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Validation of Risk-Based Performance Indicators: Safety System Function Trends

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ABSTRACT

This report describes and applies a process for validating a model for a risk-based performance indicator. The purpose of the risk-based indicator evaluated, Safety System Function Trend (SSFT), is to monitor the unavailability of selected safety systems. Interim validation of this indicator is based on three aspects: a theoretical basis, an empirical basis relying on statistical correlations, and case studies employing 25 plant years of historical data collected from five plants for a number of safety systems. Results using the SSFT model are encouraging. Application of the model through case studies dealing with the performance of important safety systems shows that statistically significant trends in, and levels of, system performance can be discerned which thereby can provide leading indications of degrading and/or improving performances.

Methods for developing system performance tolerance bounds are discussed and applied to aid in the interpretation of the trends in this risk-based indicator.

Some additional characteristics of the SSFT indicator, learned through the data-collection efforts and subsequent data analyses performed, are also discussed. The usefulness and practicality of other data sources for validation purposes are explored. Further validation of this indicator is noted. Also, additional research is underway in developing a more detailed estimator of system unavailability.

EXECUTIVE SUMMARY

Brookhaven National Laboratory (BNL) and its subcontractor, Science Applications International Corporation (SAIC), have been conducting research in the development, evaluation, and validation of an indicator which can be used to monitor the performance of safety systems. The purpose of this research, sponsored by the Office of Research of the U.S. Nuclear Regulatory Commission, is to develop more responsive indicators of system performance using available data basically associated with safety performance.

This report describes work carried out to validate a safety system function trend (SSFT) indicator. By taking into consideration general logic models of plant systems, SSFT indicators utilize data collected on trains or plant components to form an indicator of system unavailability. This indicator is then smoothed to produce an SSFT indicator. Because of the level of data employed, viz., train/component downtime data, SSFT indicators are more responsive to changing trends then the current NRC indicator of safety system failures (SSFs), since the latter indicator employs observations of system failures as opposed to downtime observations at the train/component level. As such, the SSFT indicator, through its construction, the information it requires, and the statistical characteristics it possesses, is able to detect trends more quickly and with a higher degree of reliability.

Basic information used in constructing the SSFT indicator include the unobserved portions of the downtime associated with components discovered failed as well as maintenance, test and repair downtimes, all of which are necessary for estimating the unavailability of systems. This process not only yields a more responsive measure of safety system performance, it also provides a framework for evaluating plant safety performance on a broader plane, using higher levels of risk measures such as core-melt frequency. In addition, since the SSFT indicator is risk based, corresponding warning limits, or tolerance bounds, on these indicators can be determined that also have a risk as their basis. These risk-based warning limits depict when the unavailabilities of systems have deteriorated sufficiently to impact core-melt frequency and public health risk.

This report describes the theoretical bases for the SSFT indicator, employing risk and reliability approaches, which show that the SSFT indicator is directly tied to plant risk and safety performance. Empirical analyses are presented which describe the smoothing techniques employed and statistical tests performed for analyzing significant trends and for determining abnormally high levels of system unavailability. Utilizing approximately 25 plant years of historical data on equipment failures and downtimes, case studies are also reported to demonstrate the performance of the SSFT indicator.

The case studies involved estimating the performance of the auxiliary feedwater system and the emergency power system at two plants and the auxiliary feedwater system at three additional plants. The SSFT indicator for these systems and plants provided a significant amount of information for these case studies. In a number of cases, significant trends in system unavailability were observed and periods of abnormally high unavailability levels identified. One case in particular, the SSFT indicator showed an abnormally high level before a shutdown had occurred. This shutdown was largely due to system problems that, in retrospect, were also flagged by the indicator. After restart, the indicator decreased significantly, conveying that changes instituted during the extended plant outage had measurable, beneficial effects in terms of improvements in system availability.

Various plots are presented to graphically illustrate how the output of the SSFT indicators can be used to provide an effective means for viewing and interpreting the indicators. The contributions from component repair and maintenance downtimes and from undetected failure downtimes are clearly depicted in these graphical output. These show that the undetected downtime contributions are generally the dominant contributors to system unavailability. However, these are some situations when downtimes associated with maintenance activities dominate the unavailability observed. Other aspects of system performance can be gleaned from these presentations. For example, the effects of technical specification requirements on system unavailability are presented which can provide feedback for possible technical specification improvements.

The studies documented show that the SSFT indicators correlated with the SSF indicators and provided much faster response. Because the SSFT indicator is also risk-based, it can provide more direct measures of impacts to risk. Thus, the SSFT indicator appears to be a highly useful and powerful tool for monitoring safety system performance and for aggregating basic plant information to monitor safety performance.

Because of these encouraging results, it is recommended that SSFT indicators be further pursued in terms of additional applications and understanding further the properties of this indicator.

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ACKNOWLEDGEMENT

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1. INTRODUCTION

The purpose of this report is to summarize and document research conducted under the sponsorship of the Nuclear Regulatory Commission (NRC) on the validation of quantitative indicators of safety performance. This work, performed under the project "Risk-Based Performance Indicators," FIN A-3295 for the Office of Research (RES), is considered part of NRC's Performance Indicator Program which is being coordinated through the Office for the Analysis and Evaluation of Operational Data (AEOD).

In approving the Performance Indicator Program presented in SECY-86-317, the Commission directed the staff to continue to explore and develop new indicators beyond those included in the current program. The current set of performance indicators is logically related to safety but in a qualitative way. The purpose of this part of the overall developmental effort on new indicators is to develop risk and reliability methods for improving objectivity and to augment the predictive capabilities of the current set of indicators.

Work proceeded at Brookhaven National Laboratory (BNL) in developing more objective indicators that would respond faster than the currently used indicators to changes in plant safety margins. In April 1988, SECY-88-103 described the results of research to develop an indicator for safety system unavailability that is more responsive for indicating trends than the currently used indicator, viz., Safety System Failures. This new indicator estimates unavailability of safety-system trains rather than just counting those instances of complete system inoperability[1,2].

The Commission, in response to the research reported, requested more in-depth validation of the new indicator, Safety System Function Trends, using actual plant data[3,4].

Also, the EDO concluded that proposed rulemaking to obtain train-level data for this indicator is premature, given the state of development. In particular, a concern was noted that implementing this indicator, through rulemaking, could have the unintended effect of decreasing safety by increasing the frequency of on-line testing[5].

The collection of train-level unavailability data for this validation phase of the research project was coordinated through AEOD's parallel trial program for analyzing candidate indicators of maintenance effectiveness. This trial program also utilized actual operational data from a set of commercial power reactors for evaluating candidate indicators of maintenance effectiveness.

Validation of this indicator, Safety System Function Trends (SSFT) is based on three aspects: the theoretical basis, case studies, and statistical correlations.

The theoretical basis has been already documented,[6,7] and will be highlighted in Section 2. The case studies, reported in Section 3, involve engineering interpretations of trends in the SSFT indicator using system- and train-level data collected at eight plant sites. Plant operational histories were also used to interpret trends in the unavailability indicators. This data set included data collected at plants during the earlier phases of this research project as well as data collected during July-August 1988 as part of the trial program conducted by AEOD on maintenance indicator evaluation.

Statistical significance in the trends and in the levels of the safety system unavailability indicator are also discussed in Section 3, along with evaluations of the dominant contributors to system unavailability.

In Section 4 the indicator is compared with observed system failures. An example is presented which shows that the number of hours/year a system is expected to be unavailable correlates with the number of failures which that system experienced over an eight-year period.

The issue of valid tolerance bounds for determining warning levels is discussed in Section 5. An approach for estimating tolerance bounds, less approximate than the one employed in Section 3, is explored and an application described.

Section 6 documents preliminary statistical analyses performed to show whether correlations existed between this new indicator and the currently used indicators.

Lessons learned in analyzing plant historical data are delineated in Section 7. In this section the use of industry's component failure reporting system, NPRDS, in lieu of using historical records maintained by the plant, is addressed. This section also discusses the inherent uncertainties in the approach used for calculating the SSFT indicator, especially in the use of direct observations of component failures, together with estimates of expected downtimes associated with these failures.

Summary and conclusions are given in Section 8; backup material and additional results are provided in the attendant appendices.

2. THEORETICAL BASIS AND TECHNICAL APPROACH RATIONALE

The overall objective of this research project is to develop and validate a method which more fully utilizes basic risk and reliability technology to help select, interpret, and evaluate quantitative indicators of safety performance at operating plants.

As illustrated in Figure 1, operational safety requires a low frequency of transients coupled with a high availability of safety systems needed to respond to these transients. The underlying concept of risk-based indicators deals more directly with the risk implications of events and activities that occur at a plant. These events and activities depend upon the frequencies at which they occur. For example, the risk implication of component failures depends upon the frequency at which failures occur; and, as part of the frequency implications, the recurrence of the event also needs to be considered. The duration of the event can also have risk implications, for example, where unavailability considerations enter. The likelihood of an accident progressing to core damage is the product of the frequency of initiating events and the probability that safety systems will not respond and the operator will not recover from this initial upset condition. Therefore, one measure of the safety-performance of operating nuclear power plants is the unavailability of important safety systems, i.e., the probability that safety systems will not respond when needed.

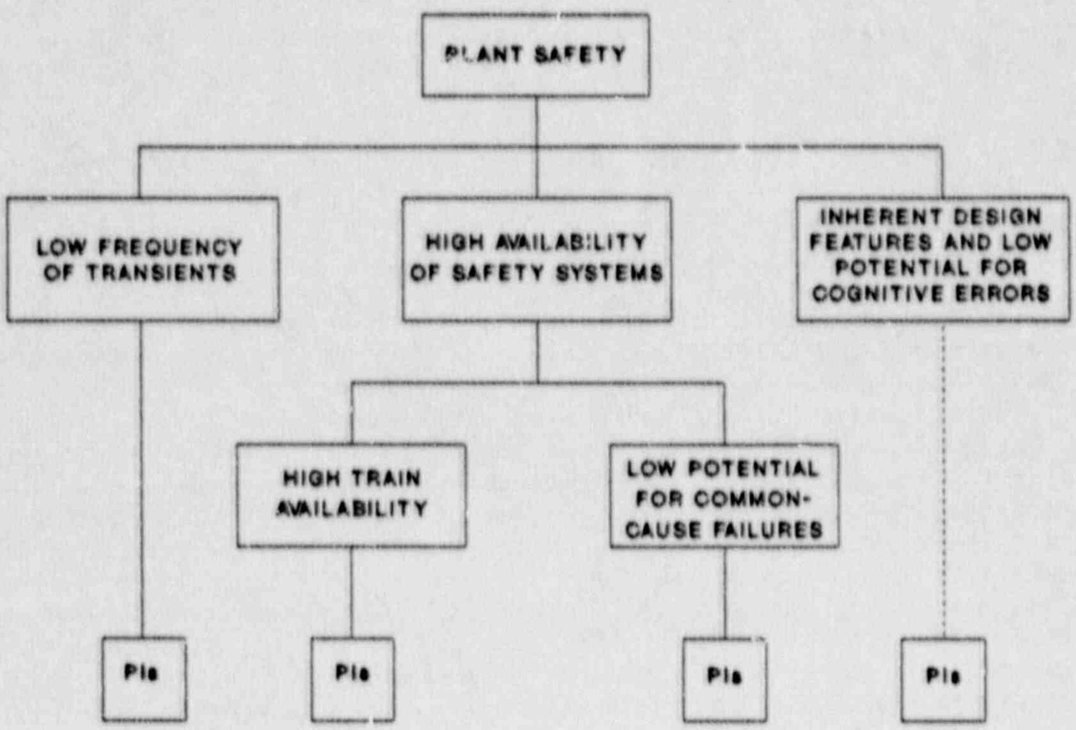

Figure 1. Plant safety logic model.

Indicators of unavailability of safety systems are intended to track changes in safety margins (i.e., loss of system redundancy) before loss of system function. Such indicators can be based on loss of components or train function. In contrast to NRC's currently used indicator of safety systems performance, which is safety system failures reported through Licensee Event Reports (LERs), this improved approach utilizes more frequent and more basic data, and results in a more responsive estimate of the safety margin of important systems. Thus, this improved indicator should more accurately reflect the magnitude and trend of unavailability thereby providing indications of potential declining system performance before loss of system function is observed. As such, the thrust of the research effort has been on developing approaches that rely on system operational data, coupled with risk and reliability models, for estimating system unavailability. The basic operational data used to estimate unavailability are the frequency and durations with which trains within selected safety systems are brought down for preventive and corrective maintenance and for surveillance tests. The primary sources of these data are plant's operator logs, plant records on limiting conditions of operation (LCOs) and maintenance work requests.

These data provide the necessary ingredients for developing two basic measures of equipment and system performance, viz., availability and reliability. Both measures are important to safety and risk. The equipment must be available to perform its function and must be reliable for carrying out its function. Equipment which fails often but is quickly repaired has a low reliability and a high availability, whereas equipment that fails infrequently but remains down for a long time has a high reliability and a low availability. When combined with systems models, trending changes in these two basic measures with time can provide a means for estimating changes in the system's ability to perform its function.

Recognizing that operational data on system trains can be somewhat "noisy" several characteristics of indicators of unavailability were evaluated to assess various smoothing techniques as well as the ability of the indicators to filter out noise and to estimate unavailability.

The theoretical basis for investigating basic characteristics of risk-based performance indicators is described in Reference 6 which shows how train-level data can be aggregated to obtain information on system performance. Additionally, Reference 7 presents the results of statistical simulations, using assumed train-level information, that further provide technical justification for the use of these indicators. These simulations explore the trend detection power of the indicator versus the safety system failure indicator and the viability of using existing plant operational data with the developed approach.

These simulation studies, reported in two cited references, have shown that the SSFT indicator can be a more responsive indicator than the safety system failure indicator, SSF. In addition, these studies have shown that more powerful statistical tests can be utilized to test the significance of the trends and levels of this risk-based indicator. These past studies form the technical foundation upon which rests the validation process of the SSFT indicator. However, further developmental work is currently underway in the areas of: i) indicator aggregation, ii) statistical/engineering interpretation, and iii) indicator refinement to include dependent failures.

This theoretical concept was tested with existing historical data, collected from unit logs at eight plants (five sites) and supplemented, where appropriate, with maintenance records. Approximately 25 reactor years of historical data were used to validate the SSFT indicator for selected safety systems. The operating histories ranged between 5 1/4 years at one plant to approximately 2 years at other plants depending on the relative ease with which archival information could be collected.

For each plant and for each system, information on the number of times trains are taken out of service and the amount of time trains are down were aggregated over calendar quarters. Critical hours within each quarter were also ascertained to obtain train unavailability. Simplified system models (based on the number of system trains) were used for calculating the unavailability indicator of selected safety systems.

Processed data were plotted, smoothing techniques employed, and statistical tests performed to assess significance of the level of the indicator and of the trends observed. Levels and trends were evaluated in concert with past events and perception of the performance of each plant during the observation period.

The results of this validation process are discussed in the sections that follow.

3. CASE STUDIES

This section presents results of the SSFT indicator approach using past historical data collected at five plants. These data were largely collected as part of AEOD's evaluation of candidate maintenance performance indicators conducted in July-August 1988. The plants where data was collected for SSFT analysis were selected to answer the following questions:

1. For a plant where a major operational event occurred, does the indicator show poor or degrading performance before the event, and has performance improved after restart?

2. For a plant where performance changed over time, does the indicator show this change?

3. For a plant with few safety problems, does the indicator reflect generally good performance?

In Section 3.1, the basic approach for calculating train-level and system-level indicators of unavailability is summarized. This method, computes specific train/system unavailability based on train-level downtime information averaged over three previous non-zero downtime quarters. A non-zero downtime quarter is defined as that quarter of a calendar year within which a train in a specific system was "brought down" for test, maintenance, or repair.

Results employing this approach are presented in Sections 3.2, 3.3, and 3.4. Five case studies, using historical data collected from five plants for two specific systems, are described in these three subsections.

The question regarding the time a component could have been in a failed state (undetected downtime) prior to when it was discovered as failed is addressed in Section 3.5. In this subsection, the relative contributions of undetected downtime and detected downtime to system unavailability are analyzed.

Adjustments to the system unavailability indicator trends which take into account requirements imposed by technical specifications are discussed in Section 3.6 and examples are presented which show the effects of tech spec controls on unavailability trends. Issues regarding the averaging process employed and uncertainties in data employed for calculating the basic downtime parameters are discussed in a later section. More detail on the approach taken for these case studies can be found in Reference 8.

3.1 Approach Summary

For two of the five case studies, the safety systems analyzed were the Auxiliary Feedwater System (AUX-FEED) and the Emergency AC Power System (EPS). The remaining three case studies include only AUX-FEED. For each of the systems, trends in the SSFT indicator with time are depicted in terms of changes in 1) system unavailability, 2) average train unavailability, and 3) system unavailability based on train averages*. Superimposed on each is a train unavailability goal of 0.05/train for aux. feed and 0.1/train for EPS. How these level and trend tests are performed will be discussed later. Also shown are those periods in which the plant had a major shutdown, either scheduled or unscheduled. The dotted lines in each of the figures represent periods of plant shutdown.

The unavailability results presented in each of the figures are obtained by first calculating the unavailability of individual system trains within each quarter and then dividing by the number of critical hours within each quarter. The results presented are based on averaging over the past three quarters, or number of quarters containing three quarters, where trains within the system analyzed were brought down for repair. This indicator forms a running average indicator where only the past three quarters of downtime information are used along with the reported critical time within each quarter and those intervening. This approach serves to smooth the behavior of the system unavailability estimate while still showing time trends and significant changes in the estimate. This approach then is a compromise between calculating the unavailability based on all past down times of system trains (as presented in Section 6) and those calculated based on only the train downtime in each quarter.

In calculating the system unavailability indicator, the average train unavailability indicator was first calculated by recording the total downtime per quarter for each train and then aggregating the downtime data by summing over all the trains in the system. Average train values were obtained by dividing this aggregated value by the number of trains within the system. System unavailability, based on average train unavailability, was obtained by raising the average train value to a power equal to the number of trains within the system. The calculations are re-initiated after each shutdown period.

Tables of the calculated indicator values are provided in Appendix A. These calculations were performed using historical plant data listed in Appendix H. Further calculational details are documented in References 6 and 7 and the three-downtime average approach is further described in Reference 8. For completeness, however, we highlight in Appendix B the statistical trend tests performed; in Appendix C we provide the rationale for safety system selection; and in Appendix D we detail further the basic measures of equipment/system performance as well as the data collection and calculational procedures.

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*Unavailability based on train average is somewhat similar to INPO's approach for tracking system unavailability.

3.2 Plant 1 - System Unavailability Trends

System unavailability trends for the Auxiliary Feedwater System (AUX-FEED) and Emergency Power System (EPS) for Plant 1 are shown in Figures 2 and 3 respectively. For this plant, AUX-FEED is a three train system; EPS is comprised of two trains. Each figure presents the following: 3-quarter cycle average unavailability, average train unavailability, and system unavailability based on average train unavailability.

In the spreadsheet table, shown in Appendix A, for the AUX-FEED system for Plant 1, the downtime hours per quarter per train (DWNA, DWNB, DWNC) include the detected plus undetected hours. Undetected downtime hours are included in the calculations when a failure (loss of function) of a train is noted. For these cases, the undetected downtime added to the observed downtime hours is taken as one-half the interval from the last demand or test of the train.

The aggregated train unavailability (summed over 3 trains) and the average train unavailability over a 3 1/2 year period (1985 - Mid-1988) are presented in Figure 2a. The left-hand ordinate in Figure 2a represents the aggregate (summed across three trains) train unavailability; the right-hand ordinate represents the average train unavailability, i.e., the aggregated value divided by the number of trains. System unavailability, obtained by cubing (3 trains) the average train availability is shown in Figure 2b.

The unavailability of the auxiliary feedwater system for Plant 1 (Figure 2) indicates a slight increase prior to the plant shutdown which began in the second quarter of 1986 and lasted until the second quarter of 1987. However, the magnitude of the calculated unavailability is seen to be well below the 95% warning limit.* After the shutdown, the indicator value is above the warning limit, possibly indicative of increased off-line testing and maintenance initiated as a result of plant modifications that took place during the shutdown. However, there is a downward trend in the indicator over 4 quarters after this unscheduled shutdown.

The EPS train and system unavailabilities (Figures 3a and 3b) show an increasing trend from 85-1 and leveling off two quarters prior to the unscheduled shutdown in 86-2. After the shutdown, the unavailability of the EPS is above the warning limit in 87-3 and remains at a fairly high level through 88-2.

Overall, the changes in the level of system performance for the AFWS and EPS are quite large. The AFWS increase could be explained as an initial period of extremely low unavailabilities where no downtimes were reported for several quarters, and those downtimes that were reported were of short duration. Subsequently, even a moderate increase in downtimes would appear relatively large. This reason, coupled with one identified train failure

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*An approximate 95% tolerance bound is based on train unavailability goal values of 0.05/train for AUX-FEED and 0.1/train for EPS.

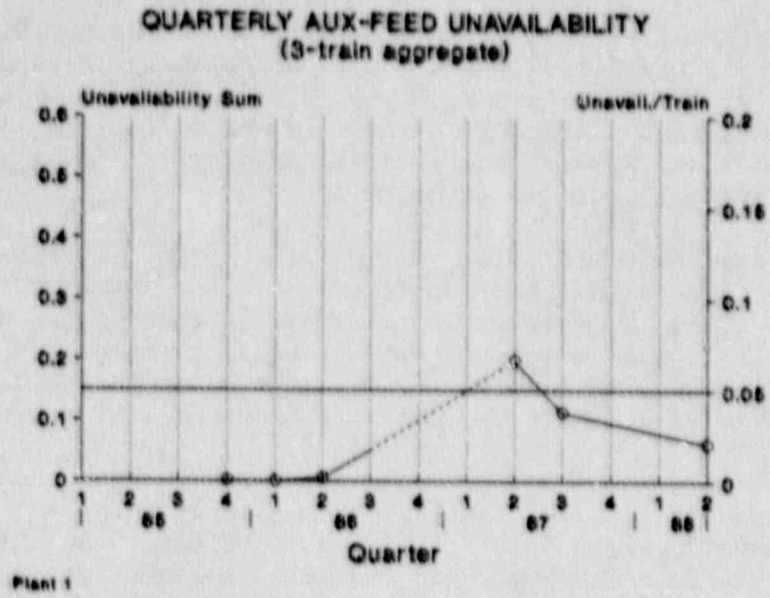


Figure 2a

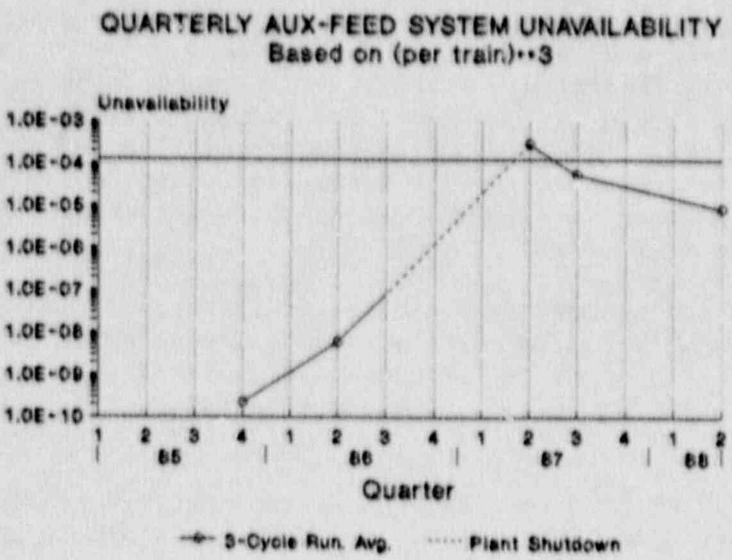


Figure 2b

Figure 2. Plant 1, auxiliary feedwater system unavailability indicator: a) unavailability per train, b) system unavailability

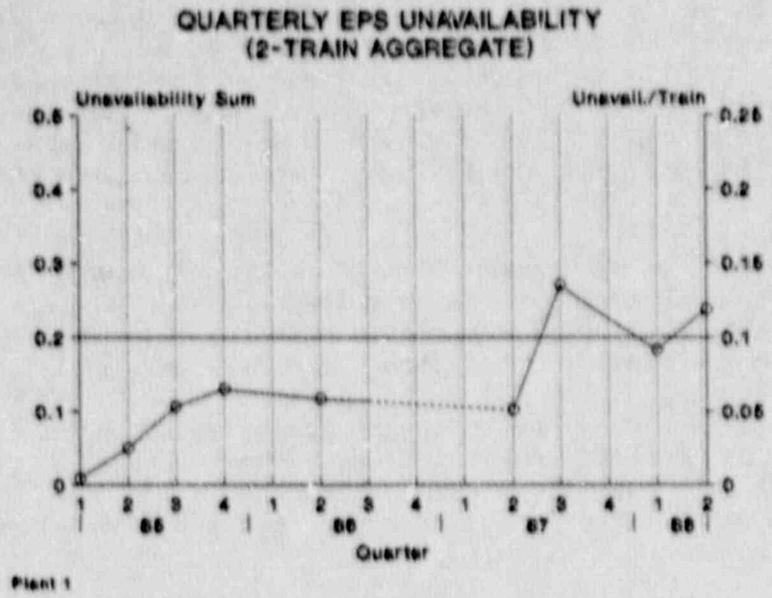


Figure 3a

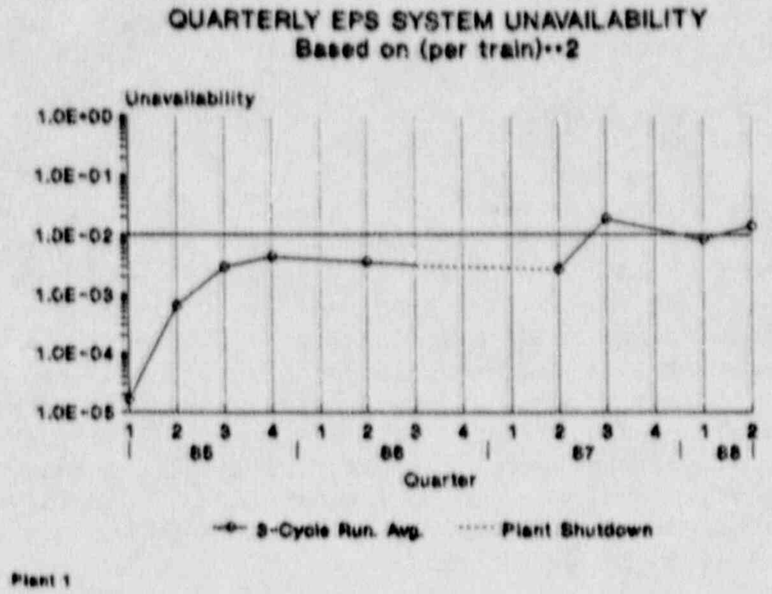


Figure 3b

Figure 3. Plant 1, EPS unavailability indicator: a) unavailability per train, b) system unavailability

(Train 8c) in 87-2 provides an explanation to the sharp rise in AFWS unavailability. The EPS also exhibited a relatively large increase from 85-1 through 88-2, approximately an order of magnitude increase at train level, and approximately a two-order of magnitude increase at the system level. The EPS increase, however, was steady throughout the period under analysis going from a low of 3E-4 to a high of approximately 2E-2 after the outage. This increase can be attributed to four train failures, two occurring in the same quarter (87-3).

In a parallel[9] study engaged in developing and demonstrating a maintenance indicator evaluation process, the frequency and duration of maintenance-related activities at Plant 1 associated with two classes of equipment (valves and pumps) were analyzed and significant trends determined.

The results from this analysis were presentations of the trends in a relative maintenance ineffectiveness indicator that is based on normalized values of the downtime (DT) associated with maintenance activities, and the number of reported equipment failures (F) across nine systems. For example, in Figure 4 the following information is depicted:

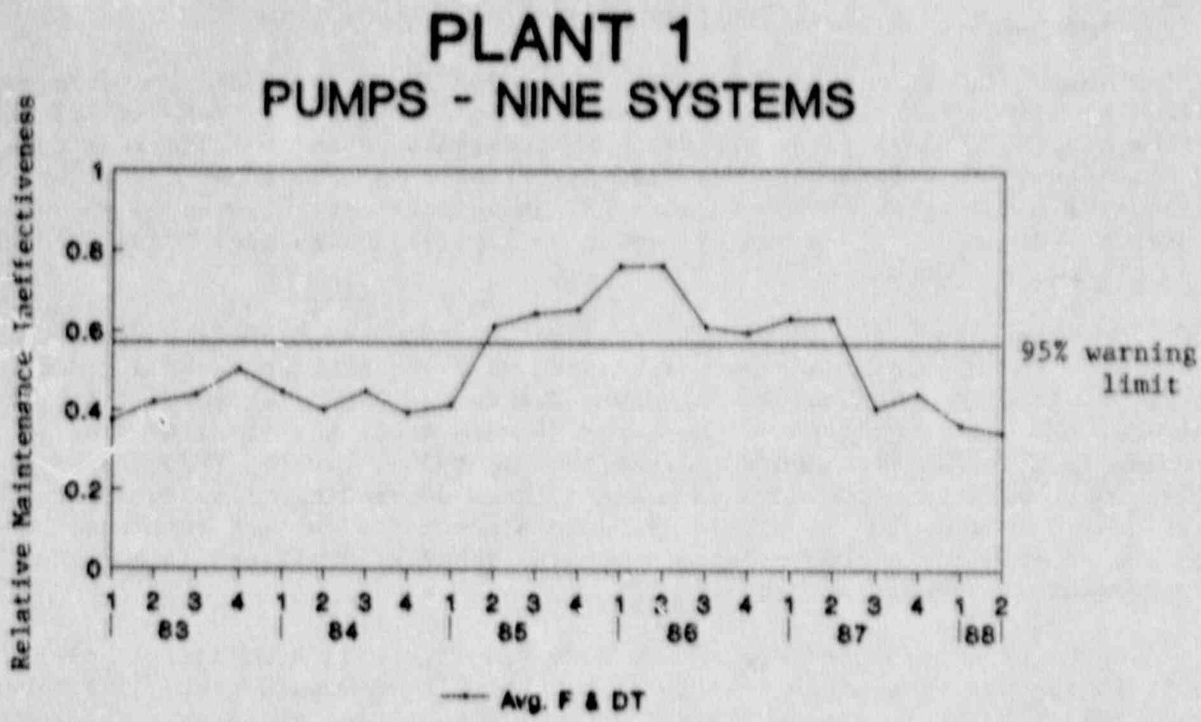
1. Effective maintenance on both pumps and valves significantly deteriorated from 1983 until the major shutdown occurred at Plant 1 in 1986. The significance in the trend was at least 95%.

2. For both pumps and valves, the level of maintenance ineffectiveness was above the 95% warning level for approximately one year prior to the major shutdown in the second quarter of 1986.

3. After the plant restarted in 1987, maintenance effectiveness seems to be improving.

More details of the approach used for exploring a measure of maintenance ineffectiveness are provided in Reference 9. Overall, it appears that both of these indicators for this case study would appear to be inconsistent. Where the maintenance effectiveness indicator and the system unavailability indicator both show increasing trends prior to the 86-2 outage, the maintenance indicator shows an immediate decrease after the outage; whereas, the system unavailability indicators reach their respective peaks just after the outage with both the AFWS and EPS violating the 95% warning limit. The AFW system did show an improving trend after this initial large increase, the EPS however remained fairly high until the end of the period analyzed (88-2). This seems to be consistent since the AFW system, as compared to the EPS system, is largely composed of pumps and valves.

It appears that the system unavailability indicator can provide an indication of ineffective maintenance; however, the SSFT indicator did not fully show an improving trend as that indicated by the maintenance effectiveness indicator. This may be due to the local behavior of the two systems analyzed for the SSFT indicator (AFW and EPS) versus the broad scope (nine systems) undertaken in the calculation of the maintenance effectiveness indicator.



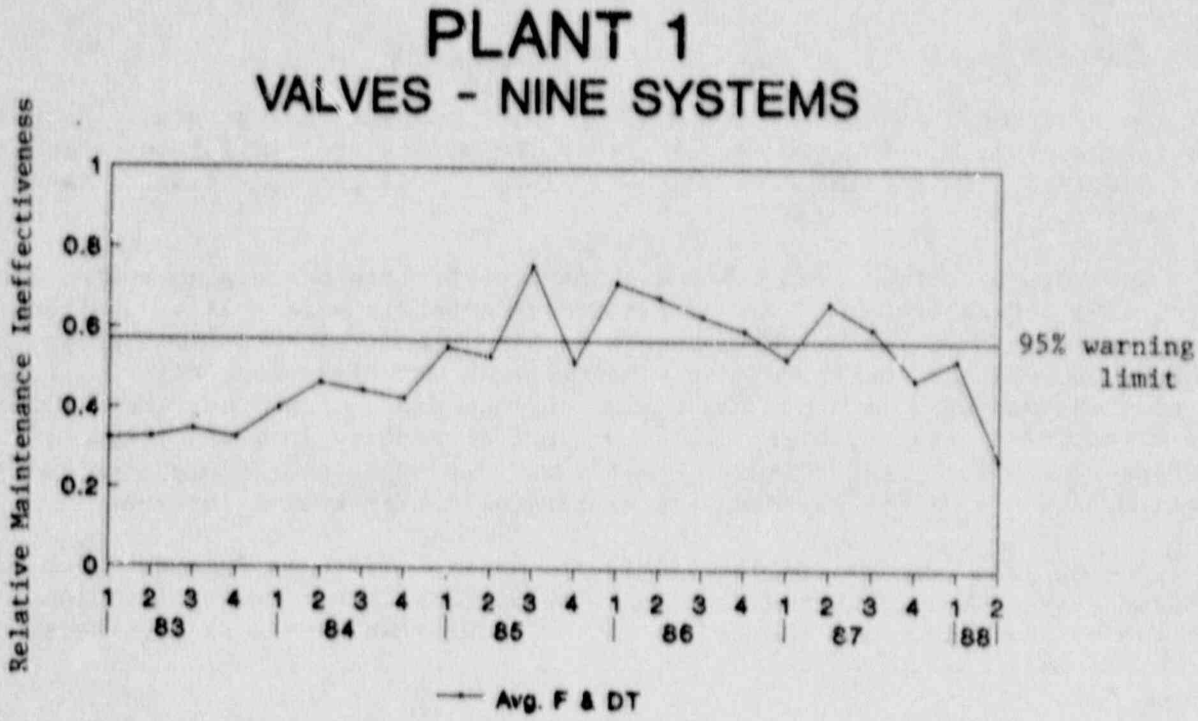


Figure 4. Plant 1, equipment maintenance effectiveness indicator: a) pumps, b) valves

3.3 Plant 2 - System Unavailability Trends

Plant 2 also experienced a major, unplanned shutdown. This shutdown occurred in 1985. For this plant, trends in the unavailability for the AUX-FEED system and the EPS are respectively shown in Figures 5 and 6. The same type of unavailability information depicted for Plant 1 is also shown for Plant 2. Figures 5a and 5b show trends in AUX-FEED unavailability; Figures 6a and 6b depict trends in EPS train and system unavailability. The basic data used are also listed in Appendix A.

For this plant, the auxiliary feedwater system unavailability remained well above the 95% tolerance bounds between 83-2 and the unplanned shutdown in 85-2. In fact, the shutdown was largely due to AUX-FEED problems. The high value of the indicator tends to convey a concern about the likelihood of impending problems and incidents. After this shutdown, the AUX-FEED unavailability decreased and continued on a significant decreasing trend during the last year. This could imply that design and procedure changes that were instituted during the shutdown had measurable, beneficial effects in terms of improvements in unavailability.

On the other hand the EPS showed a decreasing trend from 83-2 to 87-1 while in the last year from 87-1 to 87-4, there is an upward trend in EPS unavailability but still below the tolerance limit. These changes in the level are large and seem to indicate that the performance of this system needs to be watched and causes for these changes determined.

3.4 Plants 3, 4 and 5 - System Unavailability Trends

None of these plants experienced any major, unplanned shutdowns. Results are grouped together in this section since the plants are similar and the data were obtained from similar data sources. These three plants are all located on one site.

The turbine-driven pump train and the two electric motor pump trains were first analyzed separately. Data presented in Appendix A for Plant 3 reflects these separate calculations with turbine-driven pump train downtimes shown in the column DWNT and the two electric motor train downtimes respectively listed in the DWNA and DWNB columns that appear in Appendix A. However, the turbine train and the average electric trains did not separately show significantly different behavior. Accordingly, the figures depicting AUX-FEED system unavailability trends are based on aggregating all three trains together.

The AUX-FEED system unavailability for Plant 3 (Figures 7a and 7b) shows a generally increasing trend from 85-2 to 87-1 and then a decreasing trend. The system unavailability changed by approximately two orders of magnitude (a factor of 100) over this period.

The AUX-FEED system unavailability for Plant 4 (Figures 8a and 8b) shows a general upward trend from 85-2 to 86-3 and then a downward trend from 86-3 to 87-4. The system unavailability changed significantly over this period, varying by orders of magnitude.

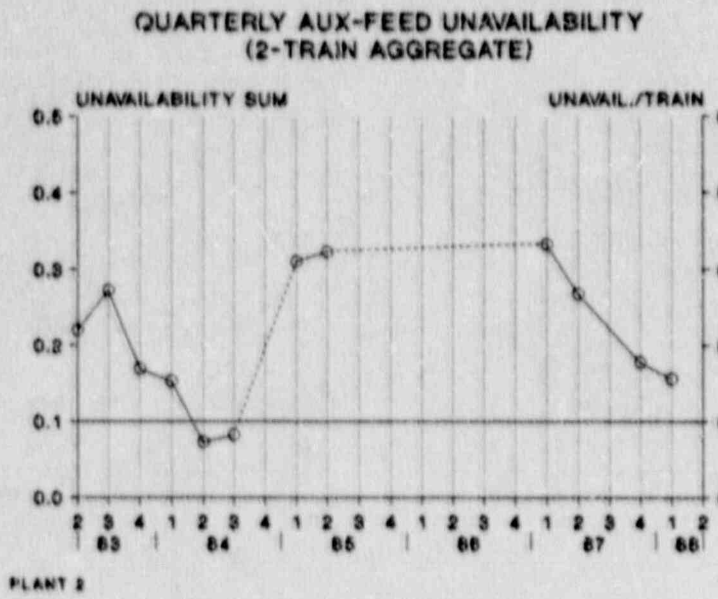


Figure 5a

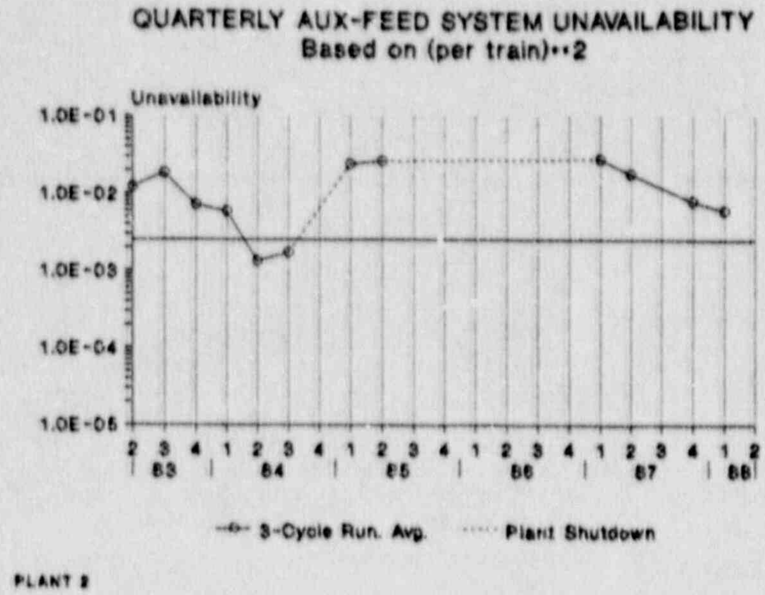


Figure 5b

Figure 5. Plant 2, aux feed system unavailability indicator:
a) unavailability per train, b) system unavailability

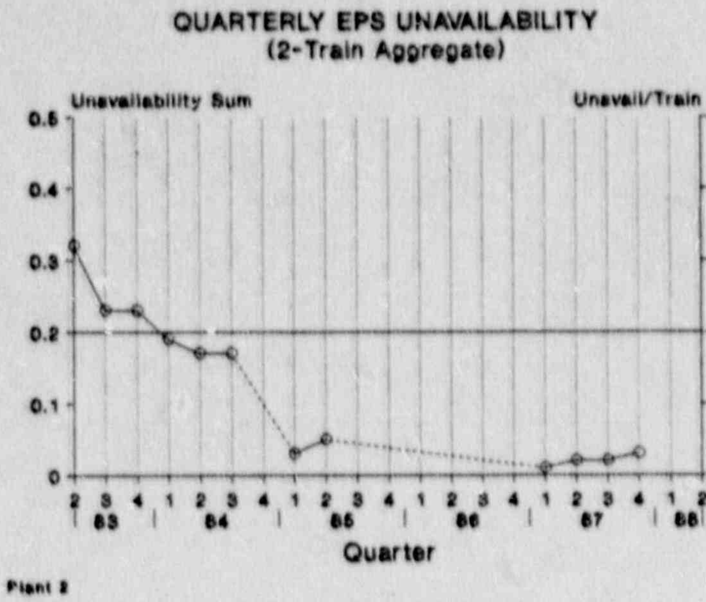


Figure 6a

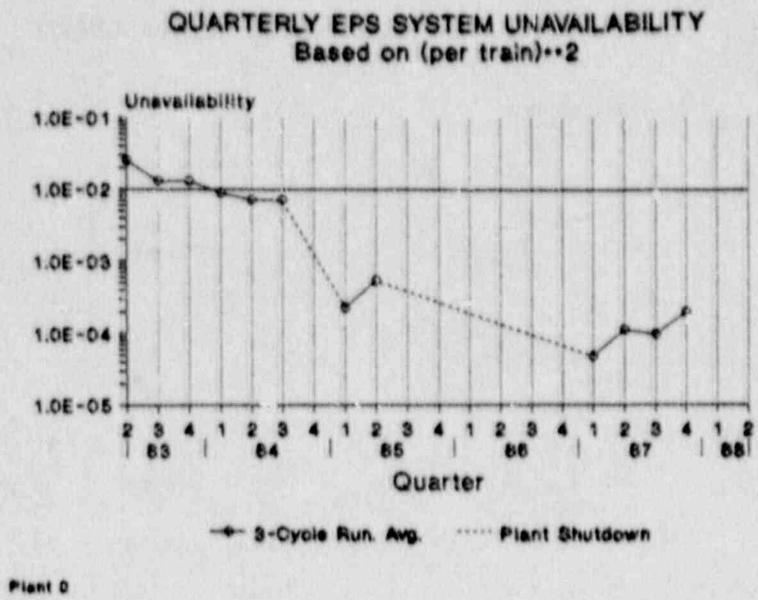


Figure 6b

Figure 6. Plant 2, EPS unavailability indicator: a) unavailability per train, b) system unavailability

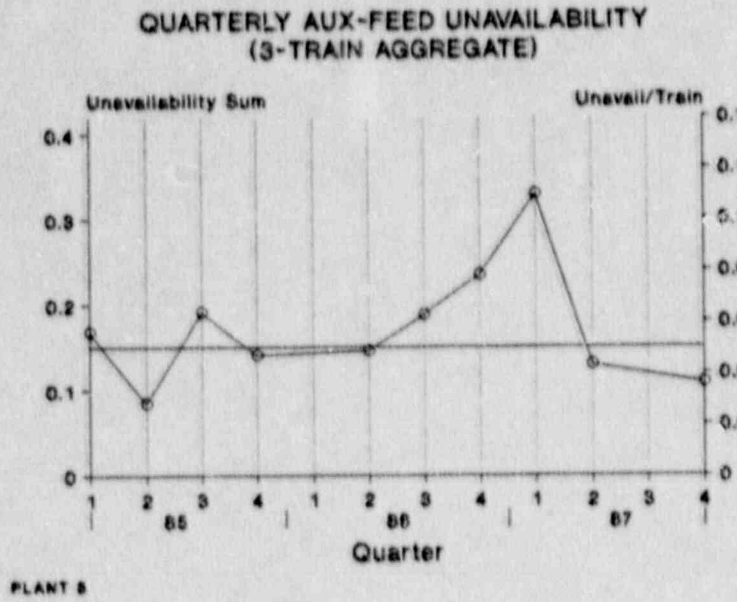


Figure 7a

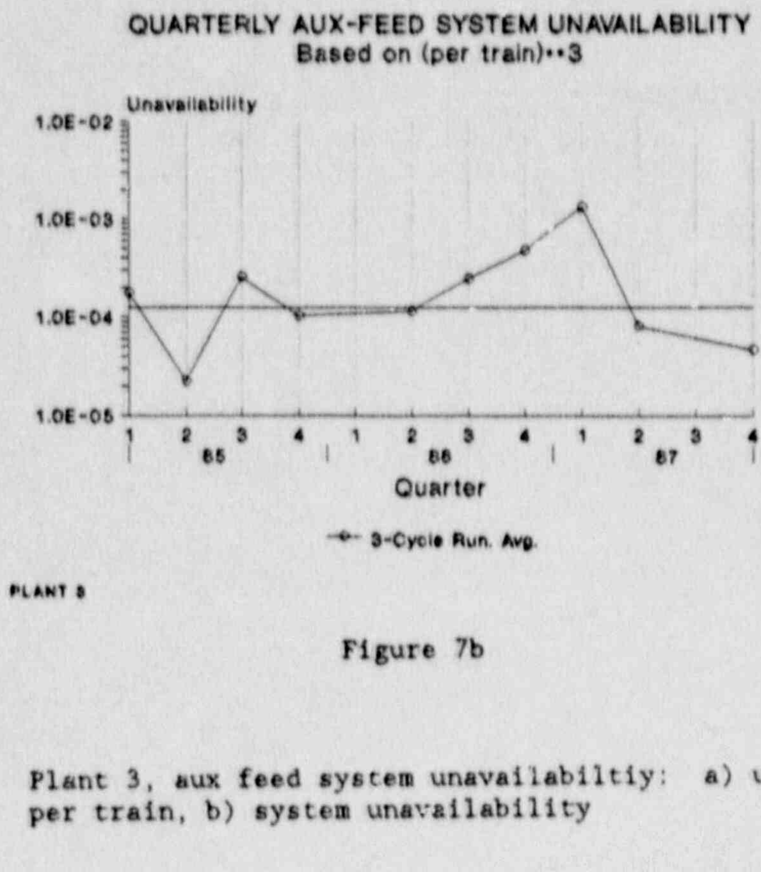


Figure 7b

Figure 7. Plant 3, aux feed system unavailabiltiy: a) unavailability per train, b) system unavailability

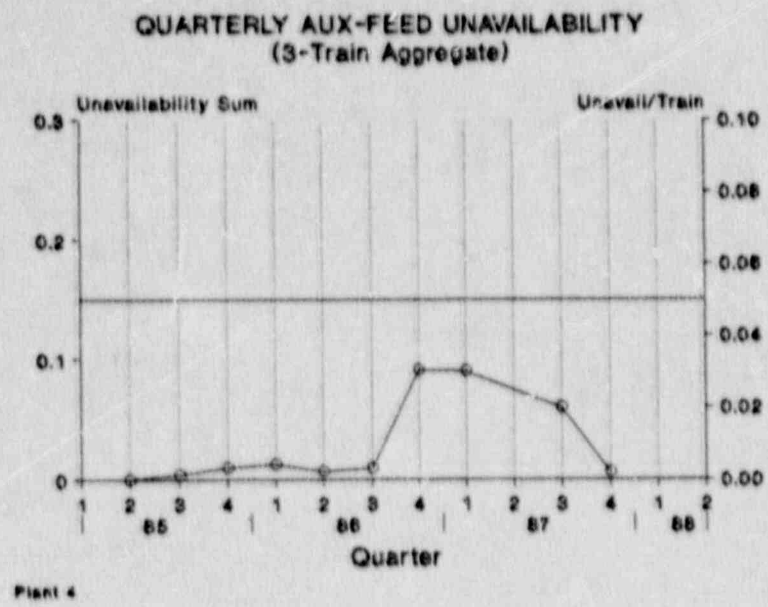


Figure 8a

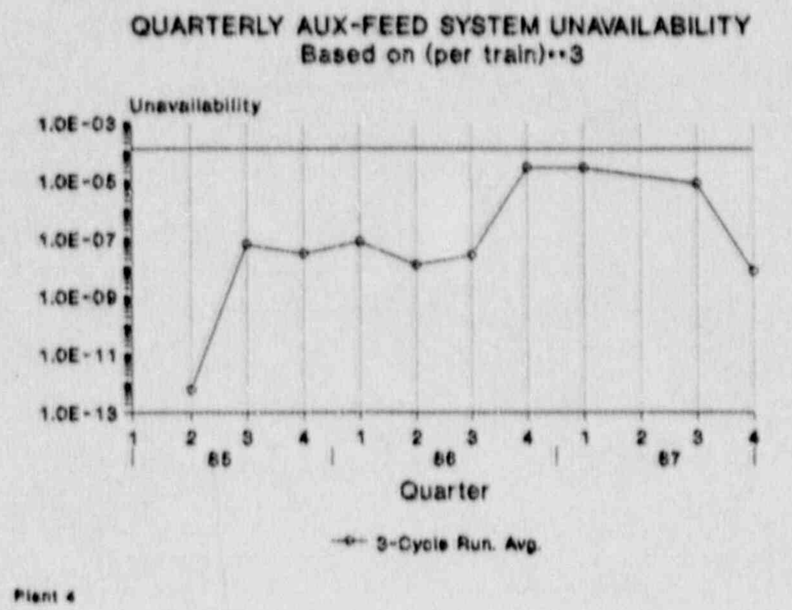


Figure 8b

Figure 8. Plant 4, aux feed system unavailability: a) unavailability per train, b) system unavailability

The AUX-FEED system unavailability for Plant 5 (Figures 9a and 9b) significantly increased over the period from 85-2 to 86-3 though remaining below the tolerance limit.

