THE GENERAL METHODOLOGY OF AN INTEGRATED HUMAN EVENT ANALYSIS SYSTEM (IDHEAS) FOR HUMAN RELIABILITY ANALYSIS METHOD DEVELOPMENT

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The General Methodology of the Integrated Human Event Analysis System (IDHEAS-G) is a product of the U.S. Nuclear Regulatory Commission (NRC) to provide a general framework for human reliability analysis (HRA) method developers to develop application-specific HRA methods. IDHEAS-G[1] is based on the cognitive basis structure for HRA developed by the NRC (NUREG-2114[2] "Cognitive Basis for Human Reliability Analysis"). An example of an application-specific HRA method developed from the IDHEAS-G methodology is the IDHEAS method for internal, at-power applications[3] jointly developed by the NRC and the Electric Power Research Institute (EPRI).

IDHEAS-G uses four macrocognitive functions to represent a task demand on human cognition: detecting information, understanding the situation, making decisions and planning the response, and executing actions. Each macrocognitive function is assumed to be performed in a team and organizational work environment. Therefore, the communication, supervision, and teamwork are embedded in each macrocognitive function. For each macrocognitive function, IDHEAS-G identifies the basic cognitive process steps with each step achieving a specific sub-cognitive function to successfully achieve the objective of the corresponding macrocognitive function. The failure modes and performance influencing factors (PIFs) of each cognitive process step are identified. The cognitive elements, failure modes, and PIFs are generic and comprehensive. The relationships between cognitive elements and PIFs are identified first based on the review results in NUREG-2114 then enhanced and organized as a single, comprehensive model for practical use for HRA. These relationships are summarized and organized based upon macrocognitive functions, error modes, and PIFs. To develop application-specific HRA methods, application-specific terms can be used in the place of IDHEA-G generic terms. As for guidance, the IDHEAS-G provides guidance for performing an HRA include qualitative and quantitative analyses. This paper describes the IDHEAS-G's analysis process for HRA and the corresponding technical elements in the process.

I. INTRODUCTION

The NRC's Staff Requirement Memorandum SRM-M061020[4] requested the staff "to evaluate the different human reliability models in an effort to propose a single model for the agency to use or guidance on which model(s) should be used in specific circumstances." The NRC's Office of Nuclear Regulatory Research (RES) has taken the lead in addressing SRM-M061020. The strategic approach has been performed according to three levels, as described below:

1) Developing a cognitive basis as the foundation for HRA. The cognitive basis should address the following: How humans perform complex cognitive tasks; what enables humans to reliably perform tasks; and what causes human failures? Such a cognitive basis addresses the fundamentals of human cognition and it is applicable to human performance in any context. The cognitive basis was developed through review, synthesis and analysis of cognitive literature. The outcome is documented in NUREG-2114 "Cognitive Basis for HRA." This product is the basis for developing a general HRA methodology.
2) Developing a general HRA methodology that provides HRA process and guidance in implementing the process. We refer this methodology as the General Methodology of *an Integrated Human Event Analysis System (IDHEAS-G).* The IDHEAS-G serves as a basic material to develop application specific HRA methods.
3) Developing application-specific HRA methods based on the IDHEAS-G. Based on the application-specific needs, an application-specific method can either simply reference certain portions of the IDHEAS-G with further development or modify the IDHEAS-G's basic material to meet the application specific needs.

This paper discusses the above second item, IDHEAS-G.

II. OVERVIEW OF IDHEAS-G

This paper focuses on the discussion of performing an HRA for developing a probabilistic risk assessment (PRA) model in a multi-disciplined team environment. The team members have a collective expertise of PRA, HRA, plant and radiation behavior simulation, systems engineering, and other specific domain knowledge. Additionally, the team members closely interact with each other to produce a qualitative analysis of the risk of the subject of interest. IDHEAS-G provides the guidance for performing an HRA in the team environment. The guidance can be used by HRA method developers to develop application specific HRA methods. Some HRA applications are not performed in a PRA context. These HRA applications may only be used for identifying potential human vulnerabilities and estimating human error probabilities (HEPs) in a process that human reliability has significant effects on the safety of the system and personnel. For this type of HRA application, a portion of the IDHEAS-G elements can be used to support the HRA method development. However, this type of application is not discussed in this paper.

