May 14, 2014

The Honorable Allison M. Macfarlane
Chairman
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

SUBJECT: HUMAN RELIABILITY ANALYSIS MODELS

Dear Chairman Macfarlane:

In a November 8, 2006 Staff Requirements Memorandum (SRM), resulting from the October 20, 2006 meeting with the Advisory Committee on Reactor Safeguards (ACRS), the Commission directed us to "work with the staff and external stakeholders to evaluate the different Human Reliability models in an effort to propose either a single model for the agency to use or guidance on which model(s) should be used in specific circumstances." Substantial progress has been made toward meeting the SRM objectives. The staff decided that development of a single methodology is the best approach. Work remains to refine the proposed methods and models into a form that can be used for practical human reliability analysis. This report contains a summary of significant research accomplishments. It also provides detailed recommendations that should be addressed before the methodology is endorsed for use.

During the 614th meeting of the ACRS, May 8-10, 2014, we met with representatives of the NRC staff to review two interim work products from this research.

- Draft NUREG-2114, "Building a Psychological Foundation for Human Reliability Analysis"
- Draft NRC/EPRI report, "An Integrated Decision-Tree Human Event Analysis System (IDHEAS) Method for NPP Internal At-Power Operation"

Our Subcommittee on Reliability and Probabilistic Risk Assessment has met periodically with the staff, their contractors, and personnel from the Electric Power Research Institute (EPRI) for briefings on this research project on April 7, 2010; October 18, 2010; April 20, 2011; December 14, 2011; January 16, 2013; April 24, 2013; and January 15, 2014. During these reviews, we also had the benefit of the documents referenced.

CONCLUSIONS AND RECOMMENDATION ON MAJOR ACCOMPLISHMENTS

1. Draft NUREG-2114 contains valuable information to improve understanding of the theoretical basis for human cognitive performance, the causes for human errors, and a structured framework to assess the contributions to errors in the context of an evolving event scenario. It should be published.

2. Elements of the IDHEAS methodology will enhance documentation of the human reliability analysis (HRA) process, reduce analyst-to-analyst variability in its use, and improve traceability of the bases for differing assessments.

DETAILED RECOMMENDATIONS FOR THE IDHEAS METHODOLOGY

1. The IDHEAS report should document the rationale for excluding specific cognitive mechanisms and performance influencing factors delineated in draft NUREG-2114 from explicit consideration in the assessment of each crew failure mode.

2. The qualitative assessment guidance should emphasize the need to develop operational narratives which adequately describe the entire context of the evolving event scenario, how that scenario affects all information and stimuli in the operators' environment, and factors that may influence personnel response in that context, considering the effects on all plant systems and functions, regardless of their inclusion in the probabilistic risk assessment (PRA) models. Examples of good operational narratives should be provided.

3. A formal and complete expert elicitation process should be conducted to develop human error probabilities and associated uncertainty distributions for each combination of contextual factors in the final version of every decision tree.

4. Uncertainties in the human error probabilities should be derived directly from the expert elicitations.

5. The guidance for estimation of the available time window and the time required to perform each action should include explicit evaluation of the uncertainties in those times. The probability that an action cannot be completed within the available time window should be included as a contribution to the overall HRA results.

6. Formal pilot testing of the IDHEAS methodology should be performed. The testing should be conducted by multiple teams of analysts who have a range of practical experience with evaluating human performance in PRA applications. Teams should include members with expertise in nuclear power plant engineering, operations, and the plant-specific PRA, as well as human performance and HRA. Each team should evaluate the same set of PRA event scenarios that cover a range of human actions and anticipated crew failure modes.

BACKGROUND

The November 8, 2006 SRM evolved from the observation that many HRA methods are currently available to evaluate personnel performance as an integral part of a PRA. There is ample evidence that the analysis results can vary substantially, depending on the selected HRA methodology and different analyst applications of a particular model.

