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Maintenance Effectiveness Indicator

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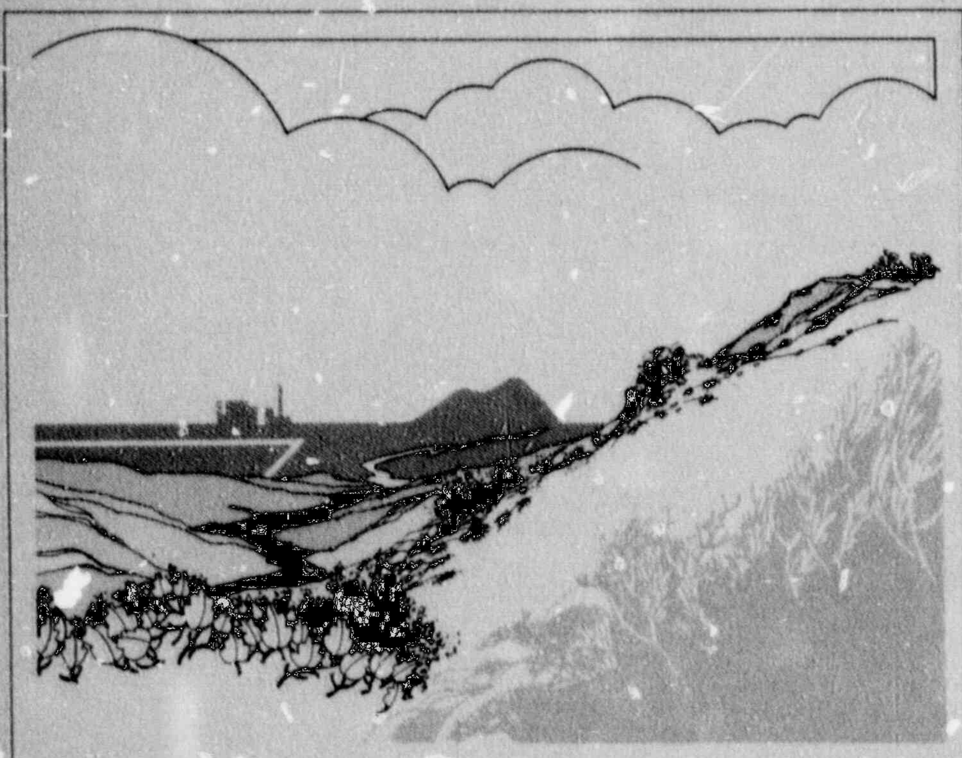

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ABSTRACT

The U.S. Nuclear Regulatory Commission's (NRC's) Office for Analysis and Evaluation of Operational Data (NRC/AEOD) has been pursuing the development of measurement systems to ascertain the effectiveness of maintenance programs in commercial U.S. nuclear power plants. The previous reports AEOD/S804A, *Preliminary Results of the Trial Program for Maintenance Performance Indicators*, and S804B, *Application of the NPRDS for Maintenance Effectiveness Monitoring*, documented the development and validation of a maintenance effectiveness indicator for selected boiling water reactor (BWR) plants and components. The present effort extends the earlier AEOD findings and validates the maintenance effectiveness indicator for use with both BWR and pressurized water reactor (PWR) commercial nuclear power plants.

The development and validation of the maintenance effectiveness indicator are discussed in this report, along with the results of applying the indicator to component failure data for PWR and BWR plants over a two-year study period. The appendices are issued under a separate volume, because they contain proprietary information. For more information regarding the appendices contact Ms. B. M. Brady of NRC/AEOD at (301) 492-4499.

FIN No. L1345—Maintenance Effectiveness Indicator Development

SUMMARY

The U.S. Nuclear Regulatory Commission's (NRC's) Office for Analysis and Evaluation of Operational Data (NRC/AEOD) has been pursuing the development of measurement systems to ascertain the effectiveness of maintenance programs in commercial U.S. nuclear power plants. The previous reports, AEOD/S804A, *Preliminary Results of the Trial Program for Maintenance Performance Indicators*, and S804B, *Application of the NPRDS for Maintenance Effectiveness Monitoring*, documented the development and validation of a maintenance effectiveness indicator for selected boiling water reactor (BWR) plants and components. The present effort extends the earlier AEOD findings and validates the maintenance effectiveness indicator for use with both BWR and pressurized water reactor (PWR) commercial nuclear power plants. This effort is a joint undertaking by the NRC/AEOD and by EG&G Idaho, Inc., of the Idaho National Engineering Laboratory (INEL).

The maintenance effectiveness indicator uses a methodology that evaluates the Nuclear Plant Reliability Data System (NPRDS) component failure data for preselected systems and signals any increase in the failure rate that exceeds a predetermined value. The number and frequency of these flagged failure rate increases is then trended for all systems considered over the study period to obtain a measure of the level of maintenance effectiveness at a plant. This approach is similar to statistical process control analyses used extensively by manufacturing industries to indicate when their quality of manufactured components is degrading by noting when the component failure rate is beyond what is expected from random fluctuations.

The purpose of this indicator is to aid in trending the effectiveness of each plant's maintenance program in ensuring equipment performance, i.e., that the equipment will operate as intended. To accomplish this purpose, the indicator is based on the failure histories of a range of components; histories large enough in number to provide an adequate sampling of how the plant equipment is performing. In this approach, individual failures and the increases in failure rate are not necessarily safety significant per se. This approach contrasts with some other performance indicators such as automatic scrams, safety system failures, and safety system actuations where some level of safety significance is attached to each constituent event. The maintenance effectiveness indicator flags are not intended to provide a basis for immediate regulatory response. Rather, the accumulation of these flags over time should provide indication of improvement or decline in a plant's maintenance program.

The methodology used to develop the maintenance effectiveness indicator was performed in a four-step process. First, the components and systems whose failure rates would be monitored were identified for both BWR and PWR plants. Selection of these components was based on NPRDS reporting guidelines, on the premise that this equipment would normally be functioning while the plant is operating, and that in general, their failure could lead to a plant outage. Second, the failure data for the selected systems and components were downloaded from the NPRDS data base and verified as completely received. The downloaded NPRDS failure data were then reviewed for reporting consistency and accuracy. Third, previously developed display methods were enhanced and expanded to depict the maintenance effectiveness indicator flags. These flags highlight failure data when the failure rate exceeds the predetermined threshold value. Finally, areas that may warrant further study were identified.

The maintenance effectiveness indicator was then validated to show that the indicator was reflecting the parameter being measured, i.e., maintenance effectiveness; to demonstrate that the indicator was useful in revealing maintenance-related trends of equipment performance, i.e., results of the maintenance process; and to show that the indicator was consistently applied across all plants. A cause analysis was performed of the narratives in the individual NPRDS failure reports that contributed to the failure rate increases flagged by the indicator. The results of the analysis showed that a majority of the failures that contributed to the flagged failure rate increases involved inadequate or ineffective maintenance. A second analysis was performed by comparing maintenance effectiveness indicator results with equipment failures documented in individual licensee event reports (LERs) submitted by plants to meet the reporting requirements specified in 10 CFR 50.73, the so-called LER rule. The analysis showed that plants with a high number of maintenance-related events, as reported in the LERs, were also noted as having a high number of indicator flags.

Finally, the indicator was applied to component failure data from all commercial nuclear power plants for a two-year study period (March 1986 through June 1988). Five conclusions were determined from the results. First, the maintenance effectiveness indicator was validated for monitoring the maintenance process for all PWR and BWR plants. This analysis

reconfirmed the applicability of the indicator for BWR plants and established the applicability for PWR plants.

Second, the necessary processes have been developed and verified to conclude that the maintenance effectiveness indicator is now ready for production use. The components were identified that should be monitored for evaluating maintenance effectiveness. The methodology used to download the NPRDS data was verified and found to be effective for both BWR and PWR plants. The indicator display methods were developed to indicate the maintenance effectiveness, first, at a plant level and, second, in comparison with its nuclear steam system supplier (NSSS) reactor vendor group as a first approximation of a peer comparison.

Third, the results of the maintenance effectiveness indicator calculations for all plants identified an overall improvement in the level of maintenance performance over the two-year period. Each NSSS reactor vendor group showed an improvement in maintenance effectiveness.

Fourth, plants with ineffective maintenance programs consistently produced a higher-than-average number of flags, when compared with their peers. The higher number of flags was observed regardless of whether or not a plant was in an outage. This conclusion was obtained even though the indicator has an inherent sensitivity to outages, and failures and indicator flags tend to cluster within outages.

Fifth, the maintenance effectiveness indicator does not have the consistent ability to predict equipment forced outages. A failure within a system that led to an equipment forced outage was preceded by an indicator flag only 12% of the time.

In response to Commission direction, the NRC staff broadened its maintenance indicator effort by establishing a demonstration project with industry in September 1989. The goal of this project is to achieve technical consensus on feasible methods for monitoring the area of maintenance performance. The group, which consists of NRC staff from AEOD and representatives from six utilities, the Nuclear Utility Management Resources Committee, and the Institute of Nuclear Power Operations, began work by examining the component failure-based indicator described above. This project will continue into the early part of 1990, and the results will be considered in planning future work on maintenance indicators.

The appendices contain material that support the findings in the body of the report. Much of the data in the appendices is proprietary and should be protected accordingly.

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CONTENTS

FIGURES

TABLES

ABBREVIATIONS, ACRONYMS, AND INITIALISMS

AEOD	NRC Office for Analysis and Evaluation of Operational Data
AFW	auxiliary feedwater
BOP	balance of plant
BW	Babcock & Wilcox (NSSS)
BWR	boiling water reactor
CE	Combustion Engineering (NSSS)
CFR	Code of Federal Regulations
CVCS	chemical and volume control system
FSAR	Final Safety Analysis Report
GE	General Electric (NSSS)
INEL	Idaho National Engineering Laboratory
INPO	Institute of Nuclear Power Operations
LER	Licensee Event Report
LWR	light water reactor
NERC	North American Electric Reliability Council
NPRDS	Nuclear Plant Reliability Data System
NRC	U.S. Nuclear Regulatory Commission
NSSS	nuclear steam system supplier
ODE	outage-dominating equipment
ORNL	Oak Ridge National Laboratory
PC	personal computer
PWR	pressurized water reactor
RCS	reactor coolant system
RPS	reactor protection system
SCSS	Sequence Coding and Search System
WE	Westinghouse (NSSS)

MAINTENANCE EFFECTIVENESS INDICATOR

1. INTRODUCTION

The U.S. Nuclear Regulatory Commission's (NRC's) Office for Analysis and Evaluation of Operational Data (NRC/AEOD) has been pursuing the development of measurement systems to ascertain the effectiveness of maintenance programs in commercial U.S. nuclear power plants. This document describes the development, validation, and application of a maintenance effectiveness indicator for monitoring both pressurized water reactors (PWRs) and boiling water reactors (BWRs). This indicator is now ready for implementation. This effort was a joint undertaking by the NRC/AEOD and by EG&G Idaho, Inc., of the Idaho National Engineering Laboratory (INEL).

1.1 History

The NRC has initiated a program whose goal is to improve maintenance programs at each commercial nuclear power plant. A major part of the program was the development of the proposed rule, "Ensuring the Effectiveness of Maintenance Programs for Nuclear Power Plants," 10 CFR 50.65, which was issued on November 28, 1988.[1] Subsequent to the issuance of the proposed rule, the NRC has released a Staff Requirements Memorandum[2] that provides further understanding of the proposed NRC position and direction.

In support of the proposed rule and in response to the Memorandum, the NRC/AEOD and the INEL have developed a methodology to monitor the effectiveness of each plant's maintenance program.

The first major reporting of methodology development was issued in October 1988 as AEOD/S804A, *Preliminary Results of the Trial Program for Maintenance Performance Indicators*, transmitted to the NRC under the letter SECY 88-289.[3] That report concluded that measurement of maintenance effectiveness was feasible and that the best measure of maintenance effectiveness would likely be based upon the component reliability and failure history.

A second report on this subject was issued in January 1989 as AEOD/S804B, *Application of the NPRDS for Maintenance Effectiveness Monitoring*.[4] The findings of that report stated that the Nuclear Plant Reliability Data System (NPRDS)[5] was a viable source of data to derive maintenance effectiveness indicators. That report also documented the development of a practical and usable indicator for BWRs, which was derived from component failure records submitted by each BWR plant to the NPRDS. The indicator demonstrated a capability to monitor plant maintenance effectiveness.

1.2 Present Effort

A complete treatise on the development, validation, and application of a maintenance effectiveness indicator program is presented in the following sections of this report. The indicator described previously in the AEOD/S804A[3] and AEOD/S804B[4] reports was reexamined and extended to a broader scope of BWR outage-dominating systems and equipment. This report identifies PWR systems and components comparable to those selected for the BWR and validates the indicator for PWR use.

An overview description of the indicator and the procedure to implement it for monitoring maintenance effectiveness are described in Section 2.