Once an initiating events have been identified, a conventional PRA model is represented by event trees and fault trees. Each event tree starts with an initiating event followed with event sequences to represent the classes of scenarios following the initiating event. The event sequences identify the important component, system, structure, and human responses that are needed to mitigate the event to prevent the undesired consequences from occurring. In a multi-disciplined PRA team, a common practice is that the PRA analyst would draft the event tree that includes the important components and human actions. In parallel, the HRA analyst analyzes the relevant material (e.g., procedures, training manual, and safety analysis report, and event reports, etc.) to identify the expected component and human responses from the operational perspective. Based on the analysis results, the HRA analyst would interact with the rest of the team to improve the event tree model. This could include modifying the evet tree and providing a more specific scope of the modeled human actions (i.e., human failure events in PRA term).

III. THE SIX STEP REPRESENTATION OF AN HRA PROCESS

The IDHEAS-G specifies a six-step HRA process to perform an HRA. This section provides a general discussion of these six steps. The flow of the six steps represents the major technical activities involved with the HRA process. They are represented in a sequential order for the convenience of discussion. In reality, performing these steps are an iterative process and with interaction with the other team members of the PRA team. The six steps cover the qualitative and quantitative analyses described as the following:

Step 1. Scenario analysis and operational narrative

This steps aims to obtain a holistic understanding of the event and the scenario progression. The HRA analysts analyze the scenario progression from the human's perspective in operating the plant (or system). This is different from the PRA analysts developing an event tree from a top-down safety analysis perspective. In other words, PRA analysts ask the question "What components and human actions are needed to mitigate the event?" The HRA analysts ask the question "How will the human respond to the event based on their training and other available resources?" The product of Step 1 is a documentation of the scenario progression from the operational perspective (i.e., human's eyes). This includes the expected scenario progress paths and the automatic component responses and human actions occurring in the scenario. The expected human and component responses are used to represent the baseline scenario. The "What-If" questions are asked on the important components and human actions initially identified in the baseline scenario to identify the other scenarios when the component or human fails to respond as expected.

Step 2. Human Failure Event analysis

The scenarios identified in Step 1 are expected to provide more detailed information than needed to be represented in an event tree. Step 2 is to summarize the information to match the information detail in a PRA event tree. The product of Step 2 is to identify the important human actions to be modeled in the PRA event tree and to clarify the scopes of these human actions. These representative human actions are called human failure events (HFEs) in PRA.

Step 3. Model the HFE

Step 3 is to perform a detailed qualitative analysis for an HFE. An HFE is typically labeled as the human actions that need to be performed to achieve the desired plant function. The human actions are generally labeled as the human physical actions needed to interfere with the scenario progression. However, the full scope of an HFE occurs much earlier to include the detecting, understanding, and deciding process that leads to action. The crew response diagram (CRD) is a graphical diagram representation to represent the detailed human activities within an HFE. A CRD includes the critical tasks that need to be successfully performed to achieve the HFE's plant function and the error recovery paths to the failures of performing these critical tasks.

Step 4. Quantification model
The IDHEAS-G provides technical elements of macrocognitive functions, error modes, and PIFs as the building blocks to estimate the HFEs' HEPs.

