Available online at www.sciencedirect.com

ScienceDirect

Procedia Manufacturing 00 (2015) 000–000

SAND2015-2706C

Procedia MANUFACTURING

www.elsevier.com/locate/procedia

6th International Conference on Applied Human Factors and Ergonomics (AHFE 2015) and the Affiliated Conferences, AHFE 2015

Insights from Pilot Testing of the IDHEAS HRA Method

Huafei Liao[a]*

[a]*Sandia National Laboratories, Albuquerque, NM, USA, 87185*

Abstract

Human reliability analysis (HRA) is used in the context of probabilistic risk assessment (PRA) to provide risk information regarding human performance to support risk-informed decision-making with respect to high-reliability industries. The IntegrateD Human Event Analysis System (IDHEAS) was developed as a new HRA method with an intention to reduce unnecessary and inappropriate variability in HRA results and improve the reliability of human error probability (HEP) estimates. The method has a strong theoretical basis of human performance and cognitive psychology, and employs a cause-based quantification model. This paper documents a study conducted by the author to pilot test IDHEAS to (1) identify issues that needed be addressed and (2) provide feedback to refine the method before the method was finalized. It first provides an introduction on IDHEAS, and presents sample IDHEAS analysis results for illustration purposes. Then, it discusses insights from the testing in terms of strengths and weaknesses of the method.

Peer-review under responsibility of AHFE Conference.

Keywords: Human reliability analysis; the IntegrateD Human Event Analysis System (IDHEAS), nuclear power plant (NPP)

1. Introduction

Human reliability analysis (HRA) can be defined as the use of systems engineering and behavioral science methods in order to render a complete description of the human contribution to risk and to identify ways to reduce that risk. It is used in the context of probabilistic risk assessment (PRA) to provide risk information regarding human performance to support risk-informed decision-making with respect to high-reliability industries. For

* Corresponding author. Tel.: +0-505-284-6170; fax: +0-000-000-0000 .
E-mail address: hnliao@sandia.gov

Peer-review under responsibility of AHFE Conference.

example, risk information from HRAs is an important input to the U.S. Nuclear Regulatory Commission (NRC) for their licensing and regulatory decisions.

In the current state of the art of HRA, variability in HRA results is still a significant issue, which in turn contributes to uncertainty in PRA results. The existence and use of different HRA methods that rely on different assumptions, human performance frameworks, quantification algorithms, and data, as well as inconsistent implementation from analysts, appear to be the most common sources for the issue, and such issue has raised concerns over the robustness of HRA methods.

With sponsorship of the U.S. Nuclear Regulatory Commission (NRC) and Electric Power Research Institute (EPRI), the IntegrateD Human Event Analysis System (IDHEAS) was developed as a new HRA method to advance the state of the art of HRA [1]. With an intention to reduce unnecessary and inappropriate variability and improve the reliability of HEP estimates, it explicitly or implicitly integrates many good features and strengths of existing HRA methods and practices. For example, the strength of ATHEANA's qualitative analysis and CBDT's causal structured approach that allows for traceability of HEP calculation have been incorporated into IDHEAS (see [1] for more discussion). Furthermore, by updating the theoretical basis of HRA with the state of knowledge on human performance and cognitive psychology, IDHEAS has the ability to address the cognitive aspects of human behavior within the qualitative analysis, which has been identified as a limitation of most HRA methods, and perform the quantitative analysis with an enhanced understanding of the influence of contextual factors. Since the method is based on cognition, and can, therefore, provide the basic fabric for handling human performance in different situations, issues such as errors of commission and errors of omission are treated at the level of the cognitive mechanism contributing to the error rather than as a different class of errors.

The theory of macrocognition is adapted in the human performance model within IDHEAS to elucidate the complexity of human cognition. Macrocognition is a term originally coined by Cacciabue and Hollnagel [2] to describe cognition in real-world settings, where domain experts must make complex and rapid decisions in risky or high-stakes situations [3]. According to the macrocognition theory, a macrocognitive function is the high level mental activity that must be successfully accomplished to perform a task or achieve a goal in a naturalistic environment [4]. In IDHEAS, five macrocognitive functions are identified: *detecting and noticing*, *understanding and sensemaking*, *decision making*, *action*, and *team coordination* [5].

Another important concept in IDHEAS is that of proximate causes. A proximate cause is the result or manifestation of the failure of a cognitive mechanism, and thus can be readily identifiable as the basic contributing cause of the failure of a macrocognitive function. The proximate causes are identified through an extensive literature survey (see [5] for more details).

