Developing a New HRA Quantification Approach from Best Methods and Practices

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Abstract: The Office of Nuclear Regulatory Research (RES) of the U.S. Nuclear Regulatory Commission is sponsoring work in response to a Staff Requirements Memorandum (SRM) directing an effort to establish a single human reliability analysis (HRA) method for the agency or guidance for the use of multiple methods. One motivation is the variability in Human Failure Event (HFE) probabilities estimated by different analysts and methods. This work considers that a reduction of the variability in the HRA quantification outputs must address three sources: differences in the scope and implementation of qualitative analysis, the qualitative output-quantitative input interface, and the diversity of algorithms for estimating failure probabilities from these inputs. Two companion papers (Mosleh et al. and Hendrickson et al.) describe a proposed qualitative analysis approach The development of the corresponding quantification approach considers a number of alternatives including a module-based hybrid method and a data-driven quantification scheme. This paper presents on-going work and the views of the contributors.[1]

Keywords: Human Reliability Analysis, quantification, guidance

1. BACKGROUND: A DIVERSITY OF HRA METHODS

A range of Human Reliability Analysis (HRA) methods are used today in the Probabilistic Safety Assessments (PSAs) of nuclear power plants. The diverse methods have been developed at various times since the late 1970s. The Technique for Human Error Rate Prediction (THERP) was published in 1983 [1]. The HCR/ORE time reliability curves and the Cause-Based Decision Tree methods arose in 1992 [2]. More recent additions include ATHEANA (NUREG-1624, Rev. 1, 2000 [3]; and its User's Guide, NUREG-1880, 2007 [4]) and SPAR-H (NUREG/CR-6883, 2005) [5].

Differences in the failure probabilities for a Human Failure Event (HFE) obtained with different HRA methods and/or from different analysts lead to difficulties for some applications of PSA for risk-informed decision-making. This issue is one of the motivations for the effort to establish a single HRA method for the USNRC or guidance for the use of multiple methods.

This work focuses on the Human Reliability Analysis for the response to the initiators modeled in a Probabilistic Safety Assessment, also referred to as Cat. C or post-initiator actions. At the present time, it is additionally limited to internal event PSA scenarios for full-power operating conditions.

This paper presents on-going work and the views of the contributors, with the aim to present some of the main issues for the method development. Section 2 highlights some characteristics of HRA quantification in practice. Three sources of variability in the quantitative results are identified. Section 3 presents one of the solution strategies under consideration: a "hybrid" method that is essentially a toolbox with guidance for the selection of the "tools". In Section 4, the outlook for enlarging the role of data in HRA quantification is discussed.

[1] The information presented in this paper does not currently represent an agreed-upon NRC staff position. The NRC has neither approved nor disapproved its technical content.

Two companion papers (Mosleh et al. [6] and Hendrickson et al. [7]) describe a proposed qualitative analysis approach. This qualitative analysis approach is intended to connect to the quantitative approach discussed in this paper.

2. QUANTIFICATION IN PRACTICE

2.1 Practice of multiple methods

A look at various PSAs and Individual Plant Examinations (IPEs) shows that a range of different HRA methods are in use today. In the U.S., some of the methods used include THERP [1], ASEP [8], the HCR/ORE curves [2], the Cause-Based Decision Trees (CBDTs) [2], SPAR-H [5], and ATHEANA [3,4]. In some PSAs, one HRA method is used for the analysis of all of the post-initiator HFEs. However, there is also an accepted practice of using different methods for different types of HFEs or for the different subtasks that make up one HFE.

An early example of this practice of using different methods for different types of HFEs or different HFE subtasks is the THERP methodology itself. THERP uses two different approaches to quantify the HFE subtasks. One approach is the Time Reliability Curve for diagnosis tasks, which considers that the failure probability for these tasks is most influenced by the time available for diagnosis. (Today the TRC is more broadly applied to various cognitive tasks ranging from situation assessment to decision and response selection.) In THERP, the second approach consists of tables of basic failure probabilities for various manipulation and execution subtasks, with additional adjustments. This second approach considers that the quantification of such subtasks begins with a basic failure probability associated with the type of subtasks, with subsequent adjustments for performance shaping factors (PSFs) that characterize the performance context. Although THERP is typically viewed as one method, it is thus a mixture of at least two quantification approaches.

A second combination of methods that is frequently seen for the HRA of post-initiator actions is the combination of HCR/ORE time reliability curves and Cause-Based Decision Trees. This combination is supported by the EPRI HRA Calculator [9]; as a toolbox, the EPRI HRA Calculator additionally includes THERP, ASEP, and SPAR-H. A survey of HRA practice showed that the use of two or more different HRA methods for post-initiator action quantification is common also in international practice [10].

