SAND94-2709C

Human Event Observations in the Individual Plant Examinations*

John Forester

Sandia National Laboratories

Abstract

A major objective of the Nuclear Regulatory Commission's (NRC) Individual Plant Examination (IPE) Insights Program is to identify the important determinants of core damage frequency (CDF) for the different reactor and containment types and plant designs as indicated in the IPEs. The human reliability analysis (HRA) is a critical component of the probabilistic risk assessments (PRAs) which were done for the IPEs. The determination and selection of human actions for incorporation into the event and fault tree models and the quantification of their failure probabilities can have an important impact on the resulting estimates of CDF and risk. Therefore, two important goals of the NRCs IPE Insights Program are (1) to determine the extent to which human actions and their corresponding failure probabilities influenced the results of the IPEs and (2) to identify which factors played significant roles in determining the differences and similarities in the results of the HRA analyses across the different plants. To obtain the relevant information, the NRC's IPE database, which contains information on plant design, CDF, and containment performance obtained from the IPEs, was used in conjunction with a systematic examination of the HRA analyses and results from the IPEs. Regarding the extent to which the results of the HRA analyses were significant contributors to the plants' CDFs, examinations of several different measures indicated that while individual human actions could have important influences on CDF for particular initiators, the HRA results did not appear to be the most significant driver of plant risk (CDF). Another finding was that while there were relatively wide variations in the calculated human error probabilities (HEPs) for similar events across plants, there was no evidence for any systematic variation as a function of the HRA methods used in the analyses. Moreover, much of the variability in HEP values can be explained by differences in plant characteristics and sequence-specific factors. Details of these results and other findings are discussed.

Introduction

The HRA is a critical component of the probabilistic risk assessments (PRAs) done for the individual plant examinations (IPEs). The determination and selection of human actions for incorporation into the event and fault tree models and the quantification of their failure probabilities can have an important impact on the resulting estimates of core damage frequency (CDF) and risk. The two main goals of this paper are to provide an overview of the different human reliability analyses (HRAs) that were conducted

*This work was supported by the U.S. Nuclear Regulatory Commission and performed at Sandia National Laboratories, which is operated for the U.S. Department of Energy under Contract Number DE-AC04-94AL85000.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

for the IPEs and an assessment and comparison of the results from the various HRAs and the impact they had on the results of the IPEs. Much of the discussion below is based on a detailed review of the IPEs for 26 plants [11 boiling water reactors (BWRs) and 15 pressurized water reactors (PWRs)]. The sample included plants from the different vendors and from the various categories, such as BWR 2s, 3s, 4s, 5s, and 6s, and PWRs with different numbers of loops, etc. For some of the specific operator actions discussed, data from 17 BWRs and 32 PWRs were examined.

A variety of approaches and methods were used in conducting the HRAs for the IPEs. The quantification methods used included the traditional ones such as THERP,[1] ASEP,[2] SLIM,[3] HCR,[4] and OATS,[5] and more recent methods such as those proposed by Electric Power Research Institute (EPRI) (EPRI NP-6560-L[7] and EPRI TR-100259[8]) and that proposed by Dougherty and Fragola in their recent book.[8] In many cases, combinations of the various methods were used and in several instances, EPRI's SHARP[9] was used as the guiding framework for conducting the HRA. On the basis of the sample of IPEs reviewed, it appeared that any given method was just as likely to be used for analyzing a PWR as a BWR. In other words, there did not appear to be any bias in selecting particular methods for application to particular types of plants.

In general, the different HRA analyses separated the human action events into the traditional categories: pre-initiator and post-initiator (with the post-initiator events subcategorized as either "response actions" or "recovery actions"). In the context of the PRA, pre-initiator human actions are those which, if performed incorrectly or at inopportune times, can render instrumentation or systems unavailable when they are needed to respond to an accident. These actions typically include failures in calibrating instrumentation or failures in correctly restoring systems after maintenance. Post-initiator human actions are those required in response to initiating events or related system failures. Post-initiator response-type actions are generally distinguished from recovery-type actions in that the response actions are usually explicitly directed by emergency operating procedures (EOPs). Alternatively, recovery actions may entail going beyond written procedures, using systems in relatively unusual ways, or recovering failed or unavailable systems in time to prevent undesired consequences. The treatment of each of the three categories of human actions and the basic results are discussed, in turn, below.

Treatment of Pre-Initiator Human Actions

While all of the various HRAs performed for the IPEs addressed pre-initiator human actions in some way, their treatment varied somewhat across plants. For example, several plants simply dismissed the pre-initiator human action events by arguing that their failure probabilities are insignificant or that the human failure probabilities associated with such events are contained within the system unavailability data. Some plants explicitly considered events concerned with the failure to restore systems after maintenance, but dismissed miscalibration events (or at least failed to provide any evidence that they considered them). Other plants used a screening approach in which all the pre-initiator events were assigned relatively conservative failure probabilities and were only quantified explicitly if they proved to be important after initial quantification of the accident sequences. At least one plant calculated HEP values for several general classes of pre-initiator events and applied those values to the relevant actions throughout the fault trees. Of the 26 IPEs reviewed for pre-initiator events, only 13 plants (five BWRs and eight PWRs) performed detailed quantification of all or at least most of the identified pre-initiator human actions prior to final quantification of the accident sequences. Seven other plants performed detailed quantification on only a few potentially important events (two to five events) that survived initial quantification. THERP[1] and ASEP[2] were the most frequently used methods for quantifying the failure probabilities of pre-initiator human actions.

Results of Pre-Initiator HRA

In general, the average failure probabilities for pre-initiator human actions tended to be slightly lower for PWRs than for BWRs. For the eight BWR plants which conducted detailed quantification on any pre-initiator events (screening values excluded), the mean of the average pre-initiator human error probability (HEP) value from each plant was 0.0075. For the 12 PWRs which conducted detailed quantification of pre-initiator events, the mean was 0.0028.

For the 13 plants that performed detailed quantification of all or at least most of the identified pre-initiator events (as opposed to quantifying only a few potentially significant events), eight of the 10 lowest mean HEP values were from PWRs, with the six lowest values coming from PWRs. The mean pre-initiator HEP values for these 13 plants are presented in Figure 1. Plant type (BWR or PWR) is

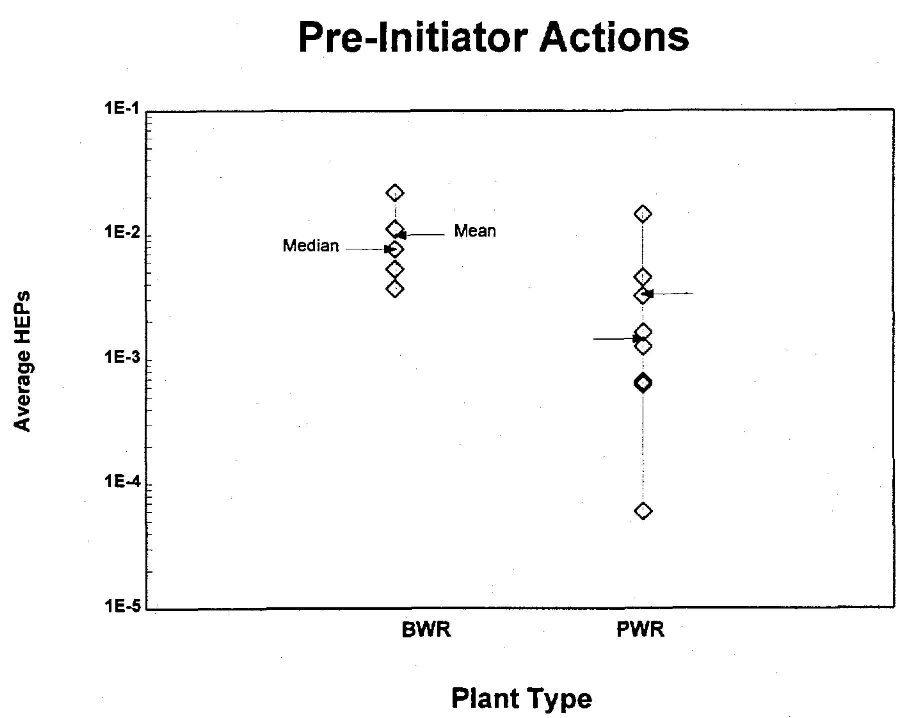

Figure 1. Average Pre-Initiator HEPs for Plants Performing Detailed Quantification of All (or at Least Most) of the Identified Pre-Initiator Events by Plant Type