IDHEAS employs a cause-based quantification model and assesses the HEP of a human failure event (HFE) based on the explanations of why the HFE might occur in terms of macrocognitive functions and proximate causes. The model has the following two major elements (see [1] for more details). The first is crew failure modes (CFMs). Similar to the Information-Decision-Action (IDA) model [6-7], nuclear power plant (NPP) operators' interaction with the plant is divided into three phases in IDHEAS: *plant status assessment*, *response planning*, and *action or execution*. These phases are proposed to occur sequentially; that is, progressing to a later phase assumes success in the previous phase(s). Fourteen CFMs are identified to describe the various kinds of failures that can potentially occur and are manifested to an outside observer in the three phases. As shown in Table 1, a majority of the CFMs identified fall within the plant status assessment phase. These CFMs include failing to obtain and process the critical data required to make a correct plant status assessment. CFMs within the response planning stage assume a correct plant status assessment has been made, but an error occurs in formulating the response and deciding upon a course of action. Finally, CFMs within the final stage of action/execution cover errors that occur in either performing the action incorrectly (i.e., an error of commission) or in not performing the action at all (i.e., an error of omission).

The second element is decision trees (DTs). Similar to Cause-Based Decision Tree (CBDT), a decision tree (DT) is constructed to represent each CFM and illustrate possible paths to the CFM. The branching points within each DT elucidate the performance influencing factors (PIFs) that are the most relevant to the cognitive mechanisms that can result in the CFM. The PIFs are contextual factors that influence the likelihood of activation of the proximate causes of macrocognitive function failure. For each CFM, the relevant PIFs were determined based on whether they can lead to the CFM in question in an observable and quantifiable manner for internal at-power NPP events (see [1, 5] for more details). Fig. 1 shows a DT for CFM Wrong data Source Attended To. If the characteristics associated with the PIF at a branch point are optimal to good performance (i.e., no identifiable negative PIF characteristic), the down direction is chosen; otherwise the up branch is chosen.

Table 1. Crew failure modes (CFMs) within the phases they represent

Phase of response	**Plant status assessment**	**Response planning**	**Execution**
Crew failure mode (CFM):	Key alarm not attended to†	Delay implementation†	Fail to initiate execution
	Data misleading or not available	Misinterpret procedure†	Fail to execute response correctly†
	Premature termination of critical data collection	Choose inappropriate strategy	
	Critical data misperceived†		
	Wrong data source attended to†		
	Critical data not checked with appropriate frequency		
	Critical data dismissed/discounted†		
		Misread or skip step in procedure*†	
	Critical data miscommunicated**†		

* May occur in either 'Response Planning' or 'Execution' phases.

** May occur in any of the three phases.

† CFM for which data was collected.

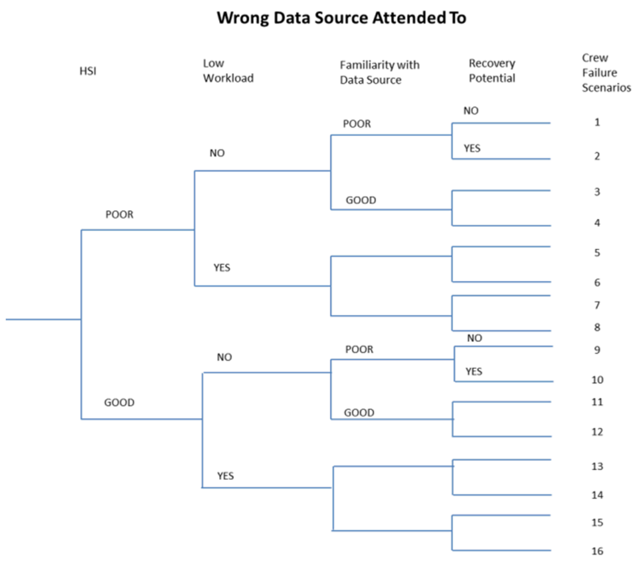

Fig. 1. Decision tree for CFM 'Wrong Data Source Attended To'.

The advantage of the quantification model described above is that it can prompt the analyst to assess the existence of and/or the "strength" or relevance of those factors that have been identified as affecting the occurrence and persistence of each CFM. The information concerning these factors can be determined either directly from the definition of the PRA scenario, or by review of operating practices, details of the procedures, the nature of the training and experience, etc. As a result, the HEP for an HFE is assessed on the basis of explanations of why the HFE might occur in terms of cognitive failure mechanisms, the consequences of those mechanisms, and the characteristics of the PIFs.