The use of combinations of HRA methods for post-initiator HFE quantification is motivated by the fact that the different methods have different strengths, information requirements, and suitability for different types of HFE tasks. The recent work in the International HRA Empirical Study has also shown, based on a set of reference data collected in a simulator study, that the various HRA methods have different strengths in terms of modeling and quantifying the HFEs. Although this benchmark result is limited in terms of the HFEs treated, it is worthwhile to note that no individual HRA method showed a clearly superior performance, in terms of qualitative and quantitative predictive power.

2.2 Sources of variability in the estimation of failure probabilities

The set of HRA analyses produced with different methods for the same HFEs (same reference plant, crews, and information basis) in the HRA Empirical Study provides the opportunity to identify possible sources of variability in the estimated failure probabilities. Three main sources of variability in HRA analysis may be identified:

- **Differences in the qualitative analyses.** In this paper, the qualitative analysis refers to the analysis of an HFE in terms of its subtasks and of the context factors and issues that influence the performance of the subtasks. The scope and definition of the factors considered in qualitative analyses differs. This means that the factors and issues identified as problematic, or conversely, as contributing to successful performance, vary across qualitative analyses of the same HFEs.

- **Quantification of the performance factors and issues** (identified in the qualitative analysis) **and of the HFE probability**. HRA methods may assign different failure probabilities to basic tasks or quantify differently the influence of the performance shaping factors, i.e. the strength of their influence on the basic failure probabilities. These quantitative differences may be due to differences in the underlying probabilistic model(s), the underlying human performance or expert data embedded in the method, or in the types of basic elements used for decomposing an HFE or HFE subtask. This source of variability is in essence the quantification "algorithm" inherent to each method, which transforms quantification inputs into failure probabilities. The differences in the algorithm may be structural, for instance, relating to the level of decomposition used in modeling an HFE and the types of elements into which the HFE is decomposed. In addition, differences in the quantitative results may also relate to the parameters or constants used in quantification, for instance, the weights and multipliers for the PSFs provided by the method (rather than those determined for specific HFEs or HFE subtasks based on the qualitative analysis). On the whole, this variability may also be viewed as a problem of "calibrating" the different methods.
- **Assignment of performance factor ratings** (and weights, if not provided by the method). This source of variability relates to the scaling of performance factors or issues. This source of variability may be viewed partly a problem of calibrating the analysts and partly as a problem of the method, i.e. a problem of the available guidance for rating the factors. To some degree, this source of variability acts between the qualitative analysis, which identifies the performance issues and conditions, and the quantification, which determines the failure probabilities from the factor ratings. This source of variability is removed when two analysts with the same information about the HFE and the performance conditions produce the same factor ratings.

Achieving the objective of obtaining consistent failure probabilities from different analysts requires addressing all three sources of variability. To obtain the same failure probability for an HFE, the analysts must identify the same issues and factors, they must convert this qualitative information into the same ratings (or other quantification method inputs), and the quantification method must process these inputs consistently to yield the failure probability.

The comprehensive HRA qualitative analysis approach described in the companion papers presented in this conference (Mosleh et al., and Hendrickson et al,) is an attempt to address the first source of variability. The quantification approach discussed here addresses the second source of variability. The third source of variability is the coupling of these qualitative analysis and quantification and requires corresponding guidance.

2.3. A reference equation for quantification

In comparing HRA methods, the differences in the quantification algorithm are readily apparent. As noted, HRA methods or quantification approaches can differ both in the structure of their quantification equations as well as in the constants or parameters of the equations. In this context, it is worth noting that the various equations (or methods) may be viewed at a higher level as different approaches to solving the same basic equation (1) for the probability of the HFE.

$$p(HFE \mid S) = \sum_i \left[p\left(HFE \mid C_i\right) \times p(C_i \mid S) \right] \qquad (1)$$

In this equation, S refers to the PSA scenario, as defined by the initiating event, preceding hardware failure events, and preceding HFEs, that make up a general context for the HFE of interest. The context Ci refers to scenario variants or sub-scenarios that fall within the PSA scenario; the notion of considering multiple variants of the PSA scenario is used by some of the more recent HRA methods. The failure probability of the HFE is the sum over such sub-scenarios. This notion is emphasized in the narrative-based methods, which frequently seek to identify specific and often aleatory contextual elements that contribute strongly to failure. In contrast, in PSF-centered methods, base failure probabilities that may represent an overall failure rate for a nominal context are adjusted to account for the PSF differences between this nominal context and the scenario-specific PSA context. Both classes of quantification methods are in essence covered by the above equation as long as the notion that human error probability is context-anchored, as symbolized by the term $p(HFE|C_i)$. Additional simplifications and assumptions regarding the various terms in the above general equation can be shown to result in the HEP calculation method of some of the popular HRA methods (e.g., SPAR-H [5] and CBDT [2]).