To support their research under the SRM, the staff first convened expert workshops to identify desirable attributes of an HRA model. Those features include a sound underlying technical basis to model human performance, completeness, reliability, repeatability, and transparency. The staff then evaluated existing models and concluded that, while each methodology has specific strengths, no model satisfies all of the desirable attributes. Experience from international and U.S. empirical studies also supported a conclusion that all current methods have some general limitations that contribute to variability in the HRA results for the same human failure event. Those limitations involve lack of a consistent underlying theoretical basis for human cognitive performance, variable emphasis and guidance for performing a scenario-based qualitative assessment to identify the context for each action, inadequate linkage between the qualitative analyses and the quantification models, and differences in the selection and assessment of performance shaping factors. A primary finding was the need for guidance to perform a thorough qualitative analysis, including development of a scenario that adequately describes its evolution from the operators' perspective. Based on these conclusions, the staff decided to develop an integrated HRA methodology that would incorporate the recognized strengths of existing models and provide enhanced methods and guidance to address identified weaknesses.

To address the need for a consistent theoretical basis for human performance, the staff first performed a comprehensive review of contemporary research in the areas of cognitive psychology, human factors, and neuroscience. That review provided the foundation for development of the structured taxonomy of human failure mechanisms and their contributing causes that is described in draft NUREG-2114, "Building a Psychological Foundation for Human Reliability Analysis."

To address shortcomings in the evaluation of human actions and the quantification of human error probabilities for PRA applications, the staff and EPRI have collaborated to develop the Integrated Decision-tree Human Error Analysis System (IDHEAS) methodology. This effort has been focused initially on the application of HRA methods and models to evaluate operator response to internal events such as transients, failures of support systems, and losses of reactor coolant that occur during plant power operation. The approach takes advantage of the procedural guidance that is available for many of these actions and the extensive experience among nuclear power plant personnel and HRA experts in evaluating these scenarios. The resulting methods and models are documented in the draft NRC/EPRI report, "An Integrated Decision-Tree Human Event Analysis System (IDHEAS) Method for NPP Internal At-Power Operation." The staff and EPRI are currently extending the IDHEAS methodology to be more generally applicable for evaluation of human performance during other types of scenarios such as fires, floods, and seismic events, and for events that occur during other plant operating modes.

DISCUSSION

Our review focused on the following interim work products from this research.

Draft NUREG-2114, "Building a Psychological Foundation for Human Reliability Analysis"

The taxonomy in draft NUREG-2114 is derived from an extensive review of contemporary research on cognitive psychology and the causes for human errors. It is specialized for applications in the nuclear power plant domain, which involve trained personnel, a structured team of responders, and actions that are often guided by procedures. In this context, a person's ability to achieve a desired outcome involves five fundamental macrocognitive functions: Detecting and Noticing, Understanding and Sensemaking, Decision Making, Action, and Teamwork. Each macrocognitive function is examined to progressively identify proximate causes (cognitive failures), cognitive mechanisms, and performance influencing factors that affect a person's behavior.

The hierarchical framework in draft NUREG-2114 supports a systematic assessment of possible contributions to human errors in the context of a PRA event scenario. The intermediate constructs of proximate causes and cognitive mechanisms demonstrate the extent to which the framework accounts for the causes for human errors. They describe how failures of each macrocognitive function may evolve through the cognitive processing of available information. The structure also shows how causal mechanisms are related to distinct performance influencing factors such as the availability and quality of control room displays, clarity and applicability of procedures, training, and personnel experience that can be evaluated objectively within the context of the PRA event scenario model.

The taxonomy in draft NUREG-2114 was developed to apply universally to any HRA methodology. As such, it does not provide guidance for assigning a relative importance to each performance influencing factor, evaluating its degree of goodness or badness, or a methodology for quantification of human error probabilities. Guidance for those elements of the analysis process depends on details of the particular HRA methodology and its associated quantification models. However, a proposed HRA methodology would be deficient if it does not clearly demonstrate how it incorporates these fundamental elements of human performance.