An important step in developing the quantification model is to establish a probability scale for the end point of the DT. This is achieved through expert elicitation because of the lack of real-world data. The objective of this study was to collect applicable human performance data and relevant information as a reference and technical basis to support and therefore reduce uncertainty in expert judgments regarding the likelihood that the context implied by the path through the DT results in the failure represented by a CFM.

This paper documents a study conducted by the author to pilot test IDHEAS to (1) identify issues that needed be addressed and (2) provide feedback to refine the method before the method was finalized. Note that since some HEPs associated with the DT branches were not developed at the time of testing, the testing focused more on the qualitative insights obtained with IDHEAS. That is, the study focused on the method's ability to identify operator performance driving factors and failure mechanisms than matching the HEPs predicted by IDHEAS with failure probabilities derived from the simulator data (see Section 2). Also note that a separate study is undergoing to systematically test IDHEAS before its deployment. Although the two studies were somewhat related, the latter is larger in scale in terms of scope and the number of analysts. Thus, the findings of this study are considered preliminary and the latter study is expected to produce more conclusive findings.

2. Testing Scenarios

The study tested IDHEAS with the three scenarios and five HFEs developed in the US HRA Empirical Study (see [8] for detailed description on scenarios and HFEs). Scenario 1 was a total loss of feedwater (LOFW) followed by a steam generator tube rupture (SGTR), for which three HFEs were defined. Scenario 2 was a loss of component cooling water (CCW) and reactor cooling pump (RCP) sealwater, for which one HFE was defined. Scenario 3 was an SGTR scenario without further complications, for which one HFE was defined. The scenarios were simulated by four crews from a participating US NPP on a full-scope training simulator in that study.

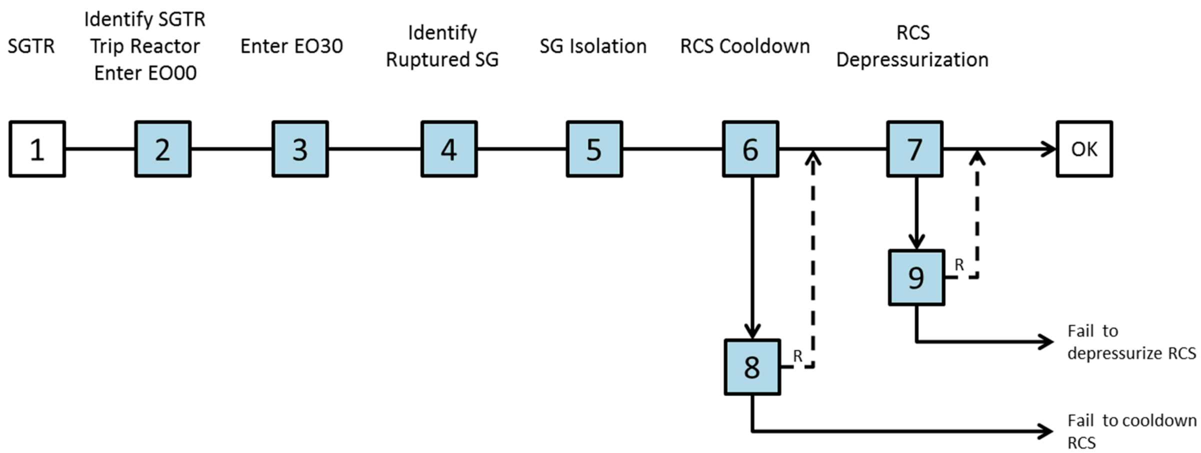

Fig. 2. Crew Response Tree (CRT) of Scenario 3

In general, IDHEAS analysis process consists of the following steps:

1. HFE identification and definition.
2. Feasibility assessment in terms of various factors, including time requirements, manpower, cues, procedure, training, accessible location, and equipment availability.
3. Characterization of the expected success path.
4. Identification of critical tasks and sub-tasks and construction of a crew response tree (CRT) to represent the critical tasks and sub-tasks.
5. Development of a timeline and an operational narrative.
6. Identification of opportunities for operators to recover from errors to be incorporated into the CRT.

7. CFM evaluation and HEP calculation
8. Model integration though reasonableness check of HEPs and capture of potential dependencies between actions in the same sequence.

Since the focus of the paper is insights from the testing of IDHEAS, only the CRT and CFM evaluation results of Scenario 3 are shown below in Fig. 2 and Table 2 for illustrative purpose. Note that since HEPs for the DTs were not developed at the time of testing, HEPs are not provided in Table 2.

