (Modified Figs. 3–1 of NUREG-2199 [3]).

Table 2
Examples of "major PSFs to be considered in responding to accidents [2].

PSF	Type of tasks that should mainly be taken into account for each PSF	
	Cognitive task	Execution task
Applicability and suitability of training and experience	○	○
Suitability of relevant procedures and administrative controls	○	○
Availability and clarity of instrumentation (cues)	○	
Time available and time required to complete action	○	○
Complexity of required diagnosis and response	○	○
Workload, time pressure, stress	○	○
Team/crew dynamics and crew characteristics	○	○
Available staffing and resources	○	○
Ergonomic quality of human-system interface (HSI)	○	○
Environment in which the action needs to be performed		○
Accessibility and operability of equipment to be manipulated		○
Necessity for special tools		○
Communication (strategy and coordination) as well as whether one can be easily heard		○
Special fitness needs		○
Consideration of "realistic" accident sequence diversions and deviations	○	

4.1. Outline of narrative information

In order to substantiate the narrative described in Chapter III, the NRRC's HRA guide stipulates more concretely the following three types of narrative information so that the information necessary may be collected for HRA about the target accident scenario and HFE. Specific details are given below.

4.1.1. Task structure information

NUREG -2199 [3] recommends the CRD (Crew Response Diagram) (Fig. 1) to describe the process from the occurrence of an opportunity to become aware of the need for the task being evaluated (Queues such as alarms and indication values) to cognition/diagnosis and execution.

Therefore, information on [1] plant prerequisites [2], indications [3], successful task processes, and [4] opportunities for error recovery is organized based on a review of the accident scenarios and procedures covered. Task structure information is defined in diagramming the process from cue occurrence, which prompts a realization of the need for human action tasks, through cognition/diagnosis and execution as well as recovery in cases of error (Fig. 1). CRD information may enhance a common understanding among participants when conducting an HRA team discussion or interview. During this process, CRD corrections and refinements are made and a better awareness is achieved based on realistic situations.

4.1.2. Time progression information

Time progression information is aggregated using the timeline illustration diagram as given in the NRC Fire HRA Guidelines (NUREG-1921 [5]) and NUREG-2199 [3]. The diagram of the timeline is shown in Fig. 2. This figure is also used in ERPI's HRA Calculator®, a quantification tool, and is commonly used to organize the time evolution in HFEs.

Time information such as the whole scenario time (system time window) (T_{sw}) during which the task to be evaluated must be completed, and the delay time until a cue occurs (T_{delay}) can be obtained from physical analyses, such as thermal-hydraulic analysis.

The time involved in cognition (T_{cog}) and the time required for execution ($T_{execute}$) are determined in realistic time as measured by training observation or by the result of the interviews from crew.

In the case of tasks performed under extreme conditions such as in External Event PRAs and responses using mobile equipment, the actors of "cognitive tasks" (e.g. general manager and chief manager at Technical Support Center (TSC)) and that of "execution tasks"

Table 3
Example of items and formats for collecting and compiling task structure information [2].

Items	Example of survey contents	a. Plant information	b. On-site surveys, training observations	c. Interviews with relevant personnel
Plant conditions	**Operating state of equipment, annunciators etc.**	Plant condition information which is found in accident scenarios and procedures.	–	–
Cues	**Cues (annunciators, indications of indicators, environmental state) to make personnel detect the occurrence of an event, possibility of checking, etc.**	Cue information which is found in procedures.	–	How personnel can detect the occurrence of an event and describe it.
Success path	**Location for performing, actors, procedures, starting conditions for each cognitive task and execution task, etc.**	Success path information which is found in procedures (step corresponding to each task).	Success path information which should be added to the tasks which are identified using the procedures.	Additional tasks besides those identified using the procedures
Opportunity for error recovery	**Personnel who recover each cognitive task and execution task and opportunities for recovery**	Opportunities for error recovery which are found in procedures.	Opportunities which are found.	Potential personnel who notice a failure such as personnel who themselves have failed to carry out the task, personnel in the same shift, shift supervisor/manager, and cues to notice the failure.