The development of the maintenance effectiveness indicator is presented in Section 3. Much of the methodology described in this section was extended from earlier efforts presented in the AEOD/S804B report.

The results of validating the maintenance effectiveness indicator are summarized in Section 4. The goal was to ensure that the indicator produced an accurate picture of maintenance effectiveness on a plant-by-plant basis. The validation methodology was also extended from earlier efforts documented in the AEOD/S804B report.

The results from using the indicator to evaluate U.S. plants for determining the industry trends in maintenance program effectiveness are presented in Section 5.

Section 6 includes the conclusions reached from efforts described throughout this report.

Appendices A through G contain material that support the findings in the body of the report. Much of the data in the appendices is proprietary and should be protected accordingly. The main body of the report, when detached from the Appendices, is non-proprietary.

1.3 Future Efforts

The maintenance effectiveness indicator described in this report represents the completion of the first phase of a two-phase NRC/AEOD program. The indicator is ready for implementation. Further refinements and additions can be made, however. The second phase will address three such areas.

First, the normalization of indicator results to each plant's time-in-life will be evaluated. During the development of the indicator, a cursory analysis indicated that additional information about an individual plant's maintenance effectiveness might be obtained if the fuel cycle history, including the present time within a fuel cycle, would be tracked concurrently with the indicator. This system would allow comparison of a plant's performance to its NSSS vendor peers at any time within the plant's multi-fuel cycle history (e.g., "How is Plant A performing at the end of fuel cycle 3, when compared with its peers when they had reached the end of their third fuel cycle?").

Second, studies will be conducted on how to process and portray the outage-dominating equipment failure data according to maintenance program category (e.g., mechanical, electrical, instrumentation and control). The intent is to generate an additional indicator to show maintenance effectiveness. The additional indicator could help identify a specific area or areas of a plant's maintenance program as needing improvement.

Third, the AEOD/S804A report described other possible maintenance effectiveness indicators whose merits were notable but the indicators required further conceptual development and subsequent validation. The most promising of these additional indicators will be pursued to complement the present indicator.

2. OVERVIEW OF MAINTENANCE EFFECTIVENESS INDICATOR

A description of the maintenance effectiveness indicator and the procedure to implement the indicator as part of a monitoring program are the topics of this section.

2.1 Description Of Maintenance Effectiveness Indicator

The maintenance effectiveness indicator is determined by scanning the NPRDS component failure data for each system being monitored and signaling an increase in the failure rate (failures per month) when it exceeds a predetermined threshold. The number of these flagged failure rate (failures per month) increases is then trended for all systems considered over a specified study period to obtain a measure of the level of maintenance effectiveness at a plant. Note that only immediate and degraded failures are monitored by the indicator, not the incipient failures (as defined by NPRDS reporting criteria).

The immediate and degraded component failures from 10 to 12 different systems are tracked by the indicator. These systems and components historically have been dominant contributors to forced outages and reside in either the NSSS or the balance of plant (BOP).

An indicator result example for a Westinghouse plant is shown on Figure 1. The monthly total number of flags is displayed in the trend plot in the lower right-hand corner of Figure 1. These data were derived from the component failure rate increases that were flagged for the 10 different systems being monitored. In this example, a total of 12 failure rate increases were signaled during the approximately two-year study period. The distribution of flags among the systems is seen on the left side of Figure 1.

To supplement the trending of the indicator data, the trend plot also presents the cumulative number of flags for the plant and the average cumulative number for that plant's vendor group over the study period.

Shown in the upper right-hand corner of Figure 1 is an area of the graphical output display currently under development. That area depicts the output trend from a new indicator that, when completed, will facilitate interpretation of maintenance effectiveness. This area is identified under the heading of Maintenance Category. Here, all failure data, regardless of the system, have been grouped by the various organizations that comprise a maintenance program (e.g., mechanical/electrical, instrumentation and control). The same indicator formula is again used to scan the component failure data and flag those failure rates within each maintenance area that exceed a predetermined threshold. It should be noted that this maintenance category indicator was based on the same data used for the maintenance effectiveness indicator. It should also be noted that the number of flags in the maintenance category display may not be equal or even exist for the same month as the flags in the system displays. The calculations for the new indicator are based on the number of reports for each system. The time when the theshold value was exceeded could be different.

The maintenance effectiveness indicator presented in this report represents a step toward developing a system for the comprehensive assessment of the maintenance effectiveness program. To get a complete picture, the maintenance effectiveness indicator should not be used alone. Other sources of information and other indicators will be required.

The purpose of this indicator is to aid in trending the effectiveness of each plant's maintenance program in ensuring equipment performance, i.e., that the equipment will operate as intended. To accomplish this purpose, the indicator is based on the failure histories of a range of components; histories large enough in number to provide an adequate sampling of how the plant equipment is performing. In this approach, individual failures and the increases in failure rate are not necessarily safety significant per se. This approach contrasts with some other performance indicators such as automatic scrams, safety system failures, and safety system actuations where some level of safety significance is attached to each constituent event. The maintenance effectiveness indicator flags are not intended to provide a basis for immediate regulatory response. Rather, the accumulation of these flags over time should provide indication of improvement or decline in a plant's maintenance program.

2.2 Implementation Procedure

The maintenance effectiveness indicator has been validated and is ready for immediate use. A quarterly reporting of indicator results is presently envisioned by the NRC/AEOD staff. To perform routine production, six steps will be followed that result in producing the indicator graphical output (Figure 1). Most of the process has been automated through the use of personal computers (PCs).

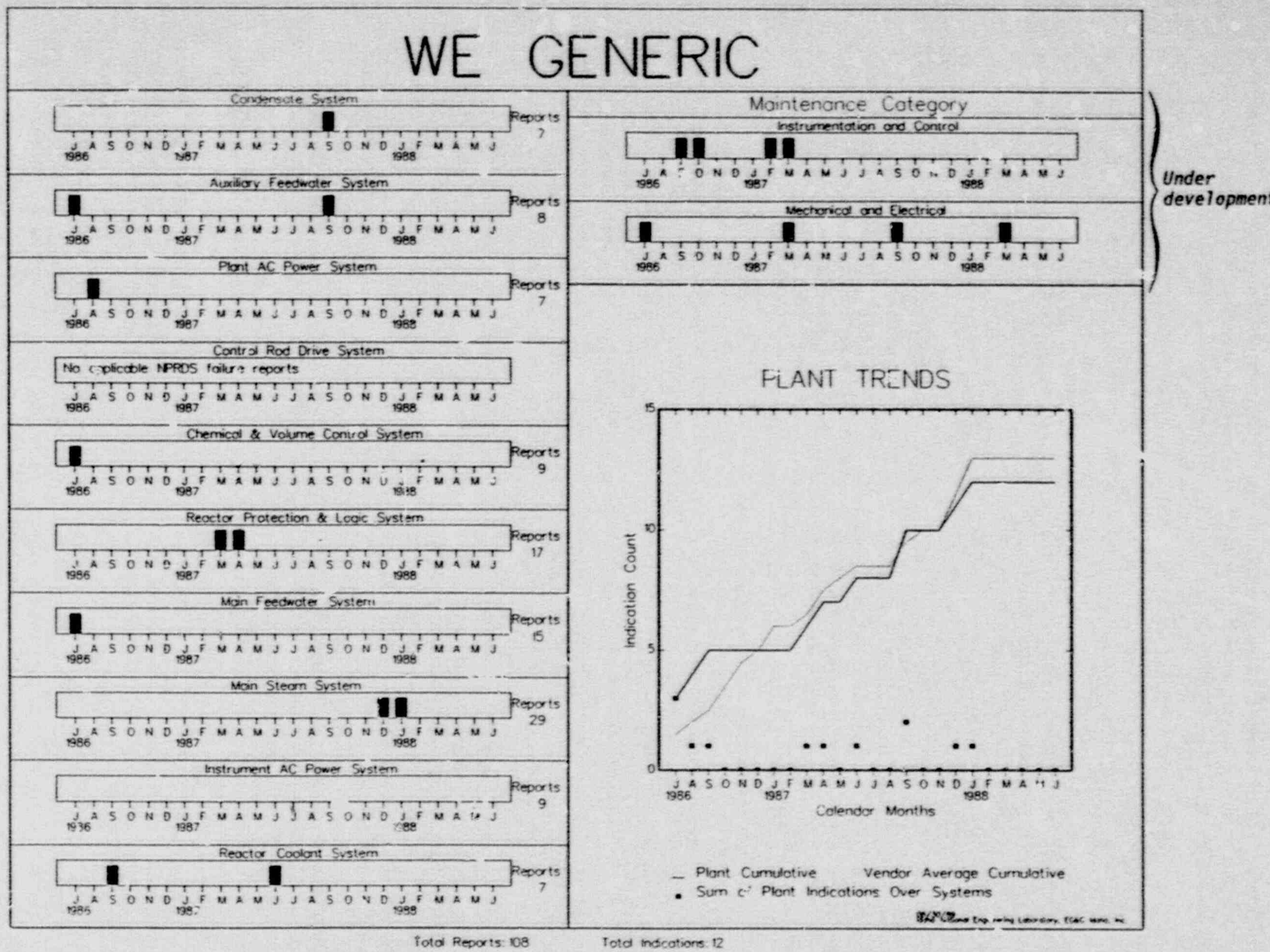

Figure 1. Example display from maintenance effectiveness indicator.

1. *Select study period*—A 28-consecutive-month period is selected.

2. *Download failure data*—Both immediate and degraded failure data are downloaded collectively and treated hereafter as a single entity. The transfer is electronically performed from the NPRDS computer system to a PC. (See Sections 3.3.1 through 3.3.3 for more details.)

3. *Verify downloaded data*—This step ensures that all data from the systems and components of interest were obtained as requested. (See Section 3.3.4.)

4. *Perform NPRDS data quality assurance review*—The data are reviewed to ensure accuracy and consistency. (See Sections 3.4.1 and 3.4.2.)

5. *Process failure data with indicator*—The component failure rates are reviewed and the indicator flags are generated, as are the vendor trend data and the graphical display output. (See Sections 3.5 and 3.6.)

6. *Quality verify the data*—Verify the downloaded data and accuracy of the indicator displays.

This six-step process will be repeated quarterly, using a one-month sliding window described in Section 3.5. The oldest three months of data will be deleted, and the next three newer months of data will be added to define the study period.

The data used for the maintenance effectiveness indicator are selected based on failure discovery date. The latest failure discovery date for the component failure data being processed for a specific maintenance effectiveness indicator has a failure discovery date about six months before the date the indicator was calculated. This delay is based on the length of time required for the licensee to report failures, for NPRDS failure report codification, and for data quality assurance.

The implementation procedure was used to process the component failure data for all plants during the study period, March 1986 through June 1988. A complete set of output displays is provided in Appendix C. These plots are proprietary and should be handled accordingly. Appendix G summarizes the overall process that will be followed for full implementation of the maintenance effectiveness indicator program.

In response to Commission direction, the NRC staff broadened its maintenance indicator effort by establishing a demonstration project with industry in September 1989. The goal of this project is to achieve technical consensus on feasible methods for monitoring the area of maintenance performance. The group, which consists of NRC staff from AEOD and representatives from six utilities, the Nuclear Management Resources Committee, and the Institute of Nuclear Power Operations (INPO), began work by examining the component failure-based indicator described above. This project will continue into the early part of 1990, and the results will be considered in planning future work on maintenance indicators.

3. MAINTENANCE EFFECTIVENESS INDICATOR DEVELOPMENT

Section 3 presents a detailed description of the development activities that led to the establishment of the maintenance effectiveness indicator. Presented are the specific activities, analyses, and justifications that were used to (a) select system and component failures for tracking; (b) develop and apply search strategies to download the appropriate failure data and supporting information; (c) verify that the data are accurate and consistent; (d) verify the computer software used to calculate maintenance effectiveness indicator flags and display the maintenance effectiveness indicator results. Before presenting the details of each of these areas, the results are summarized below.

3.1 Summary of Development

The maintenance effectiveness indicator has two components: (a) the analytical expression that is used to denote when an increase in the failure rate is indicative of degradation in maintenance effectiveness and (b) the graphical display techniques for visual depiction of the results.

The analytical expression chosen for the indicator was taken from the AEOD/S804B report.

The analytical expression can be restated as follows:

> The expression involves the number of component failures discovered during each month in a continuous five-month period for each of the selected systems. Dividing the number of component failures for each of the systems in a selected time period by the number of months in the time period, it then calculates the average component failure rate for each system for (a) the first three months of the five-month time span and (b) the last two months of the span. The expression then compares the two average rates and, if the rate in the last two months exceeds that of the first three months by more than a threshold value, an indicating mark is placed in the last month of the five-month span. The program then adds the next more recent month and drops the oldest month, i.e., the five-month span is shifted forward one month, and the failure rate calculations and comparison are repeated. This moving window approach has the effect of providing multiple indicating marks over successive months if an increase in failure rate exceeds the threshold value or if it is sustained over a number of months.