Table 2. Crew failure modes (CFMs) applicable for each Crew Response Tree (CRT) node

CRT Node	Crew failure modes	Scenario #
2	Key Alarm not Attended to	7
3	Misread or Skip Critical Step(s) in Procedure	13
4	Fail to Execute Simple Response Correctly	15
	Misread or Skip Critical Step(s) in Procedure	13
5	Fail to Execute Complex Response Correctly	15
	Misread or Skip Critical Step(s) in Procedure	13
	Critical Data not Checked/Monitored with Appropriate Frequency	11
6	Fail to Execute Complex Response Correctly	15
	Misread or Skip Critical Step(s) in Procedure	14
	Critical Data not Checked/Monitored with Appropriate Frequency	11
7	Fail to Execute Complex Response Correctly	15
	Misread or Skip Critical Step(s) in Procedure	14
	Critical Data not Checked/Monitored with Appropriate Frequency	11

3. Insights from the pilot testing

3.1. Strengths

3.1.1. Structured qualitative analysis framework

IDHEAS qualitative analysis process consists of Step 1 through Step 6 listed in Section 2. These steps constitute a structured framework that seems to be valid, logic and robust. In addition, since the opportunities for both errors and for recovery are represented as nodes on the CRT, the CRT provides a graphical tool to communicate, illustrate, and document of the qualitative analysis results, which contribute to traceability of qualitative analysis. Thus the qualitative analysis framework can not only help analysts at differing levels of expertise produce a highly detailed qualitative analysis but also is expected to reduce inter-analyst variability.

3.1.2. Consideration of cognitive activities

The consideration of cognitive activities is an important contributor to the adequacy of HRA predictions, because it can help analysts understand the difficulties in operators' situation assessment and/or response planning while a scenario progresses. However, the ability to address operator cognition is a limitation of most HRA methods. IDHEAS is a method firmly grounded in the state-of-knowledge on human factors and human performance. Thus, it is not surprising to see that IDHEAS has relatively more focus on addressing the cognitive aspects of human performance compared to other HRA methods. This is evidenced by the fact that most of the CFMs fall within the status assessment and response planning phases (see Table 1).

Human nature never changes, because it is governed by a set of cognitive mechanisms that do not change from individual to individual. The mechanisms dictate how human behavior is driven or shaped by various contextual factors, and serve as the basis for the contextual factors to express themselves through observable human behavior. In other words, the variability in human behavior originates from the variability in the contextual factors. Human behavior will repeat itself with slight variations when the same or similar contextual factors arise in the future. The concept of CFMs allows analysts to addresses human failure at the level of the underlying cognitive mechanisms and associated contextual factors, thus, as mentioned above, errors of commission and errors of omission are not treated as a different class of errors.

Since the theoretical framework used to ground the IDHEAS quantification model is based on cognition by explicating the causal relationships between observed human performance and contextual factors, the method (1) provides a framework for analysts to identify and characterize contextual factors and failure mechanisms that can cause failures at the cognitive level and (2) provides a structured and systematic way to incorporate such information into the quantification process. That is, IDHEAS lends analysts the ability to understand, characterize, and then quantify operator cognitive failure with reduced subjectivity. Given that complex scenarios normally involve relatively more cognitive challenges compared to easy scenarios, IDHEAS' ability to address diagnosis activities as operators work through procedures is another edge to deal with scenario complexity with reduced reliance on analysts' experience and expertise (see Section 3.1.3).

3.1.3. Development of detailed timelines and operational narratives to treat complexity

One of the reasons for the strength of the qualitative analysis is the need for HRA analysts to develop a detailed performance timeline and a detailed operational narrative to support qualitative analysis. This activity starts at the early stage of the qualitative analysis process and continues in an iterative manner as more information becomes available down the process. The timeline aims to capture (1) the plant status trajectory in terms of the timing of cues and other plant process parameters that are required for operators to correctly perform the required response or to realize an opportunity for recovery, and (2) the time at which operators are expected to reach critical steps in the procedure. The narrative focuses on how operators can successfully respond to a plant event with an emphasis on procedures, cues and associated timing. CFMs and DTs provide a framework and a tool to identify complicating contextual factors. Rather than examining a set of characteristics of the HFE, e.g. assessing procedural guidance and other PSFs at an overall level, the development of the timeline and the narrative requires close interaction with plant experts and a thorough understanding of the scenario, the required tasks, how these are performed, and the contexts for these tasks. That is, the understanding of the HFE is not taken for granted as a basis for the quantification but is instead developed explicitly in the analysis process. As a result, many scenario-specific timing and performance issues can be effectively identified. This is necessary and important for obtaining rich insights into dynamics of complex scenarios. Of course, explicit documentation of the understanding of the HFE increases traceability.