3.5 Undetected vs Detected Downtime Contributions

The previous results were obtained by including both the undetected downtime contributions and the detected downtime contributions of system components. The undetected downtime is an estimate of the fault-exposure time before the actual fault is discovered. That is, components within standby safety system could have been in a failed state prior to when the component was discovered failed. Therefore, to estimate the total number of hours a component is unavailable, the fault-exposure time is added to the time required for repairing the failed component. This section addresses which of the two contributors, viz., the undetected downtime or the detected downtime, dominate the observed trends.

For each of the plants investigated plots of the undetected and detected downtime contributions were generated for each of the systems analyzed. These are presented in Reference 8. As an example, Figures 10a and 10b show these two contributions for the AUX-FEED system for Plant 2. These figures, along with those presented in Reference 8, indicate that both contributions are important and need to be recorded for establishing significant trends and for helping to determining the underlying factors which contribute to changing performance. The issue of undetected vs detected downtime is further discussed in Section 7.

3.6 Tech Spec Corrected System Unavailability Indicators

The system unavailability indicators in the previous sections can be considered as transformations (squares or cubes) of indicators of train unavailability. Recall, the warning limit in each plot was defined for a single train and was simply scaled for the system plots. Technical specification requirements that do not allow multiple trains to be down for maintenance at the same time are not taken into account by the approach previously described.

In this section, two examples are presented which show how tech spec requirements control system unavailability. Two cases are re-analyzed, i.e., the EPS unavailability for Plant 1 and Plant 2. More details of the approach are discussed in Reference 8.

Briefly, the corrected system unavailability was calculated by first separating the total train downtime per quarter into a maintenance detected downtime and a failure undetected downtime. Train unavailability due to maintenance downtimes was then averaged using the same three-quarter downtime averaging procedure previously described. Since the number of failures observed for these two cases was small, contributions to the corrected system indicator from train failures were simply calculated as the total undetected downtime over the entire recording period divided by the product of the total number of critical hours and the number of trains within the system. Thus, train unavailability due to the observed train failure downtimes contributed a

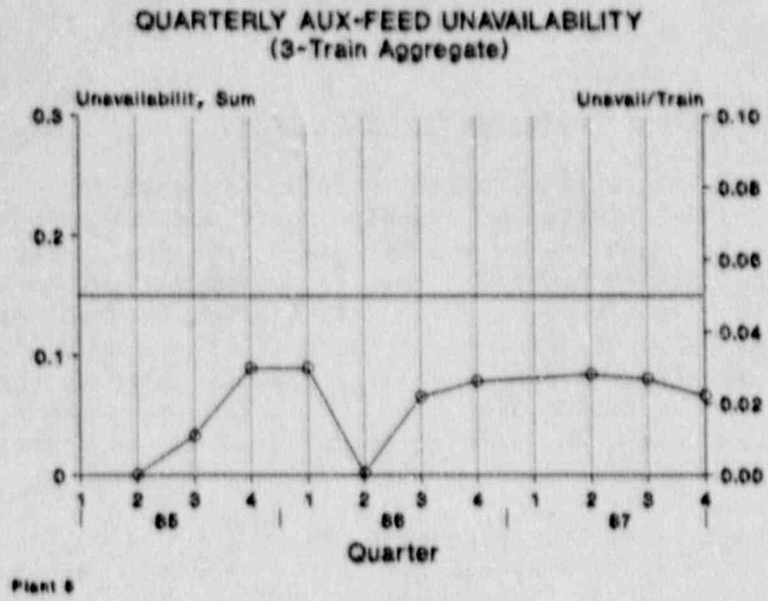


Figure 9a

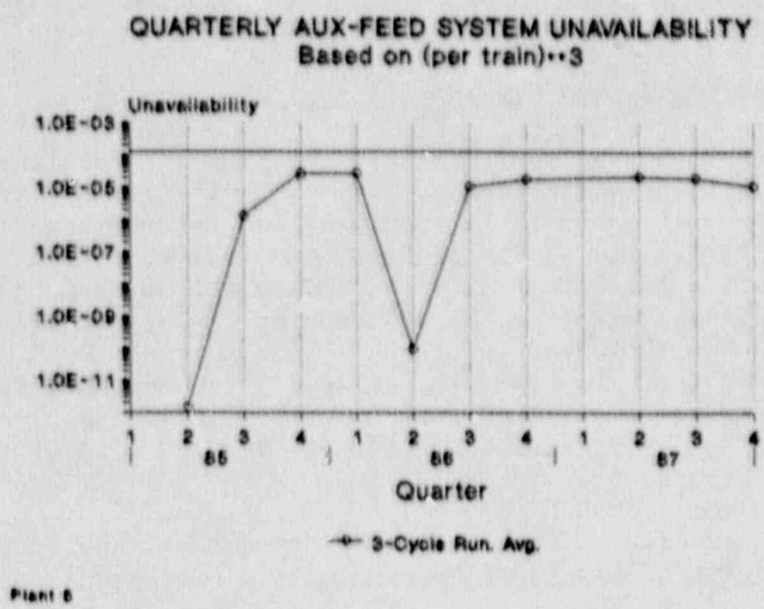


Figure 9b

Figure 9. Plant 5, aux feed system unavailability: a) unavailability per train, b) system unavailability

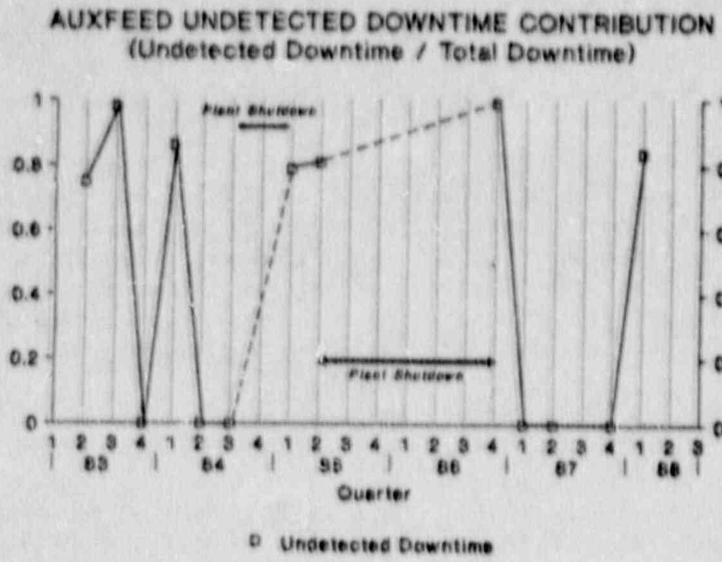


Figure 10a

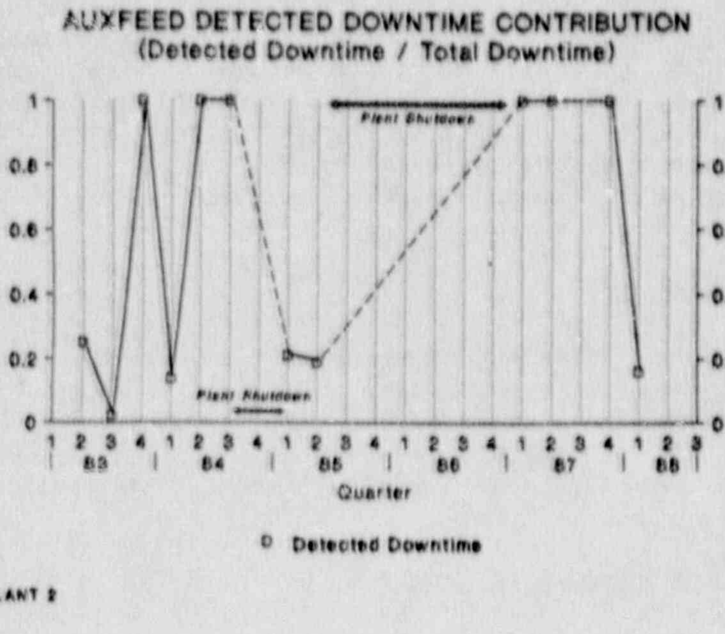


Figure 10b

Figure 10. Plant 2 train downtime contributions: a) undetected downtime, b) detected downtime

constant value to the other factors that measure system unavailability. For a two train system, for example, the corrected system indicator is calculated as the sum of two terms. One term is the square of the train unavailability due to failures; the other is the product of failure contribution to train unavailability with the unavailability contribution due to maintenance.

Figures 11 and 12, taken from Reference 8, respectively summarize the results for the EPS in Plants 1 and 2 obtained by using this procedure to correct for tech spec requirements. Figures 11a and 12a provide comparisons between the corrected system indicator and the uncorrected indicator. The curves noted in each of these two figures as "3-Cycle Run Ave" are the same plots as those presented in Figures 3b and 6b. The curves denoted as "Tech Spec" present the trend in EPS unavailability using the method just described.

Figures 11b and 12b provide representations of the failure and maintenance contributions to the tech spec corrected indicator.

Comparing the two curves in Figures 11a and 12a we observe that the tech spec corrected unavailability indicator shows reduced swings in the unavailability variation. This provides an indication as to how tech spec requirements can control unavailability. In both figures, the same general time trends are shown for each indicator.

The contributions to the corrected, two-train EPS (Plant 1) unavailability indicator shown in Figure 11b shows that the maintenance-failure contribution is the dominant contributor to this system whereas in Figure 12b the contributions from failures and failure-maintenance interactions are nearly equal for the three-train EPS (Plant 2). We conclude from observing this trend that maintenance performed on EPS at Plant 2 is near optimal. Overall, we observe through these two examples that indicators of train unavailability are more responsive in showing performance trends than the tech-spec corrected system unavailability.

3.7 Case Study Summary

In this chapter, five out of the eight case studies were examined. The emphasis in this chapter was on examining relative changes in unavailability, the levels of unavailability observed, the significance of these levels as well as the significance of the observed trends, especially before and after plant shutdowns. Also, the case studies focussed on examining unavailability trends for two systems.

Based upon historical information, Plants 1 and 2 were chosen to address the first two questions posed at the beginning of this chapter, i.e.,

- For a plant where a major operational event occurred, does the indicator show poor or degrading performance before the event, and has performance improved after restart?
- For a plant where performance changed over time. does the indicator show this change?

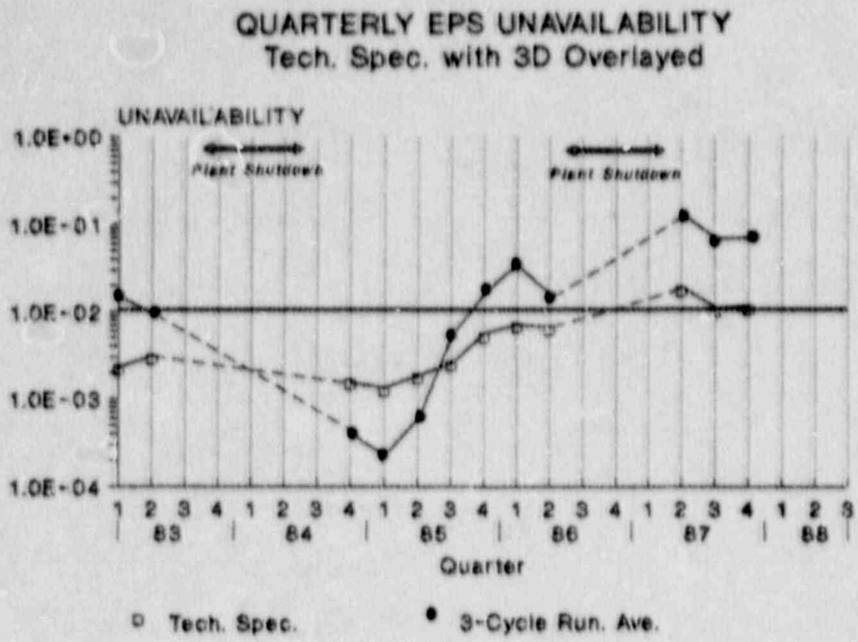


Figure 11a

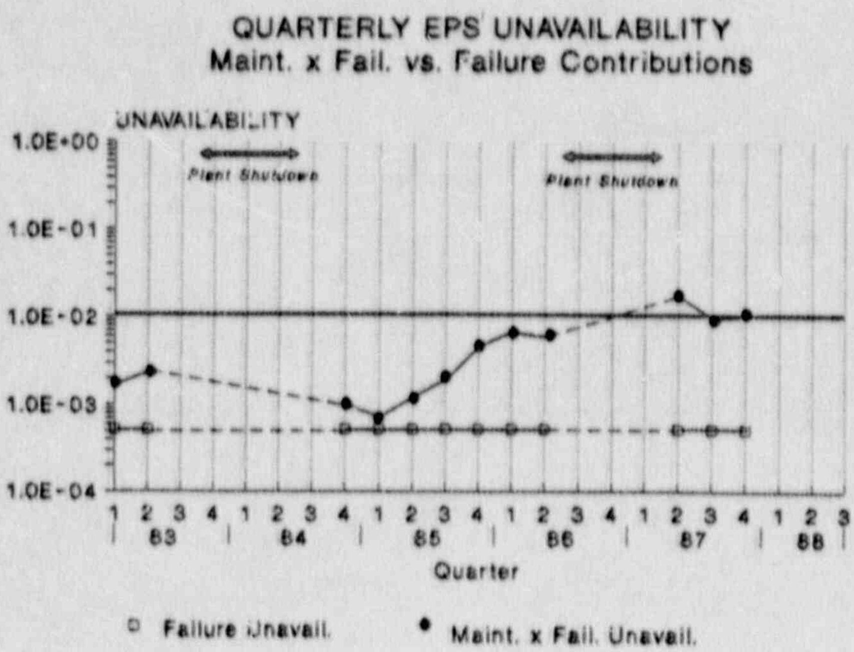


Figure 11b

Note: Data Source: Plant Maintenance work orders

Figure 11. Contributions to EPS unavailability, Plant 1: a) tech spec contributions, b) maintenance and failure contributions

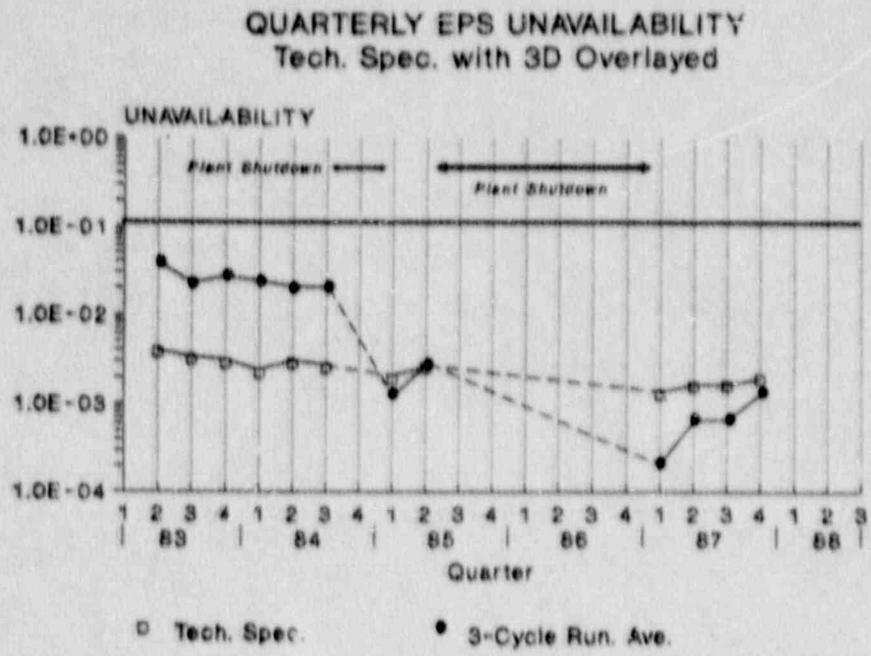


Figure 12a

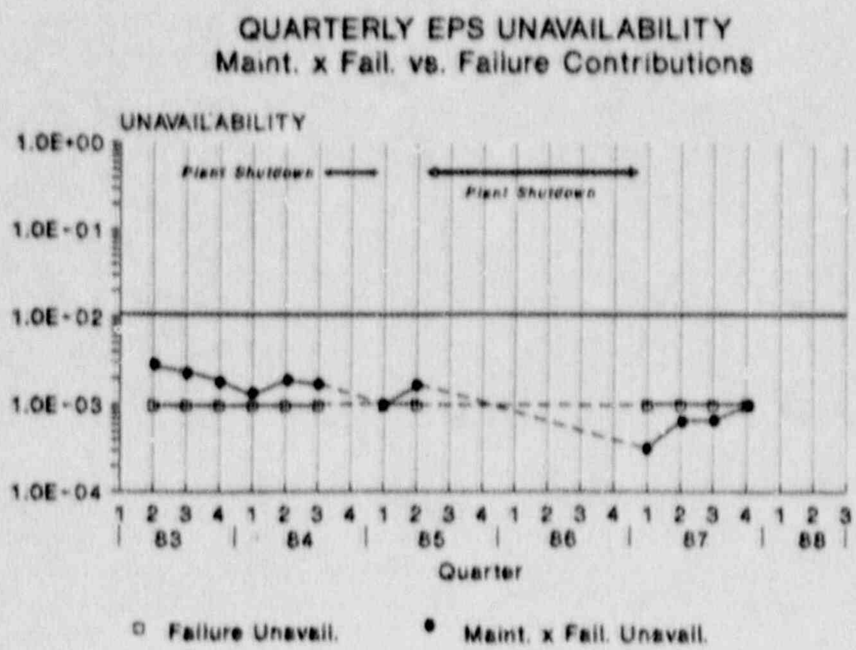


Figure 12b

Figure 12. Contributions to EPS unavailabiltiy, Plant 2: a) tech spec contributions, b) maintenance and failure contributions

Plants 3,4, and 5 appeared to be valid examples for responding to the third question i.e.,

- for a plant with few safety problems, does the indicator reflect generally good performance?

Although answers to each of these three questions cannot be definitively given, the calculated system unavailability indicators for these five plants show an ability to identify significant time trends and to identify those time periods when the unavailability becomes high enough to flag attention.

Since unavailability is a direct factor in the risk and core-melt frequency of a plant, the SSFT indicators are measures of the risk and core-melt frequency performance, particularly when key systems are evaluated. It thus appears that these indicators can provide a sensitive tracking and auditing tool to track and audit key factors of safety performance. Causes associated with significant trends and levels in the unavailabilities that are beyond expected tolerance limits can then be investigated to identify good practices or to identify potential corrective measures for bad practices.

Refinements in the approach, especially in accounting for those unavailability contributions associated with common-cause failures, should be further investigated to obtain more realistic appraisals of system performance. An approach for including common-cause contributions into the model are described in Reference 7. Differences in the results when this factor is included in the statistical simulations is also discussed in Reference 7.

The case studies presented in this report did not take into account the contributions of common-cause failures to system unavailability. Only the effects of independent failures were addressed. The potential usefulness for including the contribution of dependent failures in the unavailability model becomes apparent when we compare the results depicted for Plants 4 and 5 with the results from the other three plants. For the first three plants, system unavailability appears to be dominated by independent failures. However, the low unavailability values exhibited for Plants 4 and 5 lead to the conclusion that common-cause failures could be a dominant contributor to system unavailability. As such, the model should be modified for accounting for this additional contributor.

Based upon the observations made through these case studies, it is therefore recommended that these indicators be pursued further, especially in developing and understanding these indicators as well as in performing further applications using plant data. In addition, the model should be extended to account for all types of failures, dependent as well as independent.

Approximate tolerance bounds were employed in these investigations. It is therefore recommended that procedures be developed for obtaining more accurate representation of the tolerance bounds on safety systems being monitored. This aspect is discussed in a later section.

4. SAFETY SYSTEM FUNCTION TREND INDICATOR VS OBSERVED SAFETY SYSTEM FAILURES

Results of performing exploratory correlation analysis between the SSFT indicator and NRC's current set of performance indicators are discussed in Section 6. The results documented, mainly based on statistical evaluations using Spearman correlation coefficients, were obtained using quarterly-based information on both sets of indicators. Contrary to our expectations, quarterly data for one of the NRC current set of indicators, Safety System Failures (SSFs), did not show a strong correlation with the SSFT indicators. This was retrospectively attributable to the small amount of SSF data, especially when quarterly data is used.

For example, a total of three AFWS and one EPS failures were observed over a period spanning eight years for all the plants* under investigation. This translates to 0.05 AFWS failures per year and 0.03 EPS failures per year. It is, therefore, not surprising that correlation coefficients, based on quarterly data, showed no relationship between the SSFT indicator and the number of SSFs. A simplified approach, described in this section, was used to aggregate system failures in order to investigate relationships between observed system failures and trends in the corresponding SSFT indicator. An application of the approach shows that the unavailability of a selected safety system is directly related to the number of failures of that system, which tends to corroborate the simulations performed in Reference 6 and 7.

Basically, the approach employed examines whether the expected unavailability (SSFT) for a given system correlated with the failures that occurred for the system. In the particular system analyzed, viz., AFWS, the SSFT is based on roughly three years of historical data, while the system failure data were taken from eight years of LER data. This period of eight years was selected because:

1. it was the period for which LERs were available for all the PWR case study plants under investigation, and

2. it was considered to be a sufficient period to observe system failure.

Table 1 is a compilation of the system failures identified through a review of the LERs. Figure 13a depicts a scatter plot of the number of observed system failures versus a three-year average value of the SSFT indicator. (Three years was the average time span of train downtime data common to each plant for the SSFT indicator calculation.)

*Three out of the eight plants use hydro electric power for emergency power and therefore were not included in this survey; similarly, one BWR plant was not included in the AFWS survey.

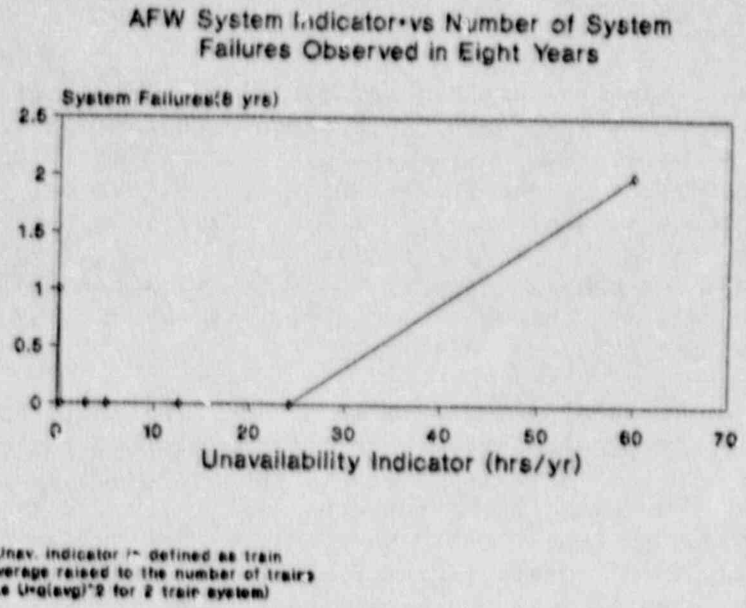


Figure 13a

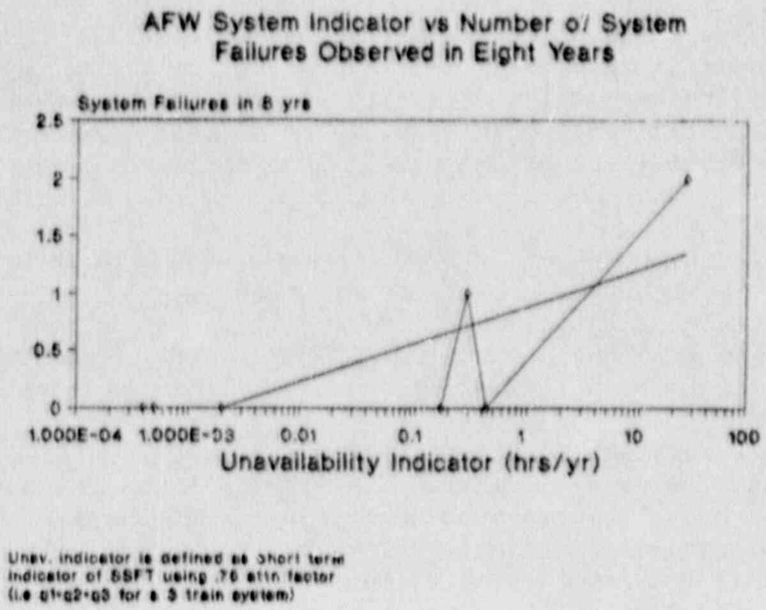


Figure 13b

Figure 13. AWF system unavailabiilty vs observed system failures: a) based on train average, b) based on system model

Table 1. Compilation of Observed System Failures AFWS and EPS; Source: LER

Plant #	AFWS			EPS		
	# Failures	LER#	Date	# Failures	LER#	Date
1	1	002	1-06-82	1	025	6-26-81
2	2	094	12-26-80	0		
		013	6-09-85			
3	0	---	----	N/A	N/A	
4	0	---	----	N/A	N/A	
5	0	---	----	N/A	N/A	
6	N/A	N/A		0	---	
7	0	---		0	---	
8	0	---	----	0	---	

In Figure 13, results are depicted based on AFW system unavailabilities calculated using average train values (Figure 13a) and individual train values (Figure 13b) for each of the seven plants analyzed. In Figure 13a, the behavior of the observed AFW system failures and the calculated AFW system unavailability based on train averages do not seem to be consistent. However, in our judgment there is a consistency when one considers the noise associated with the data. In this calculation of system unavailability the average values are made up of contributions that are dominated by single trains. In Figure 13a for the three plants with system unavailabilities greater than 10 hrs/yr and no observed failures, the turbine driven trains for each plant were the major contributors to the average train unavailability. Calculating the system level unavailability using this method did not correlate as well with the observed system failures obtained from the LER data as compared to the method used to generate Figure 13b.

In Figure 13b, the same observed system failure data are presented but the system unavailability indicator is now based on individual train data and not average train data. In this case, a 0.75 attenuation factor is used along with simplified AFW system model for each of the seven plants (see Appendix B and Reference 7). The results shown in Figure 13b include unavailability calculations using train data for the AFWS of Plant 7. A log-regression line is also shown in Figure 13b indicating a consistent trend between system failures and system unavailability.

The following conclusions can be drawn from these two figures:

1. Both figures show a clear relationship between the observed system failures and the calculated unavailability indicators. Confidence levels based on the randomization process for both figures are above 80%. The confidence level for the proportionality of the SSFT indicator in Figure 13b is as high as 95%.

2. The SSFT indicator using train averaged data did not describe the observed reliability of Plant 7. However, the SSFT indicator using individual train data does account for the behavior of Plant 7's AFWS reliability.

It should be noted that none of the system failures were used in evaluating the SSFT indicators, hence avoiding any possibility of biasing the relationships.

This example tends to validate the hypothesis that the indicator of unavailability for selected safety systems is directly related to the number of failures of those systems. Although more data would be useful in this regard, the performance trends shown in Section 3 also lend credence to the usefulness of this indicator.

5. DETERMINATION OF TOLERANCE BOUNDS

The approach used for validating the indicator of unavailability of selected safety systems is based on three aspects: a theoretical basis, an empirical basis, i.e., statistical correlations, and case studies.

The theoretical concept, based on the assumption that trends and significant changes in the unavailability of safety systems give a direct measure of trends and significant changes in the safety and risk of a plant, was tested through case studies as discussed in Section 3. Observations of plant/system performance drawn from these case studies were made using an approximate 95% tolerance bound value, previously described.

In this section, a less approximate method for obtaining tolerance bounds which was investigated is described and applied to one of the case studies presented in Section 3.

5.1 Tolerance Bound Objectives

Establishment of the tolerance bounds around an indicator aids in its interpretation. It can help in determining which values of indicators are significantly high or low. It also can aid in assessing whether an indicator's behavior is consistent with a given performance goal. There are a variety of ways to define tolerance bounds depending upon the usage and the objective of the study. Two objectives of general interest to this project, and in specifically evaluating indicators for safety system unavailabilities, are to develop tolerance bounds to:

1. show whether the values of the indicator are significantly high or low, at any given quarter, in comparison with built-in design expectation, and

2. provide a measure of the uncertainty (variations) of the indicator in any given quarter. Uncertainty in this context reflects the present performance of the equipment rather than its built-in design value and therefore accounts for such factors as aging, wear-out, improper maintenance, etc.

Tolerance bounds to meet objective (1) are considered useful for screening and identifying abnormally high or low values of an indicator as compared to its built-in design expectation. Tolerance bounds to meet objective (2) facilitate the projection of the indicator behavior into the future (part of the predictor indicator function). This can also be used for investigating whether or not a prescribed performance goal is met.

5.2 Determination of Tolerance Bounds

In this exploratory analysis, we have concentrated on developing tolerance bounds for comparing performance indicators against design expectations. A computer program which is described in Appendix E was developed to estimate these tolerance bounds. The program accepts two input files. A brief description of these files is provided in the following (for more detail, please refer to the cited appendix). The two input files are:

1. Reliability data file: containing the design-based reliability data of the components being monitored. Each record usually consists of the component name, component failure rate information (mean and error factor for log-normal distribution), and the test and maintenance information.

2. Cutset file: containing the cutsets associated with the logic tree for which the indicator is evaluated.

Figure 14 shows the SSFT indicator of an average train of AFWS at Plant 1 (the indicator is similar to the INPO indicator but with an attenuation factor of 0.75). The results show that the AFWS at Plant 1 performed within the bounds of its built-in design reliability in the early stages of the data collection period where the unavailability was below the lower 10% limit. This is not an unexpected result within the first five quarters of calculating the indicator of SSFT. As indicated in Reference 7, when calculating the SSFT using a .75 attenuation factor and quarterly data the instability could last up to five quarters. Similar results can be obtained for other types of indicators studied by this research project. It should be noted that SSFT indicators with an attenuation factor of zero (exactly what INPO calculates) have a 10 percentile lower bound of zero, and 95 percentile upper bound of about the same obtained here. Therefore, with a train-averaged indicator, it would be almost impossible to violate the lower bound regardless of how perfectly the system is operating unless periods longer than a quarter are used.

Based on this preliminary study, the following general conclusions can be made:

1. The developed tolerance bounds for individual trains (or a system composed of one train) based on quarterly data (for a design reliability expected for a typical train in nuclear power plants) is effectively between zero and one for a long period of time. Therefore, monitoring of a single train would not provide information regarding the level of performance (it may provide trend information but not level information).

2. As the number of trains increased and the train indicators are aggregated in some manner, the tolerance bounds would improve (become much narrower). The method of aggregation plays an important role in the width of the tolerance bounds, however, it appears to have secondary effect compared to the number of trains.

3. The use of an attenuation factor is also important in narrowing the tolerance bounds (the higher the attenuation factor the narrower the tolerance bounds). However, as discussed in Reference 7, large attenuation factors would create sluggish behavior therefore minimizing the effect of the local variations.

Further work in the area of tolerance bounds determination for the purpose of screening and prediction is currently planned.

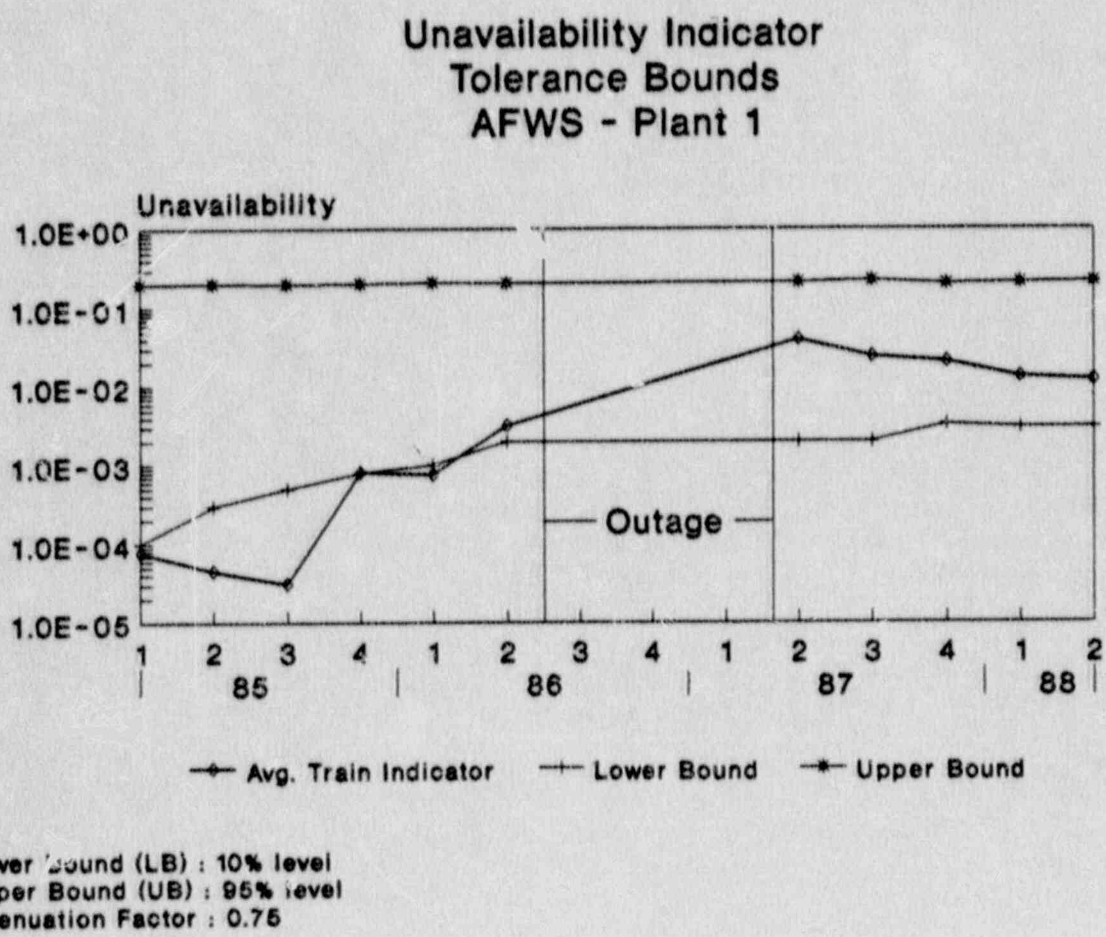


Figure 14. Train unavailability tolerance bounds, Plant 1, AFW system

6. EXPLORATORY STATISTICAL ANALYSIS - CURRENT PIs VS SSFT INDICATOR

The case studies previously discussed pointed out that indicators of system unavailability exhibit sufficient information for identifying those periods when system performance is above or below prescribed tolerance bounds and whether or not trends are significant. It was generally concluded that based upon the five cases studied, measures of system unavailability showed promise for being a responsive indicator of safety system performance and thereby could provide additional information for analyzing overall plant performance as well as helping to assess performance in specific functional areas within the plant, such as maintenance.

In this section, we describe and discuss some of the exploratory statistical analyses that were performed to draw inferences between this indicator and other currently used indicators. Test statistics between the following two sets of indicators were determined using quarterly performance indicator data from the eight plants:

Set 1: Current Performance Indicators:

EFO/1000	Equipment forced outages/1000 critical hours,
SSF	Safety system failures,
SIGE	Significant events,
SSA	Safety system actuations,
FOR	Forced outage rate.

Set 2: Unavailability Indicators

QS(AFW)	Auxiliary feedwater system (AFW) unavailability,
QT(AFW)	Average train unavailability for AFW system,
QS(EPS)	Emergency power system (EPS) unavailability,
QT(EPS)	Average train unavailability of EPS,
QS(HPCI)	High-pressure coolant injection (HPCI) system unavailability,
QS(RCIC)	Reactor core isolation cooling (RCIC) system unavailability, and
QT(AFW&EPS)	Aggregate average train unavailability.

For each of the eight plants, we examined the degree of correlation between these two sets of data. In addition to within-plant correlations, across-plant correlations were also conducted. The results show that little or no correlations exist between the two sets of data. Reasons for this lack of correlation are given and further statistical analysis is recommended.

Also investigated was whether or not the parameters in Set 2 lead or lag the current set of performance indicators, listed in Set 1. This analysis was performed to ascertain whether an indicator of system unavailability provides a leading indicator of plant performance. Recall that the statistical simulations performed[5,7] demonstrated that the system unavailability indicator showed degrading trends sooner than safety system failures. In this context, it should also be noted that the simulations utilized idealized train data. It remains to be proven if such attributes are demonstrable using real, quarterly-averaged, train data, and if not, why.

6.1 Composite Representations Between Sets of Indicators

Figures 15 and 16 are sample presentations of elements within each of the two data sets. Figures 15a and 15b respectively show the unavailability indicator for the AFWS and EPS for Plant 1; Figures 16a and 16b respectively show the average train unavailability for each of these two systems. Each figure presents five plots. In each plot, one of the five current NRC performance indicators (Set 1 list) is superimposed. A complete set of figures for the eight plants are provided in Appendix F. The system unavailability shown was calculated using all past history (Appendix H), and calculations were not re-initialized after shutdowns.

These plots were developed primarily for visual comparison of the two sets of parameters and to ascertain whether or not one can distinguish leading or lagging behaviors between each set of parameters or corresponding trends. Our investigations show that, in general, none are readily apparent nor is there any indication of relationships between trends in the two sets of indicators.

6.2 Lag-Zero Cross-Correlation Results

Table 2 lists the entire collection of within-plant correlation coefficients between contemporaneous indicator values within Set 1 and Set 2. For example, this table reveals that in Plant 1, the correlation between the AFW system unavailability indicator (QS(AFW)) and the equipment forced outage rate indicator (EFO/1000) is 0.274; whereas for Plant 3, the correlation between these two parameters is 0.775. Using the EPS system unavailability indicator (QS(EPS)), similar comparisons for these two plants show a negative correlation. Indeed, the results do not appear interesting. The reasons why are given below with more detail provided in Appendix G.

One drawback to looking at each plant correlation coefficient is that we are inspecting a number of statistics simultaneously in judging the statistical significance of results using quarterly-based information. A correlation coefficient is judged to be statistically significant if it is so far (in absolute value) from zero that the probability of its being this far by accident is, for example, less than 0.05. If we have such an aberrant coefficient, we conclude that it is probably not by accident, and the two parameters are actually related. However, since in this exploratory analysis we are examining a large number of statistics simultaneously, a pair (or several pairs) can show "significance" by accident. The problem we have just alluded to is called the Simultaneous Testing Problem.

For our exploratory analysis, one way to possibly circumvent this problem was to inspect the average of the coefficients across plants rather than the entire collection of coefficients. The average values are listed in Table 3 along with respective measures of significance based on using Fisher's

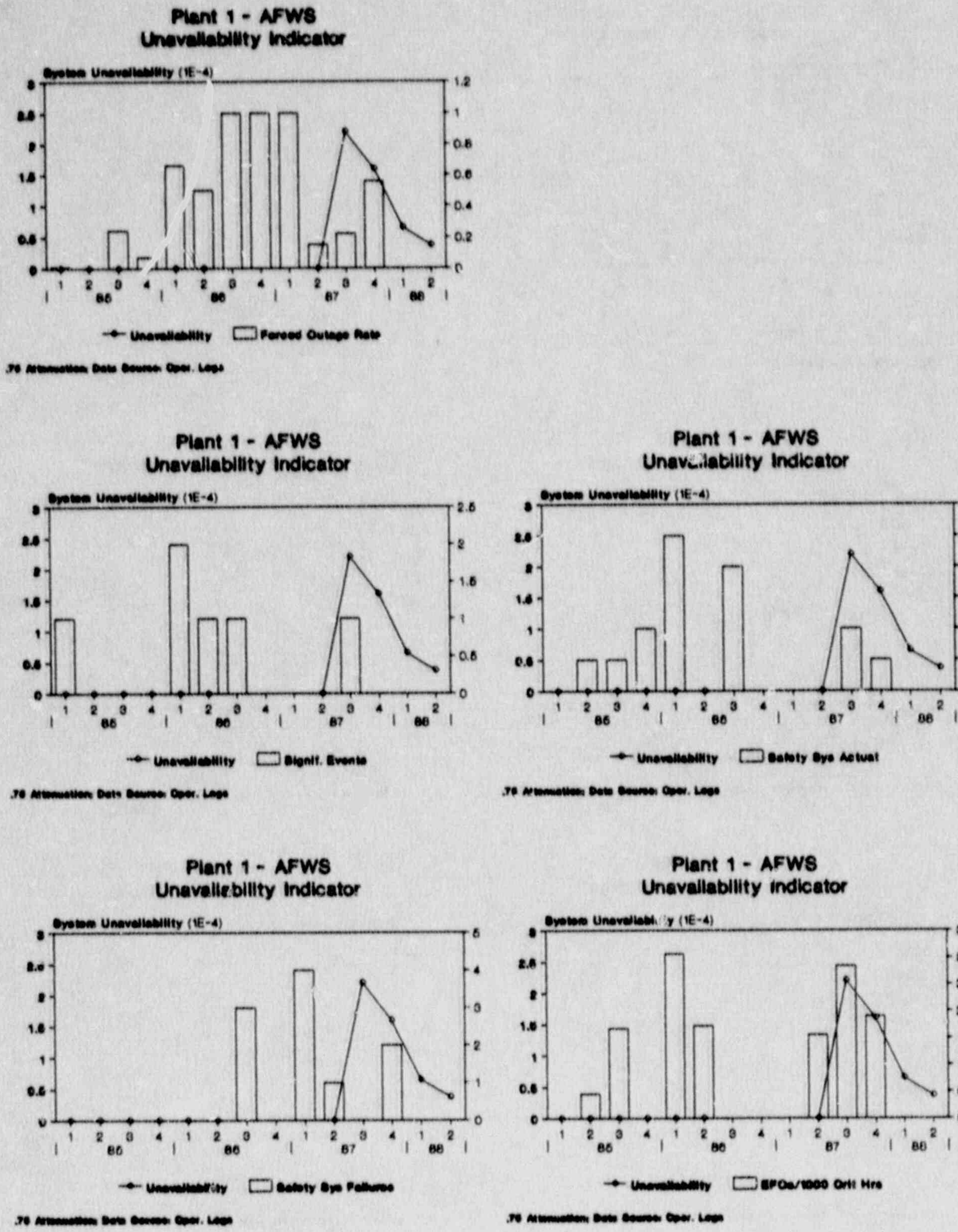
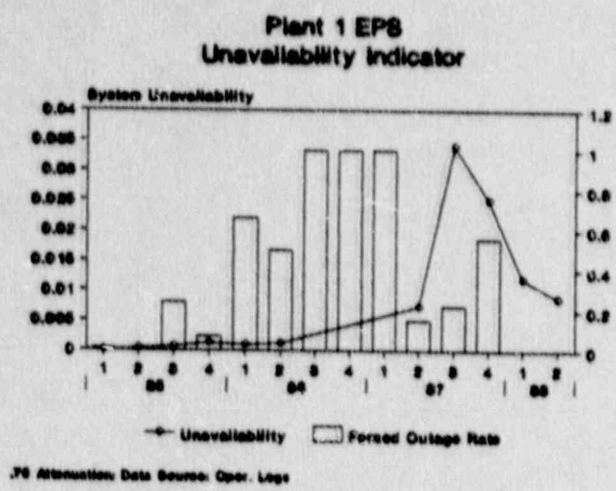
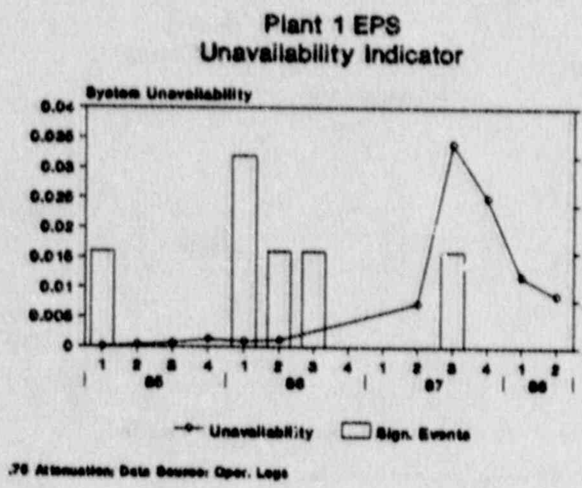
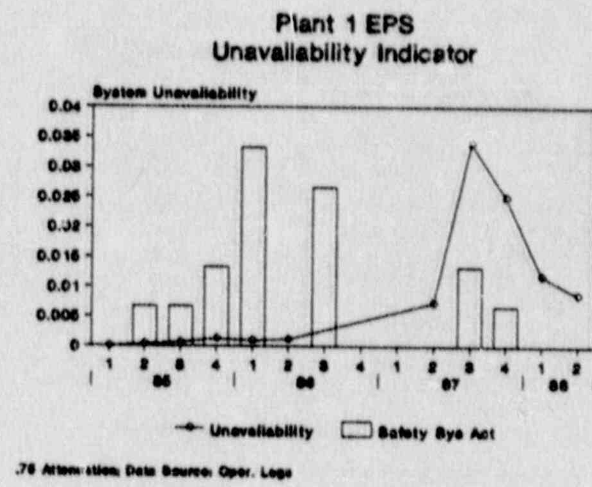
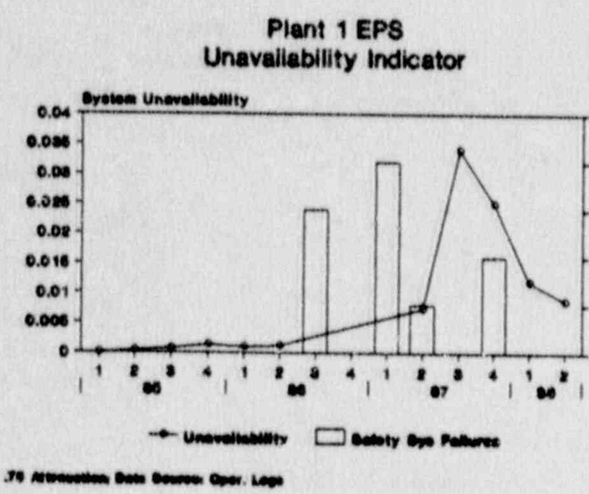


Figure 15a. Plant 1, system unavailability indicators and current performance indicators









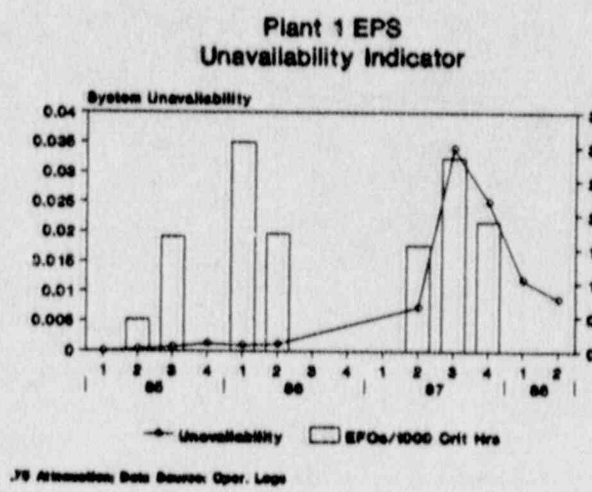


Figure 15b. Plant 1, system unavailability indicators and current performance indicators

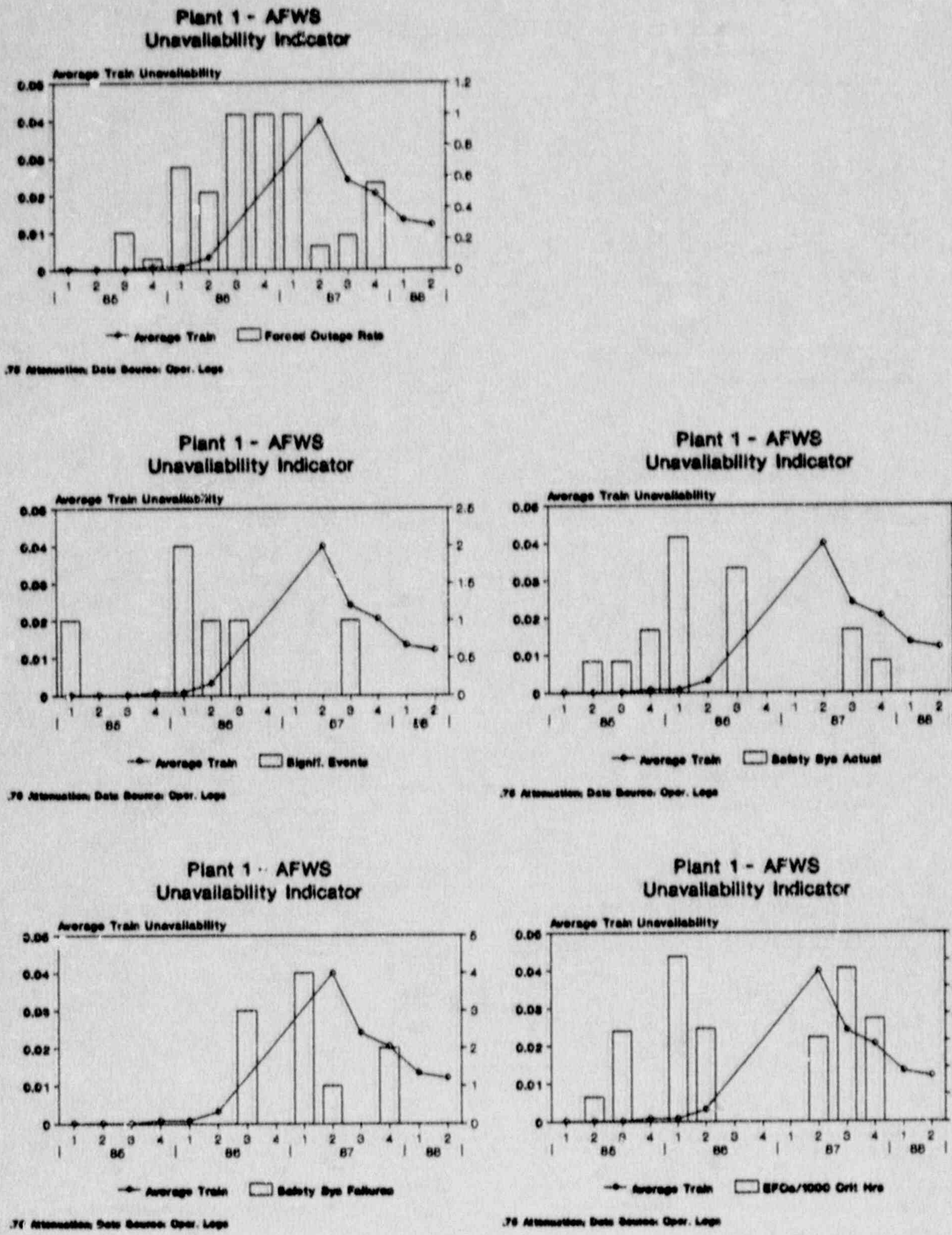


Figure 16a. Plant 1, average train unavailability indicators and current performance indicators

