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Establishing Minimum Acceptable Values for Probabilities of Human Failure Events

Practical Guidance for Probabilistic Risk Assessment

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ABSTRACT

Human reliability analysis, as it is conducted in probabilistic risk assessments, relies on the use of various models of human performance, informed by relatively sparse data from actual experience. Such an approach can give rise to a degree of skepticism, especially when the methods produce very low probabilities of failure. At some level, there is a perception that there is a limit to the reliability of operating crews and that available methods do not necessarily capture all the important causes of failure. As a result, a variety of approaches have been taken to defining limiting or minimum values that should be used in lieu of low calculated probabilities. Up to this point, there has been no consensus practice in setting or using such minimum values. This report describes the issues associated with setting minimum values for human failure probabilities. The report further proposes guidance in the form of a set of values considered to be appropriate for various types of accident contexts addressed in PRAs. It is expected that this guidance may be applied in probabilistic risk assessments performed by the nuclear industry and that it may be revised or refined as a result of insight gained from that experience.

Keywords
Probabilistic risk assessment
PRA
Human reliability analysis
HRA
Human error probability

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1
INTRODUCTION

Probabilistic risk assessments (PRAs) employ a systematic process to identify the ways in which accidents can occur in a nuclear power plant and to estimate the frequencies of those accidents. An understanding of the roles of operators and other plant personnel is essential to a meaningful characterization of these accidents. Estimating the accident frequencies relies in large part on collecting and evaluating empirical data from operating experience for a variety of parameters. While operating experience can be used to assess such parameters as the frequencies of events that can initiate an accident sequence, or the probability that a particular piece of equipment will fail to function when it is needed, collecting such data to characterize the types of potential human failures of most interest in a PRA is not feasible.

Instead, human reliability analysis (HRA) relies on models that account for factors that are expected to influence human performance under accident conditions, incorporating limited data from simulator exercises and other sources to the extent possible. A number of different methods and models for HRA have been developed and are currently used in PRAs. Each of these models incorporates a degree of expert judgment in its formulation and in the quantitative values it employs. Moreover, no method claims to provide an entirely objective or comprehensive treatment of the reliability of operating crews in responding to an upset event.

Depending on the conditions for which a particular analysis is being conducted, analysts using some of these methods can calculate extremely low probabilities of failure for an operating crew. There is at least a perception that these methods may not adequately capture the relevant influences on the operating crews, such that these failure probabilities are underestimated. There is also an expectation that there is an inherent (albeit unknown) limitation to the reliability of operating crews.

An additional complication arises when, as is often the case, an accident sequence includes more than one human failure event (HFE). There is a need to consider the potential for dependence among these HFEs, but if they are judged to be essentially independent, their joint probabilities can be very low.

These considerations have given rise to a variety of approaches to deal with limits on human reliability through the years. Among these approaches are the following:

- Some PRAs, and especially those using some of the early HRA methods in which time was the primary variable considered, simply applied the values calculated, irrespective of how low they might have been.
- Other earlier PRAs, including many of those performed during the Individual Plant Examination (IPE) program, applied a minimum probability of 1×10^{-4} for any individual

human failure event. There was far more variability with respect to the manner in which dependencies among HFEs were addressed in these earlier PRAs (often, they were not explicitly considered).

- In NUREG-1792, the NRC suggested the following [1]:

  > "The total combined probability of all the HFEs in the same accident sequence/cut set should not be less than a justified value. It is suggested that the value not be below ~1E-05 since it is typically hard to defend that other dependent failure modes that are not usually treated (e.g., random events such as even a heart attack) cannot occur. Depending on the independent HFE values, the combined probability may need to be higher."

There is no objective answer or consensus opinion regarding the question of how much credit should be given for operator actions when evaluating accident scenarios in a PRA. The purpose of the work described in this report is to suggest a practical approach to the issue of both the minimum value that might be applied for an individual HFE, and for the joint probability for multiple HFEs that occur in the same cut set or accident sequence (for which dependency among the HFEs must be considered).

A related issue arises when a HFE is evaluated for a situation in which the conditions for operator response are optimal, such as for a well practiced, relatively simple response, with ample time for correction of any errors made, good information available (indications and procedures) to guide operator response, etc. The possibility that the use of current methods may result in overestimating the probability for such a HFE is also addressed in this report.

This report describes further (in Section 2) some of the considerations that relate to the issue of establishing minimum probabilities for HFEs. Section 3 presents the results of an informal survey that was conducted to gain additional insight into current practices among utilities in the U.S. with regard to the use of minimum probabilities. Section 4 suggests a set of minimum values that appear to be reasonable and provides guidance for how these values could be used most effectively. Section 5 provides conclusions and observations regarding the potential impact of the use of minimum values in risk-informed decision-making.

It should be noted that the discussions in this report are limited to consideration of HFEs associated with actions that are relevant after an upset has occurred. This report does not address pre-initiator HFEs (i.e., those failures that leave a system or component in an unavailable state following test or maintenance activities).

2
ISSUES IN APPLYING MINIMUM VALUES FOR HUMAN ERROR PROBABILITIES

This section describes some of the ways in which minimum or limiting probabilities for human failure events have been defined for use in PRAs, and further addresses some of the reasons for using them. The primary purpose in adopting a minimum or limiting value is to recognize that there may be causes of human failure that have not been thought about, or that are not accounted for in the particular HRA method that is used. In this way, the limiting value is one way to treat completeness uncertainty of the "unknown unknown" kind. An event characterized by a limiting value is essentially a placeholder for the contribution to the probabilities for failures from causes that have not been conceived. The role of these minimum or limiting values for individual HFEs differs from that for multiple, potentially dependent HFEs. These considerations are discussed separately in the sections that follow. This section also discusses some of the impacts on the use of results and insights from PRAs that can result from including them in a PRA model.

The Role of Minimum Values

There are a number of HRA methods in current use. These methods include the following:

- Empirical models such as the time-reliability correlation in the Human Cognitive Reliability with Operator Reliability Experiments (HCR/ORE) approach [2, 3];
- Models based on the use of performance-shaping factors (PSFs), such as SPAR-H [4] and the Technique for Human Error Rate Prediction (THERP) [5]; and
- Models that focus on the causes of failure, including the cause-based decision tree (CBDT) method [3] and ATHEANA [6].

All of these methods rely to some extent on the use of expert judgment in the formulation of the model, the data used, or both. Because human behavior in general, and the nature of human interactions with a nuclear power plant in particular, can be complex, there is an understandable reluctance to accept low probabilities that may be calculated from some of these methods, even when an analyst believes the likelihood of failure to be essentially negligible.