This research has reached a mature level of development. Draft NUREG-2114 contains valuable information to improve understanding of the theoretical basis for human cognitive performance, the causes for human errors, and a structured framework to assess the contributions to errors in the context of an evolving event scenario. It should be published.

Draft NRC/EPRI report, "An Integrated Decision-Tree Human Event Analysis System (IDHEAS) Method for NPP Internal At-Power Operation"

The following elements of the IDHEAS methodology will enhance documentation of the HRA process, reduce analyst-to-analyst variability in its use, and improve traceability of the bases for differing assessments.

- Timelines are used to document information about progression of the event scenario; the time window that is available to complete the desired actions; emergence of operator cues; key transitions in expected operator performance; and the time that is needed for personnel to diagnose the situation, decide what to do, and implement those decisions.

- Crew response trees document the analyst's understanding of key elements of the operators' expected response, including their use of procedures, transition points that introduce the possibility for errors, the potential consequences from those errors, and opportunities for recovery before an undesired condition occurs. The crew response trees and their documentation also facilitate development of the operational narrative, the qualitative assessment of personnel performance, and the identification of salient factors which influence that performance.

- The decision tree framework provides a single display that consolidates the wide range of contextual situations identified during the qualitative analyses that support development of the crew response trees. Each "path" through the decision tree represents a particular combination of those contextual factors. In practice, an analyst identifies the scenario-specific context for particular branch points in the crew response tree, and then looks up that combination on the decision tree to find the corresponding quantification result. The structured questions of the decision tree provide a consistent scope of analyst assessments of key performance influencing factors that affect each relevant crew failure mode. The use of consensus human error probabilities provides a traceable process from the analyst's qualitative evaluations to the final numerical estimate for each crew failure mode and an overall human error probability.

- The methodology requires systematic documentation of the analyst's rationale for each step in the assessment process. The documentation facilitates identification of analyst-to-analyst differences in the assessments, examination of the reasons for those differences, and understanding of their effects on the estimated human error probabilities.

As noted in our introductory remarks, work remains to complete development and testing of the proposed IDHEAS methodology for its use in practical human reliability analyses. The following items provide our detailed comments and recommendations on elements of the methodology and models that need additional attention and refinement.

<u>Interface with Draft NUREG-2114</u>

Appendix C of the IDHEAS draft report describes how the five fundamental macrocognitive functions described in draft NUREG-2114 are addressed in the three phases of personnel response that are used to frame the IDHEAS methodology. The appendix also lists each crew failure mode and documents the proximate causes, cognitive mechanisms, and performance influencing factors that were judged to be most relevant to that failure mode. In some cases, the appendix describes the rationale for concluding why evaluation of a particular proximate cause is unnecessary.

The appendix does not document why many cognitive mechanisms and performance influencing factors are excluded from explicit consideration for each crew failure mode. That justification is important for understanding how the IDHEAS methodology has considered the entirety of the theoretical basis from draft NUREG-2114. It is also critical for understanding why this focused application of the methodology for procedure-based actions does not fully address all elements of human cognitive performance that are delineated in draft NUREG-2114. Those judgments are important to inform the critical reexamination of the excluded cognitive mechanisms and performance influencing factors when the IDHEAS methodology is extended for a comprehensive assessment of human performance during other types of event scenarios.

The IDHEAS report should document the rationale for excluding specific cognitive mechanisms and performance influencing factors delineated in draft NUREG-2114 from explicit consideration in the assessment of each crew failure mode.

Guidance for Qualitative Assessment

The staff reviews of current HRA methods and the experience from international and U.S. empirical studies identified an important general deficiency in the emphasis and guidance for performing a scenario-based qualitative assessment to clearly document the context for each action. Guidance for development of the scenario narrative and the qualitative assessment process is distributed among Chapters 2, 3, and 4 of the IDHEAS draft report.