3. A QUANTIFICATION APPROACH FROM BEST METHODS AND PRACTICES

3.1. The case for a module-based hybrid method

The current practice of using multiple HRA methods for the quantification of post-initiator HFEs, as applied in many PSAs, inspires a solution to the problem of variability in the estimates of HFE failure probabilities that is based on a toolbox of HRA quantification approaches. Each approach would constitute a module. Guidance is then needed for selecting the modules to ensure that, when modeling and quantifying a given HFE, different analysts select the same quantification modules and match them consistently to the HFE subtasks. This guidance would identify a quantification to match the characteristics of the HEF subtask and performance conditions.

A toolbox combined with such tool selection guidance may be viewed as a hybrid quantification method. The challenges for a module-based hybrid are discussed in the following.

3.2. Challenges

The development of the “toolbox” and “hybrid method” involve three problems. First, the quantification approaches to be included need to be selected. In a middle term perspective, both approaches are constrained by the available methods or parts of methods. An important problem is therefore the development of **guidance for tool selection**. A second problem to be addressed is **the identification of gaps** in the coverage of the available quantification approaches. The third problem which apply more to the tool box approach is to ensure the **compatibility of the failure probabilities estimated with different approaches** for the HFE subtasks.

Guidance for tool selection. In the toolbox approach the development of the guidance for selecting a quantification approach from the toolbox is a problem of matching the quantification approach with the HFE subtasks that it is best suited for. In doing so, one aim is to reduce the number of candidate approaches for the quantification of a subtask. In principle, the combination of HFE subtask type, the relevant performance factors, and the given performance conditions should lead to the identification of a single, best quantification approach for this subtask.

For a given subtask, the guidance for tool selection needs to recommend quite clearly a quantification approach. Otherwise, the variability due to the choice of a quantification method for the post-initiator HRA is only transformed into a problem of the selection of the quantification method for HFE subtasks.

The related work on the qualitative analysis approach, described in the companion papers [Mosleh et al and Hendrickson et al], proposes a systematic process and guidance to ultimately identify one or more of the most relevant failure mechanisms associated with each HFE subtask. Secondly, the mid-layer model that supports the identification of failure mechanisms additionally identifies the performance shaping factors that are particularly relevant for each failure mechanism. In this context, it is worth noting that the level of treatment of failure mechanisms within the quantification approaches of the toolbox or hybrid method may not match these failure mechanisms. This means that the guidance for tool selection will in many cases identify a quantification approach to addresses a set of related failure mechanisms rather than individual failure mechanisms. In other words, it could address the HFE at a higher, more aggregated level such as the HFE subtask.

In developing the qualitative analysis approach and the quantification approach, the possibility of coupling the qualitative and quantitative analysis at different levels is intentional. Some of the priorities in the development of the qualitative analysis approach were a) to obtain a consistent and comprehensive classification of failure mechanisms, and b) to support the analysis of the factors that would influence these failure mechanisms with the available knowledge from the psychological and human factors literature. These priorities are intended to ensure a comprehensive and credible qualitative analysis independent of the available quantification methods or approaches. Such a qualitative analysis has an inherent value in terms of identifying potential performance issues, independent of the current limits of quantification.

Identification of gaps. The available quantification approaches cover HFE cognitive subtasks (diagnosis, situation assessment, decision, response selection, and to some extent the cognitive elements of control actions) and execution subtasks (perception of alarms, reading of indications, and manipulation). One of the challenges for the development of both the toolbox and hybrid quantification approaches is to identify the gaps in the coverage of the existing quantification approaches as failure mechanisms are identified for the HFE subtasks, together with the relevant PSFs.

Two types of gaps are of concern. The quantification approaches may not address failure mechanisms identified in the qualitative analysis. This issue goes beyond the level of treatment of the failure mechanisms treated by a given quantification approach. For instance, the quantification method may address an error type that regroups a set of failure mechanisms while its underlying model, assumptions, and data do not consider one of these failure mechanisms either implicitly or explicitly. The second type of gap relates to the PSFs addressed by a quantification approach for a given error type or failure mechanism.

With regard to the toolbox approach as a methodology, the guidance for module selection needs to support the user by identifying the performance issues and factors that are not addressed for each HFE due to these gaps.

Compatibility of failure probabilities estimated with different quantification "tools". A third challenge for a module-based hybrid method that mixes different quantification approaches taken from a range of HRA methods is the consistency of the failure probabilities. As noted earlier, individual methods may be better at treating certain types of tasks or at modeling the effect of specific performance shaping factors. The superiority of different methods in specific areas indeed motivates their collection in a toolbox and the development of a hybrid.