The display (Figure 1) presents the indicator results (total indications per month) for an individual plant, as well as the system-by-system basis, and then shows the overall trends in maintenance effectiveness for the plant.

The scope of the present effort was expanded over the effort documented in the AEOD/S804B report to encompass all operating PWR and BWR plants that report to the NPRDS.

The results of this development effort are consistent with those of the previous AEOD reports. The following general statements can be made based on the evaluation of the findings:

- The number of components that are reportable to the NPRDS and the number of components being monitored for the maintenance effectiveness indicator were totaled and compared for all plants for each NSSS vendor. Approximately the same percentage of the reportable components is being monitored for each of the four NSSS groups.

- The review of failure reports revealed that the licensees and INPO correctly categorize the failure severity level.

- As a result of the NPRDS data review, no patterns of deficiencies were identified in the specific areas of failure report coding, data entry, or reporting consistency between units from sites or utilities with multiple units.

- The method for processing and displaying the indicator data and trends was developed, verified, and prepared for implementation.

- The processing and display methodology was compared to the traditional statistical control process display method. The two methods were found to correlate well.

3.2 System and Component Selection

This section describes the basis for selecting the systems and components whose failures were examined by the maintenance effectiveness indicator. The scope of the present study considered both PWR and BWR plants and selected systems and components for each

NSSS design. The final list of monitored equipment was determined by repeated evaluations of the systems and components reportable to NPRDS (e.g., initial selection of components using historical data and operating plant experience, evaluation of the candidate list to identify outage dominating equipment, comparison with industry data to assess significance of reported failures, and comparison of the list of systems and equipment with other sources).

Three criteria were used to select the systems and components to be tracked for maintenance effectiveness. The first selection criterion was that the systems and components had to be included in the reportability scope of the NPRDS. The identification of the reportable systems and components was made from the lists provided in the NPRDS coding manuals.

The second criterion was to restrict the list of candidates to systems and equipment that historically have been dominant contributors to forced outages. That is, the set of equipment was limited to outage-dominating equipment (ODE) within the scope of NPRDS reportability guidelines and considered to be important to the overall operation of the plant. The equipment that meets the ODE criterion could cause a plant outage should a failure be experienced. Because of the importance of the equipment, maintenance would be performed more uniformly among plants, and failures would be discovered and reported to the NPRDS more consistently regardless of the relative aggressiveness of the operating crew.

The third criterion was that the set of equipment include NSSS and BOP components for the light water reactor (LWR) plants. This condition was observed to ensure that the application of the maintenance effectiveness indicator was valid for all reactor plant types, systems, and components.

The decision to exclude a system or component from the list was based on other criteria, for example, equipment not covered by the NPRDS, equipment not meeting ODE criteria, or equipment not pertinent for power operation. The effort to substantiate the candidate list was closely tied to other ongoing activities, such as executing data retrieval, data base development, and analysis of equipment failures.

INEL personnel reviewed the list of systems and equipment that were within the scope of NPRDS reportability and obtained a set of components that were ODE candidates. This set was further evaluated by determining if the equipment was required for power operation or during plant shutdown conditions. The systems were further evaluated to determine if they were standby safety systems. The purpose of screening the list in this manner was to identify components that were considered ODE with respect to normal plant power operation or power ascension activities. The other two categories were evaluated to consider equipment that might have been overlooked in the initial selection of the components to be analyzed.

The candidate system and component list was repeatedly screened by retrieving sample NPRDS data to assess the numbers and types of failures reported and at other times by referencing earlier studies and reports. If a system or component within a system was considered to not be required for power operation and had few reported failures, then the system or component was deleted from the list. However, if a system or component was considered to be required for power operations although there were few reported failures, then other references, such as the Gray Book[6] or other documents, were reviewed to justify including the equipment in question on the candidate list. For example, the essential service water system for BWR plants was initially removed from the candidate list and later reinstated based on the review of the number of NPRDS failure reports and engineering records.

The Gray Book data[6] were reviewed for operating plant histories from January 1986 to June 1988 to verify that the equipment list included all systems and components important for tracking maintenance effectiveness or to verify that adequate justification for deletion existed. The number of events in each category that could affect or be affected by maintenance performance was recorded. The tally of events was grouped into the following failure causes: maintenance, design, personnel error, and unknown. Based on the results of this exercise, the areas with the highest event totals were evaluated further to determine whether specific systems or equipment should be added to the list of components considered in this study.

The list of systems and components was also compared to the results presented in the *Generating Availability Report*,[7] prepared by the North American Electric Reliability Council (NERC). The NERC report determined and ranked system/component outages and deratings because of the event causes based on outage frequency. The list of systems and components was also compared to a compilation performed by the S.M. Stoller Corporation.[8-10] The Stoller reports determined and ranked the contributing factors to plant unavailability down to the component level. For the purposes of the present study, some dominant contributors from the NERC and Stoller reports were not included in the list of candidate equipment. The reasons for excluding these items were (a) they were components associated with passive systems, (b) they were components lacking routine maintenance activities and could not be trended, or (c) they were components that were outside the NPRDS reportability scope. Further additions were made to the list of selected components based on the NERC and the Stoller reports.

When the selections were finalized, it was determined that approximately 30% of the reportable components are being monitored as a part of the maintenance effectiveness indicator program for each of the NSSS vendors. Approximately 30% of the reportable components are monitored for Westinghouse type plants, 28% each for General Electric and Combustion Engineering, and 31% for Babcock and Wilcox. Further discussions are provided in Appendix A.

The lists of monitored systems and components are presented in Tables 1 through 4 for General Electric, Westinghouse, Combustion Engineering, and Babcock and Wilcox commercial nuclear power plants, respectively. The tables identify the systems and major equipment by NSSS vendor. Overall, between 31 and 33 different types of components are being monitored.

During the component and system selection process, a limitation was noted in the NPRDS. As discussed in the AEOD/S804B report, NPRDS does not currently include certain BOP systems and components that have historically been significant contributors to plant outages, such the turbine-generator and associated support systems, the condenser, the circulating water system, non-nuclear portions of the service water and closed cooling water systems, the instrument air system, and the service air system. In December 1988, May 1989, and June 1989, official steps were taken by the NPRDS User's Group to include the main generator, main turbine, and condenser in the NPRDS reporting scope. The ability to monitor these systems is certainly desirable. However, their absence does not invalidate the indicator as a monitoring tool. (See Section 4.)

3.3 NPRDS Data Downloading

Once the system and component selection was completed, the next step was to download the data from the NPRDS. The download process involved four steps: developing the data base search strategy, verifying the strategy, downloading the component failure data from the NPRDS, and verifying the integrity of the download.

The NPRDS is a comprehensive source of design characteristics (engineering data) and performance history (failure data) of key equipment installed in U.S. nuclear power plants. The NPRDS has been established as a systematic reporting system for gathering equipment failure data, engineering records, and documentation of successful resolutions to failure problems. The NPRDS provides a data source to help the user detect, analyze, correct, and prevent similar failures from occurring within his facility. The vigilance of the licensees for submitting accurate, complete, and detailed accounts of the events is important so that the data can be shared and understood by all users. This system is managed and maintained by INPO and is located on INPO's computer system in Atlanta, GA. Access to the NPRDS data base for the purpose of this study was accomplished via the INEL's Network Control Center (NCC) Communication system using SIM3278/PC™ (SIMPC),[11] which is an INPO-supplied telecommunications software package.[a]

The NPRDS user guidelines[5] have been developed to expedite the data downloading process and to achieve three general purposes:

- Enable U. S. nuclear plant personnel to enter the design characteristics and performance data for key systems and components directly into the data base.
- Allow the U.S. nuclear plant user to search the data base and retrieve and display information desired.
- Provide information in a manner best suited for the intended use and study.

Meeting these purposes, the NPRDS failure data become practical as a data source for monitoring maintenance effectiveness.

To satisfy the data requirements of the maintenance effectiveness indicator, a semi-automated procedure was developed. The failure data were first downloaded from the NPRDS computer system to PCs located at the INEL. The downloaded data were obtained using the NPRDS-provided software. The

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a. Mention of specific products and/or manufacturers in this document implies neither endorsement or preference nor disapproval by the U.S. Government, any of its agencies, or EG&G Idaho, Inc., of the use of a specific product for any purpose.

Table 1. General Electric systems and components

System	Component Description
Control Rod Drive (CRD)	CRD Mechanism
	CRD Flow Control Valve
	CRD Flow Control Valve Operator
	CRD Supply Pump
	CRD Supply Pump Motor
	CRD Supply Pump Motor Circuit Breaker (CktBkr)
Feedwater (FW)	FW High Pressure Heater
	FW Pump
	FW Pump Motor
	FW Pump Motor CktBkr
	FW Pump Turbine
	FW Pump Turbine Governor
	Main FW Regulating Valve Bypass Valve
	Main FW Regulating Valve Bypass Valve Operator
	Main FW Regulating Valve
	Main FW Regulating Valve Operator
	Bistable/Switch
	Indicators/Recorders
	Transmitter/Primary Detector/Element
	Integrator/Computation Module, E-P Converter
	Instrumentation, Controllers
Main Steam (MS)	MS Automatic Depressurization Safety Valve
	MS Automatic Depressurization Safety Valve Operator
	MS Containment Isolation Valve
	MS Containment Isolation Valve Operator
Main Steam (MS) (continued)	MS Containment Isolation Valve Operator CktBkr
	MS Safety/Automatic Depressurization Discharge Pipe Vacuum Breaker
	MS Safety Valve
	MS Turbine Bypass Valve
	MS Turbine Bypass Valve Operator
Reactor Protection – Neutron Monitoring	Bistable/Switch
	Indicators/Recorders
	Transmitter/Primary Detector/Element
Reactor Recirculation (RECIRC)	Bistable/Switch
	Indicators/Recorders
	Transmitter/Primary Detector/Element
	RECIRC Pump
	RECIRC Pump Motor
	RECIRC Pump Motor CktBkr
	RECIRC Pump Discharge Valve
	RECIRC Pump Discharge Valve Operator
	RECIRC Pump Discharge Valve Operator CktBkr
	RECIRC Pump Suction Valve
	RECIRC Pump Suction Valve Operator
	RECIRC Pump Suction Valve Operator CktBkr
	RECIRC Pump Motor Generator Set Generator
	RECIRC Pump Motor Generator Set Coupling
	RECIRC Pump Motor Generator Set Motor

Table 1. (continued)

System	Component Description
Reactor Recirculation (RECIRC) (continued)	RECIRC Pump Motor Generator Set Motor CktBkr RECIRC Flow Control Valve RECIRC Flow Control Valve Operator
Plant AC Distribution	Unit Auxiliary Transformer Unit Auxiliary Transformer Feeder CktBkr to Bus Unit Start–up Transformer Unit Start–up Transformer Feeder CktBkr to Bus Relays Electrical Conductors, Bus, Cable, Wire
Condensate	Condensate Booster Pump Condensate Booster Pump Motor Condensate Booster Pump Motor CktBkr Condensate Hotwell Pump Condensate Hotwell Pump Motor Condensate Hotwell Pump Motor CktBkr Condensate Low Pressure Heater
Steam Shutoff –Radiation Monitoring System	Relays Transmitter/Primary Detector/Element Bistable/Switch Integrator/Computation Module, E–P Converter Circuit Breakers, Contactors, Controllers
Nuclear Steam Supply Shutoff	Bistable/Switch Integrator/Computation Module, E–P Converter
Nuclear Steam Supply Shutoff (continued)	Circuit Breakers, Contactors, Controllers Transmitter/Primary Detector/Element Valves, Dampers Valve Operators
Reactor Protection	Bistable/Switch Transmitter/Primary Detector/Element Indicators/Recorders Circuit Breakers, Contactors, Controllers
Instrument AC Power	Instrument AC Power Supply Inverter Instrument AC Power Supply Inverter Input CktBkr Instrument AC Power Supply Inverter Output CktBkr Instrument AC Power Motor Generator Set Generator Instrument AC Power Motor Generator Set Generator Output CktBkr Instrument AC Power Motor Generator Set Motor Instrument AC Power Motor Generator Set Motor CktBkr Relays
Essential Service Water	Essential Service Water Pump Essential Service Water Pump Motor Essential Service Water Pump Motor CktBkr Valves, Dampers Valve Operators

