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《Technical Note》

Comparative Evaluation of Three Cognitive Error Analysis Methods Through an Application to Accident Management Tasks in NPPs

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Abstract

This study was performed to comparatively evaluate selected Human Reliability Analysis (HRA) methods which mainly focus on cognitive error analysis, and to derive the requirement of a new human error analysis (HEA) framework for Accident Management (AM) in Nuclear Power Plants (NPPs). In order to achieve this goal, we carried out a case study of human error analysis on an AM task in NPPs. In the study we evaluated three cognitive HEA methods, HRMS, CREAM and PHECA, which were selected through the review of the currently available seven cognitive HEA methods. The task of reactor cavity flooding was chosen for the application study as one of typical tasks of AM in NPPs. From the study, we derived seven requirement items for a new HEA method of AM in NPPs. We could also evaluate the applicability of three cognitive HEA methods to AM tasks. CREAM is considered to be more appropriate than others for the analysis of AM tasks, HRMS is also applicable to the error analysis of AM tasks. But, PHECA is regarded less appropriate for the predictive HEA technique as well as for the analysis of AM tasks. In addition to these, the advantages and disadvantages of each method are described.

Key Words : human reliability analysis, human error analysis, cognitive error analysis accident management

I. Introduction

The reliability of hardware components in nuclear power plants (NPPs) has reached to the acceptably high through the technology development and design improvements. Human as an operator, however, is a component with a certain boundary of reliability caused by inherent cognitive characteristics and/or limitations. It is reason why human is known as a bottleneck to the system or plant safety. The results of Probabilistic Safety Assessments (PSAs) also demonstrated that human error is a major contributor to the plant risk. To enhance the plant safety, human error should be studied in advance to find the way to reduce or prevent it.

From the viewpoint of safety assessment, HRA has been performed as a part of PSAs of NPPs. It plays a role in providing PSAs with the value of human error probability in performing given tasks. For such request of PSAs on the HRA, the conventional HRA methods such as THERP[1], HCR[2], SLIM[3], and Time Reliability Correlation[4] have focused on the quantitative assessment of observable aspects rather than on the qualitative analysis of cognitive aspects of human tasks. However, since the operator tasks in emergency operation are mainly composed of cognitive activities such as monitoring, diagnosis, decision making, and planning, the cognitive error analysis becomes more important. Due to this limitation of the conventional HRA, even after the completion of HRA, it was not powerful to make any specific recommendations for error reduction. In addition, HRA without detailed cognitive error analysis is likely not only to give lower estimates than what really it is, but also to omit the important consequences to system or environment. To overcome these limitations of the conventional HRA methods, the research on human error has been actively performed after late eighties[5]. Recently some approaches to develop new cognitive HEA method have been undertaken based on the theoretical background of cognitive science or psychology.

According to Kirwan[6], HEA identifies what kinds of human error could occur (error mode), why they occur (error causes), and how they occur (error mechanisms). However, with the conventional HRA methods, it is difficult not only to identify the underlying mechanisms of human error but also to obtain the human error reduction measures. Since most functions of operator in emergency situation are mainly composed of cognitive activities, the error analysis should focus on the cognitive or decision making processes of operator. Reason[7] also says that slip is easily revealed and can be recovered within a short time period, but mistake is hardly corrected without the intervention of some external agent. To follow this trend toward cognitive error, the currently being developed HEA methods have their focus on the cognitive error analysis [5].

In this paper, we summarized the result and the insight obtained from the case study of cognitive HEA on an AM task in NPPs. First, we reviewed the current trend of HEA that was started to complement the conventional HRA. Second, we selected three HEA methods, HRMS (Human Reliability Management System)[8], CREAM (Cognitive Reliability and Error Analysis Method)[9] and PHECA (Potential Human Error Cause Analysis)[10] based on the review, which are directly applicable to the task of AM. The selected methods were comparatively evaluated by applying them to the task of 'the reactor cavity flooding'. And third, we summarized the merits and demerits of three methods in viewpoint of applicability to the HEA in NPPs, and also identified the requirements for the further development of HEA. Section II gives a brief description of the selection process, and the approaches, models and classification structures of the three methods, and the comparison between each method. The application to an accident management task and its results are described in Section III, the comparative evaluation of three methods and the requirement for further study in Section IV, and the study is concluded in Section V.