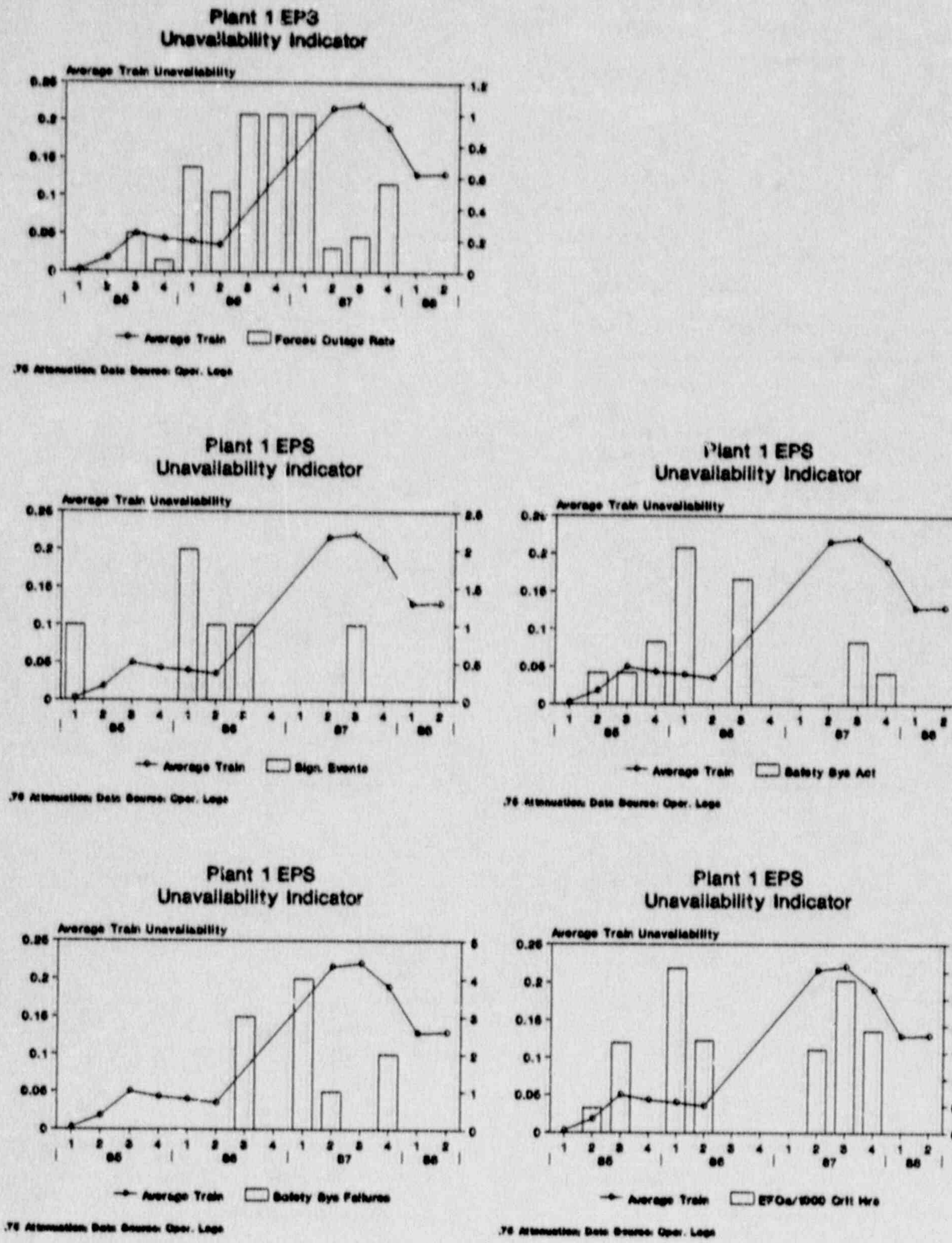


Figure 16b. Plant 1, average train unavailability indicators and current performance indicators

Table 2. Lag-Zero Cross-Correlation (Within Plant)

Plant		QS(AFW)	QT(AFW)	QS(EPS)	QT(EPS)	QS(HPCI)	QS(RCIC)	QT(AFW+EPS)
1	EFO/1000	0.274	0.004	-0.119	0.188	N/A	N/A	0.158
	SSF	-0.143	-0.321	-0.216	0.021	N/A	N/A	-0.095
	SIGE	0.245	-0.066	-0.339	-0.182	N/A	N/A	-0.178
	SSA	0.129	-0.246	0.034	0.030	N/A	N/A	-0.063
	FOR	-0.193	-0.576	-0.436	-0.375	N/A	N/A	-0.519
2	EFO/1000	-0.020	-0.064	-0.099	-0.121	N/A	N/A	-0.097
	SSF	0.335	0.124	0.002	-0.105	N/A	N/A	0.073
	SIGE	0.867	0.711	0.908	0.791	N/A	N/A	0.734
	SSA	-0.018	-0.171	-0.123	-0.183	N/A	N/A	-0.212
	FOR	-0.418	-0.556	-0.337	-0.448	N/A	N/A	-0.638
3	EFO/1000	0.775	0.482	N/A	N/A	N/A	N/A	N/A
	SSF	-0.198	0.169	N/A	N/A	N/A	N/A	N/A
	SIGE	-0.257	-0.359	N/A	N/A	N/A	N/A	N/A
	SSA	0.000	0.000	N/A	N/A	N/A	N/A	N/A
	FOR	0.258	0.217	N/A	N/A	N/A	N/A	N/A
4	EFO/1000	-0.025	-0.066	N/A	N/A	N/A	N/A	N/A
	SSF	-0.161	0.299	N/A	N/A	N/A	N/A	N/A
	SIGE	0.522	0.554	N/A	N/A	N/A	N/A	N/A
	SSA	0.166	-0.214	N/A	N/A	N/A	N/A	N/A
	FOR	0.695	0.077	N/A	N/A	N/A	N/A	N/A
5	EFO/1000	-0.011	-0.053	N/A	N/A	N/A	N/A	N/A
	SSF	-0.211	-0.251	N/A	N/A	N/A	N/A	N/A
	SIGE	0.328	0.181	N/A	N/A	N/A	N/A	N/A
	SSA	-0.264	-0.201	N/A	N/A	N/A	N/A	N/A
	FOR	-0.230	-0.235	N/A	N/A	N/A	N/A	N/A
6	EFO/1000	N/A	N/A	0.333	0.684	-0.057	-0.089	N/A
	SSF	N/A	N/A	-0.501	-0.450	-0.487	0.599	N/A
	SIGE	N/A	N/A	0.000	0.000	0.000	0.000	N/A
	SSA	N/A	N/A	-0.426	-0.336	-0.318	0.131	N/A
	FOR	N/A	N/A	0.635	0.514	-0.204	-0.025	N/A
7	EFO/1000	-0.414	0.007	-0.415	-0.792	N/A	N/A	-0.383
	SSF	-0.454	-0.550	0.577	0.043	N/A	N/A	-0.479
	SIGE	-0.262	0.051	-0.275	-0.815	N/A	N/A	-0.355
	SSA	0.031	-0.205	-0.260	0.243	N/A	N/A	-0.067
	FOR	-0.279	-0.034	-0.2[illegible]4	-0.837	N/A	N/A	-0.442
8	EFO/1000	0.000	-0.159	0.000	-0.161	N/A	N/A	-0.159
	SSF	0.000	-0.150	0.000	-0.155	N/A	N/A	-0.151
	SIGE	0.000	-0.227	0.000	-0.196	N/A	N/A	-0.217
	SSA	0.000	-0.219	0.000	-0.171	N/A	N/A	-0.205
	FOR	0.000	0.737	0.000	0.740	N/A	N/A	0.739

Key: QS()= System Unavailability; QT()= Train Avg. Unavailability ; N/A= Not Applicable

z-transformation. The results shown in this table tend to confirm that determining correlations between contemporaneous, quarterly-averaged information is not the way to investigate relationships between these two sets of performance data. We presented these results for completeness and document the approach in Appendix G.

These negative findings are presented to show that because of the relatively noisy nature of the variables, different statistical approaches for finding relationships between and amongst the risk-based indicators and the current set of performance indicators need to be explored. This research project will be exploring different approaches.

Table 3. Lag Zero Cross Correlations (Across-plant)

	Average r Values						
	QS(AFW)	QT(AFW)	QS(EPS)	QT(EPS)	QS(HPCI)	QS(RCIC)	QT(AFW+EPS)
EFO/100	0.0611	0.0216	-0.075	-0.0408	-0.0567	-0.0889	-0.1203
SSF	-0.1379	-0.0882	-0.0346	-0.1228	-0.4875	0.5988	-0.167
SIGE	0.3022	0.2317	0.0984	-0.0689	N/A	N/A	0.0672
SSA	-0.0213	-0.2074	-0.1936	-0.0616	-0.3178	0.1307	-0.1138
FOR	0.0051	-0.0528	-0.1057	-0.0811	-0.204	-0.025	-0.2151
	Heterogeneity Test						
	QS(AFW)	QT(AFW)	QS(EPS)	QT(EPS)	QS(HPCI)	QS(RCIC)	QT(AFW+EPS)
EFO/100	0.0545	0.8503	0.7243	0.1046	N/A	N/A	0.8452
SSF	0.6148	0.5297	0.3604	0.8272	N/A	N/A	0.7198
SIGE	0.0018	0.0822	0.0001	0.0007	N/A	N/A	0.0202
SSA	0.8279	0.9984	0.8868	0.8026	N/A	N/A	0.9014
FOR	0.0391	0.0302	0.1008	0.0064	N/A	N/A	0.0055
	Test Against Zero Correlation						
	QS(AFW)	QT(AFW)	QS(EPS)	QT(EPS)	QS(HPCI)	QS(RCIC)	QT(AFW+EPS)
EFO/100	0.0694	0.9094	0.8357	0.1754	0.899	0.842	0.9099
SSF	0.6886	0.6288	0.4949	0.8603	0.2335	0.1222	0.8049
SIGE	0.0004	0.0671	0.0001	0.0022	N/A	N/A	0.0342
SSA	0.9225	0.8559	0.8392	0.881	0.4617	0.7688	0.904
FOR	0.0704	0.0424	0.1452	0.0112	0.6436	0.9554	0.0046

Key: QS()= System Unavailability; QT()= Train Avg. Unavailability ; N/A= Not Applicable

6.3 Non Zero-Lag Cross Correlation Results

In attempting to ascertain whether indicators within each set lead or lag indicators in the other set, analyses were performed using pairs (Set 1 parameters vs Set 2 parameters) of data where one element in Set 2 lagged or led one element in Set 1 by 1, 2, 3, and 4 quarters. Tables 4 and 5 present similar information as contained respectively in Tables 2 and 3, but for this

Table 4. Lag Minus-Four Cross-Correlation (Within Plant)

Plant		QS(AFW)	QT(AFW)	QS(EPS)	QT(EPS)	QS(HPCI)	QS(RCIC)	QT(AFW+EPS)
1	EFO/1000	0	0.6085	-0.3495	-0.4626	N/A	N/A	0.2121
	SSF	0	0.0539	0.2366	0.5964	N/A	N/A	0.3658
	SIGE	0	0.4084	0.0193	-0.0834	N/A	N/A	0.1411
	SSA	0	0.4236	0.1595	0.012	N/A	N/A	0.3307
	FOR	0	0.2918	0.6304	0.7751	N/A	N/A	0.6482
2	EFO/1000	-0.1799	-0.2147	-0.1763	-0.2238	N/A	N/A	-0.2761
	SSF	-0.2413	-0.3146	-0.2249	-0.2565	N/A	N/A	-0.3828
	SIGE	-0.2382	-0.2122	0.1191	0.0794	N/A	N/A	-0.1404
	SSA	0.4605	0.2129	-0.2687	-0.2239	N/A	N/A	0.1173
	FOR	0.3518	0.0189	-0.2393	-0.059	N/A	N/A	-0.0034
3	EFO/1000	-0.3697	-0.1104	N/A	N/A	N/A	N/A	N/A
	SSF	-0.3565	-0.3717	N/A	N/A	N/A	N/A	N/A
	SIGE	-0.2521	-0.5008	N/A	N/A	N/A	N/A	N/A
	SSA	0	0	N/A	N/A	N/A	N/A	N/A
	FOR	-0.2997	-0.164	N/A	N/A	N/A	N/A	N/A
4	EFO/1000	0.8982	-0.1749	N/A	N/A	N/A	N/A	N/A
	SSF	-0.2867	-0.2889	N/A	N/A	N/A	N/A	N/A
	SIGE	-0.1889	-0.2113	N/A	N/A	N/A	N/A	N/A
	SSA	-0.2756	-0.2887	N/A	N/A	N/A	N/A	N/A
	FOR	0.2928	-0.4637	N/A	N/A	N/A	N/A	N/A
5	EFO/1000	-0.367	-0.3335	N/A	N/A	N/A	N/A	N/A
	SSF	-0.2672	-0.3543	N/A	N/A	N/A	N/A	N/A
	SIGE	-0.3166	-0.2766	N/A	N/A	N/A	N/A	N/A
	SSA	-0.2185	-0.3032	N/A	N/A	N/A	N/A	N/A
	FOR	-0.2045	-0.2646	N/A	N/A	N/A	N/A	N/A
6	EFO/1000	N/A	N/A	-0.3696	0.7917	-0.2188	-0.14	N/A
	SSF	N/A	N/A	-0.1291	-0.1356	0.3475	-0.462	N/A
	SIGE	N/A	N/A	0	0	0	0	N/A
	SSA	N/A	N/A	0.8482	-0.2932	-0.712	0.8044	N/A
	FOR	N/A	N/A	-0.0395	0.688	-0.4668	0.198	N/A
7	EFO/1000	0.2654	0.0002	-0.8635	0.7243	N/A	N/A	0.1131
	SSF	0.3653	-0.4883	-0.6084	-0.4578	N/A	N/A	-0.7295
	SIGE	-0.2747	-0.2966	-0.2548	0.1566	N/A	N/A	-0.2731
	SSA	0.6389	0.7917	-0.5774	-0.5605	N/A	N/A	0.7477
	FOR	-0.1314	-0.1252	-0.6803	0.9257	N/A	N/A	0.0123
8	EFO/1000	0	0	0	0	N/A	N/A	0
	SSF	0	0	0	0	N/A	N/A	0
	SIGE	0	1	0	0.999	N/A	N/A	0.9999
	SSA	0	0	0	0	N/A	N/A	0
	FOR	0	0.9601	0	0.2943	N/A	N/A	0.5354

Key: QS()= System Unavailability; QT()= Train Avg. Unavailability ; N/A= Not Applicable

Table 5. Lag Minus-Four Cross-Correlations (Across Plant)

Average r Values

	QS(AFW)	QT(AFW)	QS(EPS)	QT(EPS)	QS(HPCI)	QS(RCIC)	QT(AFW+EPS)
EFO/100	0.0494	-0.0321	-0.4397	0.1659	-0.2188	-0.14	0.0123
SSF	-0.1573	-0.294	-0.1814	-0.0634	0.3475	-0.462	-0.2488
SIGE	-0.2564	-0.0335	-0.0388	0.0509	N/A	N/A	-0.0908
SSA	0.1513	0.1673	0.0404	-0.2664	-0.712	0.8044	0.3986
FOR	0.0018	0.0362	-0.0822	0.5248	-0.4668	0.198	0.2981

Heterogeneity Test

	QS(AFW)	QT(AFW)	QS(EPS)	QT(EPS)	QS(HPCI)	QS(RCIC)	QT(AFW+EPS)
EFO/100	0.015	0.3371	0.8926	0.2589	N/A	N/A	0.7046
SSF	0.8344	0.9558	0.5656	0.0738	N/A	N/A	0.0906
SIGE	0.794	0.2851	0.8689	0.9193	N/A	N/A	0.7762
SSA	0.3159	0.3916	0.3759	0.9437	N/A	N/A	0.8574
FOR	0.6308	0.3714	0.0644	0.091	N/A	N/A	0.2195

Test Against Zero Correlation

	QS(AFW)	QT(AFW)	QS(EPS)	QT(EPS)	QS(HPCI)	QS(RCIC)	QT(AFW+EPS)
EFO/100	0.0271	0.4465	0.4522	0.3775	0.824	0.8879	0.843
SSF	0.7267	0.657	0.6703	0.1346	0.6081	0.4796	0.1423
SIGE	0.6877	0.4695	0.9633	0.9803	N/A	N/A	0.9058
SSA	0.4133	0.4343	0.5388	0.8998	0.3728	0.2666	0.4959
FOR	0.7536	0.4751	0.1161	0.0094	0.6129	0.841	0.1404

Key: QS()= System Unavailability; QT()= Train Avg. Unavailability ; N/A= Not Applicable

case, the "row" variables lead the "column" variables by 4 quarters (one year) as identified in the tables by the "lag minus-four" description. A complete set of tables is provided in Appendix G.

The tables of across-plant averages (Tables 3 and 5 and similar ones in Appendix G) represent some compression of results but not enough to resolve the simultaneous testing issue discussed in Appendix F. We restricted our investigation further by comparing the Set 2 variables with only the SSF variable in Set 1 and only looking at those values when the unavailability indicators (Set 2) lead the SSF indicator. This results in 20 statistics. Inspection of the tests for "heterogeneity" reveals significance values ranging from 0.09 to 0.96 whereas the significance for "tests against zero correlation" range from 0.09 to 0.86. Considering the number of statistics investigated, these significance values are also uninteresting for similar reasons as those noted previously.

7. DATA ANALYSIS: LESSONS LEARNED

In this section, we highlight some of the lessons learned through the course of this study. We provide our assessment of the data collection process, our judgments as to why we focussed on specific systems, and the viability of other data sources besides the records archived at plants. We also amplify why we consider it important to include undetected downtime in the calculations for the SSFT indicator and why we chose the averaging schemes employed instead of other average approaches such as those presently employed in trending the current set of performance indicators.

7.1 Data Collection Process: Lessons Learned

The results presented in the report are based on examining approximately 25 plant years of operating data. These data were largely culled from reading the operators' logs at eight plants. Primary emphasis was in extracting downtime information for trains within specific safety systems. Where possible, information within operators' logbooks and LCO logbooks were supplemented with the plant's maintenance work requests (MWRs), Technical Specifications and system diagrams, as well as reliability data each plant provides through the NPRDS, and performance data each plant gives INPO. Data from the NRC's current performance indicator tracking databases were also employed in this analysis.

Extracting train downtime information from operator daily logbooks was a tedious process, especially when information had to be obtained from the plant's archives. Because each plant has its own way for maintaining and recording information, and since each operator within a plant has his own style of inputting daily plant status, the data collection process and analysis had to be geared to each plant's mode of operation. As such, the quality of data extracted and the subsequent analysis may not have been as consistent as one would like.

Data collection difficulties notwithstanding, the results obtained using indicators of safety system unavailabilities appear to provide a meaningful tracking and auditing tool. Causes for changing performance of selected safety systems can be investigated to identify the underlying reasons.

7.2 Systems Trended: Lessons Learned

During this validation process, we also found that investigating two or three systems (e.g., for PWRs: EPS, AFWS, and possibly HPI service water; for BWRs: EPS, HPCI, RCIC, and perhaps Residual Heat Removal) was sufficient for validating the indicator and ascertaining significant trends. For the other important safety systems proposed in SECY 88-103, the train failures occurred too infrequently to provide useful trends.

7.3 Data Sources: Lessons Learned

To possibly circumvent the tedious data collection process and to help plan an implementation strategy for trending the SSFT indicator in the future, this project also explored the usefulness of employing industry's component failure reporting system, NPRDS, as the prime source of downtime information. Although comparative results obtained from using NPRDS in lieu of plant records are not conclusive, several concerns in using NPRDS have been raised throughout the course of this study. Foremost is the concern that not all utilities report regularly to the NPRDS, although the number and quality of reports has been increasing. Another concern is the accuracy of the restoration time reported to NPRDS, which is critical for determining the downtimes of safety system trains. A few of the recorded restoration times seem inordinately high. Also, it was sometimes difficult to extract from the NPRDS narrative an indication of the component or system train associated with the particular event. On the contrary, operators' logs identify when components/trains within safety systems are down in order to help plant personnel manage and control requirements imposed through Technical Specifications. However, sometimes operators' logs were unclear as to whether component failures were severe enough to cause loss of train function. Further work involving the use of NPRDS as a source of data for calculating the SSFT indicator is currently planned along with collecting data from plants that maintain particularly good equipment histories.

Comparisons between the SSFT indicator and INPO's Safety System Performance (SSP) indicator are also inconclusive, largely due to the short time period since INPO implemented the SSP indicator. In some instances, plant records containing data for calculating the SSP indicator, which were subsequently given to INPO, were inconsistent, largely in estimating the undiscovered downtime of safety system trains. Our results have shown that undiscovered downtime can be as important an ingredient as the observed downtime in determining significant trends and levels in system performance.

However, examination of the usefulness of INPO's approach for calculating safety system performance is currently planned. Retrogressive analyses will be performed, and comparisons in trends between the SSFT and SSP indicators will be made utilizing data at those plants that are considered to have particularly good records on equipment histories.

7.4 Uncertainties in Determining Undetected Downtime Contributions: Lessons Learned

In our calculations observed train failures were assumed to have occurred midway between the time period the train was last observed to be operational and the time it was discovered failed. Usually, this downtime period was equated to one-half the surveillance test interval imposed by tech spec requirements on specific components whose failure would render the train of the system inoperable. Granted, this piece of information on standby components cannot be extracted from "hard" data. However, by assuming the train failed midway between demands placed on this train (operational demands or test demands) we are employing in the calculation procedure for the indicator a measure of the expected value of the time of failure that assumes the probability of failure within the interval is small (e.g., less than 0.1). The same approach is normally used in reliability/unavailability analyses and hence the approach is consistent with the usage of the data employed. There are those who may question the use of observed data, (e.g., numbers of component failures, the time taken to repair components, etc.) with assumed (not observed) information, e.g., the overall time a standby component may have been in a failed state prior to failure discovery (i.e., the undetected downtime). However, we consider it extremely important to include undetected downtime associated with failures, even if it has to be provided as an estimate to an expected value. If this additional factor was not included with measurable downtimes, then failures would be counted equally as other maintenance/test activities in determining train/system unavailabilities. We feel that this would not only give an incorrect unavailability measure, but it would also penalize the benefits ascribed to maintenance. From a trending point of view, maintenance downtimes will tend to convey the same deleterious effect on system unavailability as failures. In our judgment, penalizing maintenance activity (maintenance downtime for predictive, preventive, and corrective actions) is not only incorrect but it can have potentially the negative effect of causing maintenance to be reduced when it should not be reduced, assuming a system performance trending strategy were in place. Preventive maintenance downtime trends would have the same effect in assessing unavailability as times required to repair components.

But, if undetected downtimes are included for failures and trended accordingly, contributions from failure occurrences would be more heavily weighted then contributions due to maintenance activities. This is because total downtime due to failures (detected plus undetected) is generally much larger than the downtimes associated with maintenance and the undetected contribution is generally larger than the detected contribution. By performing maintenance regularly and effectively, failures are reduced and hence unavailability is reduced. It is only when the maintenance downtime becomes inordinately large (as compared to the total failure downtime) that maintenance dominates the unavailability thereby providing an indication of ineffective maintenance.

7.5 Averaging Procedures Employed: Lessons Learned

In Section 3, a three-downtime quarter averaging procedure was employed for calculating and trending the SSFT indicator. Recall that this entailed the formulation of a running average indicator where past history covered the previous three yearly quarters that contained non-zero downtimes for a system train. The unavailability is calculated by dividing the downtime in these past three quarters or however many quarters are required to have three quarters of non-zero downtime, by the cumulative critical operating hours. This downtime quarter-cycle averaging process is a modification of an approach described in Reference 6. Other averaging schemes, using one- and two-downtime quarters were explored and discussed in Reference 8. Also reported in this reference are system unavailability trends, obtained by taking one quarter and four quarter run averages regardless of whether quarters contained train downtimes. All these averaging approaches utilized the same data listed in Appendix H. The results presented show that indicators which average downtimes (i.e., cycle-based) are better for smoothing than indicators which simply average quarters (e.g., four quarter running average). Comparing one-cycle, two-cycle, and three-cycle results indicate that the three-cycle scheme exhibits the best compromise for smoothing the observations without masking out significant trends in the indicator of system unavailability. Of course, when there are few quarters with zero downtimes, then the cycle-based indicator yields nearly the same results as the quarter running average indicator.

8. SUMMARY/CONCLUSIONS

This report is a summary of work conducted on the validation of the safety system function trend (SSFT) indicator. This indicator provides a measure of the unavailability of important safety systems and is considered to be more responsive than just counting those instances of complete system inoperability.

Validation of this indicator of unavailability for selected safety systems has been based on three aspects:

- a theoretical basis, employing risk and reliability approaches, which show that this indicator can be directly tied to plant safety performance,
- an empirical basis, employing powerful statistical tests and data smoothing techniques for analyzing significant trends and levels for alert, and
- case studies which resorted to analyzing approximately 25 plant years of historical data on equipment performance.

The case studies in Section 3 have shown that indicators of unavailability of important safety systems convey a significant amount of information through their magnitude and their ability to identify significant time trends. The capability of the indicator is encouraging and appears to provide a meaningful tracking and auditing tool for evaluating key factors of plant safety performance. In Section 4, an example calculation is presented which shows that the SSFT indicator for a selected safety system correlates with the number of failures of that system.

The inclusion of both discovered and undiscovered downtime in the approach is considered valid; it has been shown that undiscovered downtime can be a significant contributor to unavailability. If undiscovered downtime were not included, then downtimes due to component failures will essentially have the same weight as downtimes due to preventive maintenance. We conclude that if such an indicator (not including undiscovered downtime contributions) were implemented then the purpose of performing maintenance would be lost since downtimes and frequencies associated with preventive maintenance activities have equal weight in the indicator calculations as unavailability contributions associated with repair of failed components.

Because the SSFT indicator is risk-based, corresponding tolerance bounds can be determined that also have a risk basis. Sections 3 and 5 highlight how these tolerance bounds can be calculated based on risk measures which thereby provide a framework for interpreting the observed levels in system unavailability. For example, one of the case study plants shows the SSFT indicator trend and level for several quarters before and after an event involving loss of feedwater. Before the event, the level of the average train unavailability for AFWS was well above the tolerance bounds for this system. We conclude that this kind of indication over the several quarters could have triggered some corrective action to be taken if this information had been monitored. In another case study example, the SSFT indicator shows that system performance has improved. In particular, actions taken by Plant 1 after a major shutdown beginning in the second quarter of 1986 seem to corroborate improving trends depicted by the SSFT indicator.

Causes of significant trends and causes of high estimates of system unavailabilities beyond tolerance values can then be investigated to identify practical corrective measures, or conversely, sound engineering practices.

Correlations between the SSFT indicator and the set of indicators currently trended by NRC, as discussed in Section 6, produced uninteresting results. This was largely due to the type of analysis performed in attempting to develop correlations using quarterly averaged information for both sets of indicators. We recommend that different statistical approaches, possibly using non-parametric statistics, be further explored as was done in Reference 9.

Lessons were also learned as a result of the effort spent in collecting plant historical data, in analyzing that data, and in examining the utility and practicality of other data sources, such as NPRDS. Indeed, the process required for collecting and analyzing historical data from plant records was found to be tedious. However, we feel that this is largely due to how each individual plant records information on the downtime of trains, the variability in operator's logs associated with how each operator individually records daily system status, and the quality and level of detail with which each of the plants surveyed maintain information on equipment histories. Notwithstanding, the power of the SSFT indicator, as presented through this study, suggests that further analyses be conducted using data from plants purported to have good records on equipment histories. These data can then be used to further benchmark the amount of uncertainty inherent in the SSFT indicator.

Based upon lessons learned through the efforts in analyzing train-level unavailability data, it is further recommended that existing databases such as those maintained by the nuclear industry, e.g., NPRDS, be further examined in parallel with analysis performed using historical records maintained at plants. We also recommend that data obtained from these plants be used to perform similar retrogressive analyses, as documented in this report, to compare trends in the SSFT indicator and INPO's Safety System Performance Indicator.

Our preliminary analysis regarding the utility of NPRDS, in lieu of using historical data at plants, tends to indicate that NPRDS would be difficult to use unless changes are made in the NPRDS reporting system. It would have been very helpful if component data reported to NPRDS included information that could readily identify the system trains in which these components are located.

Because of the encouraging results obtained, we summarily recommend that these risk-based indicators be further pursued in terms of understanding their properties. The indicator of Safety System Function Trends appears to be a valid indicator of plant safety performance. Probabilistic Safety Analysis (PSA) logic shows that this indicator is directly related to plant safety performance. This hypothesis has been validated, through utilization of plant historical data, by showing that the indicator correlates with safety system failures. Furthermore, the indicator detects trends in plant safety performance faster than safety system failures. Statistically significant trends and levels in the indicator can be discerned and used to help recognize whether or not improvement programs are effective in improving plant safety performance. In this context, the underlying causes of the trends observed should be pursued and broader applications carried out.

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9. REFERENCES

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APPENDIX A. CASE STUDIES: DATA TABLES

The first two tables on the following pages present the results for Plant 1. In Table A-1 for the AUX-FEED system, the downtime hours per quarter per train (DWNA, DWNB, DWNC) include the detected plus undetected downtime hours. Undetected downtime hours occur only when a failure (loss of function) of the train is discovered; the undetected downtime hours are calculated as one-half the interval from the last demand or test of the train. The aggregated train unavailability (summed over the 3 trains) and the average train unavailability are also listed in the table. The data shown in Table A2 for "EPS" follow similar lines; other information presented corresponds to definitions presented in Table A3. Plant 2 data (Tables A4 and A5) follow similar lines, except AUX-FEED is a two-train system.

The results for the AUX-FEED systems of Plants 3, 4, and 5 follow in Tables A6 through A8. These results are grouped together since the plants are similar and the data were obtained from similar data sources. Table A6 contains additional data because the turbine pump train (DWNT) and the electric motor pump trains (DWNA, DWNB) were separately analyzed.

Table A.1

PLANT 1: AUX-FEED

YEAR	QUARTER	CRITICAL HOURS	CUMM. CRIT. HRS.	DWNA	DWNB	DWNC	DOWN TOTAL	3 AVERAGE	3 AVG. / TRAIN	(PER TRAIN)^3
85	85-1	2160	3711	0.00	0.00	0.00	0.00	NA	NA	NA
	85-2	2183	5894	0.00	0.00	0.00	0.00	NA	NA	NA
	85-3	1784	7678	0.00	0.00	0.00	0.00	NA	NA	NA
	85-4	1363	9041	0.00	13.50	0.00	13.50	1.80E-03	6.01E-04	2.17E-10
86	86-1	327	9368	0.00	0.00	0.00	0.00	NA	NA	NA
	86-2	1163	10531	0.00	35.70	0.00	35.70	5.48E-03	1.83E-03	6.0[illegible]E-09
	86-3	0	10531	0.00	0.00	0.00	0.00	NA	NA	NA
	86-4	0	10531	0.00	0.00	0.00	0.00	NA	NA	NA
87	87-1	0	10531	0.00	0.00	0.00	0.00	NA	NA	NA
	87-2	1937	12468	0.00	21.90	364.00	385.90	1.99E-01	6.64E-02	2.93E-04
	87-3	1762	14230	14.20	14.20	6.93	35.33	1.14E-01	3.80E-02	5.4[illegible]E-05
	87-4	528	14758	0.00	0.00	0.00	0.00	NA	NA	NA
88	88-1	1574	16332	0.00	0.00	0.00	0.00	NA	NA	NA
	88-2	2043	18375	0.37	1.40	59.00	60.77	6.14E-02	2.05E-02	8.59E-06

Table A.2

PLANT 1: EPS

YEAR	QUARTER	CRITICAL HOURS	CUM. CRIT. HRS.	DWN1	DWN2	DOWN TOTAL	3 AVERAGE	3 AVG. / TRAIN	(PER TRAIN)^2
85	85-1	2160	3711	17.42	0.00	17.42	8.06E-03	4.03E-03	1.63E-05
	85-2	2183	5894	152.62	46.67	199.29	4.99E-02	2.49E-02	6.22E-04
	85-3	1784	7678	381.83	50.70	432.53	1.06E-01	5.30E-02	2.81E-03
	85-4	1363	9041	35.95	22.60	58.55	1.30E-01	6.48E-02	4.19E-03
86	86-1	327	9368	0.00	0.00	0	NA	NA	NA
	86-2	1163	10531	0.00	50.75	50.75	1.17E-01	5.84E-02	3.41E-03
	86-3	0	10531	0.00	0.00	0	NA	NA	NA
	86-4	0	10531	0.00	0.00	0	NA	NA	NA
87	87-1	0	10531	0.00	0.00	0	NA	NA	NA
	87-2	1937	12468	168.00	29.20	197.2	1.02E-01	5.09E-02	2.59E-03
	87-3	1762	14230	425.67	376.00	801.67	2.70E-01	1.35E-01	1.82E-02
	87-4	528	14758	0.00	0.00	0	NA	NA	NA
88	88-1	1574	16332	32.17	31.00	63.17	1.83E-01	9.15E-02	8.38E-03
	88-2	2043	18375	525.52	12.00	537.52	2.37E-01	1.19E-01	1.41E-02

Table A.3

DEFINITIONS OF LABELS USED IN THE TRAIN AND SYSTEM UNAVAILABILITY TABLES

Label Name	Label Description
3 AVERAGE	3-Cycle Running Average for the 3-train or 2-Train aggregate
3 AVG./TRAIN	3-Cycle Running Average per train for the 3-train or 2-train aggregate
(PER TRAIN)^3	The cube of the 3 AVG./TRAIN the 2-train aggregate
A&B 3 AVG./TRAIN	3-Cycle Running Average per train for the 2-train aggregate
A&B DOWN TOTAL	Number of hours trains A&B were down
A&B (PER TRAIN)^2	The square of A&B 3 AVG./TRAIN
A&B(PER TRAIN)^2 * T	The product of A&B (PER TRAIN)^2 with T 3 AVG.

Label Name	Label Description
CRITICAL HOURS	Hours of plant operation for the current quarter
CUMM. CRIT. HRS.	Total number of hours of plant operation to date
DOWN TOTAL	Number of hours all trains were down
DWNx	Number of hours train "x" was down
T 3 AVG.	3-Cycle Running Average for train T
NA	Not applicable; not calculated due to zero "CRITICAL HOURS" in the quarter, or zero "DOWN TOTAL" for that quarter.

Table A.4

PLANT 2: AUX-FEED

YEAR	QUARTER	CRITICAL HOURS	CUMM. CRIT. HRS.	DWN1	DWN2	DOWN TOTAL	3 AVERAGE	3 AVG. / TRAIN	(PER TRAIN)^2
83	83-2	2184	2184	83.42	397.00	480.42	2.20E-01	1.10E-01	1.21E-02
	83-3	940	3124	361.33	6.55	367.88	2.72E-01	1.36E-01	1.84E-02
	83-4	2116.3	5240.3	6.80	29.82	36.62	1.69E-01	8.44E-02	7.13E-03
84	84-1	1915	7155.3	35.55	321.27	356.82	1.53E-01	7.66E-02	5.86E-03
	84-2	2184	9339.3	42.88	13.42	56.30	7.24E-02	3.62E-02	1.31E-03
	84-3	1747	11086.3	45.72	21.33	67.05	8.21E-02	4.11E-02	1.69E-03
	84-4	0	11086.3	0.00	0.00	0.00	NA	NA	NA
85	85-1	1741	12827.3	83.41	456.92	540.33	3.10E-01	1.55E-01	2.41E-02
	85-2	1484	14311.3	111.47	389.88	501.35	3.23E-01	1.62E-01	2.61E-02
	85-3	0	14311.3	0.00	0.00	0.00	NA	NA	NA
	85-4	0	14311.3	0.00	0.00	0.00	NA	NA	NA
86	86-1	0	14311.3	0.00	0.00	0.00	NA	NA	NA
	86-2	0	14311.3	0.00	0.00	0.00	NA	NA	NA
	86-3	0	14311.3	0.00	0.00	0.00	NA	NA	NA
	86-4	0	14311.3	0.00	0.00	0.00	NA	NA	NA
87	87-1	1969	16280.3	150.23	504.95	655.18	3.33E-01	1.66E-01	2.77E-02
	87-2	1284	17564.3	119.17	98.60	217.77	2.68E-01	1.34E-01	1.80E-02
	87-3	1894	19458.3	0.00	0.00	0.00	NA	NA	NA
	87-4	2165	21623.3	270.12	156.27	426.39	1.78E-01	8.88E-02	7.89E-03
88	88-1	1556	23179.3	37.75	391.58	429.33	1.56E-01	7.78E-02	6.05E-03
	88-2	NA	NA	NA	NA	NA	NA	NA	NA

Table A.5

PLANT 2: EPS

YEAR	QUARTER	CRITICAL HOURS	CUMM. CRIT. HRS.	DWN1	DWN2	DOWN TOTAL	3 AVERAGE	3 AVG. / TRAIN	(PER TRAIN)^2
83	83-2	2184	2184	660.08	43.33	703.41	0.32	0.16	2.59E-02
	83-3	940	3124	14.08	0.00	14.08	0.23	0.11	1.32E-02
	83-4	2116.3	5240.3	54.33	422.83	477.16	0.23	0.11	1.30E-02
84	84-1	1915	7155.3	398.17	54.08	452.25	0.19	0.09	9.00E-03
	84-2	2184	9339.3	95.58	38.58	134.17	0.17	0.09	7.32E-03
	84-3	1747	11086.3	370.50	17.72	388.22	0.17	0.08	6.95E-03
	84-4	0	11086.3	0.00	0.00	0.00	NA	NA	NA
85	85-1	1741	12827.3	41.22	11.38	52.60	0.03	0.02	2.28E-04
	85-2	1484	14311.3	80.08	16.67	96.75	0.05	0.02	5.36E-04
	85-3	0	14311.3	0.00	0.00	0.00	NA	NA	NA
	85-4	0	14311.3	0.00	0.00	0.00	NA	NA	NA
86	86-1	0	14311.3	0.00	0.00	0.00	NA	NA	NA
	86-2	0	14311.3	0.00	0.00	0.00	NA	NA	NA
	86-3	0	14311.3	0.00	0.00	0.00	NA	NA	NA
	86-4	0	14311.3	0.00	0.00	0.00	NA	NA	NA
87	87-1	1969	16280.3	27.23	0.00	27.23	0.01	0.01	4.78E-05
	87-2	1284	17564.3	39.88	1.92	41.80	0.02	0.01	1.13E-04
	87-3	1894	19458.3	0.00	32.70	32.70	0.02	0.01	9.77E-05
	87-4	2165	21623.3	56.82	19.90	76.72	0.03	0.01	2.00E-04
88	88-1	1556	23179.3	0.00	0.00	0.00	NA	NA	NA

Table A.6

PLANT 3: AUX-FEED

YEAR	QUARTER	CRITICAL HOURS	CUM. CRIT. HRS.	DWNA	DWNB	DWNT	A&B DOWN TOTAL	DOWN TOTAL	3 AVERAGE	3 AVG./TRAIN	(PER TRAIN)^3
85	85-1	2157	2157	0.18	0.13	362.10	0.31	362.41	1.68E-01	5.60E-02	1.76E-04
	85-2	2149	4306	0.30	0.22	0.00	0.52	0.52	8.43E-02	2.81E-02	2.22E-05
	85-3	2208	6514	380.71	7.98	493.65	388.69	882.34	1.91E-01	6.37E-02	2.59E-04
	85-4	1939	8453	0.00	0.00	6.31	0.00	6.31	1.41E-01	4.71E-02	1.04E-04
86	86-1	1041	9494	0.00	0.00	0.00	0.00	0.00	NA	NA	NA
	86-2	1134	10628	0.00	0.00	36.05	0.00	36.05	1.46E-01	4.88E-02	1.16E-04
	86-3	1949	12577	366.65	366.23	362.17	732.88	1095.05	1.88E-01	6.25E-02	2.45E-04
	86-4	1825	14402	0.15	0.85	15.62	1.00	16.62	2.34E-01	7.79E-02	4.74E-04
87	87-1	1856	16258	373.40	0.00	367.00	373.40	740.40	3.29E-01	1.10E-01	1.32E-03
	87-2	2162	18420	0.12	0.08	0.00	0.20	0.20	1.30E-01	4.32E-02	8.06E-05
	87-3	1522	19942	0.00	0.00	0.00	0.00	0.00	NA	NA	NA
	87-4	1374	21316	5.28	0.00	0.00	5.28	5.28	1.08E-01	3.60E-02	4.65E-05

Table A.6 (Cont'd)

PLANT 3: AUX-FEED (CONTINUED)

YEAR	QUARTER	A&B 3 AVG.	A&B 3 AVG./TRAIN	A&B (PER TRAIN)^2	T 3 AVG.	A&B(PER TRAIN)^2 * T
85	85-1	1.44E-04	7.19E-05	5.16E-09	1.68E-01	8.67E-10
	85-2	1.93E-04	9.64E-05	9.29E-09	NA	NA
	85-3	5.98E-02	2.99E-02	8.94E-04	1.31E-01	1.17E-04
	85-4	NA	NA	NA	1.02E-01	NA
86	86-1	NA	NA	NA	NA	NA
	86-2	NA	NA	NA	8.48E-02	NA
	86-3	1.08E-01	5.38E-02	2.90E-03	6.67E-02	1.93E-04
	86-4	9.30E-02	4.65E-02	2.16E-03	8.43E-02	1.82E-04
87	87-1	1.97E-01	9.83E-02	9.67E-03	1.32E-01	1.28E-03
	87-2	6.41E-02	3.21E-02	1.03E-03	NA	NA
	87-3	NA	NA	NA	NA	NA
	87-4	5.48E-02	2.74E-02	7.51E-04	NA	NA

Table A.7

PLANT 4: AUX-FEED

YEAR	QUARTER	CRITICAL HOURS	CUMM. CRIT. HRS.	DWNA	DWNB	DWNT	DOWN TOTAL	3 AVERAGE	3 AVG./TRAIN	(PER TRAIN)^3
85	85-1	1235	1235	0.00	0.00	0.00	0	NA	NA	NA
	85-2	1319	2554	0.32	0.32	0.00	0.64	2.51E-04	8.35E-05	5.83E-13
	85-3	1998	4552	8.88	7.97	36.10	52.95	1.18E-02	3.92E-03	6.04E-08
	85-4	2189	6741	0.33	0.17	0.90	0.5	9.82E-03	3.27E-03	3.51E-08
86	86-1	2152	8893	0.35	0.00	26.02	26.37	1.26E-02	4.20E-03	7.39E-08
	86-2	2183	11076	0.17	0.17	17.00	17.34	6.78E-03	2.26E-03	1.15E-08
	86-3	1099	12175	0.00	0.00	4.60	4.6	8.89E-03	2.96E-03	2.60E-08
	86-4	1819	13994	0.00	0.00	440.03	440.03	9.06E-02	3.02E-02	2.75E-05
87	87-1	2143	16137	10.23	0.00	0.00	10.23	8.99E-02	3.00E-02	2.69E-05
	87-2	2061	18198	0.00	0.00	0.00	0	NA	NA	NA
	87-3	2192	20390	0.00	0.00	38.48	38.483	5.95E-02	1.98E-02	7.80E-06
	87-4	2209	22599	1.17	0.00	0.00	1.17	5.80E-03	1.93E-03	7.22E-09

Table A.8

PLANT 5: AUX-FEED

YEAR	QUARTER	CRITICAL HOURS	CUM. CRIT. HRS.	DWNA	DWNB	DWNT	DOWN TOTAL	3 AVERAGE	3 AVG./TRAIN	(PER TRAIN)^3
85	85-1	1907	1907	0.00	0.00	0.00	0.00	NA	NA	NA
	85-2	2183	4090	0.00	0.00	3.58	3.58	8.76E-04	2.92E-04	2.49E-11
	85-3	913	5003	0.00	1.05	373.67	374.72	7.56E-02	2.52E-02	1.60E-05
	85-4	1138	6141	0.00	0.00	0.90	0.90	8.36E-02	2.99E-02	2.66E-05
86	86-1	2157	8298	0.00	0.00	1.67	1.67	8.97E-02	2.99E-02	2.67E-05
	86-2	2183	10481	1.75	3.13	0.00	4.88	1.36E-03	4.53E-04	9.32E-11
	86-3	2196	12677	405.10	14.71	1.70	421.51	6.55E-02	2.18E-02	1.04E-05
	86-4	1300	13977	0.20	0.13	19.12	19.45	7.85E-02	2.62E-02	1.79E-05
87	87-1	52	14029	0.00	0.00	0.00	0.00	NA	NA	NA
	87-2	1673	15702	0.17	0.12	0.00	0.29	8.45E-02	2.82E-02	2.24E-05
	87-3	2208	17910	0.55	19.85	381.52	401.92	8.06E-02	2.69E-02	1.94E-05
	87-4	2209	20119	0.00	0.13	0.00	0.13	6.61E-02	2.20E-02	1.07E-05

APPENDIX B. STATISTICAL TESTS AND TOLERANCE BOUND CONSIDERATIONS

Kendalls' τ test was applied to the original data points, i.e., the total train downtimes/quarter (the "DOWNTOTAL" column in the data sheets provided in Appendix A) was used to test for significant time trends. A trend was considered significant if the significance level was less than 0.05.

Approximate tolerance bounds (at the 95% level) were calculated as 2 standard deviations from an unavailability goal value of $5(10)^{-2}$/train for the AUX-FEED system and $1(10)^{-1}$ for the EPS. For these case studies, estimates of the standard deviation were obtained though estimates of the standard deviation of the logarithms of the train unavailabilities (a test for log normality did not reject the hypothesis). These standard deviation estimates were then applied to the goal value.

A less approximate approach for determining tolerance bounds is described in Appendix E.

APPENDIX C. SELECTION OF SYSTEMS FOR UNAVAILABILITY INDICATORS

The following considerations were taken into account in selecting the safety systems for implementation of unavailability indicators.

1. The change in core-melt frequency as a result of a change in system unavailability/unreliability was to be comparatively significant, that is:

   $$\delta P(CM)/\delta P(S_i) = \text{Comparatively large}$$

   where $\delta P(CM)$ is the core-melt frequency and $P(S_i)$ is the overall unreliability and unavailability of system S_i.

2. The change in system unavailability/unreliability as a result of a change in a train within the system was to be comparatively large, that is:

   $$\sum_{j=1}^{k} \delta P(S_i)/\delta P(T_{ij}) = \text{Comparatively large},$$

   where the system is composed of k trains.

The final selection criterion used for identifying the safety systems is given by:

$$M = \delta P(CM)/\delta S_i \cdot \sum_{J=1}^{k} \delta P(S_i)/\delta P(T_{ij})$$

The quantity M was calculated for various safety systems for two BWRs (Grand Gulf and Limerick) and three PWRs (Arkansas Nuclear 1, Calvert Cliffs, and Oconee-2). The average M values for various systems for the two BWRs and three PWRs were then calculated and are given in Table C.1.

Generally, the M values are large for those systems which have the following attributes:

1. large impact on core-melt frequency,

2. small number of redundant trains or large unavailability/unreliability for each train, and

3. systems with large common mode contribution.

Table C.1. Trending Importance Measures for Safety Systems

Systems	PWRs Trending Measure	Contribution (%)	Systems	BWRs Trending Measure	Contribution (%)
AFWS	9.54E-4	12	RPS	4.35E-4	14
SR/RVC	1.16E-4	1.5	ESFAS	3.28E-4	11
HPIS	1.21E-4	1.5	RHR	1.25E-4	4
LPIS	9.98E-7	<<.1	SSWS	3.96E-4	13
ECCR (LPR & HPR)	1.41E-4	2	EPS/DC	2.48E-4	8
SWS/ESWS	2.32E-3	29	EPS/AC	1.05E-3	34
EPS/DC	1.75E-3	22	ADS	1.98E-6	<<1
EPS/AC	2.29E-3	29	RCICS	2.93E-4	10
RPS	2.74E-4	3	HPCS/HPCI	1.86E-4	6
HHSWS	1.32E-5	<.1	LPCIS	1.28E-6	<<1
			LPCS	6.69E-7	<<1

The final systems selected for BWRs and PWRs are given in Table C.2. These systems account for about 90% of the total core-melt frequency change, that is:

$$\alpha = \sum_{\substack{\text{selected} \\ \text{systems}}} M_i \Big/ \sum_{\substack{\text{all} \\ \text{systems}}} M_i \simeq 0.9$$

Therefore, these systems are proposed for short-term implementation of unavailability indicators.