Issues and Practices for Individual HFEs

Analyses using the majority of the models noted above do not, in fact, result in very small human error probabilities (HEPs) for individual HFEs. The HCR/ORE correlation and other time reliability correlations are exceptions in that they can produce very small HEPs when the time window for completion of an action is large in comparison with the estimated time for operator

response. It was in response to this outcome that the CBDT model was proposed as a method for providing an alternative probability for a HFE by recognizing that there could be mechanisms of failure that time alone would not necessarily mitigate.

The vast majority of HRA efforts among utilities in the U.S. involve the use of these methods, which were developed by the Electric Power Research Institute (EPRI). The HCR/ORE [2, 3] and CBDT [3] are complementary approaches to evaluating the probability of failure in the cognitive phase (i.e., in the detection of a situation to which operator response is needed, the diagnosis of the situation, and formulation of any decisions regarding what the response should be). In general, failures to carry out a response once it is decided upon are evaluated using elements of THERP [5]. All of these methods have been incorporated into the HRA Calculator® software developed by EPRI [7]. This software was developed in large measure to promote the proper and consistent application of the methods. When these HRA methods are used properly, it is rare that the resulting HEPs are so low that they raise questions. This leads to two different consequences:

- The specification of an alternative minimum value should be largely irrelevant, since the calculated values are generally not unreasonably low.
- Some human failures can become the dominant contributors to certain accident sequences, contrary to what would seem to be reasonable expectations.

Despite the first point, the lack of a definitive position regarding what constitutes an unreasonably low HEP still gives rise to debate in specific applications.

The second of these consequences refers to cases in which the conditions are close to ideal, but current methods for HRA may not be adequate to capture these conditions. An example would be scenarios that involve the loss of the main condenser as a heat sink for a BWR. This would lead to the need to reject decay heat to the suppression pool. Eventually (for many such scenarios, over tens of hours), cooling would need to be established for the suppression pool to preserve it as a heat sink. A typical probability calculated for failure of the operating crew to establish suppression pool cooling is on the order of 1×10^{-5}. Because there are diverse means by which cooling can be established, the unavailability of the function due to system failures may be relatively low. The probability that the operating crew will fail to act can therefore result in a significant contribution to the frequency of core damage. This is a well-trained, straightforward action, with adequate time for review and correction of errors, substantial additional resources available, etc. It can be argued that this HFE should not be an important contributor to core-damage frequency. The assessment provides little in the way of useful insight into how plant safety might be further improved. This, therefore, is an example of where an HRA method, formally applied, may not give realistic credit for operator actions, and may produce a result that is arguably too high. Inclusion of artificially significant contributors can distort the relative importance of other contributors, and can be detrimental to the effective use of the PRA.

Consequently, for HEPs associated with single functions, there are two aspects that need to be addressed: limiting values that serve as a check on whether an analysis has produced an unreasonably low HEP; and values that may be used in lieu of the formal estimated HEP, when that value can be argued to be inappropriately large for certain circumstances.

The guidance for the NARA HRA method [8] introduced the concept of human performance limiting values (HPLVs), which are intended as limits on the human tasks represented within an accident cut set. These HPLVs are applied whenever the HRA method being used produces a very low HEP. The way these values are described suggests that they are applied on an individual functional basis rather than for a group of different functional tasks in an event sequence. Several different values are provided that are to be applied under different conditions. The NARA guidance identifies the role of these HPLVs as addressing completeness uncertainty; they are included to address the fact that analysts cannot envisage everything.

The MERMOS method [9] is another method that uses a limiting value. In this approach, the HEP is evaluated using the following equation:

$$P(HFE) = \sum_{\substack{identifiable \\ scenarios}} P(identifiable\ failure\ scenarios) + P_r$$

MERMOS provides a method for evaluating the probabilities of the identifiable failure scenarios, and P_r represents a residual probability of failure of the HFE. The hypothesis underlying the inclusion of this residual probability is that scenarios exist that cannot be envisaged. In other terms, the hypothesis is put forward that the probability of a function failing is not nil, and represents a completeness uncertainty. In practice, this residual probability is between 1×10^{-4} and 1×10^{-5}. In this construct, the limiting value would dominate when the HRA method would result in a HEP lower than that limiting value.

Other methods, such as SPAR-H [4], are self-limiting by virtue of the prescriptive nature of the method, which allows reduction of the basic HEP by specified factors. The minimum HEP, based on the diagnosis portion, is 1.25×10^{-5}.

With regard to other guidance, the ASME/ANS PRA Standard [10] is silent in the matter of whether a limiting or minimum value should be applied in the course of assessing an individual HFE. The "Good Practices" documented in NUREG-1792 [1] do not call explicitly for establishing a minimum value. In discussing the need to check the reasonableness of calculated HEPs, however, Good Practice # 8 infers that a reliable human action should have a failure probability in the range of 0.001 to 0.0001:

> "For an HFE, is [*sic*] there one or two dominant PSFs that exist or is the cumulative effect of the relevant PSFs such that they are either so negative or so positive that a "sanity check" would suggest a high HEP (e.g., 0.1) or a low HEP (e.g., 0.0001), respectively?

> For example, if the procedures and training fit the scenario well, the cues will be clear, there is plenty of time available, and the actions are simple and familiar, then an HEP of 0.001 to 0.0001 would be reasonable."

Each of these approaches reflects the judgments and expectations of the authors; none is grounded on objective evidence. Nevertheless, it is important to keep these expectations in mind in considering a recommended approach.

Treatment of Dependencies Among HFEs

Many of the cut sets or other representations used to quantify the frequencies of accident sequences include more than one HFE. As is the case with other elements of a PRA, it is important to consider the potential for dependence among these HFEs. This dependence can arise from a variety of elements of the response to an upset event, including the potential that multiple actions are triggered by the same set of cues; the same operating crew would often be involved in the actions; the actions may be close in time, etc. The consideration of these dependencies is, therefore, an important and necessary element of a HRA.

Although there is no consensus with regard to how these dependencies should be addressed, the approach incorporated into the HRA Calculator® is in widespread use, at least within the nuclear industry in the U.S. This approach, outlined in Figure 2-1, entails assessing certain shared characteristics of HFEs in a pair-wise fashion to determine a qualitative level of dependence. These qualitative levels are then interpreted probabilistically using a set of rules defined in THERP (these were originally set forth to address dependence among sequential tasks in a process). The qualitative levels are as follows:

- Complete (conditional probability of 1)
- High (conditional probability ~0.5)
- Moderate (conditional probability ~0.15)
- Low (conditional probability ~ 0.05)
- Zero (i.e., independent probabilities apply)

Other methods, including SPAR-H, have used similar approaches to assessing levels of dependence among multiple HFEs.