Table 2. Westinghouse systems and components

System	Component Description
Reactor Coolant (RCS)	RCS Pump
	RCS Pump Motor
	RCS Pump Motor Circuit Breaker
	Primary Safety Relief Valve
	Pressurizer Spray Valve
	Pressurizer Spray Valve Operator
	Pressurizer Spray Valve Operator Circuit Breaker
	Pressurizer Power–Operated Valve
	Pressurizer Power–Operated Valve Operator
	Pressurizer Power–Operated Relief Block Valve
	Pressurizer Power–Operated Relief Block Valve Operator
	Pressurizer Power–Operated Relief Block Valve Operator Circuit Breaker
Control Rod Drive (CRD)	CRD Inverter/Generator
	CRD Motor Generator Set Motor
	CRD Reactor Trip Circuit Breaker
	CRD Reactor Trip Bypass Circuit Breaker
	CRD
Main Steam (MS)	MS Isolation Valve
	MS Isolation Valve Operator
	MS Isolation Valve Operator Circuit Breaker
	MS Power–Operated Relief Valve
	MS Power–Operated Relief Valve Operator
	MS Power–Operated Relief Valve Operator Circuit Breaker
Main Steam (MS) (continued)	MS Safety Relief Valves
	MS Atmospheric Discharge Valve
	MS Atmospheric Discharge Valve Operator
	MS Atmospheric Discharge Valve Operator Circuit Breaker
	Relays
Instrument AC Power	Instrument AC Power Supply Inverter
	Instrument AC Power Supply Inverter Input Circuit Breaker
	Instrument AC Power Supply Inverter Output Circuit Breaker
	Circuit Breakers, Contactors, Controllers
Main Feedwater (MFW)	MFW Pump
	MFW Pump Motor
	MFW Pump Motor Circuit Breaker
	MFW Pump Turbine
	MFW Pump Turbine Governor
	MFW Regulating Valve
	MFW Regulating Valve Operator
	MFW Regulating Valve Bypass Valve
	MFW Regulating Valve Bypass Valve Operator
	MFW Containment Isolation Valve
	MFW Containment Isolation Valve Operator
	MFW Containment Isolation Valve Operator Circuit Breaker
	Bistable/Switch
	Indicators/Recorders
	Transmitter/Primary Detector/Element

Table 2. (continued)

System	Component Description
Main Feedwater (MFW) (continued	Integrator/Computation Module, E–P Converter
	Instrumentation, Controllers
	MFW Containment Check Valves
	MFW High Pressure Heater
Reactor Protection and Logic	Bistable/Switch
	Indicators/Recorders
	Transmitter/Primary Detector/Element
	Integrator/Computation Module, E–P Convertor
	Instrumentation, Controllers
	Relays
Chemical and Volume Control	Charging Pump
	Charging Pump Motor
	Charging Pump Motor Circuit Breaker
	Valves, Dampers
	Valve Operator
Plant AC Power	Unit Auxiliary Transformer
	Unit Auxiliary Transformer Feeder Circuit Breaker to Unit Bus
	Unit Start–up Transformer
	Unit Start–up Transformer Feeder Circuit Breaker to Unit Bus
Plant AC Power (continued)	Relays
	Electrical Conductors, Bus, Cable, Wire
	Transformer, Shunt Reactors
Auxiliary Feedwater (AFW)	AFW Discharge to Steam Generator Isolation Valve
	AFW Discharge to Steam Generator Isolation Valve Operator
	AFW Discharge to Steam Generator Isolation Valve Operator Circuit Breaker
	AFW Pump
	AFW Pump Motor
	AFW Pump Motor Circuit Breaker
Condensate	Condensate Booster Pump
	Condensate Booster Pump Motor
	Condensate Booster Pump Motor Circuit Breaker
	Condensate Hotwell Pump
	Condensate Hotwell Pump Motor
	Condensate Hotwell Pump Motor Circuit Breaker
	Condensate Low Pressure Heater
	Valves, Dampers
	Valve Operator

Table 3. Combustion Engineering systems and components

System	Component Description
Reactor Coolant/Control Instrumentation (RCS)	R[illegible]
	RCS Pump Motor
	RCS Pump Motor Circuit Breaker
	Primary Safety Relief Valve
	Pressurizer Spray Valve
	Pressurizer Spray Valve Operator
	Pressurizer Power–Operated Relief Valve
	Pressurizer Power–Operated Relief Valve Operator
	Pressurizer Power–Operated Relief Block Valve
	Pressurizer Power–Operated Relief Block Valve Operator
	Pressurizer Power–Operated Relief Block Valve Operator Circuit Breaker
Control Element Assembly	Control Element Drive Inverter/Generator
	Control Element Drive Reactor Trip Circuit Breaker
	Control Element Drive
Main Steam (MS)	MS Isolation Valve
	MS Isolation Valve Operator
	MS Isolation Valve Operator Circuit Breaker
	MS Power–Operated Relief Valve
	MS Power–Operated Relief Valve Operator
	MS Safety Relief Valves
	MS Atmospheric Discharge Valve
	MS Atmospheric Discharge Valve Operator
	MS Atmospheric Discharge Valve Operator Circuit Breaker
Main Steam (MS) (continued)	MS Turbine Bypass Valve
	MS Turbine Bypass Valve Operator
Instrument AC Power	Instrument AC Power Supply Inverter
	Instrument AC Power Supply Inverter Input Circuit Breaker
	Instrument AC Power Supply Inverter Output Circuit Breaker
	Circuit Breakers, Contactors, Controllers
Main Feedwater (MFW)	MFW Pump
	MFW Pump Motor
	MFW Pump Motor Circuit Breaker
	MFW Pump Turbine
	MFW Pump Turbine Governor
	MFW Regulating Valve
	MFW Regulating Valve Operator
	MFW Regulating Valve Bypass Valve
	MFW Regulating Valve Bypass Valve Operator
	MFW Containment Isolation Valve
	MFW Containment Isolation Valve Operator
	MFW Containment Isolation Valve Operator Circuit Breaker
	Bistable/Switch
	Indicators/Recorders
	Transmitter/Primary Detector/Element
	Integrator/Computation Module, E–P Convertor
	Instrumentation, Controllers
	Relays
	MFW Containment Check Valves

Table 3. (continued)

System	Component Description
Main Feedwater (MFW) (continued)	MFW High Pressure Heater
Reactor Protection	Bistable/Switch
	Indicators/Recorders
	Transmitter/Primary Detector/Element
	Integrator/Computation Module, E–P Convertor
	Instrumentation, Controllers
	Relays
Chemical and Volume Control	Charging Pump
	Charging Pump Motor
	Charging Pump Motor Circuit Breaker
	Valves, Dampers
	Valve Operator
Plant AC Power	Unit Auxiliary Transformer
	Unit Auxiliary Transformer Feeder
	Circuit Breaker to Unit Bus
	Unit Start–up Transformer
	Unit Start–up Transformer Feeder
	Circuit Breaker to Unit Bus
	Relays
	Electrical Conductors, Bus, Cable, Wire
Auxiliary/Emergency Feedwater (AFW)	AFW Discharge to Steam Generator Isolation Valve
	AFW Discharge to Steam Generator Isolation Valve Operator
	AFW Discharge to Steam Generator Isolation Valve Operator Circuit Breaker
	AFW Pump
	AFW Pump Motor
	AFW Pump Motor Circuit Breaker
	Valves, Dampers
	Valve Operator
	Instrumentation, Bistable/Switch
Condensate	Condensate Booster Pump
	Condensate Booster Pump Motor
	Condensate Booster Pump Motor Circuit Breaker
	Condensate Hotwell Pump
	Condensate Hotwell Pump Motor
	Condensate Hotwell Pump Motor Circuit Breaker
	Condensate Low Pressure Heater
	Valves, Dampers
	Valve Operator

Table 4. Babcock and Wilcox systems and components

System	Component Description
Reactor Coolant (RCS)	RCS Pump
	RCS Pump Motor
	RCS Pump Motor Circuit Breaker
	Primary Safety Relief Valve
	Pressurizer Spray Valve
	Pressurizer Spray Valve Operator
	Pressurizer Spray Valve Operator Circuit Breaker
	Pressurizer Power–Operated Relief Valve
	Pressurizer Power–Operated Relief Valve Operator
	Pressurizer Power–Operated Relief Block Valve
	Pressurizer Power–Operated Relief Block Valve Operator
	Pressurizer Power–Operated Relief Block Valve Operator Circuit Breaker
	Valves, Dampers
	Bistable/Switch
	Transmitter/Primary Detector/Element
Control Rod Drive (CRD)	CRD
	CRD Reactor Trip Circuit Breaker
Main Steam (MS)	MS Isolation Valve
	MS Isolation Valve Operator
	MS Isolation Valve Operator Circuit Breaker
	MS Power–Operated Relief Valve
	MS Power–Operated Relief Valve Operator
	MS Safety Relief Valves
	MS Atmospheric Discharge Valve
Main Steam (MS) (continued)	MS Atmospheric Discharge Valve Operator
	MS Turbine Bypass Valve
	MS Turbine Bypass Valve Operator
	Relays
Instrument AC Power	Instrument AC Power Supply Inverter
	Instrument AC Power Supply Inverter Input Circuit Breaker
	Instrument AC Power Supply Inverter Output Circuit Breaker
	Circuit Breakers, Contactors, Controllers
Feedwater (MFW)	MFW Pump
	MFW Pump Turbine
	MFW Pump Turbine Governor
	MFW Regulating Valve
	MFW Regulating Valve Operator
	MFW Regulating Valve Bypass Valve
	MFW Regulating Valve Bypass Valve Operator
	MFW Containment Isolation Valve
	MFW Containment Isolation Valve Operator
	MFW Containment Isolation Valve Operator Circuit Breaker
	Bistable/Switch
	Indicators/Recorders
	Transmitter/Primary Detector/Element
	Integrator/Computation Module, E–P Convertor
	Instrumentation, Controllers
	Relays

Table 4. (continued)

System	Component Description	System	Component Description
Feedwater (MFW) (continued)	MFW Containment Check Valves MFW High Pressure Heater	Emergency Feedwater System (EFW) (continued)	EFW Pump Motor EFW Pump Motor Circuit Breaker Valves, Dampers Valve Operator Bistable/Switch
Reactor Protection	Bistable/Switch Indicators/Recorders Transmitter/Primary Detector/Element Integrator/Computation Module, E–P Convertor Instrumentation, Controllers Relays	Condensate System	Condensate Booster Pump Condensate Booster Pump Motor Condensate Booster Pump Motor Circuit Breaker Condensate Hotwell Pump Condensate Hotwell Pump Motor Condensate Hotwell Pump Motor Circuit Breaker Condensate Low Pressure Heater Valves, Dampers Valve Operator
Plant AC Power	Unit Auxiliary Transformer Unit Auxiliary Transformer Feeder Circuit Breaker to Unit Bus Unit Start–up Transformer Unit Start–up Transformer Feeder Circuit Breaker to Unit Bus Relays Electrical Conductors, Bus, Cable, Wire	Integrated Control System	Circuit Breakers, Contactors, Controllers Transmitter/Primary Detector/Element Integrator/Computation Module, E–P Convertor Electronic Power Supply
Emergency Feedwater System (EFW)	EFW Discharge to Steam Generator Isolation Valve EFW Discharge to Steam Generator Isolation Valve Operator EFW Discharge to Steam Generator Isolation Valve Operator Circuit Breaker EFW Pump	Letdown Purification and Makeup	Charging Pump Charging Pump Motor Valves, Dampers Valve Operator

downloaded data were then converted to data files that could be used by dBase III Plus,[12] a PC data base management system, to determine the number of component failures. The number of component failures became input for the graphical displays of the indicator data. The graphical displays were generated using a specially tailored program written in the MODULA 2 programing language.[13] In a separate but similar procedure, the engineering data contained in the NPRDS computer system were also downloaded to analyze and verify the selected systems, components, and applications required to generate the indicator data.

3.3.1 Search Strategies. To expedite the download of the desired data from the NPRDS, several preliminary searches and cursory analyses were performed. The extent of the data records had to be defined, which involved repeated searches and evaluations based on the initial list of candidate equipment. Downloading the failure data by NSSS vendor was found to be the most expeditious method to retrieve the failure data.

The preliminary activities also determined that two search queries of, and downloads from, the NPRDS data base were required to obtain the data representing each NSSS vendor. The first query downloaded data by system and application codes and the second by system and component codes. This procedure resulted in a total of eight queries and downloads (two downloads for each of the four reactor vendors). A set of data for each vendor was maintained separately during the data manipulation process to ensure that the evaluation was performed on a NSSS vendor-specific level.

The search and download activities involved numerous steps. The search process was modified repeatedly to obtain all data that were considered for this study. Following is a summary of the process used to obtain the data, verify the search strategy, complete the search query, and download the data:

1. Select the NPRDS search and display variables (i.e., data fields).

2. Verify the search strategy before executing the search query.

3. Store the search strategy for future reference.

4. Verify the appropriateness of the query criteria or modify accordingly.

5. When the data query has been executed, scroll through the output data file to verify that it matches exactly what was desired. If it is found to be unacceptable, modify the search strategy and repeat the query until the desired data file appears to be satisfactory.

6. Select the destination for the downloading output file (e.g., PC hard disk, PC printer, or storage onto a PC floppy disk for printout later).

7. Transfer the NPRDS failure data to the PC hard disk (if it is not already there) as an ASCII file. Convert the ASCII file to a dBase III Plus data file using the programs described in Section 3.3.3.

