CONF-9105244--1
BNL-NUREG-46451

An Assessment of the Risk Significance of Human Errors in Selected PSAs and Operating Events*

BNL-NUREG--46451

DE91 016916

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ABSTRACT

Sensitivity studies based on Probabilistic Safety Assessments (PSAs) for a pressurized water reactor and a boiling water reactor are described. In each case, human errors modeled in the PSAs were categorized according to such factors as error type, location, timing, and plant personnel involved. Sensitivity studies were then conducted by varying the error rates in each category and evaluating the corresponding change in total core damage frequency and accident sequence frequency. Insights obtained are discussed and reasons for differences in risk sensitivity between plants are explored. A separate investigation into the role of human error in risk-important operating events is also described. This investigation involved the analysis of data from the USNRC Accident Sequence Precursor program to determine the effect of operator-initiated events on accident precursor trends, and to determine whether improved training can be correlated to current trends. The findings of this study are also presented.

INTRODUCTION

In recent years it has become increasingly clear that the risk associated with nuclear power is strongly influenced by human performance. Although human errors have contributed heavily to the two core melt events that have occurred at power reactors, effective performance during an event can also prevent a degraded situation from progressing to a more serious accident, as repeatedly shown in the U.S. operating experience. Two studies were sponsored by the USNRC over the last three years in an attempt to quantify the potential impact of human performance on risk and to derive insights on how to limit risk. The first study investigated the sensitivity of risk to human error using the probabilistic safety assessments (PSAs) for several nuclear power plants. The second study involved an analysis of recent risk-significant operating events in U.S. reactors to determine the role of human error in these events and to identify whether improved training can be correlated to current safety trends. The results of these studies are the subject of this paper. While significantly different in character, the findings of both studies confirm the importance of human error, and support a regulatory strategy of reducing human errors and improving the likelihood of success for recovery actions through increased emphasis on emergency operating procedures, accident management preparation, and operator training.

*This work was performed under the auspices of the U.S. Nuclear Regulatory Commission.

SENSITIVITY STUDIES

Background

In 1980, Brookhaven National Laboratory performed a study for the USNRC on the sensitivity of risk parameters to human error rates using the WASH-1400 model for the Surry plant (Westinghouse pressurized water reactor). This model included treatment of approximately 100 human errors, most of which were pre-accident errors, e.g., calibration errors and failure to properly reposition valves. The study confirmed the risk significance of human error and provided additional insights into risk important sequences and categories of human actions at Surry (Reference 1).

The insights from the Surry study were considered by NRC to be of potential value in guiding licensing and inspection activities. The results, however, were plant-specific and influenced by assumptions and level of detail in the human reliability analysis (HRA). Notably, this early PRA did not model operator recovery actions. Accordingly, an effort was initiated in 1987 to update and expand the insights from the original study to reflect advances in HRA techniques and additional nuclear steam supply system designs. The program involved the conduct of extensive analyses of the sensitivity of risk to human error based on the PSA for a pressurized water reactor (PWR), followed by similar analyses using a PSA for a boiling water reactor (BWR). These studies are described in detail in References 2 and 3, respectively. Most recently, similar sensitivity analyses have also been performed by the USNRC for several of the plants studied in NUREG-1150. These analyses are not discussed in this paper.

Approach

The level 1 portions of the PSAs for Oconee, Unit 3 (Babcock & Wilcox PWR) and LaSalle, Unit 1 (General Electric BWR/5) were selected as the basis for detailed sensitivity studies. The Oconee PSA was performed by the Electric Power Research Institute for Oconee, Unit 3 and published as NSAC-60 in 1984 (Reference 4). This PSA was selected because it included the most detailed treatment of human error in a PWR study at that time. As an example, the Oconee PSA includes over 500 individual human errors, of which over 200 remained after truncation. The LaSalle PSA used was a 1988 the NRC Risk Methods Integration and Evaluation Program. The LaSalle study was selected for analysis because it was considered to be a state-of-the-art BWR study and unique in its extensive use of simulator-based human error rate data.

A human error categorization scheme was developed to allow insights to be drawn from the sensitivity studies. Human errors modelled in the respective PSAs were then categorized according to such factors as timing (pre-accident or during-accident), location (inside or outside control room), and personnel involved (e.g., licensed reactor operator, non-licensed operator, and maintenance personnel). A profile of the types of human errors in each PSA is presented in Figure 1. Major differences are (1) a larger number of human errors in the Oconee PSA, due in part to the representation of numerous individual human errors in the LaSalle study by "generic" errors, and (2) the presence of only a limited number of pre-accident errors in the screened cutsets of the LaSalle PSA in contrast to a nearly equal number of pre-accident and during-accident errors in Oconee.

Sensitivity calculations were conducted by varying the human error probabilities (HEPs) for all errors and for individual categories of errors, and investigating the corresponding changes in total core damage frequency (CDF) and accident sequence frequency. HEPs were generally varied by multiplicative factors over ranges which depended on the type of error. The largest range extended from 1/30 up to 30 times the base case value of the HEP (without exceeding a maximum HEP of 1.0). Such variations in HEPs on a global basis are considered hypothetical, and for practical purposes, smaller variations around the base case probabilities may be of more interest. A summary of the more significant results are provided below.

Sensitivity of Total Core Damage Frequency

Total core damage frequency for both Oconee and LaSalle was found to vary significantly as all HEPs were varied simultaneously over their full range (Figure 2). The Oconee CDF variation is over four orders of magnitude, compared to less than two orders of magnitude for LaSalle. For both plants, the bulk of the change in CDF occurs within a factor of 3 to 10 from the base case.

The large difference in sensitivity between Oconee and LaSalle was investigated and was found to be due to a combination of factors, the most important of which include: (1) the presence of multiple HEs in cutsets of the dominant sequences of Oconee, (2) a larger number of HEs in the Oconee PSA, and (3) higher base case HEPs in the LaSalle PSA. Both plant design differences (such as a Standby Shutdown Facility and an Emergency Feedwater System at Oconee which require manual actions) and PRA/HRA modelling differences (such as a decision to not include calibration errors in the LaSalle PSA) contribute to these factors. The significance of multiple human errors in the dominant cutsets is illustrated in Figure 3, which shows that by only doubling the HEPs, cutsets with multiple human errors begin to dominate the risk profile.