It should be expected that the potential for, and degree of, dependency is related to the human failure mechanism. However, in the approaches outlined above—and in most current PRAs—this is not generally addressed in any detail. From the quantification point of view, the same conditional probabilities are applied regardless of the origin of the dependency.

A more realistic and defendable approach to the treatment of dependency between HFEs would clearly be to base it on consideration of the underlying human failure mechanisms in a manner analogous to the way in which common cause failures are addressed. As an example, consider

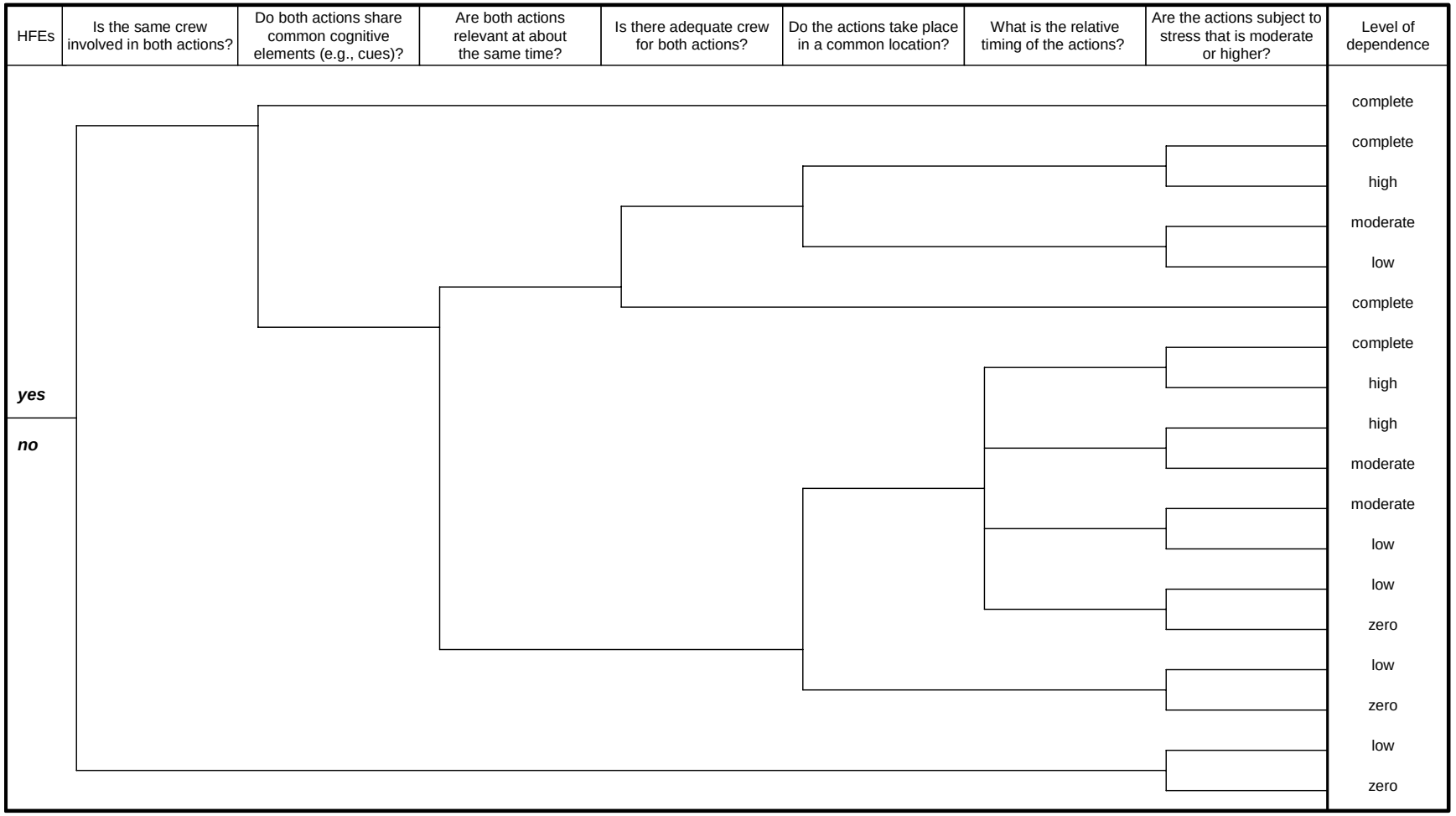

Figure 2-1
Dependency Model from HRA Calculator® [7]

the Information/Decision/Action (IDA) framework [11] for characterizing human failures. One failure mode of the "I" module is an incorrect situation assessment, which translates into an inappropriate plan of action for the actual situation, but one that would have been correct for the situation perceived. As the plant changes with time, there is the possibility, facilitated by the structure of the suite of emergency operating procedures (EOPs), of revisiting the situation assessment and getting back on track. Therefore, for this incorrect situation assessment to be a cause of failing the required actions, the operators would have to persist in maintaining the incorrect assessment.

For many HFEs in accident-sequence cut sets, particularly those that are related to the same critical safety function, one potential failure mechanism therefore is the persistence of an initial situation assessment. This can be argued to have a low probability based on the nature of the EOPs and aids such as those used to track critical safety functions, coupled with the fact that for most accidents, plant changes are slow enough that they allow the possibility of recovery.A failure mechanism related to the "D" module is making an incorrect decision given the correct situation assessment. An example could be entry into an incorrect procedure. This could lead to failure of a number of functions, but again, there are nearly always opportunities for self-correction.

A failure mechanism related to the "A" module is a failure to execute the series of required steps properly. In the case of multiple HFEs, this could be a large number of different sets of actions.

It is not unreasonable to suggest that the likelihood of failures of multiple HFEs through these different mechanisms is potentially very different. Yet, as indicated above, when quantifying the degree of dependency in a typical PRA, the same conditional probability is used whether the contributions to the HFEs are dominated by a cognitive or an execution failure.

Another potential cause for dependency is the time element. For example, if there is a series of responses that has to take place, then taking too long in the failed attempt to perform the first can lead to increased failure of the subsequent actions. This type of dependency would be difficult to model in the framework of current PRAs, but could be modeled in a dynamic PRA.