3.3.2 Verification of Search Strategies. Once the search strategies were constructed, they were verified to confirm that they captured the desired data. To verify the search strategies and criteria used to obtain failure data from the NPRDS, test runs to download data were made. The test runs specified preselected systems, applications, and components from eight plants (two from each vendor). Several methods of verification were used:

1. Access the NPRDS computer and review the failure data to identify the number of failure report counts for the appropriate systems and application and component codes to be selected during the query. These data were compared to the search criteria for completeness and accuracy.

2. Download the test data and convert to a dBase III Plus data file. Compare the number of records generated in the NPRDS failure count to the number of records in the data file for consistency.

3. Compare the data fields requested by the query to the data files. Verify that they were transferred to the data files as specified. Review the records for completeness and accuracy.

The above process was also used to verify the engineering data that were downloaded. However, for the engineering data, the comparison was performed using the total number of components selected rather than actual failure records. The results of the count of the components and failure records are presented in Appendix A.

3.3.3 Component Failure Data Retrieval. After the search strategies and criteria were verified using the process discussed above, it was possible to download all data from the NPRDS required for developing, validating, and analyzing the effectiveness of plant maintenance. Once the download was complete, a customized computer program was developed to automate the conversion to a data file. The SIMPC software package was used to download the data from the NPRDS to ASCII files. The ASCII files were in turn converted to the desired output files using a dBase III Plus program which, at the same time, verified that selected fields were downloaded correctly.

3.3.4 Retrieval Verification. The integrity of the downloaded NPRDS data was verified using three methods: (a) automated verification checks; (b) manually counting the number of data entries in the NPRDS and verifying that the appropriate number of systems, components, application codes, and plant records were actually downloaded; and (c) randomly scanning the data records as they were downloaded and/or entered to ensure data accuracy.

The first method involved automated verification checks. The dBase III Plus programs were developed to verify the accuracy and consistency of selected fields having interdependent relationships.

Other miscellaneous automated checks were made on several of the remaining data fields to enhance the evaluation and validation process. Examples of the fields that were verified were the discovery and the reporting dates and appropriate system and component codes.

The second method for verifying the data retrieval was to count the number of data entries in the NPRDS and verify that the appropriate number of systems, components, application codes, and plant records were actually downloaded. If the initial search request did not yield any data, the original data count was reinvestigated to ensure that there were indeed no data available for retrieval. This exercise was performed in conjunction with the data checks described for the search strategy verification in Section 3.3.1.

The third method was to randomly scan the data records as they were downloaded to ensure data accuracy. These data checks were performed repeatedly to ensure that the data appeared to be complete before executing the extensive data download process. This activity was performed in conjunction with the verification reviews described earlier.

As the entire data file was verified, some preliminary analyses were performed. These analyses consisted of evaluating each licensee's reporting consistency for all systems and components and verifying that plants from the same site and utility were reporting in a consistent manner. In addition, the reporting patterns of each licensee were compared to other licensees having the same NSSS vendor. These analyses were performed by counting the records for each plant and verifying that no apparent discrepancies were noted in specific components and systems being reported.

3.4 NPRDS Quality Assurance Review

The NPRDS was selected as the principal data source for equipment failure information based on the same logic as presented in the AEOD/S804B report.[4] The use of NPRDS data for indicating maintenance effectiveness was based on the assumption that the data were entered accurately. To ensure that this assumption was correct, it was necessary to verify the accuracy. The verification process included an assessment of the licensee's categorization of equipment failures, e.g., incipient, degraded, or immediate; entry of interdependent fields; and entry of codes that were specified for a particular NSSS vendor. For the purposes of this study, incipient failures were not included in the derivation of the maintenance effectiveness indicator, as these reports do not appear to be consistently provided by all plants.

The timeliness of reporting failure data to the NPRDS was, and will continue to be, a concern. At present, the average time between failure discovery and NPRDS reporting is 60 to 90 days. A 180–day delay is generally used to ensure that essentially all reportings have been submitted. A review of reporting timeliness was not conducted for this effort. However, upon implementation of the indicator program, a review of reporting timeliness will be conducted on a calendar quarter schedule.

3.4.1 Reporting Consistency. The licensee reporting practices were addressed first. A representative sample of equipment failure records for each licensee was studied to identify and assess differences and similarities in the reporting patterns. To simplify and standardize the basis for establishing a pattern of reporting failures, only the fundamental attributes were considered, such as types of failures, systems and equipment involved, failure cause codes, plant operating condition, and consistency in reporting from sites or utilities having more than one unit.

One consideration was the consistency in reporting for the situation where multiple units share the same site, organizational structure, or NSSS vendor maintenance philosophy. For these plants, the reporting patterns were found to be nearly identical, particularly if an event occurred in a system or component common to these units.

Another consideration was the possibility of inconsistencies in reporting specific systems and components. No inconsistencies were noted.

From the results of the reporting pattern analyses, no significant deviations were noted from the NPRDS guidance for reporting systems, components, failure cause codes, or plant operating status. Minor differences existed in the level of detail reported at various plants. However, examination of selected failure reports provided assurance that the important details were accurately preserved. No significant deviations were noted for reporting consistency between units from utilities or sites with multiple units.

3.4.2 Verification of NPRDS Coding. To ensure that the NPRDS coding had been performed correctly, the data were verified two ways: (a) computer program verification during data file construction and (b) manual verification during a failure report narrative review.

The first way of verifying coding accuracy, as discussed previously in Section 3.3.4, was performed during the data file construction. During the construction, several key fields were verified as having been coded accurately and consistently. No inconsistencies were identified.

As a portion of the narrative review, described in more detail in Section 4.2, a sample of NPRDS records was studied to verify that the failure data were correctly entered in the appropriate data fields. Accuracy of the data entry process was verified by comparing the licensee's narrative descriptions of the event with the corresponding NPRDS-coded failure data. The results of the evaluation of the field codes indicate a high degree of accuracy in the field codification. The results are discussed further in Appendix B.

3.4.3 Accuracy of Failure Severity Determination. Three severity levels for failures have been defined in the NPRDS coding manual:[5] immediate, degraded, and incipient. As discussed in S804B, the decision was made that incipient failures should not be included in the trending of failures tracked by the maintenance effectiveness indicator because they were not reported consistently. This decision was based on the knowledge that the NPRDS does not require that incipient failures be reported. A sample of failure reports for each plant was examined to confirm correct classification of events by severity type. The classification of severity level was verified during a review of reports having the classification of immediate and degraded and then in a review of reports having a classification of incipient.

The results of the evaluation of the failure categories indicate that there appears to be a high degree of accuracy in the failure categorization. During the review of reports classified as immediate and degraded failures, one report appeared to have been misclassified. The review of the reports classified as incipient identified 13 reports out of 142 reviewed as having a classification that was incorrect. The 9% error was considered to be acceptable. The results are discussed further in Appendix B.

3.5 Indicator Formula

The methodology used by the maintenance effectiveness indicator has been evolving since early 1988. The basic concept of an NPRDS-based indicator was introduced in the AEOD/S804A report and later refined for the AEOD/S804B report. Mathematically, the indicator notes when the failure rate of individual components within a system increases by a predetermined threshold value. Physically, the continued presence of flags by the indicator denotes a degradation of maintenance effectiveness.

No distinction is made between an immediate failure and a degraded failure. The NPRDS data from both types of failures are consolidated and evaluated collectively.

The indicator formula consists of two parts: the time spans over which component failure rates are compared and the threshold value that the failure rate increase between two consecutive time spans must exceed to set the flag.

Determining the time spans for failure rate comparisons involved several considerations. On one side, the time spans had to be short enough to give the quickest response times and possibly allow the plant personnel to mitigate further degradation of maintenance. On the other side, the time spans had to be long enough to ensure that the formula was not overly sensitive and set a flag too quickly.

A basic trial-and-error approach was used to optimize the time spans for comparison. The smallest time spans were determined to be one month because of the practicality of implementing the indicator program and to obtain a reasonable (i.e., manageable) sample size. Thus, one-month intervals became the smallest increment for developing the data file of failure report counts. The comparison of indicator flags from a one-month sample to another, however, exhibited an undesired overly sensitive response. To reduce the sensitivity, a time-averaging method was used. Each time span was progressively increased by averaging the failure rates of consecutive months (e.g., averaging the failure rates of January and February) and comparing that average with the average failure rate of the next set of months (e.g., the average failure rate for March and April).

The combination that provided the desired level of sensitivity was to compare the average failure rates over a continuous five-month period. The average failure rate over the first three months was compared to the average failure rate over the next two months. To determine a history of rate change indications, the time spans were shifted forward one month (e.g., add the next most recent month and drop out the oldest month). Then, the failure rate averages were recalculated and again compared to determine if the failure rate between two consecutive time spans had increased enough to set a flag.

The threshold value to set a flag was established in AEOD/S804B through an evaluation and comparison process. Several available sources of operational events data were examined to identify which events warranted a maintenance effectiveness flag. Then, the NPRDS failure data were processed with the indicator formula, and the threshold value was adjusted until the appropriate sensitivity of the formula was obtained. The threshold value of 1.01 was chosen from this evaluation process.

The formula for deriving the maintenance indicator flag was the same as that described in the AEOD/S804B report, namely:

Trigger the maintenance effectiveness indicator flag if over a five month interval

$$[(M_i + M_{i-1}) / 2] - [(M_{i-2} + M_{i-3} + M_{i-4}) / 3] > C$$

where

M_i = number of total failures for month under consideration

$M_{i-1}, M_{i-2}, M_{i-3}, M_{i-4}$ = number of failures for months that are one, two, three, and four months previous to M_i respectively

C = threshold value (1.01 for this study).

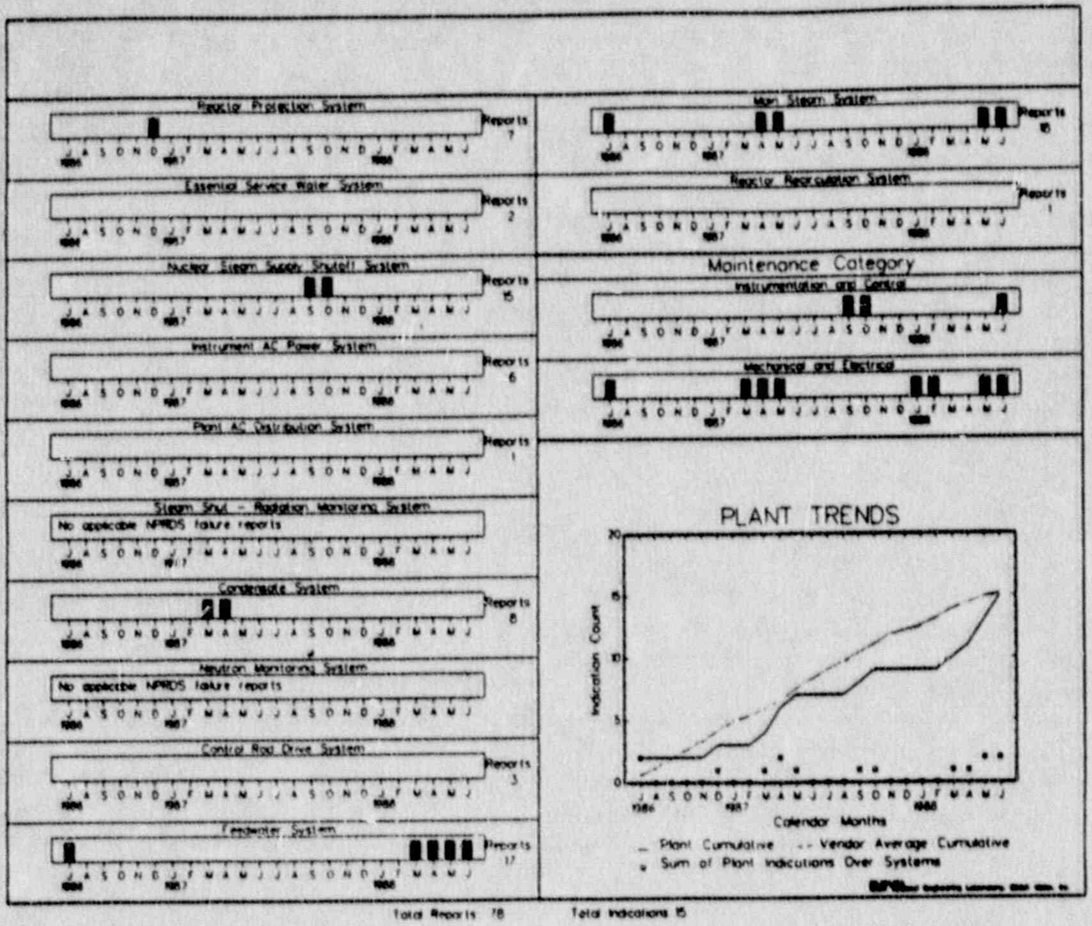
If the threshold value was exceeded, then a flag was denoted at the reporting period, M_i, corresponding to the last month under consideration (that is, the most recent month).

The results of applying the formula on a system-by-system basis are used to obtain the indicator data, namely, the total number of indicator flags per month, summed across all systems being monitored.

