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A classification scheme of erroneous behaviors for human error probability estimations based on simulator data

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ABSTRACT

Because it has been indicated that empirical data supporting the estimates used in human reliability analysis (HRA) is insufficient, several databases have been constructed recently. To generate quantitative estimates from human reliability data, it is important to appropriately sort the erroneous behaviors found in the reliability data. Therefore, this paper proposes a scheme to classify the erroneous behaviors identified by the HuREX (Human Reliability data Extraction) framework through a review of the relevant literature. A case study of the human error probability (HEP) calculations is conducted to verify that the proposed scheme can be successfully implemented for the categorization of the erroneous behaviors and to assess whether the scheme is useful for the HEP quantification purposes. Although continuously accumulating and analyzing simulator data is desirable to secure more reliable HEPs, the resulting HEPs were insightful in several important ways with regard to human reliability in off-normal conditions. From the findings of the literature review and the case study, the potential and limitations of the proposed method are discussed.

1. Introduction

The reliability of human operators has been recognized as a determinant factor in socio-technical systems such as nuclear power plants (NPPs), chemical plants, and aviation, where securing the safety of systems is crucial [1–3]. Many types of human reliability analysis (HRA) methods, which produce a human error probability (HEP) for a given task or context, have been developed and implemented as an important aspect of probabilistic risk assessments in complex systems [4]. However, it was recently indicated that the empirical data that supports the basis to validate the HEP estimates is insufficient for the following reasons [5,6]. First, because the reference datasets used with current HRA methods were mostly generated in the 1970s, new data reflecting the state of the art of human error trends according to changes in instrument and control systems and training programs is required. Secondly, solid empirical evidence which supports statistical validations of human reliability estimates is necessary to enhance the transparency of HRA results. Lastly, HEP estimates should be based on a classification scheme that reflects the characteristics of human cognitive process models.

For this reason, several databases have been constructed, as addressed in earlier work [5,6]. For example, the U.S. Nuclear Regulatory Commission (NRC) developed the SACADA (scenario authoring, characterization, and debriefing application) system to collect the human reliability data of licensed operators of full-scope simulators [6]. Via an agreement between the NRC and the company involved, information regarding situational factors and performance results of significant tasks, referred to as training objective elements, is recorded in this system. The context information levels are determined by scenario designers, while the performance results, including the overall performance results, error modes, error causes, error recovery outcomes, scenario end effects, and remediation efforts, are evaluated by the operators using the debriefing information from each simulation. On the other hand, KAERI (the Korea Atomic Energy Research Institute) has also established a data collection framework, the HuREX (Human Reliability data Extraction), to gather information about the characteristics of (1) overall scenarios and crews, (2) crew responses during task completion efforts, and (3) performance shaping factors (PSFs) affecting unsafe acts from full-scope simulations in off-normal situations [7]. The obtained data are accumulated in the OPERA (Operator Performance and Reliability Analysis) database. To minimize the variability in the data-gathering process results, all information about the context and crew performance is inputted by dedicated analyzers using audio-visual records, parameter logs, and event-action logs. In addition, the template was designed to mainly collect data using directly measurable or observable surrogates, such as number of manipulation tasks described during a procedural step instead of the subjective difficulty rankings of task complexity levels.

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The databases supporting HRA can be classified in terms of whether each database represents a computed HEP list for a given context according to their own HEP estimation methods or whether it describes human performance levels on a given task with contextual information. For HEP-based databases such as the Nuclear Computerized Library for Assessing Reactor Reliability (NUCLARR) [8], the Computerized Operator Reliability and Error (CORE) database [9], and the GRS (Gesellschaft für Anlagen und Reaktorsicherheit) HEP list [10], the number of error opportunities, the number of error occurrences and the corresponding HEP values are shown for each observed situation. However, human-performance-based databases such as the SACADA and OPERA database describe how successfully operators performed the given tasks and which factors were related to operator performance instead of representing probabilistic error rates [6,7]. These types of databases allow closer examinations of the contextual factors that can affect performance levels in detail; however, a mathematical treatment is also required to generate meaningful statistics from the databases to support the current HRAs.

To generate quantitative estimates regarding the human reliability from human-performance-based data, it is important to define an appropriate classification scheme for the erroneous behaviors revealed in the data. Specifically, different types of tasks are expected to require different information processing activities of humans. These differences consequently influence the discrepancies between the HEPs related to the different tasks as the many HRA methods or databases presented [4,6–10]. It was also found that the relationships between the PSFs and the HEPs strongly depend on the error type or task type [4,5,11]. Therefore, the erroneous behaviors identified during the data collection process should be categorized based on the classification scheme and the number of erroneous behaviors, and the opportunities pertaining to these errors should be determined with the scheme to generate HEPs for each error type.

A classification scheme of erroneous behaviors should be defined considering the following requirements. First, the types of human errors completely entail all possible erroneous behaviors during the control tasks in given systems. To this end, all types of human cognitive activities which can arise when interacting with complex systems should be considered in the categorization of each error type [12]. In addition, if an operator performs a task by following one or more procedures, all tasks required during the procedures should be associated with the developed error types. Second, the meanings of human error types should be comparable to the error types provided in popular HRA methodologies and conventional database; hence, when a HEP is predicted by the collected data, the result can be used to update or validate existing HEP values. Finally, the classification scheme should enable a transparent evaluation of the success or failure of human behaviors and should allow a determination of the relevant error type from the collected data. To do this, the error types should be mutually exclusive and clearly understandable to potential users of the scheme.

The SACADA database includes comprehensive taxonomies of error causes or errors modes [6]. However, because large numbers of error types are addressed in this database and error types are selected from among them only when an instance of performance deficiency is found, sufficient discussion regarding which error types can be quantified and how the probability of each type of erroneous behavior can be predicted should be included. To this end, this paper proposes a classification scheme for erroneous behaviors identified using the HuREX framework after reviewing the literature related to the abovementioned requirements [7]. In addition, a case study is conducted to verify that the proposed scheme can be successfully implemented for the categorization of erroneous behaviors and to assess whether the scheme is useful for HEP quantification. For this end, a process to count quantities related with the HEP estimations is also developed. Because the OPERA database includes reliability information relevant to the operators of main control rooms (MCRs) and off-normal situations during which one or more procedures are considered, a classification scheme was also developed for the proceduralized tasks of MCR operators. Full descriptions of the erroneous behavior identification and quantification processes are available as a technical report [13].