While it is beyond the scope of this document to propose a new approach to the quantification of dependence, the considerations above can be used to inform a set of criteria for identifying the degree of dependence, including when to conclude that HFEs are independent.

It should be further noted that the ASME/ANS Standard [10], in Supporting Requirement HR-G7, includes the following statement: "For multiple human actions in the same accident sequence or cut set, ….. , ASSESS the degree of dependence, and calculate a joint probability that reflects that dependence."

As noted in the introduction to this report, NUREG-1792 [1] addresses more explicitly the need to consider a minimum value for the joint probability of multiple HFEs:

> "The resulting joint probability of the HEPs in an accident sequence should be such that it is in line with the above characteristics [which are the conditions

under which the operator actions may be dependent] and the following guidance, unless otherwise justified:

- The total combined probability of all the HFEs in the same accident sequence/cut set should not be less than a justified value. It is suggested that the value not be below ~1E-05 since it is typically hard to defend that other dependent failure modes that are not usually treated (e.g., random events such as even a heart attack) cannot occur. Depending on the independent HFE values, the combined probability may need to be higher."

In this way, NUREG-1792 introduces formally the concept of a limiting value on the combined HEP, and the use of such a value is widely regarded as being expected in regulatory applications. While it may not have been intended as an absolute limit, but more as a sort of trigger, to have the analyst check lower joint HEPs to see if some underlying dependence had been overlooked, it has often been interpreted as absolute.

When a limiting value for the combined HEP for a group of HFEs is proposed, it would be applied when the prescribed approach for dealing with dependency results in a total combined HEP that is less than that limiting value. A strict application of the guidance from NUREG-1792 above would be to apply the limiting value even if the HFEs were considered to be independent according to the criteria the analyst has adopted for determining the degree of dependence or independence.

This has caused difficulty in applying the Significance Determination Process (SDP) of the NRC's Reactor Oversight Process, particularly for shutdown events, where operator action is usually an important part of the response, and where the initiating event may have been due, to some extent, to human action. Using a minimum value of 1×10^{-5} has resulted in findings that would otherwise have characterized an event or condition as having very low risk becoming "white" findings.

Therefore, while it might be reasonable to adopt some sort of limit, it needs to be done carefully, so that the results of PRAs are not distorted by arbitrary assignments of probabilities. As discussed in detail later on, any limiting values should be consistent within the context of the scenarios in which they are applied.

Implications of Minimum Values for HFEs

The results of PRAs are among the inputs to the process of making decisions concerning the operation and design of a nuclear power plant. Inclusion of limiting values for HEPs (or groups of HEPs) can have an impact on the results used to make these decisions, depending on the values used, and on the overall design of the plant. For plants with high redundancy and diversity such as certain European plants that have, in addition to the usual complement of safety systems, a bunkered diverse set of systems, the limiting values are, along with common-cause failure, likely to be the most significant contributors to risk. When the minimum values indeed turn out to be significant to the results being used to support a decision, they become key sources of model uncertainty as defined in the ASME/ANS PRA Standard [10] and Regulatory Guide 1.200

[12]. Therefore, it is imperative that the assumptions underlying these limiting values be justified and documented to provide decision-makers with the information they need. Furthermore, when limiting values are included, guidance is needed on how to interpret their impact on the results used for decision-making. For example, since they represent a completeness uncertainty, when using the model for an application, it could be useful to run sensitivity cases to determine the critical values at which the limiting values change the conclusions in a significant way. If these critical values can be argued to be unreasonable then they can be eliminated, since they would not be key sources of uncertainty.

This approach inverts the issue of identifying arbitrary minimum values by not trying to pick numbers as such, but producing a qualitative consideration of the factors that would argue against a critical value for the HEP or combined HEP.

From the point of view of looking for improvements to plant design or operations, limiting values are not particularly useful, since what they represent is the impact of an unknown cause or causes. Since the causes are undefined, there is no basis for suggesting improvements. A comparison can be made to the inclusion of the reactor pressure vessel (RPV) failure in a PRA model. Failure of the RPV is generally modeled as an initiating event that cannot be mitigated and therefore leads directly to core damage. In the PRA model, the RPV failure acts as a placeholder which, because its frequency is considered low enough, does not impact any decisions. If, however, a decision is to be made based partly on the assessment of a change in risk, e.g., using Regulatory Guide 1.174 [13], since this contribution is effectively a single-element cut set, its contribution to the change would be zero. For this type of decision, inclusion in the model is irrelevant.

In contrast to the case of the RPV failure, a basic event with the assigned minimum value can occur in cut sets in combination with other basic events, and therefore the limiting value chosen can affect the importance measures for those basic events as well as the absolute measures of risk or changes in risk metrics. Therefore, the limiting values have to be chosen to be as reasonable as possible so that they do not distort the results and lead to inappropriate decisions.

As an example, consider a minimum value for a single HFE. It is necessary to include HFEs related to all essential operator functions in the model, even those that are believed to be highly reliable and therefore have a very low HEP, because they could be critical single points of failure of the plant function they support. Including them in the PRA model helps preserve the visibility of the required function, so that steps can be taken to preserve the performance needed to maintain the acceptable level of risk. It is not useful, however, for the limiting value of the HEP to be such that it overwhelms the contribution from hardware failures. Therefore, for individual HFEs, one possibility is to set the lower limit at some value which is lower than the typical hardware failure probability for the system/function. While the cut sets containing the HFE may be truncated when solving the model, the fact that the HFE is in the logic structure is sufficient to ensure that, should the likelihood of the complementary sets of events in the cut sets in which the HFE appears increase, its significance would not be overlooked.

A particular consideration in defining minimum values for HFEs relates to the granularity of the HRA modeling. Operator responses are included in the PRA logic models by constructing the

event trees in such a way that the successes of human responses modeled at the function level are implicit in the event tree branching structure, and the failures are represented as HFEs, either explicitly as branch points on the event tree or as basic events in the fault trees that are used to evaluate the functional or systemic failures in the event tree. There is, however, no standard for the level of resolution for defining HFEs. For example, some PRA modelers may choose to represent the failure of a function by two HFEs, one representing the cognitive failure and one representing the execution failure. This has been done, for example, as one way to explicitly address, in part, the cognitive dependency between multiple HFEs. An example is the modeling of the responses in a common PWR emergency procedure that is evoked upon a loss of all feedwater. One approach is to define a HFE to represent the failure to enter the procedure at all, a high-level cognitive failure to recognize the lack of cooling via the steam generators, and a HFE to represent the failure to initiate feed-and-bleed cooling, which would be a failure to execute a critical step within the emergency procedure. Another approach would be to model the HFE as including both the initial cognitive failure to enter the proper procedure and the failure to execute the feed-and-bleed cooling step. Thus, in the first case a failure of the function "initiate feed-and-bleed cooling" would be represented as follows:

$$p_{total} = p(\text{fail to enter procedure}) + p(\text{fail to execute feed - and - bleed cooling})$$

In the second case, there would be just one term:

$$p' = p(\text{fail to initiate feed - and - bleed cooling})$$

The "prime" in the second case indicates that the HFE is defined differently in that it includes more causes of failure. When limiting values are applied this needs to be done recognizing these different HFE definitions; it would not make sense to apply the same limiting value to each of the terms in the first case and to the single term in the second.