To further support the use of the formula, a statistical process control analysis was performed on the same data used by the maintenance indicator formula. The purpose of this analysis was to verify that the maintenance effectiveness indicator was highlighting possible degradation of maintenance effectiveness. The basis for comparison is a recognized, applicable statistical methodology known as statistical process control, which produces a graphical output called control charts.

These control charts are used throughout the manufacturing industry to track defect levels by visually and statistically separating random variations (such as random equipment failures) from the assignable variations that can be tied to a cause (such as equipment failures because of ineffective maintenance). Random variations are characteristic of the process and tend to be statistically predictable. In contrast, assignable variations tend not to be predictable by statistical means. For this study, plant operation was considered as the process, and equipment failures that lead to interruption of operation were considered as variations of the process.

The control charts for the plants were derived from the same set of NPRDS component failure data that was used for the maintenance effectiveness indicator calculations. The control charts cover the same period as the indicator data and display the cumulative number of the equipment failures on a monthly basis for each plant. An example of a control chart along with a corresponding maintenance effective indicator plot is shown in Figure 2.



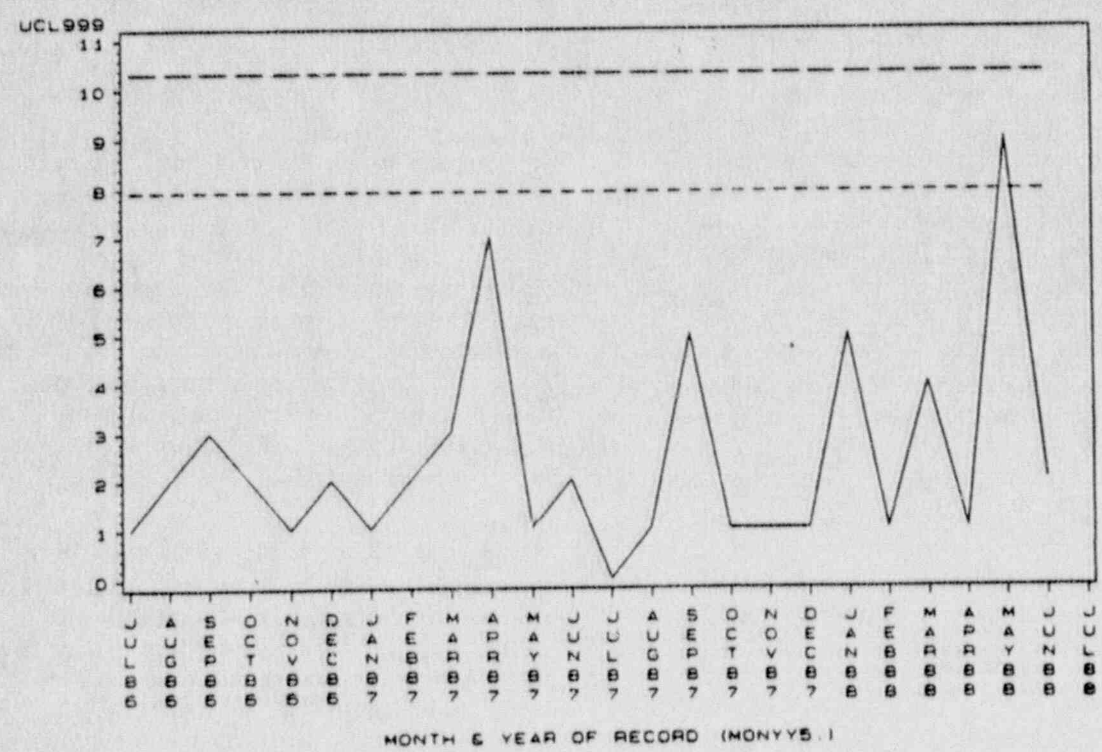


Figure 2. Comparison of maintenance effectiveness indicators to a control chart.

It is important to recognize that control charts and maintenance effectiveness indicator plots do not display exactly the same information. In this study, the control charts displayed the failures associated with both assigned and random variations. Conversely, the maintenance effectiveness indicator screened the failures that were associated with random fluctuations of the plant operation. To compare data representative of a more common level of performance of the plant and equipment, it was necessary to disregard the random failures of the control chart. By not considering the random failures on the control chart for the validation analysis, the majority of the failure data remaining on the control charts were those instances when the control limits were reached or exceeded. That is, the number of failures during a month was beyond what was expected from random failures alone.

The control limits were used to indicate the degree to which the process was performed within acceptable limits. For this study, the control limits were statistically derived for each plant to separate the random failures from the failures attributed to an assignable cause.

The control chart for each plant displayed the number of equipment failures summed across all systems for the month. Two control limits were indicated directly on the charts: (a) the *high* threshold represented the level beyond which the process was considered to be ineffective if it was exceeded once during the reporting period and (b) the *middle* threshold represented the level beyond which the process was considered to be ineffective if it was exceeded two out of three times during the reporting period.

For this study, a third control limit was used to evaluate the instances when the middle limit was closely approached but not exceeded. For these cases, the indication was considered to be *marginal* if the number of failures for the month approached within two failures of the middle control limit.

As mentioned earlier, an analysis was performed by comparing the control charts with the maintenance effectiveness indicator plots for each plant. The purpose was to verify that the maintenance effectiveness indicator was highlighting possible degradation of maintenance effectiveness. For this analysis, each time that the *high*, *middle*, or *marginal* limit was reached or exceeded, the corresponding reporting period was examined on the indicator plot. A direct correlation was considered to exist only if the control chart and the indicator plot both showed trends of increasing failures.

Figure 2 is an example of the control chart and indicator plot to illustrate the comparison of the results. The control chart shows that the *middle* limit was exceeded for the month of May 1988. Also, the control chart shows that there is a *marginal* indication for the month of April 1987, because its count (7) approached the *middle* limit (8). By comparing the reporting periods in the indicator plot, it can be seen that the corresponding reporting periods each had two indicator flags. The associated trends were increasing, which indicated that a direct relationship exists between the control chart and the indicator display. Thus, when comparable setpoints were used, the results were comparable. Similar analyses were performed for all BWRs and PWRs. The complete results are presented in Appendix F.

Briefly, the results of the correlation analysis determined that direct relationships exist between the control charts and the indicator displays. The degree of correlation for the *high*, *middle*, and *marginal* control limits was 88%, 84%, and 83%, respectively. When the three limits were combined, the correlation to the maintenance effectiveness indicator plot indication was 87%. That is, when the control chart indicated that the number of component failures was beyond a random level, then the maintenance effectiveness indicator also illustrated, for 87% of the comparisons, a noticeable increase in the cumulative number of indicator flags.

As expected, the closest relationship occurred for the comparison of the *high* threshold cases with the indicator counts. The relatively high percentage of correlation for all control levels demonstrated that the maintenance effectiveness indicator was a valid measure of those periods when the individual plant's rate of failures increased beyond what was expected from random fluctuations.

3.6 Display Methods

After the maintenance effectiveness indicator formula was finalized, a computer program for calculating the indicator results was developed. The output from the calculations program was entered into a computerized display program.

This section describes the methods chosen for displaying the maintenance effectiveness indicators. A brief history of the selection and development of past and present display methods is discussed. Human factors engineering experts were involved with the selection of the optimum indicator display methods. The merits and limitations of other display options were also considered.

In the AEOD/S804B report, the maintenance effectiveness indicator was portrayed by a plot showing the cases where the failure rate exceeded the threshold value for the systems being considered. Examination of the plots for a given plant enabled the reader to identify changes in the failure rate and to identify increases that exceeded the predetermined threshold value (1.01). The increase in failure rate was signified on the plot by a flag at the corresponding failure rate change and monthly reporting period. Based on this information, a comparison of the failure data with the operating performance of the plant could determine whether the licensee's maintenance program was effectively implemented by visually demonstrating when the failure rate exceeded the threshold value.

The evaluation of the original display techniques used in the AEOD/S804B report identified four areas that required extension or addition for the expanded scope of the present study. The first requirement was to expand the display to accommodate the increased number of systems that would be monitored. That expansion was performed. The second requirement was to identify for each system the number of failure reports that were used to calculate the maintenance indicator flag. The present display now identifies that number based on the number of reports that were downloaded to validate the indicators for a system. This information is provided near the plot for the each system. Also, a total of the reports that is downloaded for all systems was provided at the bottom of the plot page. The third requirement was to identify the cumulative number of indicator flags for all systems for the entire study period. This information is provided at the bottom of the plot page.

The final addition was a trend display method to portray the actual indicator results. The revised presentation method had to meet two criteria:

1. The display should be simple so that it could be easily evaluated.

2. The display should be comprehensive enough to clearly depict the trend.

The display method that was finally selected as meeting these criteria was a histogram to display the indicator data, along with a cumulative indicator trend line to enhance the interpretation of the data. To derive the cumulative indicator trend line, the system flags are totaled for each month, and a line is calculated by adding the failures over the study period. The line is then plotted on the plant trend graph.

To enhance a trend analysis, a second trend line was added to display NSSS vendor trend information. The addition of the vendor trend information allowed a comparison of each plant's performance to a peer group.

For this study, the NSSS vendor group was selected as a first approximation of a peer group. To obtain legitimate comparisons among the members of a peer group, the membership needs to be carefully selected. It is anticipated that a continual re-evaluation of peer group membership will be performed while the indicator program is fully implemented and later used in production operation.

The NSSS vendor trend line was created by totalling the monthly system counts for all plants with the same reactor vendor. The monthly totals were divided by the number of plants being considered. A cumulative trend line was then calculated, using the same equation as was used for calculating the plant trend line. The vendor trend line was then plotted on the same graph as the plant trend line. The display techniques are described in more detail in Appendix C.

One additional portion of the display plots has not been discussed, noted on the display under the heading of Maintenance Category. Under this heading are two displays: (1) Instrument and Control and (2) Mechanical and Electrical. These two displays present results from an indicator that is still under development. In these displays, all failure data, regardless of the system being monitored, have been grouped by the various organizations that comprise a maintenance program (mechanical and electrical, and instrument and control). The maintenance effectiveness indicator formula has been used to flag those failure rates that exceed the predetermined threshold value. The maintenance category indicator calculations have been based on the same ODE data as used for the maintenance effectiveness indicator. Note that the number of flags in the maintenance category display may not be equal in number or appear in the same month as the flags for the system displays. The calculations for the new indicator are based on the total number of reports for all systems, where the system flags are based on the number of reports for each system. The time when and if the threshold value was exceeded could be different.

The mechanical and electrical activities are combined into one group for this maintenance category study because of the difficulty encountered when trying to segregate these two interrelated areas. As more data become available, it may be possible to divide the maintenance activities into three categories: mechanical, electrical, and instrument and controls. After the data were segregated, the indicator formula was used to flag failure rates within each maintenance area that exceed the predetermined threshold. This area requires further development.

Once the display methods were completed, a quality assurance review of the programs was undertaken to ensure that the indicator displays that were generated correctly represent the data. The quality assurance review started with the development of files simulating the data that would be downloaded from the NPRDS computer. The simulated data contents were developed to verify the data accuracy, including a field verification as described in Section 3.4.2. When the data verification was completed, the data were entered into the display program, and indicator displays were printed. The indicator displays were compared to the original simulated data to ensure that the graphical presentations demonstrated the data correctly.

All of these display methods are based on a two-year study period. For final implementation, the displays will likely be extended to portray a three- or possibly four-year study period. The extended display will allow comparison of a plant's performance during the current fuel cycle to its performance during the previous fuel cycle.

3.7 Areas of Further Study

The maintenance effectiveness indicator presented in this report represents a step toward developing a system for the comprehensive assessment of the maintenance effectiveness program. To get a complete picture of the licensee's operation, the maintenance effectiveness indicator should not be used alone. Other sources of information and other indicators will likely be required. During the preparation of this report and the other NRC reports, additional candidate indicators were identified, which are still under consideration. Examples are discussed below:

1. INEL and NRC personnel have identified, and are in the process of developing, a method for presenting a normalized time-in-life of a plant as part of the maintenance effectiveness indicator display. During the development of the indicator, a cursory review indicated that additional information about an individual plant's maintenance effectiveness might be obtained if the fuel cycle history, including the present time within a fuel cycle, would be tracked concurrently with the indicator data. This display technique would allow comparison of a plant's performance to its NSSS vendor peers at any time within the plant's multi-fuel cycle history (e.g., "How is Plant A performing at the end of fuel cycle 3, when compared with its peers when they had reached the end of their third fuel cycle?").

2. Another example is the use of ODE component failures to identify operations areas or categories within the plant that appear to be experiencing the major portion of the failures. The proposed method for evaluating the categories is to separate the type of equipment that failed into groups based on the organization that would be responsible for the maintenance. On a trial basis, the equipment has been separated into two categories: (a) mechanical and electrical and (b) instrumentation and controls. The advantage of considering the data in this manner is that it mimics the typical organizational structure of many licensee maintenance programs. It is thought that the results for each indicator category will identify the stronger and weaker maintenance organizations at each plant and possibly note any biases in the maintenance philosophy. Also, this indicator provides another check on the licensee's categorization of the equipment and system failures.