2. Related work

To fulfill the four requirements of the classification scheme mentioned in the introductory section, previously investigated human cognitive process models are reviewed in this section. The categories of nominal HEPs provided in the current HRA methods and the structures of the current human reliability databases are discussed as well. The operating procedures for emergency situations are also analyzed to extract the proceduralized tasks. Finally, the characteristics of the HuREX framework relevant to determination of the human error types are explained.

2.1. Cognitive process models

Although there are various types of cognitive process models, the decision ladder template presented by Rasmussen is recognized as the best known complex system control model [14,15]. Eight cognitive activities are included in this template. These are the activation, observe, identify, interpret, evaluate, define task, formulate procedure, and execute activities. The decision ladder template has been applied for the grouping of erroneous behaviors in various fields [15–18]. For example, Reason developed the generic error modeling system (GEMS) using an adjusted version of the decision ladder template as the technical basis [16]. Fucke et al. also derived cognitive activities in aviation from the decision ladder template [17], and Silva and Nicholson classified unreliable airspeed events based on the activity list developed in Fucke et al. [18].

Several methods for assessing human reliability or task demand levels utilize simplified cognitive process models [12,15,19–22]. For example, ATHEANA (A Technique for Human Event ANAlysis), a second-generation HRA method, describes basic cognitive activities in off-normal situations involving four steps: monitoring/detection, situation assessment, response planning, and response implementation [19]. O'Hara et al. addressed identical cognitive activities with the ATHEANA model in a study for the generic primary tasks of NPP operators [20]. Hollnagel established a simplified version of the cognitive process model known as SMoC (Simple Model of Cognition) for the CREAM (Cognitive Reliability and Error Analysis Method) HRA method [15]. The SMoC model has four activities which are similar to those of the ATHEANA model. These are the observation/identification, interpretation, planning/choice, and action/execution activities. Patterson and Hoffman's macrocognitive framework, the IDAC (Information, Decision, and Action in Crew context) model, and the IDHEAS (Integrated Decision-tree Human Error Analysis System) also presented four or five cognitive activities in dynamic systems; these are not novel activities from the ATHEANA or SMoC model, though emphasis is placed on communication and coordination issues [12,21,22].

Some HRA models, including the CREAM, ATHEANA, and IDHEAS methods, describe detailed cognitive tasks or failure modes for each cognitive activity. For instance, in the CREAM method, the three error types for the 'observation/identification' activity in the SMoC are presented. These are termed 'wrong object observed', 'wrong identification', and 'observation not made'. The IDHEAS method also categorizes detailed failure modes that are associated with cognitive activities and predicted HEPs for several failure modes [23].

2.2. Error types in the HRA methods and database

The error types on the nominal HEP lists in the THERP (Technique

Table 1
The proceduralized tasks according to descriptions of the Westinghouse and CE-based EOPs.

Category	Proceduralized task	Description examples in EOPs
Information verification	Verifying alarm occurrence	Determine a turbine trip alarm
	Verifying state of indicator	Verify that one reactor coolant pump is running
	Synthetically verifying information	Verify if safety injection completion conditions are satisfied
	Reading simple value	Read the charging pump flow rate
	Comparing parameter	Verify if the pressurizer level is within 25–35%
	Comparing using graph constraint	Check if the reactor coolant system subcooling margin is within the subcooling operation area on the attached graph
	Comparing for abnormality	Check if the containment vessel is in an adverse state
	Evaluating trend	Check if the pressurizer level is stable
Procedure transfer	Transferring procedure	Perform the diagnostic procedure
	Transferring step in procedure	Go to step 22.0
Situation evaluation	Diagnosing	Investigate the cause of a pressurizer relief valve abnormality
	Identifying overall status	Evaluate the necessity of plant cooling
	Predicting	Evaluate the long-term plant status
Execution	Manipulating simple (discrete) control	Close the steam bypass control valve
	Manipulating simple (continuous) control	Establish the set point of the steam generator power operated relief valve at 81.5 kg/cm^2
	Manipulating dynamically	Discharge steam to the condenser using the turbine bypass valve
	Notifying/requesting to MCR outside	Stop the reactor coolant pump using a field breaker

for Human Error Rate Prediction) [24], ASEP (Accident Sequence Evaluation Program) [25], K-HRA (Korean Human Reliability Analysis Method) [26], SPAR-H (Standardized Plant Analysis Risk-Human) [27], HEART (Human Error Assessment and Reduction Technique) [28], CBDTM (Cause-Based Decision Tree Method) [29], Phoenix [30], IDHEAS [23], and CREAM (Cognitive Reliability and Error Analysis Method) [15] methods were reviewed to generate the HEP estimates comparable to the existing HRA methods [31]. Some HRA methods, such as the ASEP, K-HRA, and SPAR-H methods, essentially classify the HEPs into diagnosis and execution HEPs. The ASEP and K-HRA methods also distinguish the execution HEPs into the error probabilities during the step-by-step and dynamic types of tasks. The THERP method, which has become a significant source of the quantitative indices used in several HRA methods, provides error probabilities for a wide range of erroneous behaviors. With reference to procedure-based behaviors of MCR operators during off-normal situations, the errors considered in THERP can be summarized into the following types: a failure to use written procedures, procedural item omissions, display selection commissions, quantitative information reading commissions, qualitative information commissions, and control selection or use commissions. THERP also subdivides detailed error types according to the task type or interface type. The Phoenix, CREAM, and IDHEAS methods present well-structured HEP lists on the basis of the frameworks of cognitive activities, such as the IDAC and SMoC models. They define the potential failure modes relevant to each cognitive activity and offer a nominal HEP for each failure mode. The CBDTM established the eight failure modes related to the activities of understanding the situation and making decisions. These modes are the information unavailability, attention failure, misleading or miscommunicated data, misleading information, step omission, misunderstanding of a procedure instruction, misunderstanding of the decision logic during a procedure, and the procedure violation modes. The HEART method presented HEPs for the eight error types that are attributable to certain task characteristics, such as the task complexity or level of familiarity and the training level. However, these attributes are often described as PSFs and are not considered as determinants of error types in other HRA methods [32,33].