Step 5. Calculating HEPs
The IDHEAS-G calculates an HFE's HEP using two elements. The first element looks at the time sufficiency of performing the HFE as a whole. This assesses, under a normal pace of implementation, the likelihood that the tasks may not be completed in time. This assessment assumes that the human does not make mistakes in implementing and performing these tasks at their normal pace. The second element is human error due to all reasons other than the time sufficiency covered in the first element. The second element is labeled as cognitive error. The term cognitive here includes the macrocognitive functions of detecting, understanding, deciding, and action performed in teamwork environment. The second element's application subject is the critical tasks of the HFE. Most of the HRA methods in use calculate an HFE's HEP by viewing the HFE as a whole without explicitly identifying the critical tasks of the HFE. IDHEAS-G makes the critical task modeling explicit. This creates a benefit for documenting and reviewing the modeling. The two elements to calculate the HEP of an HFE is represented in Equation 1.

$$\text{HEP(HFE)} = \text{Pt(HFE)} + \Sigma\text{Pc(Critical Task\_i)} \quad \text{for } i = 1 \text{ to } N \qquad \text{Eq.1}$$

Where
Pt is the probability of failure due to the time available being insufficient. This is calculated based on the relation between the estimated time required and the time available of the HFE.

Pc is the cognitive failure probability of the critical tasks of the HFE. The cognitive here could be modeled at three levels: (1) at the highest level, the Pc is a single item representing all failures other than being due to insufficient time; (2) at the mid-level, the Pc includes four elements representing failures of the following four macrocognitive functions: detecting information, understanding the situation, making decisions and planning the response, and implementing the recovery actions; and (3) at the bottom level, the Pc includes the individual error modes that could occur in performing the critical task. Therefore, the cognitive HEP (Pc) of a critical task can be implemented at either of the following levels shown in Equation 2.

For a critical task: Eq. 2

$$\begin{aligned} &\text{Pc} \\ &= \text{P(Detecting)} + \text{P(Understanding)} + \text{P(Deciding)} + \text{P(Action)} \\ &= \Sigma\text{P(Error Mode\_i)} \quad \text{for } i = 1 \text{ to } N \end{aligned}$$

Where N is the total number of error modes applicable to the critical task.

The reason for having the three levels of approach to calculate Pc has less to do with the accuracy of the Pc value and more to do with modeling the task dependency. Some HRA applications' results are sensitive to task dependency. To provide proper modeling and justification, the types of error are likely needed to be specified. The IDHEAS-G's three-level approach provides flexibility to choose the optimal level of detail based on the HRA application.

Step 6. Integration
Finally the HRA results need to be integrated into the PRA model. This could require modeling dependency between HFEs and the final HEP uncertainty. A few HRA methods have developed dependency models. These models typically specify a dependency level using THERP's[5] five-level dependency model by considering a few PIFs without explicitly looking into the underneath cognitive mechanisms. This approach is an approximate approach to accommodate the fact that these HRA methods do not provide the modeling structure with a sufficient level of detail to address the task dependency more directly. IDHEAS-G argues that appropriately modeling task

dependency requires the identification of the cognitive functions or the error modes between the two tasks that failed. At this time, IDHEAS-G does not have a dependency model or an uncertainty model. Developing a dependency model based on cognitive functions and error modes is a planned task.

VI. TECHNICAL ELEMENTS AND CONSIDERATIONS

This section describes the technical elements and technical considerations of each of the six HRA process steps discussed in section III. The steps of one to three are qualitative analysis, and the steps of four to six are quantitative analysis. The IDHEAS-G's qualitative analysis describes a thought process to collect the necessary information to establish a good foundation to perform a quality HRA. The HRA method developers can simply adopt the IDHEAS-G's qualitative analysis to focus their efforts on developing the application-specific quantitative analysis to shorten the method development time. Compared to the qualitative analysis, the IDHEAS-G's quantitative analysis is currently less developed. This is because the quantitative analysis is more technically challenging and more diverse from one HRA application to another. This is especially true because the IDHEAS-G aims not only to provide a comprehensive list of error modes and PIFs but to also provide their relationships quantitatively, with a psychological basis in order to provide sound technical bases for consistent quantitative analysis estimation of HEPs. In the long run, this approach provides a structured, convenient way to perform incremental improvements when new human performance evidence becomes available. The IDHEAS-G also aims to improve modeling the other important HRA elements such as task dependency by including the guidance in the IDHEAS-G methodology. Because of limited resources, other HRA technical elements such as error of commission and uncertainty are addressed with less detail than the other elements.