indicated in the figure. Since the same basic pre-initiator HRA method was used in essentially all the IPEs (i.e., THERP[1]\ASEP[2]), an attempt was made to determine why several plants (which happened to be PWRs) had mean pre-initiator HEP values an order of magnitude lower than the others. The results of the investigation indicated that the plants which obtained the relatively smaller HEPs had performed rather detailed and extensive modeling of the pre-initiator human action events. The smaller HEP values might be attributable to a more thorough application of the pre-initiator HRA methods than was done for some of the other plants. At a minimum, there was no indication that the smaller pre-initiator HEP values were related to careless application of the methods.

While six of the 10 plants with the lowest overall CDF were plants that either used screening values for pre-initiator events or failed to analyze the pre-initiator events, there was little evidence that the treatment of pre-initiator events would correlate strongly with a plant's resulting CDF (see Figure 2). For PWRs in particular, there was no apparent relationship between mean pre-initiator HEP values and CDF.

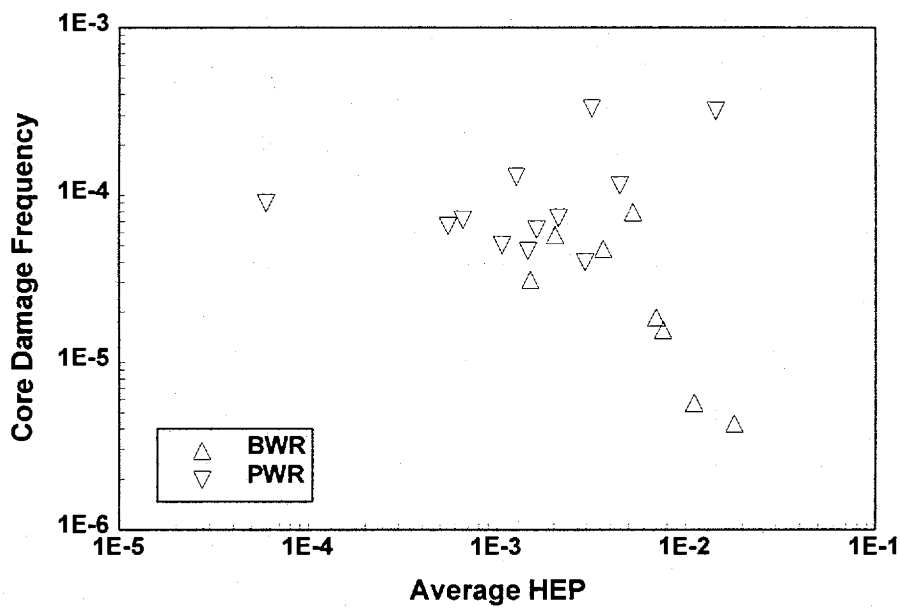

Figure 2. Average of Plant Pre-Initiator HEPs as a Function of Plant CDF

For the BWRs, there was some suggestion that larger mean pre-initiator HEPs were associated with smaller CDF estimates. This pattern of results suggests that the pre-initiator HRA results were not, in general, significant drivers of CDF. Obviously, such a result does not imply that all pre-initiator human error events are unimportant. Specific pre-initiator human error events could still be important contributors to particular accident sequences. However, a review of the IPEs which performed an analysis of pre-initiator events found only four pre-initiator human actions that had been found to be significant on the basis of importance to CDF. The four actions were (1) miscalibration of core spray injection permissive, (2) breaker maintenance error on the 4160-volt bus, (3) failure to realign the fire water cross-tie valves after test or maintenance, and (4) operator failure to realign standby liquid control (SLC) valves following test or maintenance. All four actions were from BWRs.

Treatment of Post-Initiator, Response-Type Human Actions

The HRA of the post-initiator, response-type human action attempts to quantify the likelihood that operators will fail to conduct the various actions necessary to respond to an initiating event or accident scenario. As noted above, most of the necessary response-type actions would be indicated in the plant emergency operating procedures. The analysis of post-initiator response actions is a critical part of the HRA and there are number of factors related to the methodology and approach used to quantify the actions that could have a significant impact on the results of the analysis. Some of these factors, which were perceived as likely to be important, and their general treatment in the IPEs are discussed below.

In quantifying the HEPs for post-initiator response human actions, several of the plants used a single HRA methodology, while others used a combination of HRA methods to address different aspects of the analysis. In general, it appears that the different methods that were used to accomplish the HRA can be grouped into five basic categories or groups of methods. They include:

1. A modified version of SLIM[3] that relies on subjective estimates of the impact of various performance influencing factors (PIFs) on the operator's likelihood of failure. In addition to being the only method that consistently relies directly on subjective estimates by experts to derive the HEPs for the post-initiator human actions, this method is also distinguished by the fact that the impact of time on the performance of a task is determined on the basis of subjective estimates as opposed to the time reliability correlations (TRCs) used by most other HRA methods. This method was used in seven of the 26 IPEs reviewed.

2. A combination of the decision tree method described in EPRI-TR-100259,[7] along with ASEP[2] and THERP.[1] The decision tree method was used to quantify the diagnosis portion of the action. While the decision tree method may use subjective estimates to determine the degree to which time is relevant to performance on a particular task, the impact of time as a PIF was usually taken into account by using the TRC from ASEP[2] or THERP.[1] That is, when time was a limiting factor, a TRC was used to determine diagnosis failure probability. Values from THERP[1] were used to quantify the execution portion of the human actions. This method was used in six of the 26 IPEs reviewed.

3. The human cognitive reliability (HCR)[4] method or the operator reliability experiments (ORE)-based modification of the HCR method (EPRI NP-6560-L)[6], which are TRC methods that may also use THERP[1] to quantify the execution portion of the action (used in four of the IPEs reviewed).

4. The method described in the book by Dougherty and Fragola[8] that offers a number of different "tools" for doing HRA, but that also proposes the use of TRCs for determining HEPs. In one IPE that used this method, it was stated that the method is functionally a combination of SHARP[9] and HCR[4] and therefore may be similar to method three above (used in two of the IPEs reviewed).

5. The THERP[1] method or the ASEP method (which is a method derived from THERP[1]) or some combination of the two methods (used in seven of the IPEs).

In addition to the basic HRA methodology used to quantify the post-initiator HEPs, there are a number of other factors related to how the analysis was conducted that could have an impact on the results. Many of these factors may or may not have a direct impact on the derivation of HEPs, but may reflect on the nature and extensiveness of the analysis performed for the HRA or on how the HRA was incorporated into the PRA. Thus, their influence could be quantitative, qualitative, or both. Several of these factors and their treatment in the IPEs are discussed below.

One potentially important factor concerns the extent to which accident progression and context effects were taken into account in determining the HEPs. For example, an operator action indicated by the emergency operating procedures can be called for in the context of a variety of different initiators and after different patterns of previous operator and system failures or successes. Therefore, in order to be able to realistically quantify the human potential for failure or success, context effects and dependencies across a given accident sequence should be considered. While most of the IPEs clearly considered context and dependencies in analyzing post-initiator actions, some did not. Two plants analyzed operator actions only to the extent needed to determine the conditions that would yield the highest failure probability for a given human action event. The HEP for the action in that context only was then quantified and the resulting "conservative" value was assigned in all cases where the event occurred. Other IPEs addressed context only in cases where extreme differences in HEPs would be expected, and several either failed to consider context or dependency at all, or at least failed to provide any evidence that they had done so in their documentation.