The GRS has estimated several HEPs from the plant experience data [10]. Although the estimated HEPs are limited to the availability of operational experience sources, the types of human errors were clearly distinguished into commission and omission errors. For commission errors, the GRS's HEP list categorizes the error types based on cognitive activities, such as ‘identifying or defining the task’ and ‘action execution control’. On the other hand, there are more than one hundred NPP-related HEPs in the CORE database [9]. The CORE database contains several types of relevant information, such as the component type, error mode type, or human action type, for each HEP. For example, a human action type is assigned to a HEP from among the following candidates: information perception, information processing, problem solving and decision making, object identification, complex/continuous manipulation, simple/discrete manipulation, and communication, with a final category entitled 'various'. These candidates can be seen as a combination of the cognitive activities in the cognitive process models and the execution error types in ASEP-style HRA methods [25,26].

In summary, the HRA methods and databases quantifies or estimates the HEPs that are basically classified according to task types or cognitive activities. In addition, commission and omission error modes are often considered for each task or activity to represent the error types.

2.3. Proceduralized tasks

The EOPs (Emergency Operating Procedures) generally require crews to obtain information about the plant status, with subsequent instructions about how to operate the components, contact with personnel in out of the MCR, or transfer the EOPs according to the plant status [34]. In this study, all proceduralized tasks in the Westinghouse and CE (combustion engineering) types of EOPs were scrutinized [35,36]. To determine the significant tasks in the procedures, the 22 optimal recovery procedures and six functional recovery procedures in total for the Westinghouse EOPs were considered. The eight optimal recovery procedures and two functional recovery procedures comprising a set of CE-based EOPs were also analyzed. From the EOPs, 17 proceduralized tasks were extracted, as given in Table 1.

The list of proceduralized tasks in Table 1 was determined based on the instruction contents in EOPs. For example, the ‘diagnosing’ task does not merely infer the performance of the diagnostic action procedure, as the diagnostic action procedure provides a flowchart-like process which consists of several tasks in the categories of ‘information verification’ and ‘procedure transfer’. The ‘diagnosing’ task was defined to consider the instructions in some EOP steps that explicitly require an investigation of the cause of the leak or failure without explicit guidance.

The manipulation tasks are initially classified into the dynamic and simple manipulations according to the execution task types in the ASEP method. In this study, the simple manipulation refers to a single operation of a control that the given procedure indicates step by step.

Although the THERP method, the CORE database, and the GRS HEP list provide nominal or empirical HEPs by interface types, such as a rotary selector or a two-position switch, because data from many different plant simulators are collected and various interfaces are used in the simulators, the two types of controls defined in the THERP handbook were considered [24]: the continuous and the discrete controls. The continuous control is a control type by which a point can be adjusted within a numerical range. The discrete control type is used to select a state from among a limited number of candidates (e.g., typically two or three buttons). On the other hand, the dynamic manipulation task includes situations in which two or more components should be operated or other component states or parameters should be monitored to accomplish the given goal. Maintaining a level of 50% can be an example of a dynamic manipulation task, as this task requires both controlling an inlet or outlet valve and watching the tank level.

2.4. Characteristics of simulator data collection

The HuREX framework provides an identification process for any erroneous behavior, known as an unsafe act (UA), and the data items to be collected for context information affecting human reliability. How the IGTs (information gathering templates) were developed and how UA (unsafe act) information is collected using the developed templates are specifically explained in the earlier work [7,13]. In this sub-section, the UA information collection process with the UA identification method is briefly introduced to review the characteristics of the OPERA database.

The IGTs, which were developed to collect HRA supporting information from full-scope simulator data, consist of the overview, response, and UA IGTs. Using the overview IGT, the following information can be obtained: (1) overall information about plant and simulations, such as the plant type or simulation completion time; (2) operator information such as age, work experience, and operational licenses; (3) training experience; (4) environmental issues; (5) observed procedural path; (6) scenario information including initiating events and failed systems or components; and (7) crew characteristics and dynamics, such as the leadership styles of shift supervisors and the cooperative attitude of board operators. How successfully the operators performed the given tasks are evaluated and recorded in the response IGT with the following information: task type, typical performer of the task, component type, component index, and system type. The UA IGT provides a data field for the variables pertaining to (1) an overall description of the identified UA and its causality, (2) related plant/system issues, (3) time pressure, (4) task familiarity, (5) task complexity, (6) procedure clarity and description quality, (7) interface quality, (8) communication quality, and (9) recovery information.

Fig. 1 shows the sequence used to put a set of human reliability information into the OPERA database using the IGTs. The data input process starts with the insertion of the basic scenario and environmental information. The audio-visual record of the given simulation is analyzed to identify the procedural path used by the operator based on the EOPs. If a communication log of the audio-visual record exists, the log can also be employed during the entire input process for analyzing operator's the communication contents. From the procedural path, whether the tasks succeeded or failed are determined based on the UA identification process. The task characteristics of all successful and failed tasks are then analyzed and inputted in the response IGT. To alleviate the analysis efforts, a pre-accumulated database containing the task characteristics associated with the descriptions in EOPs, such as the task types, component types, and system types, is utilized. The related context information with the identified UAs is recorded in the UA IGT. Finally, crew characteristics information regarding the operators' performances overall are added to the overview IGT.

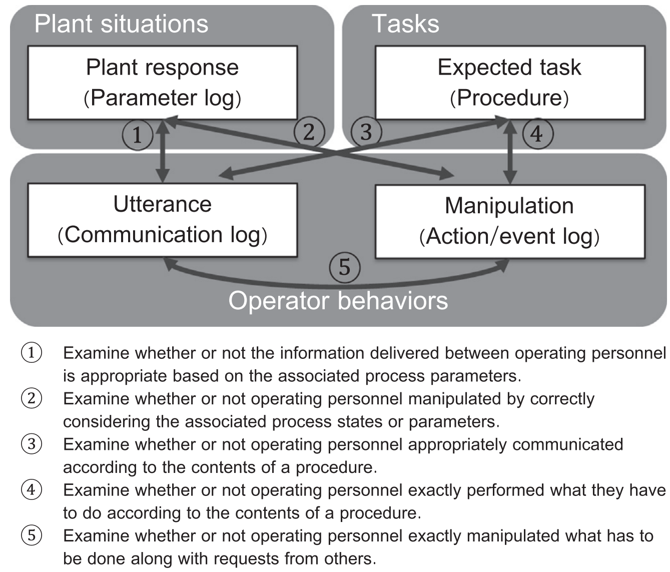

Fig. 2. Practical methods for identifying deviations from simulator data, reproduced from earlier work [7].