The step four "quantitative model" is the link between the qualitative analysis and the quantitative analysis. In most cases, an essential objective of HRA is to calculate HEPs. An important objective of qualitative analysis is to support quantitative analysis. The IDHEAS-G uses the factor-based approach to calculate HEPs (instead of the expert elicitation based approach). Therefore, an essential objective of the qualitative analysis is to identify the relevant PIFs and their statuses to estimate the HEPs. When HRA analysts are performing the qualitative analysis, it is expected that the HRA analysts are familiar with the error modes and PIFs. So the potential error modes and PIFs, along with their statuses, can be identified during the performance of the qualitative analysis.

As stated earlier, the IDHEAS-G uses a factor-based approach instead of expert elicitation approach to calculate HEPs. This approach is consistent with most of the HRA methods in use. Choosing the factor-based approach over the expert elicitation approach considers issues affecting HRA application such as generating timely results (for practical implementation of the HRA applications within time and resource constraints), analyst-to-analyst variability, transparency, consistency in documentation, and calculating HEPs based on a large pool of scientific evidence, etc. Expert elicitation is good for performing analyses where no applicable HRA methods are available, for performing special, in-depth analysis, or for developing new factor-based HRA methods. This paper's authors believe that the factor-based HRA methods have advantages in practicality for most HRA applications over the expert elicitation approach.

The IDHEAS-G aims to provide a thorough cognitive process and elements for developing HRA methods for a wide range of applications. These cognitive processes and elements may not all be needed for an HRA application. The elements such as failure modes and PIFs are specified at a level that are suitable for most nuclear plant HRA. However, this may not be the case for certain HRA applications. Some HRA applications may need finer element distinctions. While other HRA applications only have information available at a higher level. It is impractical to require information with more detail than what can be provided. For example, HRA for plants still in the design stage has less available information compared to the HRA for operating plants. The HRA method developers are expected to modify the IDHEAS-G's elements to meet their application needs. The modification can include splitting, eliminating, merging, and regrouping, etc. of the IDHEAS-G's cognitive elements. An important purpose of the IDHEAS-G's cognitive elements is to provide a comprehensive list for the HRA methods developers to consider to prevent omitting important human performance considerations.

VI.A. Step 1. Scenario analysis and operational narrative

This step provides a narrative description of the scenario to understand the expected scenario progression and identify the key human performance considerations. The expected scenario is referred to as the baseline scenario. The scenario narrative is supplemented by an event timeline. The event timeline represents the baseline scenario's incidents in a chronological order. Symbols are used to identify the following four types of incidents: system responses (e.g., automatic responses or latent failure), human cognition or actions, system generated information important to trigger human actions, and notes to provide explanations of system and human responses to supplement the readers' understanding.

The scenario narrative describes the baseline scenario from four perspectives: scenario context, crew context, system context, and task context. These four contexts aim to provide a holistic understanding of the scenario progression and identify the issues that may affect the scenario progression in a negative manner. The *scenario context* provides a birds-eye view of the scenario for a holistic understanding of the scenario progression before diving into the detailed analysis. The scenario context description includes the following elements: initial plant conditions, initiating events, and latent failures; expected important system and human responses, etc. The *Crew context* identifies the human constraints in responding to the event such as the available staffing could be stretched thin to respond to multiple demands, the need of coordinating with the organizations or teams that do not usually work together, and adverse environmental conditions in performing the needed tasks, etc. The *system context* identifies the needed instrumentation, components, or equipment that may not be in their ideal condition (e.g., could be operating outside of their designed conditions) or any component operational constraints (e.g., can be operated only for a limited time or duration) for the task implementation. The *task context* identifies the constraints in implementing the task due to intrinsic complexity of the task (e.g., need to be performed with high precision, etc.). Together, the scenario context, crew context, system context, and task context provide basic information to identify the error modes and PIFs for estimating HEPs.