Another issue concerns whether the human actions were separated into a diagnosis component and an execution component. Except under conditions where the time available for diagnosis is very short or there are no relevant emergency operating procedures, many of the existing HRA methods would produce HEPs for the execution segment that are significantly larger than for the diagnosis segment. However, the HCR model does not in general explicitly quantify the execution phase of the task and assumes that the HCR diagnosis curve is adequate for most situations. Two of the 26 IPEs that were reviewed took such a position.

Other factors having a potential impact on the results of the HRA include whether the analysts conducted simulator exercises to assess the performance of the control room crews in responding to important accident sequences and whether the analysts performed walk-throughs of important operator actions that must be performed outside the control room during emergency situations. Conducting simulator exercises and directly evaluating the demands placed on operators who are carrying out actions inside and outside the control room provide the HRA analysts with important information regarding PIFs that is likely to bear on the probability of successfully completing a given task. Obviously, another important factor is the extent to which important PIFs are considered and applied in determining the HEPs.

The review of the 26 IPEs indicated that essentially all of the HRA analyses attempted to apply the PIFs explicitly indicated by the methodologies being used. However, the level of analysis that accompanied the application of the PIFs appeared to vary across the different plants. For many of the IPEs, it was difficult to determine (on the basis of the documentation provided) exactly how much effort was actually dedicated to a careful analysis of the potential impact of PIFs on HEPs. Objectively, only nine out of the

26 IPEs appeared to conduct simulator exercises and apparently only seven out of the 26 performed walk-throughs of ex-control room actions. These findings are tempered by the fact that the applications of the SLIM-based methodology involved fairly extensive interviews of operators and plant personnel. Operators and relevant plant personnel participated in the SLIM-based analyses and provided their judgments regarding the extent to which various PIFs would affect the performance of important tasks. Thus, even though the SLIM-based HRAs (seven out of the 26) did not typically conduct simulator exercises or walk-throughs of ex-control room actions, they did obtain relevant information. It can certainly be argued that the judgments of the people performing the tasks, in the context of a systematic application of subjective estimate techniques, are as viable a source of information as direct observations by the analysts. Nevertheless, even if the seven IPEs that used the SLIM-based approach are added to the group that clearly did the observations, there remains 30% to 40% of the IPEs reviewed that either failed to obtain information important to valid HEPs or that failed to document that they had done so.

Results of HRA of Post-initiator Response-Type Actions

Summary of Quantification Results for Post-Initiator Response-Type Human Actions

In order to provide a general overview and summary of the results from the post-initiator HRA analyses, several different measures were examined. The measures included the overall average of the post-initiator response HEPs grouped by such factors as plant and plant type, the average of the HEPs for what might be considered the "typical" human actions necessary to respond to various accident scenarios, the average of the HEPs for human actions identified in the IPEs and in NRC reviews of the IPEs as dominant post-initiator human actions, and the specific HEPs for both "typical" and dominant human actions. The results from examining each of these measures are discussed in turn below.

Examination of General Measures of Post-Initiator HRA Results

The average of the post-initiator response-type HEPs for each of the 26 IPEs reviewed is presented by plant type (PWR vs. BWR) in Figure 3. As can be seen in the figure, the range of values across plants is an order of magnitude for both BWRs and PWRs. Similar to the pre-initiator HEPs, the post-initiator HEPs for PWRs tended to be lower than those for BWRs. A Satterthwaite T-test of the difference between means indicated that the mean of the values for PWRs (0.049) was significantly less than that for BWRs (0.101) [$T_{(14df)} = 2.55, p < 0.01$]. In order to determine (at a global level) the extent to which the overall post-initiator HRA analysis for each plant was a significant driver in determining the plant's CDF, a test of the correlation between the average post-initiator HEP for each plant and the CDF for each plant was conducted. While the test failed to indicate a statistically significant relationship ($r = -0.306, p < .10$), the trend was toward an inverse relationship (e.g., the higher the average HEP value, the lower the CDF). This finding indicates that when a general measure of the overall post-initiator HRA analysis is used (the average of the post-initiator response HEPs for each plant), it appears that the HRA analysis of post-initiator response actions is not the most significant driver in determining CDF. It should be noted, however, that these results are based on averages and therefore do not imply that specific human actions are unimportant contributors to CDF or that the results of the IPEs are unaffected by the way in which the HRA methods are applied to the quantification of specific human actions. Clearly, the way in which specific human actions were quantified could have had a significant impact on CDF for particular initiators and sequences, and such effects could be "washed out" by examining only averages.

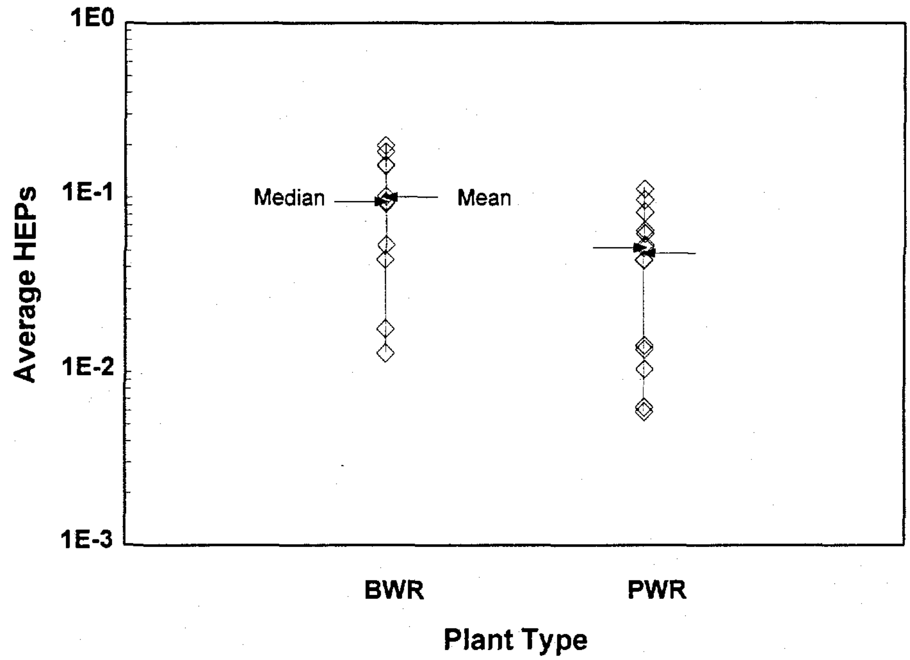

Figure 3. Average Post-Initiator Response Type HEPs by Plant Type

In regard to the impact the different HRA methods may have had on the quantification of the post-initiator HEPs, an examination of the average post-initiator HEPs by the HRA method failed in general to reveal any apparent trends. The only detectable pattern was that the averages of the HEPs from the IPEs using the SLIM-based HRA method tended to be numerically close to one another (e.g., four of the values ranged from 0.045 to 0.062), and to lie toward the middle of the distribution of HEPs.

Another measure used to provide an overview of the results of the HRA analyses was the average of the HEPs on the dominant human actions identified in each IPE. Determination of the dominant human actions was based on the "importance measures" presented in the IPEs and, when available, from comments contained in the reviews of the IPEs conducted by the NRC's contractors. Before discussing the results, it should noted that for some IPEs it was difficult to determine the dominant human actions and for others there were multiple cases of an action that had been identified as being dominant, but little guidance regarding which of the multiple cases was the one which ranked high in the importance measure results. In these cases, all of the values for that event were included as dominant actions and this resulted in some plants having many values contributing to the mean of the dominant human actions, while others had only a few.