2. Description of the Selected HEA Methods

2.1. Selection of the HEA Methods

We comparatively reviewed the recently developed HEA methods for the case study [11]. The methods reviewed for the study are as follows: GEMS[12], SHERPA[13], PHECA[10], Murphy Diagram[14], HRMS[8], COSFAH[15], and CREAM[9]. These methods, according to their specific purposes, have their own frameworks and various levels of depth in view of approach, taxonomy, and model. For example, some methods were developed for systematic description of error mechanisms, like GEMS, and other methods for the specific applications. In this study, to facilitate the selection process of the appropriate method for accident management tasks, these methods were classified according to three basic classification rules. The first classification was made according to whether a method is for retrospective analysis, which identifies causes of events or accidents that have already happened, or for prospective (predictive) analysis, which predicts future error occurrences or the potential for human error using task context. Secondly, methods that have an appropriate taxonomy for error analysis were collected together. And, thirdly, classification was made according to the cognitive level (i.e., skill, rule, and knowledge-based level) to which each method can identify.

For the analysis of accident management tasks, it should be predictive method with appropriate error taxonomy, and be able to analyze errors to the knowledge-based level of cognitive behaviors. The followings are the selected methods that meet three basic requirements.

- Predictive methods: SHERPA, PHECA, HRMS, and CREAM.
- Methods with appropriate error taxonomy: GEMS, HRMS, SHERPA, PHECA, COSFAH, CREAM.
- Methods with a capability to treat the various levels of cognitive behaviors: GEMS, PHECA, Murphy Diagram, HRMS, CREAM.

Finally, among the above-mentioned HEA methods, we selected three methods, HRMS, CREAM and PHECA, which meet all of three basic requirements, i.e. the predictive methods with both the appropriate error taxonomy and the capability to treat the various levels of cognitive behaviors. The brief descriptions of the selected three methods including characteristics of each method are as follows.

2.2. Description of the Selected Methods

2.2.1. HRMS (Human Reliability Management System) [8]

HRMS has its main focus on the identification of error causes to obtain the error reduction mechanisms. It uses the term, psychological error mechanisms (PEMs), to represent error causes. The performance shaping factors (PSFs) are not used explicitly in the process of error identification but used in the quantification of human error probability.

For the model of human cognition, HRMS is based on the eight information processing stages of Rasmussen' s step-ladder model [16]. Based on the cognitive stages, it provides 45 potential External Error Modes (EEMs) and 65 Psychological Error Mechanisms (PEMs) over eight cognitive stages. The assessor firstly identifies the potential EEMs by answering approximately 40 questions, and then is shown a subset of PEMs associated with the identified EEM. Finally, he or she chooses one of PEMs considering the task situations. The identification process of EEMs and PEMs highly relies on assessor expertise and judgment. Kirwan says that HRMS ideally would consider PSFs or the type of task involved (or both factors) in helping the assessor to decide those factors, but this is not yet feasible given the current state of knowledge [6].

HRMS consists of three modules which includes the task analysis module, the task classification module, and the error analysis module. The task analysis module provides what the operator is required to do. The hierarchical task analysis (HTA) technique is usually used. The task classification module identifies whether a task step contains the cognitive error potential or not. The error analysis module identifies potential errors associated with a task using error taxonomy based on the information processing stages of step-ladder.

2.2.2. CREAM (Cognitive Reliability and Error Analysis Method) [9]

CREAM was developed for both the retrospective analysis and prospective analysis. In the retrospective analysis, the causes of incidents or events are identified to input to system modification. On the contrary, the prospective analysis predicts the potential for and the consequences of human error in a given system. The output obtained from the retrospective analysis can be used as the evidence data for the development of a predictive analysis model.

CREAM is developed on the basis of the two fundamental models. The one is the contextual control model (COCOM). The COCOM regards that human cognition is not performed sequentially as in the Rasmussen' s step-ladder model, but recursively. And, the control of human cognition is determined by the context (task and situation). The other is the simple model of cognition (SMoC), which views the cyclical nature of human cognition composed of four cognitive stages, i.e., observation, interpretation, planning and execution.