Similar to the earlier definitions of human errors [37] or UA [27,38], the UA can be seen as "an action inappropriately taken by plant personnel, or not taken when needed, resulting in a degraded plant safety condition" [13]. An UA is therefore identified among the deviated behaviors in the procedures by considering the consequences of the UAs when the authorized procedure for the given situation is regarded as a standard MCR operator behavior [7,13]. Fig. 2 depicts the proposed method for clarifying the deviated behaviors from simulator data. For instance, the clarification process usually proceeds by broadly reviewing whether the operators suitably followed the given procedures (arrow (3) in Fig. 2) and then evaluating how the dialogue or control behaviors of the operators coincide with on-going parameters or mutual communication (arrow (1) and (5) in Fig. 2). When an operator performs dynamic manipulation tasks or undertakes any type of task with abstract directions from a shift supervisor, the manipulating behaviors are examined by comparing with the procedures and parameter logs. Once the deviated behaviors are clarified as

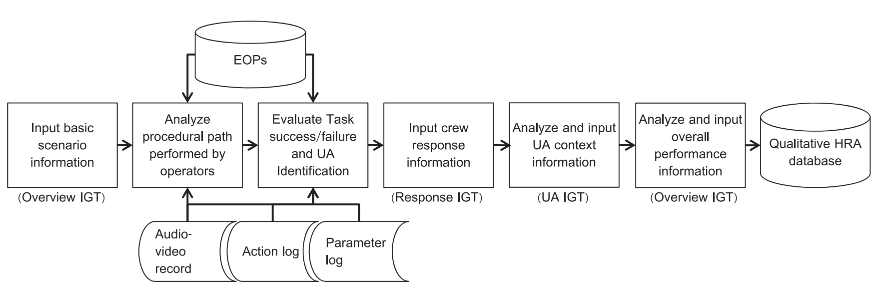

Fig. 1. Process used to generate HRA supporting data using the templates developed by KAERI.

Table 2
The cognitive activities to be carried out for proceduralized tasks.

Proceduralized task	Cognitive activity
Verifying alarm occurrence	Response planning and instruction (directing information gathering); Information gathering and reporting
Verifying state of indicator	Response planning and instruction (directing information gathering); Information gathering and reporting
Synthetically verifying information	Response planning and instruction (directing information gathering); Information gathering and reporting
Reading simple value	Response planning and instruction (directing information gathering); Information gathering and reporting
Comparing parameter	Response planning and instruction (directing information gathering); Information gathering and reporting
Comparing in graph constraint	Response planning and instruction (directing information gathering); Information gathering and reporting
Comparing for abnormality	Response planning and instruction (directing information gathering); Information gathering and reporting
Evaluating trend	Response planning and instruction (directing information gathering); Information gathering and reporting
Transferring procedure	Response planning and instruction
Transferring step in procedure	Response planning and instruction
Diagnosing	Situation interpreting
Identifying overall status	Situation interpreting
Predicting	Situation interpreting
Manipulating simple (discrete) control	Response planning and instruction (directing manipulation); Execution
Manipulating simple (continuous) control	Response planning and instruction (directing manipulation); Execution
Manipulating dynamically	Response planning and instruction (directing manipulation); Execution
Notifying/requesting to MCR outside	Response planning and instruction (directing notification/request); Execution

UA candidates, the UAs are selected from among them by evaluating the consequences of the deviation. In other words, when a deviated behavior contributes to inappropriate component controls, inappropriate procedure progressions, or inappropriate contact with other organizations, it is regarded as an UA.

The properties of the HuREX framework can be summarized as follows. First, full-scope simulator data were employed. Although incumbent or reserved operators participated in the simulator experiments or training programs, there exist environmental and psychological differences between the collected data and plant-experience-based data. Second, as noted in the introduction section, the collected data largely depends on observational information rather than on subjective self-reporting methods or audits. For example, the UAs are identified at the behavioral level, such as the dialogue or actions of the operators, and not at the cognitive-psychological levels. When a board operator omits reporting the occurrence of an alarm, whether s/he has failed to heed the alarm or has instantaneously lost any memory of the alarm reporting task is not revealed. The failure of an alarm occurrence task is simply marked. Most context information that affects human performance is also collected according to the observable/measureable variables. When an UA is found, for example, the developed IGT does not inquire into the operator's temporal pressure using questionnaires, as in the NASA-TLX method [39], instead collecting where the UA is located among the procedural phases: (1) the UA occurred before the initial response to the EOP operation, (2) the UA occurred before the completion of the diagnosis during the EOP operation, and (3) others. That is, it is assumed that the procedural phases may cause different temporal pressures on the operators. Lastly, the procedures are used as the main criteria to identify UAs. This implies that the error types of erroneous behaviors are also distinguishable according to the characteristics of the descriptions of the procedure.

3. Proposed classification scheme

Similar to the earlier work introduced in Section 2.1, the cognitive process model of the crew team underlying the proposed classification scheme is assumed to include the following activities: information gathering, situation interpretation, response planning, and execution. Coordination and communication between operators was not separately considered in the cognitive process model because the collected data does not support distinguishing an UA caused by a communication failure with an UA by another kind of activity failure. Instead, because the information gathering and response planning behaviors performed during off-normal situations are usually conducted with proper communications, such as verbal reports and instructions according to the command and control protocol [40], it can be assumed that these behaviors necessarily involve the communicative activities. Hence, the two basic cognitive activities can be expressed by the terms 'information gathering and reporting' and 'response planning and instruction'.

Based on the established cognitive model, it is possible to define the error types corresponding to the detailed cognitive failure modes of each cognitive activity, akin to the failure types established in the CREAM, ATHEANA, and IDHEAS methods and the SACADA database. However, it is not easy to observe the detailed failure modes from the empirical data, as the HuREX framework does not formally include a debriefing process to identify the root causes of UAs. Even though that these types of information obtained from the debriefing process might exist, the debriefing process, which is generally performed subjectively, is often uncertain as regards an accurate identification of the failure modes for a given event [41].