The qualitative analysis guidance is focused primarily on information that is needed to support performance of a feasibility assessment and development of a crew response tree for the specific action that is evaluated in the PRA logic model. The guidance is developed in a manner that focuses the analyst's attention on the particular tasks that are necessary to achieve that desired response. This emphasis can inappropriately cause the analyst to lose perspective for the complete spectrum of scenario-specific conditions that may require operator attention. That perspective is essential for an analyst to perform an integrated assessment of all factors that may influence personnel performance in the context of the evolving scenario.

For example, PRAs often exclude many balance-of-plant systems that are judged to be unimportant to risk. However, complex scenarios that are evaluated in the PRA may include conditions that affect those systems and jeopardize important investment-protection equipment. Operator efforts to cope with all evolving conditions can cause distractions or introduce conflicting priorities. These conflicts have occurred during actual events.

The qualitative assessment guidance should emphasize the need to develop operational narratives which adequately describe the entire context of the evolving event scenario, how that scenario affects all information and stimuli in the operators' environment, and factors that may influence personnel response in that context, considering the effects on all plant systems and functions, regardless of their inclusion in the PRA models. Examples of good operational narratives should be provided.

Expert Elicitation of Human Error Probabilities

The quantification of human error probabilities is anchored by numerical values that are derived from a structured expert elicitation process for each decision tree. This element of the methodology is both pragmatic and reasonable, provided that the experts carefully account for the context of each crew failure mode, its contributing performance influencing factors, and the inherent uncertainties in their assessments. The staff plans to eventually use operational experience and data from simulator training exercises to benchmark the expert assessments and reduce uncertainties. However, for the foreseeable future, data-based evaluation of human error probabilities will, of necessity, be limited to actions for which relatively high failure rates may apply, due to an inability to compile the tens of thousands of relevant independent data samples that would be needed to support direct estimation of very low error probabilities.

Appendix D of the IDHEAS draft report summarizes the results from two workshops that were conducted to organize and perform the expert elicitations. The elicitations remain incomplete. The report notes that the first workshop resulted in changes to some crew failure modes and decision trees. However, questions remain about the logic structure and supporting performance influencing factors for several decision tree paths. A full group consensus human error probability distribution was developed for only one path through only one decision tree. Preliminary consensus distributions were developed for 13 additional paths in a total of seven decision trees. Distributions were suggested for several other paths, but the report notes that these estimates should be used "with great caution" because they did not benefit from a full evaluation by the expert group. Many individual paths have not been evaluated, and no estimates are available for any paths in seven decision trees.

The expert elicitation process provides several vital functions for development of the final IDHEAS models. Feedback from the experts is used to clarify the logic structure and supporting information for each crew failure mode and decision tree. Once the experts and the methodology authors have reached a consensus understanding of the framework, the experts can then provide informed estimates of the human error probabilities, their uncertainties, and the rationale for their assessments. It is also important for the experts to examine every path through each decision tree, because subtleties in some intermediate paths may not be addressed adequately by a simplified focus on only the extreme conditions that may produce the highest and lowest error probabilities.

A formal and complete expert elicitation process should be conducted to develop human error probabilities and associated uncertainty distributions for each combination of contextual factors in the final version of every decision tree.

Integrated Assessment of Uncertainty

The topic of uncertainty is afforded only cursory attention in the IDHEAS draft report.

Chapter 7 notes that parametric uncertainty in the human error probabilities should be estimated by assuming a lognormal probability distribution and applying guidance from NUREG/CR-1278 (THERP). This is astonishing. A key element of the expert elicitation process that is summarized in Appendix D of the IDHEAS draft report focuses explicitly on assessment of the experts' individual uncertainties and development of a consensus mean value and uncertainty distribution for each human error probability. The HRA results should use those uncertainty distributions, and not arbitrarily retrofit uncertainties that are not based on the supporting expert assessments.

