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A RISK METHODOLOGY TO EVALUATE SENSITIVITY OF PLANT RISK TO HUMAN ERRORS*

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Abstract

This paper presents an evaluation of sensitivity of plant risk parameters, namely the core melt frequency and the accident sequence frequencies, to the human errors involved in various aspects of nuclear power plant operations. Results are provided using the Oconee-3 Probabilistic Risk Assessment model as an example application of the risk methodology described herein.

Sensitivity analyses in probabilistic risk assessment (PRA) involve three areas: (1) a determination of the set of input parameters; in this case, various categories of human errors signifying aspects of plant operation, (2) the range over which the input parameters vary, and (3) an assessment of the sensitivity of the plant risk parameters to the input parameters which, in this case, consist of all postulated human errors, or categories of human errors. The methodology presents a categorization scheme where human errors are categorized in terms of types of activity, location, personnel involved, etc., to relate the signficance of sensitivity of risk parameters to specific aspects of human perforamnce in the nuclear plant. Ranges of variability for human errors have been developed considering the various known causes of uncertainty in human error probability estimates in PRAs. The sensitivity of the risk parameters are assessed using the event/fault tree methodology of the PRA. The results of the risk-based sensitivity evaluation using the Oconee-3 PRA as an example show the quantitative impact on the plant risk level due to variations in human error probabilities. The relative effects of various human error categories and human error sorts within the categories are also presented to identify and characterize significant human errors for effective risk management in nuclear power plant operational activities.

Introduction

The significance of human errors on nuclear power plant risk has been well recognized over a number of years. In analyzing the actual events observed in nuclear power plants, ranging from minor safety significance to major safety significance, it is seen that human errors played a role in almost all cases. Probabilistic risk assessments (PRAs) of nuclear power plants since the Reactor Safety study (WASH-1400)[1] explicitly incorporate human intervention in assessing risks from nuclear power plants. These risk assessment models provide the basis for analyzing the risk impact from human errors. Sensitivity of Risk Parameters to Human Errors in Reactor Safety Study for a PWR (Samanta et al., NUREG/CR-1879, 1981)[2], conducted for the Surry plant, provided a methodology for assessment of human error impacts on plant risks through a sensitivity study recognizing the variability in human error probabilities.

The treatment of human errors in PRAs has improved significantly along with the understanding of the error probabilities and the variabilities associated with them. In this study, the basic approach of NUREG/CR-1879[2] is used and extended to assess the risk impact of human errors using a current PRA with improved human error modeling. The PRA for Oconee-3 nuclear power plant was chosen for this evaluation. A number of insights are developed and presented that have broad applications both for addressing nuclear power plant risk from human errors and in modeling aspects of human reliability analysis.

This paper summarizes the risk methodology used in assessing the sensitivity of human errors in the Oconee-3 nuclear power plant and presents the important insights obtained in the study. Methodological details on various aspects of this study and expansion on the results can be obtained in Samanta et al., 1988[3]. Following this introduction, Section 2 presents the risk-based sensitivity evaluation process which can be used for assessing the sensitivity of nuclear power plant risk to human errors. Section 3 presents the results of the Oconee study, along with the interpretations and insights derived, and Section 4 summarizes the major findings of the study.

Risk-Based Human Error Sensitivity Evaluation Process

The methodology for sensitivity evaluation presented here uses a plant specific probabilistic risk assessment (PRA). In this study, the Oconee-3 nuclear plant PRA conducted by EPRI and Duke Power Company (Sugnet et al., NSAC/60, 1984)[4] was used to assess the sensitivity of its risk parameters to human errors. Only the internal events portion of the PRA was used for this analysis; i.e., sequences initiated by external events such as fires, earthquakes, and floods were not considered. Even though there are differences among nuclear power plant PRAs and in human reliability analysis (HRA) from one PRA to another, the process of sensitivity evaluation presented below and used to obtain the Oconee results is applicable to any PRA. Figure 1 presents the broad elements in the human error sensitivity evaluation which consists of the following:

1. Identification of human errors and the associated probabilities in the PRA,
2. Categorization of the human errors,
3. Development of the range of human error probabilities for sensitivity evaluation,
4. Strategy for sensitivity evaluation,
5. Calculation of risk parameter values due to HEP changes, and
6. Assessment and interpretation of results.

In the following sections, these elements are discussed separately with examples from the Oconee application.

Identification of Human Errors (HEs)

The first step in carrying out the human error sensitivity evaluation using a plant-specific PRA is to identify the human errors considered in the PRA. PRAs