When quantified with diverse modules, the failure probabilities for different subtasks may be mismatched. In other words, there may be issues with combining the failure probability for subtask 1 quantified with module A with the failure probability for subtask 2 quantified with module B. These mismatches may be due to differences among the methods concerning the performance conditions assumed to be "nominal", i.e. the performance context for which the base failure probabilities, before adjustments, apply. A second source of mismatches at the quantitative level may be the degree of pessimism or conservatism associated with the method. For instance, a method may be "calibrated" somewhat pessimistically to account for variabilities in performance factors that it does not explicitly model.

3.3. Extensions

It can thus be seen that development of a toolbox or hybrid method that takes advantages of the strengths of a variety of quantification approaches involves several significant challenges. In contrast, one of the advantages of the module-based hybrid method is that it can be extended to meet the needs of further applications of HRA, beyond the limits of the current target scope (internal events at full power).

For instance, the suitability of the existing quantification methods for operator actions with large time windows, i.e. on the order of many hours, remains an open issue. Such time windows are commonly seen in PSAs for shutdown operation, for example, as well as in PSAs for some types of nuclear power plant designs. For such actions, the performance factors related to time constraints and workload, which are central in many current HRA methods, may be less influential in the estimation of the failure probabilities. Other factors and considerations, such as the credit for the capacities for emergency response and accident management added by a technical support center, or coordination and communication with personnel outside the control room, need to be accounted for.

For such needs, a dedicated quantification approach, i.e. a new tool or module, may be added to the toolbox. At the same time, for such aspects of the HFEs that are shared among HRA applications, the existing quantification modules will continue to be used. In this way, the module-based hybrid method may contribute to more consistency in the analytical treatment of similar HFE subtasks and performance conditions and counteract the development of methods dedicated for new HRA applications.

4. OUTLOOK FOR A DATA-DRIVEN QUANTIFICATION APPROACH

In the hybrid quantification approach as described above, the quantification modules or tools are the various approaches used in different HRA methods today. The selection guidance provided with the toolbox serves to identify a module appropriate for the failure mechanism (or sets of failure mechanisms) identified for an HFE by means of the qualitative analysis based on the mid-layer model (Hendrickson et al). The mid-layer model additionally identifies the PSFs relevant to each failure mechanism. As noted earlier, the hybrid method may have gaps, in other words, failure mechanisms and/or PSFs that are not covered by the modules, due to the reliance on existing HRA quantification methods. For such gaps, new modules would need to be developed.

The mid-layer model of the qualitative analysis approach is used to identify systematically the various failure mechanisms relevant for an HFE. On the basis of psychological models of human performance, the PSFs relevant to these failure mechanisms have been identified. In the hybrid method, the selection guidance uses this classification of HFE subtask types and failure mechanisms as a basis for selecting quantification modules. For the development of new modules, the model-based relationships among failure mechanisms and PSFs additionally suggest a path for the development of data-driven quantification modules.

The gaps of the module-based hybrid method in terms of its coverage of failure mechanisms and performance conditions point to specific needs for HRA data collection. The relationships among failure mechanisms and PSFs furthermore suggest, on the basis of behavioral theory and models, the PSFs that need to be addressed in data collection. For the data-driven quantification modules, an implementation based on Bayesian Belief Networks that would connect failure mechanisms to PSFs is a possible candidate. In this outlook, the qualitative analysis approach, the selection guidance of the hybrid quantification approach, HRA data collection, and the application of this data in HRA quantification have a common underlying basis, i.e., the model that relates observables to errors and corresponding probabilities. The challenge of course is in devising data capture methods that can be used to extract quantitative evidence from different types of data and data sources that are not designed to support probabilistic analysis.

5. CONCLUSION

The variability in the failure probabilities obtained for Human Failure Events estimated in different HRA analyses is a concern. In response to a Staff Requirements Memorandum (SRM), an effort has been initiated to establish a single human reliability analysis (HRA) method for the USNRC or guidance for the use of multiple methods. This effort considers that a reduction of the variability in the HRA quantification outputs must address three sources: differences in the scope and implementation of qualitative analysis, variability in converting the qualitative outputs of these analyses into the quantification inputs, and the diversity of algorithms for estimating failure probabilities from these inputs.

A qualitative analysis approach outlined in two companion papers (Mosleh et al. [6] and Hendrickson et al. [7]) is proposed to address the first source of variability. The mid-layer model (Hendrickson et al.). provides a classification of failure mechanisms with associated performance shaping factors. The development of a new HRA quantification approach envisions in the short term a toolbox or hybrid method toquantify the contributions of these failure mechanisms. The challenges for these two alternative methods include the development of guidance for module selection and the identification of the gaps in coverage. An additional issue is the compatibility of the failure probabilities estimated for the HFE subtasks with different quantification approaches. The advantages of the proposed solutions for qualitative and quantitative HRA include the extensibility for addressing other HRA application needs. The long-term perspective calls for a direct quantification of probabilities of failure mechanisms within the framework of equation 1 and based on various types of information including nuclear operating experience, simulator data, and when appropriate, data from other industries and applications.

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