Table 4
Example of items and formats for collecting PSF information [2].

PSF [7]	Example of survey content	a. Plant information	b. On-site surveys, training observations	c. Interview with relevant personnel
Applicability and suitability of training/experience	➢ **State of training implementation under conditions similar to applicable accident scenarios**	–	–	➢ State of training implementation under conditions similar to an applicable accident scenario.
Suitability of relevant procedures and administrative controls	➢ **Need to refer to multiple procedures** ➢ **Potential negative effects when complying with procedures** ➢ **Ease of understanding intent of description in procedures** ➢ **Completeness of description in procedures** ➢ **Use of procedures**	Results of considering procedure content.	–	➢ Whether multiple procedures need to be used to respond to an applicable scenario. ➢ Whether any undesirable results may happen if procedures are complied with literally ➢ Whether procedures are written in a way that the intent is clearly understood. ➢ Whether all information necessary for diagnosis is described in procedures. ➢ Whether personnel perform operations while checking the procedures.
Availability and clarity of instrumentation (cues)	➢ **Operational state of annunciators/indicators as cues** ➢ **State of annunciators/indicators (ambiguous, unclear)**	–	Describe the state of annunciators/ indicators.	➢ Whether annunciators/indicators as cues function correctly ➢ Whether indications of indicators are clear.
Time available and time required to complete the action	**Time Progression Information in Section *V.A.2.* ($T_{s\ w}$, T_{delay}, T_{cog}, $T_{execute}$, etc.)**	Results of event progression analyses and those which are found in accident scenarios.	The measured time until cue occurs, from a cue occurring to execution tasks determined, and to perform execution tasks.	The analyst asks the crew how many minutes, on average, it takes to complete the task, minimum, maximum and average, to complete the task.
Complexity of required diagnosis and response	**Complexity of tasks**	Results of considering procedure content. .	Personnel actions.	Whether an applicable task is considered as a complex task such as requiring adjustment operation while checking plant parameters.
Workload, time pressure, stress	➢ **Interruptions** ➢ **Balance between number of operators and of tasks** **Expected plant response**	Results of considering procedure content.	Personnel actions.	➢ Whether personnel perform an applicable task with interruptions ➢ Whether the number of tasks is larger than the number of personnel for handling them. Whether the plant will go into an undesirable state during performance of an applicable task.
Team/crew dynamics and crew characteristics	➢ **Mix of knowledge level and experience** **Attitude toward asking and correcting, uniting power**	–	Personnel actions.	➢ Whether personnel with different knowledge levels and experiences work together. Whether personnel practice checking and pointing out one another's action, regardless of whether it is described in procedures.
Available staffing and resources	**Number of personnel**	Results of considering procedure content.	Number of personnel.	How many personnel are involved in an applicable task?
Ergonomic quality of human-system interface	➢ **Ease of locating instrumentation** **Readability of instrumentation**	–	Arrangement, configuration, monitoring and checking state of control panel and instrumentation.	➢ Whether the layout, segmentation and labelling of the control panel allow personnel to locate required instrumentation. Whether instrumentation is easily readable.