Sensitivity of Accident Sequence Frequency

Certain sequences are dominated by cutsets involving multiple human errors and exhibit strong sensitivity to changes in HEPs. An example for Oconee is the loss of instrument air sequence which includes a failure to provide feedwater within 30 minutes combined with a failure to recover instrument air in one hour. Other sequences are hardware dominated and less sensitive to changes in human error rates, such as large break LOCAs that progress rapidly and provide little opportunity for operator intervention. The sensitivity of the dominant sequences for Oconee is depicted in Figure 4. The curve for total core damage frequency is influenced by different sequences at each extreme. As HEPs are increased, sequences dominated by human actions define the curve, whereas when HEPs are reduced, the curve is defined by hardware-dominated sequences.

Pre-Accident Versus During-Accident Errors

Sensitivity analyses for both Oconee and LaSalle suggest that actions taken during the course of an accident (e.g., operator errors and recovery actions) have far greater impact on risk than errors made prior to an event (e.g., failure to restore a valve to the proper position after maintenance). Results for Oconee are shown in Figure 5 and are similar to those for LaSalle. While consistent with intuition, these results should be interpreted cautiously, recognizing that PSAs do not offer a complete treatment of pre-accident activities and errors, and that the sensitivity analysis did not explore the impact of human error on initiating event frequency. Nevertheless, the sensitivity evaluation highlights the importance of emergency operating procedures and training in mitigating important accident sequences.

Personnel Type

Calculations were also performed to investigate the sensitivity of core damage frequency to errors committed by various categories of personnel. Results of these evaluations indicate that core damage frequency is most sensitive to activities (and associated errors) which are the primary responsibility of the licensed reactor operator. Due to the significance of during-accident errors and the licensed reactor operator, additional evaluations were conducted for those actions involving coordination between the licensed reactor operator and other personnel, and those actions carried out solely by the reactor operator. Results of these analyses (Figure 6) indicate that actions involving coordination between the licensed reactor operator and non-licensed operator have a greater influence on core damage frequency than actions involving any other categories of personnel. These results point out the importance of communications, team training, and the non-licensed operators themselves.

Simulator-Based Human Error Probabilities

Approximately 70 percent of the human errors represented in the LaSalle PSA were quantified using data collected on the LaSalle plant-specific full scope simulator. This included essentially all of the errors associated with activities in the control room. As shown in Figure 7, despite the extensive use of simulator data, "simulator-based" human errors did not have a dominant effect on core damage frequency. Instead, core damage frequency for LaSalle was found to be most strongly influenced by human actions/errors which would be taken outside the control room and which could not be readily simulated. In particular, these errors were associated with recovery of offsite AC power and repair of the emergency diesel generator. This sensitivity evaluation illustrates that not all important human actions can be simulated in a standard control room simulator, and that for such errors alternative types of training may be beneficial. The potential role of training in reducing the incidence of human error was investigated in a separate study as discussed below.

ROLE OF HUMAN ERROR AND TRAINING IN RECENT OPERATING EVENTS

Background

The Accident Sequence Precursor (ASP) program at the USNRC is an ongoing activity in which operational events that occur at light water reactors are screened for precursors to more significant accidents based on risk significance. The results from the ASP program, including estimated conditional core damage probabilities for accident sequences of interest, are used to identify potential problem areas and emerging trends in the incidence and severity of precursor events.

In 1990, the USNRC undertook a study of the ASP data to determine the effect of operator-initiated events on the general trends identified in the ASP program, and in particular, to identify whether improved training can be correlated to the current improving trends in the risk significance of precursor events. A summary of the approach and findings is provided below.

Approach

The USNRC staff, supported by Brookhaven National Laboratory, reviewed the licensee event reports (LERs) for all precursor events during 1984 through 1989 and identified and characterized human errors that occurred in these events. Recognizing that the classification of a human action as an error can involve a significant amount of judgment, the validity of this assessment was confirmed by comparison with the human error classifications reported in the annual ASP status reports (Reference 5). To provide additional verification, a human error identification protocol was applied to precursor events for 1989. This protocol is currently undergoing further development for systematically searching the computerized nuclear documents database (NUDOCS) for LERs involving human error.

Each identified human error was evaluated by a three-member panel to determine whether nuclear power plant training programs should be effective in preventing the error. Specifically, for each error the panel determined whether "training, as it exists today in the nuclear industry and as it would reasonably be expected to develop over the next few years, could be effective in preventing the error." However, while the panel may have determined that training could be effective in preventing a specific error, such a determination does not indicate that training would absolutely prevent an error from occurring. Many factors can contribute to an error, and training is but one.

Finally, this additional information was sorted in various ways to identify any correlations between improving trends in the ASP data and major improvements in industry training programs implemented over the 6-year period; specifically, the INPO-managed accreditation of utility training programs and implementation of plant-specific or plant-referenced control room simulators required by 10 CFR 55.45(b).

Results

Of the 184 precursor events reviewed, 93 involved one or more human errors. The 93 LERs with human errors had a total of 165 human errors; about half of these errors occurred prior to the event, about 25% initiated the event, and the remaining 25% occurred during the response to the event. Of the 93 events involving human error, 57 (slightly more than half) were judged to be affected by training programs. (A precursor event was considered to be affected by training if at least one of the human errors occurring in the event was judged to be affected by training.)

Figure 8 shows the distribution of the events involving human error over the 6-year period in terms of the number of LERs and cumulative conditional core damage probability (CCDP). On average, nearly half of the cumulative CCDP is due to events involving human error. The risk that is associated with those events related to human error and training appears to be decreasing slightly by visual examination, however, this trend is not statistically significant.

Human-initiated events account for about 20 percent of the ASP events, with nearly equal contributions from licensed operators, non-licensed operators, and maintenance technicians. The number of human-initiated events has remained relatively constant from 1985 to 1989. With the exception of the Davis-Besse event in 1985, these events did not contribute appreciably to the cumulative CCDP.

In Figure 9a, the total number of human errors occurring in the ASP events is presented broken down by personnel type. The types of personnel considered are control room operators and senior reactor operators (CROs/SROs); non-licensed operators (NLOs); electrical maintenance, instrumentation and control, and mechanical maintenance technicians (EMTs/ICTs/MMTs); and technical staff and management (TSM). No significant trends in the number of errors committed by any of the four personnel types are apparent. However, an interesting pattern emerges when the effect of training on the types of errors committed by each category of personnel is considered. As shown in Figure 9b, most of the errors committed by licensed operators could have been affected by training and, therefore, might be further reduced through improved training programs. Figure 9e presents the opposite trend for technical staff and management, where most of the errors occurred in procedure writing and other areas not easily rectified through technical training. Results for non-licensed operators and maintenance technicians (Figures 9c and 9d) are between those for operators and the management/technical staff, and indicate that training can affect slightly more than half the errors committed by these personnel.