CREAM provides eight context factors named the common performance conditions (CPCs). The assessor should perform error analysis with considering these CPCs. CREAM also defines 15 types of cognitive activity according to task characteristics to facilitate the analysis. Each cognitive activity type has predefined dominant cognitive stages. Total 12 cognitive function failures (as EEMs in HRMS) are defined over four cognitive stages. Accordingly, the assessors should firstly identify the appropriate cognitive activity type to a given task step, then refer to the corresponding cognitive stages, and finally, determine the most probable cognitive function failure with considering CPCs.

2.2.3. PHECA (Potential Human Error Cause Analysis) [10]

PHECA was developed to aid system design by providing the designer with a list of design factors relevant to human error. The 187 performance shaping factors (PSFs) are used to represent these design factors. To identify human error related PSFs (i.e., design factors), the assessor firstly should determine the task type, the response type, and the error type for each task step. The assessor then could obtain a list of PSFs relevant to system design based on the established link between these three types and PSFs. Even though the method originally was developed in search of system design factors, it also can be used for error analysis because the error types and the error causes are identified in the process of PHECA analysis.

For the model of human cognition, PHECA uses a little simplified model with six information processing stages adapted from the Rasmussen' s step-ladder model. PHECA classifies the task type into seven categories, the response type into seven, and the error type into ten using the HAZOP[17]-type keyword. The assessor determines most probable or most important error types among the error types relevant to response type based on the information collected from the task analysis.

3. HEA Application to an Accident Management Task

3.1. Description of the Task

For a case task during the accident management situation, we selected 'the reactor cavity flooding strategy', which was suggested for the prevention or to delay the time of the reactor vessel failure at the time of core damage. The task procedures associated with this strategy were redescribed on the basis of WOG SAMG (Westinghouse Owners Group Severe Accident Management Guidance) [18] considering the design characteristics of the Korean nuclear power plant.

When the entry conditions to SAMG, which is described in ERG (Emergency Response Guidance), are satisfied, the control room operators primarily use the SACRG (Severe Accident Control Room Guidance) prior to the TSC (Technical Support Center) being functional. Then, TSC personnel diagnoses the plant conditions and selects the appropriate SAG (Severe Accident Guideline) using the DFC (Diagnostic Flow Chart). The parameters in the DFC are prioritized. If the setpoint for a given parameter is exceeded, one of the SAGs is referenced for evaluation. When referenced from the DFC, the TSC would evaluate the benefits and negative impacts of implementing the various severe accident management strategies contained in a referenced guideline and then decide whether to implement any of the strategies.

The task associated with the reactor cavity flooding strategy selected for the case application is adapted from the SAG-4 in SAMG, INJECT INTO CONTAINMENT, among the eight SAGs. The original SAG-4 in SAMG is composed of 1) Identification of the system availability, 2) Evaluation of negative and positive impacts, 3) Implementation and verification of strategy, and 4) Identification of long term concerns. But, in this study, we defined for the case application task procedures from the point where to decide whether to reference the SAG-4 using the DFC to the point where to decide whether to implement the strategy using the SAG. Then, the task procedures were divided into three tasks as follows:

- Task RCF1 : Decide whether to reference the SAG-4 using DFC.
- Task RCF2 : Identify the availability of the relevant system for the implementation of the strategy in SAG-4.
- Task RCF3 : Decide whether to implement the strategy by evaluating the negative impacts from the implementation of the strategy and the consequences of NOT implementing the strategy.

In this paper, we summarized the results of the application of three methods to the only Task RCF3. The readers who want to look at all the results are recommended to refer to Reference [19]. Task RCF3 consists of the following task steps in summary:

1. Evaluate the negative impacts relevant to the implementation of the strategy.
2. Evaluate the mitigating actions for the negative impacts.
3. Evaluate the consequences of NOT implementing the strategy.
4. Decide whether to implement the strategy by evaluating the negative impacts from the

implementation of the strategy and the consequences of NOT implementing the strategy.

3.2. Application of Each Method

The application summaries of three HEA methods to Task RCF3 are shown in Table 1, 2 and 3, respectively. The three results are described briefly as follows.