The average of the HEPs from the dominant human actions is presented by plant type in Figure 4. As with the overall averages of the post-initiator HEPs, a large range of values was found across plants, with the lowest and highest values differing by two orders of magnitude for both BWRs and PWRs. While six of the nine lowest average values were from PWRs, the means for the dominant human actions for PWRs and BWRs were not significantly different (0.072 and 0.075 respectively). A test of the correlation between the average HEPs for the dominant human actions from each plant and the CDF for each plant failed to even approach significance ($r = -0.039$, NS). An examination of the average dominant human action HEPs by the HRA method indicated that there was no detectable systematic variation in the values as a function of method.

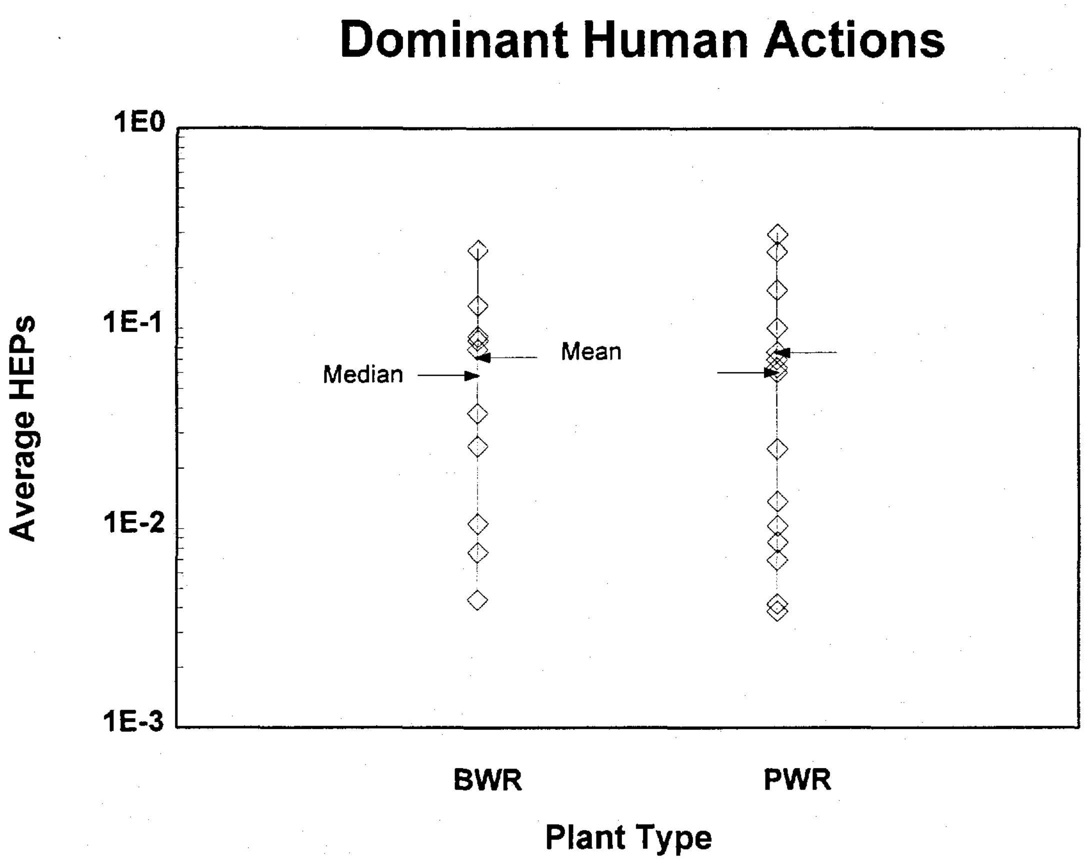

Figure 4. Average HEPs for Dominant Human Actions by Plant Type

The final "general" measure of the results of the HRA analyses was the average HEP from the human actions classified as "typical" human actions. Examples of typical human actions from BWRs included events such as initiation of standby liquid control (SLC), manual scram, level control with high and low pressure systems, inhibition of automatic depressurization system (ADS), manual depressurization, containment venting, and use of the fire water system. Examples from PWRs include events such as boron injection, feed and bleed, switchover from injection to recirculation, containment cooling, initiation of safety injection, providing makeup for alternate or auxiliary feedwater, control of feedwater, use of standby feedwater, steam generator depressurization, and prevention of steam generator overfill.

The results from the examination of the average HEPs for the typical human actions from each plant were only somewhat similar to the general pattern of results found with the two measures discussed above. While the difference between the mean value for BWRs (0.047) and PWRs (0.034) was not large, the six lowest average values came from PWR IPEs. Furthermore, the range of values was greater for PWRs, with greater than an order of magnitude between the lowest and highest values. The difference between the lowest and highest values for BWRs was only 0.064, indicating that when the HEP values from all typical human actions are taken together, the analyses of BWRs produced similar estimates of the likelihood of human error. The average HEPs for the typical human actions are presented by plant type in Figure 5.

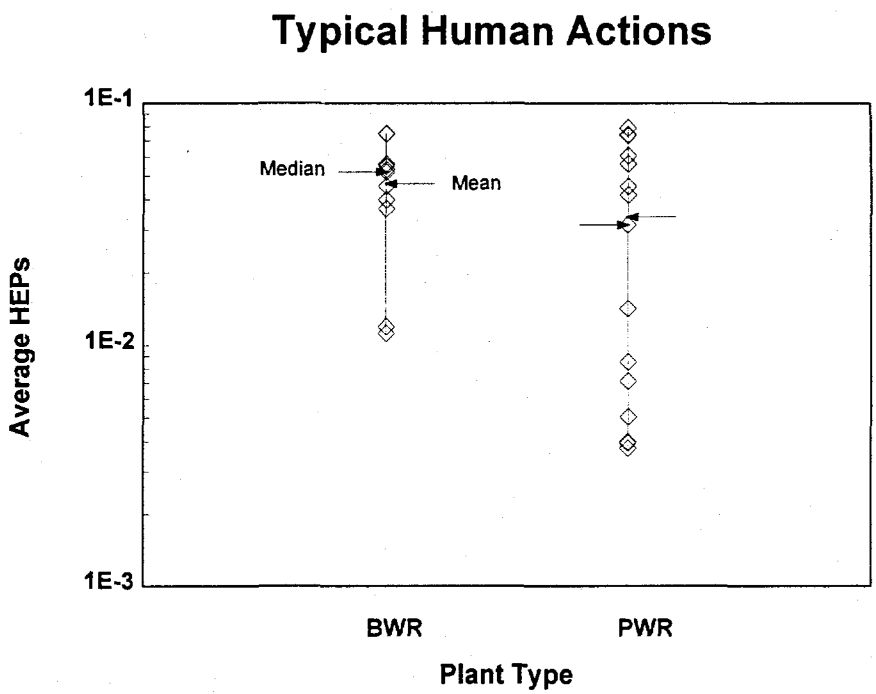

Figure 5. Average HEPs for Typical Human Actions by Plant Type

Examination of Specific Post-Initiator Response-Type Human Actions

Turning to the HEPs for specific human actions, several of the dominant and/or typical human actions from PWRs and BWRs were selected and their HEPs compared across plants. Before discussing the results from this analysis, it should be noted that many of the plants may have had multiple values for a given human action because they considered context and dependency effects, while other plants may have had only a single value or, for various reasons, no value at all. For example, PWRs with automatic switchover from injection with the emergency core cooling system (ECCS) to recirculation did not always model a human action to recover a failed automatic initiation.