The guidance for development of timelines and performance of feasibility assessments notes that there are uncertainties in both the PRA-based time window that is available for completion of an action and in estimates for the amount of time that is actually required to perform the action. The guidance addresses these uncertainties only in a general manner, recommending that analysts should collect a range of estimates, develop nominal values for the expected response times, and assess a maximum time for response of the slowest crew. The concept of a time margin is also used to provide qualitative confidence in the feasibility of an action, but that margin is based on the estimated average crew response time. These techniques are useful for an initial qualitative assessment of action feasibility. They do not provide a systematic evaluation of the uncertainties to support quantification of the overall human error probability.

In some cases, a careful quantitative assessment of the uncertainties in the estimated times may identify situations in which there is an overlap in the "tails" of the uncertainty distributions. In other words, there is some probability that the time required to perform an action exceeds the available time window, despite the fact that the best estimates show some margin. The intersection of these uncertainty distributions represents a contribution to the overall probability that a crew will not successfully complete the required action. This contribution is not currently quantified in the IDHEAS methodology. A thorough assessment of each action should account for the probability that it cannot be completed within the available time window, in addition to the human error probability that is derived from the decision tree analyses (accounting for the complementary probability that the action can be completed within the available time window). The guidance for estimation of the available time window and the time required to perform each action should include explicit evaluation of the uncertainties in those times. The probability that an action cannot be completed within the available time window should be included as a contribution to the overall HRA results.

Pilot Applications

Chapter 8 of the IDHEAS draft report notes that the methodology has not been tested. It is also noted that "whether this testing is to be done as a formal pilot is yet to be determined."

Limited case studies have been performed, but only by individuals who were either part of the project team or were peripherally associated with the project. The examples in Chapter 6 and Appendix A are useful to illustrate the analysis process. However, these types of structured tutorials are often subject to misinterpretation when analysts are confronted by a variety of practical PRA scenarios.

Experience from the development of other complex methodologies, such as those used for the modeling and analysis of plant fires, has demonstrated the value and the need for comprehensive pilot applications that critically test all elements of the method in a practical PRA context. Without thorough pilot testing, any methodology is invariably destined to encounter numerous unanticipated questions and issues that could limit its use, perhaps under conditions when time pressures are paramount and adequate resources are not available for thoughtful resolution of technical queries.

Formal pilot testing of the IDHEAS methodology should be performed. The testing should be conducted by multiple teams of analysts who have a range of practical experience with evaluating human performance in PRA applications. Teams should include members with expertise in nuclear power plant engineering, operations, and the plant-specific PRA, as well as human performance and HRA. Each team should evaluate the same set of PRA event scenarios that cover a range of human actions and anticipated crew failure modes.

We look forward to our continuing interactions with the staff and external stakeholders as the IDHEAS methodology is refined, tested, and extended to address other events and plant operating modes.

Dr. Dennis Bley and Dr. Joy Rempe did not participate in our deliberations on these matters.

Sincerely,

/RA/

John W. Stetkar
Chairman

REFERENCES

1. Staff Requirements Memorandum M061020, November 8, 2006 (ML063120582)

2. U.S. Nuclear Regulatory Commission, "Building a Psychological Foundation for Human Reliability Analysis," NUREG-2114, Final Draft, December 6, 2013 (ML14014A292)

3. U.S. Nuclear Regulatory Commission and Electric Power Research Institute, "An Integrated Decision-Tree Human Event Analysis System (IDHEAS) Method for NPP Internal At-Power Operation," Final Draft, September 30, 2013 (ML13354B698)

4. Swain, A. D. & Guttman, H. E., "Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications," NUREG/CR-1278, U.S. Nuclear Regulatory Commission, 1983 (ML071210299)

5. OECD Halden Reactor Project, "The International HRA Empirical Study - Phase 2 Report - Results from Comparing HRA Methods Predictions to HAMMLAB Simulator Data on SGTR Scenarios, Appendix A," HWR-915, March 2010 (ML102770651)