3.1.4. Formal self-consistent quantification approach

The causal logic model employed in IDHEAS provides a formal quantitative approach for translating qualitative findings into quantitative impact. The use of CFMs and DTs ensues that HEPs are assessed in well-defined and self-consistent manner with a systematic and robust exploration of PIFs linked to CFMs. For each DT branch point, questions are provided to help analysts choose DT branches. These questions, to some extent, serve as the guidance for quantitative analysis, and thus can help reduce undue analysts' subjective judgment in accounting for plant- and scenario-specific influences on operator performance. In summary, the quantification approach can help not only reduce inter-analyst variability but also, as discussed in Section 3.1.5, increase traceability.

3.1.5. Traceability

Traceability clearly constitutes one of the major strengths IDHEAS. As noted above, the qualitative analysis framework and the use of CRTs enhance the traceability of the qualitative analysis. The traceability of the quantitative analysis can be attributed to its quantification approach. The DTs establish a clear link between the quantification inputs and the HEP values. This makes the derivation of the HEPs with the DTs and the identification of which PIFs contributed to the HEPs fully traceable and repeatable (given the same quantification inputs). How the various PIFs are weighted in determining the final HEP relative to each other can be determined by examining the contributions of the factors from the DTs. Analysts' answers to the questions associated with the DT branch points establish the link between the qualitative analysis and the quantification inputs (e.g., PIF ratings). However, since the answers are in the simple form of "Yes" or "No", the method's ability to trace how the PIF ratings are derived from the qualitative analysis or the identification of the failure mechanisms associated with operational expressions is, to some extent, a function of analysts' documentation of their decision process. Particularly, good documentation of the rationale will be necessary to allow traceability, if (1) analysts attempt to stretch the method to incorporate PIFs that are not directly addressed in the DTs or (2) analysts may bias or alter the rating of PIFs based on other information identified that is not covered by the questions associated with DT branches. Nonetheless, the questions provide a good framework and guidance for documenting how the issues and factors identified as relevant and important to HFE failure translate into PSF ratings or identified failure mechanisms.

3.1.6. Insights for error reduction

Rich insights for error reduction can be derived from IDHEAS results. The qualitative analysis process, including development of timelines and operational narratives, supports identification specific potential performance issues for the tasks associated with an HFE. The causal logic model with cognitive mechanisms as its building blocks encourage an exploration of the interaction between dynamic scenario conditions with operators' behavior, and thus provides an explanation of why and how performance issues may arise and what contextual factors are important. These insights are valuable for training, plant design, and risk management decision-making.

3.2. Weaknesses

3.2.1. Fairly extensive resources needed for qualitative analysis

The resources needed for an IDHEAS application is a function of the level of detail of the corresponding qualitative analysis, including the development of the timeline and the operational narrative. For an application with a highly detailed qualitative analysis, the resources can be fairly extensive. However, the value of the highly detailed qualitative results obtained suggests that this cost does have its benefits: quality and traceability of the qualitative results, and insights for error reduction. It should be noted that since IDHEAS was still under development when this study was performed, it did not have a friendly user interface. As a result, much effort was spent on documenting analysis results. Improvement on method usability can help reduce the cost associated with IDHEAS applications.

3.2.2. Judgment in evaluation of PIF levels

Questions are provided for analysts to determine PIF levels at a DT branch point. Some questions rely, to some extent, on subjective descriptions rather than are based on concrete, objective, and measurable criteria. This may hinder the utility of the questions as subjectivity in analysts' interpretation of the questions and judgment in their answers to the questions may become a potential source of inter-analyst variability. In addition, the questions represent of the state of knowledge of the method developers of the factors that need to be evaluated to determine PIF levels. Analysts' judgment will be needed for factors that are not covered by the questions. Thus, the completeness of the questions needs to be tested and improved when necessary. However, even with improvement, it will still be difficult to cover all scenario-specific factors.