3.2.1. Summary of HRMS Application

Table 1 shows the results of the application of HRMS method to Task RCF3. The task step 1 is to evaluate the negative impacts such as 'insufficient injection source' and 'containment severe challenge from a hydrogen burn'. This step comprises 'observation' and 'state identification' stages, the probable EEMs are 'confusing information gathered' and 'incorrect-state identification', and the PEMs associated with the EEMs are 'integration failure' and 'inaccurate recall'. In the step '1.1.1. Check if core has not been reflooded', the operator(s) gains from his memory the fact on whether the core has been reflooded or not. Since this may confuse the operator(s) under accident management situation, it is required to prepare another operator aid so that he may not depend on only his memory. The step 2 is related to the evaluation of mitigating actions for negative impacts. This requires the cognitive stages of 'evaluation' and 'procedure selection', for the operator(s) should evaluate whether it is possible to take an action of the given mitigating actions in a given plant state and to make a positive effect to the plant. The EEM associated with this step could be the 'procedure inadequately formulated' because the primary activity of this step is relevant to the procedure formulation of the suggested mitigating actions. And the PEM could be 'inadequate mental model', for the operator(s) may be inexperienced in this procedure.

The step 3 is related to the evaluation of the consequences of not implementing the strategy. Quantifying the consequences is quite difficult due to the uncertainties associated with the phenomena and the information. Since this step is related to the evaluation of consequences, the cognitive function is primarily performed at the 'interpretation' stage. At this stage, the incorrect or incomplete interpretation as an EEM could be most probable due to lack of knowledge (PEM: inadequate mental model). The step 4 is to make a decision whether to implement the strategy or not based on the above evaluations. This step could be difficult depending on the event scenarios because of the various uncertainties. This step could appear the judgment error (EEM) due to the inadequate mental model (PEM).

3.2.2. Summary of CREAM Application

Table 2 shows the results of the application of CREAM method to Task RCF3. Since the cognitive activity types associated with the step 1 are the kinds of 'observe', 'compare', and 'identify', they are composed of 'observation' and 'state identification' cognitive functions. And, the relevant cognitive function failure could be 'I2. decision error' associated with 'state identification'. The step 2 requires the operator(s)' knowledge and experiences to prepare the specific mitigating actions, therefore the cognitive activity type could be the 'evaluate' type, and the failure could take place in the process of formulating relevant procedures (i.e., P2. inadequate plan formulated). The step 3 and 4 are related to the evaluation of consequences and the decision-making, respectively, therefore, the 'evaluate' cognitive activity type and the 'I2. decision error' failure

Table 1. Application of HRMS to 'Reactor Cavity Flooding Tasks'

Task Step	IPS (Cognitive Stage)	EEM	PEM
Task 3 : Making a decision on whether to implement the strategy.			
1. Evaluate the following negative impacts associated with implementing the strategy.			
1.1. Check the following two conditions, and if both conditions are satisfied, there will be 'insufficient injection source'.	System state identification	Incorrect-state identification	Integration failure
1.1.1. Check if core has not been reflooded.	Observation/System state identification	Confusing information gathered	Inaccurate recall
1.1.2. Check the following condition: RWST level < (L09) %.	Observation/System state identification	Incorrect-state identification	Integration failure
2. Evaluate mitigating actions.			
2.1. If there is a possibility of insufficient containment injection source, then evaluate the following mitigating actions.			
2.1.1 Evaluate the action of 'Increase RWST refill rate'.	Evaluation/Procedure selection	Procedure inadequately formulated	Inadequate mental model
2.1.2 Evaluate the action of "Control containment injection flowrate to maintain RWST water level greater than (L09) %.	Evaluation/Procedure selection	Procedure inadequately formulated	Inadequate mental model
3. Evaluate the consequences of NOT injecting into the containment (Containment challenge due to Basemat Meltthrough, RPV failure may not be delayed, Fission products from ex-vessel core debris, Consequences of HPME, Combustible gas generation due to CCI, Recirculation problem).	Interpretation	Incorrect or Incomplete interpretation	Inadequate mental model
4. Determine if containment injection should be initiated by comparing the consequences of NOT injecting into the containment versus the negative impacts of injecting into the containment.	Evaluation	Judgement error	Incomplete mental model

Table 2. Application of CREAM to 'Reactor Cavity Flooding Tasks'