6. Chang, et al, "Methodology for Collection and Analysis of Simulator Data for HRA Applications," Paper submitted to PSAM-11, June 2012 (ML120520534)

7. Criscione, et al, "Overview of Licensed Operator Simulator Training Data and Use for HRA," Paper submitted to PSAM-11, June 2012 (ML120520541)

8. Roth, et al, "Model-based Framework for Characterizing Contextual Factors for HRA Applications," Paper submitted to PSAM-11, June 2012 (ML120520538)

9. U.S. Nuclear Regulatory Commission, "The International HRA Empirical Study – Final Report," unpublished, December 2012 (ML12352A142)

10. U.S. Nuclear Regulatory Commission, "International HRA Empirical Study – Phase 3 Report - Results from Comparing HRA Methods Predictions to HAMMLAB Simulator Data on LOFW Scenarios," NUREG/IA-0216, Volume 3 (unpublished), January 2013 (ML12349A075)

11. U.S. Nuclear Regulatory Commission Office of Nuclear Regulatory Research, "Summary of External Review and Revision – NUREG-2114," December 2013 (ML13354B693)

12. U.S. Nuclear Regulatory Commission Office of Nuclear Regulatory Research, "Peer Review of IDHEAS: Background, Summary of Comments and Resolution of Suggested Changes," December 2013 (ML13354B720)

13. U.S. Nuclear Regulatory Commission Office of Nuclear Regulatory Research, "IDHEAS Testing Manual," December 2013 (ML13354B729)

14. Liao, H., "IDHEAS Testing Report," Sandia National Laboratory, December 2013 (ML13354B704)

15. Whaley, A., "IDHEAS Validation Exercise," Idaho National Laboratory, December 2013 (ML13354B711)

16. Liao, et al., "Leveraging Existing Human Performance Data for Quantifying the IDHEAS HRA Method," Paper submitted to PSAM-12, December 2013 (ML13354B715)

9. U.S. Nuclear Regulatory Commission, "The International HRA Empirical Study – Final Report," unpublished, December 2012 (ML12352A142)

10. U.S. Nuclear Regulatory Commission, "International HRA Empirical Study – Phase 3 Report - Results from Comparing HRA Methods Predictions to HAMMLAB Simulator Data on LOFW Scenarios," NUREG/IA-0216, Volume 3 (unpublished), January 2013 (ML12349A075)

11. U.S. Nuclear Regulatory Commission Office of Nuclear Regulatory Research, "Summary of External Review and Revision – NUREG-2114," December 2013 (ML13354B693)

12. U.S. Nuclear Regulatory Commission Office of Nuclear Regulatory Research, "Peer Review of IDHEAS: Background, Summary of Comments and Resolution of Suggested Changes," December 2013 (ML13354B720)

13. U.S. Nuclear Regulatory Commission Office of Nuclear Regulatory Research, "IDHEAS Testing Manual," December 2013 (ML13354B729)

14. Liao, H., "IDHEAS Testing Report," Sandia National Laboratory, December 2013 (ML13354B704)

15. Whaley, A., "IDHEAS Validation Exercise," Idaho National Laboratory, December 2013 (ML13354B711)

16. Liao, et al., "Leveraging Existing Human Performance Data for Quantifying the IDHEAS HRA Method," Paper submitted to PSAM-12, December 2013 (ML13354B715)

Accession No: **ML14134A328** **Publicly Available** **Y** **Sensitive** **N**
Viewing Rights: ☒ NRC Users or ☐ ACRS Only or ☐ See Restricted distribution

OFFICE	ACRS	SUNSI Review	ACRS	ACRS	ACRS
NAME	JLai	JLai	CSantos	EMHackett	EMH for JWS
DATE	05/14/14	05/14/14	05/14/14	05/19/14	05/19/14

OFFICIAL RECORD COPY