The strongest argument for a link between industry training programs and precursor data trends is provided by comparing the frequency of operator errors in the precursor events as a function of the status of the licensee's operator training program and the availability of a plant-referenced simulator at the time of each event. Table 1 provides the results of this assessment for control room operators and senior reactor operators. These results indicate a notably lower frequency of training-sensitive errors at plants that have both an accredited training program and a plant-referenced simulator.

Caution should be used in interpreting and applying the results of this assessment because of the limited nature of the precursor database and the multiplicity of factors that influence the observed trends.

CONCLUSIONS

The sensitivity evaluations performed for Oconee and LaSalle and the analyses of accident sequence precursor events together provide valuable insights into the role of the human in plant risk and means by which risk might be reduced. Most importantly, the sensitivity studies confirm the significance of actions taken by operators in response to an event, and the importance of activities which involve coordination between licensed reactor operators (inside the control room) and non-licensed operators outside the control room. These findings support a regulatory strategy of reducing human errors and improving the likelihood of success for recovery actions through continued emphasis on emergency operating procedures, accident management preparation, and operator training.

The reduced frequency of operator errors at plants with both accredited training programs and plant simulators provides evidence that training may reduce the incidence of error and that this strategy is already paying off. As the sensitivity evaluations indicate, however, control room simulation cannot address all important events and recovery actions, and training for certain actions may need to be accomplished through other means. Accordingly, this is an area that will be specifically addressed in future activities under the accident management program.

REFERENCES

1. NUREG/CR-1879, "Sensitivity of Risk Parameters to Human Errors in Reactor Safety Study for a PWR", Brookhaven National Laboratory, January 1981

2. NUREG/CR-5319, "Risk Sensitivity to Human Error", Brookhaven National Laboratory, April 1989

3. NUREG/CR-5527, "Risk Sensitivity to Human Error in the LaSalle PRA", Brookhaven National Laboratory, March 1990

4. NSAC-60, "Oconee PRA: A Probabilistic Risk Assessment of Oconee Unit 3", NSAC-EPRI, June 1984

5. NUREG/CR-4674, "Precursors to Potential Severe Core Damage Accidents", Oak Ridge National Laboratory

Table 1. Correlation Between CRO/SRO Errors and Training/Simulator Status

Training/Simulator Status at Time of Event	No. of CRO/SRO Errors Affected by Training per 100 Reactor Years*
. No accredited CRO/SRO training; no plant-referenced simulator	17.8
. No accredited CRO/SRO training; plant-referenced simulator	5.6
. Accredited CRO/SRO training; no plant-referenced simulator	4.8
. Accredited CRO/SRO training; plant-referenced simulator	5.4

Normalized to reflect the number of operating reactors in each training/simulator status category in the year of the event