3. Indicators that can provide a quantitative assessment of the component failure rates for each plant and the failures of standby safety systems are being considered. Both proposed indicators provide data for use in conjunction with the maintenance effectiveness indicator. One indicator under consideration is a ratio that compares the number of failures that have occurred for a system relative to the total number of system components. A second indicator under consideration provides a method for evaluating maintenance effectiveness on standby safety systems. Standby safety systems are those systems whose functions are interrelated to the systems and equipment that have historically played roles in causing forced outages. Both of these indicators are an expansion of the original efforts of the previous AEOD/S804A and S804B reports and are acknowledgments of the importance of considering quantitative measures and other plant systems to assess maintenance effectiveness. The development of these indicators is in the preliminary stage at this time.

4. VALIDATION

In the NRC Staff Requirements Memorandum[2] dated June 26, 1989, the Commission defined the criteria for validation of performance indicators as follows.

> "Prior to implementing and seeking Commission approval of any performance indicator, the staff *should demonstrate the effectiveness of each indicator by retrogressive analysis with actual plant data.*"

The validation method employed for the maintenance effectiveness indicator was a series of analyses based on comparisons between the indicator and actual plant data. The intent was to ensure that the indicator: (a) measured the attribute of interest, i.e., maintenance effectiveness; (b) was useful in revealing maintenance-related trends of equipment performance (i.e., results of the maintenance process); and (c) was consistently applied across plants.

The remainder of this section summarizes the validation activities and their findings. Detailed results are presented in the Appendices or in selected references. Before presenting the details of each of these areas, the results are summarized below.

4.1 Summary of Validation

The first step in the validation process consisted of demonstrating that the indicator measured the attribute of interest, i.e., maintenance effectiveness. This criterion was satisfied through a detailed analysis of the narratives in individual NPRDS failure records that caused the failure rate increases flagged by the indicator. The results of this analysis showed that a majority of the failures that contributed to the flagged failure rate increases involved ineffectively performed maintenance. The details of this analysis are discussed in Section 4.2.

While selecting the systems and components whose failures would be trended by the indicator (Section 3.2), a specific goal was to ensure that the failure data analyzed were consistent across plants. As a result, the set of equipment chosen for monitoring has historically been a dominant cause of equipment outages, so-called ODE. In particular, emphasis was placed on selecting major components in systems that support power operation. Failures of this equipment are much more likely to be identified for repair in a timely manner, thereby minimizing the potential impact of the variations in the identification of failures because of the relative aggressiveness of the operating crew. In addition, information obtained from licensee personnel at plants indicates that, although the NPRDS reporting rate may vary widely from unit to unit, important failures (failures that could influence plant operation to such a degree that a plant outage could occur at their plant or another plant) are generally reported to NPRDS with a high degree of consistency and regularity.

This consistency across plants was supported and reinforced by the analysis described in Section 4.3. In this analysis, the indicator results were compared with maintenance-caused equipment failures documented in individual licensee event reports (LERs) submitted by licensees to meet the reporting requirements specified in 10 CFR 50.73, the so-called LER Rule. This rule ensures that LERs are consistently reported across plants. The results showed a direct relationship between the number of maintenance-related events reported in the LERs and the number of flags generated by the indicator.

The industry historical trends and other related analyses discussed in Section 5 provide additional support and credence to the validity of the indicator. The number of failure reports for the individual plants was generally within the expected statistical range over the time span considered. In addition, the cyclic behavior of the indicator data shows the influence of relatively long outage periods, such as refueling, which correspond to periods of enhanced maintenance activities.

Finally, a plant-specific retrospective trend analysis, using actual plant data, demonstrated that the indicator reveals improvements to or degradation of maintenance at a plant. This analysis consisted of the review of routine monthly inspection reports for the period July 1986 through June 1988 for two sites, each with two units of similar design, residing in the same NRC region. In this analysis, the monthly inspection reports were reviewed for indication of programmatic problems with the maintenance programs at both sites, and the results were compared with the calculated indicator results for the four units. The plant-specific conclusions derived from the review of the inspection reports were verified through telephone contact with the cognizant NRC regional office. The indicator results for the two sites illustrated that both sites had increasing component failure rates, i.e., ineffective maintenance programs during the time period considered. The reviews of the monthly inspection reports and the discussion with NRC inspectors supported this finding. Further details of the analysis can be found in an AEOD technical report.[14]

Overall, the results of the root-cause analysis and LER correlation analyses satisfied the NRC Staff Memorandum criteria for validation of performance indicators. The retrospective analyses of actual component data were used, in part, to add credence to the validation analyses.

The discussion of the root-cause analyses and the LER correlation analyses are presented in Section 4.2 and 4.3, respectively. Section 5 presents the results of the retrospective analyses regarding historical trends in the industry, the influence of plant status on indicator results, and the capability of the maintenance effectiveness indicator to predict system failures.

4.2 Root-Cause Analysis

A key assumption in the development of the maintenance effectiveness indicator is that the indicator is a direct or nearly direct measure of maintenance effectiveness. To be accurate, the data base being evaluated by the indicator must reflect failures resulting from ineffective maintenance. That assumption was validated using the data from the narrative descriptions of 3881 selected NPRDS failure records that produced the indicator flags. The failure reports were reviewed by persons familiar with systems and components of commercial nuclear power plants, participation in plant maintenance inspections, and the use of the NPRDS.

Each failure record within the NPRDS contains the licensee's narrative description of the failure event. An analysis of selected narratives was performed to confirm that most of the reported failures that contributed to producing indicator flags had a root cause attributable to ineffective maintenance. This information was obtained in earlier studies reported in the AEOD/S804B report,[4] which addressed only BWR plants. A complete treatment of both BWR and PWR plants was performed for the present analysis.

The data for the analysis were gathered by first reviewing the maintenance effectiveness indicator results for each plant over a two-year period and identifying the periods when failure rate increases were flagged. A sample of the failure record narratives was then examined that corresponded to component failure rate increases flagged by the indicator. The examination of the NPRDS narratives was performed to confirm the relationship between the component failure rate increases and maintenance effectiveness. The narrative descriptions of 3881 NPRDS component failure records that contributed to approximately 400 failure rate increases were reviewed during the examination. Based on the NPRDS narrative descriptions and the extensive review personnel knowledge of operating plants, the cause of each failure was assigned to one of five distinct categories. In particular, the categories were analyzed to assess the relative contribution of ineffective maintenance to equipment failures.

1. *Ineffective Maintenance*—Recorded as either corrective or preventive and includes failures experienced while conducting, or as a consequence of, maintenance, upkeep, repair, surveillance, testing, and calibration of plant equipment. Examples include personnel errors of omission and commission by maintenance staff, procedure problems resulting in inadequate/improper maintenance, problems traceable to maintenance program administrative control, and equipment failures because of improper previous repair.

2. *Random*—Failures of this type usually occur in electronic equipment and are rare in operating equipment. As the term implies, no pattern is associated with the failure; therefore, this type of failure would not be expected to be a recurring problem.

3. *Design/Installation/Construction* — Failures experienced while performing, or as a consequence of, design, fabrication, construction, and installation of equipment, systems, and structures. Examples include personnel errors of omission and commission, procedures problems resulting in inadequate or improper design or installation, and problems traceable to design or construction program administrative control.

4. *Normal Aging/Wearout/End of Life*—Failures caused by a component or system reaching its end of life by normal aging or wearout.

5. *Unknown*—Insufficient information was provided in the failure narrative to determine the root cause of the failure.

The conclusion was that about 80% of the component failures reported in the NPRDS that produced the indicator flags, did involve maintenance ineffectiveness. On a plant-specific basis, the contribution ascribed to ineffective maintenance ranged from 0% to 100%. However, for a majority of cases, the maintenance effectiveness indicator can confidently be said to reflect maintenance effectiveness. The percentage of maintenance-related failures is not necessarily a profile of all NPRDS failures, just the NPRDS components and their failure reports that were considered for this study.

The evaluation results are summarized and depicted in Figures 3 through 6. The percent contribution is shown for each of the five failure cause categories (random, design, normal, maintenance, and unknown). Again, these figures show that the overwhelming majority of failures are attributed to maintenance-related causes.

4.3 Correlation with Licensee Event Report Maintenance Data

Much of the NRC staff's current efforts rely on its routing monitoring of plant and licensee operations, generic guidance, and plant-specific oversight to improve consistency in the application of the reporting requirements. For routine monitoring, the resident NRC inspectors monitor operations on a daily basis through their review of plant logs and other plant reports while they and the NRC regional personnel are involved in daily event reviews. The licensees' determination of reportability is routinely subject to NRC regional oversight. Generic guidance, NUREG 1022,[15] information notices, and generic letters are employed to provide feedback to licensees. In some cases, the NRR/AEOD Headquarters staff is requested by the NRC regions or licensees to provide an interpretation of the reporting requirements. The NRC Offices of Nuclear Reactor Regulation (NRR) and AEOD coordinate interpretations during the daily event reviews and other special activities. The goal is to provide consistent guidance to licensees and to ensure the reporting of all safety significant events.

An analysis was performed to compare the maintenance effectiveness indicator results with the equipment failures documented in individual LERs submitted by plants to meet the reporting requirements specified in 10 CFR 50.73, the so-called LER rule.[16] This rule ensures that LERs are consistently reported across plants. The analysis showed a direct relationship between the number of maintenance-related events reported in the LERs and the number of flags generated by the indicator. That is, plants with a high number of indicator flags also experienced a high number of maintenance-related operational events. And conversely, plants with a low number of indicator flags also experienced a low number of maintenance-related operational events. This trend is consistent for both BWR and PWR plants. A discussion of the LER analysis follows.

The root causes of operational events were evaluated as part of the validation process. In this analysis, the maintenance effectiveness indicator results were compared with root cause data derived from the reportable events documented in the LERs.

The source of the LER data was the Sequence Coding and Search System (SCSS),[17] a computerized data base of LERs maintained by the Nuclear Operation and Analysis Center staff at the Oak Ridge National Laboratory (ORNL). As part of the SCSS program, the ORNL staff has developed a technique to classify the root causes of the events reported in LERs. One of these cause classifications is maintenance.

The maintenance cause category covers the entire range of programmatic deficiencies related to maintenance, surveillance, testing, and calibration. These deficiencies are deemed attributable to:

1. *Maintenance personnel errors*—Personnel errors associated with the performance of surveillance, testing, calibration, or radiation protection activities, and

2. *Poor maintenance practices*—Equipment failures that are strongly indicative of problems with maintenance implementation, such as improper lubrication, corrosion because of boric acid precipitation, short circuits, and improper prior repairs.

As described in the AEOD/S804B report, this validation task determined whether plants with high (or low) frequencies of maintenance-related operating events also exhibited high (or low) numbers of maintenance effectiveness indicator flags.

To perform this comparison, the mean number of maintenance-related events occurring per month during the period of interest was calculated for each of the selected PWR and BWR plants. This calculation was based on the number of events identified in the SCSS data base that involved maintenance deficiencies (i.e., maintenance-related events). Then, the total number of maintenance effectiveness indicator flags for each plant was also calculated for the same study period.