For combinations of HEPs, the situation is not so easily addressed. However, it should, in all likelihood, not be a 'one-size-fits-all' limiting value, but should allow for differences in context for different sets of responses, and for differences in modeling approaches. Barry Kirwan, in his proposed set of limiting values [8] recognizes this to some extent.

These considerations and issues are reflected in the formulation of a set of suggested minimum values, presented in Section 4.

3
SURVEY OF CURRENT PRACTICES

An informal survey was conducted to compare current practices with respect to defining and using minimum values for probabilities of HFEs among utilities. This survey covered most of the utilities operating nuclear power plants at multiple sites in the U.S. The intent of this survey was to look for any common practices, patterns among the practices, and particular issues that have arisen with regard to minimum values for human error probabilities.

The survey requested responses to the following eight questions:

1. Do you employ a value below which you do not allow the probability of an individual post-initiator human failure event (HFE) to fall?
2. If so, what value (or values) do you use? What, if any, reference or justification do you provide in conjunction with the value?
3. If you use the EPRI HRA methods (HCR/ORE and/or CBDTM, plus THERP for execution), how often do you encounter HFEs for which you calculate probabilities low enough that you substitute the lower bound?
4. If you use lower bounds instead of the calculated value, please provide descriptions of the HFEs and the scenarios in which they occur.
5. In addressing dependencies among post-initiator HFEs, do you similarly employ a lower bound for the composite probability?
6. If so, what value do you use? What reference or justification do you provide in conjunction with the value?
7. Please provide examples of the scenarios that involve combinations of HFEs for which the lower bound is applied.
8. Please summarize any findings or suggestions related to the use (or lack) of lower limits for HFE probabilities generated in the course of a PRA peer review.

Seven responses were received from six utilities (one utility follows somewhat different practices at each of two plants). The results are summarized in Table 3-1. Only one plant had information relating to question 4, because none of the other responses indicated that there had been a need to substitute a minimum value for the calculated value for any individual HFE.

Table 3-1
Summary of Current Practices in the Use of Minimum Values

Utility	What minimum value(s) are used for individual HFEs [Q1 and Q2]	How frequently is the minimum applied? [Q3]	What minimum value(s) are used for multiple HFEs? [Q5 and Q6]	Examples of scenarios for which minimum values are applied [Q7]
A	Value documented as 1E-4, but in practice minimum value of 1E-3 is applied.	No values calculated below 1E-4; very few changed to 1E-3. All others were calculated to be above 1E-3.	No minimum value applied.	N/A
B	None. Calculations reviewed and adjustments made on a case-by-case basis when deficiencies (e.g., in procedures) or excess credit for intra-event recovery are judged to be present.	Changes to analyses rarely required.	None. Very low joint probabilities are reviewed for reasonableness; sensitivity studies are conducted for joint values below 1E-8.	N/A
C	None applied.	N/A	None applied.	N/A
D (Plant A)	Minimum value of 1E-6, with careful review of any HFEs with probability less than 1E-5.	No cases. All HFEs except one have probabilities above 1E-5. The exception entails failure to establish suppression pool cooling, and its probability is above 1E-6.	For combinations of HFEs with action required within 24 hr: 1E-6.	Failure to control reactor pressure-vessel (RPV) level using high pressure injection; failure to depressurize the RPV to allow injection at low pressure; failure to restore room cooling to switchgear room; and failure to align portable generator to supply battery charger (actions required from 10 min to 6 hr after initiating event).
			For combinations of HFEs with action required beyond 24 hr, and for which additional cues and symptoms are available: 5E-7	Failure to initiate suppression pool cooling in the long term, and failure to vent containment.

Table 3-1 (continued)
Summary of Current Practices in the Use of Minimum Values

Utility	What minimum value(s) are used for individual HFEs [Q1 and Q2]	How frequently is the minimum applied? [Q3]	What minimum value(s) are used for multiple HFEs? [Q5 and Q6]	Examples of scenarios for which minimum values are applied [Q7]
			For HFEs that are judged to be independent, no minimum value was applied. Independence was judged to be adequate for actions that • have diverse symptoms, • occur at widely different times, and • involve different crew members.	
D (Plant B)	None specified. All HEPs are above 1E-5, which is noted to be above the limit suggested by NUREG-1792.	N/A	For scenarios with time windows less than 12 hr: 1E-5 (citing NUREG-1792).	Failure to initiate feed-and-bleed cooling after total loss of feedwater coupled with failure to refill fuel-oil tank for station blackout compressor several hours later.
			For scenarios with time windows approaching 12 hr: 1E-6.	Failure to refill fuel-oil tank for station blackout compressor several hours after trip; loss of auxiliary feedwater (AFW) due to failure to refill storage tank within about 12 hr; and failure to initiate feed-and-bleed cooling after loss of all feedwater.

Table 3-1 (continued)
Summary of Current Practices in the Use of Minimum Values

Utility	What minimum value(s) are used for individual HFEs [Q1 and Q2]	How frequently is the minimum applied? [Q3]	What minimum value(s) are used for multiple HFEs? [Q5 and Q6]	Examples of scenarios for which minimum values are applied [Q7]
			For two selected scenarios, no lower limit is applied.	• Failure to refill fuel-oil tank for station blackout compressor several hours after trip; loss of AFW due to failure to refill storage tank within about 12 hr; and failure to switch over to high-pressure recirculation after having successfully initiated feed-and-bleed cooling. • Loss of AFW due to failure to refill storage tank within about 12 hr; failure to align an alternate source of suction to AFW; failure to initiate feed-and-bleed cooling; and failure to open minimum-flow valves for charging pumps.
E	None applied.	N/A	For scenarios with time available less than 15 hr: 1E-6 For scenarios with time available greater than 15 hr: 5E-7.	None cited.