Environment in which the action needs to be performed	**Environment in which a task is performed (lighting, temperature/ humidity, radiation dose)**	Results of considering content/ drawings in procedures.	Task environment.	Whether environment (lighting, temperature/humidity, radiation dose) in which a task is performed is severe.
Accessibility and operability of equipment to be manipulated	➢ **Accessibility to the location for executing task** **Operability of equipment used in task execution**	–	Accessibility, layout and shape of operation tools and state of operation.	➢ Whether access to a location to perform an applicable task is severe. Whether operability of equipment used in an applicable task is different from that of standard equipment.
Necessity for special tools	**Need for keys, ladders, hoses, etc.**	Results of considering procedure content.	Necessity and usage of special tools.	Whether special tools (keys, ladders, hoses, **etc.**) are required for execution of applicable task.
Communications (strategy and coordination) as well as whether one can be easily heard	➢ **Degree of communication closeness** **State of communication equipment**	–	State of communication.	➢ Whether personnel maintain appropriate communication so that they can resolve any miscommunications which may likely arise in relation to an applicable execution task. Whether communication equipment between the workplace and the control room functions correctly.
Special fitness needs	**Special state that may affect fitness (use of heavy and awkward tools and equipment, movement of hoses, climbing)**	Results of considering procedure content.	Existence of a special state.	Whether there are any special conditions that may affect personnel's fitness for execution of an applicable task.
Consideration of "realistic" accident sequence diversions and deviations	➢ **Assumed state of annunciators** **State of annunciators/ indicators(incorrect/inconsistent)**	–	–	➢ Whether all cues necessary for an applicable task are in the state described in the procedures. Whether indicator indications are correct and any inconsistencies present between indicators.

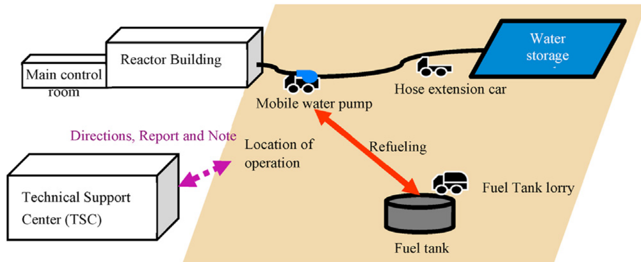

Fig. 3. Overview of the emergency water injection task cued by deficiency of injection functions [2].

(e.g., emergency operations personnel at the field) may differ, or multiple "execution tasks" may be performed at different locations once a directive is issued.

In an emergency situation, fieldworker has limited information available. Therefore, the execution of fieldworker is not done by only their cognition, but by the close cooperation with TSC. TSC is responsible for recognizing cue and making decisions for mitigation measures, and fieldworkers can follow the instructions to prevent confusion during mitigation operations. In such a case, because the narrative differs depending on the actors, multiple timelines for each actor are created without assembling everything into one timeline. Also, tasks related to transmission/receipt (directives and reports of their completion via communication equipment such as phones) of information between the actors is evaluated and their correlation illustrated. This multiple task timeline is used in "the emergency water injection task cued by the information of deficiency of injection functions" in the embodiment described in Section V. An example of a multiple task timeline diagram is shown in Fig. 5 in Section V.

4.1.3. Performance shaping factor (PSF) information

Depending on the performance shaping factors (PSF) used in the quantification method, information is collected through analysis of procedures, estimation of plant information, and interviews with operators/instructors. Since the PSF items and content collected here depend on the quantification methods, it is important for HRA teams to understand and grasp the actual situation by conducting field confirmation, training observation, and interviews as widely