3.2.3. Sensitivity of binary decision trees

Although the decision tree approach to quantification can increase method traceability, the binary nature of the trees has been criticized for its unrealistic or simplistic representation of the real world. Within a binary decision tree, each PIF can only have two levels (e.g., high vs. low, good vs. bad). From a qualitative point of view, this approach does not reflect the fact that contextual conditions change on a continuous spectrum. From a quantitative point of view, a change in PIF levels can lead to a significant change in the HEP (e.g., a change of one order of magnitude). That is, as PIFs change on a continuous spectrum, the HEP can change abruptly as in a step function rather than continuously as in a continuous function. The abrupt change in the HEP can cause the method to be very sensitive to analysts' choice of PIF levels, and becomes a source of inter-analyst variability when a PIF is in a gray area between the two levels defined in a DT.

3.2.4. Inadequate guidance for task analysis and CRT construction

Task analysis is a critical part of the HRA qualitative analysis process. At its core, the purpose of task analysis is to identify opportunities for plant operators to fail as input to the quantification of the HEPs. This is achieved by an identification and definition of the critical tasks and critical sub-tasks in the performance of the response. As mentioned above, the CRT is a graphical tool to represent the critical tasks and critical sub-tasks. Although the method provides a clear structure for performing and documenting a task analysis, more guidance would be needed on the scope and depth of a qualitative analysis. Particularly, there was inadequate guidance on task decomposition and identification of critical tasks and critical sub-tasks. Clarification on what constitute a critical task or critical sub-task would also be helpful.

4. Conclusions

Based on discussion above, it is clear that IDHEAS provides a structured qualitative analysis process for analysts to develop an understanding of scenario progression and contextual factors. The cause-based quantification approach ensures self-consistent assessment of HEPs and increase traceability. In addition, the CFMs and DTs provide a framework and a tool to identify many scenario-specific performance issues, address them at the cognitive level, and thus serve as a coherent coupling between qualitative analysis and quantitative analysis (i.e. translating qualitative analysis results into quantitative impact). However, the method is expected to be labor extensive due to its focus on qualitative analysis. Guidance needs to be improved to reduce unnecessary analysts' judgment.

As noted above, the findings of this study are considered preliminary. Due to its limited scope, some important aspects of IDHEAS were not tested. For example, it was not feasible to evaluate inter-analyst variability, which is an important HRA method evaluation criterion, as the present study only involved one analyst. Similarly, since the HEPs for DT end points were not developed, it was not feasible to evaluate whether the method would produce potential optimistic HEPs for difficult HEFs and differentiate HFEs with different levels of complexities (i.e. method sensitivity). Since the HFEs tested in the study were pre-defined, it was also infeasible to test method guidance for HFE identification. More systematic testing efforts are needed to address those questions.

References

[1] U.S. Nuclear Regulatory Commission. NRC/EPRI Draft Report on Integrated Decision-Tree Human Event Analysis System (IDHEAS). Washington, D.C.: U.S. Nuclear Regulatory Commission; 2013.

[2] Cacciabue PC, Hollnagel E. Simulation of cognition: Applications. In J.-M. Hoc, P.C. Cacciabue & E. Hollnagel (Eds.), Expertise and technology: Cognition & human–computer cooperation: 55-73. Hillsdale, NJ England: Lawrence Erlbaum Associates, Inc; 1995.

[3] Klein GA, Ross KG, Moon BM, Klein DE, Hoffman RR, Hollnagel E. Macrocognition. Intelligent Systems, IEEE 2003;18(3): 81-85.

[4] Letsky M. Macrocognition in Collaboration and Knowledge Ineroperability. Paper presented at the 51st Annual Meeting of the Human Factors and Ergonomics Society, Baltimore, MD; 2007.

[5] Whaley AM, Xing J, Boring RL, Hendrickson SML, Joe JC, LeBlanc KL, Lois E. Building a Psychological Foundation for Human Reliability Analysis, NUREG-2114. Washington, DC: U.S. Nuclear Regulatory Commission; 2012.

[6] Shen SH, Mosleh A. Human error probability methodology report. RAN: 96-002. Calvert Cliffs Nuclear Power Plant: BGE; 1996.

[7] Smidts C, Shen SH, Mosleh A. The IDA cognitive model for the analysis of nuclear power plant operator response under accident conditions. I. Problem solving and decision making model. Reliability Engineering & System Safety 1997;55(1): 51-71.

[8] Forester J, Liao H, Dang VN, Bye A, Presley M, Marble J, Broberg H, Hildebrandt M, Lois E, Hallbert B, Morgan T. The US HRA Empirical Study – Assessment of HRA Method Predictions against Operating Crew Performance on a US Nuclear Power Plant Simulator. NUREG-2156. US Nuclear Regulatory Commission, Washington, DC; 2014.