Table C.2. Systems Selected Based on Trending Importance Measures

PWRs	BWRs
Auxiliary Feedwater System (AFWS)	Reactor Protection System (RPS)
High-Pressure Injection System (HPIS)	Standby Service Water System (SSWS)
Emergency Service Water System (SSW/ESW)	Emergency Power System-DC (EPS/DC)
Emergency Power System - DC (EPS/DC)	Emergency Power System-AC (EPS/AC)
Emergency Power System - AC (EPS/AC)	Reactor Core Isolation Cooling System (RCICS)
Reactor Protection System (RPS)	High-Pressure Core Injection System (HPCS/HPCI)

APPENDIX D. BASIC MEASURES OF EQUIPMENT/SYSTEM PERFORMANCE AND CALCULATION PROCEDURES

Introduction

Two basic measures of equipment and system performance are availability and reliability. In failure space, these two basic measures can also be expressed as unavailability and unreliability. Unavailability is measured by the number of hours the equipment is down in a given period. Unreliability is measured by the number of failures in a given period. Unreliability and unavailability measure different aspects of equipment performance. Equipment which fails often but is quickly repaired has a low reliability and a high availability, whereas equipment which fails infrequently but remains down for a long period has a high reliability and a low availability.

Both reliability and availability are important to safety and risk. The equipment must be available to perform its function, and it must be reliable to actually carry out its function. Availability thus measures whether the equipment is up so that it can perform its function if called upon and reliability measures whether the equipment can carry out its function without failure.

Basic Measures of Unreliability and Unavailability

Unreliability is measured by the failure rate r defined by:

r = Number of failures/Time period.

Unavailability is measured by the fraction of the time period when the equipment or system is down (q) and is defined by:

q = Downtime hours/Time period;

in this case, normalization according to number of critical hours in the time period is generally performed.

The downtime hours include all contributions to downtime, not only from failures but also from corrective and scheduled maintenances as well as undetected downtime contributions.

Unavailability q can equivalently be measured by the downtime frequency m and average downtime duration d:

q = md

m = number of downtimes/time period

d = downtime hours/number of downtimes

The unavailability can also be decomposed into its contributions:

$$q = (md)_{failures} + (md)_{corrective\ maintenances} + (md)_{scheduled\ maintenances} + \ldots\ldots \quad (6)$$

The unavailability and unreliability of a piece of equipment is usually time dependent. For example, as equipment ages, the failure rate and hence the unreliability can increase but the unavailability may remain constant. However, in some instances, maintenance effectiveness can cause the equipment failure rate to decrease by eliminating failure causes.

To better understand the relation between unavailability and unreliability in terms of failure probability for a component or a system to perform its function we provide a simplified example.

For a component with a periodic test interval of O, we observed n failures in a time period, T. We also assume that the occurrence rate of failure causes does not vary with the status of the component. For example, the probability of failure cause to occur during the standby mode would be the same as the failure occurrence probability during startup and operation of the component. This assumption is valid especially for cases where a component is over-designed (large built-in safety margin), such that the additional stresses caused by startup and operation would not increase the failure rate of the component. This is usually the case for safety components in nuclear power plants.

If the component is to start and operate for a period of θ_0, the probability of not performing its function can be expressed as:

$$p = q + r\theta_0 \quad ,$$

where q and r are the unavailability and the unreliability indicators (or measures) for the component. Now if we assume that a system is composed of two redundant trains or components, the probability that the system fails on demand can be expressed by:

$$P_s = q_1q_2 + \theta_0\ (r_1q_2 + r_2q_1) + sot \quad ,$$

or

$$P_s = Q_s + \theta_0\ R_s + sot \quad ,$$

where "sot" stands for small second order terms.

Therefore, unavailability and unreliability indicators for the system are respectively:

$$Q_s = q_1q_2 \quad ,$$

and

$$R_s = r_1 q_2 + r_2 q_1 \quad .$$

The associated equations for various system configurations can be composed accordingly.

In general, to understand the behavior of unavailability and unreliability, these quantities need to be tracked over time. The formulation of unavailability and unreliability discussed earlier allows one to determine the capabilities for tracking various quantities vs the level of information collected. The following table presents various options for data collected vs performance measures evaluated. Therefore, the minimal information requirements for tracking both unreliability and unavailability measures of a piece of equipment are to collect the total observed downtime and the number of failures in the period. If the failures are not recorded then the equipment failure rate and hence its unreliability cannot be measured. In addition, if failure downtimes are not recorded then their contribution to unavailability (which is usually significant) cannot be included. On the contrary, classifying all downtimes as failure-caused will result in significant overestimation of both the unavailability and unreliability. This type of classification of downtimes would discourage effective maintenance and may result in a negative impact on safety through misleading feedback. Hence, failures need to be differentiated from other types of maintenance downtimes and failure durations should be weighted differently than other factors that lead to component downtimes.

Table 1. Data Collected vs Performance Measured

Data Collected	Performance Measured
Observed downtime in a period	Equipment unavailability from repair times and maintenances
Observed downtime and the number of failures	Total equipment unavailability from the sum of failures, repair times, and maintenances
	Equipment failure (unreliability)
	Maintenance effectiveness
Times of downtimes, causes, and downtime durations	Detailed equipment unavailability and unreliability
	Detailed maintenance effectiveness

Indicators vs Measures

In the previous section, the basic concept and formula for measures of unreliability and unavailability were discussed. Measures are statistical quantities (random variables) that usually change with time. Therefore, at any instant of time, measures can be described by a certain probability distribution function with some parameters (e.g., means & variance) that depend on that instant of time. If the measures were time invariant, their distributions and the associated parameters are constants (not changing with time), then indicators could be established to provide estimates of the parameters of these distributions with certain confidence levels. Furthermore, one could establish empirical distributions of these measures given a set of data (observations).

For a measure with a time invariant distribution (sometimes called ergodic-stationary process), the mean of the measure can be estimated by a time average or a running average indicator.

"An indicator of the mean for a measure which does not vary with time is usually the most efficient when the indicator is the running average of the measure. Efficiency is measured by the variance of the indicator (the smaller the variance, the more efficient the indicator.)"

Therefore, there is a distinct difference between a measure and an indicator as described in the above example. An indicator estimates a parameter of the distribution of a measure.

Unfortunately, measures are not usually time invariant, so indicators need to be defined to show the variation in the parameters of the measures with respect to time. For example, one may wish to define an indicator which is sensitive to a change in the mean of a measure. This indicator may not necessarily be the same as those indicators that were defined earlier for estimating the mean of a time invariant measure.

In the above two examples, one can distinguish between two types of indicators of time-independent and time-dependent measures. For the time independent case the running average is an indicator of the mean. That is, at any point, it estimates the mean of the measure without bias and, depending on the distribution of the measure, it may have minimum variance in the class of all unbiased estimators. In the time-dependent case, the running average is not a good estimator of the mean because it does not respond quickly to changes in the mean over time. In this project, sometimes we call the earlier indicators monitoring indicators and the latter trending indicators. There are various types of indicators for trending and monitoring. Some of these indicators have been discussed in the previous reports.

Straightforward Indicators From Minimal Information Requirements

For a time period (e.g., a quarter of a year) the minimum data collected for each train is:

d = total observed downtime, and

f = number of failures.

The most basic indicator of train unreliability or failure rate r can be calculated by the running average:

$$r = (f+F)/(\ell+L) \quad ,$$

where:

F = the total accumulated failures up to the last time period, and

L = the total accumulated time period excluding the last period (ℓ).

We will show that this indicator will not be a sensitive trending indicator because it retains the whole history with no attenuation. A modified indicator can be established by attenuating the retained history, hence reducing the inertia and creating a more sensitive indicator of unreliability. This modified indicator is established according to the following procedure.

The retained history for each train consists of 3 numbers, the accumulated failures, F, the accumulated downtime, D, and the accumulated observation time, L.

The indicator calculations for the nth period, F_n, D_n, and L_n are updated according to the following formulae:

$$F_n = f_n + \alpha F_{n-1} \quad ,$$

$$D_n = d_n + f_n \cdot U + \alpha D_{n-1} \quad ,$$

$$L_n = \ell_n + \alpha L_{n-1} \tag{10}$$

where f_n, d_n, and ℓ_n are the number of failures, the cumulative observed downtime, and the number of critical hours in the nth time period for a specific train, respectively. The factor, α, is arbitrarily taken to provide an attenuation factor for the past history. This factor can be varied between zero and one. The average undetected downtime, U, is assumed to be one half of the periodic test interval.

Justification for this factor was obtained through simulation studies.

The indicators of unreliability and unavailability of a train then can simply be determined using the following equations:

$$r_n = F_n/L_n \quad ,$$

$$q_n = D_n/L_n \quad .$$

In this report the focus has been on trending system/train unavailability.

Procedure Guide for Indicator Implementation

This section discusses the various steps employed in the data collection and analysis efforts. The basic steps are:

One-Time Information Gathering,

Data Collection Procedure, and

Initial Values for Indicators and Quantification.

One-Time Information Gathering

This section describes the type of information that needs to be gathered prior to the actual data collection phase. These are:

1. No. of trains in the system and one line diagram,
2. Periodic test interval for trains or each train if they are different, and
3. The success criteria of a system in terms of the number of trains (or different success paths)

The number of trains in a system usually is straightforward information that can be obtained from the plant FSARs. In some cases (such as RPS), a system is composed of several sections with different number of redundancies (or trains). In these cases a one-line block diagram is needed of the system with the trains properly identified.

The success criteria of a system in terms of the number of trains (or different success paths) can be identified by reviewing either the vendor or plant-specific accident analysis report. If a system has several success criteria for different initiating events, all of these success criteria are to be documented, even though the most stringent one will be used for short-term implementation.

The collected information on the system configuration and the success criteria of the system is to be translated to the proper unreliability and unavailability equations for the system indicators. It shall be noted that if no data will be collected on multiple simultaneous train outages, the associated terms in the equations can be deleted.

Data Collection Procedure

The simplest form of data that can be collected for initial application of the unavailability indicators is the total number of failures and total downtime period for each train of a safety system. However, the indicators that are established based on this level of data cannot account for dependency between trains. Therefore, the next level of detail in data collection is to report the data on multiple train failures and downtimes in addition to single train failures and downtimes. This would allow the indicators to be more responsive to changes of system performance due to dependent failures. During this phase of the project this level of detail was not fully pursued.

The response time of the indicator can be reduced (become more responsive) if the period-based (i.e., quarter based) indicators are substituted by cycle-based indicators. However, this necessitates that in addition to train failures and downtime durations, the times at which failures or downtimes occurred must also be reported.

The predictive and trending function of indicators can be enhanced if one identifies the cause of the failure or the downtime as well as the specific component within the train. This work is also planned to be performed in the future.

During this phase of the program, the implementation of the unavailability indicators required, as a minimum, data collected on the total downtime hours and the total number of failures of each train per quarter. It was also desirable to ascertain when multiple trains were down.

Initial Values for Indicators and Quantification

The indicators in this report start with an initial value of zero assumed for L, F, and D. The indicators are expected to perform poorly in the first 4 to 5 quarters (i.e., they may jump up and down, mostly the result of their large variance) until enough history has been established.

An alternate approach is to modify the indicators by providing some initial, non-zero values for L, F, and D, thereby helping to reduce the variation in indicators at early quarters (these will be referred to as modified indicators). If the initial values for F, L, and D are denoted by F_o, L_o, and D_o, the modified indicator can be written in terms of the original indicators as follows:

$$D^*_n = D_n + \alpha^n D_o$$

$$L^*_n = L_n + \alpha^n L_o$$

$$F^*_n = F_n + \alpha^n F_o$$

where (*) represents the modified indicators that include initialization, and is the history attenuation factor which is suggested earlier to be 0.75.

The unreliability and unavailability indicators can now be written in terms of F^*_n, L^*_n, and D^*_n, in the same manner as before. For example, the unreliability indicator at the nth quarter can be written as:

$$r^*_n = F^*_n/L^*_n = (r_n + \xi_n r_o) / (1 + \xi_n)$$

where

$$\xi_n = \alpha^n \cdot L_o/L_n$$

The mean and variance of the modified unreliability indicators (μ^*_n, σ^*_n) in terms of the mean and variance of the original unreliability indicator (μ_n, σ_n) can be written as follows:

$$\mu^*_n = \mu_n /(1 + \xi_n + \xi_n r_o/(1 + \xi_n) \quad ,$$

$$\sigma^{*2}_n = \sigma_n^2/(1 + \xi_n)^2 + 2\xi_n r_o \mu_n /(1 + \xi_n)^2 \quad ,$$

where

$$r_o = F_o/L_o$$

$$\xi_n = \alpha^n L_o/L$$

To minimize the bias of the modified indicator in the mean for small n ($n=1$ or 2), the value of r_o shall be close to μ_1 and μ_2. That is, the value of r_o is to be the best estimate of the mean of the unreliability indicator.

To assure that the effect of initialization is diminished when a moderate amount of history is established, the value of ξ_n at that quarter is to be much smaller than 1. For example, if at $n=4$ the effect of initialization is set at 2.5%, then the value of ξ_4 is to be approximately equal to 0.1. For $\alpha = 0.75$ and ℓ equal one quarter, this yields a value for L_o equal to 4 quarters.

For the short-term implementation we recommend the following initial values:

L_o = 4 quarters,

F_o = The expected number of failures for the train from the generic reliability data, and

D_o = The expected annual train downtime from the generic reliability data.

After the initial values are selected the quantification of the unreliability and unavailability indicators using proper formula and data can be performed. It is also recommended that these equations and formulas be set up in a computerized format for each specific plant to facilitate the implementation.

Units of Indicators and Methods for Display

For the visual detection of a trend it is important to smooth out the jumps (or discontinuities) of the indicator, keeping in mind that too much smoothing would be disadvantageous. There are a variety of techniques. Two smoothing techniques that are simple to use are described below:

a) Running mean within a window: In this smoothing technique we could, for example, average three adjacent values of the indicator, that is:

$$r_n^+ = (r_{n-1} + r_n + r_{n+1})/3 \quad .$$

We must not extend the number of points being used too far because, if we do, we will gradually lose the character of function we are trying to visualize.

b) Running median within a window: In this smoothing technique we take the middle value of three adjacent values of the indicator and present that as the current value, that is:

$$r_n^+ = \text{med}(r_{n-1}, r_n, r_{n+1}) \quad ,$$

e.g., if at the 3rd, 4th, and 5th quarter we observe 2, 7, and 5 as the indicator, then:

$$r_4^+ = \text{med}(2,7,5) = 5 \quad .$$

The running median smoothing can be repeated until the smoothed indicator is stabilized (does not change with further repetitions). This type of smootning is usually superior to the earlier one due to its robustness against outliers. Again, we limit ourselves to three point smoothing so as not to lose the character of the indicator function. For the case studies presented in Section 3, we essentially employed the first approach.

APPENDIX E. COMPUTER ALGORITHM TO GENERATE TOLERANCE INTERVALS FOR UNAVAILABILITY INDICATORS

The algorithm requires input in the form of user responses to prompts and also two parameters files, the component definition file and the pseudo-cutset file. User responses allow specification of file names as well as the attenuation parameter, the number of time periods (quarters) and the number of iterations.

The component definition file consists of a number of records. Each record looks like this:

Name f fails corrs repairs test or this:

Name d mu_fails err_fails mu_corrs err_corrs mu_repairs test

In these records, "Name" is any arbitrary component name < = 20 characters, "f" or "d" specify whether the component has fixed parameters or parameters coming from a distribution, and all other fields are numbers. Records of the first type specify components with fixed parameters. In this case, the number of failures per quarter comes from a Poisson distribution with mean "fails," the number of corrective maintenances per quarter comes from a Poisson with mean "corrs," the quarterly average repair time (in units of one quarter) comes from an exponential distribution with mean "repairs," and the test interval is "test," expressed in units of one quarter. Records of the second type specify components with parameters that themselves come from distributions. Specifically, the number of failures per quarter comes from a Poisson distribution with a mean that itself comes from a lognormal distribution with mean "mu_fails" and error factor "err_fails." Similarly, the number of corrective maintenances in a quarter is Poisson with mean coming from a lognormal with mean "mu_corrs" and error factor "err_corrs". The average repair time in a quarter (expressed in units of a quarter) is exponential with mean "mu_repairs". Finally, the testing interval (expressed in units of a quarter) is "test."

The pseudo-cutset file has records that are best explained by the following three-line example:

```
boccio * ali
neal
carl * neal
```

In this example, unavailabilities are calculated every quarter for four components: boccio, ali, neal, and carl. These must be defined by four records in the component definition file. Every quarter, following the calculation of these four components, the final system unavailability is calculated and output according to the following formula:

q = (boccio * ali) + neal + (carl * neal)

Internal operation of the program: the program is NOT a cycle-based simulation. Rather, for each component in each quarter, a number of failures, number of corrective maintenances, and an average repair time are generated. Following this, times down due to failures and corrective maintenances are calculated according to the following expressions:

time (fail) = nbr fail * (repair time + test/2)

time (corr) = nbr corr * repair time

Total down-time d(n) is then time (fail) + time (corr). Following this, smoothing is performed as follows:

D(n) = attenuation factor * D(n-1) + d(n)

T(n) = 1 + T(n-1)

q(n) = D(n)/T(n)

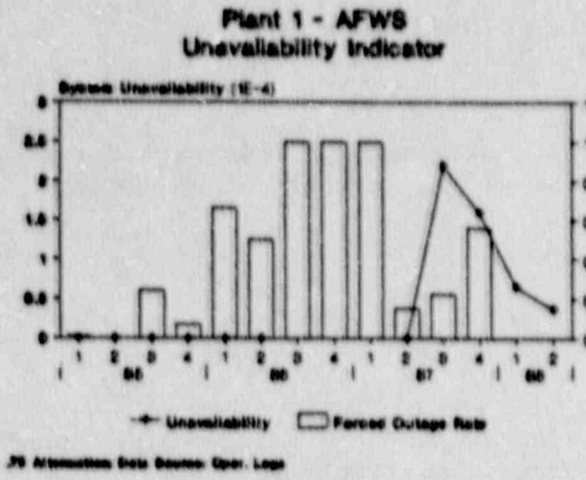
Finally, q(n) and n are output.

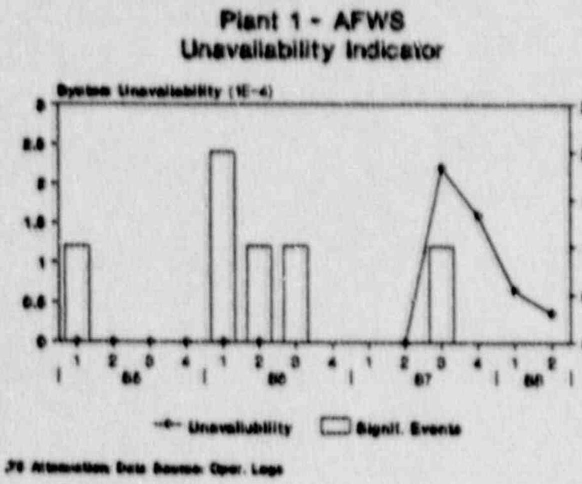
APPENDIX F. UNAVAILABILITY INDICATORS WITH CURRENT NRC SAFETY PERFORMANCE INDICATORS OVERLAID

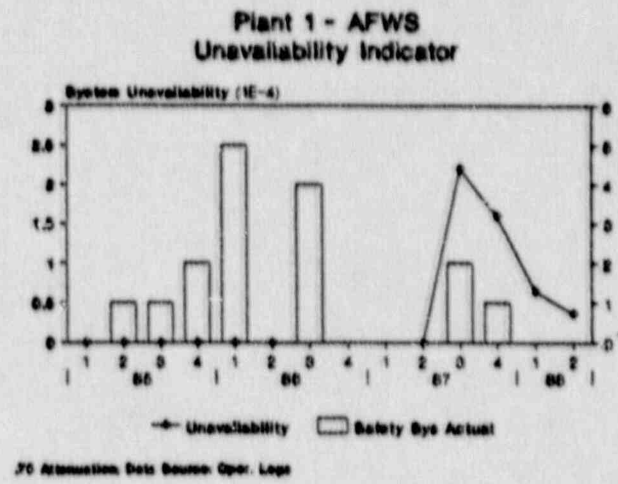
This appendix contains plots of total system and average train unavailabilities at eight plants together with five of the current set of NRC PIs:

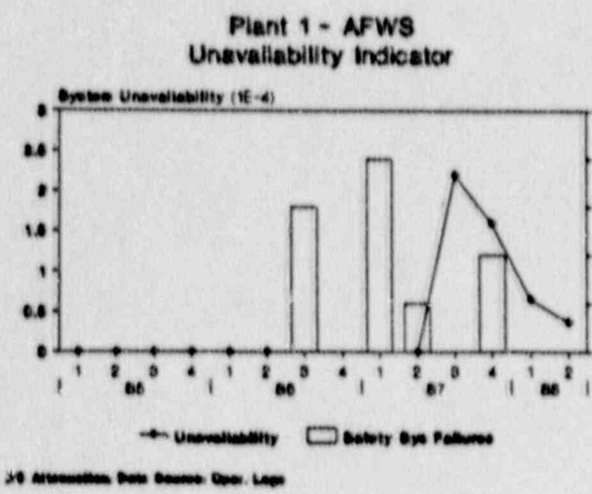
EFOs/1000 Critical Hours,
Safety System Failures,
Safety System Actuations,
Significant Events, and
Forced Outage Rate.

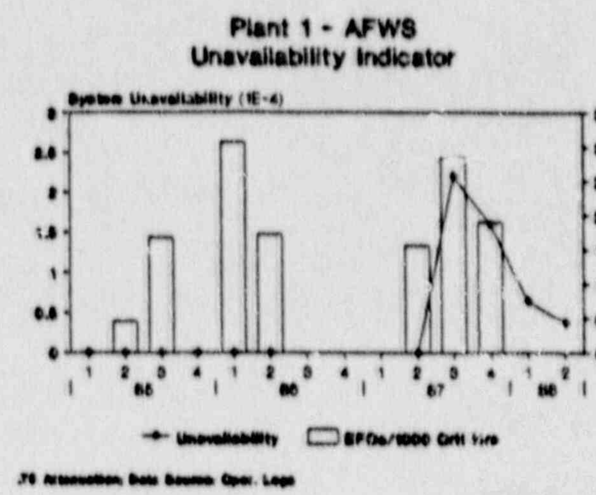
The values of unavailability are scaled on the left axis; the current PI scaled on the right axis. All values represent quarterly accumulations or ratios. All unavailability calculations utilized a 0.75 attenuation factor. Quarters containing missing unavailability data indicate periods when the plant was shutdown or data was not collected.





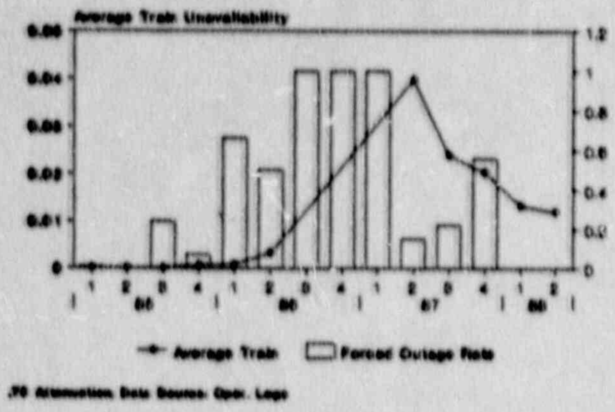




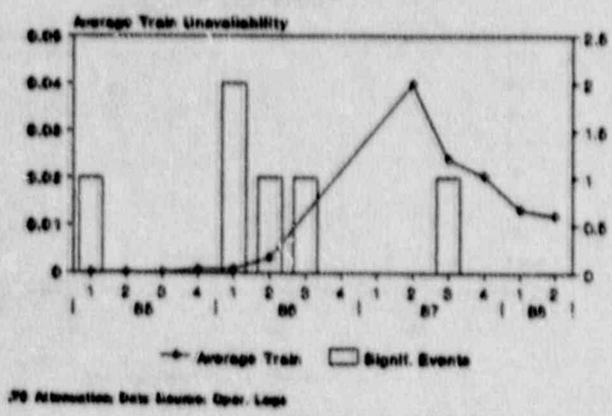


Note: Data collection period (85-1 through 88-2).

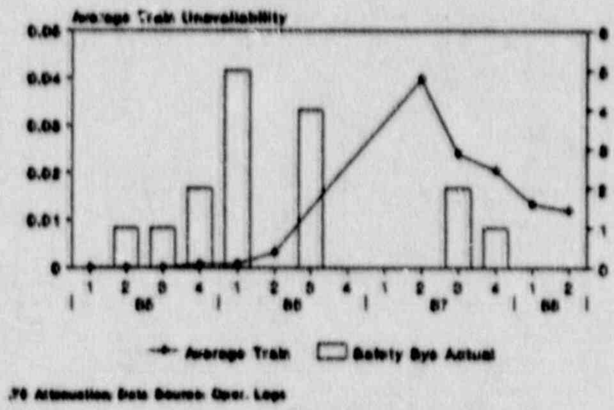
Plant 1 - AFWS
Unavailability Indicator



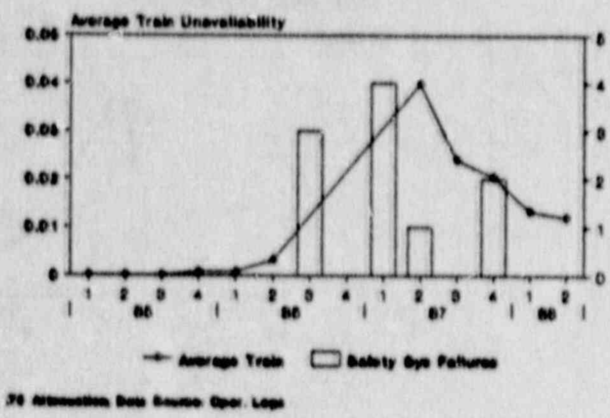
Plant 1 - AFWS
Unavailability Indicator



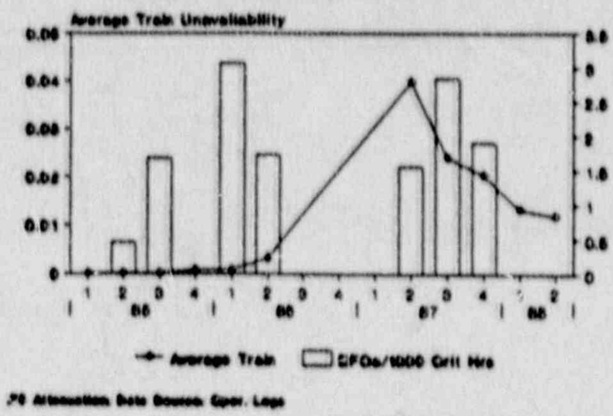
Plant 1 - AFWS
Unavailability Indicator



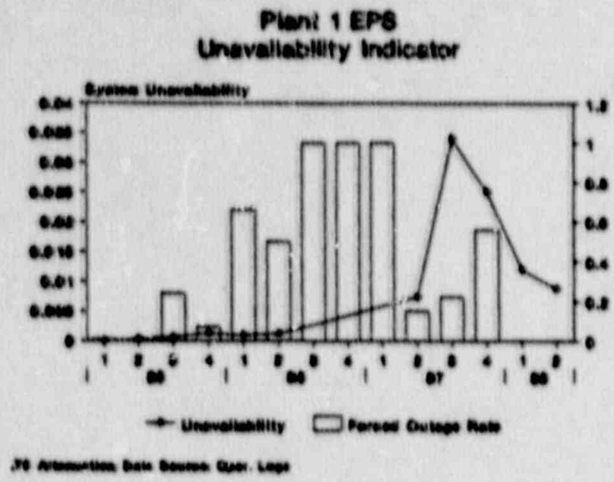
Plant 1 - AFWS
Unavailability Indicator

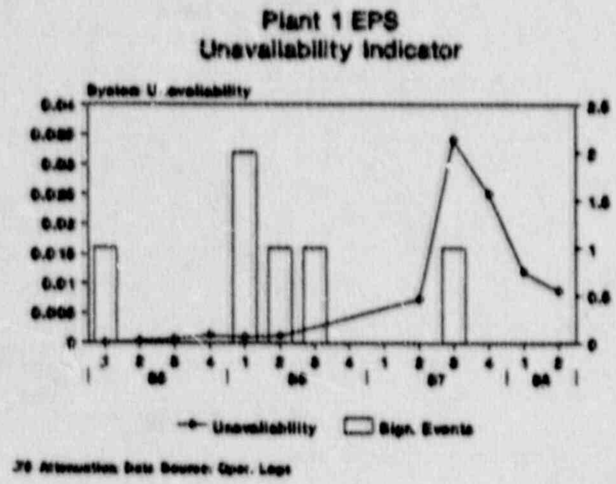


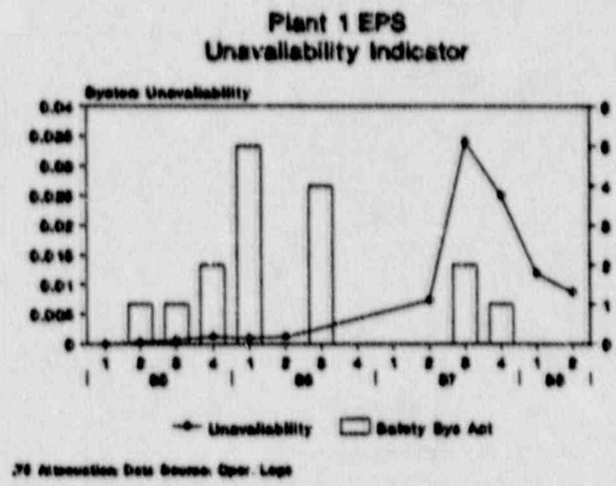
Plant 1 - AFWS
Unavailability Indicator

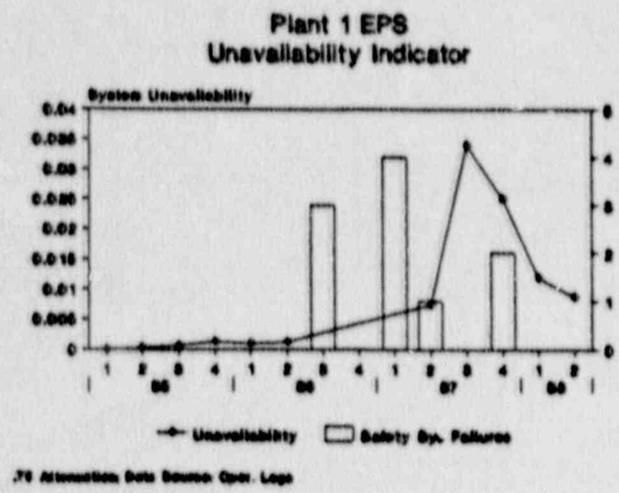


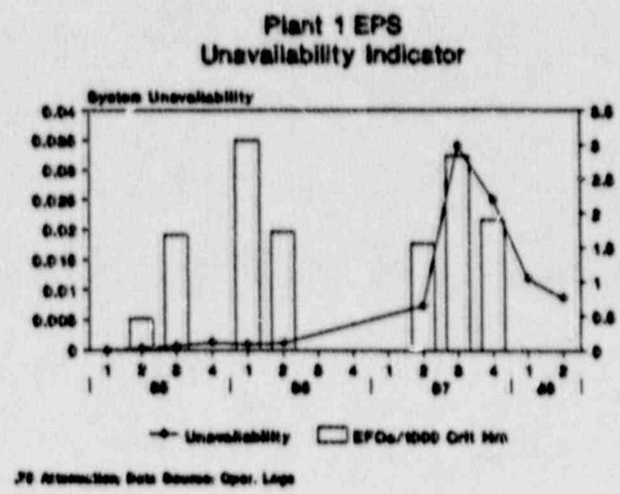
Note: Data collection period (85-1 through 88-2).





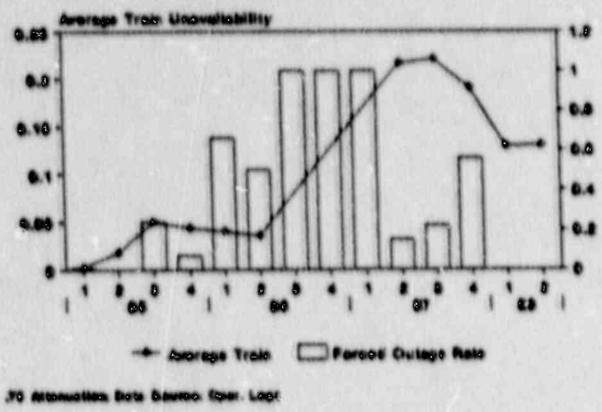




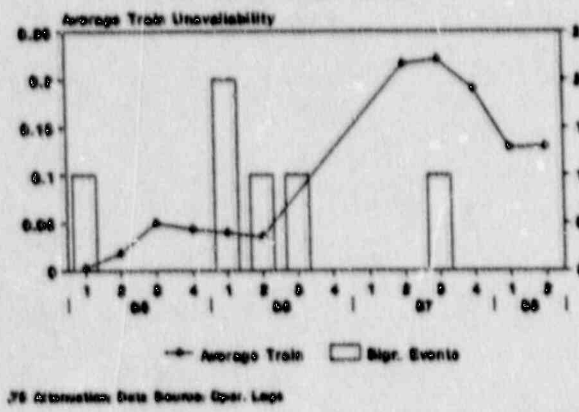


Note: Data collection period (85-1 through 88-2).

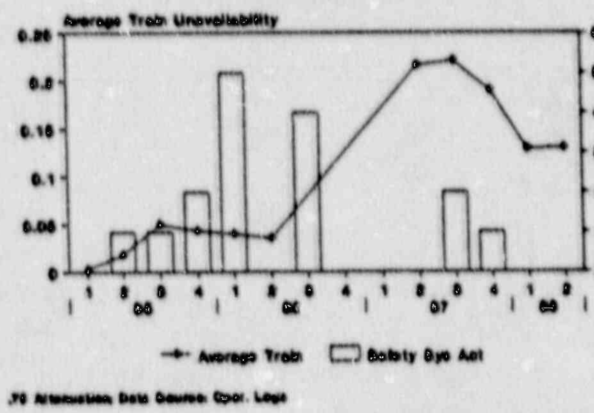
Plant 1 EPS
Unavailability Indicator



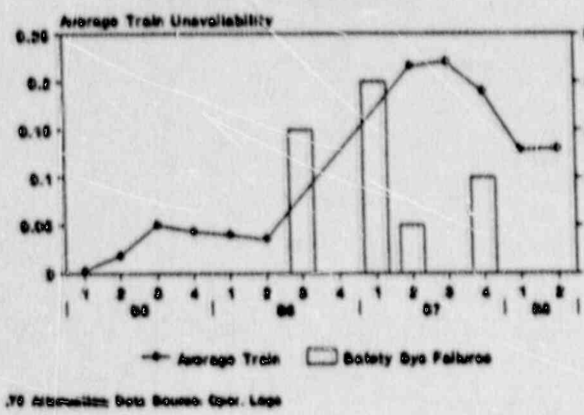
Plant 1 EPS
Unavailability Indicator



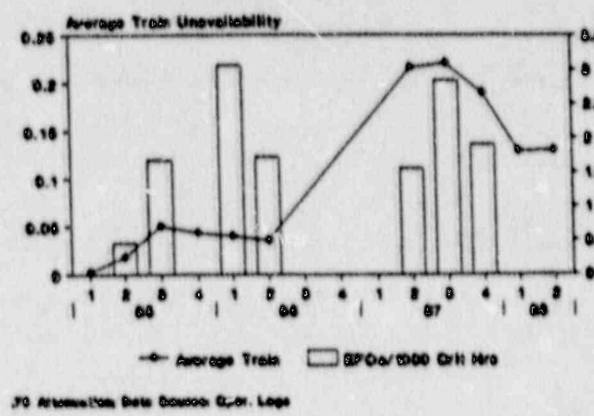
Plant 1 EPS
Unavailability Indicator



Plant 1 EPS
Unavailability Indicator

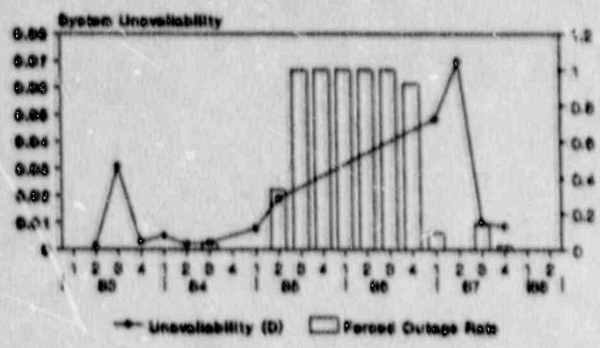


Plant 1 EPS
Unavailability Indicator



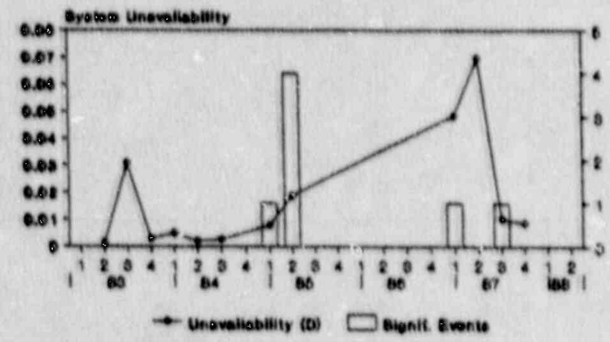
Note: Data collection period (83-2 through 88-2).

Plant 2 - AFWS
Unavailability Indicator
Definite Failures



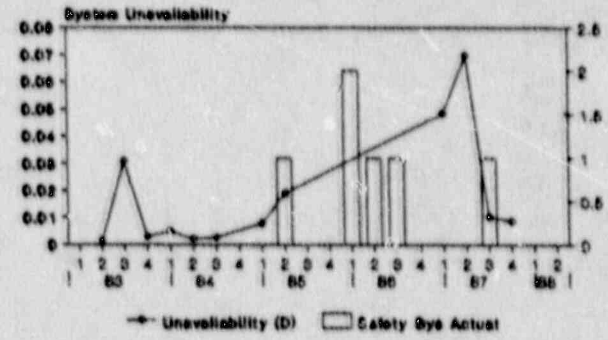
.75 Attenuation; Data Source: LOO Log

Plant 2 - AFWS
Unavailability Indicator
Definite Failures



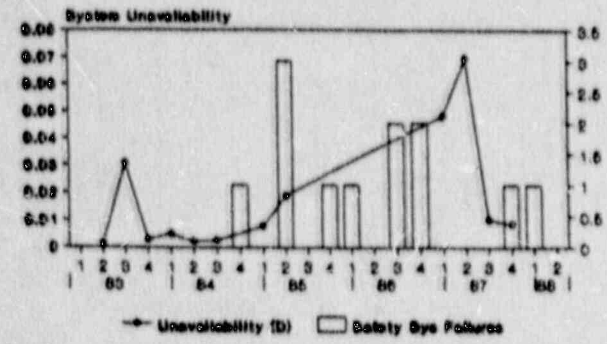
.75 Attenuation; Data Source: LOO Log

Plant 2 - AFWS
Unavailability Indicator
Definite Failures



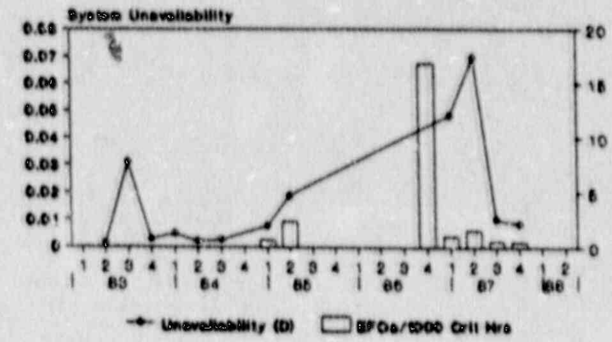
.75 Attenuation; Data Source: LOO Log

Plant 2 - AFWS
Unavailability Indicator
Definite Failures



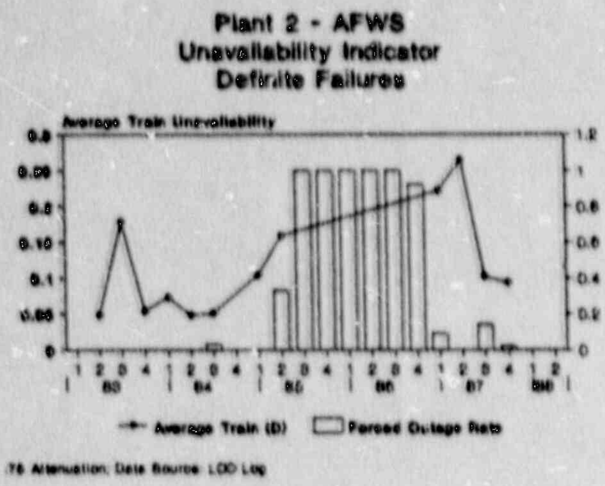
.75 Attenuation; Data Source: LOO Log

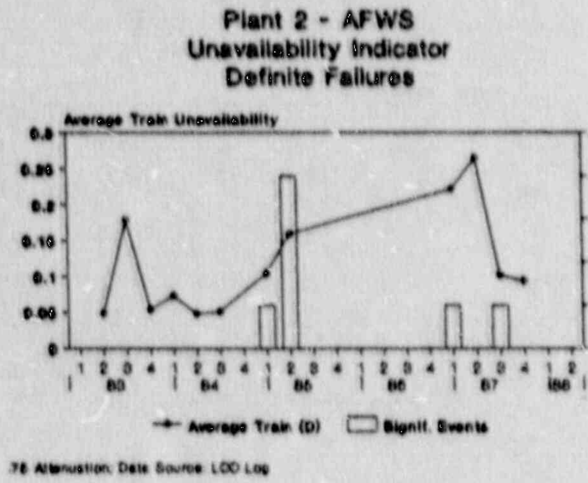
Plant 2 - AFWS
Unavailability Indicator
Definite Failures

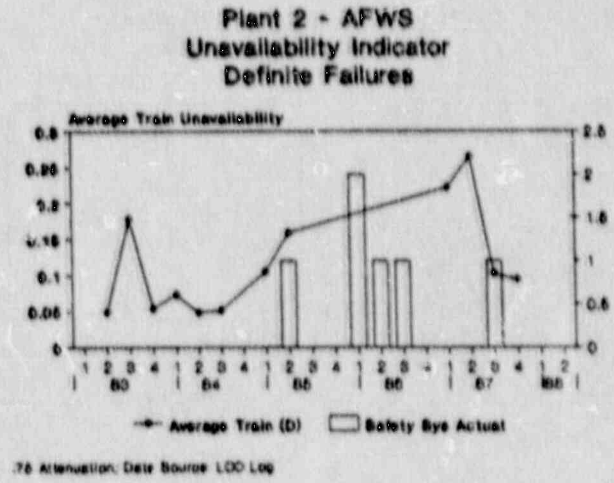


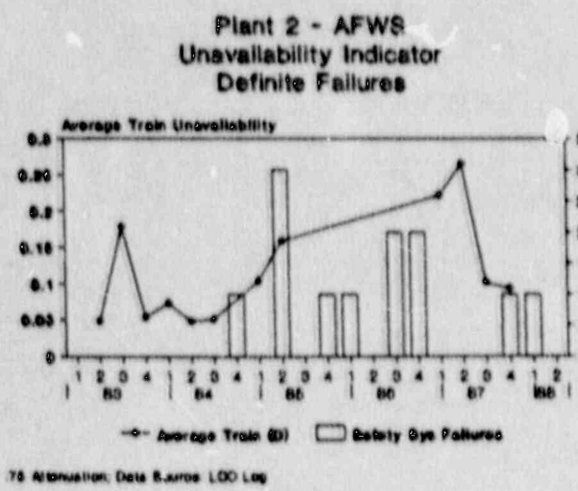
.75 Attenuation; Data Source: LOO Log

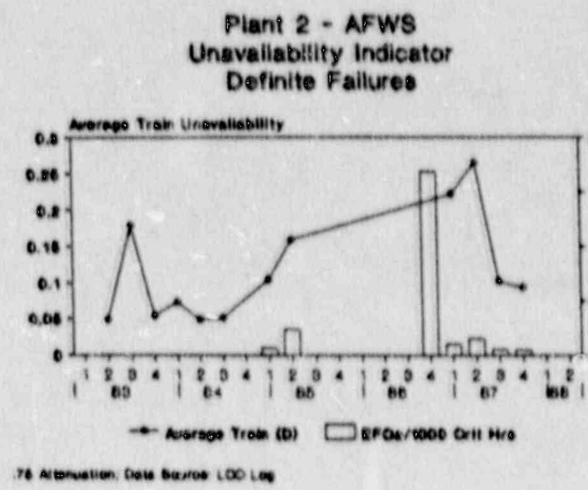
Note: Data collection period (83-2 through 88-2).





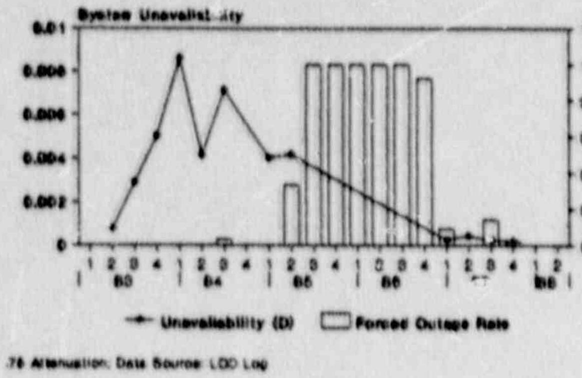




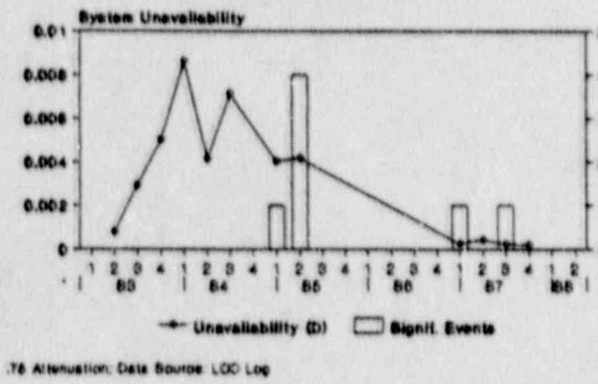


Note: Data collection period (83-2 through 88-2).

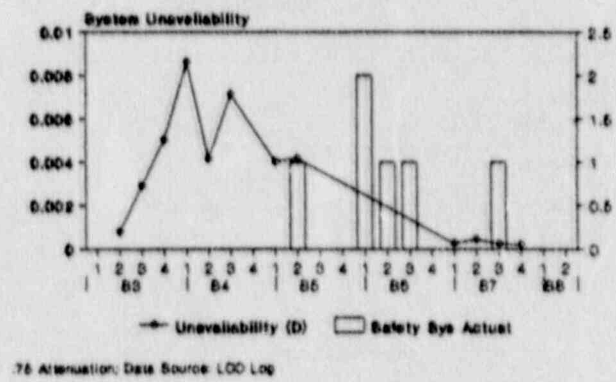
Plant 2 - EPS
Unavailability Indicator
Definite Failures



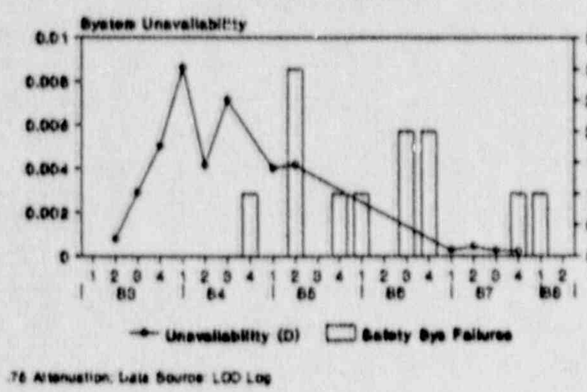
Plant 2 - EPS
Unavailability Indicator
Definite Failures



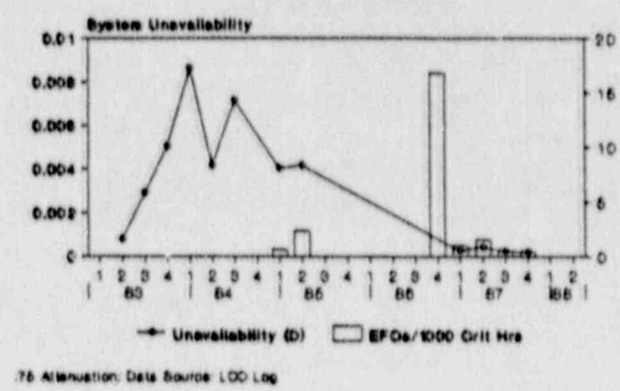
Plant 2 - EPS
Unavailability Indicator
Definite Failures



Plant 2 - EPS
Unavailability Indicator
Definite Failures

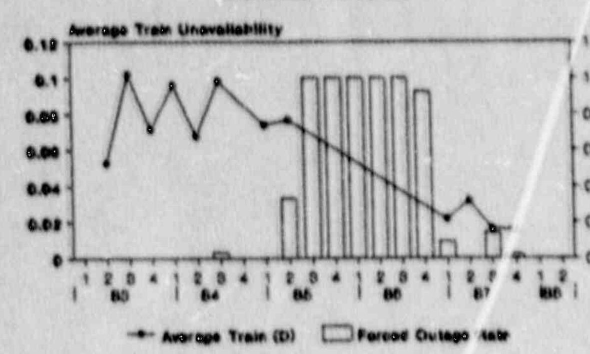


Plant 2 - EPS
Unavailability Indicator
Definite Failures



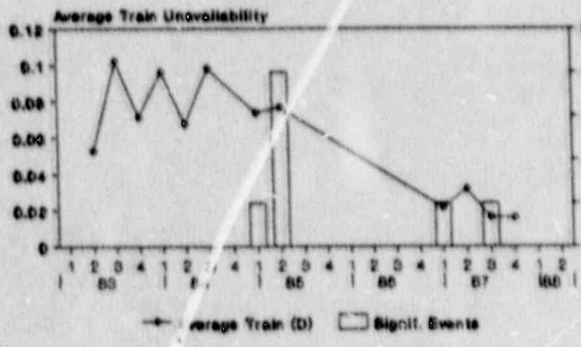
Note: Data collection period (83-2 through 88-2).