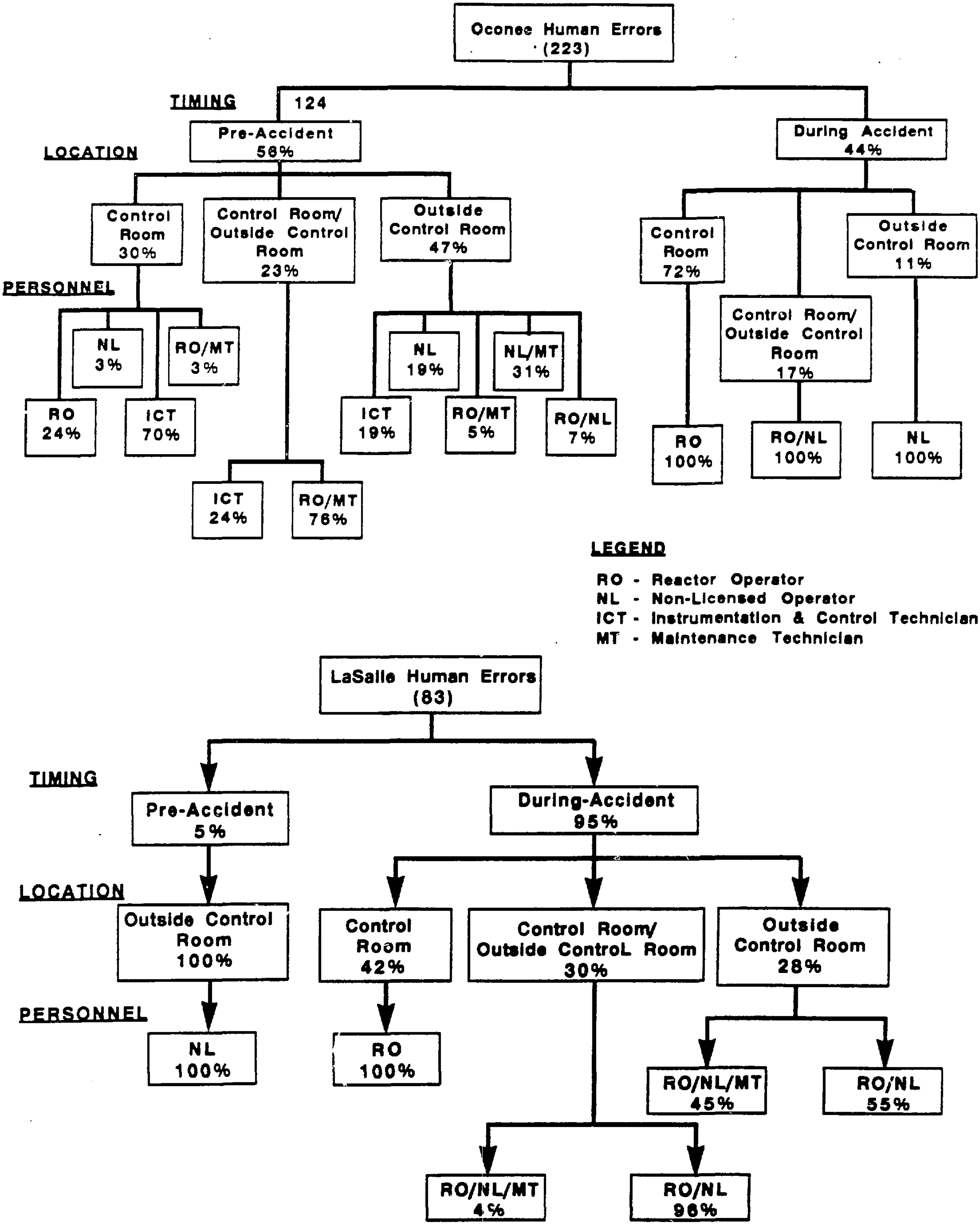

Figure 1 Breakdown of Human Errors in the Oconee and LaSalle PSAs

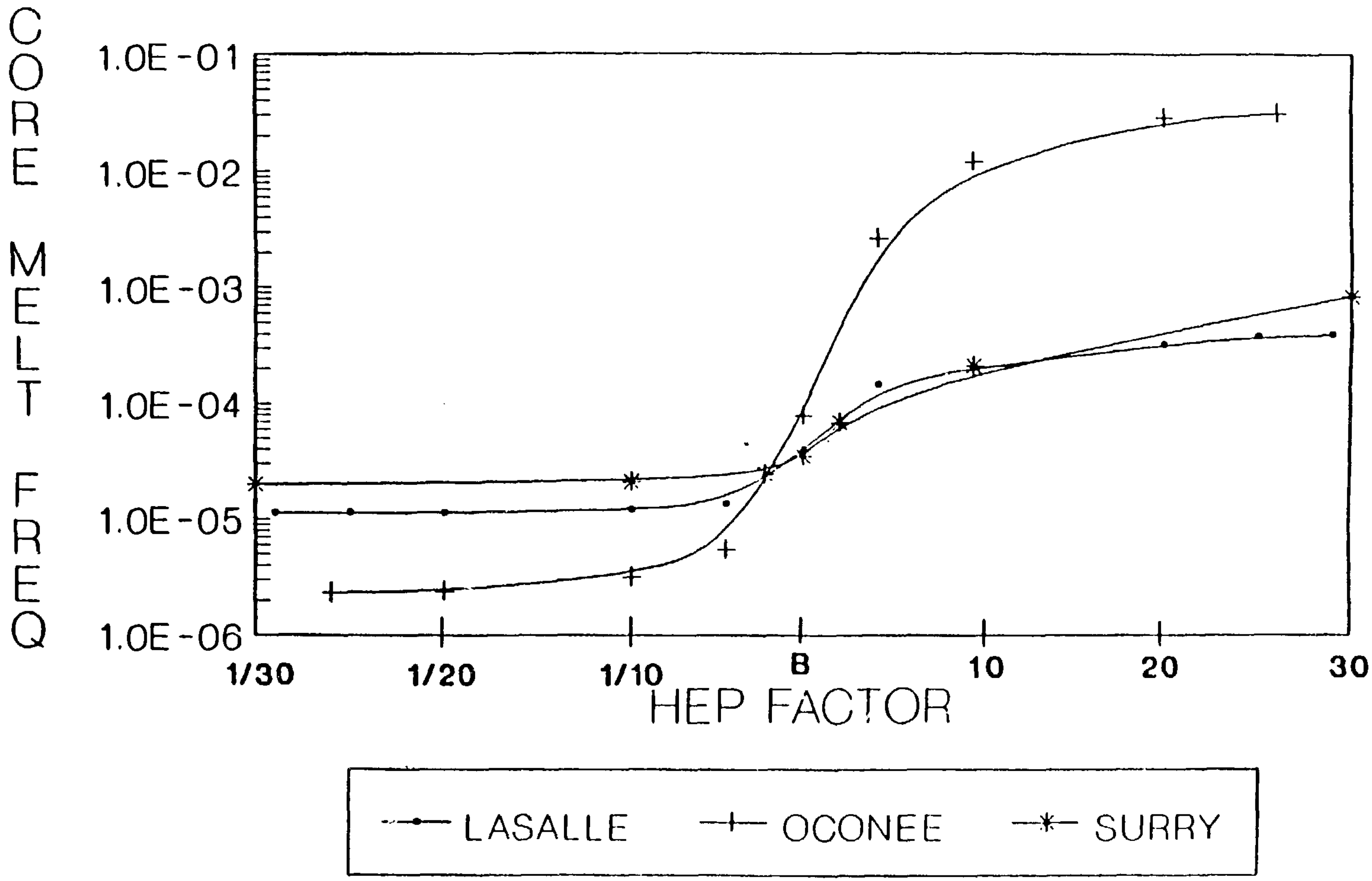

FIGURE 2 - Sensitivity to Simultaneous Variation of All HEPs

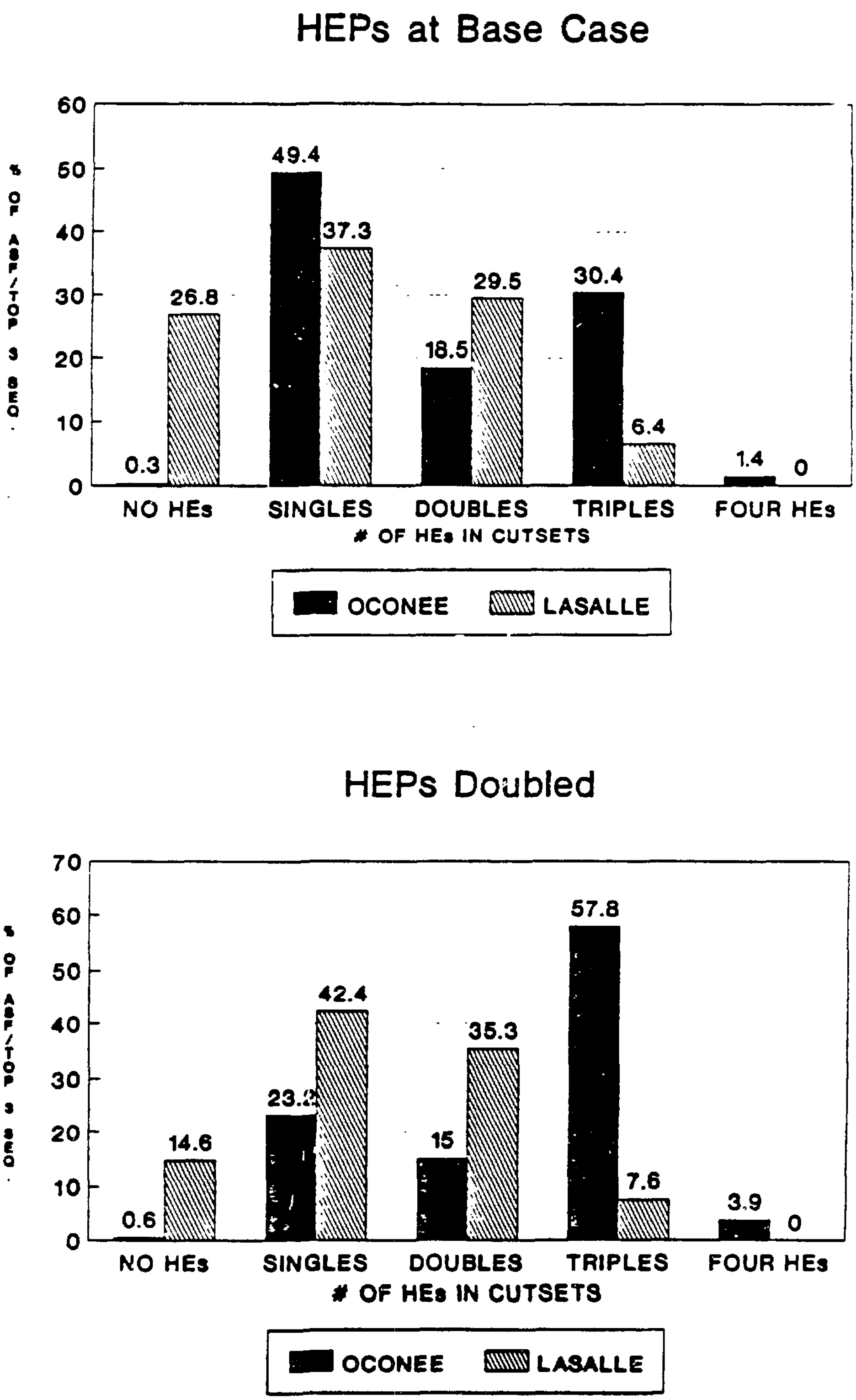