VI.B. Step 2 Human Failure Event analysis

This step identifies the HFEs based on the baseline scenario developed in Step 1. The scope of each HFE is clearly specified because each HFE could include multiple human activities that are important to the HFE success. The what-if questions are asked on the HFEs and components modeled in the PRA model to identify the new scenarios due to the component or human failing to provide the specified plant functions. This would lead to new scenarios. The new scenarios are summarized and represented by event sequences in the event tree, as in step one. This process continues until the event tree is fully developed. For the scenarios other than the baseline scenario, an extensive scenario narrative and timeline may not be needed. In this case, the HRA analysts should specify the significant context and timeline, if necessary, that is not identified in the baseline scenario for sufficient understanding of the performance challenges in these scenarios.

VI.C. Step 3 Model the HFE

Step 3 performs the task analysis and cognitive task analysis for HFEs. For each HFE of analysis, the task analysis is performed to identify the critical tasks to the success of the HFE and the error recovery opportunities of these critical tasks. A critical task has to meet all the following three criteria:

- *Task criticality* - The systems involved in the task are safety-critical, and the task involves changes to the operating configuration.
- *Task difficulty* - The task requires complex human involvement and has a good chance of human errors.
- *Recovery difficulty* - The consequences of the omitted or incorrectly performed task cannot be easily detected and corrected.

The crew response diagram (CRD) is used to communicate, illustrate, and document the outcomes of the task analysis. The opportunities for errors and error recovery are represented as nodes on the CRD. In parallel, as an essential part of developing the CRD, a detailed timeline may be created to facilitate understanding of the details. The CRD timeline is more detailed than the timeline of the baseline scenario. The subject of the CRD timeline is an HFE while the subject of the baseline scenario timeline is the whole scenario. The critical tasks, error recovery opportunities, and timeline identified in the CRD provides the essential information to estimate the HEP of the critical tasks. Development of a CRD principally follows the following process: (1) Developing the CRD along with the timeline. This include identifying the procedures that are applicable to this HFE; determining the relevant cues and their timing; identifying the crew's trained responses that are required by the procedures and form a success path; plotting the success path with each node representing the onset of a cue, a key transition point, or a required crew response; developing a timeline along the CRD by indicating the timing of the onset of the cues, when a transition needs to be made, and when a required response is expected to be performed; (2) Identifying and analyze critical tasks. Each CRD node may be associated with one or several critical tasks. Each critical task is explicitly identified in this stage; and (3) Identifying the potential recovery opportunities and paths to success. Complicated system are designed with redundancy and diversity to protect the safety. Credible opportunities may be available to recover from the critical action errors. Error recovery opportunities and their corresponding paths would be identified in the CRD.

For each critical task, cognitive task analysis is performed to identify the cognitive challenges in performing the task. The cognitive analysis evaluates each critical task (including its error recovery opportunities) according to the four macrocognitive functions: detecting, understanding, deciding, and action. The cognitive task analysis identifies the error modes and PIFs applied to each critical tasks and the error recovery opportunities.

VI.D. Step 4 Quantification Model

The IDHEAS-G is expected to expand the quantification model to cover not only the qualitative relation between macrocognitive functions, error modes, and PIFs, but also the quantitative evidence found in literature of these relations. The information will be part of the “tool sets” that the IDHEAS-G provided for the HRA methods developers to develop or modify HRA methods.