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RISK-BASED HE SENSITIVITY EVALUATION PROCESS

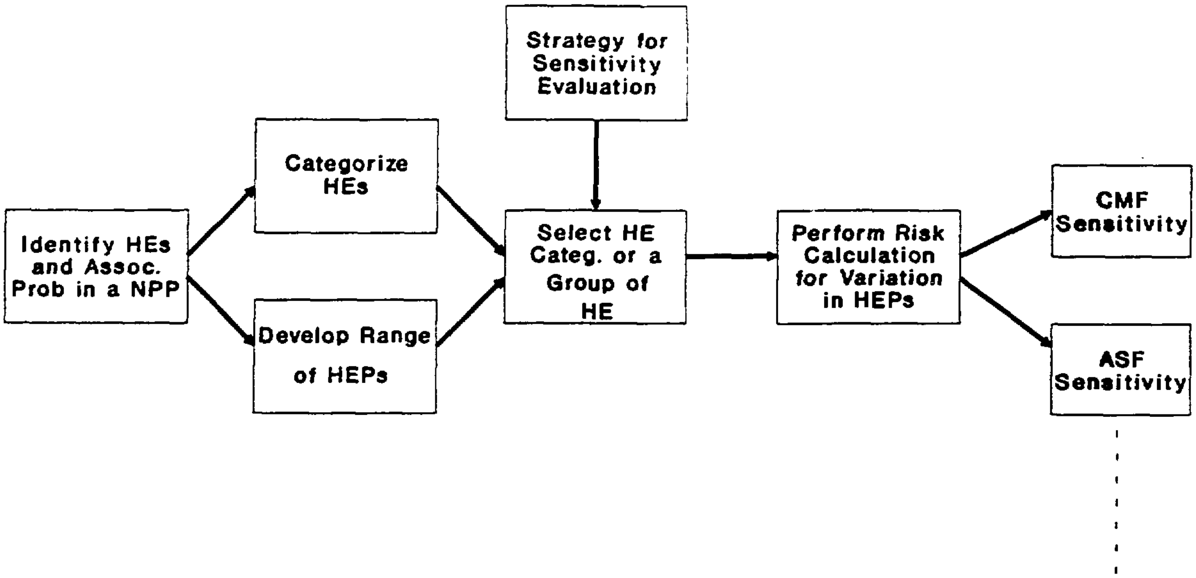


Fig. 1. ***Elements in human error sensitivity evaluation***

provide a systematic process of incorporating human errors that can lead to loss of safety functions in the plant affecting the plant risk level. Human errors appear in system fault trees and in the event trees for various initiating events. The errors of recovery (or failures to recover) are also considered to be human errors, and they are obtained from accident sequence evaluations performed following initial quantification in the PRA. At the end of this step, a complete list of human errors incorporated in the PRA and the associated mean probabilities used is obtained.

In the Oconee PRA, the human error extraction process identified 553 human errors. Sixty-four of these errors are related to external events. Since the sensitivity evaluation is focussed on risk parameter values resulting from internal initiating events, a total of 489 human errors excluding external event related human errors constituted the initial set of human errors. Within this set of 489 human errors, many had very little or no influence on the risk parameters, namely the core melt frequency and the accident sequence frequencies. In carrying out the sensitivity evaluations, the human errors that do not change the risk parameters even when their probabilities are significantly increased can be excluded from the calculation process. This was determined by examining the accident sequence level minimal cutsets (the minimal combination of basic events that cause the occurrence of an accident sequence) and excluding those human errors that appear in cutsets with frequencies of magnitude less than 10^{-10}. This process in the Oconee PRA reduced the number of human errors to a set 223 errors, which formed the final human error data base for the study.

Categorization of Human Errors

The primary purpose of a human error sensitivity evaluation is to seek patterns of human performance that alter the risk level in a plant. In seeking these patterns, various aspects and attributes of human errors need to be defined. The purpose of categorizing human errors is to define characteristics of the errors where each category provides a distinct perspective and the impact of the human errors in a specific category on the risk parameters represents the risk significance of that aspect of the human error in the plant.

The categorization scheme used in this sensitivity study is shown in Table 1. A more detailed discussion of the category and an example of each is presented in Samanta et al., 1988[3]. The categorization scheme presented incorporates the categories used in other studies (Samanta et al., NUREG/CR-1879, 1981[2], and O'Brien and Spettel, NUREG/CR-4103, 1985)[5] along with some new ones.

An examination of the categorization scheme reveals the utility of the human error categorization for a risk-based sensitivity evaluation. For example, the "TIMING" category classifies the human errors in Oconee either as a pre-accident initiator error, or as a during accident error. This category indicates the timing of the human error in chronological relationship to that of the accident-initiating event. A sensitivity evaluation for this category provides the relative significance of pre-accident initiator error with respect to during accident initiator error.

Each of the Oconee human errors was coded according to the categorization scheme to identify the groups of human errors belonging to each sub-element of the categories. In performing this task, each human error was analyzed and a distinct sub-element within each category that characterized the error was determined. For the categories defining the relationship to NRC Inspection Program (NRCPGM) and to accident initiators (ACCINIT), a human error could have been identified by more than one sub-element. Consider the human error EFTDPP1H, Turbine driven Emergency feedwater pump not

Table 1. Human Error Event Categorical Definitions Pertinent to Sensitivity Evaluation

CATEGORY	DEFINITION
TIMING	Indicates the timing of the human event relative to the accident initiating event or transient.
ACCINIT	Lists the accident initiating event(s) related to the human event.
SYSTEM	Provides the system where the human event occurs.
PERSONNEL	Identifies the individual(s) responsible for the event's occurrence.
OMCOM	Indicates whether the human event is an error of omission (human actions expected to be accomplished but not even attempted) or an error of commission (human actoins involving the completion of an improper action or an unsuccessful attempt to perform a desired action to achieve a specific goal).
EVENTTYPE	Relates the human event to the appropriate Oconee PRA established "Category of Human Error."
LOCATION	Identifies where the personnel most responsible for the human event is located.
ACTIVITY	Indicates the type of nuclear power plant activity that relates to the human event.
DEPEND	Identifies whether or not the outcome of a human event is dependent upon the outcome of another such event.
NRCPGM	Lists NRC Inspection areas which have the potential for detecting the human error event's occurrence.

restored following test or maintenance. This error results from the test and maintenance (T/M) activity, before the initiation of an accident (Pre), is an omission type (OM) error, and the responsibility for the error lies with both reactor operator and maintenance personnel (RO/MT). The NRC inspection categories that influence the error are Operations (Ops), Surveillance Testing (ST), System Walkdown (SW), and Maintenance (Maint.). Table 2 shows the categorization of some of the human errors in the Oconee PRA.

It becomes quickly apparent that not all of the categories are independent of each other. In many cases, a strong relationship exists among the categories which can be used to identify specific characteristics of the human errors in the Oconee plant. For example, if a human error extracted from the PRA was determined to be committed by a non-licensed operator (personnel category), by definition, the event occurred outside the control room (location category). Similarly, if an error was determined to be of the unavailability type (event type category), it occurred prior to an accident initiator ("Pre" in the timing category). Whenever this type of relationship was not evident, the judgment of the analyst was used to define the error. Figure 2, called the linkage diagram, shows the breakdown of the Oconee human errors in terms of a number of categories whose interrelationships are also exhibited in such diagrams. An additional figure showing the relationship among other categories can be obtained in Reference 3.