The error types of UAs were defined based on the task types performed by the operators. This approach is in good agreement with the fact that the HEP lists in most HRA methods, especially the THERP method, and databases distinguish error types by the task types and related error modes (e.g., omission errors and commission errors). The task types were determined by classifying the cognitive activities employed for each proceduralized task in Table 1. It should be noted that the proceduralized tasks in the categories of 'information verification' and 'execution' should be achieved by directing a task according to the given procedure and executing the task. Most proceduralized tasks in these categories hence include 'response planning and instruction' activities. Table 2 shows which cognitive activities are required to carry out a proceduralized task.

On the basis of the cognitive activities with the proceduralized tasks shown in Table 2, 21 task types were defined. Given that an omission error involving an entire step was emphasized in several HRA methods and databases [9,10,23,29,30], the task of 'entering step in procedure' was added as a type of response planning activity. If the corresponding error modes are assigned to the defined task types, the finally established error types can be organized as those shown in Table 3. Some UAs can occur because operators attempt to manipulate certain controls not required by the procedure in progress; these behaviors are classified as unauthorized controls.

Omission and commission errors can exist in most types of tasks, except for the 'entering step in procedure' task. For the 'simple (discrete) control' tasks, the commission errors are subdivided into the wrong device and wrong direction errors. The wrong quantity mode is also considered in the set of commission errors of the 'simple (continuous) control'. The UAs caused by instances of the 'unauthorized control', which imply the direction or execution of any type of manipulation that was not intended in the procedures, are regarded as

Table 3
The classification scheme of erroneous behaviors.

Cognitive activity	Task type	Error Mode
Information gathering and reporting	Checking discrete state - Verifying alarm occurrence	Omission error, Commission error
	Checking discrete state - Verifying state of indicator	Omission error, Commission error
	Checking discrete state - Synthetically verifying information	Omission error, Commission error
	Measuring parameter - Reading simple value	Omission error, Commission error
	Measuring parameter - Comparing parameter	Omission error, Commission error
	Measuring parameter - Comparing in graph constraint	Omission error, Commission error
	Measuring parameter - Comparing for abnormality	Omission error, Commission error
	Measuring parameter - Evaluating trend	Omission error, Commission error
Response planning and instruction	Entering step in procedure	Omission error
	Transferring procedure	Omission error, Commission error
	Transferring step in procedure	Omission error, Commission error
	Directing information gathering	Omission error, Commission error
	Directing manipulation	Omission error, Commission error
	Directing notification/request	Omission error, Commission error
Situation interpreting	Diagnosing	Omission error, Commission error
	Identifying overall status	Omission error, Commission error
	Predicting	Omission error, Commission error
Execution	Manipulation - Simple (discrete) control	Omission error, Wrong device, Wrong direction
	Manipulation - Simple (continuous) control	Omission error, Wrong device, Wrong direction, Wrong quantity
	Manipulation - Dynamic manipulation	Omission error, Wrong device, Wrong direction, Wrong quantity
	Notifying/requesting to MCR outside	Omission error, Commission error
Other	Unauthorized control - Unguided response planning and instruction	Commission error
	Unauthorized control - Unguided manipulation	Commission error
	–	Timing error (too fast/too late)

typical commission errors.

Appendix A presents a comparison matrix between the proposed classification scheme and other error types defined in the THERP, ASEP, and IDHEAS methods [23–25]. The definitions of the human errors for each method or database are not identical to this taxonomy; however, this matrix is expected to provide a guideline when any type of HEP should be reviewed or updated by employing HEPs obtained from simulator data.

4. Application to HEP quantification

4.1. Quantification process

Based on the developed classification scheme, the HEPs pertaining to the identified erroneous behaviors from the simulator data were calculated. The simulator training records of off-normal situations were analyzed. Table 4 describes the simulated scenarios for these training instances. Operators who currently work in the reference plants participated in these training programs. There are five members in each crew team: a shift supervisor (SS), a reactor operator (RO), a turbine operator (TO), an electric operator (EO), and a shift technical assistant (STA). The SS mainly leads the other members by searching for suitable procedures for a given situation, following the procedures and giving directions to others. The RO, TO, and EO collect information about plant parameters or operate controllers in response to the directions from the SS. The STA supports the other members by monitoring safety-critical features or observing the manipulating or information-gathering behaviors of the other members.

The UAs were identified from the abovementioned records by the process explained in the Section 2.4. The HEPs regarding the UAs are then calculated by the following equation, which is recognized as the most popular quantification approach [42]:

$$HEP_{M,T}=\frac{E_{M,T}}{N_{M,T}}=\frac{E_{M,T}}{E_{M,T}+S_T} \quad (1)$$

here, $N_{M,T}$ is the number of UA opportunities relevant to error mode M of task type T, $E_{M,T}$ is the number of observed UAs, and S_T is the frequency of success during the performance of a type T task.

If an omission error occurs during a certain task, it can be thought that a potential of a commission error for the task is deprived. The HEPs can be calculated differently according to the error modes by the following equation,

Table 4
Simulation scenarios of records analyzed during the HEP quantification.

Reference plant type	Scenario	Relevant procedure	Training data
Westinghouse-type plant	Interfacing System Loss of Coolant Accident (ISLOCA)	E-0 (Reactor trip or Safety injection); E-1 (loss of coolant accident); ECA-1.2 (loss of coolant accident outside the containment);	10
	Steam Generator Tube Rupture (SGTR) following a Main Steam Line Break (MSLB)	E-0 (Reactor trip or Safety injection); E-2 (Faulted SG isolation); E-3 (SGTR); ECA-3.1 (SGTR with loss of reactor coolant subcooled recovery desired)	8
CE-type plant	Control element slip down	AOP-02 (Control rod slip down or misalignment)	14
	Condenser vacuum lowering	AOP -69 (loss of condenser vacuum)	14
	04SN bus power loss	Alarm procedure-3027 (04SN DC BUS failure)	10
	Deaerator inlet valve close	AOP-66 (Condensate system abnormality)	13
	Pressurizer level controller failure	AOP-34 (Pressurizer level control system abnormality)	22
	Condensate tube leakage	AOP-67 (Condensate system line leakage)	20
	Main seal oil pump failure	AOP-82 (Generator shaft seal oil loss)	22
	Reactor coolant pump seal loss	AOP-3431F (Loss of the reactor coolant pump seal)	8
	Condensate polishing system valve closed	AOP-3531A (Reduction of deaerator level)	8

*AOP: Abnormal operating procedure.