Task Step	Activity Type	COCOM functions											
		Observation			Interpretation			Planning		Execution			
		O1	O2	O3	I1	I2	I3	P1	P2	E1	E2	E3	E4
Task 3 : Making a decision on whether to implement the strategy.													
1. Evaluate the following negative impacts associated with implementing the strategy.													
1.1. Check the following two conditions, and if both conditions are satisfied, there will be 'insufficient injection source'.	Identify					◆							
1.1.1. Check if core has not been reflooded.	Observe/Identify		◆										
1.1.2. Check the following condition: RWST level < (L09) %.	Observe/Compare					◆		◆					
2. Evaluate mitigating actions.													
2.1. If there is a possibility of insufficient containment injection source, then evaluate the following mitigating actions.													
2.1.1 Evaluate the action of 'Increase RWST refill rate'.	Evaluate								◆				
2.1.2 Evaluate the action of "Control containment injection flowrate to maintain RWST water level greater than (L09) %.	Evaluate								◆				
3. Evaluate the consequences of NOT injecting into the containment (Containment challenge due to Basemat Meltthrough, RPV failure may not be delayed, Fission products from ex-vessel core debris, Consequences of HPME, Combustible gas generation due to CCI, Recirculation problem).	Evaluate					◆							
4. Determine if containment injection should be initiated by comparing the consequences of NOT injecting into the containment versus the negative impacts of injecting into the containment.	Compare/Evaluate					◆							

• O2: Wrong identification, I2: Decision error, P2: Inadequate plan

Table 3. Application of PHECA to 'Reactor Cavity Flooding Tasks'

Task Step	Taks Type	IPS	Response type	Error type
Task 3 : Making a decision on whether to implement the strategy.				
1. Evaluate the following negative impacts associated with implementing the strategy.				
1.1. Check the following two conditions, and if both conditions are satisfied, there will be 'insufficient injection source'.	Integration	I1,I2,I3,I6	Sequence/Action	OTHER THAN, PART OF
1.1.1. Check if core has not been reflooded.	Requirement	I3,I5,I6	Sequence/Get information	NOT DONE, OTHER THAN
1.1.2. Check the following condition: RWST level < (L09) %.	Requirement	I3,I5,I6	Sequence/Get information	NOT DONE, OTHER THAN
2. Evaluate mitigating actions.	Stimulus	I1,I2,I6	Sequence/Action	NOT DONE
2.1. If there is a possibility of insufficient containment injection source, then evaluate the following mitigating actions.	Stimulus	I1,I2,I6	Sequence/Action	NOT DONE
2.1.1 Evaluate the action of 'Increase RWST refill rate'.	Interpretation	I1,I2,I3,I4, I5,I6	Sequence/Get information	OTHER THAN, PART OF
2.1.2 Evaluate the action of "Control containment injection flowrate to maintain RWST water level greater than (L09) %.	Interpretation	I1,I2,I3,I4, I5,I6	Sequence/Get information	OTHER THAN, PART OF
3. Evaluate the consequences of NOT injecting into the containment (Containment challenge due to Basemat Meltthrough, RPV failure may not be delayed, Fission products from ex-vessel core debris, Consequences of HPME, Combustible gas generation due to CCI, Recirculation problem).	Interpretation	I1,I2,I3,I4, I5,I6	Sequence/Get information	NOT DONE, OTHER THAN, PART OF
4. Determine if containment injection should be initiated by comparing the consequences of NOT injecting into the containment versus the negative impacts of injecting into the containment.	Interpretation	I1,I2,I3,I4, I5,I6	Sequence/Action	OTHER THAN, PART OF

could be dominant.

3.1.5. Summary of PHECA Application

Table 3 shows the results of the application of PHECA method to Task RCF3. The step 1 is related to the 'observation' and 'state identification'. The task type associated with 'observation' is the 'requirement' because the 'observation' activity is required to identify the system state. And, the task type associated with 'state identification' is the 'integration'. For the steps which requires more than one information, the error type 'OTHER THAN' or 'PART OF' was selected, for the operator(s) may overlook or omit some of information. The step 2 could be regarded as the 'interpretation' type. The step 3 and 4 also could be the 'interpretation' type, and the 'PART OF' or 'OTHER THAN' error type could happen due to the incomplete interpretation from the lack of knowledge.

4. Results and Interpretation of the HEA Application

As shown in Table 1, 2, and 3, HRMS and CREAM give much similar error types between each other for a given AM task. HRMS, however, seems to provide more specific error types than CREAM, and CREAM seems to be inclusive of HRMS. PHECA shows a little obscure error types of which meaning is not easily understood if the error type is not matched to the task procedure.