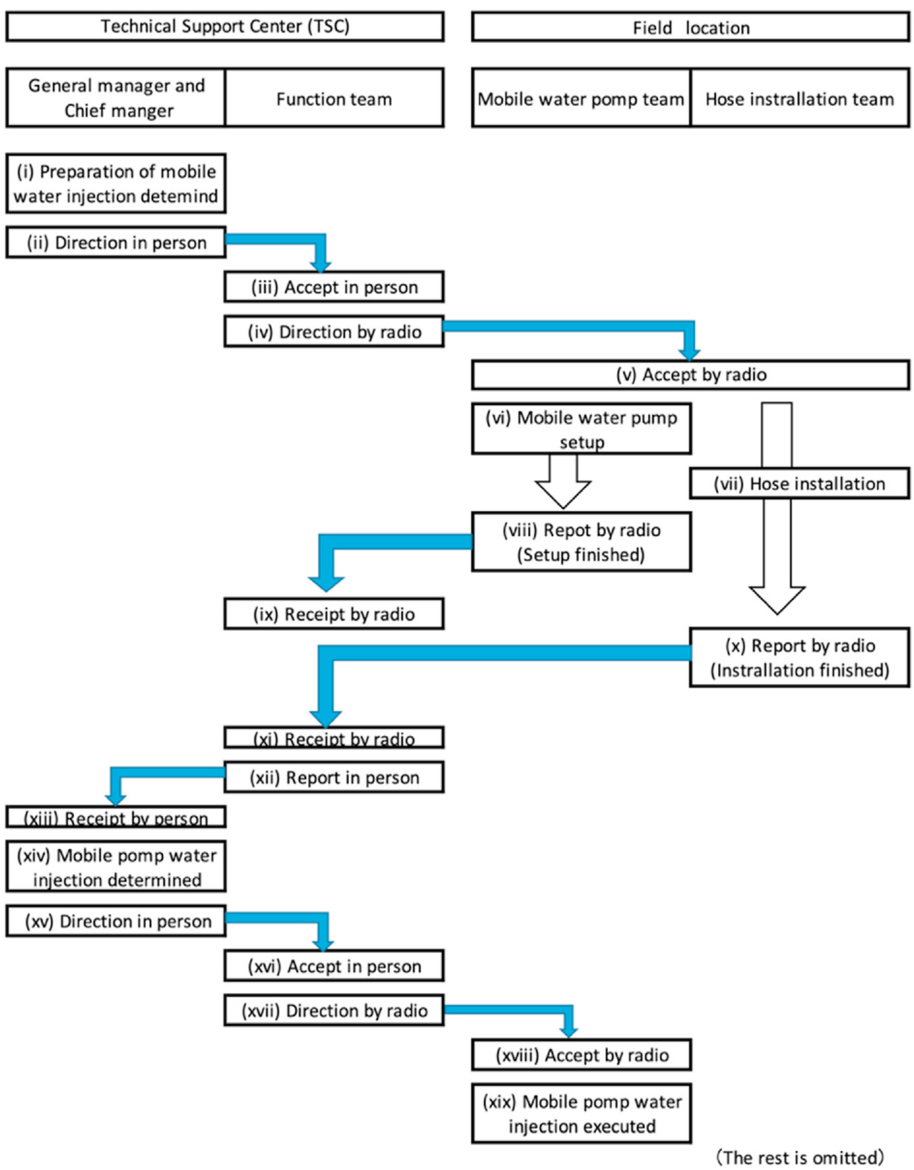

Fig. 4. Task flow of the emergency water injection task cued by deficiency of injection functions [2].