FIGURE 3 - Effect of Doubling Human Error Probabilities on Cutset Distribution

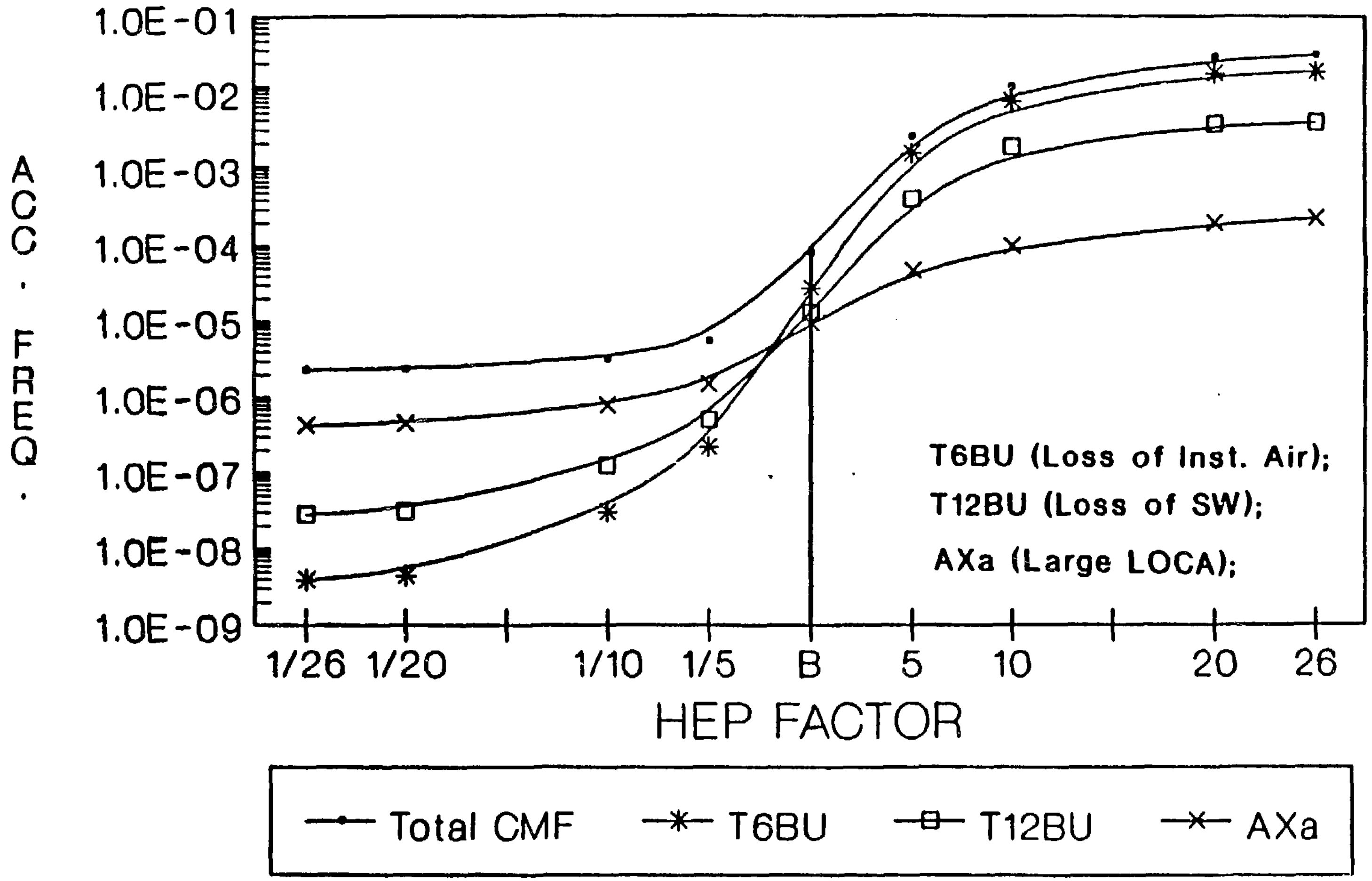

FIGURE 4 - Sensitivity of Dominant Sequences in Oconee to Simultaneous Variation of All HEPs