The first action examined was the operator action to switch from injection with ECCS to recirculation in PWRs. This action was selected because importance measures indicated that it was a dominant contributor for many PWRs. Figure 6 displays, by PWR vendor [Babcock & Wilcox (B&W),

Combustion Engineering (CE), and Westinghouse (W)], the HEPs for the switchover to recirculation for each of the 32 PWR IPEs reviewed. Values from a given plant are indicted by a number that was arbitrarily assigned to each plant. As can be seen in the figure, a large difference exists in the HEPs for

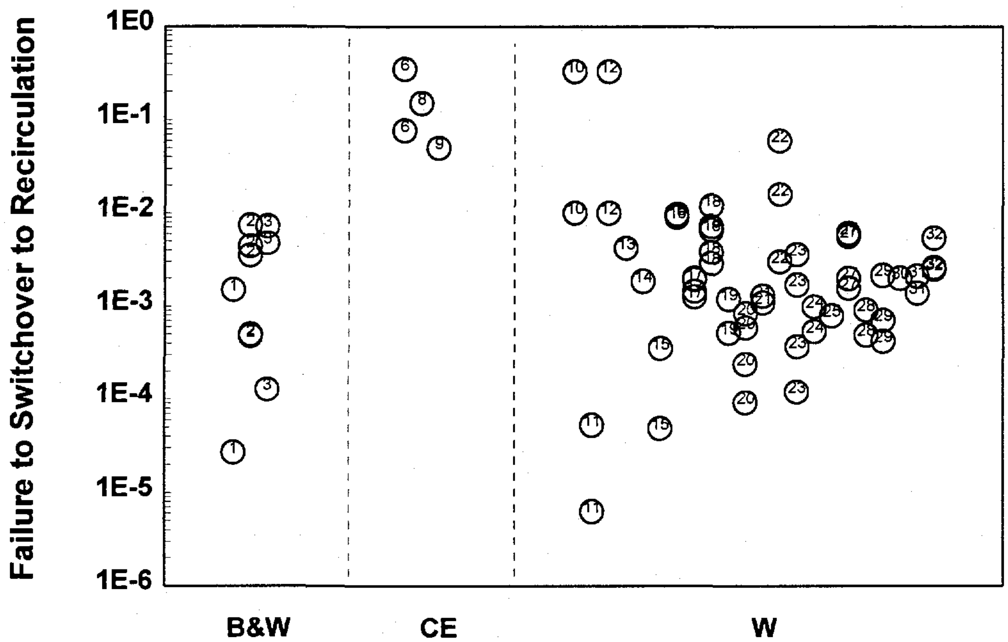

Figure 6. HEPs for Switchover to Recirculation by PWR Vendor
(Data points are numbers which were arbitrarily assigned to identify plants.)

accomplishing this action. The difference between the lowest and the highest value is several orders of magnitude. One reason for the variability in HEPs within a given plant is that success of the switchover was in general (but not always) estimated to be more likely at high pressure [e.g., small loss of coolant accidents (LOCAs)] than at low pressure (e.g., large LOCAs). One advantage for the high-pressure case was that in many instances more time was assumed to be available for the operators to diagnose and accomplish the desired actions. The relationship between failure rates and time available is displayed in Figure 7. Although the effect is not dramatic, HEPs tend to decrease when more time is available. Pressure level also accounts for much of the variance in HEPs within similar types of plants.

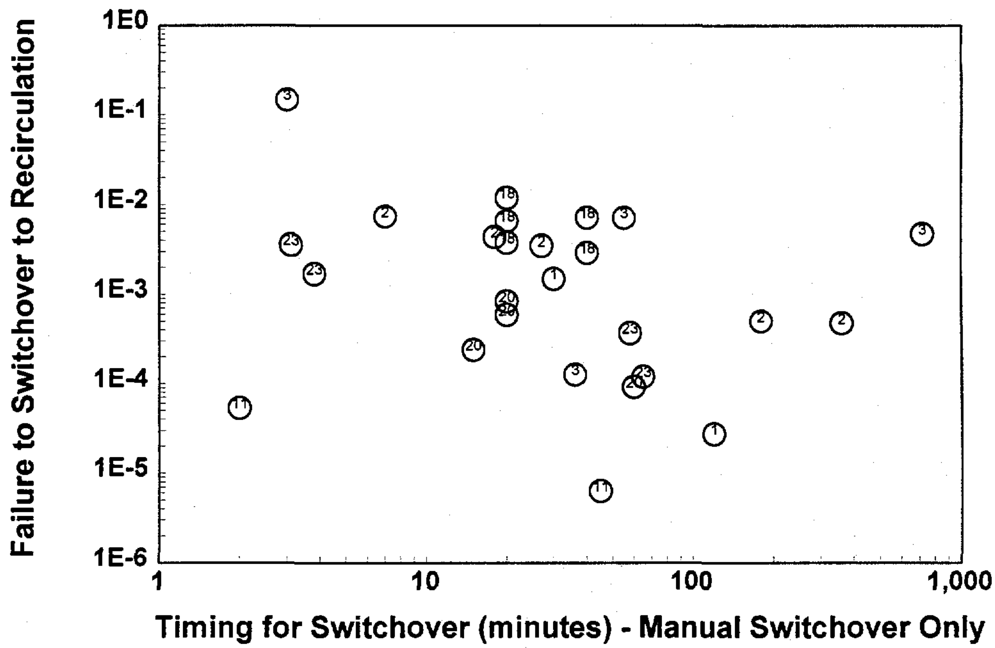

Figure 7. HEPs for Switchover to Recirculation as a Function of Time Available for the Switchover
(Data points are numbers which were arbitrarily assigned to identify plants.)

Another reason for the large differences in the HEPs across plants is that in some cases the switchover is automatic, while in others it is either a semiautomatic or completely manual operation. For plants with an automatic switchover, the operator action would be a recovery of a failed automatic actuation, while for the other plants the operators would be conducting a normal activity for the accident scenario. Thus, a difference in the HEPs for these situations would not be surprising. Of the 32 PWRs reviewed, apparently 15 required manual alignment and initiation of the switchover, with five plants having semiautomatic initiation and 12 being completely automatic. An average of each plant's average HEP for the switchover action indicated that the average HEP for plants requiring manual alignment tended to be lower than for the semiautomatic and automatic plants -- 5.5E-3, 7.7E-2, and 4.2E-2, respectively. In fact, the plants with the highest HEP values (plants numbered 6,8,9,10, and 12 in Figure 6) all had automatic or semiautomatic initiation of the switchover. The HEPs for the switchover are displayed in Figure 8 as a function of whether the action was performed manually, automatically, or semiautomatically. Semiautomatic switchover implies that either part of the task is done automatically or that under certain conditions the switchover occurs automatically (e.g., automatic under low pressure conditions, but not under high). In addition to the average failure probabilities being different, the variability of the values appeared to be much greater for the plants with automatic initiation (ranging from 0.17 to 8.0E-4), with several of them apparently failing to model human recovery of a failed auto-initiation. The values for the manual plants, however, were reasonably consistent; most of them were within an order of magnitude of each other when the high vs. low pressure factor was taken into account. The reasons for the large variability in the HEPs for the automatic (and semiautomatic) plants were not immediately apparent, but could be related to differences in indicators, procedures, and training for accomplishing a normally automatic task under accident conditions. In general, the more detailed and thorough analyses tended to produce somewhat lower failure probabilities. However, the HRAs for three of the plants with the very lowest HEPs (plants numbered 11, 15, and 20) were apparently conducted by the same analysis team and, since there was nothing obvious that made these plants unique, it appears that they may have tended toward optimism.