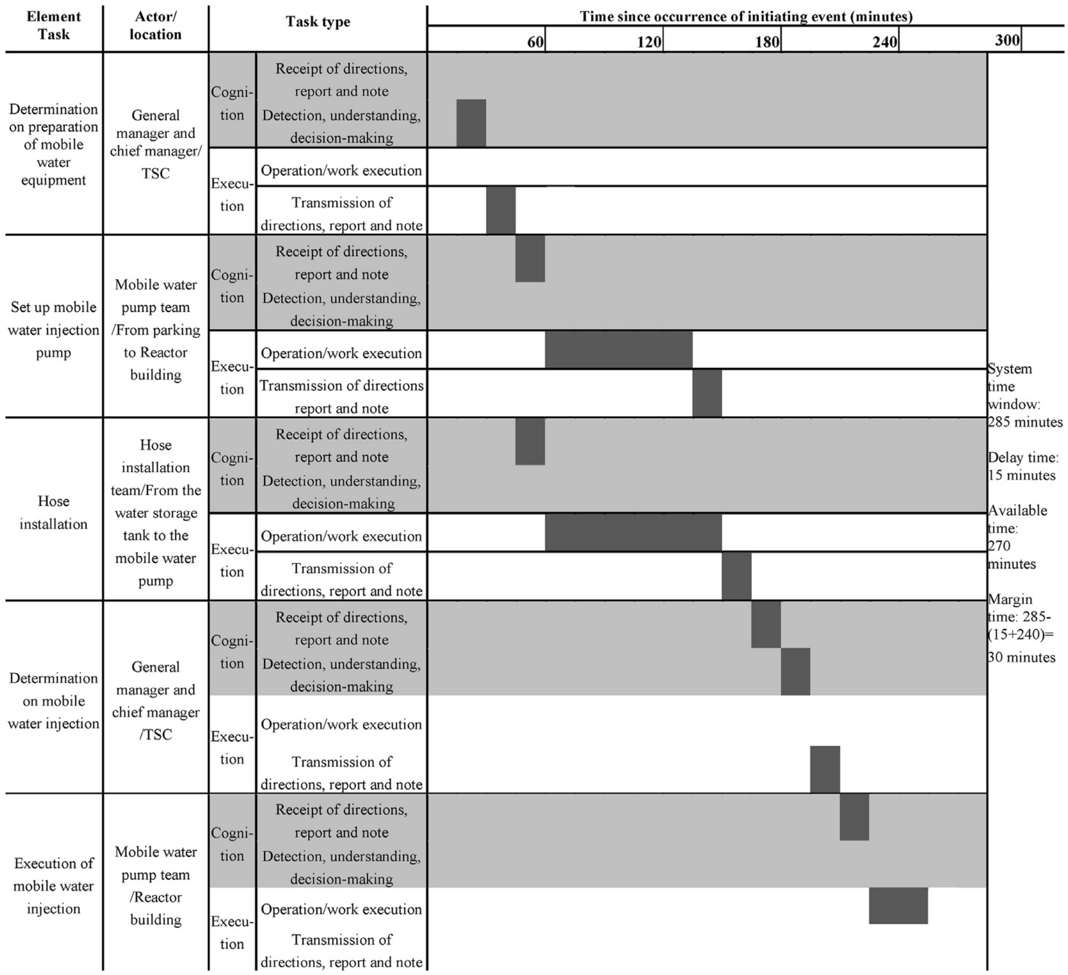

Fig. 5. Example of multiple task timeline diagram [2].

as possible assuming multiple methods. NUREG-1792 [6] shows good practices in HRA and defines factors such as training and written procedures as "major PSFs to be considered in responding to accidents". In addition, there are PSFs to be considered in the "cognitive tasks" or the "execution tasks" and PSFs to be considered in both tasks; therefore, it is essential to collect and compile information on PSFs according to the task types (i.e. cognitive tasks and/or execution task). Table 2 shows examples of "major PSFs to be considered in responding to accidents" [6] and their relation to "cognitive tasks" and "execution tasks" respectively. PSFs vary depending on quantification methods used and thus the narratives must be developed based on those PSFs.

4.2. Developing narrative information

In the NRRC's HRA guide, a standard format is created for developing narrative information so that it will be in a document format that clearly shows the basis for creating input data for HRA quantification tools. NRRC has attached the "Collection Format for Narrative Development" as an appendix to the HRA guide [2]. Table 3 shows the task structure information collection format, and Table 4 shows the PSF information format. The information for developing a narrative can be collected in three formats: (a) plant information (physical analysis results relating to accident scenarios, relevant procedures, etc.), (b) on-site surveys (including plant walk-downs) and training observation, and (c) interviews with relevant personnel (including talks-through).

5. Application example: the emergency water injection task cued by the information of deficiency of injection functions

The NRRC's HRA guide Appendix "Evaluation examples (HRA models and know-how used)" describes the qualitative analysis and the use of the extended quantification method of our HRA guide. This section provides an overview of " II. Example of Evaluation: Use of Mobile Equipment".

The emergency water injection task cued by the information of deficiency of injection functions primarily consists of executing some mobile water injection pump and refueling for the pump to continue the operation.