Through the case study, several merits and demerits of each method are identified. HRMS classifies the EEMs and PEMs based on the Rasmussen's step-ladder model. It adopts the eight stages of human cognition as the Rasmussen's model suggests. For this reason, it is obscure to distinguish inter-stages for some tasks in deciding to which stages a task step is related. For instance, the stages, such as 'identification of system state', 'interpretation', 'evaluation', and 'goal selection', sometimes appear overlapped in usual task steps. Another limitation of HRMS is that it does not give any guidance to reflect the task context into error analysis. Accordingly, the assessor considers the context (or work situation) in his (or her) own way, which can give rise to inconsistent error analysis or different outputs between assessors.

CREAM is assessed to be more systematic in approach than others. At the beginning of the analysis, CREAM assesses the work context, and then performs error analysis based on the context factors, i.e., CPCs. While the HRMS reflects the context implicitly into the error analysis, CREAM does it explicitly by providing the specific factors to be considered. CREAM however does not present the inter-relationship between the CPCs and the cognitive function failures. The unique feature of CREAM is that it uses the simple model of human cognition and the concept of cognitive activity type, which unload the obscurity of inter-cognitive-stages that has arisen in HRMS. On the other hand, the cognitive function failures are too a few in number for the error analysis of accident management task to give specific error types.

PHECA shows somewhat limitation for the predictive use of human error analysis because it was originally developed for a system design aid. One of the characteristics of PHECA is that it has a kind of links to help the assessor to identify error causes. Using the established links between each of three types (i.e., task type, response type, and error type) and error causes, the assessor has only to decide which types could be possible in a task step. This kind of links can be useful on one hand, but, on the other hand, they were not validated by any of sound theories or experimental data. This may not only decrease the feasibility of the analysis results, but also give little insights to the assessor because he or she does not know the inner-mechanisms of the links.

Table 4 summarizes the characteristics and limitations of each method. In addition to these, as one of comparison points, the human error describing factors were introduced. The human error describing factors is used to explain under what conditions a given task is performed (context), what factors could cause human error to occur or how human error could occur (error cause), and what kind of human error could be manifested (error type).

HRMS does not use the factors relevant to the description of the context or situation under a given task is performed. Neither does PHECA. CREAM, however, suggests the common performance conditions (CPCs) to be analyzed as the first step, on which the identification of human error mode should be based. For the factors to describe error causes, HRMS uses the psychological error mechanisms (PEMs), PHECA does the error causes and the performance shaping factors (PSFs), but CREAM does not provide the error cause related factors specifically. For the factors relevant to error mode, HRMS uses the external error modes (EEMs), and PHECA does the error type, which is a different form from HRMS. CREAM uses the cognitive function failures. Both the HRMS and CREAM' s error mode are based on the cognitive stages.

Table 5 summarizes the results of the comparative study from the viewpoint of applicability to HEA in NPPs. The study shows that HRMS and CREAM are basically applicable to the analysis of cognitive errors of accident management tasks. CREAM, however, is assessed to be more appropriate than others for the HEA in NPPs.

From the case study, we could also derive the specific requirement for further development of HEA framework in NPPs. They can be summarized into 7 items as follows.

- It should have capability to deal with the predictive HEA in NPPs. In a given situation during AM, the method should be able to predict what kinds of error modes could manifest themselves, through which psychological error mechanisms, and by which error causes.
- It should focus on cognitive error analysis, since most of AM tasks require human cognitive functions such as diagnosis, state identification, planning and decision making.
- It should be able to analyze various levels of human behaviors such as skill-based, rule-based, and knowledge-based behavior. In particular, the method could treat a human task that may not be described in detail in the AM procedure due to lack of knowledge or uncertainty of phenomena.
- It should identify error of commission (EOC) which can lead to severe consequences by intentionally inappropriate response.
- It should have adequate taxonomies about error type, error cause, and influence factors to human performance, specially for AM situation in NPPs.
- It should cover both of the qualitative and quantitative analysis of human error. And the quantification of error probability should be based on the qualitative analysis.
- It should be able to conduct error analysis with acceptable human resources. In addition the method should maintain the consistency in its results between analysts by minimizing the ambiguity in each step of analysis procedure.