Plant 2 - EPS
Unavailability Indicator
Definite Failures



.75 Attenuation; Data Source: LCO Log

Plant 2 - EPS
Unavailability Indicator
Definite Failures



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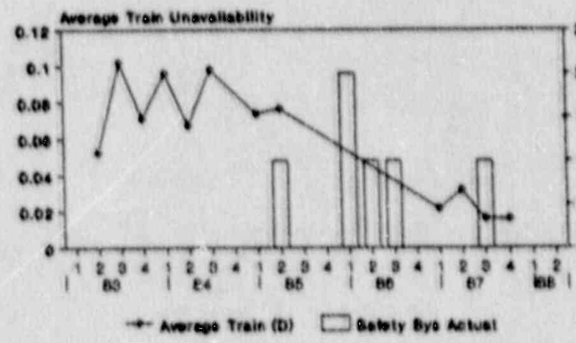
Plant 2 - EPS
Unavailability Indicator
Definite Failures



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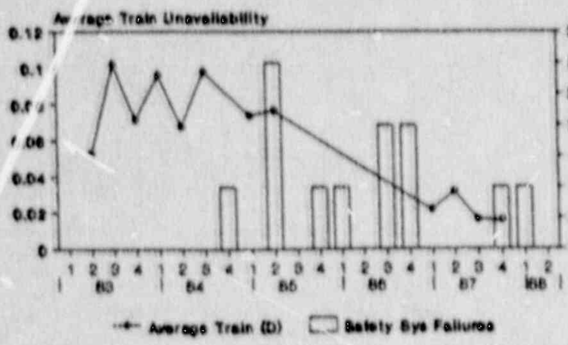
Plant 2 - EPS
Unavailability Indicator
Definite Failures



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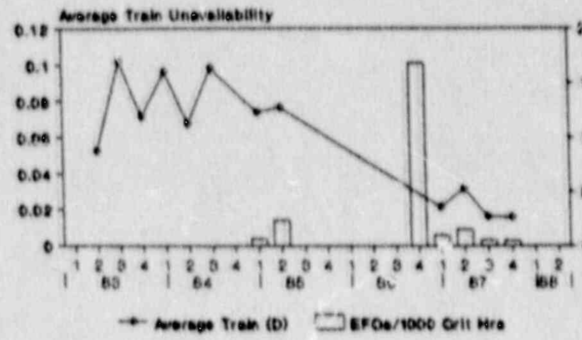
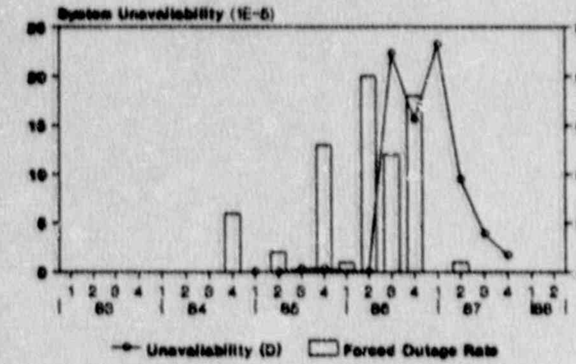
Plant 2 - EPS
Unavailability Indicator
Definite Failures



.75 Attenuation; Data Source: LCO Log

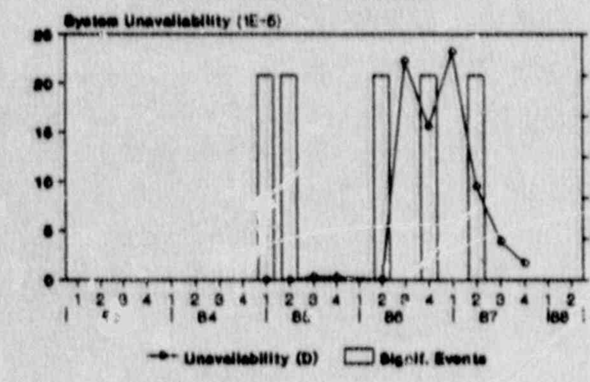
Note: Data collection period (83-2 through 88-2).

Plant 3 - AFWS
Unavailability Indicator



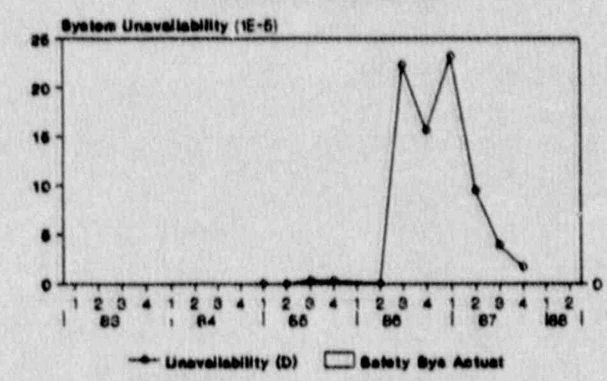
.76 Attenuation; Data Source: LCO Log

Plant 3 - AFWS
Unavailability Indicator



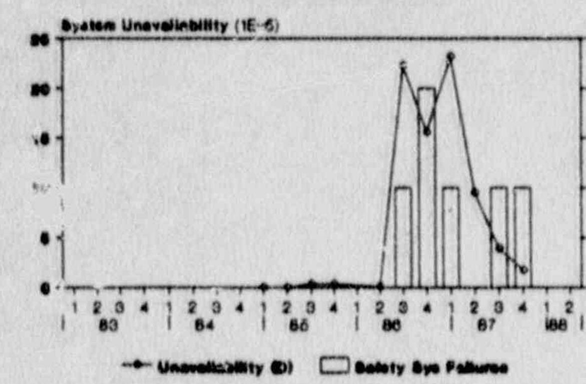
.76 Attenuation; Data Source: LCO Log

Plant 3 - AFWS
Unavailability Indicator



.76 Attenuation; Data Source: LCO Log

Plant 3 - AFWS
Unavailability Indicator



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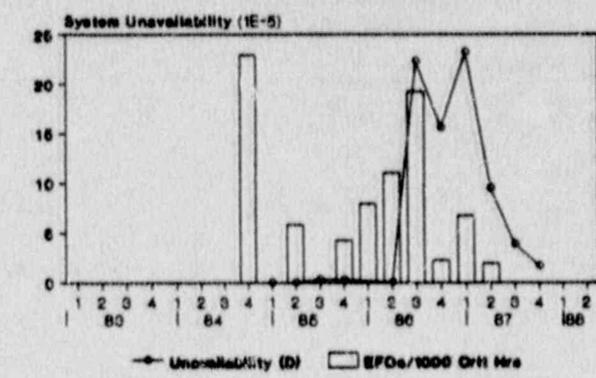
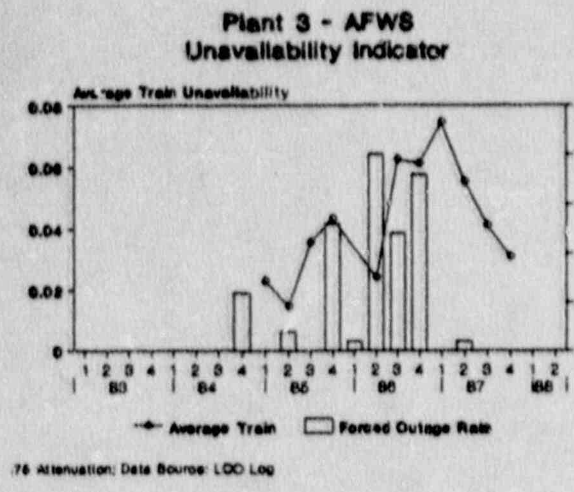
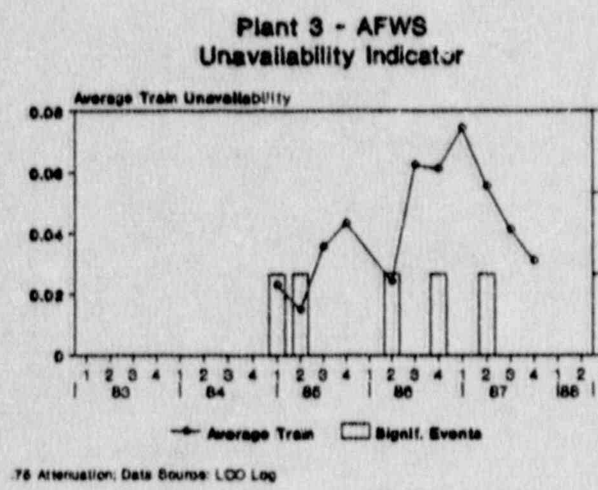
Plant 3 - AFWS
Unavailability Indicator

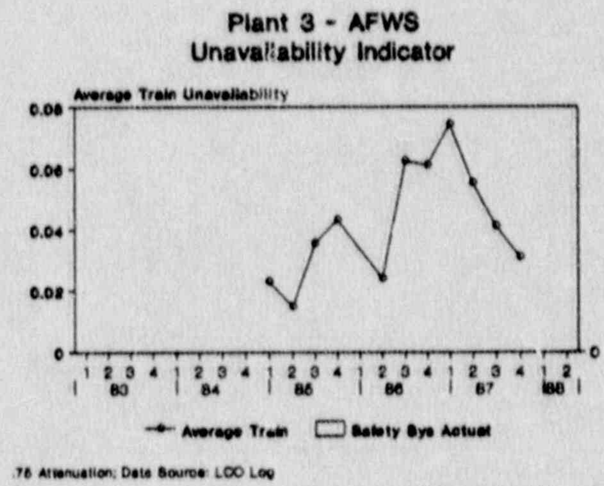


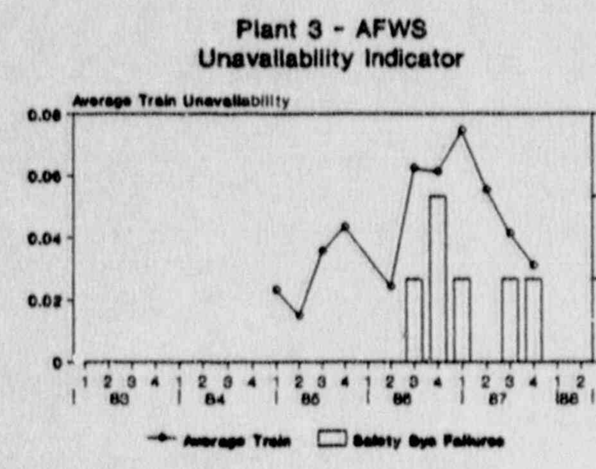
.76 Attenuation; Data Source: LCO Log

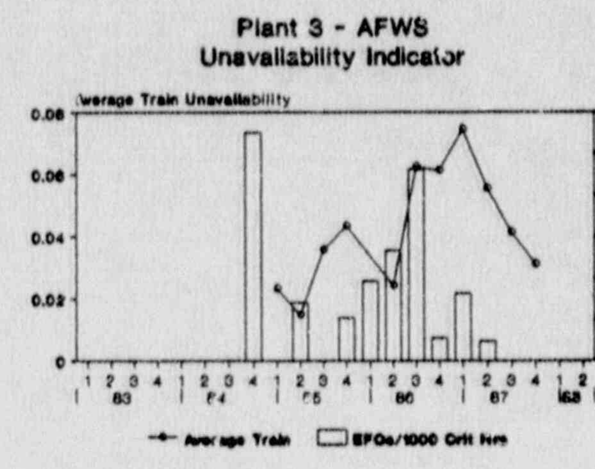
Note: Data collection period (85-1 through 87-4).





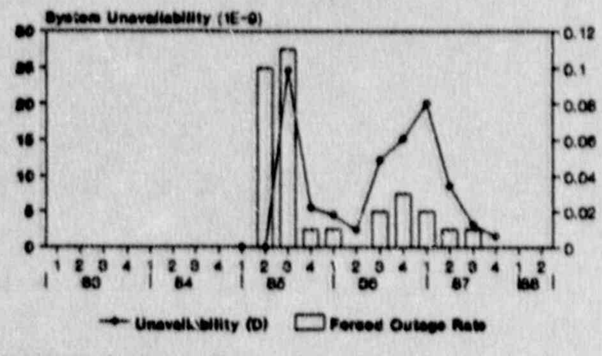






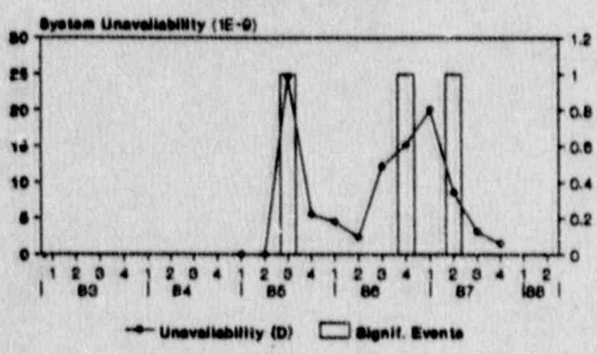
Note: Data collection period (85-1 through 87-4).

Plant 4 - AFWS
Unavailability Indicator
Definite Failures



.75 Attenuation; Data Source: LCO Log

Plant 4 - AFWS
Unavailability Indicator
Definite Failures



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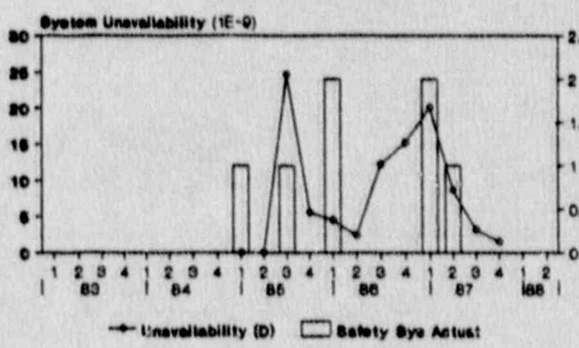
Plant 4 - AFWS
Unavailability Indicator
Definite Failures



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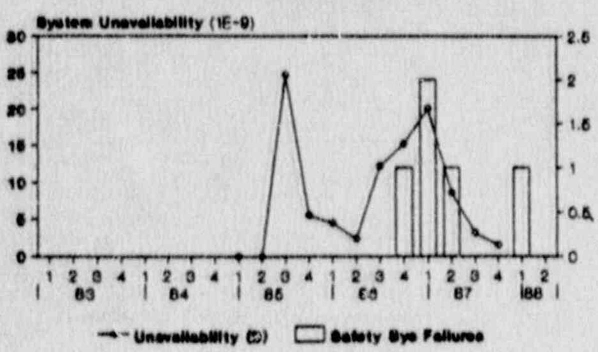
Plant 4 - AFWS
Unavailability Indicator
Definite Failures



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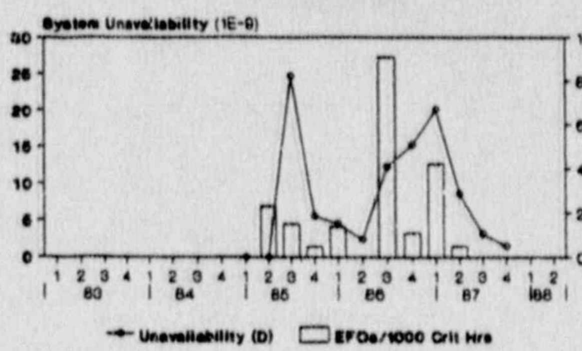
Plant 4 - AFWS
Unavailability Indicator
Definite Failures



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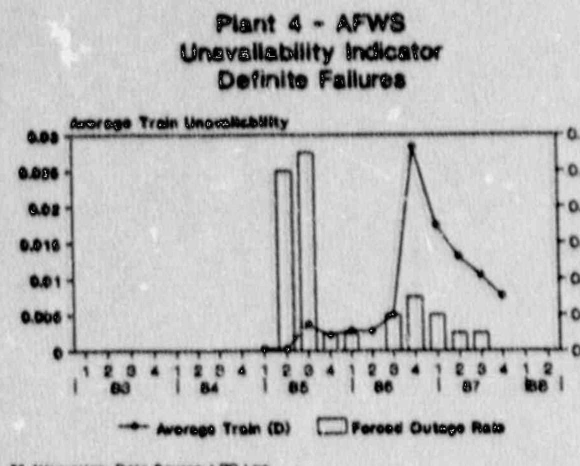
Note: Data collection period (85-1 through 87-4).



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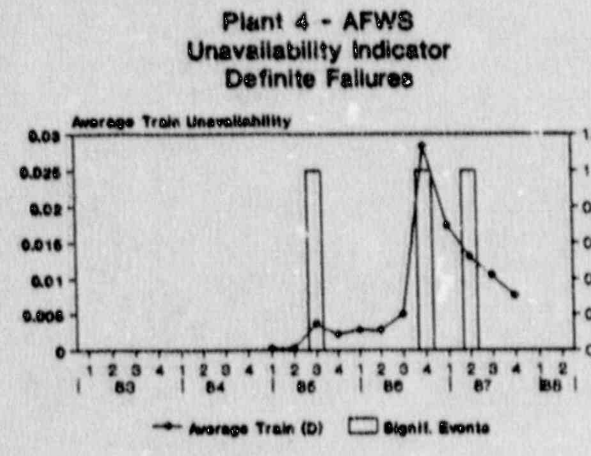

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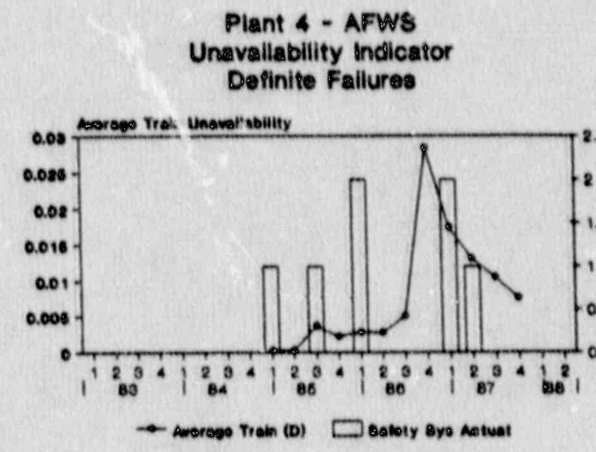

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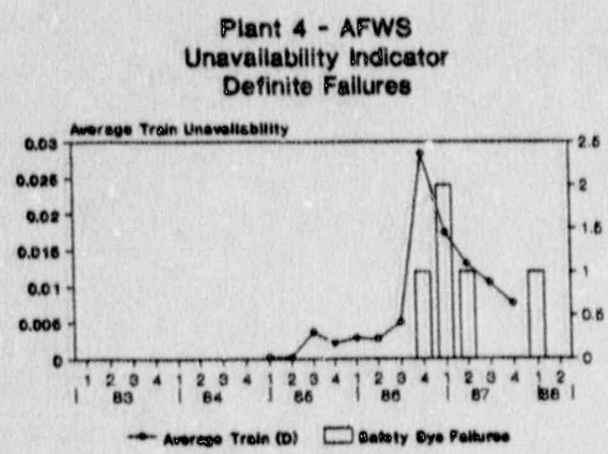

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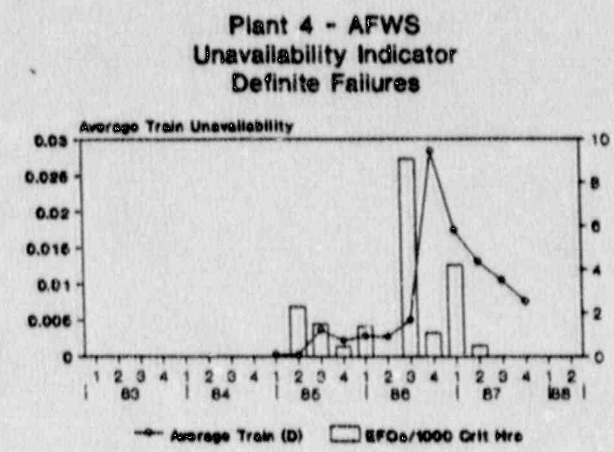
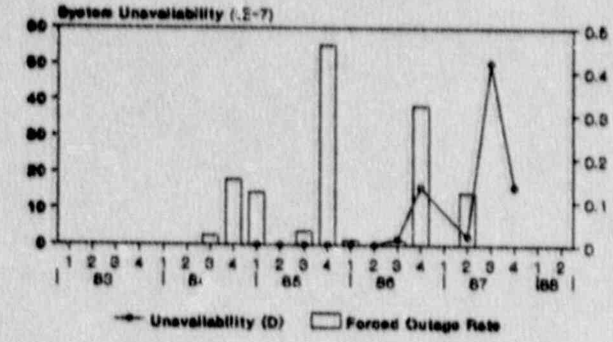


.75 Attenuation; Data Source: LCO Log

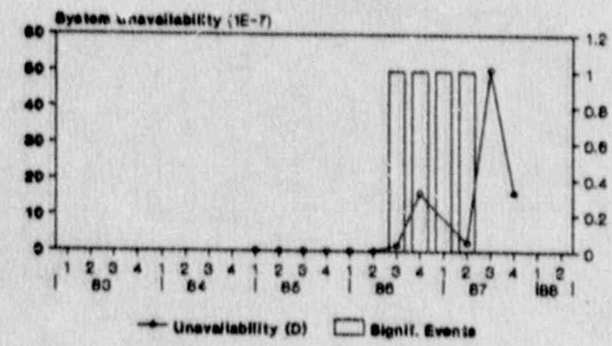
Note: Data collection period (85-1 through 87-4).

Plant 5 - AFWS
Unavailability Indicator
Definite Failures



.75 Attenuation; Data Source: LCO Log

Plant 5 - AFWS
Unavailability Indicator
Definite Failures



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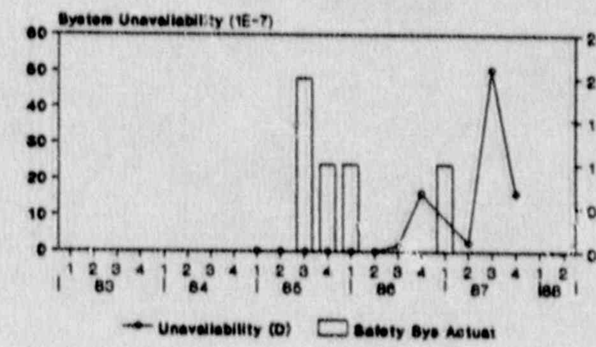
Plant 5 - AFWS
Unavailability Indicator
Definite Failures



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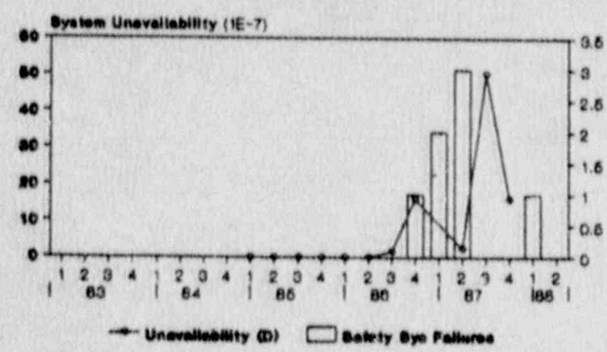
Plant 5 - AFWS
Unavailability Indicator
Definite Failures



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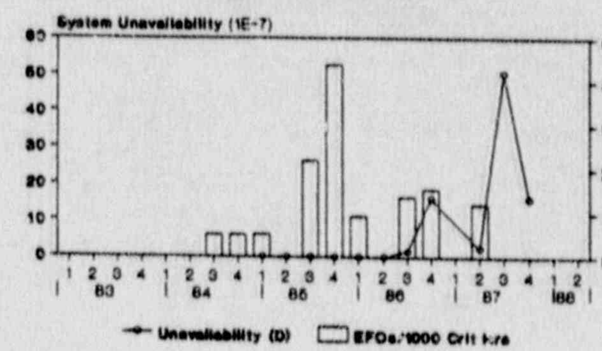
Plant 5 - AFWS
Unavailability Indicator
Definite Failures



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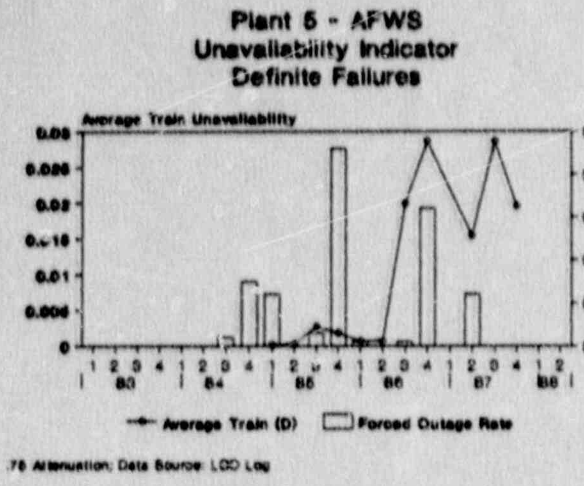
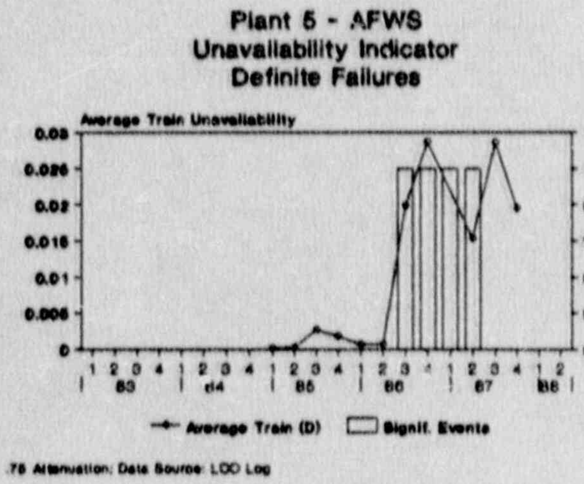
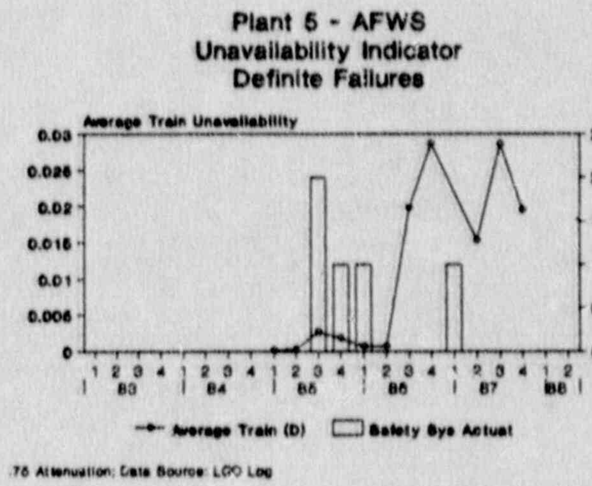
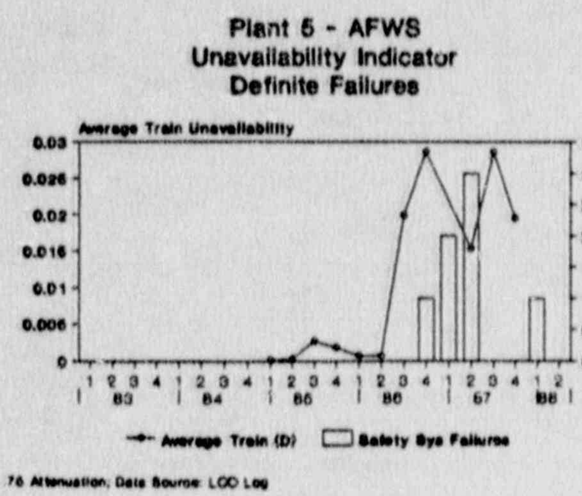
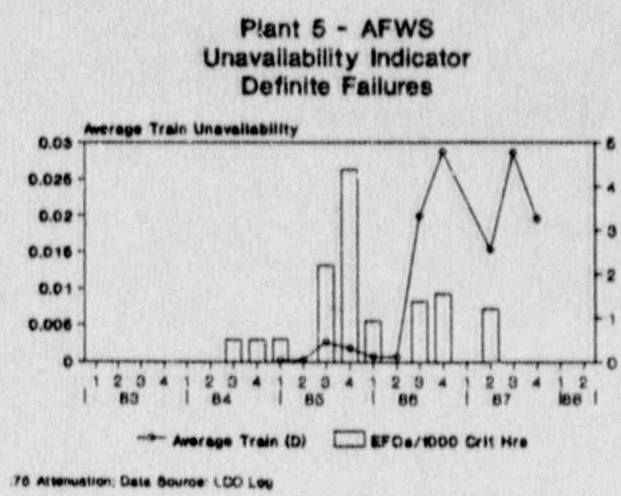
Note: Data collection period (85-1 through 87-4).





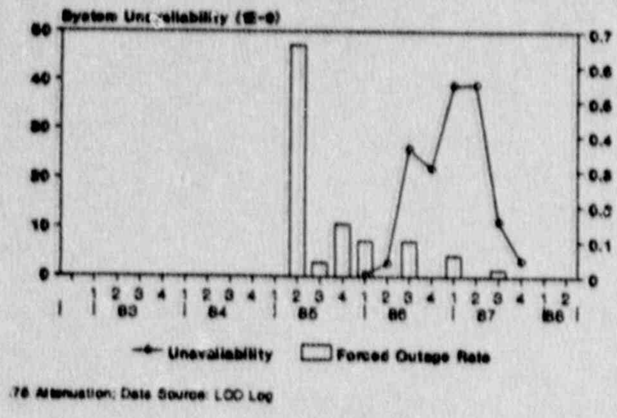




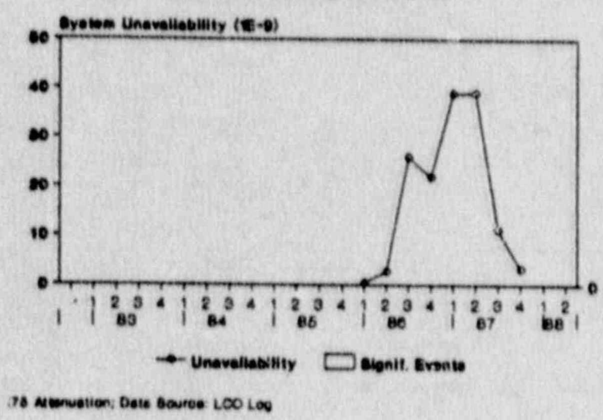


Note: Data collection period (85-1 through 87-4).

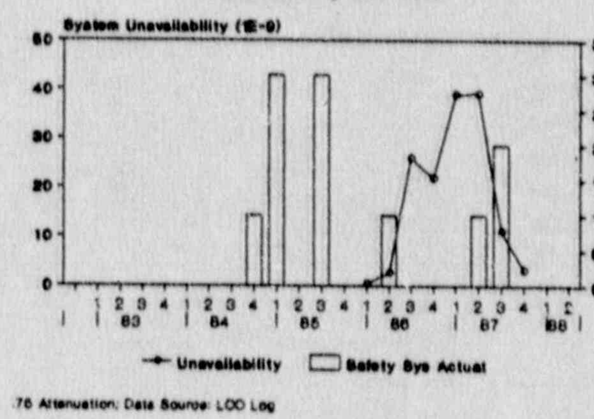
Plant 6 - EPS
Unavailability Indicator



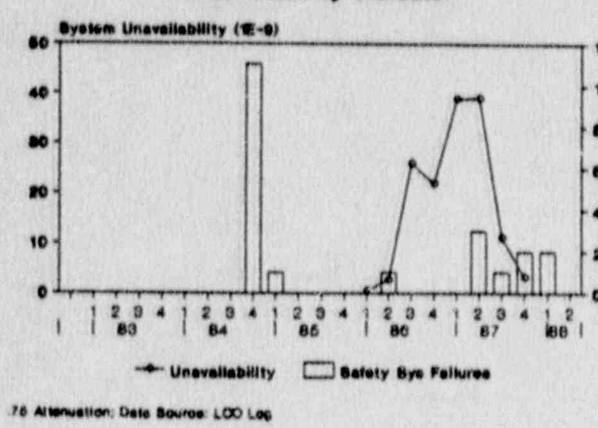
Plant 6 - EPS
Unavailability Indicator



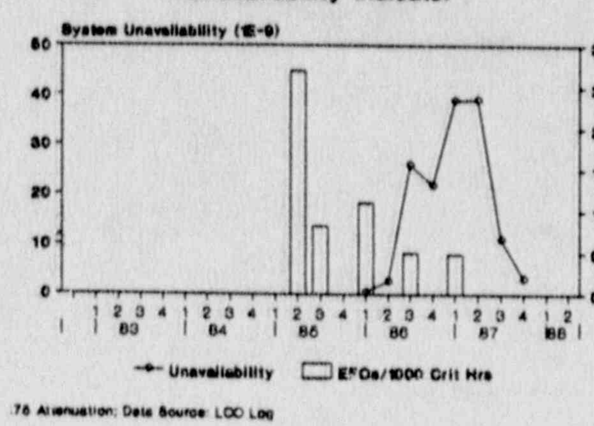
Plant 6 - EPS
Unavailability Indicator



Plant 6 - EPS
Unavailability Indicator

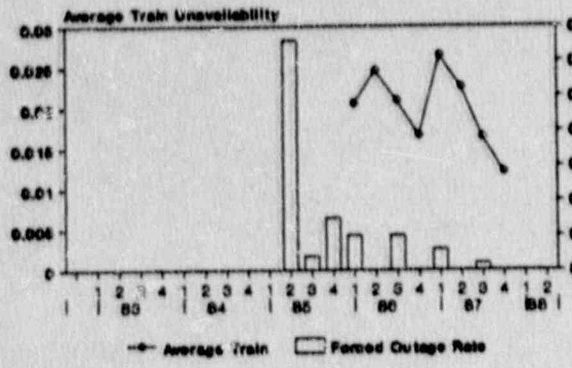


Plant 6 - EPS
Unavailability Indicator



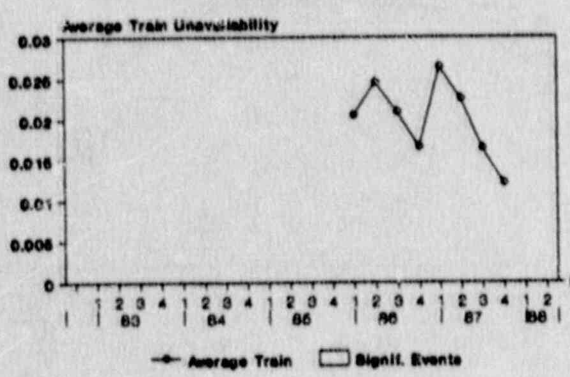
Note: Data collection period (86-1 through 87-2).

Plant 6 - EPS
Unavailability Indicator



.75 Attenuation; Data Source: LCO Log

Plant 6 - EPS
Unavailability Indicator



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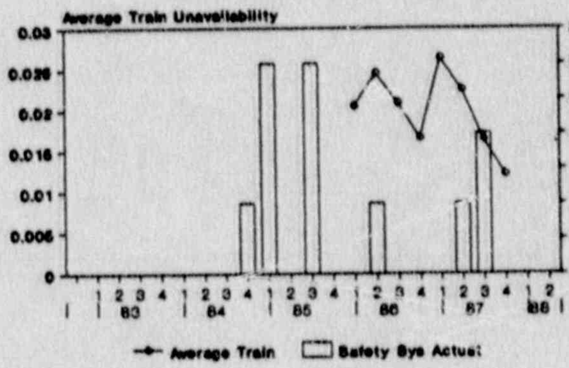
Plant 6 - EPS
Unavailability Indicator



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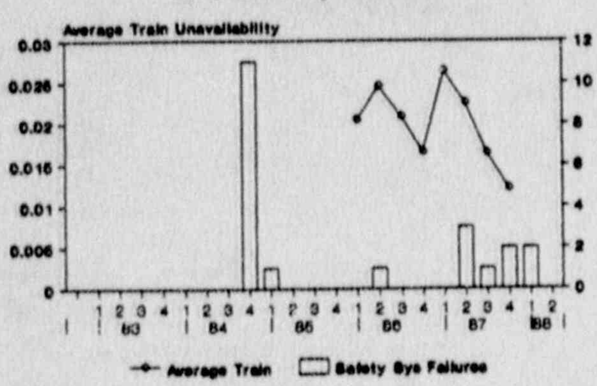
Plant 6 - EPS
Unavailability Indicator



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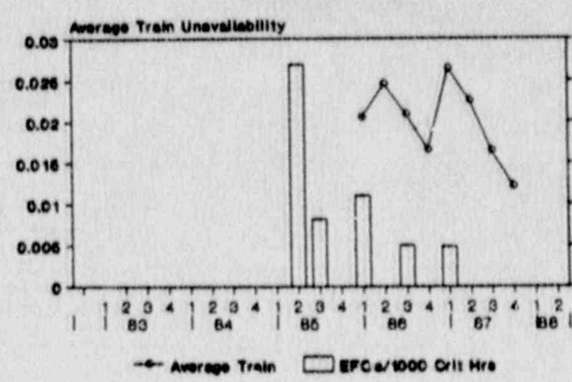
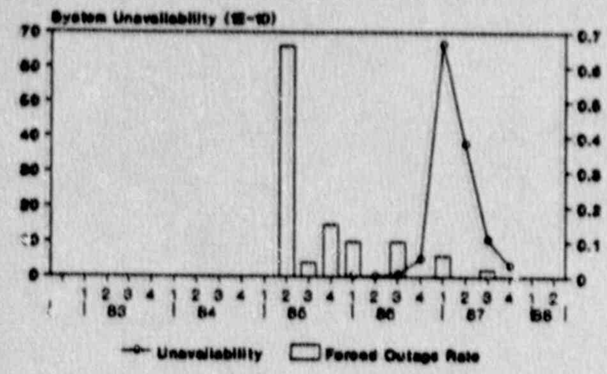
Plant 6 - EPS
Unavailability Indicator



.75 Attenuation; Data Source: LCO Log

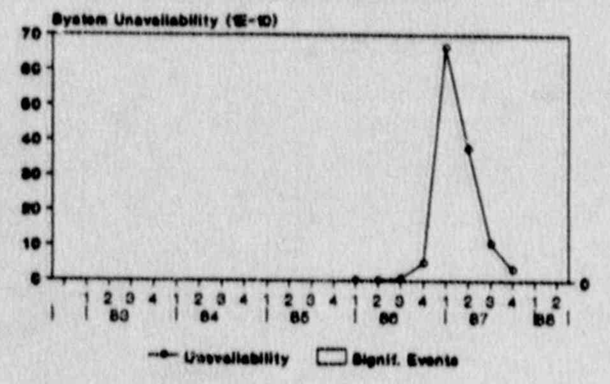
Note: Data collection period (86-1 through 87-2).

Plant 6 - RHRSW
Unavailability Indicator



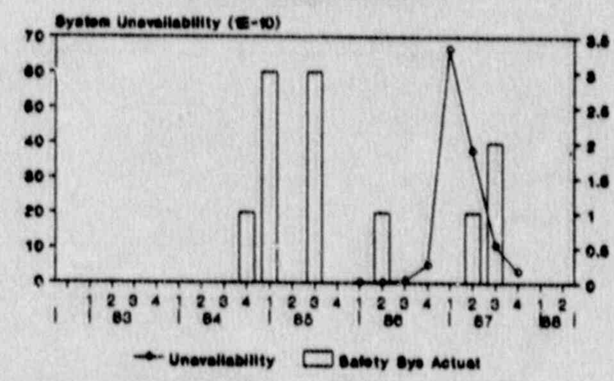
.75 Attenuation; Data Source: LCO Log

Plant 6 - RHRSW
Unavailability Indicator



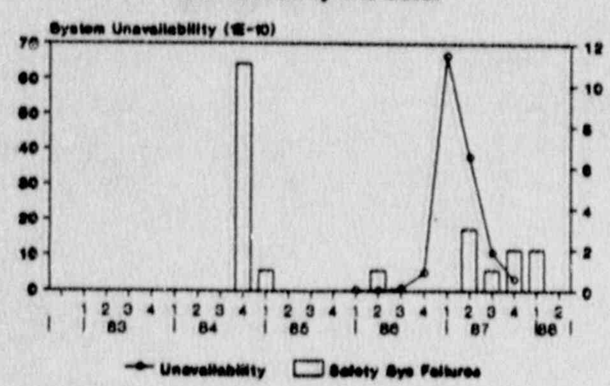
.75 Attenuation; Data Source: LCO Log

Plant 6 - RHRSW
Unavailability Indicator



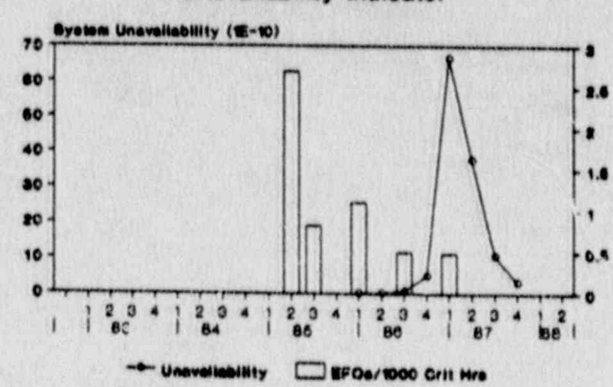
.75 Attenuation; Data Source: LCO Log

Plant 6 - RHRSW
Unavailability Indicator



.75 Attenuation; Data Source: LCO Log

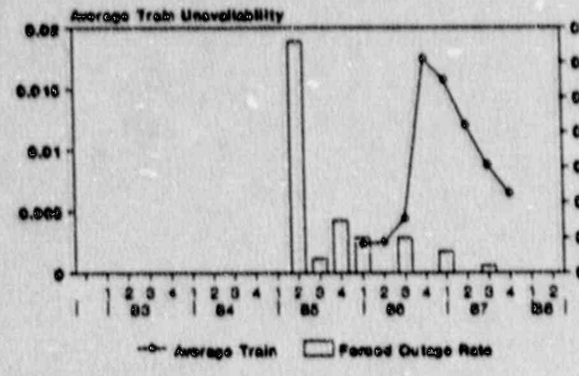
Plant 6 - RHRSW
Unavailability Indicator



.75 Attenuation; Data Source: LCO Log

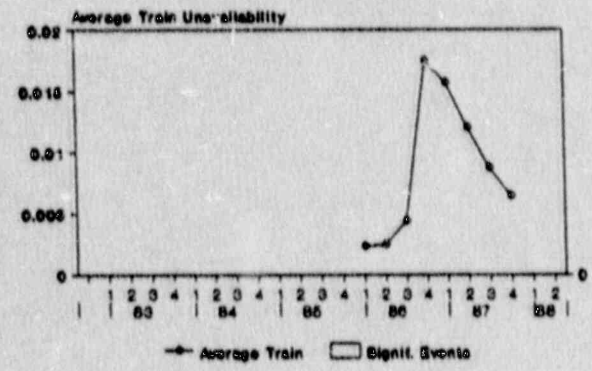
Note: Data collection period (86-1 through 87-2).

Plant 6 - RHRSW
Unavailability Indicator



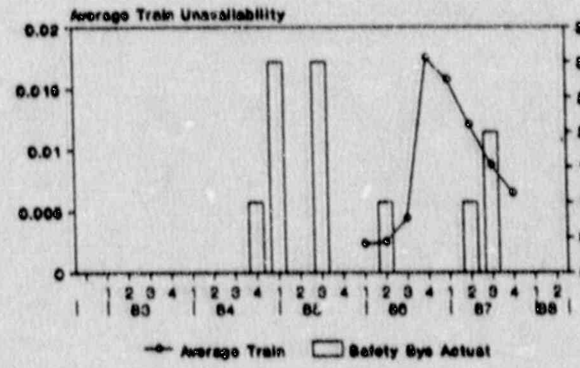
.76 Attenuation; Data Source: LCO Log

Plant 6 - RHRSW
Unavailability Indicator



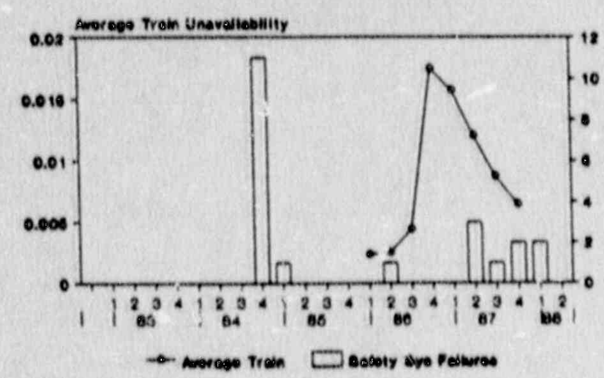
.76 Attenuation; Data Source: LCO Log

Plant 6 - RHRSW
Unavailability Indicator



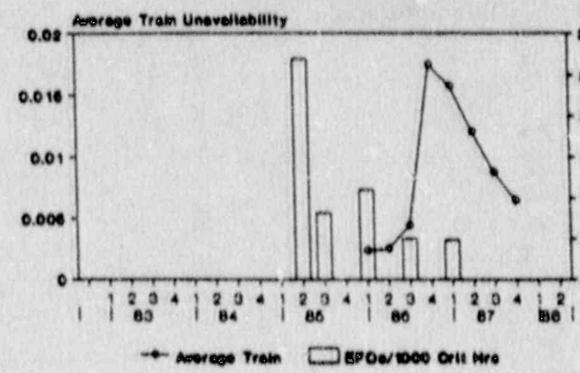
.76 Attenuation; Data Source: LCO Log

Plant 6 - RHRSW
Unavailability Indicator



.76 Attenuation; Data Source: LCO Log

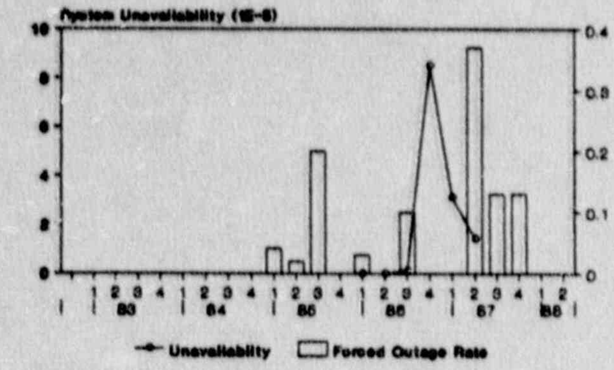
Plant 6 - RHRSW
Unavailability Indicator



.76 Attenuation; Data Source: LCO Log

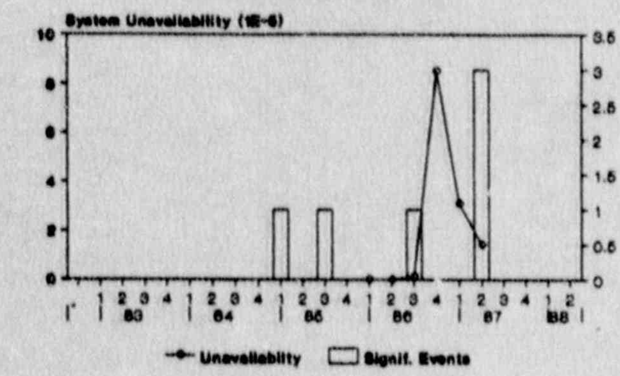
Note: Data collection period (86-1 through 87-2).