Time limits are: Starting water injection by portable pumps: time for loss of water in a tank of the reactor building. Refueling by a tank lorry for continuous operation: time for loss of fuel in a fuel tank of a mobile pump. (After the 2nd time, the time period between full of fuel and loss of half fuel is used.)

Fig. 3 shows an overview of the emergency water injection task cued by deficiency of injection functions, and Fig. 4 shows task flow.

➢ Timeline

Table 5
HEP evaluation example [2].

Task Flow and Evaluation Method Example	HEP
(i) TSC determines to prepare mobile equipment. (Evaluated by CBDT method)	5.00×10^{-4}
(iv) TSC directs the determination to operation teams by radio. "Transmission of Directions, Report and Note" is evaluated as the sum of "Forgetting to transmit" and "Error transmission" probabilities, in accordance with Appendix C-(ii) [2]. In this case, it is assumed to have been evaluated as follows. ➢ " Forgetting to transmit": 1.40×10^{-4} (Evaluated by a decision tree based on Crew Failure Mode (CFM) "E−3: Failure to start execution" of IDHEAS [3]) ➢ " Error transmission": Partial omission of information (partial misstatement): 4.84×10^{-3} Transmission of incorrect information (misstatement): 4.84×10^{-3} (Evaluated by THERP [1] Table 20-5 item 1)	9.82×10^{-3}
(v) Operation teams accept the direction by radio. "Receipt of Directions, Report and Note" is evaluated in accordance with Appendix C-(i) [2]. (Evaluated by a decision tree based on CFM "SA-3: Critical Data Misperceived" of IDHEAS [3].)	1.30×10^{-4}
(vi) the mobile water pump team prepares the mobile water pump. (Evaluated by THERP [1] method)	2.50×10^{-4}
(vii)the hose installation team extends a hose. Not evaluated due to an easy simple task:	0
(viii) The mobile water pump team reports the finish of the preparation to the TSC by radio (Same evaluation method as task (iv))	9.82×10^{-3}
(ix) The TSC receives the report from the mobile water pump team by radio (Same evaluation method as task (v))	1.30×10^{-4}
(xiv) The TSC determines to execute the mobile water injection. (Evaluated by CBDT method)	5.00×10^{-4}
(xvii) The TSC directs the determination to the operation teams by radio. Direction to execute is very simple and the HEP is only considered for "forgetting to transmit". (Evaluated by a decision tree based on CFM "E−3: Failure to start execution" of IDHEAS [3])	1.40×10^{-4}
(xviii) The mobile water pump team accepts the direction by radio. (Same evaluation method as task(v))	1.30×10^{-4}
(xix) The mobile water pump team execute the mobile water injection. (Evaluated by THERP [1] method)	1.50×10^{-4}

The new multiple time windows are developed. Although a task of mobile water injection consists of multiple elemental tasks such as mobile water injection pump set-up, hose installation, and water injection executed, they are conducted in series and time limits of each elemental task are not determined by event progression analyses. Therefore, it is assumed that their time windows are the same, in spite of calculating the HEP for each elemental task. The multiple task timeline for this example is shown in Fig. 5.

The execution of field workers is not done by only their cognition, but by the close cooperation with TSC. For this reason, regarding the cognition of field workers, "Receipt of directions, report, and note" by the instruction from TSC was set in the cognition process. TSC has set "detection, understanding and decision-making" in the cognitive process to recognize cue based on plant information and field information and make decisions.

If the field worker recognizes another cue, then the scenario needs to be modified to add successful contact and a new decision-making process at the TSC.

➢ Quantitative Evaluation (HEP calculation)

The HEP for each elemental task should be calculated based on narratives and quantification methods recommended by HRA guide [2] (evaluation of learning effects of repetitive work should be performed using Appendix B-(vii) in HRA guide [2], as necessary). And the sum of each HEP should be regarded as the HEP of the whole task. Table 5 shows an evaluation example of the flow described in Fig. 5. This assumes a situation in which there is no debris in the field and thus mobile equipment is immediately set up without clearing debris.