Table 5
Examples to evaluate the success or failure of an arbitrary step.

Procedure	Step	Instruction	Cognitive activity	Task type	Number of opportunities	Number of successes	Number of omissions	Number of commissions
E-0	#a	Goal: the reactor coolant pumps are stopped	Response planning and instruction	Entering step in procedure	1	1	0	–
E-0	#a	Verify that the reactor coolant pumps are stopped.	Response planning and instruction	Directing information gathering	1	1	0	0
			Information gathering and reporting – checking discrete state	Verifying state of indicator	2	2	0	0
E-0	#a	Stop all reactor coolant pumps.	Response planning and instruction	Directing manipulation	1	0	1	0
			Action - manipulation	Manipulating (discrete) control	0	0	0	0

$$HEP_{M,T}=\begin{cases}\frac{E_{oe,T}}{E_{oe,T}+E_{ce,T}+S_T}, & M=oe\\ \frac{E_{ce,T}}{E_{ce,T}+S_T}, & M=ce\end{cases}, \quad (2)$$

where oe and ce represent the omission and commission error modes in each task, respectively.

This equation consequently requires the frequencies of the observed UAs and UA opportunities for each error type. Because all UAs are identified based on the procedures, the error type of an UA is determined according to the proceduralized task which is related with the UA; hence, the numbers of UAs are simply quantified for each error type. To count the numbers of opportunities during the periods of the simulations in the collected data, the cognitive activities and task types in the developed scheme were assigned for every instruction that was followed by the operators in the response IGT. Using the task types in the IGT, a task normally performed during a given scenario was viewed as a successful human action, while a task where an UA was identified was regarded as a failure. Finally, the total number of success and failure behaviors for each error type is regarded as the opportunity frequency.

Table 5 shows examples of success and failure evaluations in the response IGT. The instructions in this arbitrary step indicate that it is necessary to check whether the reactor coolant pumps (RCPs) are running and to stop the pumps if they are running. To accomplish the goal of this step, the operator ingresses this step first and checks the states of the RCPs. Because there are two RCPs in this plant, the number of success behaviors becomes two when the RO correctly responds to the inquiry of the SS, who asked whether the RCPs have operated. Table 5 also shows that the SS did not give a direction to cease the RCP despite the fact that the RO reported that one RCP was running. In this case, the number of success behaviors is zero, but the omission error frequency is one. Given that the direction of the SS was omitted, the manipulation task was not attempted; hence, the number of UA opportunities is zero.

4.2. HEPs obtained from simulator data

The HEPs obtained from the simulator data are presented in Table 6. Given that certain types of erroneous behaviors were not observed during the simulations, as indicated by the zero UA cases with single asterisks in the table, the HEPs were estimated using the one-third probability assumption (i.e. $HEP_{M,T}$ =1/(3*$N_{M,T}$)) [43]. The tasks of 'identifying overall status' and 'predicting' were not done in this study (see the double-asterisked zeros in Table 6), as the simulations were terminated before applying the relevant procedural instructions. For these tasks, the HEPs were not thus produced. To secure more reliable estimates, the continuous accumulation and analyses of simulator data are desirable.

The HEPs in Table 6 were obtained using the numbers of UAs that occurred before any recovery action. Although it was found that many erroneous behaviors were recovered from the simulator data, the recovery failure rates or the post-recovery HEPs were not calculated in this case study at this point. Additional estimation results will be shown after the accumulation of more data.

Although more data should be analyzed to interpret the HEPs correctly, Table 5 provides rough insight about human reliability during off-normal conditions. Commission errors were frequently observed during the tasks regarding the 'information gathering and reporting' activity. It seems to be difficult to compare the parameters or evaluate the trends during off-normal situations when certain parameters are dynamically fluctuating (relevant HEPs: 1.282E-02 and 1.531E-02, respectively). This result implies that the types of information to be processed can affect the reliability of the human actions of gathering and reporting information.

The HEPs pertaining to the 'response planning and instruction' tasks were relatively high. The failure rates when attempting to

Table 6
The estimated HEPs from the simulation records.

Cognitive activity	Task type	Number of success	Number of omission	Number of commission	HEP (omission)	HEP (commission)
Information gathering and reporting	Total	3715	2	12	5.363E−04	3.220E−03
	Checking discrete state - Verifying alarm occurrence	353	0*	0*	9.443E−04	9.443E−04
	Checking discrete state - Verifying state of indicator	1971	2	0*	1.014E−03	1.691E−04
	Checking discrete state - Synthetically verifying information	107	0*	0*	3.115E−03	3.115E−03
	Measuring parameter - Comparing for abnormality	372	0*	0*	8.961E−04	8.961E−04
	Measuring parameter - Comparing parameter	385	0*	5	8.547E−04	1.282E−02
	Measuring parameter - Comparing in graph constraint	20	0*	0*	1.667E−02	1.667E−02
	Measuring parameter - Evaluating trend	386	0*	6	8.503E−04	1.531E−02
	Measuring parameter - Reading simple value	121	0*	1	2.732E−03	8.197E−03
Situation interpreting	Total	7	0*	6	2.564E−02	4.615E−01
	Diagnosing	7	0*	6	2.564E−02	4.615E−01
	Identifying overall status	0**	0**	0**	–	–
	Predicting	0**	0**	0**	–	–
Response planning and instruction	Total	4639	80	22	1.687E−02	4.720E−03
	Entering step in procedure	624	3	–	4.785E−03	–
	Directing information gathering	2801	8	4	2.844E−03	1.426E−03
	Directing manipulation	665	51	16	6.967E−02	2.349E−02
	Directing notification/request	306	9	1	2.848E−02	3.257E−03
	Transferring procedure	176	1	1	5.618E−03	5.650E−03
	Transferring step in procedure	67	8	0*	1.067E−01	4.975E−03
Execution	Total	743	12	2	1.585E−02	2.685E−03
	Manipulation - Dynamic manipulation	134	0*	0*	2.488E−03	WDEV, WDIR, WQNT: 2.488E−03
	Manipulation - Simple (discrete) control	584	12	WDEV: 0 WDIR: 2	2.007E−02	WDEV: 5.688E−04, WDIR: 3.413E−03
	Manipulation - Simple (continuous) control	25	0*	0*	1.333E−02	WDEV, WDIR, WQNT: 1.333E−02
	Notifying/requesting to MCR outside	301	3	1	9.836E−03	3.311E−03
Other	Unauthorized control - Unguided response planning and instruction	–	–	0	–	–
	Unauthorized control - Unguided manipulation	–	–	11	–	–