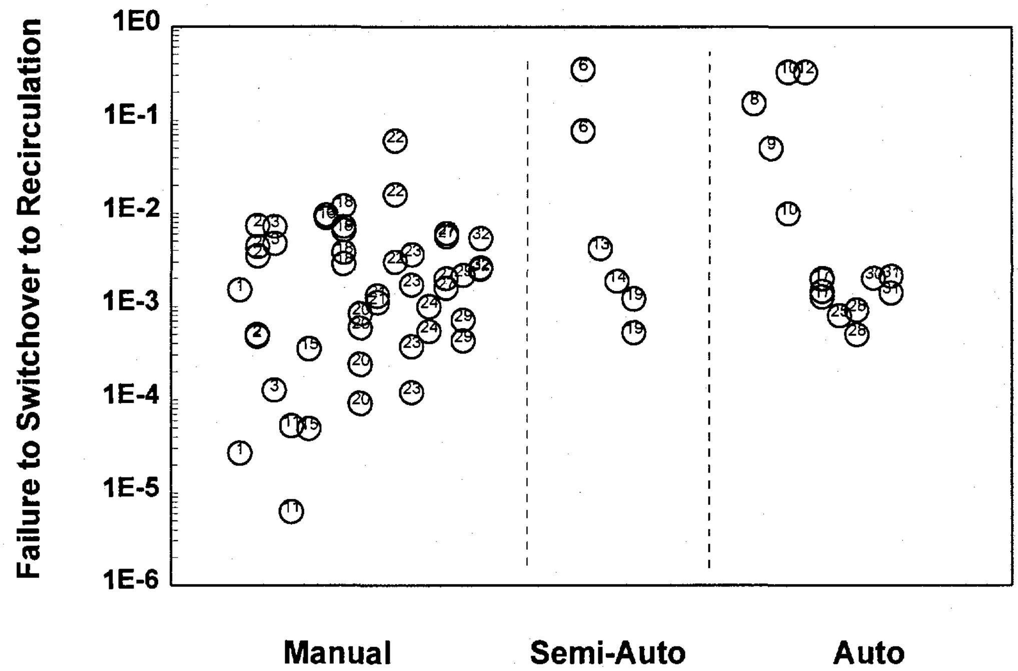

Figure 8. HEPs for Switchover to Recirculation as a Function of Whether the Action is Performed Automatically, Semiautomatically, or Manually
(Data points are numbers which were arbitrarily assigned to identify plants.)

Another specific action examined was the operator action to initiate SLC or add boron during an anticipated transient without scram (ATWS) in BWRs. As can be seen in Figure 9, a large range of values is found for the initiation of an SLC during an ATWS. For the 17 BWRs reviewed, the lowest and highest values differ by more than three orders of magnitude. At least some of the variation in the HEPs can be attributed to the fact that one of the plants has an automatic initiation of SLC and the operator action is a recovery of this failure by manual initiation. The recovery HEP is relatively higher than most of the other values derived for the initiation of SLC. An important contributor to the differences is that some analyses gave credit for initiation of SLC both early and late. In all cases, early initiation of SLC was determined to have a lower failure probability than late initiation, usually with at least an order of magnitude difference. The assumption appeared to be that if the operators failed early, they would also tend to fail late.

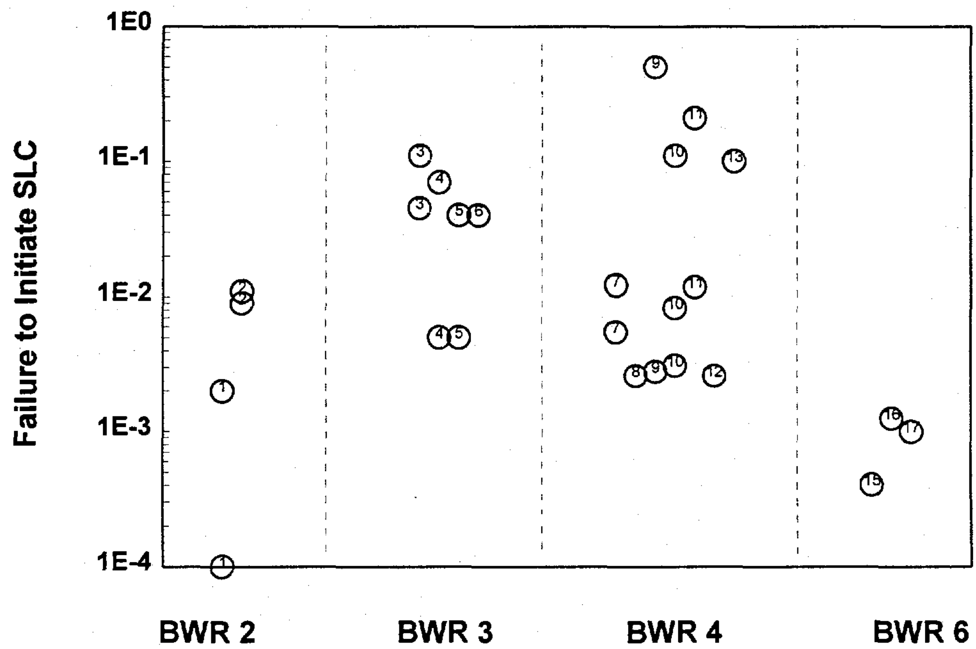

Figure 9. HEPs for Initiation of SLC by BWR Type
(Data points are numbers which were arbitrarily assigned to identify plants.)

Another factor having an impact on the HEP values was whether the condenser was assumed to be available. With the condenser available, more time was allowed for initiation of SLC and therefore lower failure probabilities were obtained. Nevertheless, even when such factors are taken into account, there would still be more than an order of magnitude difference between the lowest and highest values.

Figure 9 displays the HEPs for the initiation of SLC as function of the different types of BWRs. When the differences are examined in this way, it appears that the variation is to some extent related to plant type. In particular, with the exception of the values for one of the BWR 2s, the HEPs for BWR 6s are lower than for all the other plant types. Some of the more extreme high failure probabilities obtained for the BWR 3s and BWR 4s are related to the relatively high failure probabilities derived for initiating SLC late or for initiation of SLC when the condenser is unavailable. For example, the high HEPs values for plants numbered 9 and 11 are values for initiating SLC late and the highest values for plants 3, 4, 5, and 10 are for conditions when the condenser is unavailable. The high value for plant 13 is the recovery value for failure of the automatic initiation of SLC. In any case, even when these extreme values are ignored, there still seems to be a trend for the HEPs to decrease linearly across BWR 3s, 4s, and 6s. (The only BWR 5 reviewed had automatic initiation of SLC and did not quantify a recovery value.) The reason for the downward trend is not obvious, but could be related to a greater willingness on the part of the newer plants to use SLC. In recent years, operators' fears regarding professional repercussions from premature use of SLC seem to have lessened, but in the older plants there may be vestiges of the hesitancy to use SLC. Such a bias may not yet have been completely excised from existing training programs and updated procedures, and was therefore detectable by HRA analysts.

Another specific human action important to the ATWS scenarios in BWRs is the action designated in many of the plant emergency procedures to inhibit ADS. Inhibition of ADS is indicated by the emergency procedures to help avoid activation of low-pressure injection during an ATWS, which could increase reactivity. One reason this action is interesting is that apparently some IPEs assume that they will go to core damage during an ATWS if ADS is not inhibited. Others assume this is not the case -- that an ATWS can still be mitigated, and that inhibition of ADS can lead to problems in other scenarios if the operators fail to depressurize. As can be seen in Figure 10, there are some fairly wide variations in

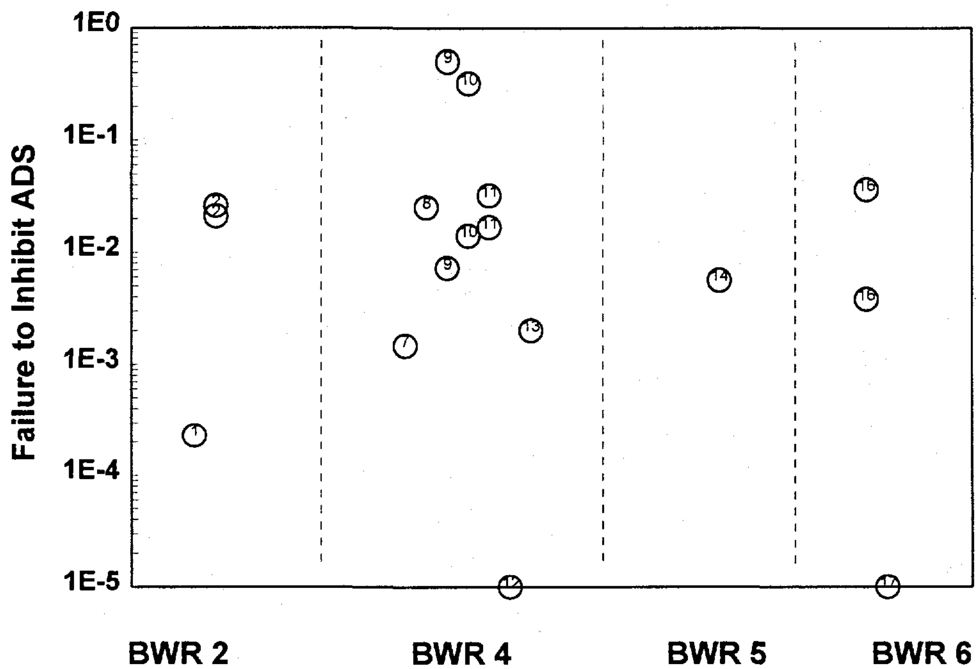

Figure 10. HEPs for Inhibition of ADS by BWR Type
(Data points are numbers which were arbitrarily assigned to identify plants.)