Development of Range of Human Error Probabilities

For a risk-based sensitivity evaluation, an important consideration is to define the entire range of variability of the input parameters whose significance in terms of their effect on the risk parameters are being evaluated. The range of variability of the HEPs in PRAs usually includes only the data uncertainty associated with these estimates. Ranges of the human error probabilities for sensitivity evaluation should consider the different causes of variability that can be assigned to the estimates.

In developing the ranges of the HEPs for sensitivity evaluation, different causes of variability defined in the literature[6-7] were taken into consideration and thus, the ranges defined are broader than those found in PRAs. The attempt also was to obtain a realistic, but at the same time, a conservative or broadest range, so that the sensitivity evaluation could cover the entire possible range recognizing the different causes of variability.

The methodology used for quantitative determination of the ranges of HEPs is drawn from the well-known statistical approach of analysis of variances (details are presented in Samanta et al.[3]). The influences of each of the variability causes is defined in terms of error factors and the variances in the HEP due to each of the causes are combined to obtain the overall variance in the HEP estimates. The resulting overall variance is then used to obtain the range of the HEP. Subjective judgments are involved in defining the error factors associated with each of the variability causes. In this study, the error factors were defined using expert judgments which took into consideration the available data sources. The approach presented is considered adequate for sensitivity evaluation since the objective is to develop realistic, but conservatively broad estimates of the ranges that account for the different causes of variability.

Reasons for Variability in Human Error Probability

The reasons for variability in HEPs used in PRAs are discussed in the PRA Procedures Guide (NUREG/CR-2300)[6] and five major sources of uncertainties are defined. In this study, these same sources are defined as the causes of variability. The range of HEPs are developed considering these variability causes; however, care was taken to define the applicability of the causes for each group of human errors.For example, the variability due to differences in task description was not considered applicable for human errors of operation. In the following, a brief description of each of the variability causes is presented.

1) Lack of actual data

This variability cause is a reflection of the sparsity of data relevant to human performance in NPPs. Even for the available information, (for example, Licensee Event Reports), the incidents involving human errors can be obtained, but the number of opportunities for making such an error is not available, thus causing an uncertainty in the estimate of the HEP. A further complication arises due to a lack of adequate description of the human errors in the incidents involving human errors in nuclear power plants.

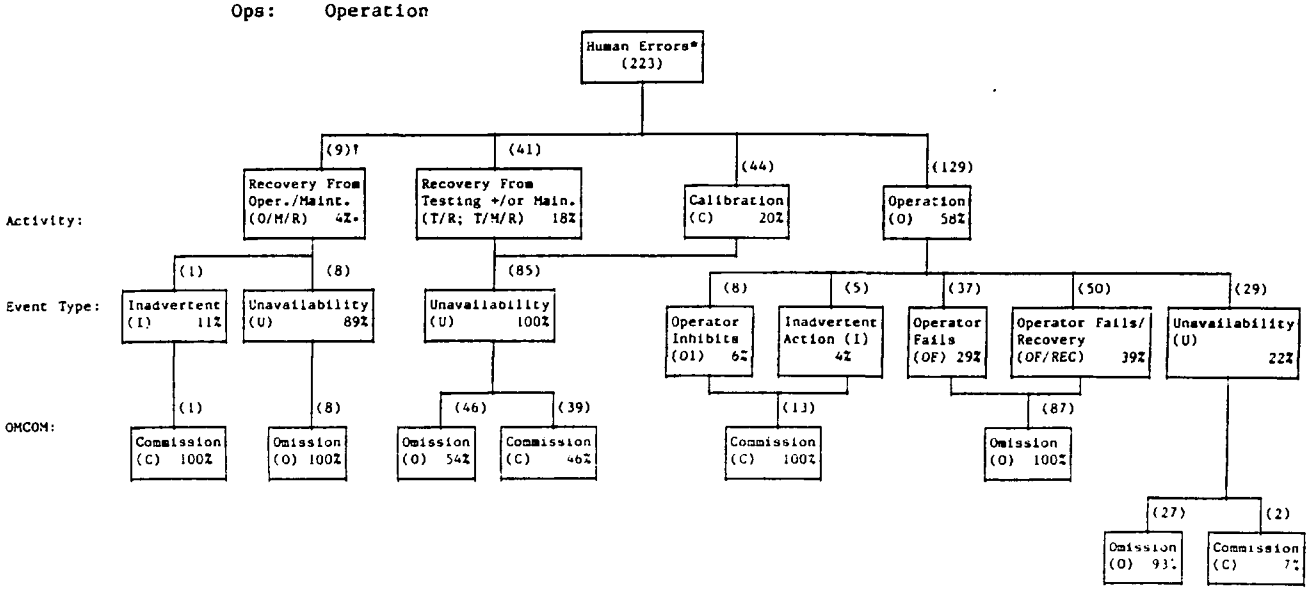
2) Inexactness of the Model

This variability cause represents the inherent weaknesses in modeling human performances. Even though various models are used in quantifying HEPs in nuclear power plants, their validity or accuracy is known to the extent that they are an approximate representation

Table 2. Examples of Human Error Categorization

DESCRIPTION OF HUMAN ERROR	ERROR CODE	ERROR CATEGORIZATION				
		Timing	Personnel	Activity	Om/Com	Loc.
1. Operator fails to initiate ASW from SSF in 30 minutes from loss of feed-water	RESSFW30	During	RO/NL	Ops	Om	CR/OCR
2. Operator fails to recover instrument air in one hour	REIA1	During	RO/NL	Ops	Om	CR/OCR
3. Operator fails to attain or maintain HPI cooling after loss of all feed-water	UTHPIH	During	RO	Ops	Om	CR
4. MOVs HP-24 and -25 (MPI ES suction valves) left un-available	HP2425MVH	During	RO	R	Om	OCR
5. BWST suction valve LP-28 left closed after maintenance	LP28VVCH	During	RO/MT	R	Om	OCR
6. Turbine driven emergency feed-water pump not restored after maintenance	EFTDPP1H	During	RO/MT	R	Om	OCR

RO/NL: Reactor Operator and Non-Licensed Operator
RO: Reactor Operator
RO/MT: Reactor Operator and Maintenance Personnel
CR: Control Room
OCR: Outside Control Room
R: Restoration
Ops: Operation



* Human Errors Considered in Risk Assessment of a Nuclear Power Plant.
† Indicates the total number belonging to the category.
• Indicates the percentage of level above.