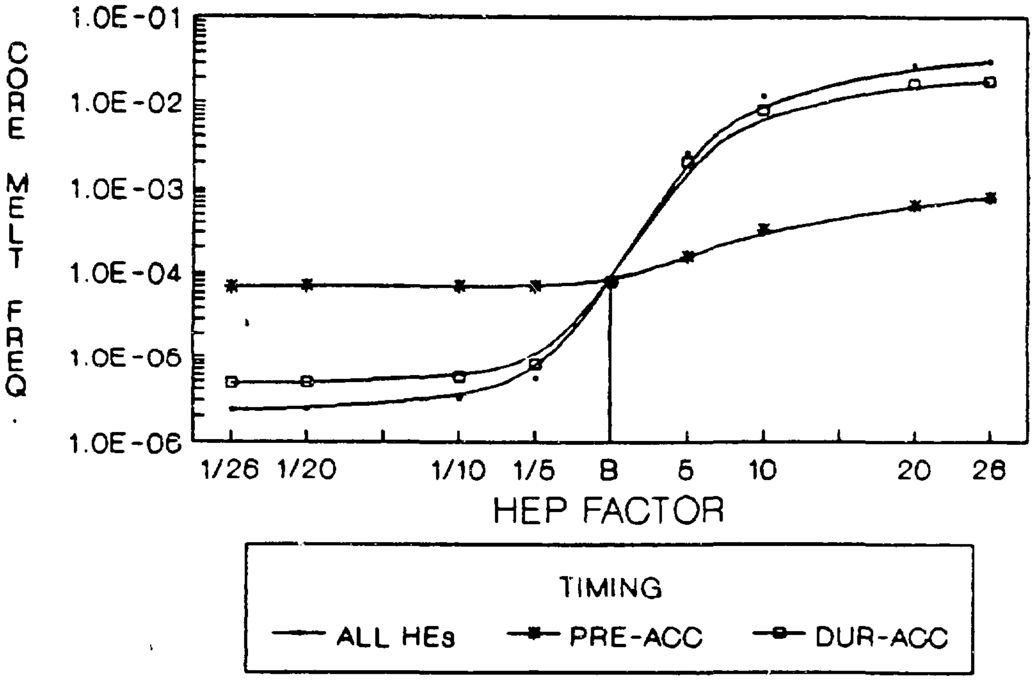

FIGURE 5 - Sensitivity to Pre-accident and During-accident Errors for Oconee

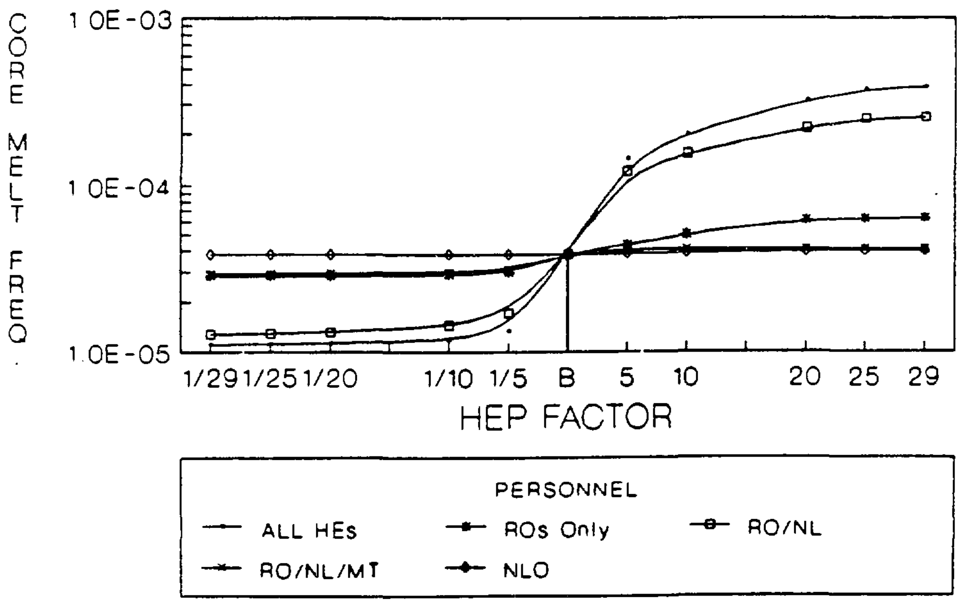

FIGURE 6 - Sensitivity to Personnel Type and RO Interactions for LaSalle

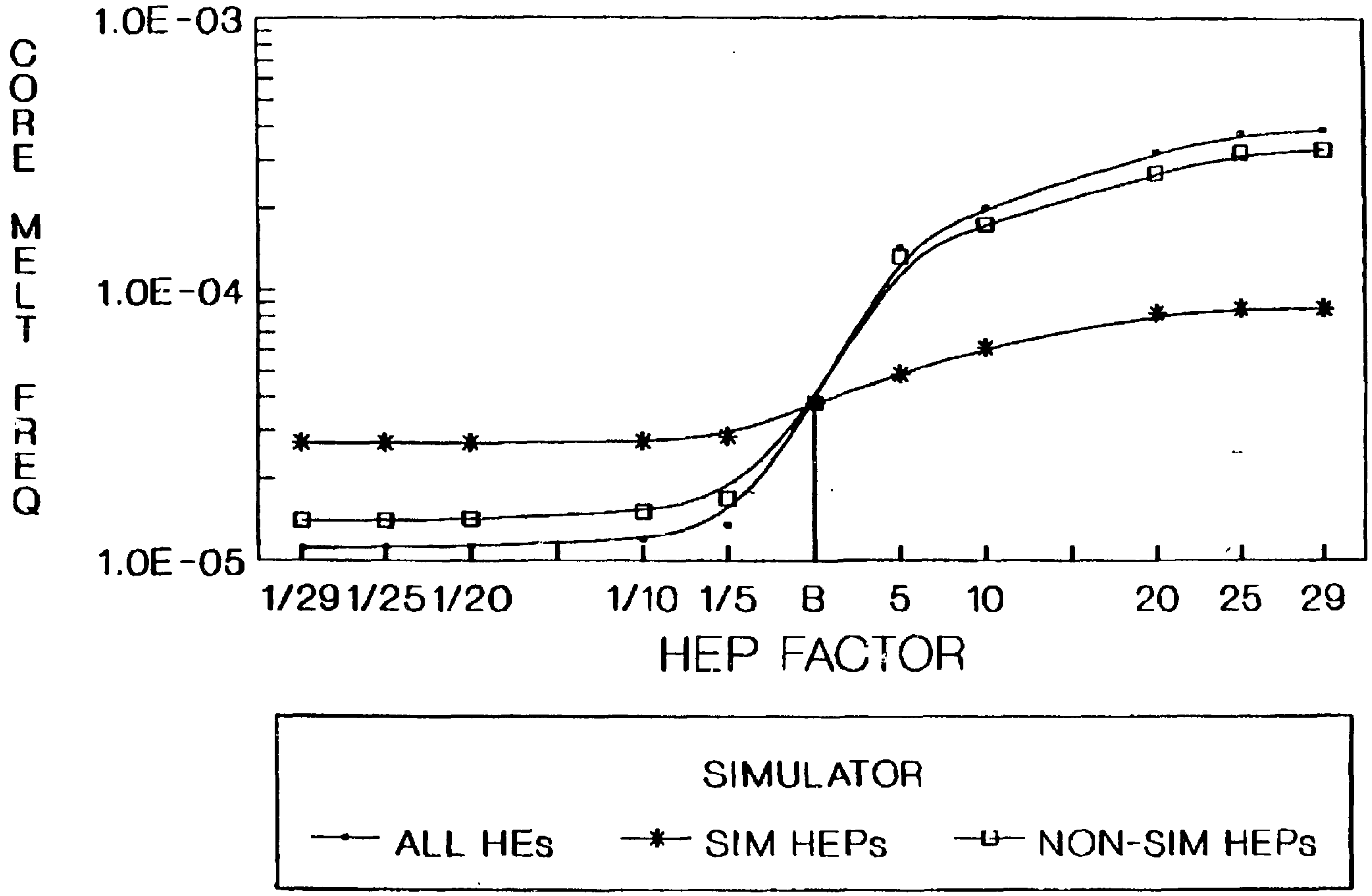