the HEPs for failing to inhibit ADS. However, much of the difference seems to be caused by outliers on both ends of the distribution. The two extreme values (plants 9 and 10) on the high failure probability end of the distribution are related to ATWS events in which no high-pressure makeup is available. The two extremely low values (plants 12 and 17) were both derived by the same analyst, who apparently determined that the training, procedures, and other relevant PIFs at the plants guaranteed a low probability of failure.

The last specific operator action examined was the PWR event for initiating feed and bleed (15 plants sampled). The difference between the lowest and highest HEPs (see Figure 11) is greater than two orders of magnitude, but with the one plant with multiple outlier values excluded, the HEPs tend to be less than an order of magnitude apart. This moderate lack of variability suggests that the feed and bleed operation may be perceived and executed in similar ways across the plants that have the feed and bleed capability.

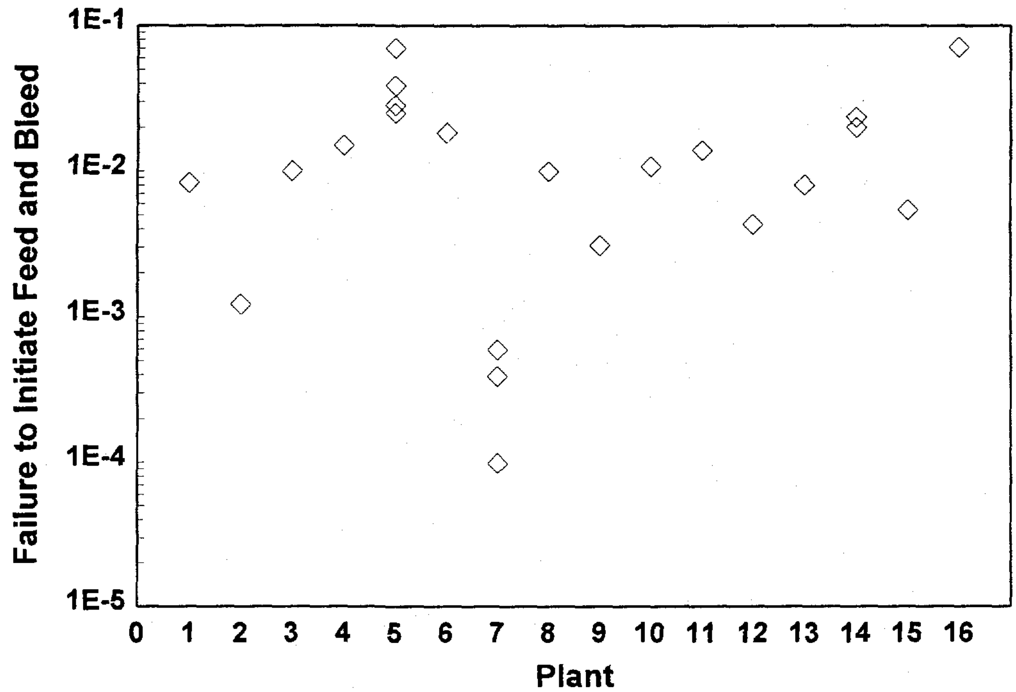

Figure 11. HEPs for Initiation of Feed and Bleed by Plant Number

Influence of HRA Characteristics on Quantitative Results

As discussed above, there are several factors related to how the HRA analyses were conducted that could have affected the results. These factors may affect the quantitative results of the analysis or they may affect only the qualitative results. That is, such factors may lead to variations in the resulting HEPs, or they may just affect the quality and usefulness of the results in terms of what is learned from performing the analysis. To determine whether any of the various factors influenced the quantitative results, the relationships between the post-initiator response-type HEPs (all, dominant, and typical) and whether the HRA analyses considered context effects, conducted simulator exercises, or conducted walk-throughs of ex-control room actions, were examined. The examination failed to detect any apparent relationships between these factors and the averages of the HEP values used in the analysis. Apparently such factors did not influence the more general, and therefore possibly less sensitive, estimates of HEP results.

To further explore the impact of such factors as consideration of context effects, use of simulator exercises, and use of walk-throughs of ex-control room actions on HRA quantification, the relationships between these factors and the HEPs for some of the specific operator actions were examined. Using the data from nine BWR plants for which the relevant information had been obtained, the relationship between the average HEP values for the initiation of SLC and the HRA-related factors was examined. The results of this examination failed to reveal any apparent relationships. However, when the average of the values for the switchover to recirculation in PWRs was examined (14 plants), some indication of a pattern was detected. Of the 14 plants examined, the plants with the six lowest average HEP values for initiating the switchover were plants that did not perform simulator exercises or do walk-throughs of ex-control room actions. In fact, eight of the 10 lowest values came from plants that did not perform simulator exercises or do walk-throughs. This finding may indicate that simulator exercises and walk-throughs tend to make analysts somewhat less optimistic in their derivation of HEPs.

Treatment of Post-Initiator Recovery-type Actions

A review of 49 IPEs indicated that while most of the IPE reports discussed the need for the identification of potential recovery actions and the application of recovery action HEPs to the cut sets, only 31 (63%) of the IPEs explicitly identified the recovery actions and their HEPs. Of the 31 submittals that did explicitly identify recovery actions and document the quantification results, they all applied essentially the same HRA method that was used in their analysis of the post-initiator human actions. Many of the plants identified only a few recovery actions, while others included many recovery actions in their analyses. One reason for the differences in the number of recovery actions modeled by the different plants was that some of the analyses included multiple occurrences of the same action, with the HEPs for a given action differing as a function of context (e.g., time available to complete the action in different scenarios, etc.). Another reason for differences in the numbers of recovery actions was that some plants appeared to have used screening values for recovery-type actions and only explicitly quantified those that survived screening.

Of the 49 submittals examined, only 21 (43%) included recovery of failed or unavailable systems (exclusive of recovery of off-site power) as part of their recovery analysis. On the basis of a sample of 26 of the 49 submittals, the number of actions involving recovery of failed systems constituted approximately 20% of all recovery actions.

Results of Post-Initiator Recovery HRA

A sample of 26 IPEs was reviewed to obtain estimates of the HEPs obtained for the recovery actions. Of these 26, six BWRs and nine PWRs had explicitly identified and quantified post-initiator recovery-type actions. The average recovery action HEPs for these 15 plants are presented in Figure 12. As might be expected, in general the average HEPs tended to be higher for the recovery-type actions than for the other classes of human actions. However, there were some fairly substantial differences in the mean HEP values across plants. The recovery HEPs for BWRs tended to be somewhat higher than those for PWRs, with the means equal to 0.163 and 0.115, respectively. For actions involving recovery of failed systems, the mean HEP values were 0.332 and 0.11 for BWRs and PWRs respectively.