6. Discussion

The NRRC HRA guide was developed primarily to improve the systematic implementation of qualitative analysis.

The three forms of narrative information provide an important basis for HRA input data and improve explanatory properties. In addition, when examining variations in scenario assumptions, it is easier to identify supplementary information to supplement the interviews because they are organized with narrative information. On the other hand, this approach has the disadvantage that the crew's time and amount of work required for interviews are not small. Therefore, it is necessary to identify the duplicate contents in the past crew interviews and reduce the number of questions as much as possible to improve efficiency.

In the application example of Chapter V, the understanding of the interaction between the teams was deepened by organizing the task flow and the multiple timelines. It was able to obtain detailed information such as the reason for the time limit for fieldworkers.

However, when applied to HRA under extreme conditions, some extensions to the quantification methods are also needed. The evaluation examples in Section V use the THERP methodology for execution failure. Because the HEP table in THERP covers human error actions that occur within the MCR of internal event level 1PRA, so, it does not describe the installation and operation of mobile equipment. For this reason, the HRA guide [2] describes how to rephrase the table of estimate HEP for these human actions in Appendix B (iii), (iv). But, it will be necessary to reassess these HEPs using domestic HRA data collection by training, or expert judgment panels. Furthermore, the results of the HRA data collection should be used to advance research on specific PSFs.

In order to improve HFE model of long-time and repetitive field actions, Appendix B (vi) describes the dependencies between THERP task steps and Appendix B (vii) describes the learning effect of repetitive work. Establishing the rules for these concepts is very important.

For future research at NRRC, it is necessary to start domestic data collection of HRA and conduct research on new quantification methods focusing on cognitive function.

7. Conclusions

In the HRA guide, CRIEPI's NRRC compiled a qualitative analysis method that collects and aggregates in a "narrative" format plant-specific and scenario-specific situations that affect human performance. Applying the qualitative analysis concepts of NUREG-2199 [3], the NRRC's HRA guide provided a systematic method of organizing the narrative format in the three steps (1) Task Structure Information, 2) Time Progression Information, 3) Performance Shaping Factors (PSF) Information).

The application evaluation example of HRA of the portable equipment was provided to deepen the understanding. The HRA guide is available in Japanese. In the future, revisions and additions will be made to reflect examples of operators' implementation.

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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References

[1] Alan D. Swain, et al., US Nuclear Regulatory Committee (NRC), Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications, NUREG/CR-1278, Final Report, US NRC, August 1983.
[2] Kirimoto Yukihiro, et al., The Human Reliability Analysis (HRA) Guide with Emphasis on Narratives (2018) - Development of Qualitative Analysis Methods and Analysis Models for Tasks on Extreme Conditions, CRIEPI Research Report O18011, CRIEPI, 2019 (in Japanese).
[3] Jing Xing, et al.. An Integrated Human Event Analysis System (IDHEAS) for Nuclear Power Plant Internal Events At-Power Application vol. 1, US NRC, March 2017. NUREG-2199.
[4] John Forester, et al., The International HRA Empirical Study : Lessons Learned from Comparing HRA Methods Predictions to HAMMLAB Simulator Data, NUREG-2127, US NRC, August 2014.
[5] Jeff Julius, et al., EPRI/NRC-RES "Fire Human Reliability Analysis Guidelines", NUREG-1921 (EPRI 1023001), Final Report, US NRC, July 2012. Final Report.
[6] Alan Kolaczkowski, et al., Good Practices for Implementing Human Reliability Analysis (HRA), NUREG-1792, US NRC, April 2005. Final report.
[7] Advisory Committee on Reactor Safeguards (ACRS), John W. Stetkar, Human Reliability Analysis Models, ML14134A328, US NRC, May 14, 2014.