WDEV: wrong device; WDIR: wrong direction, WQNT: wrong quantity.
* No UA was observed.
** No task corresponding to the error type was performed during the simulations.

correctly direct a manipulation task and transfer a step to another are remarkable. As indicated in earlier works [44,45], a crew in off-normal situations may perceive a high level of cognitive workload required to follow a procedure correctly. This implies the HRA analysts should consider the operator reliabilities of procedure-following behaviors.

The frequency of omission errors regarding discrete control manipulation tasks is higher than the omission error frequencies of the other types of manipulation tasks. This result emphasizes the importance of how accurately a plant operator can recall given tasks under complex environments compared to the operational complexity or interface characteristics.

Eleven unauthorized manipulations were found during the simulations, whereas no unauthorized cases of response planning and instructions were observed. Because these behaviors are not intended in the procedures, the potentials of their occurrence were not calculated as in the other types of HEPs. It is expected that the frequencies can be used to predict the error rate for each unit operation period in the future.

Timing errors are addressed as significant commission error modes in many HRA methods or databases. However, the failures associated with a timing issue for each task were not counted in this study. Because the data collected from the simulators includes the information of human performance times on given tasks, it is expected to estimate a HEP by comparing the performance time distribution with a thermal hydraulic criteria as shown in [46,47].

5. Discussion and conclusion

In this study, we proposed a classification scheme of erroneous behaviors in terms of HEP estimations from simulator data. Through reviews of previous studies, the task types were defined by combining the cognitive activities in a simplified cognitive process model and all types of proceduralized tasks in the EOPs to secure clarity and completeness of the scheme. The error modes addressed in the existing HRA methods were then assigned to the task types for determining the error types. To generate HEPs for the defined error types, a quantification process which straightforwardly calculates the HEPs of erroneous behaviors was also applied. By rigorously counting the number of behaviors, more reliable and traceable HEPs could be produced. From 149 instances of training data from the off-normal scenarios, the 52 HEPs were estimated as a case study. The case study showed that the proposed errors types include all types of tasks indicated in the employed procedures during various scenarios. It is also revealed that the human behaviors involved in completing the tasks can be clearly sorted into the error types and quantified as the HEPs.

Because the simplified cognitive process model was utilized in development of the classification scheme, some detailed cognitive activities were not distinctively represented in this study. For example, an activity of 'information gathering and reporting' comprises several types of activities such as continuous monitoring of parameters, detection of annunciation from a display, and observation according to an oral direction. To develop a more sophisticated scheme considering these kinds of detailed activities, the decision ladder template or similar models can be used [14].

It should also be noted that the dynamic manipulation task defined in this scheme can require various types of cognitive activities including decision making activities. For example, an adjustment task of a reactor coolant boric acid concentration is concomitant with not only lining up associated valves but also determining the target concentration of boric acids. The HEP regarding the dynamic manipulation tasks thus should be interpreted considering these cognitive activities.

The classification scheme includes the error types related to public announcements and communications with field operators or other organizations. Many existing HRA methods do not explicitly consider these types of tasks. However, our scheme defines the error types in external communications based on the proceduralized task list. Because, it has been indicated that inappropriate communications between MCR operators and other personnel sometimes affect the reliability of the system [48]. In addition, communications between MCR operators and external agents require a mediated method such as a page-phone to deliver any information; hence, the communication reliability may be degraded according to the situation awareness or speech accuracy. The HEPs of the 'notifying/requesting to MCR outside' task reflects these significances of the external communication reliability.

The error types for the arithmetic calculation and calibration tasks did not pertain to the classification scheme. The calculation tasks were addressed in the THERP and GRS HEP list, while the HEPs regarding the calibration tasks are presented in the THERP and GRS HEP list, and the CORE database [9,10,24]. However, these tasks are usually performed during normal situations, and the equipment calibration in particular is carried out by local operators. For these reasons, these factors are not required in the EOPs, and the scheme developed from the proceduralized tasks did not include them either.

Although the classification scheme was compared with the error types in several HRA methods and databases (Appendix 1), the meaning of each error type in such an association can differ depending on the methods used and our scheme in terms of the definition. For example, the diagnosis HEP in the ASEP method does not imply the failure rate for a diagnosis task. In some cases, the diagnosis failure intended by the ASEP method can entail the failures of several proceduralized tasks, such as transferring to the proper step and verifying indicators to determine the necessity of the execution. Therefore, the resultant HEPs obtained by the classification scheme should be employed for the validation of the estimates in the existing HRA by precise comparisons of the error type definitions and adjustments of the resultant HEPs.

Some HRA methods or databases provide the HEPs according to the interface types or component types. Because the response IGT in the OPERA database includes the data items for system types, component types, and the component name to be manipulated, the classification scheme can be segmented considering this information. The final HEP estimation in this project is expected to report a number of HEPs for different types of component control tasks, such as valve control or pump control tasks.

Because the severe accident management has been recognized as a significant safety issue after the Fukushima-Daiichi accident, the taxonomy of erroneous behaviors during accident managements can be developed for the level-2 HRA research. Compared with the EOPs that were considered to define the task types in this study, the severe accident management guidelines (SAMGs) have several features in terms of categorization of the proceduralized task. For example, the SAMGs often provide various measures to resolve a safety problem and require more decision-making activities [49]. It is also frequently demanded to communicate the technical support center or ex-control room operators. In addition, the operators could need to control components that were not explicitly described in the guidelines. The classification scheme developed in this study hence could be extended to cover the accident management tasks by analysis of the SAMGs.