Plant 7 - AFWS Unavailability Indicator



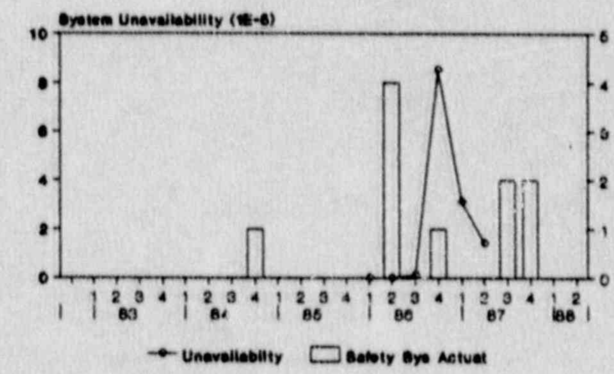
.76 attenuation, Data Source: LCO Log

Plant 7 - AFWS Unavailability Indicator



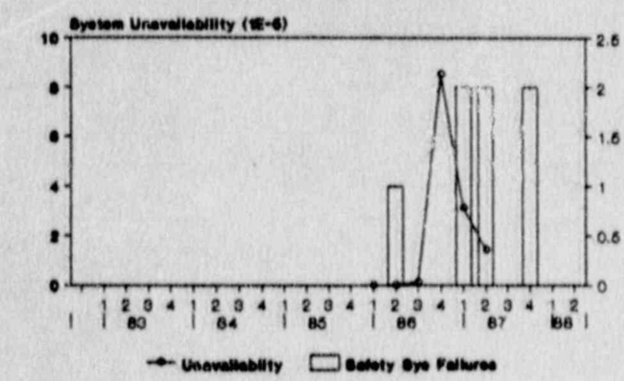
.76 attenuation, Data Source: LCO Log

Plant 7 - AFWS Unavailability Indicator



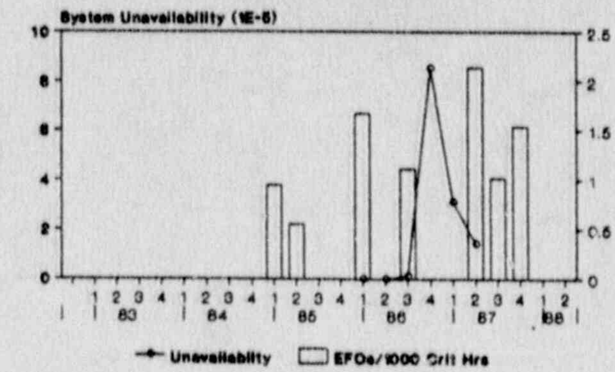
.76 attenuation, Data Source: LCO Log

Plant 7 - AFWS Unavailability Indicator



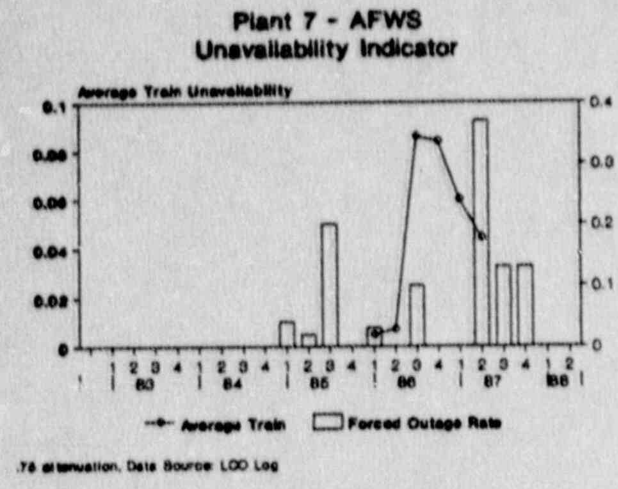
.76 attenuation, Data Source: LCO Log

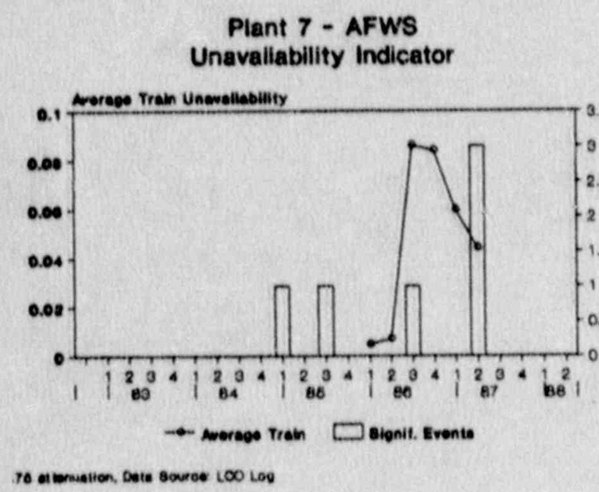
Plant 7 - AFWS Unavailability Indicator

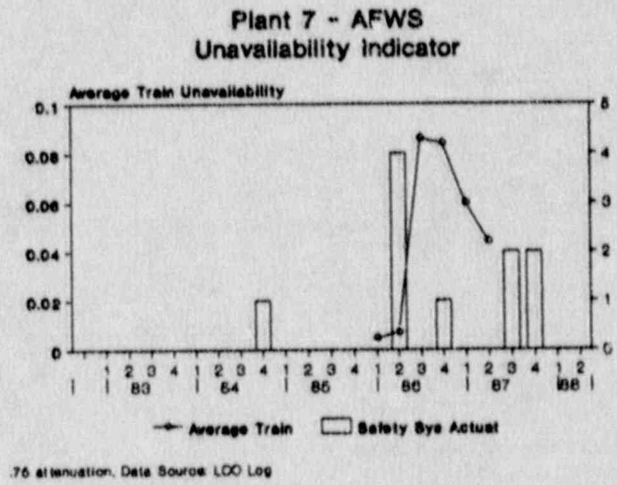


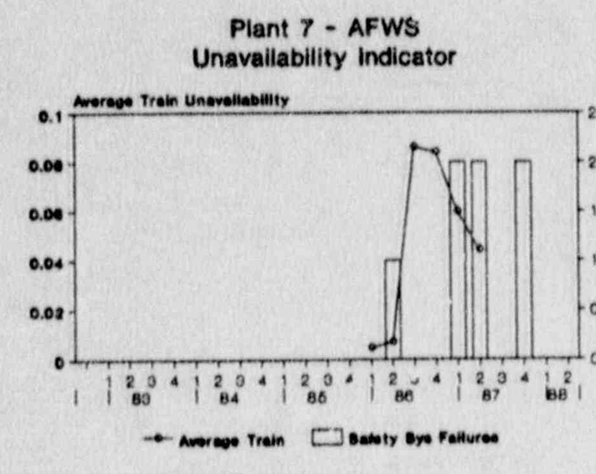
.76 attenuation, Data Source: LCO Log

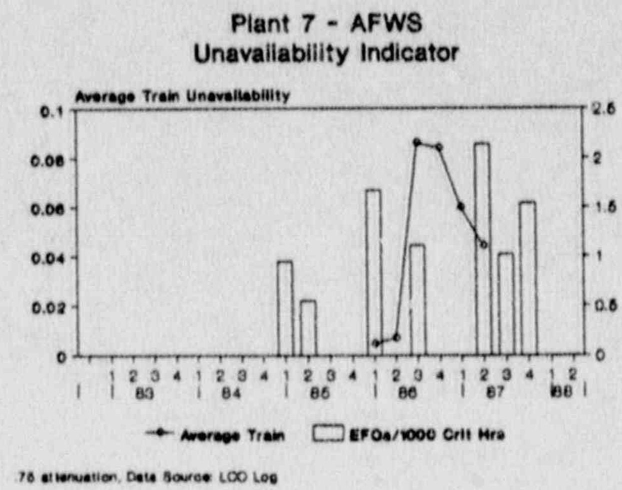
Note: Data collection period (86-1 through 87-2).



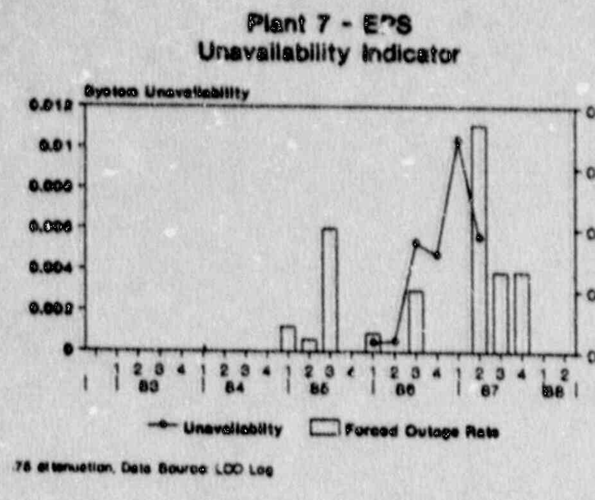


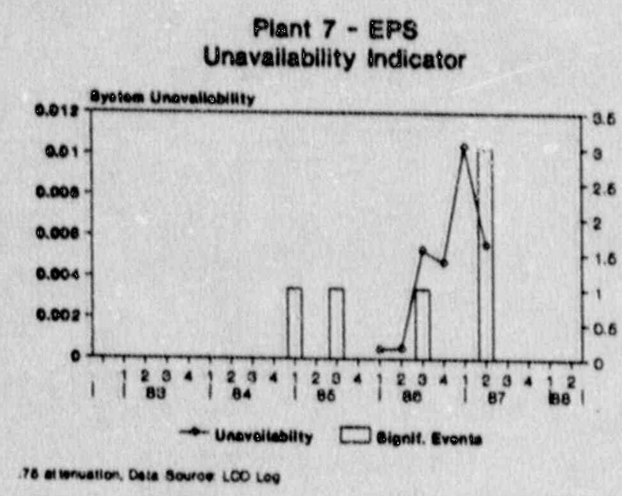


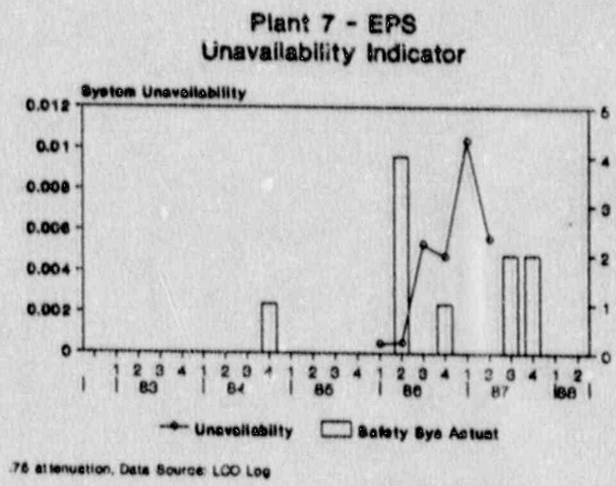


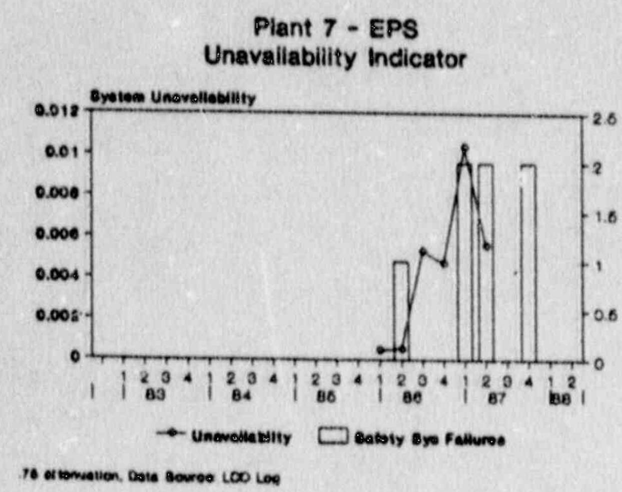


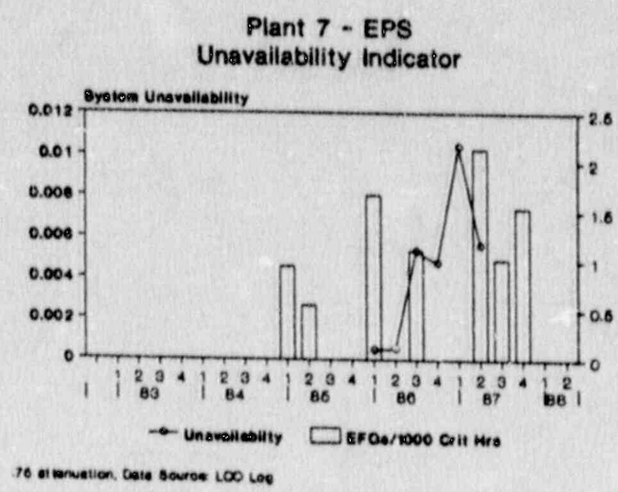
Note: Data collection period (86-1 through 87-2).





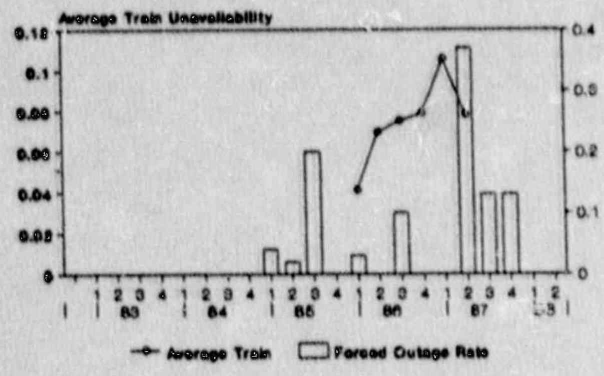






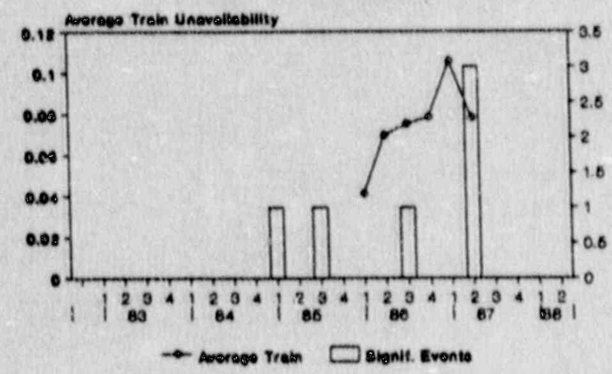
Note: Data collection period (86-1 through 87-2).

Plant 7 - EPS
Unavailability Indicator



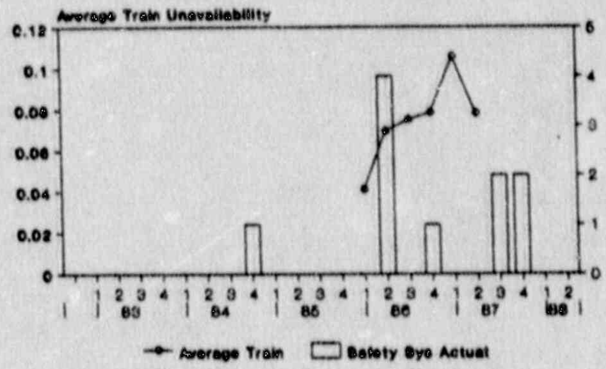
.75 attenuation, Data Source: LCO Log

Plant 7 - EPS
Unavailability Indicator



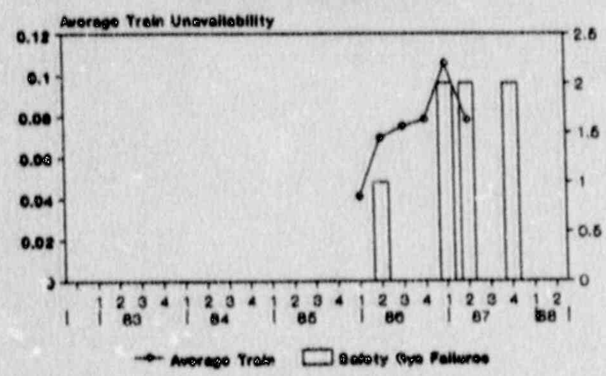
.75 attenuation, Data Source: LCO Log

Plant 7 - EPS
Unavailability Indicator



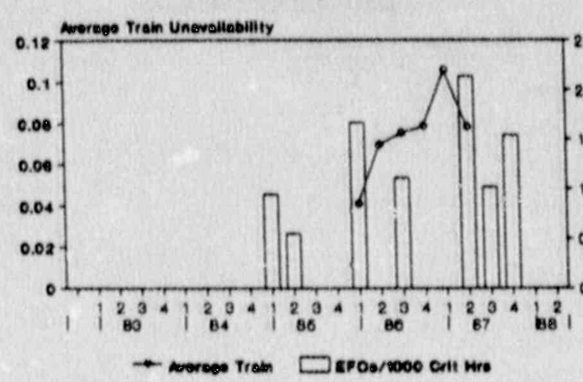
.75 attenuation, Data Source: LCO Log

Plant 7 - EPS
Unavailability Indicator



.75 attenuation, Data Source: LCO Log

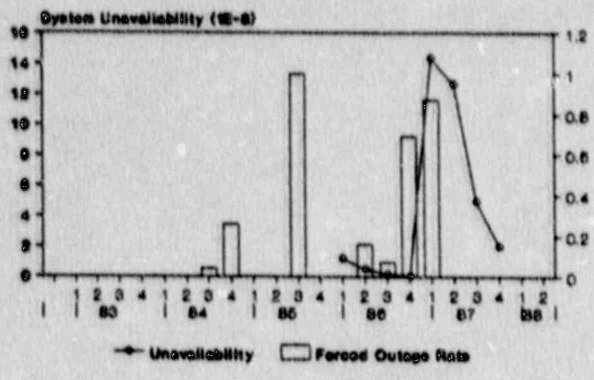
Plant 7 - EPS
Unavailability Indicator



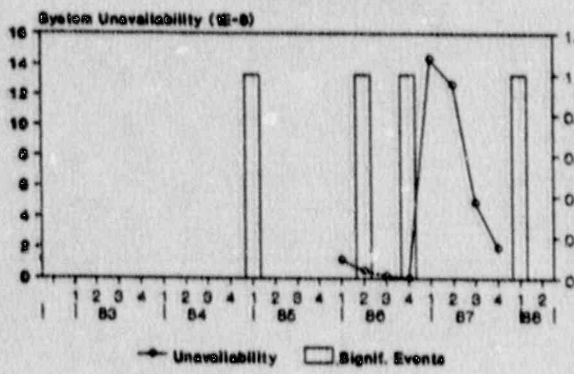
.75 attenuation, Data Source: LCO Log

Note: Data collection period (86-1 through 87-2).

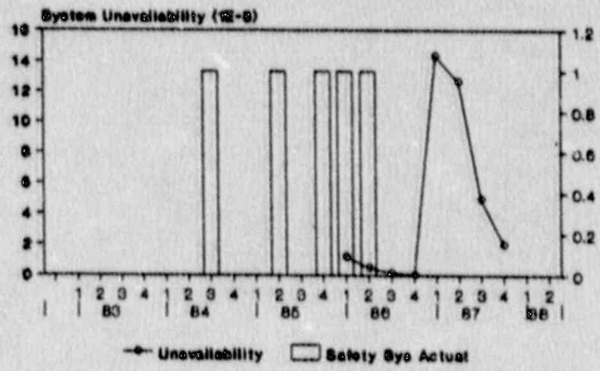
Plant 8 - AFWS
Unavailability Indicator



Plant 8 - AFWS
Unavailability Indicator



Plant 8 - AFWS
Unavailability Indicator



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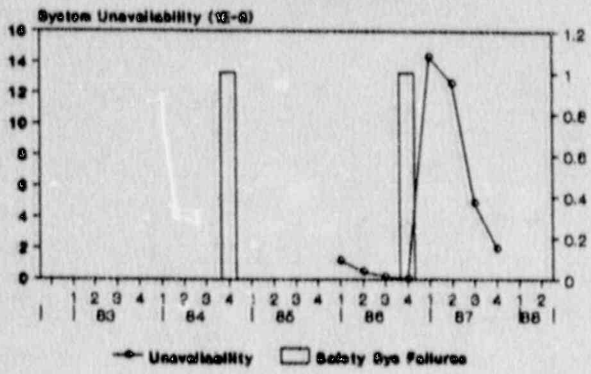
Unavailability Indicator



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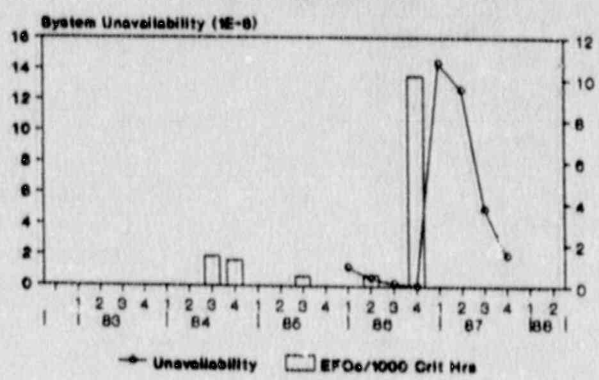
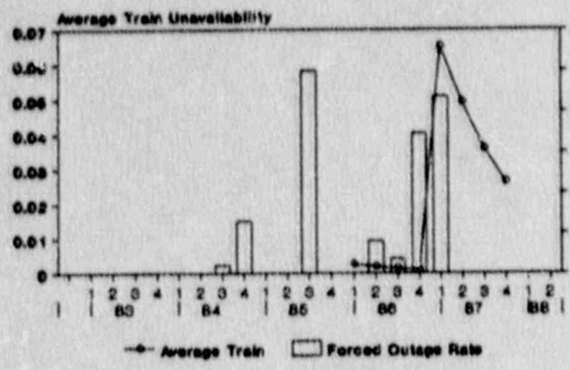
Unavailability Indicator

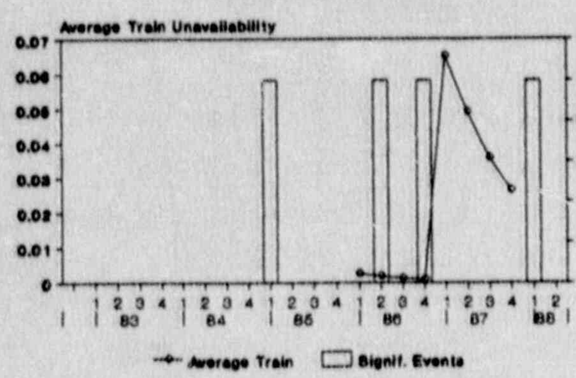


Note: Data collection period (86-1 through 87-2).

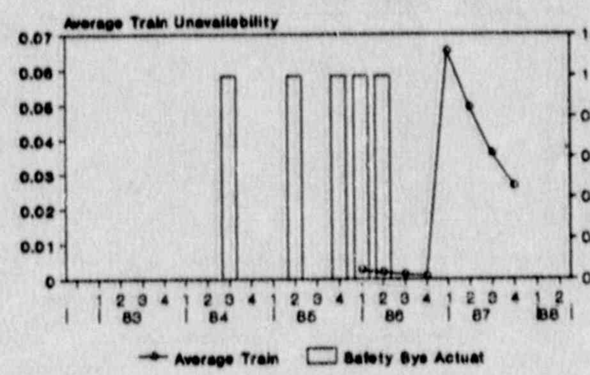
Plant 8 - AFWS
Unavailability Indicator



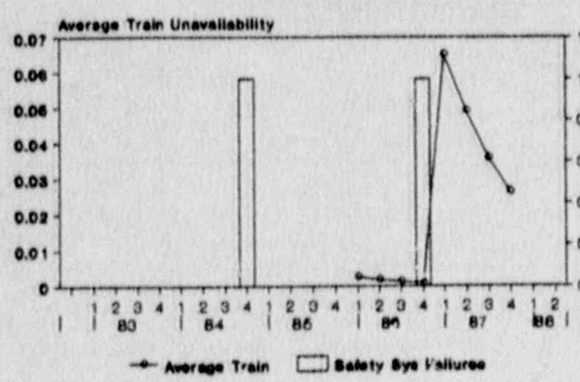
Plant 8 - AFWS
Unavailability Indicator



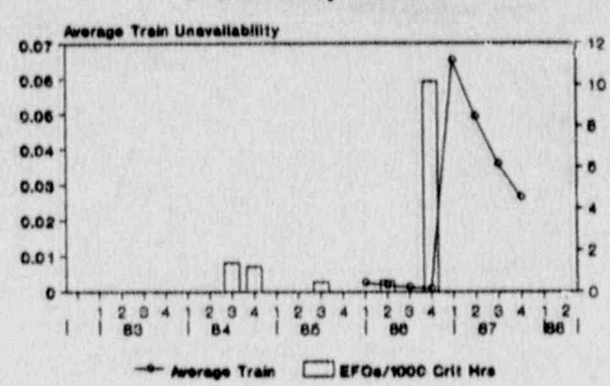
Plant 8 - AFWS
Unavailability Indicator



Plant 8 - AFWS
Unavailability Indicator

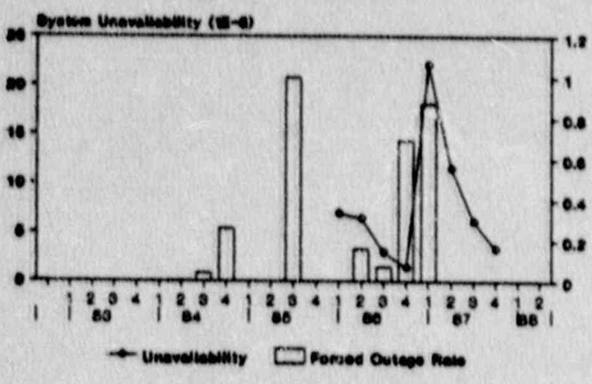


Plant 8 - AFWS
Unavailability Indicator

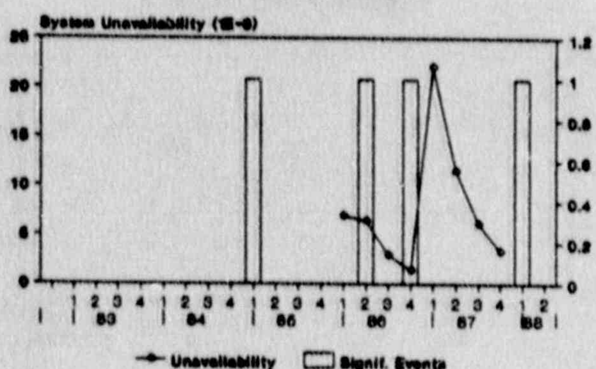


Note: Data collection period (86-1 through 87-2).

Plant 8 - EPS
Unavailability Indicator



Plant 8 - EPS
Unavailability Indicator



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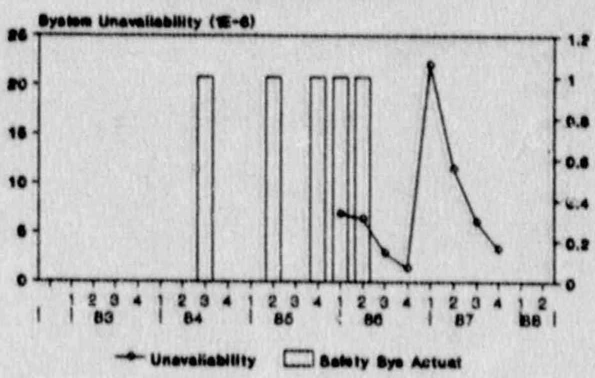
Unavailability Indicator



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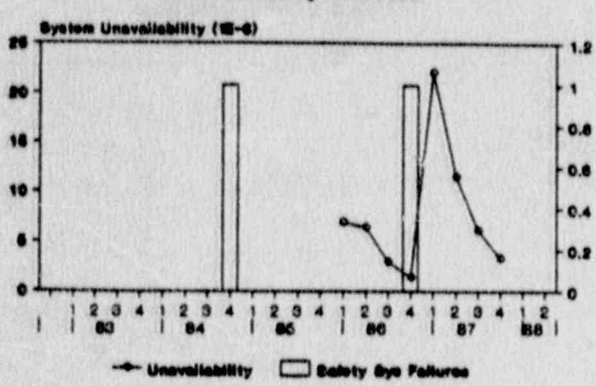
Unavailability Indicator



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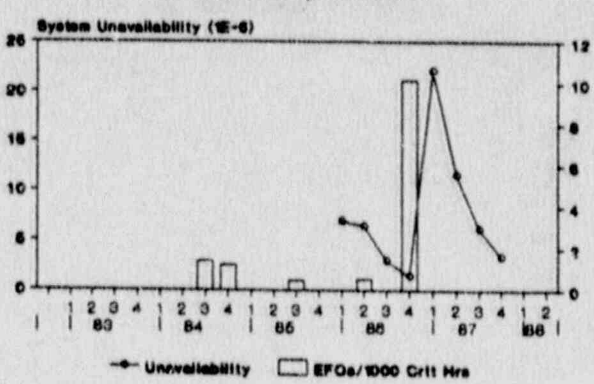
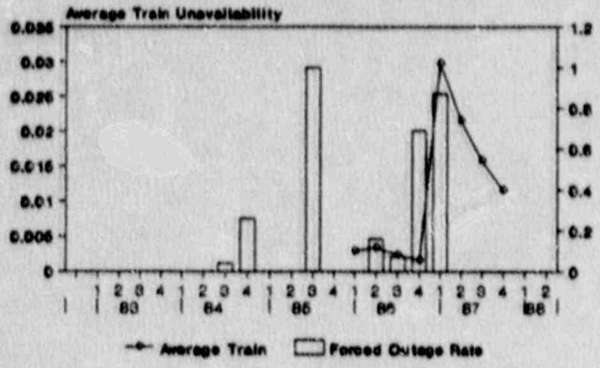
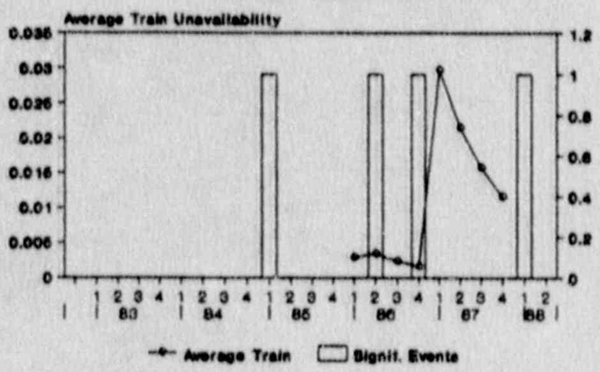


Note: Data collection period (86-1 through 87-2).

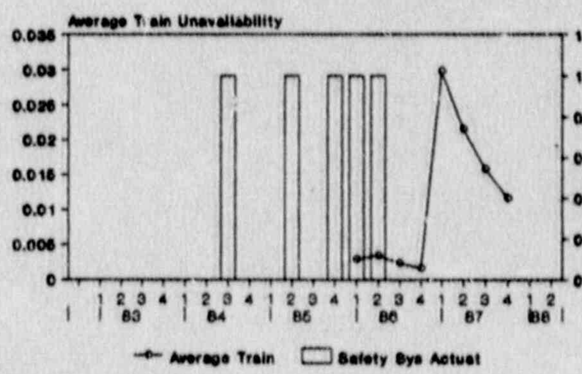
Plant 8 - EPS
Unavailability Indicator



Plant 8 - EPS
Unavailability Indicator



Plant 8 - EPS
Unavailability Indicator



Plant 8 - EPS
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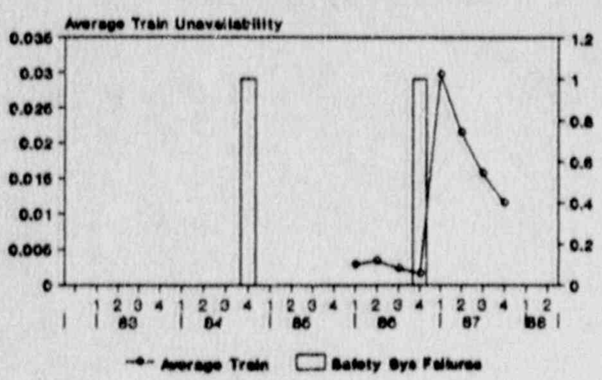
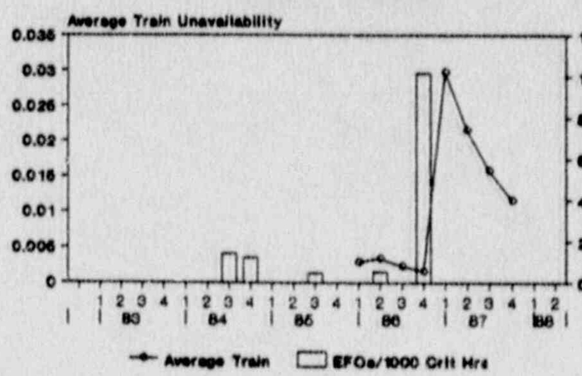


Plant 8 - EPS
Unavailability Indicator



Note: Data collection period (86-1 through 87-2).

APPENDIX G. CROSS-CORRELATIONS OF R, NRC'S CURRENT SET OF INDICATORS, WITH Q, UNAVAILABILITY INDICATORS

Assume we are investigating the behavior of two indicators x(t) and y(t) over time points t = 1, ... n, measured at several plants. A natural question to ask regarding this data is: are x and y correlated? A simple way to investigate this questions is to calculate the correlation of x and y within each plant. We may inspect either the correlation coefficient within each plant, or perhaps, look at the average of the correlation coefficients across plants.

One drawback to looking at each plant correlation coefficient is that we are inspecting a number of statistics simultaneously. The problem encountered is one of judging statistical significance of results. Usually we judge a correlation coefficient to be significant if it is so far from zero that the probability of its being this far by accident is, for example, less than 0.05. If we have such an aberrant coefficient, we conclude that it is probably not by accident; that is, x and y are actually related. Now if, instead of having only one such coefficient, we had 100, then about five of them would be "significant" at 0.05 just by accident. Clearly in this case we must do something other than use a significance level of 0.05 when deciding if results have occurred by accident or not. The problem we have just alluded to is called the Simultaneous Testing problem. There are several solutions to it. In our case, one solution is to inspect the average of the coefficients, rather than the entire collection of coefficients.

Table G.1 lists the entire collection of within-plant correlation coefficients between contemporaneous indicator values, whereas in Table G.2, we present the across-plant averages of the values of Table G.1. For example, Table G.1 reveals that, in Plant 1, the correlation between EFO and QS(AFW) is .274, and Table G.2 reveals that the across-plant average for the correlation between EFO and QS(AFW) is .0611.

Together with the across plant averages, we present measures of significance. These have been calculated with the aid of Fisher's z-transformation. If r is a correlation coefficient based on n pairs of numbers, then:

$$z = 0.5 * \log((1 + r)/(1-r))$$

has a roughly normal distribution variance:

$$1/(n-3)$$

Given a set of m z-values z(1), ... z(m), we perform two tests:

1) Test for Heterogeneity: If the z-values all reflect the same (unknown) level of correlation, then sum ((z(i) - zbar)**2) should follow a chi-squared distribution with m-1 degrees of freedom. If a heterogeneity test is non-significant (significance value is large), this means that the within-plant correlations are probably all about

the same, and the across-plant average is a reasonable estimate of these correlations. However, if the heterogeneity test is significant (significance value is small), then correlations vary across plants, so that the plant average is probably not an interesting estimator of anything. For example, a test of the heterogeneity of the correlations between EFO and QS(AFW) has a significance of .0545. Considering this test alone, we would be led to suspect that the correlation might vary from one plant to another, so that the average value (.0611) has very little meaning. Indeed, Table G.1 shows correlations ranging from -.025 (plant 4) to .775 (plant 3).

2) Test Against Zero Correlation: If all the z-values reflect a correlation of zero, then sum (z**2) should follow a chi-squared distribution with n degrees of freedom. Significance of this test indicates that at least one plant has a non-zero correlation, whereas non-significance indicates that all plants have zero correlations. It makes little sense to do this test unless the heterogeneity test is non-significant. For example, the correlation between SSF and QS(AFW) is not heterogenous (significance .6148, Table G.2), and also not significantly different from zero (significance .6886, Table G.3). Table G.1 reveals that the actual correlations range from -.454 to .333.

One of the difficulties of this approach is that, for the z-transformation to guarantee approximate normality, the distribution of x and y values should not be too extreme; data sets consisting only of 0's or 1's will probably not result in very normal z-transformations, especially if there are only a few pairs of indicator values (<20) supporting each coefficient, as here. It happens that many of the observed distributions of indicator values are rather extreme. Below, we show the percent of unique (i.e., not repeated) data values within each plant for every indicator. In our calculation of across-plant averages and significance values, we have elected to include only plants having at least 20% unique values in both R and Q indicators (Table G.3). Thus, for example, correlations between SIGE and QS(AFW) are calculated using data from plants 2 and 7 only.

It happens that contemporaneous (i.e., reflective) correlations are not the only items of interest. In fact, in our application, it is more interesting to know whether Q values are predictive than whether they are reflective or reactive. This can be investigated by calculating correlations between R values and temporally positively-shifted Q values (reactive: Q values follow R values in time), and also between R values and negatively shifted Q values (predictive: Q values precede R values in time). Collectively, these sorts of correlation coefficients are known as "cross-correlation" coefficients, and the shifts are (with some loss of precision) known as "lags." Below we present in Tables G.4-G.11 cross-correlation coefficients for shifts of -4, ... 4, and also, in Tables G.12-G.19, the across-plant average for these cross correlations. The same remarks concerning selection of plants apply to the cross correlations as they apply to the contemporaneous (i.e., lag 0) correlations.

If we have only a few plants, a single lag, and a single pair of indicators, it hardly makes a difference, from a practical point of view, whether we inspect a collection of correlations or their average. However, in the case we report here, there are eight plants, 5 * 7 = 35 pairs of indicators, and nine lags. It turns out that, supporting this plethora of results are only about 900 raw numbers. Since the number of derived statistics is in the neighborhood of 2000, there are twice as many output numbers as there are input numbers! Obviously, the simultaneous testing problem discussed earlier is very severe in this application. Although we present all statistics below (most unaccompanied by significance values), we strongly urge the reader to regard them as imprecise descriptions rather than statistical results. The tables of across-plant averages represent some compression of results, but probably not enough, unless we restrict our attention to only two or three of them. Rather than doing this, however, we have decided (before viewing the data) to investigate only correlations of QS(AFW), QT(AFW), QS(EPS), QT(EPS), and QS(AFW + EPS) with SSF. Furthermore, we will investigate only those situations in which the unavailability indicators precede SSF in time (negative lags). This results in 20 values. Inspection of the correlation results reveals no value greater than 0.5 among the within-plant correlations (Tables G.8-G.11). Furthermore, the heterogeneity test result values (Tables G.16-G.19) range from .07 to .99, depicting no pattern in ranges of averaged correlation values. We conclude from this analysis that correlations vary considerably across plants and none are larger than 0.5.

Table G.1. Lag-Zero Correlation

Plant		QS(AFW)	QT(AFW)	QS(EPS)	QT(EPS)	QS(HPCI)	QS(RCIC)	QT(AFW+EPS)
1	EFO/1000	0.274	0.004	-0.119	0.188	N/A	N/A	0.158
	SSF	-0.143	-0.321	-0.216	0.021	N/A	N/A	-0.095
	SIGE	0.245	-0.066	-0.339	-0.182	N/A	N/A	-0.178
	SSA	0.129	-0.246	0.034	0.030	N/A	N/A	-0.063
	FOR	-0.193	-0.576	-0.436	-0.375	N/A	N/A	-0.519
2	EFO/1000	-0.020	-0.064	-0.099	-0.121	N/A	N/A	-0.097
	SSF	0.335	0.124	0.002	-0.105	N/A	N/A	0.073
	SIGE	0.867	0.711	0.908	0.791	N/A	N/A	0.734
	SSA	-0.018	-0.171	-0.123	-0.183	N/A	N/A	-0.212
	FOR	-0.418	-0.556	-0.337	-0.448	N/A	N/A	-0.638
3	EFO/1000	0.775	0.482	N/A	N/A	N/A	N/A	N/A
	SSF	-0.198	0.169	N/A	N/A	N/A	N/A	N/A
	SIGE	-0.257	-0.359	N/A	N/A	N/A	N/A	N/A
	SSA	0.000	0.000	N/A	N/A	N/A	N/A	N/A
	FOR	0.258	0.217	N/A	N/A	N/A	N/A	N/A
4	EFO/1000	-0.025	-0.066	N/A	N/A	N/A	N/A	N/A
	SSF	-0.161	0.299	N/A	N/A	N/A	N/A	N/A
	SIGE	0.522	0.554	N/A	N/A	N/A	N/A	N/A
	SSA	0.166	-0.214	N/A	N/A	N/A	N/A	N/A
	FOR	0.695	0.077	N/A	N/A	N/A	N/A	N/A
5	EFO/1000	-0.011	-0.053	N/A	N/A	N/A	N/A	N/A
	SSF	-0.211	-0.251	N/A	N/A	N/A	N/A	N/A
	SIGE	0.328	0.181	N/A	N/A	N/A	N/A	N/A
	SSA	-0.264	-0.201	N/A	N/A	N/A	N/A	N/A
	FOR	-0.230	-0.235	N/A	N/A	N/A	N/A	N/A
6	EFO/1000	N/A	N/A	0.333	0.684	-0.057	-0.089	N/A
	SSF	N/A	N/A	-0.501	-0.450	-0.487	0.599	N/A
	SIGE	N/A	N/A	0.000	0.000	0.000	0.000	N/A
	SSA	N/A	N/A	-0.426	-0.336	-0.318	0.131	N/A
	FOR	N/A	N/A	0.635	0.514	-0.204	-0.025	N/A
7	EFO/1000	-0.414	0.007	-0.415	-0.792	N/A	N/A	-0.383
	SSF	-0.454	-0.550	0.577	0.043	N/A	N/A	-0.479
	SIGE	-0.262	0.051	-0.275	-0.815	N/A	N/A	-0.355
	SSA	0.031	-0.205	-0.260	0.243	N/A	N/A	-0.067
	FOR	-0.279	-0.034	-0.284	-0.837	N/A	N/A	-0.442
8	EFO/1000	0.000	-0.159	0.000	-0.161	N/A	N/A	-0.159
	SSF	0.000	-0.150	0.000	-0.155	N/A	N/A	-0.151
	SIGE	0.000	-0.227	0.000	-0.196	N/A	N/A	-0.217
	SSA	0.000	-0.219	0.000	-0.171	N/A	N/A	-0.205
	FOR	0.000	0.737	0.000	0.740	N/A	N/A	0.739

Key: QS()= System Unavailability; QT()= Train Avg. Unavailability ; N/A= Not Applicable

Table G.2. Lag-Zero Across-Plant Correlations

Average r Values

	QS(AFW)	QT(AFW)	QS(EPS)	QT(EPS)	QS(HPCI)	QS(RCIC)	QT(AFW+EPS)
EFO/100	0.0611	0.0216	-0.075	-0.0408	-0.0567	-0.0889	-0.1203
SSF	-0.1379	-0.0882	-0.0346	-0.1228	-0.4875	0.5988	-0.167
SIGE	0.3022	0.2317	0.0984	-0.0689	N/A	N/A	0.0672
SSA	-0.0213	-0.2074	-0.1936	-0.0616	-0.3178	0.1307	-0.1138
FOR	0.0051	-0.0528	-0.1057	-0.0811	-0.204	-0.025	-0.2151

Heterogeneity Test

	QS(AFW)	QT(AFW)	QS(EPS)	QT(EPS)	QS(HPCI)	QS(RCIC)	QT(AFW+EPS)
EFO/100	0.0545	0.8503	0.7243	0.1046	N/A	N/A	0.8452
SSF	0.6148	0.5297	0.3604	0.8272	N/A	N/A	0.7198
SIGE	0.0018	0.0822	0.0001	0.0007	N/A	N/A	0.0202
SSA	0.8279	0.9984	0.8868	0.8026	N/A	N/A	0.9014
FOR	0.0391	0.0302	0.1008	0.0064	N/A	N/A	0.0055

Test Against Zero Correlation

	QS(AFW)	QT(AFW)	QS(EPS)	QT(EPS)	QS(HPCI)	QS(RCIC)	QT(AFW+EPS)
EFO/100	0.0694	0.9094	0.8357	0.1754	0.899	0.842	0.9099
SSF	0.6886	0.6288	0.4949	0.8603	0.2335	0.1222	0.8049
SIGE	0.0004	0.0671	0.0001	0.0022	N/A	N/A	0.0342
SSA	0.9225	0.8559	0.8392	0.881	0.4617	0.7688	0.904
FOR	0.0704	0.0424	0.1452	0.0112	0.6436	0.9554	0.0046

Key: QS()= System Unavailability; QT()= Train Avg. Unavailability ; N/A= Not Applicable

Table G.3. Percentages of Unique Data Values for Plants and Indicators
(0's indicate three or fewer observations)

PLANT	EFO R1	SSF R2	SIGE R3	SSA R4	FOR R5	QS (AFW) Q1	QT (AFW) Q2	QS (EPS) Q3	QT (EPS) Q4	QS (HPCI) Q5	QS (RCIC) Q6	QT (AFW+EPS) Q2+Q4
1	64	33	23	35	78	9	52	42	61	0	0	71
2	57	26	23	21	57	63	63	52	68	0	0	68
3	71	20	15	7	57	41	91	0	0	0	0	0
4	64	20	15	21	42	25	91	0	0	0	0	0
5	64	26	15	21	57	33	91	0	0	0	0	0
6	54	35	7	30	63	0	0	50	87	75	62	0
7	57	20	23	28	57	50	100	50	100	0	0	100
8	42	13	15	14	57	12	62	12	50	0	0	62

Table G.4. Lag-One Cross-Correlation

Plant		QS(AFW)	QT(AFW)	QS(EPS)	QT(EPS)	QS(HPCI)	QS(RCIC)	QT(AFW+EPS)
1	EFO/1000	0.0411	-0.1911	-0.104	-0.0423	N/A	N/A	-0.1034
	SSF	0.062	-0.0193	-0.1178	0.2359	N/A	N/A	0.191
	SIGE	-0.2335	-0.1918	-0.4012	-0.2774	N/A	N/A	-0.2958
	SSA	-0.2328	-0.0919	-0.1397	-0.121	N/A	N/A	-0.1342
	FOR	-0.2485	-0.224	-0.3622	-0.2256	N/A	N/A	-0.2688
2	EFO/1000	0.2623	0.3413	-0.1156	-0.021	N/A	N/A	0.2997
	SSF	-0.1479	-0.0924	-0.2832	-0.3676	N/A	N/A	-0.1302
	SIGE	0.0729	0.0582	0.13	0.1215	N/A	N/A	0.0682
	SSA	-0.3952	-0.4083	-0.2259	-0.3617	N/A	N/A	-0.4094
	FOR	-0.4296	-0.4573	-0.446	-0.6307	N/A	N/A	-0.4882
3	EFO/1000	0.1747	0.241	N/A	N/A	N/A	N/A	N/A
	SSF	-0.1624	-0.1748	N/A	N/A	N/A	N/A	N/A
	SIGE	0.3492	0.4765	N/A	N/A	N/A	N/A	N/A
	SSA	0	0	N/A	N/A	N/A	N/A	N/A
	FOR	0.576	0.6868	N/A	N/A	N/A	N/A	N/A
4	EFO/1000	0.0681	0.8832	N/A	N/A	N/A	N/A	N/A
	SSF	-0.1612	-0.1727	N/A	N/A	N/A	N/A	N/A
	SIGE	-0.1937	-0.1974	N/A	N/A	N/A	N/A	N/A
	SSA	-0.2316	-0.2548	N/A	N/A	N/A	N/A	N/A
	FOR	0.6119	-0.0191	N/A	N/A	N/A	N/A	N/A
5	EFO/1000	-0.2352	-0.2052	N/A	N/A	N/A	N/A	N/A
	SSF	0.1512	0.4126	N/A	N/A	N/A	N/A	N/A
	SIGE	-0.0684	0.122	N/A	N/A	N/A	N/A	N/A
	SSA	-0.2638	-0.3414	N/A	N/A	N/A	N/A	N/A
	FOR	-0.1921	-0.1941	N/A	N/A	N/A	N/A	N/A
6	EFO/1000	N/A	N/A	-0.3774	0.0507	0.449	0.0871	N/A
	SSF	N/A	N/A	-0.0439	-0.5841	-0.4747	-0.2027	N/A
	SIGE	N/A	N/A	0	0	0	0	N/A
	SSA	N/A	N/A	0.045	-0.6316	-0.5299	-0.1844	N/A
	FOR	N/A	N/A	-0.5487	0.3429	0.5723	-0.0613	N/A
7	EFO/1000	0.4092	-0.1459	-0.3127	0.1983	N/A	N/A	-0.0352
	SSF	-0.2728	0.2038	-0.2981	-0.796	N/A	N/A	-0.206
	SIGE	0.9968	0.1026	-0.2037	-0.0557	N/A	N/A	0.0658
	SSA	-0.1795	0.8999	0.0472	0.122	N/A	N/A	0.8778
	FOR	0.9455	0.0352	-0.2688	0.0202	N/A	N/A	0.0419
8	EFO/1000	0	0.9978	0	0.9967	N/A	N/A	0.9978
	SSF	0	0.9995	0	0.9988	N/A	N/A	0.9997
	SIGE	0	0.6491	0	0.6445	N/A	N/A	0.6479
	SSA	0	-0.2983	0	-0.259	N/A	N/A	-0.2864
	FOR	0	0.5602	0	0.5223	N/A	N/A	0.5488

Key: QS()= System Unavailability; QT()= Train Avg. Unavailability ; N/A= Not Applicable

Table G.5. Lag-Two Cross-Correlation

Plant		QS(AFW)	QT(AFW)	QS(EPS)	QT(EPS)	QS(HPCI)	QS(RCIC)	QT(AFW+EPS)
1	EFO/1000	-0.2326	-0.1726	-0.3461	-0.37	N/A	N/A	-0.3749
	SSF	0.7673	-0.095	-0.1802	-0.0007	N/A	N/A	-0.0344
	SIGE	-0.2631	-0.1701	-0.1124	-0.6273	N/A	N/A	-0.5815
	SSA	-0.2378	-0.3048	-0.2786	-0.578	N/A	N/A	-0.5982
	FOR	0.4352	-0.2279	-0.4359	-0.0772	N/A	N/A	-0.1466
2	EFO/1000	0.1342	0.1673	-0.049	0.3309	N/A	N/A	0.192
	SSF	0.1813	0.1404	-0.0076	0.0605	N/A	N/A	0.1325
	SIGE	-0.3013	-0.3143	-0.2376	-0.2534	N/A	N/A	-0.3166
	SSA	-0.246	-0.2618	-0.2924	-0.4203	N/A	N/A	-0.2876
	FOR	-0.2863	-0.2952	-0.4485	-0.4289	N/A	N/A	-0.3184
3	EFO/1000	0.0457	0.1822	N/A	N/A	N/A	N/A	N/A
	SSF	-0.1624	-0.4753	N/A	N/A	N/A	N/A	N/A
	SIGE	-0.3312	-0.1315	N/A	N/A	N/A	N/A	N/A
	SSA	0	0	N/A	N/A	N/A	N/A	N/A
	FOR	-0.2127	-0.0516	N/A	N/A	N/A	N/A	N/A
4	EFO/1000	-0.2044	-0.2032	N/A	N/A	N/A	N/A	N/A
	SSF	-0.1612	-0.1503	N/A	N/A	N/A	N/A	N/A
	SIGE	-0.2182	-0.2531	N/A	N/A	N/A	N/A	N/A
	SSA	0.1655	-0.1721	N/A	N/A	N/A	N/A	N/A
	FOR	-0.2127	-0.2201	N/A	N/A	N/A	N/A	N/A
5	EFO/1000	-0.1472	-0.283	N/A	N/A	N/A	N/A	N/A
	SSF	0.0302	0.1804	N/A	N/A	N/A	N/A	N/A
	SIGE	-0.1053	0.013	N/A	N/A	N/A	N/A	N/A
	SSA	0.3688	0.368	N/A	N/A	N/A	N/A	N/A
	FOR	-0.2764	-0.3295	N/A	N/A	N/A	N/A	N/A
6	EFO/1000	N/A	N/A	0.6646	0.3062	-0.3087	-0.0213	N/A
	SSF	N/A	N/A	-0.2741	-0.4871	0.0034	-0.2828	N/A
	SIGE	N/A	N/A	0	0	0	0	N/A
	SSA	N/A	N/A	-0.3521	0.2832	0.2587	-0.2641	N/A
	FOR	N/A	N/A	0.4469	0.5024	-0.0781	-0.2761	N/A
7	EFO/1000	-0.2461	0.7065	0.4251	0.3827	N/A	N/A	0.8302
	SSF	0.9968	0.1026	-0.2037	-0.0557	N/A	N/A	0.0658
	SIGE	-0.3461	-0.444	0.6441	0.5127	N/A	N/A	-0.1515
	SSA	0.9603	0.0363	-0.2595	-0.2572	N/A	N/A	-0.0934
	FOR	-0.3496	-0.2803	0.2867	0.2861	N/A	N/A	-0.1142
8	EFO/1000	0	-0.1294	0	-0.1706	N/A	N/A	-0.1421
	SSF	0	-0.1137	0	-0.1549	N/A	N/A	-0.1264
	SIGE	0	-0.2012	0	-0.2366	N/A	N/A	-0.2121
	SSA	0	-0.3049	0	-0.2815	N/A	N/A	-0.2979
	FOR	0	-0.1656	0	-0.1996	N/A	N/A	-0.1761