Table 3-1 (continued)
Summary of Current Practices in the Use of Minimum Values

Utility	What minimum value(s) are used for individual HFEs [Q1 and Q2]	How frequently is the minimum applied? [Q3]	What minimum value(s) are used for multiple HFEs? [Q5 and Q6]	Examples of scenarios for which minimum values are applied [Q7]
F	Minimum value of 1E-5, consistent with NUREG-1792 and other sources.	For one plant: two HFEs out of 87 total. For one plant: one HFE of 42 total. For two plants, no HFEs for a combined total of 124 events.[1]	For one plant • for combinations of two HFEs: 1E-5. • for combinations of three or four HFES: 1E-6. All other plants use a minimum value of 1E-6.	• Failure to depressurize the RPV following failure of high-pressure injection; failure to initiate alternate low-pressure injection; and failure to establish wetwell venting for decay heat removal (BWR). • Failure to align and start standby chiller for room cooling; failure to start AFW pump; and failure to switch makeup pump to alternate cooling (PWR). • Failure to perform rapid cooldown following small loss-of-coolant accident (LOCA); failure to initiate high-pressure recirculation; and failure to start AFW when auto-start fails. • Failure to provide alternate suction source to AFW after depletion of the CST; failure to align AFW to take suction from the service water system; and failure to switch to high-pressure recirculation following a transient-induced LOCA (PWR).

[1]Examples of scenarios for which minimum values were used by Utility F in lieu of calculated values:

- Failure to make up to the condensate storage tank (CST) to support continued long-term injection for a station blackout (BWR).
- Failure to depressurize the reactor pressure vessel when temperature in the suppression pool cannot be maintained within limits (BWR).
- Failure to start a standby component cooling water pump under various conditions (PWR).

There are no entries for question 8. None of the responses indicated that a peer review had provided comments regarding the manner in which minimum values were defined or applied. It should be noted that there is anecdotal evidence that findings have been written regarding the selection or use of minimum values for other plants for which survey responses were not available.

The survey results reflect significant variability with regard to how this issue is addressed by different utilities. A common theme, however, is that the use of minimum values is rarely found to be necessary with respect to individual HFEs. This results largely from the use of methods for HRA that, when appropriately applied, do not provide extremely low probabilities for HFEs.

The use of minimum values for scenarios with multiple HFEs potentially subject to dependence has somewhat more impact. If HFEs are assessed to be largely independent of each other, the calculated joint probability of failure can be quite low. As Table 3-1 indicates, different approaches have been taken to address these very low probabilities. It is common, however, to find that for situations in which a significant level of independence can be justified, no alternative minimum value is introduced.

4
PROPOSED GUIDANCE FOR USE OF MINIMUM VALUES

In developing proposals for determining and using minimum values for HEPs, the following considerations apply:

- There needs to be a recognition that there are different approaches to PRA modeling, especially the level of detail at which HFEs are defined.
- It is important to understand the detailed timeline and context of the scenario at the appropriate level, including the following levels:
  - Cut-set,
  - Accident sequence defined at the system level, and
  - Accident sequence defined at the level of safety functions.

Of particular importance is the overall picture of the dynamics of the development of the accident, including changing plant state, additional cues, additional resources, and the applicability of procedures and training.

- There is a need to have a holistic view of the plant organization rather than focusing on the crew in the somewhat mechanistic way that is usually the case in HRA.
- Since the primary use of a PRA is to support decision-making, the assumptions behind the choice of limiting values should be documented carefully.

The two sections that follow discuss minimum values for HEPs associated with single tasks or functions and minimum values for combinations of HFEs, respectively.

Minimum Values for Individual HFEs

As described in Section 2, it can be useful to define minimum values for individual HFEs. It is important, however, that these minimum values be tailored to the manner in which the HFEs are defined, and account for the nature of the accident context.

The actions associated with HFEs can differ significantly in terms of their complexity, e.g., number and nature of tasks, the time available to perform the response compared to the time of the cue, the clarity of the cues, etc. As a result, different approaches to modeling the responses are seen in the PRA literature. These differences are reflected in the values proposed in the sections that follow.

Simple Function

For those HFEs associated with a simple function for which there is only one method of execution, there are likely to be no differences in the level of event definition between analysts. One example would be the failure to initiate depressurization of the reactor for a BWR. This could be needed to allow use of low-pressure injection to maintain level in the RPV after loss of all high-pressure injection. This is a relatively simple function to execute, well practiced, and with a significant warning time, and would be represented in nearly any PRA by a single HFE.

The need to consider use of a minimum value would arise only when the HRA method being used gives no indication of a reason for the HEP to be significant. Therefore, it seems reasonable to set the limiting value at some point that is comparable to but lower than a nominal failure probability for the system function due to hardware faults. While the cut sets containing the HFE may be truncated when solving the model, the fact that it is in the logic structure is sufficient to ensure that, should the likelihood of the complementary set of events in the cut sets in which the HFE appears increase significantly, its significance would not be overlooked.

For such actions, proper use of HRA methods such as those included in the HRA Calculator® should obviate the need for a minimum value. As a check, however, the minimum values outlined in Table 4-1 are proposed. If a HEP is calculated that is lower than the respective minimum value, the analyst should do two things:

- Check the calculation to ensure that some element has not been overlooked or underestimated (e.g., because too much credit was given to recovery within the HFE), and
- Use the minimum value, if no changes to the analysis are identified that would increase the results above the minimum value.

Table 4-1
Proposed Minimum Values for HFEs Corresponding to Simple Functions

Nature of the Action	Limiting Value	Rationale
Actions are judged to be time-constrained, or need to be performed for scenario that has the potential for distraction	1×10^{-4}	Value selected to be somewhat lower than typical hardware failure probability.
Well-practiced, familiar responses with significant time to respond, and with procedural guidance and training that leads to monitoring of plant status to assess the efficacy of response, thus allowing opportunity for self-correction; and with low workload (i.e., no distractions).	1×10^{-5}	Value is selected between the two bounding conditions.
Well-practiced, familiar responses with expansive time to respond, numerous indications of the need for action, procedural guidance and training that leads to monitoring of plant status to assess the efficacy of response, thus allowing opportunity for self-correction; and low workload (i.e., no distractions).	1×10^{-6} (note 1)	Failure is almost inconceivable given the nature of the task, the procedural guidance, and training and experience of the power plant personnel.