FIGURE 7 - Sensitivity to HEPs Based on Simulator Data for LaSalle

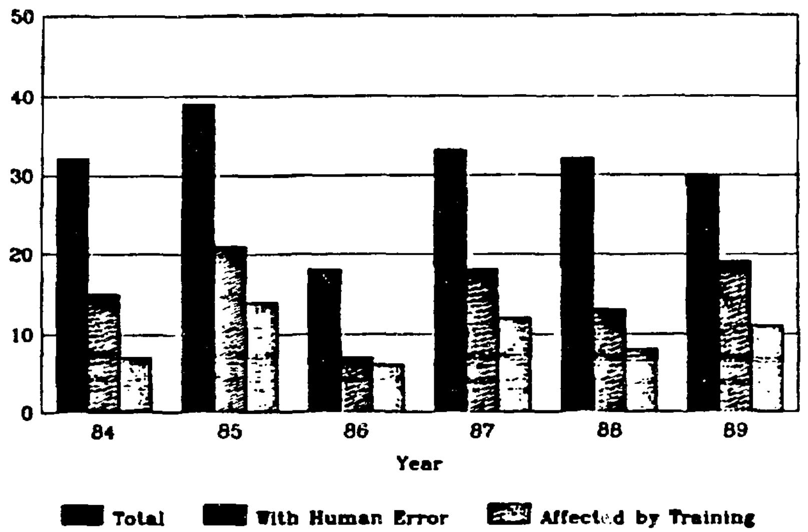

FIGURE 8.a - Number of LERs Involving Human Error

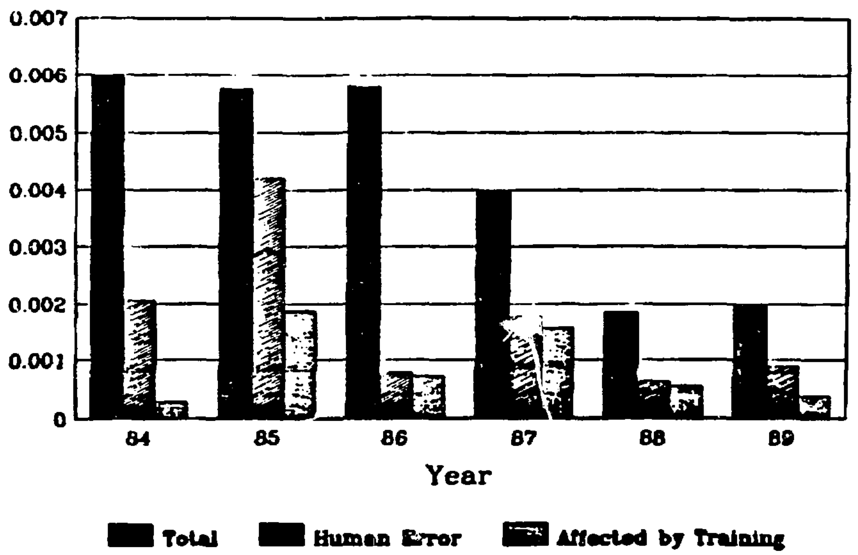

FIGURE 8.b - Cumulative CCDP for LERs Involving Human Error,
Excluding 1985 Incident at Davis Besse