Fig. 2. Linkage diagram of human error categorization based on activity, event type, and OMCOM

of the realworld situation. This, however, is true, in general, for all models and human reliability models are no exceptions.

3) Difference in Task Description (application of generic HEPs)

This variability cause results from the fact that often the same error probability is assigned for similar components, while differences in terms of actual task and work conditions exist. The available data is not adequate to distinguish among such situations. Another factor in this cause of variability is that, in some cases, the error probability was obtained from similar tasks in non-nuclear industry, and the performance shaping factors applicable in non-nuclear industry can be vastly different from those in nuclear power plants.

4) Difference among Personnel

This variability cause accounts for the variability in human performance due to individual differences. In developing estimates for PRA evaluations, an "average" person is assumed, but differences exist from one person to another.

5) Skill and Knowledge of Human Reliability Analyst

Finally, the human reliability analyst himself is a cause of variability in the HEP estimate. The experience of the analyst and the level of detail used in analyzing the errors can both influence the HEP estimates. Furthermore, the human error analyst usually does not have complete knowledge of the work situation in the plant, nor does he necessarily know the makeup of the team conducting human activities in the plant.

Ranges of Oconee HEPs

Categorization of Oconee HEPs for Range Development

In applying the methodology for developing ranges for HEPs in the Oconee PRA, the human errors were divided into distinct groups depending upon the variability causes and the associated error factors. Table 3 lists the five distinct groups along with the composite error factor derived for errors in that group. The composite error factor presented in the table are derived based on HEPs used in the Oconee PRA and the individual error factors associated with each of the variability causes.

Table 3. Error Factor Associated with Types of Human Error

Type of HE	Error Factor
Dependent HEs	26
T,M, & C HEs with HEP > 1E-3	13
T,M, & C HEs with HEP $\leq$ 1E-3	22
Operation HE/act of Commission	24
Operation HE/act of Omission	21

Upper and lower bound HEPs for each human error event in a particular group are calculated by applying the error factor to the median value of the HEP. For the last two error groups in which the base HEPs are > 0.1, the use of the error factor resulted in an upper bound greater than 1.0, which was truncated to 1.0.

Strategy for Sensitivity Evaluation

In a risk-based sensitivity evaluation, the changes in the output parameters, namely the core melt frequency, accident sequence frequency, etc., are being observed for changes in the input parameters, which in our case are the human error probabilities. For the objective of the evaluation, a specific strategy outlining the combinations of human errors (input parameters) and the output risk parameters needs to be defined. A large number of such combinations exists and the strategy specifically defines the combinations to be studied in order to effectively delineate the results being sought.

The specific objective of this study is to identify the quantitative impact of human errors in the plant risk levels, to identify the specific aspects of human errors that have higher risk impact, and to identify those categories of human errors whose improvement can provide significant risk benefits. With that objective, the specific sensitivity evaluations performed in this study and the significance of the evaluations are summarized in Table 4. Admittedly, a number of additional sensitivity evaluations can be designed to derive further insights into the human role on plant risk.

Calculation of Risk Parameter Values

The calculation of the major risk parameters in a plant, namely, the core melt frequency and the accident sequence frequencies, due to change in the human error probabilities (HEPs) were performed using the event tree and fault tree models of the Oconee PRA. The calculation process is similar to that of point estimate evaluations performed in PRAs. Individual accident sequence frequencies were computed for each set of changes in HEPs and the accident sequence frequencies were summed up to obtain the core melt frequency. The large number of calculations necessary in such a sensitivity evaluation was facilitated by the use of the PAIRWISE computer program[8,3] developed at Brookhaven National Laboratory. The PAIRWISE program is an interactive personal computer program where a select group of basic events (e.g., human errors) can be defined and their associated probabilities are changed so that the corresponding accident sequence frequencies and core melt frequencies can be obtained.

In using PRA models for sensitivity evaluations where basic event probabilities (in our case the HEPs) are significantly increased, certain precautions are necessary to appropriately calculate the risk parameter values. The accident sequence models used in sensitivity evaluation are the minimal cutset expressions of the accident sequences. In PRAs, a large number of minimal cutsets are generated for each of the accident sequences where a significant portion of them has a negligible contribution to the accident sequence frequency. For sensitivity evaluations, it is cumbersome to retain all the cutsets for repeated calculations and accordingly, only the cutsets that are the dominant contributors to sensitivity evaluation should be retained. Minimal cutsets that are the dominant contributors for calculating the expected accident sequence frequency estimates in PRAs are not the only cutsets required for sensitivity evaluations. Many cutsets that are not dominant when average HEPs are used can become dominant when calculated for increased HEPs. This is particularly so when a cutset contains multiple human errors where in a sensitivity evaluation, the probability estimates of these errors are increased simultaneously causing a significant jump in its frequency estimates, and thereby making the cutset a dominant contributor.