Key: QS()= System Unavailability; QT()= Train Avg. Unavailability ; N/A= Not Applicable

Table G.6. Lag-Three Cross-Correlation

Plant		QS(AFW)	QT(AFW)	QS(EPS)	QT(EPS)	QS(HPCI)	QS(RCIC)	QT(AFW+EPS)
1	EFO/1000	-0.2186	-0.3577	-0.3562	-0.5465	N/A	N/A	-0.5759
	SSF	-0.1532	-0.1002	-0.1613	0.7482	N/A	N/A	0.5846
	SIGE	-0.2485	-0.0392	0.2789	-0.0645	N/A	N/A	-0.0669
	SSA	-0.2299	-0.1965	-0.2783	-0.0407	N/A	N/A	-0.1016
	FOR	0.4286	0.1754	-0.1474	0.5197	N/A	N/A	0.4906
2	EFO/1000	-0.2269	-0.2538	-0.1504	-0.0321	N/A	N/A	-0.2263
	SSF	-0.3169	-0.3414	-0.3098	-0.1581	N/A	N/A	-0.3208
	SIGE	-0.2581	-0.2362	-0.0082	-0.2292	N/A	N/A	-0.2431
	SSA	-0.0359	0.0232	-0.2353	-0.1414	N/A	N/A	0
	FOR	-0.1861	-0.1193	-0.4189	-0.226	N/A	N/A	-0.1366
3	EFO/1000	-0.1245	0.2279	N/A	N/A	N/A	N/A	N/A
	SSF	-0.141	-0.3742	N/A	N/A	N/A	N/A	N/A
	SIGE	-0.3162	-0.0322	N/A	N/A	N/A	N/A	N/A
	SSA	0	0	N/A	N/A	N/A	N/A	N/A
	FOR	0.2749	0.3849	N/A	N/A	N/A	N/A	N/A
4	EFO/1000	-0.2209	-0.089	N/A	N/A	N/A	N/A	N/A
	SSF	-0.1399	-0.1498	N/A	N/A	N/A	N/A	N/A
	SIGE	0.6614	-0.1512	N/A	N/A	N/A	N/A	N/A
	SSA	-0.2205	0.5516	N/A	N/A	N/A	N/A	N/A
	FOR	-0.2274	-0.1324	N/A	N/A	N/A	N/A	N/A
5	EFO/1000	0.8536	0.7207	N/A	N/A	N/A	N/A	N/A
	SSF	0.009	0.1269	N/A	N/A	N/A	N/A	N/A
	SIGE	-0.0486	0.1455	N/A	N/A	N/A	N/A	N/A
	SSA	0.169	0.0395	N/A	N/A	N/A	N/A	N/A
	FOR	0.9208	0.948	N/A	N/A	N/A	N/A	N/A
6	EFO/1000	N/A	N/A	-0.4636	0.3904	0.3959	-0.1489	N/A
	SSF	N/A	N/A	0.5048	0.623	-0.0048	-0.1911	N/A
	SIGE	N/A	N/A	0	0	0	0	N/A
	SSA	N/A	N/A	-0.0591	0.4465	0.1903	-0.2753	N/A
	FOR	N/A	N/A	-0.1524	0.4168	0.083	0.01	N/A
7	EFO/1000	0.7551	-0.1625	-0.3876	-0.5808	N/A	N/A	-0.4331
	SSF	-0.2189	-0.2816	0.9999	0.7123	N/A	N/A	0.0942
	SIGE	-0.3461	-0.3907	-0.322	-0.4225	N/A	N/A	-0.5627
	SSA	-0.2189	-0.2816	0.9999	0.7123	N/A	N/A	0.0942
	FOR	-0.2085	-0.3874	-0.3684	-0.162	N/A	N/A	-0.4317
8	EFO/1000	0	-0.1042	0	-0.1075	N/A	N/A	-0.1053
	SSF	0	-0.1497	0	-0.1549	N/A	N/A	-0.1514
	SIGE	0	0.6491	0	0.6445	N/A	N/A	0.6479
	SSA	0	0.3705	0	0.375	N/A	N/A	0.372
	FOR	0	-0.0838	0	-0.0946	N/A	N/A	-0.0872

Key: QS()= System Unavailability; QT()= Train Avg. Unavailability ; N/A= Not Applicable

Table G.7. Lag-Four Cross-Correlation

Plant		QS(AFW)	QT(AFW)	QS(EPS)	QT(EPS)	QS(HPCI)	QS(RCIC)	QT(AFW+EPS)
1	EFO/1000	-0.2132	0.6079	0.4175	0.0266	N/A	N/A	0.2338
	SSF	0.5469	-0.0677	-0.207	-0.2473	N/A	N/A	0.2295
	SIGE	0.2294	0.0729	0.3197	0.0938	N/A	N/A	0.1014
	SSA	0.5003	0.0643	-0.1226	-0.[illegible]044	N/A	N/A	-0.3143
	FOR	0.4212	0.0188	0.0717	0.2949	N/A	N/A	0.252
2	EFO/1000	0.1066	0.2416	0.8461	0.3812	N/A	N/A	0.2662
	SSF	-0.128	-0.0664	0.1393	0.0009	N/A	N/A	-0.0602
	SIGE	-0.3354	-0.3513	-0.2595	-0.3883	N/A	N/A	-0.368
	SSA	0.6981	0.6548	-0.1038	0.5471	N/A	N/A	0.6374
	FOR	0.4815	0.4952	0.3392	0.5352	N/A	N/A	0.5156
3	EFO/1000	-0.3201	-0.2676	N/A	N/A	N/A	N/A	N/A
	SSF	-0.112	-0.3049	N/A	N/A	N/A	N/A	N/A
	SIGE	-0.378	-0.6851	N/A	N/A	N/A	N/A	N/A
	SSA	0	0	N/A	N/A	N/A	N/A	N/A
	FOR	-0.3234	-0.5798	N/A	N/A	N/A	N/A	N/A
4	EFO/1000	-0.2015	-0.1156	N/A	N/A	N/A	N/A	N/A
	SSF	-0.1111	-0.1437	N/A	N/A	N/A	N/A	N/A
	SIGE	-0.2182	-0.236	N/A	N/A	N/A	N/A	N/A
	SSA	-0.201	-0.2098	N/A	N/A	N/A	N/A	N/A
	FOR	-0.235	-0.1593	N/A	N/A	N/A	N/A	N/A
5	EFO/1000	0.2751	0.3	N/A	N/A	N/A	N/A	N/A
	SSF	-0.1505	-0.2036	N/A	N/A	N/A	N/A	N/A
	SIGE	0.0427	0.2946	N/A	N/A	N/A	N/A	N/A
	SSA	0.6995	0.4843	N/A	N/A	N/A	N/A	N/A
	FOR	-0.2618	-0.2685	N/A	N/A	N/A	N/A	N/A
6	EFO/1000	N/A	N/A	0.122	0.6338	0.0793	-0.3089	N/A
	SSF	N/A	N/A	-0.3479	0.2672	-0.1754	0.6103	N/A
	SIGE	N/A	N/A	0	0	0	0	N/A
	SSA	N/A	N/A	0.3721	0.2423	-0.2314	0.3382	N/A
	FOR	N/A	N/A	-0.2495	0.4055	0.3786	-0.3656	N/A
7	EFO/1000	-0.4159	-0.516	0.8283	0.7599	N/A	N/A	-0.0955
	SSF	-0.2189	-0.2678	-0.2037	-0.7864	N/A	N/A	-0.6299
	SIGE	-0.269	0.5322	-0.3074	-0.0967	N/A	N/A	0.4362
	SSA	-0.2189	-0.2678	-0.2037	-0.7864	N/A	N/A	-0.6299
	FOR	-0.2362	0.8942	-0.1193	0.0654	N/A	N/A	0.8448
8	EFO/1000	0	-0.1644	0	-0.1721	N/A	N/A	-0.1668
	SSF	0	-0.1497	0	-0.1549	N/A	N/A	-0.1514
	SIGE	0	-0.2756	0	-0.295	N/A	N/A	-0.2816
	SSA	0	0.3897	0	0.3881	N/A	N/A	0.3893
	FOR	0	-0.1977	0	-0.2135	N/A	N/A	-0.2026

Key: QS()= System Unavailability; QT()= Train Avg. Unavailability ; N/A= Not Applicable

Table G.8. Lag Minus-One Cross-Correlation

Plant		QS(AFW)	QT(AFW)	QS(EPS)	QT(EPS)	QS(HPCI)	QS(RCIC)	QT(AFW+EPS)
1	EFO/1000	0.1043	-0.1379	0.1283	0.3088	N/A	N/A	0.1812
	SSF	0.2857	-0.0108	-0.219	-0.2711	N/A	N/A	-0.2283
	SIGE	-0.21	0.0342	0.4159	0.2731	N/A	N/A	0.2426
	SSA	-0.0517	0.5074	0.6322	0.4077	N/A	N/A	0.4966
	FOR	0.0772	-0.2897	-0.1318	-0.2197	N/A	N/A	-0.2736
2	EFO/1000	-0.1103	-0.097	-0.1693	-0.1837	N/A	N/A	-0.1475
	SSF	-0.1302	0.0212	-0.0438	-0.0344	N/A	N/A	0.007
	SIGE	0.1901	0.399	0.0135	0.168	N/A	N/A	0.3757
	SSA	-0.065	0.0016	-0.2708	-0.2362	N/A	N/A	-0.0787
	FOR	0.0736	-0.0673	-0.2227	-0.3129	N/A	N/A	-0.1652
3	EFO/1000	-0.1765	-0.1608	N/A	N/A	N/A	N/A	N/A
	SSF	0.232	0.3054	N/A	N/A	N/A	N/A	N/A
	SIGE	0.4251	0.4532	N/A	N/A	N/A	N/A	N/A
	SSA	0	0	N/A	N/A	N/A	N/A	N/A
	FOR	0.4982	0.2785	N/A	N/A	N/A	N/A	N/A
4	EFO/1000	-0.1722	0.2701	N/A	N/A	N/A	N/A	N/A
	SSF	-0.1963	0.7273	N/A	N/A	N/A	N/A	N/A
	SIGE	-0.1741	-0.1934	N/A	N/A	N/A	N/A	N/A
	SSA	-0.2206	0.5474	N/A	N/A	N/A	N/A	N/A
	FOR	-0.1641	-0.1261	N/A	N/A	N/A	N/A	N/A
5	EFO/1000	0.0137	0.0052	N/A	N/A	N/A	N/A	N/A
	SSF	0.056	-0.0213	N/A	N/A	N/A	N/A	N/A
	SIGE	0.3275	0.1858	N/A	N/A	N/A	N/A	N/A
	SSA	-0.2952	-0.263	N/A	N/A	N/A	N/A	N/A
	FOR	0.4037	0.3554	N/A	N/A	N/A	N/A	N/A
6	EFO/1000	N/A	N/A	-0.3535	-0.1102	0.8009	-0.3914	N/A
	SSF	N/A	N/A	0.0464	0.1918	-0.4421	-0.1976	N/A
	SIGE	N/A	N/A	0	0	0	0	N/A
	SSA	N/A	N/A	-0.1539	0.311	-0.3509	0.6988	N/A
	FOR	N/A	N/A	-0.4159	-0.0553	0.5962	-0.2106	N/A
7	EFO/1000	-0.4369	-0.5269	0.7975	0.4684	N/A	N/A	-0.2486
	SSF	0.5552	-0.265	0.5843	0.5188	N/A	N/A	0.0142
	SIGE	-0.2951	-0.3611	0.9425	0.8054	N/A	N/A	0.0677
	SSA	-0.3656	-0.179	-0.3445	-0.4808	N/A	N/A	-0.399
	FOR	-0.3721	-0.458	0.9155	0.5285	N/A	N/A	-0.1564
8	EFO/1000	0	-0.185	0	-0.1903	N/A	N/A	-0.1867
	SSF	0	-0.1497	0	-0.1549	N/A	N/A	-0.1514
	SIGE	0	-0.3002	0	-0.295	N/A	N/A	-0.2987
	SSA	0	-0.165	0	-0.1474	N/A	N/A	-0.1597
	FOR	0	-0.3209	0	-0.3248	N/A	N/A	-0.3223

Key: QS()= System Unavailability; QT()= Train Avg. Unavailability ; N/A= Not Applicable

Table G.9. Lag Minus-Two Cross-Correlation

Plant		QS(AFW)	QT(AFW)	QS(EPS)	QT(EPS)	QS(HPCI)	QS(RCIC)	QT(AFW+EPS)
1	EFO/1000	0	0.2654	0.2867	0.1232	N/A	N/A	0.1915
	SSF	-0.1429	-0.2319	-0.1819	0.2105	N/A	N/A	0.0718
	SIGE	-0.21	0.3708	0.6335	0.2142	N/A	N/A	0.3018
	SSA	0	0.3995	0.2921	0.3229	N/A	N/A	0.3917
	FOR	0	0.2411	0.1357	0.2831	N/A	N/A	0.3028
2	EFO/1000	-0.2048	-0.2567	-0.1649	-0.2069	N/A	N/A	-0.2981
	SSF	-0.1287	-0.2783	-0.3136	-0.3533	N/A	N/A	-0.3741
	SIGE	-0.1836	-0.1793	0.0492	0.0214	N/A	N/A	-0.1495
	SSA	-0.2235	-0.2796	-0.3222	-0.4126	N/A	N/A	-0.4023
	FOR	0.2211	0.1165	-0.3408	-0.3939	N/A	N/A	-0.067
3	EFO/1000	0.0806	-0.1017	N/A	N/A	N/A	N/A	N/A
	SSF	0.7002	0.2437	N/A	N/A	N/A	N/A	N/A
	SIGE	-0.1952	-0.0532	N/A	N/A	N/A	N/A	N/A
	SSA	0	0	N/A	N/A	N/A	N/A	N/A
	FOR	-0.2779	-0.4799	N/A	N/A	N/A	N/A	N/A
4	EFO/1000	-0.0535	-0.1325	N/A	N/A	N/A	N/A	N/A
	SSF	-0.2192	0.2781	N/A	N/A	N/A	N/A	N/A
	SIGE	-0.1936	0.4929	N/A	N/A	N/A	N/A	N/A
	SSA	0.5833	0.2236	N/A	N/A	N/A	N/A	N/A
	FOR	-0.1307	-0.1486	N/A	N/A	N/A	N/A	N/A
5	EFO/1000	-0.2963	-0.3064	N/A	N/A	N/A	N/A	N/A
	SSF	0.4699	0.4779	N/A	N/A	N/A	N/A	N/A
	SIGE	0.3109	0.1587	N/A	N/A	N/A	N/A	N/A
	SSA	0.2482	0.2661	N/A	N/A	N/A	N/A	N/A
	FOR	-0.2047	-0.229	N/A	N/A	N/A	N/A	N/A
6	EFO/1000	N/A	N/A	0.3276	0.11	-0.3492	-0.021	N/A
	SSF	N/A	N/A	-0.3559	-0.6021	0.3773	0.1085	N/A
	SIGE	N/A	N/A	0	0	0	0	N/A
	SSA	N/A	N/A	0.3394	0.3656	0.3252	-0.4283	N/A
	FOR	N/A	N/A	0.2197	0.3873	-0.3044	-0.1492	N/A
7	EFO/1000	0.6401	-0.3807	0.0312	-0.3247	N/A	N/A	-0.5055
	SSF	0.4894	0.5874	-0.4554	-0.6712	N/A	N/A	0.2039
	SIGE	0.9343	0.0093	-0.2684	-0.0779	N/A	N/A	-0.0298
	SSA	-0.4544	-0.5502	0.5767	0.0431	N/A	N/A	-0.4788
	FOR	0.8735	-0.1851	0.029	-0.1103	N/A	N/A	-0.2225
8	EFO/1000	0	-0.2072	0	-0.1622	N/A	N/A	-0.1936
	SSF	0	-0.1721	0	-0.1271	N/A	N/A	-0.1584
	SIGE	0	-0.2687	0	-0.2387	N/A	N/A	-0.2596
	SSA	0	0	0	0	N/A	N/A	0
	FOR	0	-0.3479	0	-0.3217	N/A	N/A	-0.34

Key: QS()= System Unavailability; QT()= Train Avg. Unavailability ; N/A= Not Applicable

Table G.10. Lag Minus-Three Cross-Correlation

Plant		QS(AFW)	QT(AFW)	QS(EPS)	QT(EPS)	QS(HPCI)	QS(RCIC)	QT(AFW+EPS)
1	EFO/1000	0	-0.1922	-0.1231	-0.2335	N/A	N/A	-0.2419
	SSF	0	0.1651	0.2575	0.0248	N/A	N/A	0.0798
	$IGE	0	0.0715	0.3552	0.0036	N/A	N/A	0.0295
	SSA	0	-0.0571	0.2369	0.1385	N/A	N/A	0.0623
	FOR	0	0.1819	0.3545	0.6105	N/A	N/A	0.4802
2	EFO/1000	-0.1806	-0.2243	-0.1644	-0.1555	N/A	N/A	-0.2561
	SSF	0.1273	0.1778	0.1375	0.3454	N/A	N/A	0.3078
	$IGE	-0.2846	-0.2599	0.8528	0.839	N/A	N/A	0.0598
	SSA	0.4754	0.249	-0.1013	0.0497	N/A	N/A	0.229
	FOR	0.2891	0.1925	-0.3955	-0.3473	N/A	N/A	-0.0035
3	EFO/1000	-0.2405	-0.1758	N/A	N/A	N/A	N/A	N/A
	SSF	0.199	-0.0664	N/A	N/A	N/A	N/A	N/A
	$IGE	0.5133	0.3778	N/A	N/A	N/A	N/A	N/A
	SSA	0	0	N/A	N/A	N/A	N/A	N/A
	FOR	-0.2726	-0.1664	N/A	N/A	N/A	N/A	N/A
4	EFO/1000	-0.231	-0.2645	N/A	N/A	N/A	N/A	N/A
	SSF	-0.2484	-0.2449	N/A	N/A	N/A	N/A	N/A
	$IGE	-0.1667	-0.1465	N/A	N/A	N/A	N/A	N/A
	SSA	-0.2362	-0.2561	N/A	N/A	N/A	N/A	N/A
	FOR	-0.4716	-0.1082	N/A	N/A	N/A	N/A	N/A
5	EFO/1000	0.0425	-0.0534	N/A	N/A	N/A	N/A	N/A
	SSF	0.7627	0.6983	N/A	N/A	N/A	N/A	N/A
	$IGE	0.408	0.3303	N/A	N/A	N/A	N/A	N/A
	SSA	-0.2503	-0.3337	N/A	N/A	N/A	N/A	N/A
	FOR	0.0387	-0.0406	N/A	N/A	N/A	N/A	N/A
6	EFO/1000	N/A	N/A	-0.431	0.072	0.0245	-0.3269	N/A
	SSF	N/A	N/A	0.7883	-0.367	-0.4877	0.5177	N/A
	$IGE	N/A	N/A	0	0	0	0	N/A
	SSA	N/A	N/A	0.0466	-0.8973	0.64	0.1638	N/A
	FOR	N/A	N/A	-0.5579	-0.1512	0.3418	-0.4485	N/A
7	EFO/1000	0.106	0.7314	0.3476	0.1375	N/A	N/A	0.8783
	SSF	-0.4167	0.3319	0.4417	0.6753	N/A	N/A	0.6335
	$IGE	-0.1214	0.9533	-0.2037	-0.0584	N/A	N/A	0.8376
	SSA	0.5231	-0.4292	0.5611	0.3421	N/A	N/A	-0.3501
	FOR	0.0887	0.9271	0.0077	-0.1728	N/A	N/A	0.9776
8	EFO/1000	0	-0.2428	0	-0.2371	N/A	N/A	-0.2411
	SSF	0	-0.1999	0	-0.1832	N/A	N/A	-0.1949
	$IGE	0	-0.2942	0	-0.317	N/A	N/A	-0.3013
	SSA	0	0	0	0	N/A	N/A	0
	FOR	0	-0.399	0	-0.3632	N/A	N/A	-0.3882

Key: QS()= System Unavailability; QT()= Train Avg. Unavailability ; N/A= Not Applicable

Table G.11. Lag Minus-Four Cross-Correlation

Plant		QS(AFW)	QT(AFW)	QS(EPS)	QT(EPS)	QS(HPCI)	QS(RCIC)	QT(AFW+EPS)
1	EFO/1000	0	0.6085	-0.3495	-0.4626	N/A	N/A	0.2121
	SSF	0	0.0539	0.2366	0.5964	N/A	N/A	0.3658
	SIGE	0	0.4084	0.0193	-0.0834	N/A	N/A	0.1411
	SSA	0	0.4236	0.1595	0.012	N/A	N/A	0.3307
	FOR	0	0.2918	0.6304	0.7751	N/A	N/A	0.6482
2	EFO/1000	-0.1799	-0.2147	-0.1763	-0.2238	N/A	N/A	-0.2761
	SSF	-0.2413	-0.3146	-0.2249	-0.2565	N/A	N/A	-0.3828
	SIGE	-0.2382	-0.2122	0.1191	0.0794	N/A	N/A	-0.1404
	SSA	0.4605	0.2129	-0.2687	-0.2239	N/A	N/A	0.1173
	FOR	0.3518	0.0189	-0.2393	-0.059	N/A	N/A	-0.0034
3	EFO/1000	-0.3697	-0.1104	N/A	N/A	N/A	N/A	N/A
	SSF	-0.3565	-0.3717	N/A	N/A	N/A	N/A	N/A
	SIGE	-0.2521	-0.5008	N/A	N/A	N/A	N/A	N/A
	SSA	0	0	N/A	N/A	N/A	N/A	N/A
	FOR	-0.2997	-0.164	N/A	N/A	N/A	N/A	N/A
4	EFO/1000	0.8962	-0.1749	N/A	N/A	N/A	N/A	N/A
	SSF	-0.2867	-0.2889	N/A	N/A	N/A	N/A	N/A
	SIGE	-0.1889	-0.2113	N/A	N/A	N/A	N/A	N/A
	SSA	-0.2756	-0.2887	N/A	N/A	N/A	N/A	N/A
	FOR	0.2928	-0.4637	N/A	N/A	N/A	N/A	N/A
5	EFO/1000	-0.367	-0.3335	N/A	N/A	N/A	N/A	N/A
	SSF	-0.2672	-0.3543	N/A	N/A	N/A	N/A	N/A
	SIGE	-0.3166	-0.2766	N/A	N/A	N/A	N/A	N/A
	SSA	-0.2185	-0.3032	N/A	N/A	N/A	N/A	N/A
	FOR	-0.2045	-0.2646	N/A	N/A	N/A	N/A	N/A
6	EFO/1000	N/A	N/A	-0.3696	0.7917	-0.2188	-0.14	N/A
	SSF	N/A	N/A	-0.1291	-0.1356	0.3475	-0.462	N/A
	SIGE	N/A	N/A	0	0	0	0	N/A
	SSA	N/A	N/A	0.8482	-0.2932	-0.712	0.8044	N/A
	FOR	N/A	N/A	-0.0395	0.688	-0.4668	0.198	N/A
7	EFO/1000	0.2654	0.0002	-0.8635	0.7243	N/A	N/A	0.1131
	SSF	0.3653	-0.4883	-0.6084	-0.4578	N/A	N/A	-0.7295
	SIGE	-0.2747	-0.2966	-0.2548	0.1566	N/A	N/A	-0.2731
	SSA	0.6389	0.7917	-0.3774	-0.5605	N/A	N/A	0.7477
	FOR	-0.1314	-0.1252	-0.6803	0.9257	N/A	N/A	0.0123
8	EFO/1000	0	0	0	0	N/A	N/A	0
	SSF	0	0	0	0	N/A	N/A	0
	SIGE	0	1	0	0.999	N/A	N/A	0.9999
	SSA	0	0	0	0	N/A	N/A	0
	FOR	0	0.9601	0	0.2943	N/A	N/A	0.5356

Key: QS()= System Unavailability; QT()= Train Avg. Unavailability ; N/A= Not Applicable

Table G.12. Lag One Across-Plant Correlations

Average r Values

	QS(AFW)	QT(AFW)	QS(EPS)	QT(EPS)	QS(HPCI)	QS(RCIC)	QT(AFW+EPS)
EPO/100	0.1358	0.2744	-0.2274	0.2365	0.449	0.0871	0.2897
SSF	-0.1186	0.0262	-0.1858	-0.378	-0.4747	-0.2027	-0.0484
SIGE	0.5349	-0.0103	-0.1583	-0.0705	N/A	N/A	-0.0539
SSA	-0.2675	-0.0393	-0.0684	-0.2481	-0.5299	-0.1844	0.1114
FOR	0.3023	0.0554	-0.4064	0.0058	0.5723	-0.0613	-0.0416

Heterogeneity Test

	QS(AFW)	QT(AFW)	QS(EPS)	QT(EPS)	QS(HPCI)	QS(RCIC)	QT(AFW+EPS)
EPO/100	0.808	0	0.9794	0	N/A	N/A	0
SSF	0.9503	0.7775	0.9503	0.2313	N/A	N/A	0.702
SIGE	0.0001	0.8273	0.5069	0.6919	N/A	N/A	0.6825
SSA	0.9153	0.0399	0.9173	0.5557	N/A	N/A	0.0225
FOR	0.0044	0.0717	0.8847	0.0838	N/A	N/A	0.1537

Test Against Zero Correlation

	QS(AFW)	QT(AFW)	QS(EPS)	QT(EPS)	QS(HPCI)	QS(RCIC)	QT(AFW+EPS)
EPO/100	0.8312	0	0.8517	0	0.2797	0.8452	0
SSF	0.95	0.8679	0.8622	0.095	0.2485	0.6458	0.8699
SIGE	0	0.9406	0.5953	0.8353	N/A	N/A	0.8285
SSA	0.5573	0.0692	0.9434	0.3532	0.1871	0.6766	0.0529
FOR	0.001	0.1091	0.1982	0.1349	0.1455	0.8908	0.2319

Key: QS()= System Unavailability; QT()= Train Avg. Unavailability ; N/A= Not Applicable

Table G.13. Lag Two Across-Plant Correlations

Average r Values

	QS(AFW)	QT(AFW)	QS(EPS)	QT(EPS)	QS(HPCI)	QS(RCIC)	QT(AFW+EPS)
EFO/100	-0.0836	0.0583	0.1737	0.0958	-0.3087	-0.0213	0.1263
SSF	0.1769	-0.0495	-0.1664	-0.1208	0.0034	-0.2828	0.0546
SIGE	-0.3237	-0.3095	0.098	-0.1227	N/A	N/A	-0.3499
SSA	0.3122	-0.0669	-0.2957	-0.2431	0.2587	-0.2641	-0.3264
FOR	-0.2675	-0.2243	-0.0377	0.0166	-0.0781	-0.2761	-0.1888

Heterogeneity Test

	QS(AFW)	QT(AFW)	QS(EPS)	QT(EPS)	QS(HPCI)	QS(RCIC)	QT(AFW+EPS)
EFO/100	0.9421	0.6214	0.1922	0.4668	N/A	N/A	0.1143
SSF	0	0.7016	0.973	0.7645	N/A	N/A	0.9371
SIGE	0.889	0.958	0.3288	0.0949	N/A	N/A	0.5135
SSA	0.0296	0.5556	0.9873	0.2435	N/A	N/A	0.3507
FOR	0.9995	0.9971	0.1545	0.4167	N/A	N/A	0.9521

Test Against Zero Correlation

	QS(AFW)	QT(AFW)	QS(EPS)	QT(EPS)	QS(HPCI)	QS(RCIC)	QT(AFW+EPS)
EFO/100	0.966	0.7305	0.2721	0.592	0.4755	0.962	0.1822
SSF	0	0.7817	0.9308	0.8339	0.9939	0.5156	0.98
SIGE	0.5863	0.6459	0.5185	0.123	N/A	N/A	0.2254
SSA	0.0088	0.6607	0.6404	0.1676	0.5539	0.5453	0.1339
FOR	0.7392	0.8571	0.2229	0.5576	0.8611	0.5262	0.845

Key: QS()= System Unavailability; QT()= Train Avg. Unavailability ; N/A= Not Applicable

Table G.14. Lag Three Across-Plant Correlations

Average r Values

	QS(AFW)	QT(AFW)	QS(EPS)	QT(EPS)	QS(HPCI)	QS(RCIC)	QT(AFW+EPS)
EFO/100	0.2073	-0.0027	-0.3395	-0.1753	0.3959	-0.1489	-0.3352
SSF	-0.1615	-0.1867	0.2584	0.4814	-0.0048	-0.1911	0.1193
SIGE	-0.3021	-0.222	-0.0171	-0.2387	N/A	N/A	-0.2909
SSA	-0.0766	0.0272	0.1068	0.2442	0.1903	-0.2753	-0.0025
FOR	0.1147	0.1122	-0.2718	0.0908	0.083	0.01	-0.0412

Heterogeneity Test

	QS(AFW)	QT(AFW)	QS(EPS)	QT(EPS)	QS(HPCI)	QS(RCIC)	QT(AFW+EPS)
EFO/100	0.007	0.1742	0.9517	0.3459	N/A	N/A	0.6474
SSF	0.9774	0.9225	0	0.1233	N/A	N/A	0.1087
SIGE	0.9878	0.9011	0.6374	0.9084	N/A	N/A	0.8069
SSA	0.8751	0.4677	0	0.4539	N/A	N/A	0.9448
FOR	0.0008	0.0004	0.9172	0.403	N/A	N/A	0.3325

Test Against Zero Correlation

	QS(AFW)	QT(AFW)	QS(EPS)	QT(EPS)	QS(HPCI)	QS(RCIC)	QT(AFW+EPS)
EFO/100	0.005	0.2498	0.5259	0.3446	0.3491	0.7373	0.2871
SSF	0.9317	0.8208	0	0.0083	0.9914	0.6653	0.1759
SIGE	0.6672	0.8328	0.8232	0.8096	N/A	N/A	0.6555
SSA	0.9393	0.5924	0	0.4457	0.6666	0.5275	0.9893
FOR	0.0006	0.0002	0.6701	0.4774	0.8524	0.9822	0.4896

Key: QS()= System Unavailability; QT()= Train Avg. Unavailability ; N/A= Not Applicable

Table G.15. Lag Four Across-Plant Correlations

Average r Values

	QS(AFW)	QT(AFW)	QS(EPS)	QT(EPS)	QS(HPCI)	QS(RCIC)	QT(AFW+EPS)
EFO/100	-0.1112	0.0123	0.5535	0.3259	0.0793	-0.3089	0.0594
SSF	-0.1441	-0.1757	-0.1548	-0.1914	-0.1754	0.6103	-0.3065
SIGE	-0.3022	0.0846	-0.0824	-0.1304	N/A	N/A	0.0565
SSA	0.2444	0.1452	-0.0145	-0.1504	-0.2314	0.3382	-0.1023
FOR	-0.115	0.029	0.0105	0.2175	0.3786	-0.3686	0.3525

Heterogeneity Test

	QS(AFW)	QT(AFW)	QS(EPS)	QT(EPS)	QS(HPCI)	QS(RCIC)	QT(AFW+EPS)
EFO/100	0.7317	0.3544	0.1754	0.5016	N/A	N/A	0.8104
SSF	1	0.9976	0.8512	0.3437	N/A	N/A	0.7281
SIGE	0.8306	0.425	0.528	0.7125	N/A	N/A	0.4842
SSA	0.0556	0.243	0.7804	0.1396	N/A	N/A	0.0396
FOR	0.4812	0.057	0.7594	0.6429	N/A	N/A	0.2875

Test Against Zero Correlation

	QS(AFW)	QT(AFW)	QS(EPS)	QT(EPS)	QS(HPCI)	QS(RCIC)	QT(AFW+EPS)
EFO/100	0.8079	0.4484	0.0023	0.2608	0.8737	0.523	0.8872
SSF	0.988	0.9638	0.8652	0.3709	0.6919	0.1127	0.5498
SIGE	0.6581	0.6235	0.7258	0.8204	N/A	N/A	0.6908
SSA	0.0276	0.2335	0.896	0.1934	0.5982	0.4311	0.0908
FOR	0.5793	0.0914	0.8752	0.5174	0.4255	0.4392	0.1068

Key: QS()= System Unavailability; QT()= Train Avg. Unavailability ; N/A= Not Applicable

Table G.16. Lag Minus-One Across-Plant Correlations

Average r Values

	QS(AFW)	QT(AFW)	QS(EPS)	QT(EPS)	QS(HPCI)	QS(RCIC)	QT(AFW+EPS)
EFO/100	-0.1764	-0.1189	0.1007	0.0586	0.8009	-0.3914	-0.1004
$SF	0.1033	0.1261	0.092	0.1013	-0.4421	-0.1976	-0.069
$IGE	-0.0525	0.024	0.4573	0.4155	N/A	N/A	0.2287
$SA	-0.2366	0.1229	-0.0342	0.0004	-0.3509	0.6988	0.0063
FOR	0.0879	-0.090	0.036	-0.077	0.596	-0.211	-0.229

Heterogeneity Test

	QS(AFW)	QT(AFW)	QS(EPS)	QT(EPS)	QS(HPCI)	QS(RCIC)	QT(AFW+EPS)
EFO/100	0.9842	0.9346	0.2242	0.6681	N/A	N/A	0.8435
$SF	0.717	0.2155	0.5845	0.5537	N/A	N/A	0.7951
$IGE	0.4221	0.3646	0.1038	0.5915	N/A	N/A	0.7236
$SA	0.9742	0.2093	0.0617	0.2723	N/A	N/A	0.1614
FOR	0.4188	0.6934	0.0328	0.6082	N/A	N/A	0.9738

Test Against Zero Correlation

	QS(AFW)	QT(AFW)	QS(EPS)	QT(EPS)	QS(HPCI)	QS(RCIC)	QT(AFW+EPS)
EFO/100	0.9358	0.9407	0.3279	0.7807	0.0276	0.4083	0.9175
$SF	0.611	0.1855	0.7411	0.7134	0.2883	0.6543	0.8851
$IGE	0.7233	0.527	0.0104	0.1875	N/A	N/A	0.5545
$SA	0.8033	0.2104	0.1145	0.4147	0.4636	0.0836	0.276
FOR	0.4671	0.769	0.065	0.6683	0.1693	0.6689	0.7918

Table G.17. Lag Minus-Two Across-Plant Correlations

Average r Values

	QS(AFW)	QT(AFW)	QS(EPS)	QT(EPS)	QS(HPCI)	QS(RCIC)	QT(AFW+EPS)
EFO/100	0.0332	-0.16	0.1201	-0.0921	-0.3492	-0.021	-[illegible]014
SSF	0.2623	0.1795	-0.3267	-0.354	0.3773	0.1085	-0.[illegible]328
SIGE	0.3753	0.0669	0.1398	0.0526	N/A	N/A	0.0408
SSA	0.0384	0.0119	0.2215	0.0797	0.3252	-0.4283	-0.1631
FOR	0.0963	-0.1476	0.0109	-0.0311	-0.3044	-0.1492	-0.0817

Heterogeneity Test

	QS(AFW)	QT(AFW)	QS(EPS)	QT(EPS)	QS(HPCI)	QS(RCIC)	QT(AFW+EPS)
EFO/100	0.5719	0.9003	0.723	0.9208	N/A	N/A	0.6166
SSF	0.1494	0.3678	0.9879	0.3451	N/A	N/A	0.3954
SIGE	0.0129	0.4289	0.1036	0.832	N/A	N/A	0.5683
SSA	0.1964	0.3075	0.3586	0.2887	N/A	N/A	0.1107
FOR	0.1592	0.7949	0.6319	0.4532	N/A	N/A	0.6492

Test Against Zero Correlation

	QS(AFW)	QT(AFW)	QS(EPS)	QT(EPS)	QS(HPCI)	QS(RCIC)	QT(AFW+EPS)
EFO/100	0.7125	0.877	0.8067	0.9531	0.5278	0.971	0.645
SSF	0.0887	0.3879	0.5665	0.1913	0.4273	0.8275	0.563
SIGE	0.0115	0.6052	0.1135	0.9197	N/A	N/A	0.753
SSA	0.3022	0.4273	0.4204	0.4341	0.5589	0.4278	0.1952
FOR	0.2208	0.8061	0.7828	0.5918	0.5861	0.7946	0.799

Key: QS()= System Unavailability; QT()= Train Avg. Unavailability ; N/A= Not Applicable

Table G.18. Lag Minus-Three Across-Plant Correlations

Average r Values

	QS(AFW)	QT(AFW)	QS(EPS)	QT(EPS)	QS(HPCI)	QS(RCIC)	QT(AFW+EPS)
EFO/100	-0.1007	-0.0602	-0.0927	-0.0833	0.0245	-0.3269	0.0343
SSF	0.0848	0.177	0.4063	0.1696	-0.4877	0.5177	0.3404
SIGE	-0.203	0.255	0.3348	0.2614	N/A	N/A	0.309
SSA	0.128	-0.1654	0.1858	-0.0918	0.64	0.1638	-0.0196
FOR	-0.0655	0.0839	-0.1478	-0.0848	0.3418	-0.4485	0.2665

Heterogeneity Test

	QS(AFW)	QT(AFW)	QS(EPS)	QT(EPS)	QS(HPCI)	QS(RCIC)	QT(AFW+EPS)
EFO/100	0.9601	0.7963	0.8357	0.9523	N/A	N/A	0.1511
SSF	0.1074	0.414	0.7943	0.4012	N/A	N/A	0.7467
SIGE	0.6135	0.0115	0.0075	0.0063	N/A	N/A	0.2773
SSA	0.2703	0.7613	0.7878	0.2095	N/A	N/A	0.6582
FOR	0.5688	0.4155	0.2659	0.1172	N/A	N/A	0.033

Test Against Zero Correlation

	QS(AFW)	QT(AFW)	QS(EPS)	QT(EPS)	QS(HPCI)	QS(RCIC)	QT(AFW+EPS)
EFO/100	0.9547	0.8357	0.8847	0.9577	0.9724	0.6313	0.2577
SSF	0.128	0.3425	0.272	0.4022	0.3559	0.3208	0.3969
SIGE	0.6372	0.0106	0.0005	0.002	N/A	N/A	0.216
SSA	0.3601	0.8059	0.8152	0.3142	0.2836	0.8152	0.8235
FOR	0.6935	0.4544	0.3759	0.1937	0.6145	0.4947	0.0095

Key: QS()= System Unavailability; QT()= Train Avg. Unavailability ; N/A= Not Applicable

Table G.19. Lag Minus-Four Across-Plant Correlations

Average r Values

	QS(AFW)	QT(AFW)	QS(EPS)	QT(EPS)	QS(HPCI)	QS(RCIC)	QT(AFW+EPS)
EFO/100	0.0494	-0.0321	-0.4397	0.1659	-0.2188	-0.14	0.0123
SSF	-0.1573	-0.294	-0.1814	-0.0634	0.3475	-0.462	-0.2488
SIGE	-0.2564	-0.0335	-0.0388	0.0509	N/A	N/A	-0.0908
SSA	0.1513	0.1673	0.0404	-0.2664	-0.712	0.8044	0.3986
FOR	0.0018	0.0362	-0.0822	0.5248	-0.4668	0.198	0.2981

Heterogeneity Test

	QS(AFW)	QT(AFW)	QS(EPS)	QT(EPS)	QS(HPCI)	QS(RCIC)	QT(AFW+EPS)
EFO/100	0.015	0.3371	0.8926	0.2589	N/A	N/A	0.7046
SSF	0.8344	0.9558	0.5656	0.0738	N/A	N/A	0.0906
SIGE	0.794	0.2851	0.8689	0.9193	N/A	N/A	0.7762
SSA	0.3159	0.3916	0.3759	0.9437	N/A	N/A	0.8574
FOR	0.6308	0.3714	0.0644	0.091	N/A	N/A	0.2195

Test Against Zero Correlation

	QS(AFW)	QT(AFW)	QS(EPS)	QT(EPS)	QS(HPCI)	QS(RCIC)	QT(AFW+EPS)
EFO/100	0.0271	0.4465	0.4522	0.3775	0.824	0.8879	0.843
SSF	0.7267	0.657	0.6703	0.1346	0.6081	0.4796	0.1423
SIGE	0.6877	0.4695	0.9633	0.9803	N/A	N/A	0.9058
SSA	0.4133	0.4743	0.5388	0.8998	0.3728	0.2666	0.4959
FOR	0.7536	0.4751	0.1161	0.0094	0.6129	0.841	0.1404

Key: QS()= System Unavailability; QT()= Train Avg. Unavailability ; N/A= Not Applicable

APPENDIX H. PLANT DATA

This appendix is a compilation of the safety system trains-out-of-service hours used to calculate various unavailability indicators. This data, collected for eight plants, was reduced from either of the following sources:

plant LCO logs,
operator's logs, or
maintenance work orders.

The tables present the raw data in a reduced form, necessary for calculating the unavailability indicators. Each table is sorted chronologically by system and train detailing the following information:

QTR

System

Failure (Y/N) - an assessment of the information in the "raw" data indicating whether or not the train was functional. Question marks indicate failure uncertainty.

Downtime Date Out/Time Out - The date and time which the given train was taken out of service for maintenance (PM, CM) or surveillance which rendered the train inoperable.

Return to Service: Date/Time in - The date and time the train was declared operable.

Detected Downtime - The time the train was known to have been inoperable.

Undetected Downtime - Downtime associated with train failures taken as the average of the last known up period to the out of service date. Generally assumed to be the lesser of 1/2 of the surveillance test interval, or 1/2 last demand.

Total Downtime - Summation of detected and undetected downtime associated with each event.

Quarter Total - Quarterly summation for use in calculating the indicators.

Each table also contains plant-specific information with regard to types of trains (i.e., turbine or motor driven pumps, etc.), source of "raw" data, and any other pertinent information.

Plant 1 Safety System Trains-Out-of-Service Hours

QTR	System / Train	Critical Hours	Failure (y/n)	Downtime Date Out	Downtime Time Out	Return to Service Date In	Return to Service Time In	Detected Downtime	Undetected Downtime	Total Downtime	Quarter Total
85-1	EPSAC-a	2160	n	03/19/85	19:50	03/20/85	13:15	17.42	0	17.42	17.42
85-2	EPSAC-a	2183	n	05/21/85	11:10	05/26/85	16:35	125.42	0	125.42	125.42
85-3	EPSAC-a	1784	y	07/11/85	05:30	07/12/85	03:20	21.83	360	381.83	381.83
85-4	EPSAC-a	1363	n	10/23/85	02:55	10/24/85	14:52	35.95	0	35.95	35.95
87-2	EPSAC-a	1937	n	04/17/87	00:01	06/11/87	08:56	1328.92	0	168.00	168.00
87-3	EPSAC-a		n	08/10/87	08:00	08/10/87	15:10	7.17	0	7.17	
	EPSAC-a		y	09/03/87	11:42	09/05/87	13:50	50.13	360	410.13	
	EPSAC-a	1762	n	09/24/87	06:50	09/24/87	15:12	8.37	0	8.37	425.67
88-1	EPSAC-a	1574	n	03/13/88	22:50	03/15/88	07:00	32.17		32.17	32.17
88-2	EPSAC-a		n	04/05/88	22:11	04/06/88	04:10	5.98	0	5.98	
	EPSAC-a		y	04/16/88	17:01	04/21/88	16:35	119.57	360	479.57	
	EPSAC-a		n	05/15/88	20:00	05/16/88	16:13	20.22	0	20.22	
	EPSAC-a		n	06/06/88	20:48	06/06/88	20:55	0.12	0	0.12	
	EPSAC-a		n	06/17/88	07:45	06/17/88	11:45	4.00	0	4.00	
	EPSAC-a	2043	n	06/28/88	05:10	06/28/88	19:50	14.67	0	14.67	524.55
85-2	EPSAC-b	2183	n	04/18/85	07:20	04/20/85	06:00	46.67	0	46.67	46.67
85-3	EPSAC-b		n	07/15/85	06:00	07/17/85	04:25	46.42	0	46.42	
	EPSAC-b	1784	n	07/17/85	15:23	07/17/85	19:40	4.28	0	4.28	50.70
85-4	EPSAC-b	1363	n	11/20/85	05:15	11/21/85	03:51	22.60	0	22.60	22.60
86-2	EPSAC-b	1163	n	04/22/86	05:15	04/24/86	08:00	50.75	0	50.75	50.75
87-2	EPSAC-b	1937	n	06/07/87	22:18	06/09/87	03:30	29.20	0	29.20	29.20
87-3	EPSAC-b	1762	y	07/24/87	18:00	07/25/87	10:00	16.00	360	376.00	376.00
88-1	EPSAC-b	1574	n	03/15/88	22:25	03/17/88	05:20	30.92	0	30.92	30.92
88-2	EPSAC-b	2043	n	04/06/88	07:25	04/06/88	19:26	12.02	0	12.02	12.02
85-4	AFW-b		n	10/01/85	18:16	10/02/85	00:58	6.70	0	6.70	
	AFW-b	1363	n	10/02/85	16:15	10/02/85	23:01	6.77	0	6.77	13.47
86-2	AFW-b	1163	n	04/15/86	08:34	04/16/86	20:15	35.68	0	35.68	35.68
87-2	AFW-b	1937	n	06/23/87	16:45	06/24/87	14:41	21.93	0	21.93	21.93
88-2	AFW-b	2043	n	05/04/88	04:41	05/04/88	06:05	1.40	0	1.40	1.40
88-2	AFW-a	2043	n	05/05/88	04:06	05/05/88	04:28	0.37	0	0.37	0.37
87-2	AFW-c	1937	y	05/28/87	10:34	05/28/87	14:31	3.95	360	363.95	363.95
87-3	AFW-c	1762	n	07/02/87	08:30	07/02/87	15:26	6.93	0	6.93	6.93
88-2	AFW-c	2043	n	06/14/88	23:34	06/17/88	10:45	59.18	0	59.18	59.18
87-3	AFW-a&b		n	07/01/87	08:55	07/01/87	13:10	4.25	0	4.25	
	AFW-a&b	1762	n	07/01/87	13:12	07/01/87	23:09	9.95	0	9.95	14.20

Notes:
1. Data source: Shift supervisor's log.
2. AFWS trains "a" & "c" motor-driven; train "b" turbine driven.
3. Data collection period (85-1 through 88-2).
4. Plant shutdown periods when data was not collected: (86-3,4; 87-1).