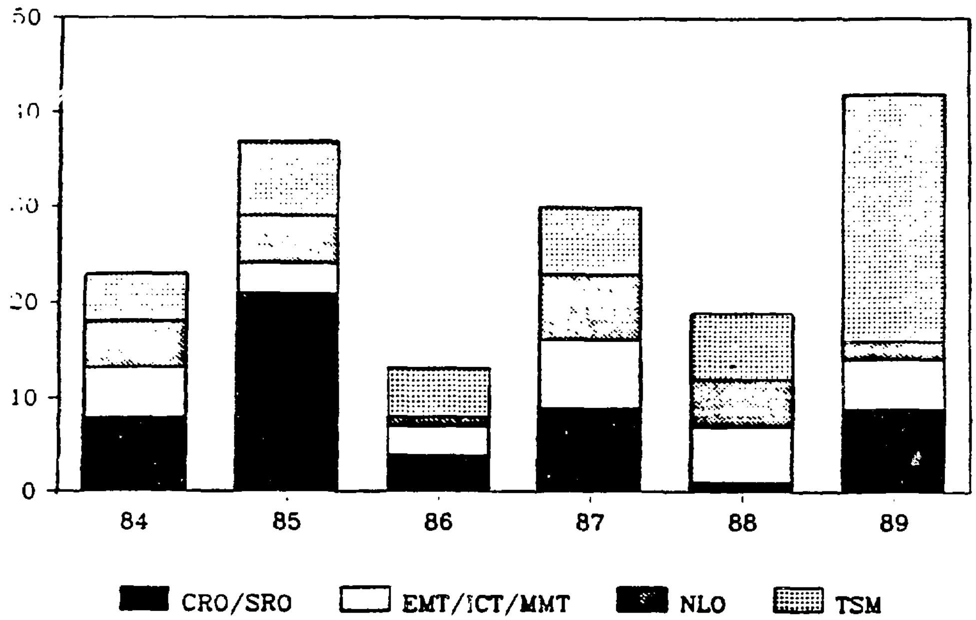

FIGURE 9.a - Number of HEs in ASP Events, by Personnel Type

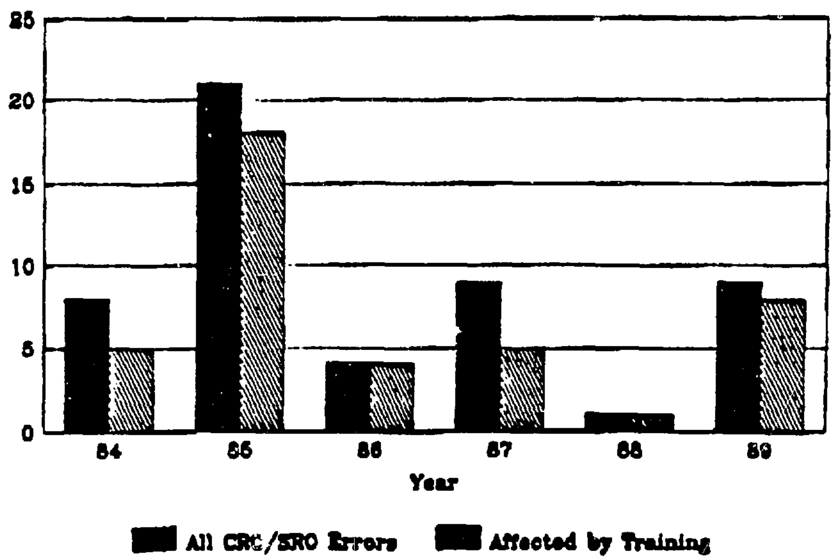

FIGURE 9.b - Number of CRO/SRO Errors Affected by Training

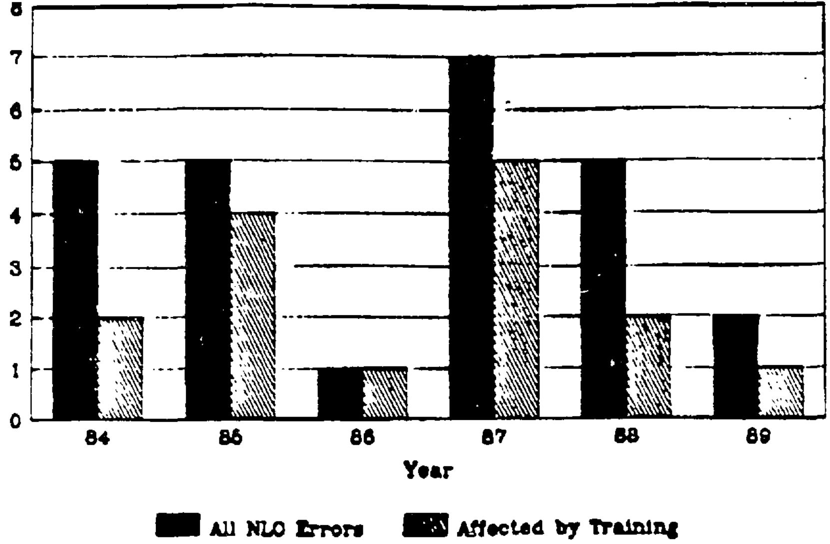

FIGURE 9.c - Number of NLO Errors Affected by Training

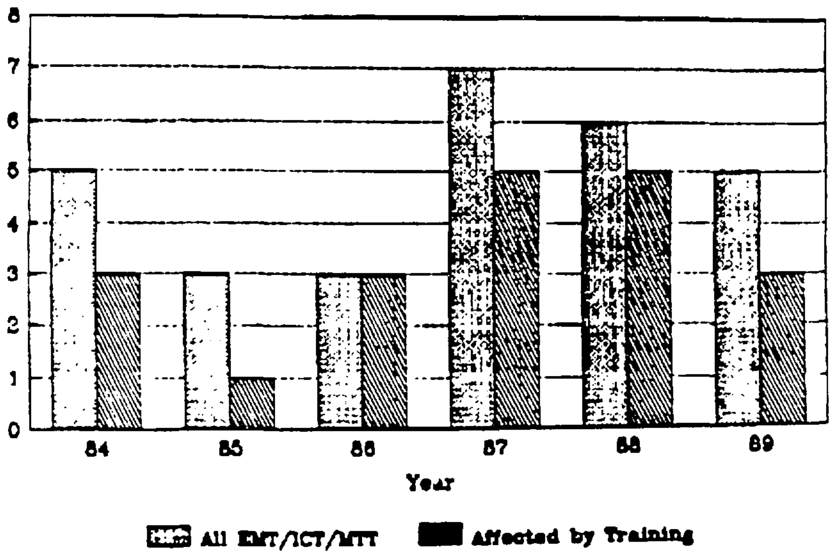

FIGURE 9.d - Number of EMT/ICT/MMT Errors Affected by Training

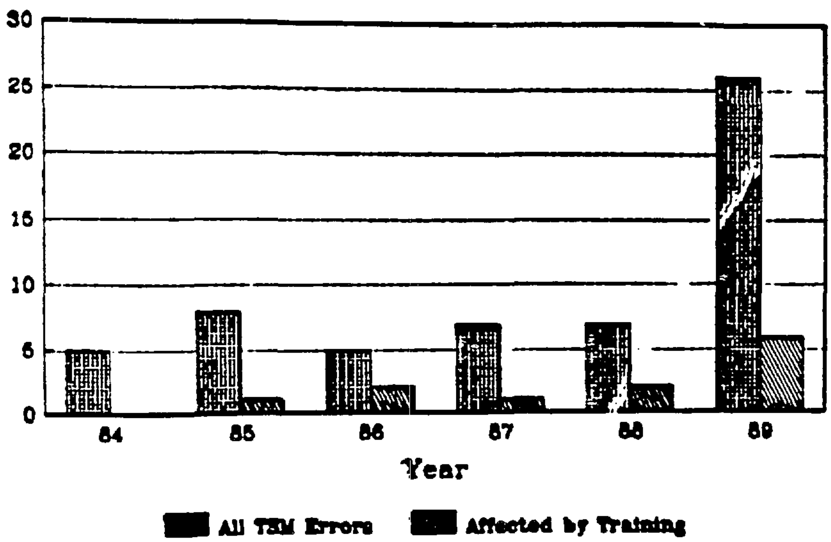

FIGURE 9.e - Number of TSM Errors Affected by Training