VI.E. Step 5 Calculating HEPs

Step 5 calculates the independent HEPs of HFEs. This is inconsistent with the conventional PRA practices in calculating the independent HEP first followed by assessing the task dependency effects for the cutsets with more than one HFE. The equation to calculate an HFE’s independent HEP is shown in equation 1. As mentioned earlier, the cognition HEP (Pc) could be calculated at three levels: error without a specific error mode, the error modes defined at the level of macrocognitive functions (i.e., detecting, understanding, deciding, and action), and the error modes defined at around 50 error modes identified in the IDHEAS-G. As mentioned earlier, the three-level approach to calculate the HEP is mainly for modeling the task dependency. For example, if a preceding action’s failure is due to slowness (think slow and act slow) this leads to the required actions not being performed in time. This, in turn, could cause undesired system responses to complicate the scenario to further delaying the implementation of the required actions. Therefore, this slowness error mode is likely a common factor affecting all downstream actions. In another case, if an HFE failure is due to the operators skipping a procedure step, this may have much less dependency effects on the downstream HFEs compared to slowness.

The three levels of resolution in calculation HFEs’ HEPs provides convenience for the HRA method developers to choose appropriate levels based on the application characteristics. The IDHEAS-G identifies the failure modes based on the failure of cognitive process steps of the macrocognitive functions. For example, the cognitive process for the *Detection* function consists of the following steps:

D1 - Establish the mental model and decision-criteria for information to be acquired
D2 - Preparation for detection
D3 - Select / identify / attend to sources of information
D4 - Perceive, register, and recognize information
D5 - Verify / modify detection
D6 - Retain / document / communicate the information

The detailed failure modes are behaviorally observable outcomes of the proximate causes. For example, the failure modes associated with D1 “Establish the mental model and decision-criteria for information to be acquired” include:

- Detection not initiated (e.g., Skip steps of procedures for detection, forget to check information)
- Wrong detection criteria were used
- Failure to prioritize information to be detected

The IDHEAS-G quantification structure aims to provide a complete set of failure modes associated with each cognitive process step. IDHEAS-G also provides links between the failure models and cognitive mechanisms underlying the failure. These cognitive mechanisms provide the cognitive basis for identifying the failures and the root causes on why the PIFs lead to a given failure mode.

VI.F. Step 6 Integration

The integration portion is less developed in IDHEAS-G. Regarding the task dependency, the authors argue that the task dependency effects are to cover the factors that are not covered by the HRA method’s PIFs. Therefore, the task dependency model is dependent on the method. Assigning a PIF to a critical task should not only look within the HFE, but it also needs to consider the view of the scenario. Therefore, certain effects considered as task dependency in some HRA methods can be reflected by the PIFs of the other methods because these methods’ PIFs address the effects.

The conventional dependency models based on factors such as same people, same location, and same cue etc., do not directly address the causes of task dependency. More appropriate assessment of the task dependency should be performed at the macrocognitive level (detecting, understanding, deciding, and action) to identify the specific error modes causing the failure of the previous HFE or critical task. If the effects have been considered in the method PIFs, then the task dependency effects can be reflected by changing the corresponding PIFs' statuses. If there are no corresponding PIFs to represent the task dependency's effects, then a separate dependency model may need to be developed to cover the effects or the PIFS may need to be expanded to include the task dependent effects. IDHEAS-G identifies comprehensive sets of error modes and PIFs to address task dependency more directly.

VI. CONCLUSIONS

IDHEAS-G is a general methodology for HRA with a solid foundation in HRA technology and experience, as well as with the state-of-knowledge of human factors and human performance. The IDHEAS methodology structure and terminology is human-centered so that it can be adapted to different conditions, hazards, and application fields. In addition, IDHEAS-G development closely interacts with the Scenario Authoring, Characterization, and Debriefing Application (SACADA)[6] HRA data method development in anticipation of using SACADA data to enhance the IDHEAS methodology. IDHEAS-G consists of the process and guidance for the full-cycle of HRA in the broad context of NPP operations. The guidance focuses on how to perform HRA under various conditions. It provides analysts the flexibility and scalability in conducting HRA under the constraints of resources, available information, and level of detail needed.

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