[1]An alternative would be to document the rationale that, for this action, the probability of the human failure is negligible. This might be done, for example, for the case of failure to initiate suppression-pool cooling at a BWR, as described in Section 2.

Single Function with Multiple Success Paths

Some functions modeled in a PRA are considerably more complex, with the possibility that multiple success paths may be relevant. Consider the following three different approaches to modeling the function "failure to establish decay heat removal" for a PWR:

1. A single HFE that represents failure to establish decay heat removal;
2. Multiple HFEs, each representing the failure of one of the tasks that provides a success path (e.g., separate HFEs for failure to establish auxiliary feedwater, failure to recover main feedwater, and failure to initiate feed-and-bleed cooling);
3. As in case 2, but including a separate HFE representing the failure to recognize the need to perform the function. This modeling approach separates out the common cognitive element from all of the subtasks.

[Note that this example is used for illustrative purposes, since it is unlikely that any HRA method would result in probabilities that would be below a suggested minimum value for this particular function.]

In this example, the HFEs in case 2 represent failures of the alternate approaches to achieving the function success. Consequently they would be considered dependent. Case 3 includes an attempt at explicitly modeling one of the causes of dependence, the recognition that the function is required.

For this more complex situation, the minimum value for the probability of the human contribution to failure of the function, taken as a whole, should be the same for all three approaches. Furthermore, it has to be determined such that the complexity introduced by the existence of alternate success paths and the potential for conflicting strategies is accounted for.

The suggested values for this more complex set of conditions are outlined in Table 4-2. The values proposed reflect the increased complexity of the response compared to a simple function. For cases that do not meet the criteria specified in Table 4-2, it is expected that values higher than 1×10^{-4} would be calculated, and would be appropriate.

For failure of a single function that is modeled using multiple HFEs, the proposed approach is to associate the minimum value with the functional failure rather than with individual HFEs. Therefore, if there is more than one HFE associated with the function as in cases 2 and 3 above, the limiting value could be introduced for each of the HFEs via an OR gate with the same basic event name to avoid double-counting.

Table 4-2
Proposed Minimum Values for HFEs Corresponding to Single Function with Multiple Success Paths

Nature of the Action	Limiting Value	Rationale
A functional response where the dependence between the failures to perform the initial success paths and the final success path is assessed to be low (i.e., conditions are good but not optimal[1].	1×10^{-4}	Value selected to be higher than that for a simple function with good (but not optimal) conditions.
A functional response for which the dependence between the failures to perform the initial success paths and the final success path is assessed to be very low (i.e., conditions are optimal).	1×10^{-5}	Same as value proposed for a simple function when the conditions are good but not optimal.
Well-practiced, familiar responses with expansive time to respond, numerous indications of the need for action, procedural guidance and training that leads to monitoring of plant status to assess the efficacy of response, thus allowing opportunity for self-correction; and low workload (i.e., no distractions).	1×10^{-6} (note 2)	Failure is almost inconceivable given the nature of the task, the procedural guidance, and training and experience of the power plant personnel

[1]Refer to Table 4-3 for the rules regarding dependence.
[2]An alternative would be to document the rationale that, for this action, the probability of the human failure is negligible.

Minimum Values for Joint HEPs

Because of the nature of this problem, i.e., dealing with true unknowns, it does not seem appropriate to include the minimum values for combined HEPs at a very detailed level, and therefore, it is proposed to address this at the functional accident sequence level. Failures of this magnitude are most likely a result of the breakdown of the complete organization. A further discussion is provided regarding relevant features of treating dependencies among HFEs, followed by a proposal for use of minimum values.

Considerations in Modeling Dependency

As indicated in Section 2, there could be a number of reasons for failing multiple responses. These would include the following:

- An incorrect situation assessment leading to an incorrect strategy for dealing with the accident.
- A delay in initial response leading to inability to complete subsequent responses.

For HFEs to be considered dependent there has to be either some common influence that extends over the expected time frame of performance of the responses, or the first failure produces conditions that make the second, third, etc. failures more likely than if the second failure were triggered by a hardware (i.e., non-human caused) failure of the first function. Aspects that can affect both the likelihood of failure of single functional responses and dependency include the following:

- The complexity of the required responses increasing the workload on the operators
- Ambiguity resulting from insufficient information from the plant or insufficient guidance in the procedures, making a clear situation assessment difficult;
- Lack of training on the responses for the specific plant conditions;
- Problems with the man-machine interface.

The responses prescribed in the EOPs and other procedures to cope with plant transients and accidents are designed to be feasible with respect to the resources available, and the operators are provided with extensive training. Thus a high rate of success should be expected. There may, however, be special circumstances in which the procedures are not optimal, and one of the tasks of the HRA is to identify such circumstances. This, in fact, is the approach taken by the newer approaches to HRA, such as MERMOS [9] and ATHEANA [6]. It is the fact that not every contingency can be envisaged, coupled with the unease associated with proposing very low probabilities, that has no doubt led to the use of cut-off, or minimum values.

Based on the above, a set of proposed rules for assessing dependency in the context of considering the relevance of minimum values has been proposed. These rules are summarized in Table 4-3.

Application of these rules requires significant judgment, not the least because the expectation is that the procedures and training are adequate for the majority of the PRA scenarios. For the purposes of this document, the most significant of these rules are those associated with low and very low dependence, since it is for those scenarios considered as being representative of very low dependence that the minimum values are likely to be applied.

Table 4-3
Proposed Rules for Levels of Dependence in Applying Minimum Values

Level of Dependence	Criteria
Independent	• HFEs are related to actions for different critical safety functions; and • Actions are separated by time; and • Actions for which failure is modeled are separated by successful actions integral to the definition of the accident sequence. • Independence is justified in this case because success in responding to the performance of a critical safety function demonstrates that the operating crew had regained a correct situation assessment even after having failed in the initial function.
For HFEs that represent alternate approaches for achieving success for the same functional response:	
Very low	• Actions are separated in time such that the plant conditions will have evolved to the point that it is evident that the first response has not resulted in the correct plant response; and • The procedural guidance includes the need for continuous monitoring of the plant status, and clear instruction to implement an alternate response should the first not succeed; and • The need for initiation of the second response is monitored by an independent member of the crew, e.g., by using functional response procedures; and • The indication that the second response is needed is accompanied by an alarm.