Plant 2 Safety System Trains-Out-of-Service Hours

QTR	System / Train	Critical Hours	Failure (y/n)	Downtime Date Out	Time Out	Return to Service Date In	Time In	Detected Downtime	Undetected Downtime	Total Downtime	Quarter Total
83-2	AFW-1		n	04/05/83	14:30	04/05/83	16:20	1.83	0	1.83	
	AFW-1		?	04/29/83	06:30	05/01/83	23:45	65.25	?	65.25	
	AFW-1		n	05/03/83	13:45	05/03/83	14:00	0.25	0	0.25	
	AFW-1		n	05/04/83	09:51	05/04/83	14:20	4.48	0	4.48	
	AFW-1		n	05/06/83	12:35	05/06/83	15:00	2.42	0	2.42	
	AFW-1		n	05/31/83	11:00	05/31/83	15:35	4.58	0	4.58	
	AFW-1		n	06/27/83	12:24	06/27/83	15:00	2.60	0	2.60	
	AFW-1	2184	n	06/28/83	09:10	06/28/83	11:10	2.00	0	2.00	83.42
83-3	AFW-1	940	y	07/25/83	14:40	07/25/83	16:00	1.33	360	361.33	361.33
83-4	AFW-1		n	10/27/83	08:55	10/27/83	11:10	2.25	0	2.25	
	AFW-1		n	11/14/83	09:10	11/14/83	10:00	0.83	0	0.83	
	AFW-1		n	11/16/83	09:35	11/16/83	11:10	1.58	0	1.58	
	AFW-1		n	11/17/83	11:05	11/17/83	11:15	0.17	0	0.17	
	AFW-1	2116	n	12/12/83	12:50	12/12/83	14:48	1.97	0	1.97	6.80
84-1	AFW-1		n	02/06/84	08:30	02/06/84	15:10	6.67	0	6.67	
	AFW-1		n	02/08/84	09:30	02/08/84	11:10	1.67	0	1.67	
	AFW-1		n	02/15/84	18:51	02/15/84	21:50	2.98	0	2.98	
	AFW-1		?	03/01/84	11:01	03/01/84	18:40	7.65	?	7.65	
	AFW-1		n	03/02/84	23:10	03/03/84	09:10	10.00	0	10.00	
	AFW-1		n	03/09/84	10:45	03/09/84	12:10	1.42	0	1.42	
	AFW-1	1915	n	03/30/84	09:45	03/30/84	14:55	5.17	0	5.17	35.55
84-2	AFW-1		n	04/03/84	08:30	04/04/84	11:25	26.92	0	26.92	
	AFW-1		n	04/05/84	14:15	04/05/84	15:30	1.25	0	1.25	
	AFW-1		n	04/30/84	12:15	04/30/84	15:20	3.08	0	3.08	
	AFW-1		n	05/03/84	09:35	05/03/84	11:40	2.08	0	2.08	
	AFW-1		n	05/31/84	12:30	05/31/84	14:10	1.67	0	1.67	
	AFW-1		n	06/01/84	12:20	06/01/84	13:20	1.00	0	1.00	
	AFW-1		n	06/20/84	17:10	06/20/84	20:30	3.33	0	3.33	
	AFW-1		n	06/20/84	13:50	06/20/84	14:55	1.08	0	1.08	
	AFW-1		n	06/21/84	12:55	06/21/84	14:22	1.45	0	1.45	
	AFW-1		n	06/22/84	13:30	06/22/84	13:55	0.42	0	0.42	
	AFW-1	2184	n	06/25/84	14:50	06/25/84	15:26	0.60	0	0.60	42.88
84-3	AFW-1		n	07/26/84	07:35	07/26/84	11:45	4.17	0	4.17	
	AFW-1		n	08/03/84	08:35	08/03/84	15:3[illegible]	7.00	0	7.00	
	AFW-1		n	08/22/84	08:35	08/22/84	[illegible]	3.05	0	3.05	
	AFW-1		n	08/30/84	07:35	08/30/84	16:30	8.92	0	8.92	
	AFW-1	1747	n	08/30/84	17:55	08/31/84	16:30	22.58	0	22.58	45.72
85-1	AFW-1		n	01/17/85	12:55	01/17/85	14:55	2.00	0	2.00	
	AFW-1		n	02/21/85	08:55	02/21/85	11:10	2.25	0	2.25	
	AFW-1		?	03/01/85	13:55	03/03/85	18:15	52.33	?	52.33	
	AFW-1		?	03/16/85	17:30	03/17/85	16:30	23.00	?	23.00	
	AFW-1	1741	n	03/19/85	13:35	03/19/85	17:25	3.83	0	3.83	83.41
85-2	AFW-1		?	04/16/85	07:15	04/18/85	10:25	51.17	?	51.17	
	AFW-1		n	05/06/85	14:15	05/06/85	18:30	4.25	0	4.25	
	AFW-1	1484	?	06/02/85	13:50	06/03/85	21:53	32.05	?	32.05	87.47
87-1	AFW-1		n	01/06/87	11:00	01/06/87	13:10	2.17	0	2.17	
	AFW-1		n	01/07/87	13:00	01/08/87	18:50	29.83	0	29.83	
	AFW-1		?	01/11/87	14:45	01/14/87	04:15	61.50	?	61.50	
	AFW-1		n	01/15/87	23:40	01/16/87	02:35	2.92	0	2.92	
	AFW-1		n	01/18/87	09:20	01/18/87	11:31	2.18	0	2.18	
	AFW-1		n	01/20/87	23:52	01/21/87	02:00	2.13	0	2.13	
	AFW-1		n	01/22/87	08:42	01/22/87	15:10	6.47	0	6.47	
	AFW-1		n	02/02/87	07:15	02/02/87	13:10	5.92	0	5.92	
	AFW-1		n	02/10/87	09:16	02/10/87	17:30	8.23	0	8.23	
	AFW-1		n	02/18/87	09:57	02/18/87	23:10	13.22	0	13.22	
	AFW-1		n	02/23/87	09:24	02/23/87	15:10	5.77	0	5.77	
	AFW-1		n	02/27/87	11:25	02/27/87	14:45	3.33	0	3.33	
	AFW-1	1969	n	03/04/87	11:10	03/04/87	17:44	6.57	0	6.57	150.23

Plant 2 Safety System Trains-Out-of-Service Hours

QTR	System / Train	Critical Hours	Failure (y/n)	Downtime Date Out	Downtime Time Out	Return to Service Date In	Return to Service Time In	Detected Downtime	Undetected Downtime	Total Downtime	Quarter Total
87-2	AFW-1		n	04/01/87	06:25	04/01/87	18:50	12.42	0	12.42	
	AFW-1		n	04/20/87	06:50	04/20/87	20:53	14.05	0	14.05	
	AFW-1		n	04/23/87	12:20	04/24/87	19:50	31.50	0	31.50	
	AFW-1		n	04/24/87	23:00	04/25/87	02:00	3.00	0	3.00	
	AFW-1		n	04/30/87	12:05	04/30/87	19:30	7.42	0	7.42	
	AFW-1		n	05/07/87	08:15	05/07/87	16:45	8.50	0	8.50	
	AFL-1		n	06/12/87	13:25	06/13/87	15:05	25.67	0	25.67	
	AFW-1		n	06/17/87	11:19	06/18/87	00:12	12.88	0	12.88	
	AFW-1	1284	n	06/24/87	13:06	06/24/87	16:50	3.73	0	3.73	119.17
87-4	AFW-1		n	10/07/87	12:10	10/14/87	17:33	173.38	0	173.38	
	AFW-1		n	10/14/87	08:30	10/14/87	13:05	4.58	0	4.58	
	AFW-1		n	10/28/87	08:34	10/28/87	12:41	4.12	0	4.12	
	AFW-1		n	11/11/87	06:35	11/11/87	17:13	10.63	0	10.63	
	AFW-1		n	11/25/87	16:42	11/26/87	00:50	8.13	0	8.13	
	AFW-1		n	12/02/87	08:33	12/03/87	02:10	17.62	0	17.62	
	AFW-1		n	12/16/87	06:08	12/18/87	06:45	48.62	0	48.62	
	AFW-1	2165	n	12/30/87	12:38	12/30/87	15:40	3.03	0	3.03	270.12
88-1	AFW-1		n	01/13/88	06:20	01/13/88	20:10	13.83	0	13.83	
	AFW-1		n	01/17/88	18:20	01/17/88	19:50	1.50	0	1.50	
	AFW-1		n	01/27/88	06:45	01/27/88	10:49	4.07	0	4.07	
	AFW-1		n	02/10/88	05:64	02/10/88	11:55	6.18	0	6.18	
	AFW-1		n	02/24/88	07:30	02/24/88	12:15	4.75	0	4.75	
	AFW-1	1556	n	03/09/88	06:33	03/09/88	13:58	7.42	0	7.42	37.75
83-2	AFW-2		y	04/08/83	07:50	04/08/83	16:50	9.00	360	369.00	
	AFW-2		?	04/15/83	07:00	04/15/83	14:50	7.83	?	7.83	
	AFW-2		n	04/18/83	08:00	04/18/83	14:15	6.25	0	6.25	
	AFW-2		n	04/19/83	08:50	04/19/83	10:40	1.83	0	1.83	
	AFW-2		n	05/16/83	06:15	05/16/83	13:15	5.00	0	5.00	
	AFW-2		n	06/13/83	09:55	06/13/83	13:45	3.83	0	3.83	
	AFW-2	2184	n	06/14/83	08:30	06/14/83	11:45	3.25	0	3.25	397.00
83-3	AFW-2		n	07/11/83	09:42	07/11/83	14:45	5.05	0	5.05	
	AFW-2	940	n	07/12/83	09:30	07/12/83	11:00	1.50	0	1.50	6.55
83-4	AFW-2		n	10/06/83	09:15	10/06/83	11:30	2.25	0	2.25	
	AFW-2		?	10/15/83	07:20	10/15/83	15:10	7.83	?	7.83	
	AFW-2		n	10/25/83	10:55	10/25/83	13:04	2.15	0	2.15	
	AFW-2		n	11/02/83	08:20	11/02/83	09:20	1.00	0	1.00	
	AFW-2		n	11/02/83	13:30	11/02/83	14:35	1.08	0	1.08	
	AFW-2		n	11/02/83	16:55	11/02/83	17:05	0.17	0	0.17	
	AFW-2		n	11/03/83	00:06	11/03/83	00:42	0.60	0	0.60	
	AFW-2		n	11/07/83	16:50	11/07/83	17:10	0.33	0	0.33	
	AFW-2		n	11/08/83	11:50	11/08/83	11:55	0.08	0	0.08	
	AFW-2		?	11/09/83	15:15	11/09/83	20:25	5.17	?	5.17	
	AFW-2		?	12/13/83	07:25	12/13/83	09:40	2.25	?	2.25	
	AFW-2	2116	n	12/29/83	09:06	12/29/83	16:00	6.90	0	6.90	29.82
84-1	AFW-2		n	01/05/84	12:47	01/05/84	13:03	0.27	0	0.27	
	AFW-2		n	01/26/84	09:25	01/26/84	11:05	1.67	0	1.67	
	AFW-2		n	02/15/84	07:20	02/15/84	18:50	11.50	0	11.50	
	AFW-2		n	02/23/84	08:50	02/23/84	10:15	1.42	0	1.42	
	AFW-2		n	03/02/84	23:10	03/03/84	06:54	7.73	0	7.73	
	AFW-2		y	03/03/84	06:54	03/04/84	21:00	38.10	120	158.10	
	AFW-2		y	03/14/84	12:00	03/14/84	22:15	10.25	120	130.25	
	AFW-2	1915	n	03/21/84	08:50	03/21/84	19:10	10.33	0	10.33	321.27
84-2	AFW-2		n	04/19/84	12:45	04/19/84	14:50	2.08	0	2.08	
	AFW-2		?	05/09/84	06:50	05/09/84	16:50	10.00	?	10.00	
	AFW-2		n	06/01/84	12:20	06/01/84	12:20	0.00	0	0.00	
	AFW-2	2184	n	06/14/84	12:10	06/14/84	13:30	1.33	0	1.33	13.42

Plant 2 Safety System Trains-Out-of-Service Hours

QTR	System / Train	Critical Hours	Failure (y/n)	Downtime Date Out	Time Out	Return to Service Date In	Time In	Detected Downtime	Undetected Downtime	Total Downtime	Quarter Total
84-3	AFW-2		n	07/05/84	06:30	07/05/84	11:40	5.17	0	5.17	
	AFW-2		n	07/12/84	08:30	07/12/84	10:15	1.75	0	1.75	
	AFW-2		?	07/31/84	07:20	07/31/84	11:55	4.58	?	4.58	
	AFW-2		n	08/09/84	08:10	08/09/84	10:10	2.00	0	2.00	
	AFW-2		n	09/05/84	13:20	09/05/84	16:00	2.67	0	2.67	
	AFW-2		?	09/06/84	07:00	09/06/84	07:30	0.50	?	0.50	
	AFW-2	1767	n	09/07/84	10:20	09/07/84	15:00	4.67	0	4.67	21.33
85-1	AFW-2		y	01/11/85	04:15	01/14/85	01:30	69.25	360	429.25	
	AFW-2		n	02/01/85	10:00	02/01/85	23:50	13.83	0	13.83	
	AFW-2		n	03/01/85	09:40	03/01/85	15:30	5.83	0	5.83	
	AFW-2	1741	?	03/07/85	08:45	03/07/85	16:45	8.00	?	8.00	456.92
85-2	AFW-2		y	04/11/85	06:50	04/12/85	06:08	23.30	360	383.30	
	AFW-2		n	04/24/85	12:30	04/24/85	14:05	1.58	0	1.58	
	AFW-2	1484	n	05/21/85	09:10	05/21/85	14:10	5.00	0	5.00	389.88
87-1	AFW-2		n	01/06/87	13:12	01/06/87	15:11	1.98	0	1.98	
	AFW-2		n	01/09/87	10:05	01/11/87	14:12	52.12	0	52.12	
	AFW-2		n	01/15/87	00:20	01/15/87	23:15	22.92	0	22.92	
	AFW-2		n	01/17/87	16:00	01/17/87	21:55	5.92	0	5.92	
	AFW-2		n	01/19/87	19:25	01/20/87	01:15	5.83	0	5.83	
	AFW-2		n	01/20/87	15:30	01/20/87	23:40	8.17	0	8.17	
	AFW-2		n	01/21/87	09:00	01/21/87	12:10	3.17	0	3.17	
	AFW-2		n	01/23/87	15:24	01/23/87	17:46	2.37	0	2.37	
	AFW-2		?	01/27/87	07:20	01/27/87	23:30	16.17	?	16.17	
	AFW-2		n	02/06/87	11:43	02/06/87	12:41	0.97	0	0.97	
	AFW-2		n	02/14/87	08:30	02/14/87	14:15	5.75	0	5.75	
	AFW-2		y	03/01/87	06:35	03/01/87	20:46	14.18	360	374.18	
	AFW-2	1969	n	03/06/87	09:15	03/06/87	14:40	5.42	0	5.4:	504.95
87-2	AFW-2		n	04/05/87	09:23	04/05/87	12:15	2.87	0	2.87	
	AFW-2		?	04/06/87	14:27	04/08/87	22:20	55.88	?	55.88	
	AFW-2		n	04/24/87	18:40	04/24/87	19:50	1.17	0	1.17	
	AFW-2		n	04/29/87	12:00	04/29/87	16:05	4.08	0	4.08	
	AFW-2		n	05/06/87	07:17	05/06/87	17:55	10.63	0	10.63	
	AFW-2		n	06/18/87	00:15	06/18/87	20:00	19.75	0	19.75	
	AFW-2		n	06/24/87	08:30	06/24/87	12:40	4.17	0	4.17	
	AFW-2	1284	n	06/26/87	06:12	06/26/87	06:15	0.05	0	0.05	98.60
87-4	AFW-2		n	10/14/87	13:06	10/14/87	17:35	4.48	0	4.48	
	AFW-2		n	10/21/87	06:45	10/21/87	19:00	12.25	0	12.25	
	AFW-2		n	10/28/87	12:44	10/28/87	17:55	5.18	0	5.18	
	AFW-2		n	11/04/87	13:55	11/05/87	21:22	31.45	0	31.45	
	AFW-2		n	11/11/87	17:16	11/11/87	21:34	4.30	0	4.30	
	AFW-2		n	11/26/87	00:55	11/26/87	04:00	3.08	0	3.08	
	AFW-2		n	12/12/87	06:59	12/16/87	00:25	89.43	0	89.43	
	AFW-2	1894	n	12/30/87	06:30	12/30/87	12:35	6.08	0	6.08	156.27
88-1	AFW-2		n	01/14/88	07:00	01/14/88	14:05	7.08	0	7.08	
	AFW-2		n	01/27/88	11:00	01/27/88	15:10	4.17	0	4.17	
	AFW-2		n	02/10/88	11:56	02/10/88	16:45	4.82	0	4.82	
	AFW-2		y	02/22/88	14:55	02/22/88	19:55	5.00	360	365.00	
	AFW-2		n	02/24/88	12:35	02/24/88	17:30	4.92	0	4.92	
	AFW-2	1556	n	03/09/88	14:00	03/09/88	19:36	5.60	0	5.60	391.58
83-2	EPSAC-1		?	04/06/83	06:35	04/06/83	20:10	13.58	?	13.58	
	EPSAC-1		?	04/13/83	06:30	04/14/83	22:15	39.75	?	39.75	
	EPSAC-1		?	04/27/83	06:30	04/29/83	07:20	48.83	?	48.83	
	EPSAC-1		n	05/11/83	06:50	05/11/83	20:15	13.42	0	13.42	
	EPSAC-1		?	05/12/83	06:25	05/12/83	18:30	12.08	?	'2.08	
	EPSAC-1		?	05/13/83	06:00	05/13/83	13:50	7.83	?	7.83	
	EPSAC-1		y	05/27/83	09:55	05/27/83	14:30	4.58	360	364.58	
	EPSAC-1		?	06/02/83	08:00	06/02/83	10:20	2.33	?	2.33	
	EPSAC-1	2184	y	06/07/83	15:40	06/08/83	17:40	26.00	132	158.00	660.41
83-3	EPSAC-1	940	n	07/08/83	06:30	07/08/83	20:35	14.08	0	14.08	14.08

Plant 2 Safety System Trains-Out-of-Service Hours

QTR	System / Train	Critical Hours	Failure (y/n)	Downtime Date Out	Downtime Time Out	Return to Service Date In	Return to Service Time In	Detected Downtime	Undetected Downtime	Total Downtime	Quarter Total
83-4	EPSAC-1		?	10/14/83	06:45	10/14/83	20:45	14.00	?	14.00	
	EPSAC-1		n	11/01/83	06:00	11/01/83	10:55	4.92	0	4.92	
	EPSAC-1		?	11/16/83	07:00	11/16/83	22:45	15.75	?	15.75	
	EPSAC-1		?	12/12/83	07:15	12/12/83	21:45	14.50	?	14.50	
	EPSAC-1	2116	?	12/27/83	10:00	12/27/83	15:10	5.17	?	5.17	54.33
84-1	EPSAC-1		n	01/30/84	06:30	01/31/84	04:55	22.42	0	22.42	
	EPSAC-1		y	02/09/84	09:40	02/09/84	10:00	0.33	360	360.33	
	EPSAC-1	1915	n	03/01/84	11:05	03/02/84	02:30	15.42	0	15.42	398.17
84-2	EPSAC-1		n	04/05/84	07:00	04/05/84	14:30	7.50	0	7.50	
	EPSAC-1		n	04/26/84	06:45	04/27/84	13:15	30.50	0	30.50	
	EPSAC-1		n	05/24/84	09:20	05/25/84	05:25	20.08	0	20.08	
	EPSAC-1		n	06/05/84	15:40	06/06/84	15:25	23.75	0	23.75	
	EPSAC-1	2184	n	06/21/84	06:30	06/21/84	20:15	13.75	0	13.75	95.58
84-3	EPSAC-1		y	07/13/84	23:25	07/14/84	00:00	0.58	360	360.58	
	EPSAC-1	1747	n	07/19/84	06:55	07/19/84	16:50	9.92	0	9.92	370.50
85-1	EPSAC-1	1741	?	01/30/85	06:57	02/01/85	60:10	41.22	?	41.22	41.22
85-2	EPSAC-1		n	05/09/85	07:05	05/09/85	15:30	8.42	0	8.42	
	EPSAC-1		?	05/13/85	07:00	05/15/85	20:50	61.83	?	61.83	
	EPSAC-1	1484	?	05/23/85	06:30	05/23/85	16:20	9.83	?	9.83	80.08
87-1	EPSAC-1		n	01/07/87	07:11	01/07/87	19:00	11.82	0	11.82	
	EPSAC-1		n	02/09/87	11:30	02/09/87	19:30	8.00	0	8.00	
	EPSAC-1	1969	n	03/25/87	07:20	03/25/87	14:45	7.42	0	7.42	27.23
87-2	EPSAC-1	1284	n	06/25/87	06:30	06/26/87	22:23	39.88	0	39.88	39.88
87-4	EPSAC-1		?	10/23/87	06:25	10/23/87	21:00	14.58	?	14.58	
	EPSAC-1	2165	?	11/11/87	06:46	11/13/87	01:00	42.23	?	42.23	56.81
83-2	EPSAC-2		?	04/22/83	14:05	04/22/83	16:30	2.42	?	2.42	
	EPSAC-2		n	05/04/83	06:30	05/05/83	00:00	17.50	0	17.50	
	EPSAC-2		n	05/18/83	06:30	05/18/83	14:30	8.00	0	8.00	
	EPSAC-2	2184	n	06/27/83	07:00	06/27/83	22:25	15.42	0	15.42	43.34
83-4	EPSAC-2		?	10/21/83	07:15	10/21/83	21:50	14.58	?	14.58	
	EPSAC-2		n	11/14/83	07:20	11/14/83	22:30	15.17	0	15.17	
	EPSAC-2		n	11/21/83	06:00	11/21/83	20:00	14.00	0	14.00	
	EPSAC-2		y	12/29/83	10:00	12/30/83	04:45	18.75	360	378.75	
	EPSAC-2	2116	n	12/31/83	11:25	12/31/83	11:45	0.33	0	0.33	422.83
84-1	EPSAC-2		?	02/15/84	06:50	02/16/84	21:30	38.67	?	38.67	
	EPSAC-2	1915	n	03/15/84	07:00	03/15/84	22:25	15.42	0	15.42	54.[illegible]
84-2	EPSAC-2		?	04/12/84	07:00	04/12/84	15:50	8.83	?	8.83	
	EPSAC-2		n	05/10/84	06:45	05/10/84	16:10	9.42	0	9.42	
	EPSAC-2		n	06/05/84	11:00	06/05/84	15:30	4.50	0	4.50	
	EPSAC-2	2184	n	06/07/84	06:45	06/07/84	22:35	15.83	0	15.83	38.58
84-3	EPSAC-2		n	07/06/84	06:35	07/06/84	15:40	9.08	0	9.08	
	EPSAC-2		n	08/03/84	08:30	08/03/84	15:58	7.47	0	7.47	
	EPSAC-2	1747	?	08/13/84	20:25	08/13/84	21:35	1.17	?	1.17	17.72

Plant 2 Safety System Trains-Out-of-Service Hours

QTR	System / Train	Critical Hours	Failure (y/n)	Downtime Date Out	Time Out	Return to Service Date In	Time In	Detected Downtime	Undetected Downtime	Total Downtime	Quarter Total
85-1	EPSAC-2	1741	n	03/15/85	07:22	03/15/85	18:43	11.38	0	11.38	11.38
85-2	EPSAC-2	1484	?	06/06/85	06:35	06/06/85	23:15	16.67	?	16.67	16.67
87-2	EPSAC-2	1284	n	05/06/87	16:40	05/06/87	18:35	1.92	0	1.92	1.92
87-3	EPSAC-2		n	08/04/87	05:45	08/05/87	08:25	26.67	0	26.67	
	EPSAC-2		?	08/28/87	08:10	08/28/87	14:00	5.83	?	5.83	
	EPSAC-2	1894	n	09/24/87	21:01	09/24/87	21:13	0.20	0	0.20	32.70
87-4	EPSAC-2	2165	?	11/18/87	06:06	11/19/87	02:00	19.90	?	19.90	19.90

Notes:
1. Data source: Shift supervisor's log.
2. Data collection period (83-2 through 88-2).
3. Plant shutdown periods when data was not collected: (84-4, 85-3 through 86-4, 88-2).

Plant 3 Safety System Train Out of Service Hours

QTR	System / Train	Critical Hours	Failure (y/n)	Downtime Date Out	Downtime Time Out	Return to Service Date In	Return to Service Time In	Detected Downtime	Undetected Downtime	Total Downtime	Quarter Total
85-1	AFW-a	2157	n	03/13/85	07:52	03/13/85	08:03	0.18	0.00	0.18	0.18
85-2	AFW-a	2149	n	04/10/85	08:14	04/10/85	08:32	0.30	0.00	0.30	0.30
85-3	AFW-a		n	07/04/85	15:48	07/04/85	21:36	5.80	0.00	5.80	
	AFW-a		n	07/04/85	14:56	07/04/85	15:34	0.63	0.00	0.63	
	AFW-a		n	07/27/85	00:01	07/27/85	08:00	7.98	0.00	7.98	
	AFW-a	2208	y	08/26/85	22:05	08/27/85	04:23	6.30	360.00	366.30	380.72
86-3	AFW-a		y	07/21/86	09:05	07/21/86	15:05	6.00	360.00	366.00	
	AFW-a	1949	n	08/29/86	07:52	08/29/86	08:31	0.65	0.00	0.65	366.65
86-4	AFW-a	1825	n	11/19/86	08:19	11/19/86	08:28	0.15	0.00	0.15	0.15
87-1	AFW-a	1856	y	01/20/87	12:56	01/21/87	02:20	13.40	360.00	373.40	373.40
87-2	AFW-a	2162	n	06/10/87	08:44	06/10/87	08:51	0.12	0.00	0.12	0.12
87-4	AFW-a	1374	n	11/10/87	08:34	11/10/87	13:51	5.28	0.00	5.28	5.28
85-1	AFW-b	2157	n	03/13/85	08:14	03/13/85	08:22	0.13	0.00	0.13	0.13
85-2	AFW-b	2149	n	04/10/85	08:53	04/10/85	09:06	0.22	0.00	0.22	0.22
85-3	AFW-b	2208	n	07/27/85	08:01	07/27/85	16:00	7.98	0.00	7.98	7.98
86-3	AFW-b		y	07/02/86	09:10	07/02/86	15:06	5.93	360.00	365.93	
	AFW-b	1949	n	08/29/86	12:57	08/29/86	13:15	0.30	0.00	0.30	366.23
86-4	AFW-b		n	11/19/86	08:46	11/19/86	08:54	0.13	0.00	0.13	
	AFW-b	1825	?	12/23/86	15:22	12/23/86	16:05	0.72	?	0.72	0.85
87-2	AFW-b	2162	n	06/10/87	09:08	06/10/87	09:13	0.08	0.00	0.08	0.08
85-1	AFW-t	2157	y	03/20/85	13:51	03/20/85	15:57	2.10	360.00	362.10	362.10
85-3	AFW-t		n	07/23/85	04:14	07/25/85	14:08	57.90	0.00	57.90	
	AFW-t		n	08/05/85	05:33	08/08/85	01:33	68.00	0.00	68.00	
	AFW-t	2208	y	09/05/85	17:45	09/06/85	01:30	7.75	360.00	367.75	493.65
85-4	AFW-t		n	11/12/85	09:25	11/12/85	09:50	0.42	0.00	0.42	
	AFW-t		n	11/13/85	09:57	11/13/85	11:00	1.05	0	1.05	
	AFW-t		n	11/14/85	09:14	11/14/85	09:27	0.22	0	0.22	
	AFW-t		n	11/14/85	15:28	11/14/85	15:36	0.13	0	0.13	
	AFW-t		n	11/15/85	08:42	11/15/85	08:52	0.17	0	0.17	
	AFW-t	1939	?	12/13/85	13:41	12/13/85	18:00	4.32	?	4.32	6.30
86-2	AFW-t	1134	?	05/11/86	23:00	05/13/86	11:03	36.05	?	36.05	36.05
86-3	AFW-t	1949	y	08/18/86	15:53	08/18/86	18:03	2.17	360.00	362.17	362.17
86-4	AFW-t		n	11/22/86	11:08	11/22/86	14:19	3.18	0.00	3.18	
	AFW-t	1825	y	12/02/86	04:41	12/02/86	16:07	11.43	1.00	12.43	15.62
87-1	AFW-t	1856	y	02/13/87	08:00	02/13/87	15:00	7.00	360.00	367.00	367.00

Notes:
1. Data source: Shift supervisor's log.
2. AFWS trains "a & b" motor driven; train "t" turbine driven.
3. Data collection period (85-1 through 87-4).
4. Train "t" failure of 12/02/86 occurred right after successful test, hence undetected downtime of ~1 hour.

Plant & Safety System Train Out of Service Hours

QTR	System / Train	Critical Hours	Failure (y/n)	Downtime Date Out	Downtime Time Out	Return to Service Date In	Return to Service Time In	Detected Downtime	Undetected Downtime	Total Downtime	Quarter Total
85-2	AFW-a	1235	n	06/05/85	10:28	06/05/85	10:47	0.32	0.00	0.32	0.32
85-3	AFW-a		n	07/10/85	09:01	07/10/85	09:54	0.88	0.00	0.88	
	AFW-a	1998	n	07/28/85	08:00	07/28/85	16:00	8.00	0.00	8.00	8.88
85-4	AFW-a	2189	n	11/21/85	09:00	11/21/85	09:20	0.33	0.00	0.33	0.33
86-1	AFW-a	2152	n	02/12/86	08:52	02/12/86	09:13	0.35	0.00	0.35	0.35
86-2	AFW-a	2183	n	05/07/86	08:55	05/07/86	09:05	0.17	0.00	0.17	0.17
87-1	AFW-a	2163	n	03/08/87	07:12	03/08/87	17:26	10.23	0.00	10.23	10.23
87-4	AFW-a	2209	?	12/30/87	15:20	12/30/87	16:30	1.17	?	1.17	1.17
85-2	AFW-b	1235	n	06/05/85	11:05	06/05/85	11:24	0.32	0.00	0.32	0.32
85-3	AFW-b	1998	n	07/28/85	16:01	07/28/85	23:59	7.97	0.00	7.97	7.97
85-4	AFW-b	2189	n	11/21/85	09:22	11/21/85	09:32	0.17	0.00	0.17	0.17
86-2	AFW-b	2183	n	05/07/86	09:16	05/07/86	09:26	0.17	0.00	0.17	0.17
85-3	AFW-t		?	07/30/85	15:54	07/30/85	17:52	1.97	?	1.97	
	AFW-t		n	08/21/85	23:40	08/21/85	23:53	0.22	0.00	0.22	
	AFW-t		n	08/21/85	13:30	08/21/85	16:51	3.35	0.00	3.35	
	AFW-t		n	08/21/85	11:15	08/21/85	11:30	0.25	0.00	0.25	
	AFW-t		n	08/22/85	09:22	08/23/85	14:17	28.92	0.00	28.92	
	AFW-t		n	08/24/85	16:24	08/24/85	16:43	0.32	0.00	0.32	
	AFW-t		n	08/25/85	05:05	08/25/85	05:25	0.33	0.00	0.33	
	AFW-t		n	08/25/85	09:12	08/25/85	09:21	0.15	0.00	0.15	
	AFW-t		n	08/26/85	16:45	08/26/85	17:05	0.33	0.00	0.33	
	AFW-t	1998	n	08/26/85	08:28	08/26/85	08:45	0.28	0.00	0.28	36.12
86-1	AFW-t	2152	?	02/12/86	16:47	02/13/86	10:48	26.02	?	26.02	26.02
86-2	AFW-t	2183	n	05/04/86	08:00	05/05/86	01:00	17.00	0.00	17.00	17.00
86-3	AFW-t	1099	?	08/14/86	11:03	08/14/86	15:39	4.60	?	4.60	4.60
86-4	AFW-t		y	10/21/86	11:30	10/24/86	10:30	71.00	360.00	431.00	
	AFW-t	1819	?	11/13/86	10:26	11/13/86	19:28	9.03	?	9.03	440.03
87-3	AFW-t		?	07/16/87	14:00	07/17/87	13:17	23.28	?	23.28	
	AFW-t		?	08/05/87	08:11	08/05/87	23:00	14.82	?	14.82	
	AFW-t	2192	n	09/15/87	10:09	09/15/87	10:32	0.38	0.00	0.38	38.48

Notes:
1. Data source: Shift supervisor's log.
2. AFWS trains "a & b" motor driven; train "t" turbine driven.
3. Data collection period (85-1 through 87-4).

Plant 5 Safety System Train Out of Service Hours

QTR	System / Train	Critical Hours	Failure (y/n)	Downtime Date Out	Downtime Time Out	Return to Service Date In	Return to Service Time In	Detected Downtime	Undetected Downtime	Total Downtime
85-2	AFW-t		n	04/25/85	13:45	04/25/85	16:55	3.17	0.00	3.17
	AFW-t	2183	n	05/14/85	13:06	05/14/85	13:31	0.42	0.00	0.42
85-3	AFW-t	913	y	07/23/85	03:35	07/23/85	17:15	13.67	360.00	373.67
85-4	AFW-t		n	10/14/85	10:29	10/14/85	10:53	0.40	0.00	0.40
	AFW-t		n	10/23/85	08:30	10/23/85	08:57	0.45	0.00	0.45
	AFW-t	1138	n	11/18/85	04:43	11/18/85	04:46	0.05	0.00	0.05
86-1	AFW-t	2157	n	03/23/86	08:02	03/23/86	09:42	1.67	0.00	1.67
86-3	AFW-t		n	09/02/86	08:43	09/02/86	09:02	0.32	0.00	0.32
	AFW-t		n	09/02/86	12:12	09/02/86	12:33	0.35	0.00	0.35
	AFW-t		n	09/02/86	14:49	09/02/86	15:18	0.48	0.00	0.48
	AFW-t	2196	n	09/02/86	17:29	09/02/86	18:02	0.55	0.00	0.55
86-4	AFW-t	1300	?	11/03/86	06:20	11/04/86	01:27	19.12	- - ?	19.12
87-3	AFW-t	2208	y	07/16/87	01:45	07/16/87	23:16	21.52	360.00	381.52
86-2	AFW-a	2183	n	06/28/86	02:55	06/28/86	04:40	1.75	0.00	1.75
86-3	AFW-a		y	08/29/86	14:15	08/29/86	19:15	5.00	360.00	365.00
	AFW-a		n	09/01/86	07:00	09/02/86	02:14	19.23	0.00	19.23
	AFW-a		n	09/02/86	08:43	09/02/86	09:02	0.32	0.00	0.32
	AFW-a		n	09/02/86	17:29	09/02/86	18:02	0.55	0.00	0.55
	AFW-a		n	09/02/86	14:49	09/02/86	15:18	0.48	0.00	0.48
	AFW-a		n	09/02/86	12:12	09/02/86	12:33	0.35	0.00	0.35
	AFW-a		n	09/10/86	10:05	09/10/86	11:15	1.17	0.00	1.17
	AFW-a	2196	n	09/18/86	17:28	09/19/86	11:30	18.03	0.00	18.03
86-4	AFW-a	1300	n	10/23/86	10:35	10/23/86	10:47	0.20	0.00	0.20
87-2	AFW-a	1673	n	06/11/87	08:21	06/11/87	08:31	0.17	0.00	0.17
87-3	AFW-a	2208	?	07/10/87	14:45	07/10/87	15:18	0.55	?	0.55
85-3	AFW-b	913	n	08/03/85	16:27	08/03/85	17:30	1.05	0.00	1.05
86-2	AFW-b		n	06/11/86	10:19	06/11/86	12:28	2.15	0.00	2.15
	AFW-b	2183	n	06/28/86	04:41	06/28/86	05:40	0.98	0.00	0.98
86-3	AFW-b		[illegible]	09/07/86	07:00	09/07/86	21:38	14.63	0.00	14.63
	AFW-b	2196	n	09/10/86	14:00	09/10/86	14:05	0.08	0.00	0.08
86-4	AFW-b	1300	n	10/23/86	11:02	10/23/86	11:10	0.13	0.00	0.13
87-2	AFW-b	1673	n	06/11/87	08:42	06/11/87	08:49	0.12	0.00	0.12
87-3	AFW-b		?	07/10/87	08:17	07/10/87	14:40	6.38	?	6.38
	AFW-b	2208	n	09/03/87	04:30	09/03/87	18:00	13.50	0.00	13.50
87-4	AFW-b	2209	n	12/02/87	10:47	12/02/87	10:55	0.13	0.00	0.13

Notes:
1. Data source: Shift supervisor's log.
2. AFWS trains "a & b" motor driven; train "t" turbine driven.
3. Data collection period (85-1 through 87-4).

QTR	System / Train	Critical Hours	Failure (y/n)	Downtime Date Out	Time Out	Return to Service Date In	Time In	Detected Downtime	Undetected Downtime	Total Downtime	Quarter Total
86-1	HPCI		n	02/13/86	00:55	02/14/86	05:55	29.00	0	29.00	
	HPCI		n	03/10/86	05:53	03/12/86	16:23	58.50	0	58.50	
	HPCI		n	03/21/86	09:10	03/21/86	15:10	6.00	0	6.00	
	HPCI		n	03/21/86	22:00	03/22/86	00:30	2.50	0	2.50	
	HPCI	1824	n	03/22/86	09:30	03/22/86	18:30	9.00	0	9.00	105.0
86-3	HPCI		n	07/19/86	06:30	07/19/86	23:40	17.00	0	17.00	
	HPCI		n	08/09/86	14:00	08/12/86	20:30	78.50	0	78.50	
	HPCI	2009	n	08/25/86	12:01	08/27/86	12:01	48.00	0	48.00	143.50
86-4	HPCI		n	12/19/86	08:00	12/19/86	09:00	1.00	0	1.00	
	HPCI	2209	n	12/22/86	10:42	12/22/86	18:57	8.25	0	8.25	9.25
87-2	HPCI		n	04/15/87	14:00	04/16/87	01:30	11.50	0	11.50	
	HPCI		n	04/16/87	15:00	04/17/87	04:30	13.50	0	13.50	
	HPCI	1073	n	05/07/87	09:00	05/09/87	21:00	60.00	0	60.00	85.00
86-1	RCIC		n	02/10/86	05:10	02/10/86	21:40	16.50	0	16.50	
	RCIC		n	02/18/86	05:00	02/18/86	20:30	15.50	0	15.50	
	RCIC		n	03/15/86	08:22	03/15/86	18:22	10.00	0	10.00	
	RCIC	1824	n	03/25/86	00:56	03/25/86	01:56	1.00	0	1.00	43.00
86-3	RCIC		n	07/21/86	23:55	07/26/86	09:55	106.00	0	106.00	
	RCIC		n	08/13/86	14:42	08/14/86	14:42	24.00	0	24.00	
	RCIC	2003	n	09/03/86	08:00	09/03/86	19:30	11.50	0	11.50	141.50
87-1	RCIC	2064	n	01/23/87	09:30	01/23/87	16:30	7.00	0	7.00	
87-2	RCIC		n	04/20/87	07:12	05/04/87	07:12	336.00	0	336.00	
	RCIC	1073	n	05/14/87	08:43	05/14/87	20:43	12.00	0	12.00	348.00
86-3	EPSAC-1		n	09/17/86	07:00	09/17/86	15:00	8.00	0	8.00	
	EPSAC-1		n	09/26/86	08:34	09/26/86	22:34	14.00	0	14.00	
	EPSAC-1	2009	n	09/29/86	16:05	09/30/86	06:05	14.00	0	14.00	36
86-4	EPSAC-1		n	12/09/86	02:30	12/09/86	16:30	14.00	0	14.00	
	EPSAC-1	2209	n	12/09/86	17:41	12/09/86	22:41	5.00	0	5.00	19
87-1	EPSAC-1	2064	n	01/09/87	12:01	01/09/87	22:01	10.00	0	10.00	10
87-2	EPSAC-1		n	04/20/87	11:40	04/22/87	15:40	52.00	0	52.00	
	EPSAC-1	1073	n	05/07/87	10:01	05/07/87	10:31	0.50	0	0.50	52.50
86-3	EPSAC-2	2009	n	09/22/86	17:30	09/23/86	10:00	16.50	0	16.50	16.50
86-4	EPSAC-2		n	11/21/86	16:45	11/22/86	00:45	8.00	0	8.00	
	EPSAC-2	2209	n	11/25/86	12:08	07/12/87	14:10	6.75	0	6.75	14.75
87-1	EPSAC-2	2064	n	01/12/87	10:34	01/12/87	19:34	9.00	0	9.00	9.00
87-2	EPSAC-2	1073	n	05/07/87	10:50	05/07/87	11:20	0.50	0	0.50	0.5
86-1	EPSAC-3		n	02/03/86	05:00	02/03/86	17:00	12.00	0	12.00	
	EPSAC-3		y	02/03/86	18:30	02/03/86	23:00	4.50	0	4.50	
	EPSAC-3		n	02/07/86	10:43	02/07/86	13:13	2.50	0	2.50	
	EPSAC-3	1824	n	02/19/86	04:50	02/19/86	21:20	16.50	0	16.50	35.50
86-3	EPSAC-3	2009	n	09/05/86	00:01	09/06/86	09:31	33.50	0	33.50	33.50
86-4	EPSAC-3	2209	n	10/01/86	10:28	10/02/86	01:28	15.00	0	15.00	15.00
87-1	EPSAC-3		n	01/13/87	08:30	01/13/87	20:30	12.00	0	12.00	
	EPSAC-3	2064	y	01/29/87	10:31	01/31/87	07:31	45.00	360	405.00	417.00
87-2	EPSAC-3	1073	n	05/07/87	11:30	05/07/87	12:00	0.50	0	0.50	0.50

Plant 6 Safety System Trains-Out-of Service Hours

QTR	System / Train	Critical Hours	Failure (y/n)	Downtime Date Out	Time Out	Return to Service Date In	Time In	Detected Downtime	Undetected Downtime	Total Downtime	Quarter Total
86-2	EPSAC-4		n	05/02/86	13:30	05/13/86	13:30	264.00	0	264.00	
	EPSAC-4	1104	n	06/26/86	05:00	06/26/86	21:00	16.00	0	16.00	280.0
86-3	EPSAC-4		n	07/02/86	18:23	07/02/86	01:23	7.00	0	7.00	
	EPSAC-4	2009	n	09/11/86	12:00	09/12/86	07:00	19.00	0	19.00	26.0
86-4	EPSAC-4	2209	n	12/16/86	10:00	12/16/86	20:00	10.00	360	370.00	370.0
87-1	EPSAC-4	2064	n	01/14/87	23:31	01/15/87	09:31	10.00	0	10.00	10.0
87-2	EPSAC-4	1073	n	05/05/87	06:16	05/07/87	13:31	55.25	0	55.25	55.3

Notes:
1. Data source: LCO logbook.
2. HPCI and RCIC are single train turbine driven systems.
3. Data collection period (86-1 through 87-2).

Plant 7 Safety System Trains-Out-of Service Hours

QTR	System / Train	Critical Hours	Failure (y/n)	Downtime Date Out	Downtime Time Out	Return to Service Date In	Return to Service Time In	Detected Downtime	Undetected Downtime	Total Downtime	Quarter Total
86-1	EPSAC-1	1792	n	01/22/86	09:45	01/22/86	15:45	6.00	0	6.00	6.00
86-3	EPSAC-1		y	09/04/86	21:11	09/05/86	04:41	7.50	360	367.50	
	EPSAC-1	1799	n	09/30/86	06:15	09/30/86	18:15	12.00	0	12.00	379.50
87-1	EPSAC-1	873	y	01/17/87	02:29	01/17/87	17:00	17.50	0	17.5	17.50
86-1	EPLAC-3		y	02/17/86	13:00	02/17/86	17:30	4.50	360	364.50	
	EPSAC-3	1792	n	02/17/86	06:25	02/17/86	12:25	6.00	0	6.00	370.50
86-2	EPSAC-3		n	04/05/86	05:50	04/05/86	15:50	10.00	0	10.00	
	EPSAC-3		n	04/15/86	06:42	04/15/86	14:42	8.00	0	8.00	
	EPSAC-3		n	06/04/86	06:40	06/07/86	13:10	78.50	0	78.50	
	VF/AC-3		n	06/09/86	15:45	06/10/86	13:45	22.00	0	22.00	
	EPSAC-3		y	06/10/86	19:30	06/12/86	13:00	41.50	360	401.50	
	EPSAC-3	938	n	06/14/86	14:25	06/14/86	18:25	4.00	0	4.00	524.00
86-4	EPSAC-3		n	10/29/86	23:31	10/30/86	20:01	20.50	0	20.5	
	EPSAC-3	1704	n	11/18/86	09:30	11/18/86	17:00	7.50	0	7.50	28.00
87-2	EPSAC-3		n	05/24/87	08:53	05/26/87	16:53	56.00	0	56.00	
	EPSAC-3		n	05/27/87	12:50	05/27/87	14:50	2.00	0	2.00	
	EPSAC-3	1401	n	06/05/87	16:10	06/06/87	16:10	24.00	0	24.00	132.00
86-1	AFWS-3a	1792	n	02/04/86	06:30	02/04/86	07:30	1.00	0	1.00	1.00
86-4	AFWS-3a	1704	n	10/17/86	11:41	10/19/86	12:41	49.00	0	49.00	49.00
87-2	AFWS-3a		n	04/16/87	15:38	04/16/87	20:08	4.50	0	4.50	
	AFWS-3a	1401	n	05/07/87	03:26	05/07/87	03:56	0.50	0	0.50	6.00
86-1	AFWS-3b	1792	n	02/04/86	06:30	02/04/86	07:30	1.00	0	1.00	1.00
86-2	AFWS-3b	938	n	04/09/86	05:20	04/09/86	14:20	9.00	0	9.00	9.00
86-4	AFWS-3b		y	10/11/86	07:41	10/11/86	17:41	10.00	360	370.00	
	AFWS-3b	1704	n	10/19/86	13:00	10/21/86	14:00	49.00	0	49.00	419.00
87-2	AFWS-3b		n	05/11/87	19:54	05/12/87	03:24	7.50	0	7.50	
	AFWS-3b	1401	n	05/12/87	09:17	05/12/87	15:17	6.00	0	6.00	78.50
86-2	AFWS-2	938	n	05/07/86	04:50	05/09/86	21:50	65.00	0	65.00	65.00
86-3	AFWS-2		n	08/18/86	12:45	08/21/86	11:16	70.50	0	70.50	
	AFWS-2		n	08/23/86	10:33	08/23/86	11:33	1.00	0	1.00	
	AFWS-2		y	08/24/86	10:22	08/24/86	14:22	4.00	360	364.00	
	AFWS-2		y	08/26/86	20:59	08/27/86	21:59	25.00	0	25.00	
	AFWS-2		n	09/05/86	09:28	09/07/86	13:28	52.00	0	52.00	
	AFWS-2	1799	y	09/24/86	20:58	09/27/86	02:58	54.00	360	414.00	926.50
86-4	AFWS-2	1704	n	10/21/86	15:00	10/23/86	16:00	49.00	0	49.00	49.00

Notes:
1. Data source: Control room logbook.
2. EPSAC train "3" shared by Units 1 & 2.
3. AFWS trains "3a" & "3b" motor-driven; train 2 turbine-driven.
4. Data collection period (86-1 through 87-2).

Plant B Safety System Trains-Out-of Service Hours

QTR	System / Train	Critical Hours	Failure (y/n)	Downtime Date Out	Downtime Time Out	Return to Service Date In	Return to Service Time In	Detected Downtime	Undetected Downtime	Total Downtime	Quarter Total
86-1	EPSAC-2	1970	n	01/23/86	09:00	01/23/86	21:30	12.50	0	12.50	12.50
86-2	EPSAC-2	1849	n	04/07/86	00:18	04/07/86	20:18	20.00	0	20.00	20.00
87-1	EPSAC-2		y	01/13/87	07:18	01/16/87	07:18	72.00	360	432.00	
	EPSAC-2	301	n	01/20/87	10:24	01/20/87	17:24	7	0	7.00	432.00
86-1	EPSAC-3	1970	n	02/17/86	06:25	02/17/86	12:25	6.00	0	6.30	6.00
86-2	EPSAC-3		n	04/05/86	05:50	04/05/86	15:50	10.00	0	10.00	
	EPSAC-3		n	04/15/86	06:42	04/15/86	14:42	8.00	0	8.00	
	EPSAC-3		n	06/04/86	06:40	06/07/86	13:10	78.50	0	78.50	
	EPSAC-3		n	06/09/86	15:45	06/10/86	13:45	22.00	0	22.00	
	EPSAC-3		y	06/10/86	19:30	06/12/86	13:00	41.50	360	401.50	
	EPSAC-3	1849	n	06/14/86	14:25	06/14/86	18:25	4.00	0	4.00	524.00
86-4	EPSAC-3		n	10/29/86	23:31	10/30/86	20:01	20.50	0	20.5	
	EPSAC-3	296	n	11/18/86	09:30	11/18/86	17:00	7.50	0	7.50	28.00
87-2	EPSAC-3		n	05/24/87	08:53	05/26/87	16:53	56.00	0	56.00	
	EPSAC-3		n	05/27/87	12:50	05/27/87	14:50	2.00	0	2.00	
	EPSAC-3	2176	n	06/05/87	16:10	06/06/87	16:10	24.00	0	24.00	85.50
86-2	AFWS-3a	1849	n	05/01/86	08:06	05/01/86	11:36	3.50	0	3.50	3.50
87-1	AFWS-3a		y	02/01/87	03:30	03/03/87	16:30	733.00	360	1093.00	
	AFWS-3a		n	02/26/87	07:10	02/26/87	15:40	8.50	0	8.5	
	AFWS-3a	301	y	03/18/87	22:40	03/19/87	10:40	12.00	360	372	1473.50
87-2	AFWS-3a	2176	n	04/02/87	11:00	04/03/87	19:00	32.00	0	32.00	32.00
86-1	AFWS-3b	1970	n	02/08/86	06:33	02/08/86	13:33	7.00	0	7.00	7.00
87-1	AFWS-3b	301	n	02/26/87	16:00	02/27/87	00:30	8.50	0	8.5	8.50
87-2	AFWS-3b		n	04/14/87	14:13	04/14/87	22:13	8.00	0	8.00	
	AFWS-3b	2176	n	06/16/87	07:04	06/16/87	13:34	6.50	0	6.50	14.50

Notes:
1. Data source: Control room logbook.
2. EPSAC train "3" shared by Units 1 & 2.
3. AFWS trains "3a" & "3b" motor-driven; train 2 (turbine-driven) no data reported.
4. Data collection period (86-1 through 87-2).

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11. ABSTRACT (200 words or less)

This report describes and applies a process for validating a modal for a risk-based performance indicator. The purpose of the risk-based indicator evaluated, Safety System Function Trend (SSFT), is to monitor the unavailability of selected safety systems. Validation of this indicator is based on three aspects: a theoretical basis, an empirical basis relying on statistical correlations, and case studies employing 25 plant years of historical data collected from five plants for a number of safety systems. Results using the SSFT model are encouraging. Application of the model through case studies dealing with the performance of important safety systems shows that statistically significant trends in, and levels of, system performance can be discerned which thereby can provide leading indications of degrading and/or improving performances.

Methods for developing system performance tolerance bounds are discussed and applied to aid in the interpretation of the trends in this risk-based indicator.

Some additional characteristics of the SSFT indicator, learned through the data-collection efforts and subsequent data analyses performed, are also discussed. The usefulness and practicality of other data sources for validation purposes are explored.

12. KEY WORDS/DESCRIPTORS (List words or phrases that will assist researchers in locating the report.)

Nuclear power plants - performance; reliability; engineered safety systems - availability; statistical data; theoretical data; statistical models; risk assessment; reactor safety; nuclear power plants - systems analysis; reactor protection systems; nuclear power plants - auxiliary water systems; nuclear power plants - power systems

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