Table 4. Summary of Sensitivity Evaluations to Assess Implications of Human Errors in Plant Risk

Sensitivity Evaluation	**Significance of the Evaluation**
1. Sensitivity with respect to all identified HEs in a plant	
a. CMF versus HEPs b. ASF versus HEPs c. Consequence Bin Frequency versus HEPs	i) identifies the role of HEs in plant risk ii) identifies the role of HEs in likelihood of accident sequences iii) identifies accident sequences that are most sensitive to HEs iv) identifies the role of HEs in consequences (bins) of accidents
2. Sensitivity of CMF to "Routine" (Pre-Accident) Human Activity	i) identifies the perturbations in the risk level due to variation in the performance level of plant staff ii) identifies the human errors deserving special attention during plant operation
3. Sensitivity of CMF to Errors of Recovery	Identifies the ability of operating staff to respond to an accident
4. Sensitivity of CMF to Categories of HEs	
a. TIMING Category	a. relative significance of during accident initiator, & pre-accident initiator HEs
b. LOCATION Category	b. role of HEs in and out of control rooms
c. PERSONNEL Category	c. risk significance of role of various types of personnel
d. ACTIVITY Category	d. risk significance of types of human activities
e. EVENTTYPE Category	e. risk significance of various types of actions
f. NRC INSPECTION Category	f. role of inspection categories
5. Relative likelihood of various accident sequences as HEPs vary	Identifies the dominance of accident sequences based on the performance of the plant crew.

To alleviate this problem, the dominant minimal cutset expressions for accident sequence frequencies were generated using HEPs equal to 1, and then using a truncation level of 10^{-10}. The cutsets that are eliminated in this process are negligible even when the HEPs are increased to their maximum values.

Assessment and Interpretation of Results

Sensitivity of Core Melt Frequency to HEP Changes

One way to identify the role of human errors on plant risk through sensitivity evaluations is to assess the sensitivity of core melt frequency to changes in the human error probabilities in the plants. In this assessment, the probabilities of all the human errors that are judged to influence the core melt frequency are being changed together. The justifications for such an approach are multifold: (a) the assessment of HEPs in PRAs are subjective, and conceivably, there may be systematic underestimation or overestimation in them, (b) the HEPs are average estimates and there are a number of causes that may vary the HEPs, and (c) a nuclear power plant may experience an improved performance or a degraded performance by its operating staff which are respectively signified by increased and decreased HEPs.

Sensitivity of the Oconee core melt frequency to multiplicative changes in the HEPs are presented in Figure 3. The probability estimates of all the human errors included in the evaluation are increased or decreased by multiplicative factors until the respective upper or the lower bound of the HEPs is reached. The behavior of the core melt frequency, i.e., it increases when the HEPs are increased and decreases when the HEPs are decreased, is expected, but still the nature of the curve provides interesting insights on the human role in the Oconee nuclear power plant.

Range of Core Melt Frequency Variation

The Oconee core melt frequency varies over four orders of magnitude (2.3E-6 to 3.1E-2) when HEPs are varied from the lower bound to upper bound values. Although a large variation in CMF due to changes in HEPs is not surprising, the significance of the Oconee CMF variation is partly attributable to plant-specific features. Namely, the dominance of the loss of instrument

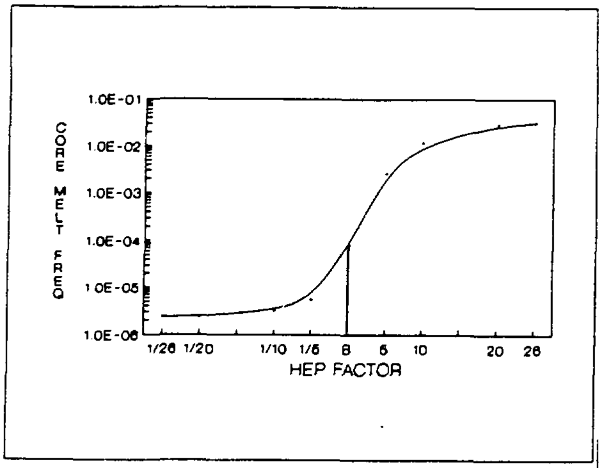


Figure 3. Overall CMF sensitivity to human error

air sequence in core melt frequency is an Oconee-specific feature. The sequence is particularly sensitive to human error, and at the upper bound of the HEPs, it contributes more than 60% of the CMF.

The behavior of the CMF curve shows strong dominance of the human errors on the plant risk. The sharp increase and decrease of the CMF around the base HEPs signifies that the terms containing human errors dominate the CMF expression. Also, the large increase/decrease in CMF for a relatively small factor change in HEPs (factor of 33 increase in CMF for a factor of 5 increase in HEPs) signifies that the dominant terms (or cutsets) contain multiple human errors. The rate of increase of CMF due to increasing HEPs is partially dependent on the manner in which the HEPs were increased. An alternative method of HEP changes based on the percentiles of lognormal distribution was also analyzed, and the results can be obtained in Reference 3.

Effect of Increased HEPs

The Oconee CMF shows a significant increase due to an increase in HEPs, and the increase in CMF is slower when HEPs are increased beyond a factor of 10. This happens because many HEPs with dominating influences reach their upper bounds when multiplied by a factor of 10. These errors typically have probabilities of 0.1 or greater, and such high probabilities are partly attributable to poor expectation of human performance and partly to lack of adequate information about them. Accordingly, there are potential human errors of risk significance in the Oconee plant that are not adequately analyzed. In some instances, there are no available procedures for the operators to follow for the errors defined in the PRA.

Desirable Level of Improvement in HEPs

Another interesting feature of the sensitivity curve is that it can indicate the desirable level of improvement in HEP for increasing plant safety (minimizing core melt frequency) when hardware failure contribution remain at the PRA assumed level. For Oconee, the curve reaches a saturation when HEPs are decreased by factors of 10, i.e, any further decrease in HEPs does not result in any noticeable decrease in CMF. This is because the terms containing human errors are sufficiently small and no longer contribute significantly to the CMF. In other words, the hardware failures dominate. It is also interesting to observe the contributions from pure hardware failures, i.e., the combination of only hardware failures that will cause a core melt is minimal, about 2.3E-6 in the Oconee plant. This value for Oconee signifies perfect human performance, i.e., the limit to which the Oconee CMF can be decreased by improving human performance without any improvement to hardware failures.