In this study, several types of HEPs were produced to verify the appropriateness of the proposed scheme. To accurately understand the resultant HEPs, the following issues should be resolved. First, these estimates were generated from simulator data and not actual plant experiences; hence, it is required to compare or update the estimates according to the results of plant experience data analyses. Because the HEPs are produced from the simulations in a limited number of scenarios, the HEPs could not be seen as nominal HEPs, which mean the probabilities where the effect of PSFs were not considered [50]. In other words, the obtained HEPs are possibly biased by one or more contextual factors. Therefore, which PSFs affected the HEPs and how much the PSFs quantitatively contribute to the probabilities should be revealed for the understanding of the human reliability. Some PSF effects on the HEPs are planned to be investigated with the proposed method in [5]. Lastly, an uncertainty due to performance variability of individual operators or uncounted issues should be taken into account during the interpretation of the HEPs. Several processes for the uncertainty propagation have been proposed and some researchers applied Bayesian updates with an assumption of the noninformative prior beta distribution to the HEP estimation [10,51,52]. These techniques are expected to deliver more plausible results than the plain HEP equation or one-third probability assumption that we employed.

As mention earlier, the HEPs were calculated by the number of UAs without consideration of recovery actions. Because the OPERA database includes the information of recovery actions for each UA, it is expected to calculate recovery failure probabilities using the OPERA database. However, due to rarity of recovery action occurrence, more simulator data should be collected to significantly estimate such probabilities. It will be attempted to generate empirical evidence of the recovery failures of erroneous behaviors or the dependencies between HEPs in the near future.

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Appendix A. Comparison table of error types in the proposed scheme and the THERP, ASEP, and IDHEAS methods

Cognitive Activity	Task Type	Error Mode	THERP	ASEP	IDHEAS
Information gathering and reporting	Checking discrete state - Verifying alarm occurrence	Omission error Commission error	– Annunciator response model		– Key alarm not attend to – Miscommunication – Wrong data source attended to – Critical data misperceived – Miscommunication
	Checking discrete state - Verifying state of indicator	Omission error			– Critical data dismissed/discounted – Critical data not checked with appropriate frequency – Miscommunication
		Commission error	– Fail to select unannunciated displays – Commission in check-reading from digital indicators		– Wrong data source attended to – Critical data misperceived – Miscommunication
	Checking discrete state - Synthetically verifying information	Omission error			– Critical data dismissed/discounted – Critical data not checked with appropriate frequency – Miscommunication
		Commission error	– Fail to select unannunciated displays		– Wrong data source attended to – Critical data misperceived – Miscommunication
	Measuring parameter - Reading simple value	Omission error			– Critical data dismissed/discounted – Critical data not checked with appropriate frequency – Miscommunication
		Commission error	– Fail to select unannunciated displays – Commission in reading and recording information from analog meter – Commission in reading and recording information from digital readout (4 digits)		– Wrong data source attended to – Critical data misperceived – Miscommunication
	Measuring parameter - Comparing parameter	Omission error			– Critical data dismissed/discounted – Critical data not checked with appropriate frequency – Miscommunication
		Commission error	– Fail to select unannunciated displays 1. Commission in check-reading from analog meters		– Wrong data source attended to – Critical data misperceived – Miscommunication
	Measuring parameter - Comparing in graph constraint	Omission error			– Critical data dismissed/discounted – Critical data not checked with appropriate frequency – Miscommunication
		Commission error	– Fail to select unannunciated displays – Commission in reading and recording information from graphs		– Wrong data source attended to – Critical data misperceived – Miscommunication
	Measuring parameter - Comparing for abnormality	Omission error			– Critical data dismissed/discounted – Critical data not checked with appropriate frequency – Miscommunication
		Commission	– Fail to select		– Wrong data source attended to

		error	unannunciated displays – Commission in check-reading from analog meters		– Critical data misperceived – Miscommunication
	Measuring parameter - Evaluating trend	Omission error			– Critical data dismissed/discounted – Critical data not checked with appropriate frequency – Miscommunication
		Commission error	– Fail to select unannunciated displays – Commission in check-reading from analog meters		– Wrong data source attended to – Critical data misperceived – Miscommunication
Response planning and instruction	Entering step in procedure	Omission error			– Misread or skip step in procedure
	Transferring procedure	Omission error	– Omission per item of instruction		
		Commission error			– Misinterpret procedure – Choose inappropriate strategy
	Transferring step in procedure	Omission error	– Omission per item of instruction		
		Commission error			– Misinterpret procedure – Choose inappropriate strategy
	Directing information gathering	Omission error	– Omission per item of instruction		– Premature termination of critical data collection
		Commission error			– Misinterpret procedure – Miscommunication
	Directing manipulation	Omission error	– Omission per item of instruction		
		Commission error			– Misinterpret procedure – Miscommunication
	Directing notification/request	Omission error	– Omission per item of instruction		
		Commission error			– Misinterpret procedure – Miscommunication
Situation interpreting	Diagnosing	Omission error	– Omission per item of instruction	– Diagnosis HEP	
		Commission error			
	Identifying overall status	Omission error	– Omission per item of instruction		
		Commission error			
	Predicting	Omission error	– Omission per item of instruction		
		Commission error			– Choose inappropriate strategy
Execution	Manipulation - Simple (discrete) control	Omission error		– Perform a critical action as part of a step-by-step task	– Failure to initiate execution
		Wrong device	– Select wrong control on a panel		– Failure to correctly execute response (simple task)
		Wrong direction	– Turn rotary control in wrong direction – Turn a two-position switch in wrong direction		
	Manipulation - Simple (continuous) control	Omission error		– Perform a critical action as part of a step-by-step task	– Failure to initiate execution
		Wrong device	– Select wrong control on a panel		– Failure to correctly execute response (simple task)
		Wrong direction			
		Wrong quantity			
	Manipulation - Dynamic	Omission error		– Perform a critical action as part of	– Failure to initiate execution

	manipulation	Wrong device Wrong direction Wrong quantity	– Select wrong control on a panel	a dynamic task	– Failure to correctly execute response (complex task)
	Notifying/requesting to MCR outside	Omission error Commission error			– Miscommunication
Other	Unauthorized control - Unguided response planning and instruction	Commission error			
	Unauthorized control - Unguided manipulation	Commission error	– Commission in operating manual controls - inadvertent activation of a control		
	–	Timing error (too fast/too late)			– Delay implementation

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