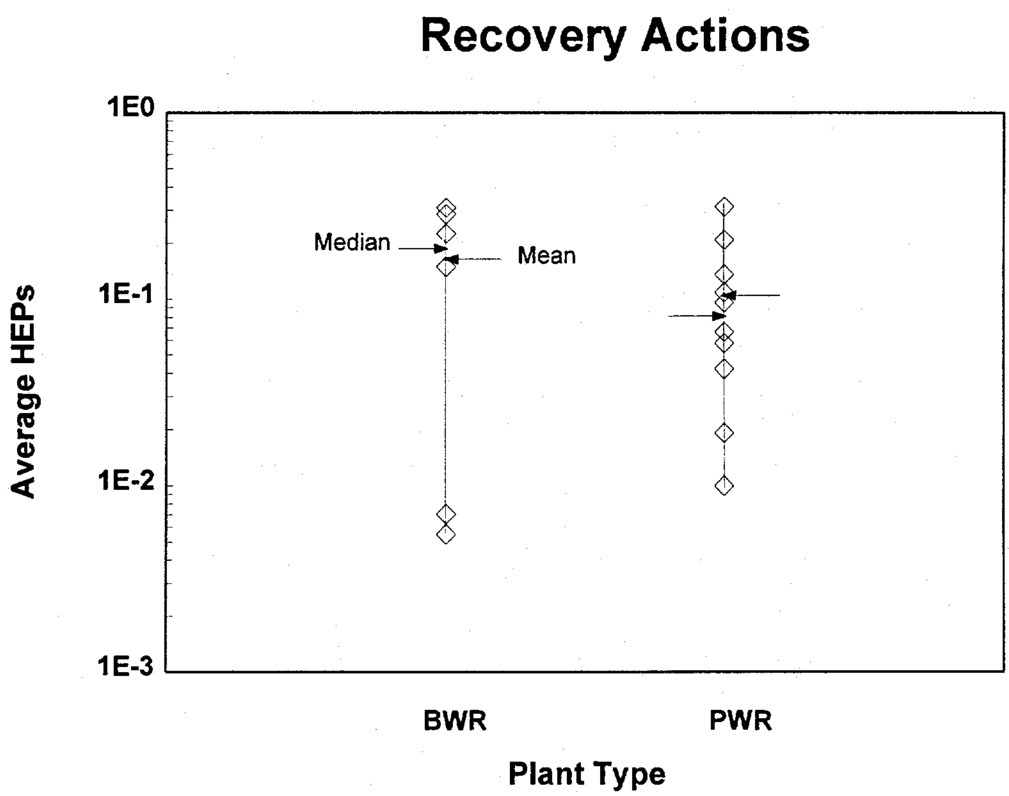

Figure 12. Average HEPs for Post-Initiator Recovery-type Actions

Summary and Conclusions

Both general and specific measures of the results of the HRAs performed for the IPEs were examined to obtain insights regarding the relationship of the HRA to the results of the IPEs. On the basis of the examination of the general measures, several conclusions are possible. First, there is no evidence of any systematic variation in the HEPs derived for the IPEs that can be attributed to the general HRA method used for quantification. In other words, the methods per se did not appear to account for the variation in HEPs obtained across the different plants.

Second, the evidence does seem to suggest that, in general, the HEPs for PWRs tend to be less than for BWRs. One reason for this trend appeared to be that several PWRs had consistently low failure probabilities relative to other plants. Whether the lower overall (and in some cases specific) HEPs for several particular PWR plants were due to aspects unique to those plants or whether they were due to optimism on the part of the analysts, is difficult to determine. It could very well be that the lower values are due to aspects such as superior training and procedures in certain plants or to somewhat simpler problems, in general, for PWRs. The latter alternative seems less likely since the general measures of HEP results from many PWRs were comparable to those from BWRs.

Next, when the average HEP values from the various submittals were used as predictors of plant CDF, there was little indication that overall HRA results were the main drivers of CDF. While the use of averages obscures the impact of the quantification of specific events on specific CDF sequences, the averages should reflect quantification trends across similar events (i.e., since similar plants tend to include similar human actions in their models, averages should provide at least some indication of the kinds of HEP values being derived for those actions). Thus, the absence of a strong correlation between these measures and overall CDF at least suggests that other, non-HRA related factors were also important to overall CDF.

Finally, on the basis of most of the measures examined, there did seem to be fairly wide variations in the HEP values obtained for different plants. However, as will be noticed in the discussions of HRA results for specific events, much of the variability appears to be related to plant-specific characteristics and modeling details, as opposed to erratic application of HRA methods.

Turning to the results of the examinations of specific events (e.g., switchover to recirculation in PWRs), perhaps the most striking aspect of the results of examining the HEPs was that there was a relatively high degree of consistency in the derived HEPs. When the various plant characteristics and sequence-specific factors considered by the analysts in determining the HEPs were taken into account, much of the variability in the HEPs could be explained. While this finding is encouraging, there were usually several outlier values found for each event that could not be straightforwardly explained and there did appear to be at least some degree of random variation. Given the current state of the art of HRA methods, it is not surprising that some of the variation in HEPs appears to be random.

A final aspect of the analysis to note is that some of the more general characteristics of how the HRAs were performed (e.g., were simulator exercises conducted, etc.), did not appear to have a consistent impact on the quantitative results of the HRA. As discussed in earlier sections in this paper, there are many aspects of how HRAs are conducted that could have important influences on both the quantitative and qualitative results (e.g., usability of the results after the analysis is completed). On the basis of the measures examined in the present analysis, however, there was only limited evidence that such factors had a significant impact on the quantitative results. Given the degree of what appears to be random variability in the HEPs obtained, it is not surprising that many of the measures used in the present analysis would be insensitive to the impact of such factors. Nevertheless, the lack of detectability should not undermine the importance of thorough application of the existing HRA approaches, particularly in regard to the usefulness of the results for guiding plant improvements.

References

1. A.D. Swain and H.E. Guttman, *Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Applications : Technique for Human Error Rate Prediction,* NUREG/CR-1278, U.S. Nuclear Regulatory Commission, Washington D.C., 1983.

2. A.D. Swain, *Accident Sequence Evaluation Program Human Reliability Analysis Procedure,* NUREG/CR-4772, U.S. Nuclear Regulatory Commission, Washington, D.C., February 1987.

3. D.E. Embrey, et al. *Slim-Maud: An Approach to Assessing Human Error Probabilities Using Structured Expert Judgment,* Vols. 1-2, NUREG/CR-3518, U.S. Nuclear Regulatory Commission, Washington, D.C., March 1984.

4. G.W. Hannaman, A.J. Spurgin, and Y. Lukic, A Model for Assessing Human Cognitive Reliability in PRA Studies, in *1985 IEEE Third Conference on Human Factors and Power Plants, Monterey, CA, June 23-27, 1985,* NY: Institute of Electronic and Electrical Engineers, 1985.

5. R.E. Hall, J. R. Fragola, and J. Wreathall, *Post-Event Human Decision Errors: Operator Action Tree/Time Reliability Correlation,* NUREG/CR-3010, Upton, NY: Brookhaven National Laboratory, November, 1982.

6. A.J. Spurgin, P. Moieni, and G. W. Parry, *A Human Reliability Analysis Approach Using Measurements for Individual Plant Examinations,* EPRI NP-6560-L, Palo Alto, CA: Electric Power Research Institute,1989.

7. G.W. Parry, *An Approach to the Analysis of Operator Actions in PRA,* DRAFT, EPRI TR-100259, Palo Alto, CA: Electric Power Research Institute.

8. E.M. Dougherty and J.R. Fragola, *Human Reliability Analysis: A Systems Engineering Approach with Nuclear Power Plant Applications*, John Wiley and Sons, 1988.

9. G.W. Hannaman and A.J. Spurgin, *Systematic Human Action Reliability Procedure (SHARP)*, EPRI-3583, Palo Alto, CA: Electric Power Research Institute, 1984.