Sensitivity of Accident Sequence Frequencies to HEP Changes

Sensitivity of individual accident sequences were analyzed for changes in the HEPs and the sensitivity curves for several of the sequences are presented in Figure 4. This curve shows the factor by which ASF varies as HEPs are varied in steps to their upper and lower bounds. As expected, accident sequence frequencies which contribute dominantly to the core melt frequency show significant variation to changes in HEPs. As high as seven orders of magnitude variation in loss of instrument air sequence is observed when HEPs are varied from the lower bound to their upper bound. The sensitivity curves of the accident sequences can be analyzed in a manner similar to that discussed for core melt frequency. Here, general observations on the influence of human errors in Oconee accident sequences are presented:

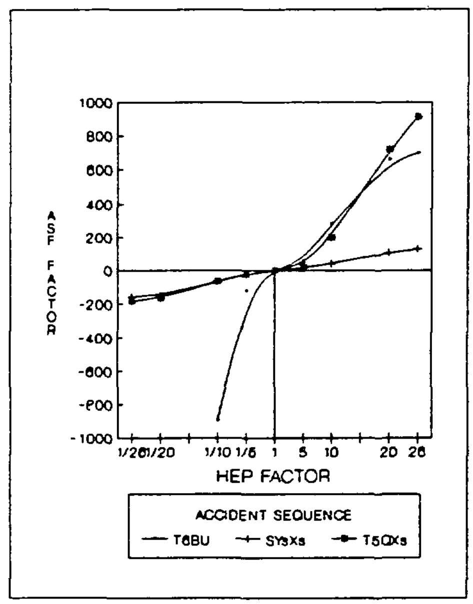


Figure 4. Sensitivity of ASF to HEP variation

i) <u>Sensitivity of the dominant accident sequences:</u> The dominant accident sequences in the Oconee PRA, for example, loss of instrument air sequence (T_6BU), loss of service water sequence ($T_{12}BU$), are very sensitive to human errors. This is expected since the Oconee core melt frequency is also sensitive to human errors.

ii) <u>Achievable level of improvement in accident sequence frequencies:</u> The dominant accident sequences show a significant decrease in their frequencies when HEPs are decreased. T_6BU is decreased by about four orders of magnitude, and $T_{12}BU$ is decreased by about three orders of magnitude when HEPs are decreased to their lower bounds from base probabilities. This is due to presence of human errors with large assigned probabilities in the dominant terms comprising the sequence.

Another interesting feature of these accident sequences is that significant improvements on frequencies can be made for relatively small improvement in HEPs. For example, a factor of 5 improvement in HEPs will decrease the T_6BU sequence frequency by a factor of 120, and the T_{12}BU sequence frequency by a factor of 26. This is because multiple human errors appear in the dominant terms of the accident sequence frequency expression. The subset of specific human errors that need to be improved to lower these sequence frequencies can be identified as a part of the sensitivity evaluations.[3]

iii) Sensitivity of accident type: Transient-initiated accident sequences show stronger human error sensitivity compared to Loss-of-Coolant-Accident (LOCA) sequences. This is expected and is considered to be of generic implications because of the following reasons. First, human actions are less effective in controlling LOCA sequences; second, transient-initiated accidents have greater chances of misdiagnosis by operators, and thirdly, transients have much longer time window for multiple operator actions following the initiating event.

iv) Sensitivity of accident sequences with high initiating event frequency: The accident sequences with relatively higher initiating event frequencies show stronger sensitivity to human errors. The accident sequences, resulting from loss of main feedwater (0.5 events/yr), loss of instrument air (0.21 events/yr), loss of condenser vaccuum (0.21 events/yr), loss of offsite power (0.12 events/yr) events are among the human error sensitive accident sequences. This implies that the events that are expected to occur during the lifetime of the plant have strong dependence on human errors and consequently, the frequencies of these accident sequences can be significantly lowered through improvement in the associated human error probabilities.

Insights on the Human Role in Plant Risk

Role of Operations Unit

In evaluating the role of the operations unit in the Oconee plant, a number of sensitivity evaluations were conducted which collectively provide valuable insights on the influence of the operations unit on the plant risk, namely the core melt frequency. Three sets of sensitivity evaluations based on the timing category, personnel category, and a category of recovery errors were conducted, and the results are presented in Figures 5 to 7.

The sensitivity evaluation of the timing category, Figure 5, shows the relative sensitivity of the pre-accident initiator and during-accident errors, where all recovery errors are considered to be during accident errors. Figure 6 shows the sensitivity of core melt frequency when the during-accident errors are split into recovery errors and non-recovery errors. Figure 7, the personnel category sensitivity curve, shows the relative sensitivity of the errors according to the responsibility of the plant-personnel - reactors operators (ROs), non-licensed operators (NLOs), and instrumentation and control technicians (ICTs).

Based on the results of the sensitivity evaluations, a number of observations consistent among the three sets of curves can be made:

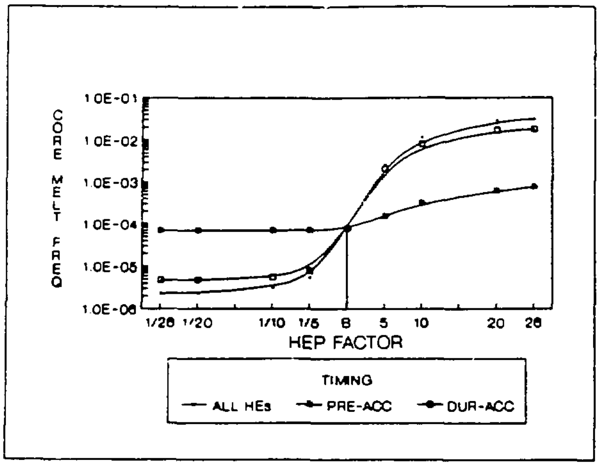


Figure 5. Sensitivity of core melt frequency with respect to human errors in timing category