Table 4-3 (continued)
Proposed Rules for Levels of Dependence in Applying Minimum Values

Level of Dependence	Criteria
Low	• Same as for "very low", but • There is no alarm indicating need for the second action.
Moderate	• Conditions fall between those for low and high dependence.
High	• The responses are required close in time such that the failure of the first attempt is not clear; and • Workload is high, resulting in the possibility of distraction; and • There is ambiguity as to plant status (e.g., failed instrumentation, unclear procedural guidance); and • Training in the specific scenario is infrequent.
For HFEs associated with responses that are for different functions:	
Very low	• The separation in time is such that the plant conditions will have evolved so that it is evident that the first response has not resulted in the correct plant response; and • The procedural guidance is clear when the second response is required and is dependent on the plant status; and • The need for initiation of the second response is monitored by a member of the crew who is independent of crew members attempting to restore the first function, e.g., shift supervisor using functional response procedures; and • The indication that the second response is needed is accompanied by an alarm; and • There is no overriding strategy for success involving trying to recover the first function.
Low	• Same as for "very low", but • There is no alarm indicating need for the second action.
Moderate	• Conditions fall between those for low and high dependence.

Table 4-3 (continued)
Proposed Rules for Levels of Dependence in Applying Minimum Values

Level of Dependence	Criteria
High	• The responses are required close in time such that the recognition that the first response has failed is unlikely; and • Workload is high and there is cause for distraction; and • There is ambiguity as to plant status (e.g., failed instrumentation, unclear procedural guidance); and • Training or procedures are inadequate for scenario.

Proposed Minimum Values for Dependent HFEs

Based on the considerations outlined in Table 4-3, a set of minimum values is proposed. For cases not covered by this table, the calculated value should be applied (e.g., if the criteria for "independent" HFEs are met, it should not be necessary to employ an alternative minimum value rather than the one calculated).

These minimum values are summarized in Table 4-4.

Table 4-4
Proposed Minimum Values for Dependent Sets of HFEs

Level of Dependence Per Table 4-3	Limiting Value	Rationale
Low	1×10^{-5}	This value is the same as that for the case of a single complex function with very low dependence. This is because this involves multiple functions, and thus the situation is more complex and can result in a higher failure probability.
Very low	1×10^{-6} (note 1)	The combination of failures is considered to be very unlikely to happen.

[1]An alternative would be to document the rationale that, for this action, the probability of the human failure is negligible.

These values are intended, in part, to accommodate the likelihood of variations of the PRA defined scenario that could affect the assessment of dependence. For example, instrumentation failures that are not modeled could in fact occur, but it is generally assumed that the occurrence of sufficient instrumentation faults to cause operator failures is very low, and would be dominated by a common-cause failure probability of low likelihood. In the case of multiple functions, multiple sets of instrumentation would have to fail, resulting in an even lower probability. As another example, differences in the assumed times to failure of either hardware or the operating crew can affect the scenario development in such a way that the conditions for the

second or third response will be different. While the failures are typically assumed to occur so that the conditions for the evaluation of the HEPs are the most demanding, this is done on the basis of an individual HFE rather than on consideration of the interrelationships among HFEs in an accident sequence.

Many PRAs currently use a single fault tree to account for all accident sequences. Since the proposal in this report is to introduce a single basic event that represents the limiting value, care must be taken to accommodate the difference in granularity of the modeling of the HFEs. Different minimum values could apply to different cut sets that contain the same group of HFEs. Therefore, an important task is ensuring that the relevant context and time-line are understood for each accident sequence cut set for which limiting values may be relevant. This may be somewhat easier for situations in which cut sets are generated on a sequence-by-sequence basis.

5
CONCLUSIONS

The role of limiting or minimum values is to address those causes of human failure that cannot necessarily be identified, whether they be associated with a single function or, more globally, several functions in the context of an accident sequence. Since the causes are unknown, the probabilities associated with the limiting values cannot be determined based on a model, and they will be determined based on assumptions and expert judgment.

When applied to a single HFE, the limiting values may be included for one of two reasons: first, when use of a particular HRA method generates a very low HEP that is below the comfort level of the analyst; second, when the analysis produces a result that is considered unreasonably conservative. Either case leads to retention in the logic model of basic events for human failures that cannot be assumed not to occur, but for which a reasonable explanation cannot be found. While the former has some merit in that it results in maintaining, in the logic structure, events related to critical operator functions, the merit of the latter is less clear. Depending on the values chosen, as discussed earlier, the presence of minimum values as risk contributors may unnecessarily complicate the interpretation of the PRA results, resulting in obscuring important insights. When applied to groups of HFEs, minimum values represent, at some level, an assessment of the limit on the efficacy of the plant infrastructure to deal with an accident.

It is generally expected that some minimum values will be needed. Because HFEs can vary significantly in their definition and in the scope of what they represent (e.g., individual tasks, cognitive versus execution failures), it may not be practical to apply a standard set of minimum values directly to the HFEs, either singly or in groups. Instead, the minimum values applied to accident sequences, or accident-sequence cut sets, are probably best applied at the functional level, regardless of how that functional response is broken down into separate HFEs for modeling purposes. An alternative would be to propose different values for different styles of modeling, though this seems unnecessarily complicated. In either case, the determination of the appropriate values cannot be made independent of the formal treatment of dependency. Unfortunately, the treatment of uncertainty is itself somewhat rudimentary. While there may be some general agreement as to when HFEs should be regarded as dependent and when they can be considered independent, the quantification of the conditional probabilities generally resorts to application of the rules taken from THERP [5], for which the basis is obscure. The treatment of dependency is discussed further in Sections 2 and 4.

The use of minimum values has implications for uses of the PRA. If a set of minimum values can be agreed upon, and the conditions under which they are applied clearly defined, they become essentially consensus positions and are removed from consideration as key sources of model uncertainty [14]. An alternative approach to accepting the minimum values as absolute is to interpret them as placeholders, and perform sensitivity studies using the PRA model to determine

at what values they become significant to a decision. A qualitative argument can then be constructed to either support or refute those values.

There are two potential interpretations of the minimum values. The first is that they represent the consensus best estimates of the limiting HEPs or joint HEPs. If this is the case, when the PRA is used in an application, the assessment of the metrics used to support the decision, be they core-damage frequency (CDF), large early release frequency (LERF), change in CDF, change in LERF, or importance measures, are accepted at face value. If these limiting values are not critical to acceptance or rejection of the decision being supported by the PRA, this is a non-controversial situation.

If, however, the values do not reflect a consensus, and they can affect the decision, this becomes more complicated. In this case, the assumptions that underlie the minimum values are important, and it is these that will be the subject of discussion. Any discussion with decision makers will likely revolve around the story that is created to justify a particular value.

6
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