Table 4. Characteristics of Three HEA Methods

Methods	Human error describing factors			Characteristics	Limitations
	context	error cause	error type		
HRMS	N/A	65 PEMs	45 EEMs	• Provision of the probable EEMs (External Error Modes) and PEMs (Psychological Error Mechanisms) based on the Rasmussen's step-ladder model	• Obscurity in distinguishing the inter-cognitive-stages, esp. between state identification, interpretation, evaluation, and goal selection. • Missing of the guidance for the assessment of context.
CREAM	8 CPCs	N/A	12 Cognitive function failure	• Guides the assessors firstly considers the given context using CPCs (Common Performance Conditions). • Uses the Simple Model of Cognition (SMoC) composed of 4 cognitive stages. • Facilitate the error analysis by providing the concept of cognitive activity types of which cognitive stages are predefined.	• Lack of specific guidance between the CPCs and the cognitive function failures. • Missing of the description of error causes or mechanisms.
PHECA	N/A	35 Error causes	10 Error types	• A technique developed for system design aid. • Representing the design factors as PSFs. • Established links between 3 types (task type, response type, and error type) and error causes, and error causes and PSFs.	• Some limitation for use in error prediction because the method focuses on identification of system design factors. • Gains little insight about error mechanisms because the inner-structure of the established links is omitted. • Established links were not validated.

Table 5. Comparative Results of Three Methods in Viewpoint of Applicability to NPPs

Method / Factor	HRMS	CREAM	PHECA
Predictivity	• predictive model • predict error types and error causes in detail	• predictive model • predict error types in detail based on context	• predictive model (restrictive) • predict PSFs
	Appropriate/**Acceptable**/Inappropriate	Appropriate/**Acceptable**/Inappropriate	Appropriate/Acceptable/**Inappropriate**
Cognitive model	• Rasmussen' s Step-ladder Model (SLM) • detailed cognitive stages(8), difficulty in application	• Hollnagel' s SMoC (simplified SLM) • simple cognitive stages(4), no difficulty in application	• Rasmussen' s Step-ladder Model • detailed cognitive stages(6), difficulty in application
	Appropriate/**Acceptable**/Inappropriate	**Appropriate**/Acceptable/Inappropriate	Appropriate/**Acceptable**/Inappropriate
Classification structure	• cognitive stage : 8 stages • task type : N/A • error type : 45 external error modes (EEMs) • error cause : 65 psychological error modes (PEMs) • context factor : N/A	• cognitive stage : 4 stages • task type : 15 cognitive activity types • error type : 12 types • error cause : N/A • context factor : 8 common performance conditions (CPCs)	• cognitive stage : 6 stages • task type : 7 types • error type : 10 types (HAZOP deviations) • error cause : 35 types (8 groups) • context factor : N/A
	Appropriate/Acceptable/Inappropriate	**Appropriate**/Acceptable/Inappropriate	Appropriate/Acceptable/**Inappropriate**

5. Conclusions

There have been several approaches to develop a new HEA method since the error of cognitive process was known as a major contributor to the erroneous human response in emergency situations. But since the framework of error analysis method is strongly dependent on the purpose and the application field of the analysis, it is needed to develop a new method for the cognitive HEA of the tasks in NPPs.

As a starting point, we reviewed and analyzed the cognitive HEA methods through the application to a task in AM phase of NPPs. We selected three methods, i.e., HRMS, CREAM, and PHECA, based on the extensive review of HEA methods recently developed, and assessed their applicability to the cognitive HEA in NPPs. We applied the three methods to the task of reactor cavity flooding after core damage.

The findings gained from the study can be summarized as follows. Firstly, CREAM turned out to be more appropriate than others from the viewpoint of overall framework such as the systematic of the approach, the models being used, and the classification structure. But, for more appropriate to HEA of AM tasks in NPPs, CREAM should have more specific classification of its taxonomy, which provides nuclear specific types of error modes, causes and influence factors. Secondly, HRMS is also applicable to the analysis of accident management tasks. However, the cognitive stages being used are too detailed to apply to the task, and it would be better to provide a guidance for the assessment of the work context. PHECA is considered to be less appropriate for the predictive HEA technique as well as for the analysis of accident management tasks. Finally, from the case study we could establish the basic requirement for the development of a new HEA method for accident management tasks in NPPs, and verify some of the functions of HRMS and CREAM could be made use of in developing the new method.

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