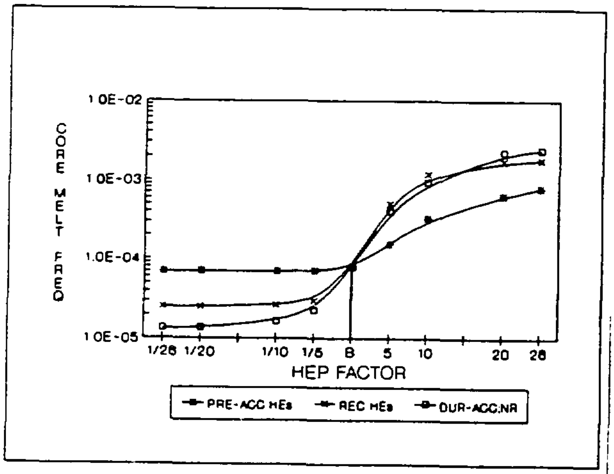


Figure 6. Sensitivity of core melt frequency to recovery errors

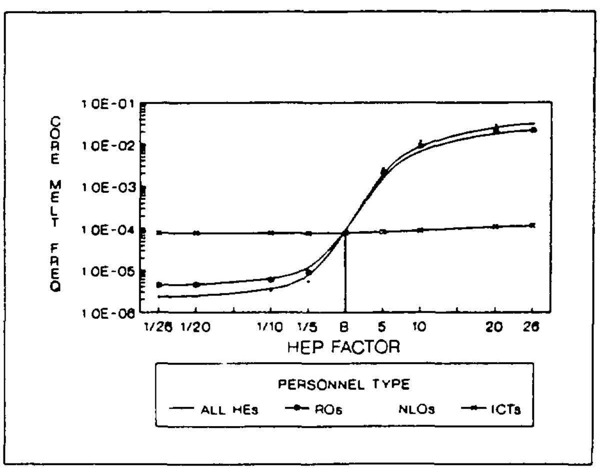


Figure 7. Sensitivity of core melt frequency with respect to human errors in personnel category

1) Dominance of During Accident Errors: During-accident errors have strong influence on the core melt frequency. This is consistent with the sensitivity curve for personnel category where the role of the reactor operators, who are primarily responsible for during accident errors, is most significant.

2) Importance of "Recovery" Actions: The "recovery errors" as defined in PRAs have strong influence on the core melt frequency. The term "recovery," as defined in the Oconee PRA, refers to a manual action taken by operators to restore an interrupted function, usually by initiating alternative equipment or sometimes, by repairing the equipment that has failed. These actions are taken primarily outside the control room and are sometimes described in procedures. When during-accident errors are split into recovery errors and non-recovery errors, their sensitivities are significant and comparable. This sensitivity result reveals an interesting insight on the role of the operations unit during an accident: the performance of procedure-based accident actions and the performance of those recovery actions, not generally called for by procedures, are about equally important.

3) Control of pre-accident errors: The pre-accident initiator human errors show sensitivity when increased from their base probabilities but do not influence the core melt frequency when decreased from their base values. This signifies that pre-accident initiator errors need to be controlled at their base values to avoid adverse effects on plant safety, but improvement in them from currently assumed values are not necessary unless hardware aspects of the plant are also to be improved.

Risk Significance of Reactor Operator and Non-Licensed Operator Responsibilities

During plant operation and accident response, reactor operators perform a number of duties that include their own actions, and coordinating other actions with non-licensed operator and maintenance personnel in a number of activities. Due to the risk significance of the during-accident errors and reactor operator role, a further sensitivity evaluation was conducted delineating various responsibilities of the reactor operators. The sensitivity curves in Figure 8 show the core melt frequency for changes in HEPs defined by reactor operator (RO) responsibility, dual reactor operator and non-licensed operator (RO/NLO) as well as dual reactor operator and maintenance personnel responsibility (RO/MT).

The insights obtained from these results can be summarized as follows:

1) Significance of RO/NLO Coordination: Among the various responsibilities of ROs, it is observed that the activities of ROs in coordination with NLOs are as significant as the actions performed by ROs only. This signifies the necessity of coordinating RO/NLO activities in assuring plant safety both before and during accidents. These results complement the results shown in Figure 6 showing the importance of recovery errors, since RO/NLO actions are primarily required in carrying out the recovery actions.

2) Significance of NLO Role: The sensitivity results presents the significant impact NLOs have on plant risk. In Figure 7, NLO activities (alone), even though not as important as RO activities, show significant impact on CMF when increased from their base values. These activities are pre-accident initiator activities and are not monitored by ROs. NLO activities supervised by ROs during an accident (discussed above)

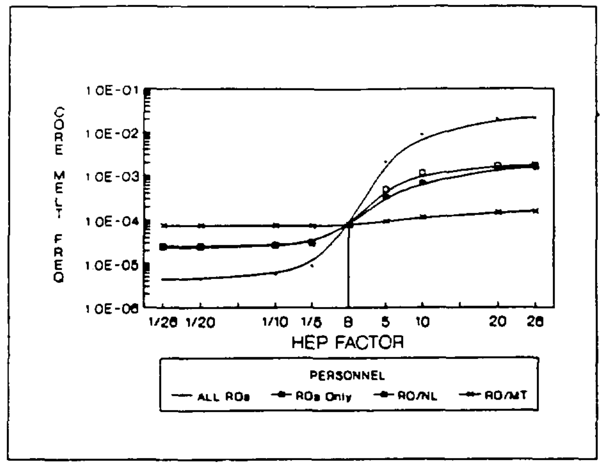


Figure 8. Sensitivity of CMF to RO errors

in restoring equipment also show significant impact on CMF (Figure 8). Overall, significant risk can be incurred in a plant due to NLO activities.

Risk Significance of the Operator Error Types

The operator errors incorporated in Oconee PRA and included in the sensitivity evaluation are divided into four types by the Oconee PRA: (i) operator fails to perform desired action, (ii) operator fails to perform recovery actions, (iii) operator inhibits (intentionally defeating the function of a system after the initiating event because the situation has been misdiagnosed), (iv) inadvertent actions (unintentionally defeating the function of a system during an event). The first two classes are omission errors whereas the last two are commission errors. Even though PRAs are criticized for not treating commission error adequately, an earnest effort in accounting for Operator Commission type errors was made in the Oconee PRA. Accordingly, a sensitivity evaluation on these categories show the significance of various types of operator actions. Figure 9 presents the CMF sensitivity curves for various types of during accident operator errors and Figure 10 shows the sensitivity of omission/commission type of errors in the plant, where pre-accident initiator errors are also included.

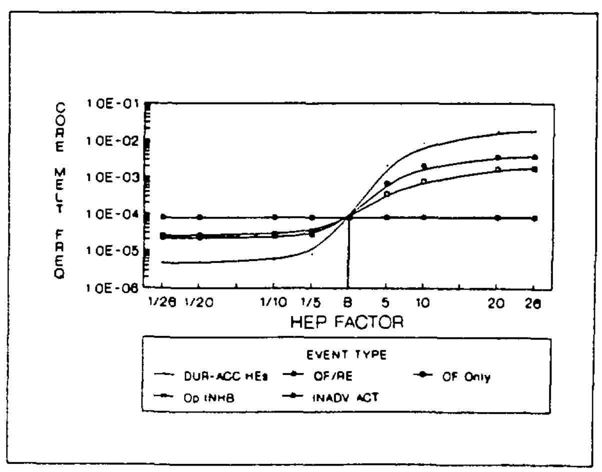


Figure 9. Sensitivity of core melt frequencies to types of during accident human errors

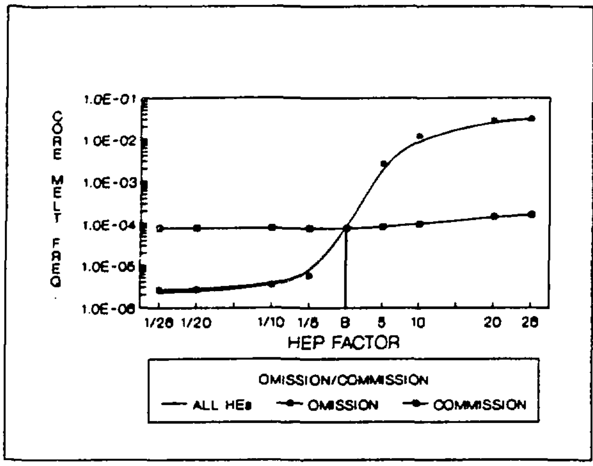


Figure 10. Sensitivity of core melt with respect to human errors in omission/commission category

Evaluation of these sensitivity curves result in the following observations:

1) Dominance of "Operator Fails to" Errors: "Operator fails to" type of actions, including operator fails to perform desired actions and operator fails to recover, dominate the sensitivity curve. The during-accident commission errors (operator inhibits and inadvertent actions) have negligible influence on CMF. This is because the commission errors are highly unlikely events and even when their probabilities are increased, they are still masked by other errors.

b) Dominance of Omission Errors: For the overall human error impact, Omission errors have a stronger influence on the sensitivity curves compared to commission errors. This is also consistent with previous observations that during accident errors and "operator fails to" errors during accident have significant influence on core melt frequency. The result is partly attributable to the treatment of omission errors in PRA models which is better compared to the treatment of commission error. Nevertheless, the general conclusions that omissions errors dominate plant risk is valid, since all postulated commission errors are likely to occur with very low average probabilities and are not expected to dominate the impact of omission errors.

Summary of Major Findings

In this study, a sensitivity evaluation was conducted to assess the impact of human errors on the risk parameters in the Oconee plant. The study results show the variation in the risk parameters, namely core melt frequency and accident sequence frequencies, due to changes in human error probabilities. The major findings based on the sensitivity evaluations are summarized below.

1) Significant variation of risk parameters due to human errors

The sensitivity evaluations for core melt frequency and accident sequence frequencies show over four order of magnitude variation in these parameters when human error probabilities are varied from their lower bound to upper bound. During plant operation, human error probabilities are not expected to vary to such extremes, and for practical considerations, variations in the short range surrounding the base error probabilities may be of more interest. *Therefore, it is noteworthy* that significant increase and decrease in risk parameters occur when all human error probabilities are increased or decreased by factors of 3 to 10 from base values.

2) Burden on the operations unit

In analyzing the during accident errors including recovery errors, it was apparent that the risk level in the Oconee plant strongly depends on the operations unit activities. Thus, a significant burden exists on the plant management and on the operating staff to control the risk from the operations of the plant. In many accident initiating events, reactor operators have to conduct multiple activities where more than one activity may involve coordination with non-licensed operators performing specific tasks outside the control room. In certain instances, such activities are to be carried out without the benefit of specific procedures.

3) Sensitivity of dominant accident sequences

The dominant accident sequences show strong dependence on human errors. Also, the accident sequences with high initiating event frequency show strong sensitivity to human errors. Thus, the events that are more likely to occur during the life of a plant can become events of significant safety concerns if humans in the plant do not perform their role adequately. Specific human actions that may be necessary in such events can be identified from a study such as this, and adequate procedures may be developed to help train the operating personnel.

4) Level of improvement in plant risk due to improvement in human performance

The results also indicate that significant improvement in plant risk parameters can be achieved through improvement in human performance. Relatively small improvement in HEPs (about a factor of two) can result in factors of 10 improvement in many accident sequences. Human factor studies can be conducted in understanding those errors to identify specific measures to improve human performance.

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