Only the plants identified on Table 5 were selected for this analysis. The selected plants are those plants which were in commercial power operation for the 28 months between January 1986 to June 1988. This

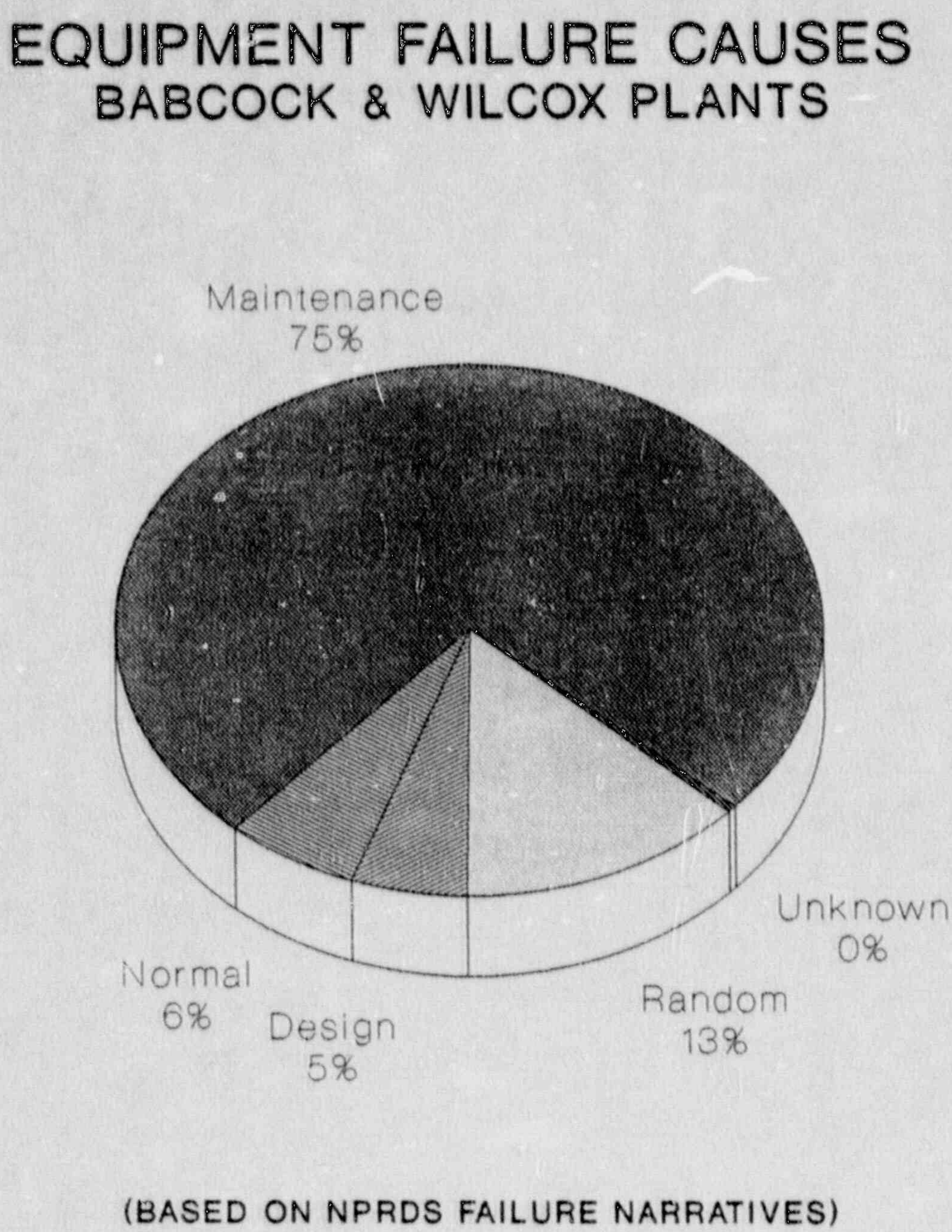


Figure 3. Component failure causes identified from NPRDS narratives for BW plants.

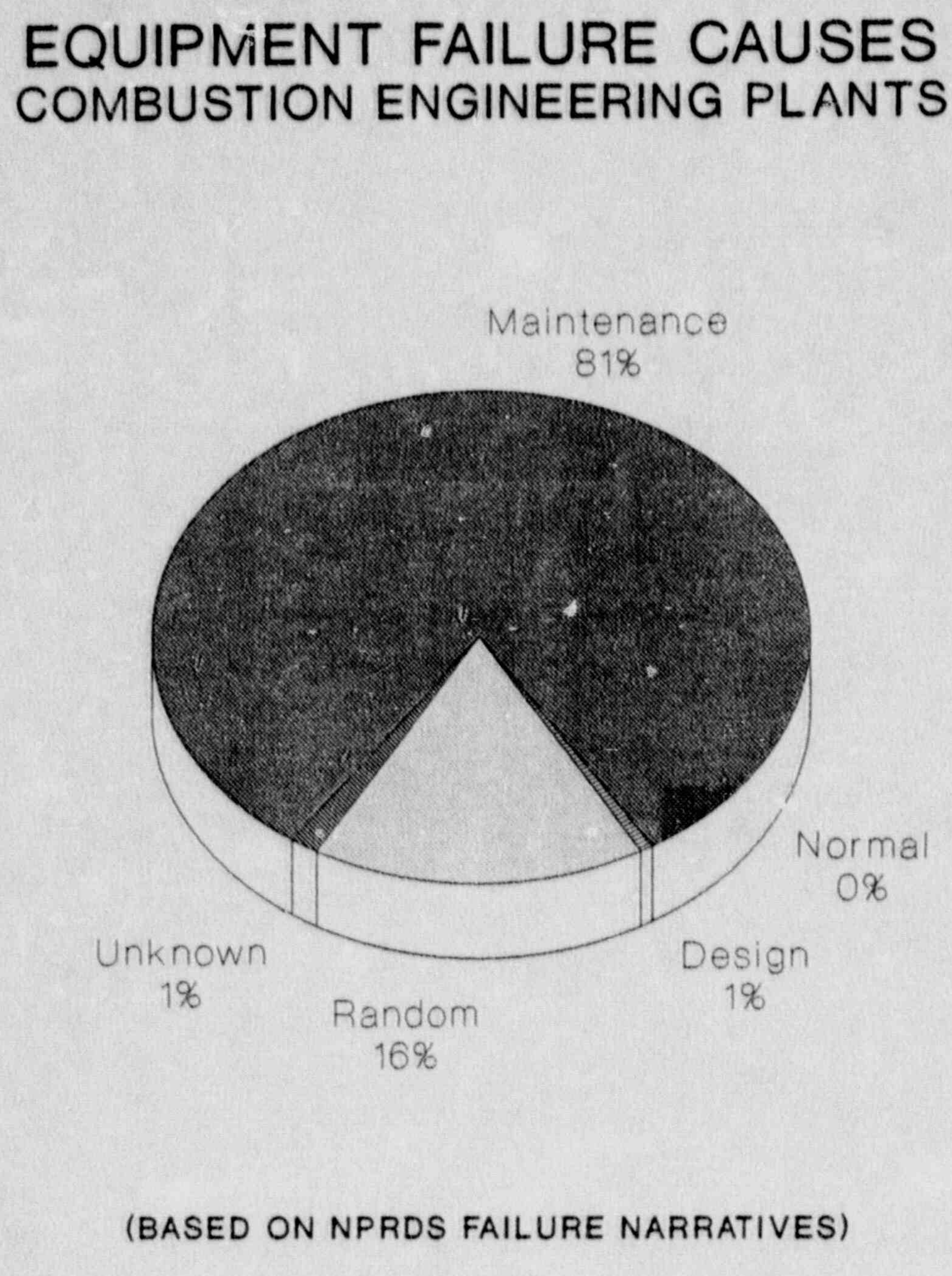


Figure 4. Component failure causes identified from NPRDS narratives for CE plants.

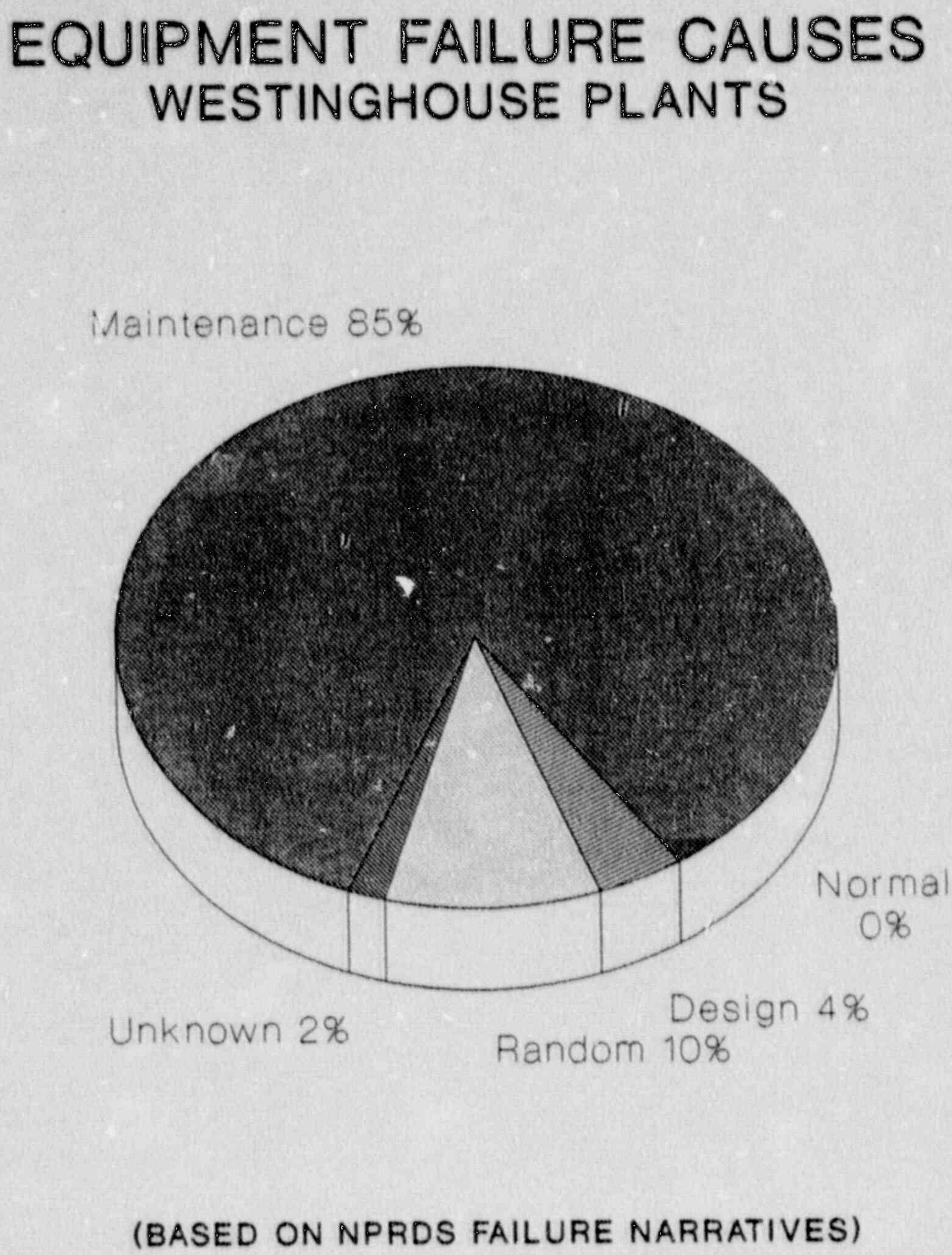
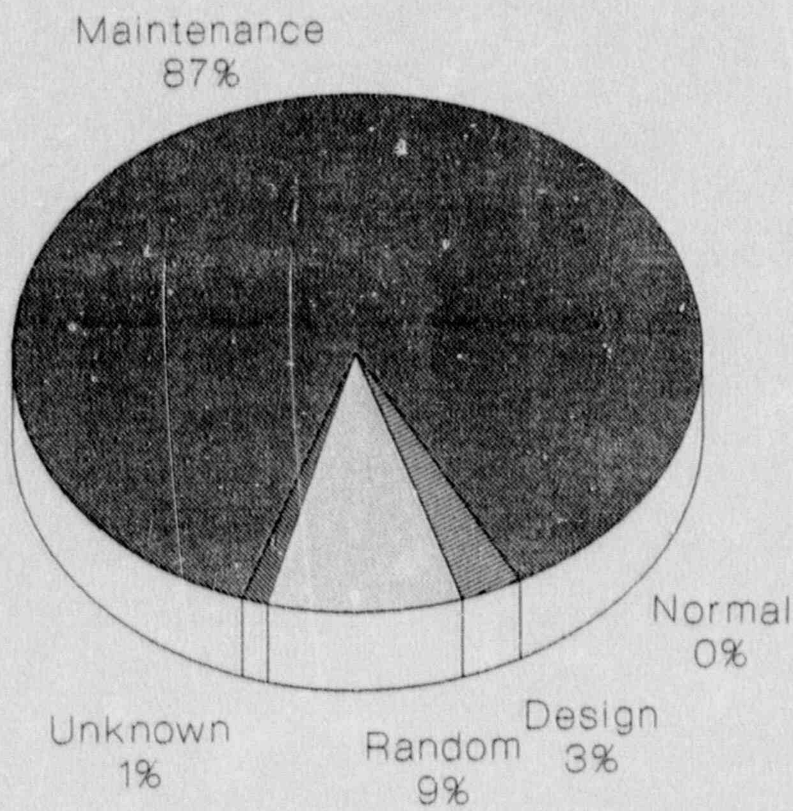


Figure 5. Component failure causes identified from NPRDS narratives for WE plants.

EQUIPMENT FAILURE CAUSES
GENERAL ELECTRIC PLANTS



(BASED ON NPRDS FAILURE NARRATIVES)

Figure 6. Component failure causes identified from NPRDS narratives for GE plants.

Table 5. Plants selected for validation

PLANT NAME	PLANT NAME	PLANT NAME
Arkansas 1	Hatch 2	Quad Cities 1
Arkansas 2	Indian Point 2	Quad Cities 2
Beaver Valley 1	Indian Point 3	Robinson 2
Brunswick 1	Kewaunee	Salem 1
Brunswick 2	LaSalle 1	Salem 2
Byron 1	LaSalle 2	San Onofre 1
Calvert Cliffs 1	Limerick 1	San Onofre 2
Calvert Cliffs 2	Maine Yankee	San Onofre 3
Catawba 1	McGuire 1	St. Lucie 1
Cook 1	McGuire 2	St. Lucie 2
Cook 2	Millstone 1	Summer
Cooper Station	Millstone 2	Surry 1
Crystal River 3	Millstone 3	Surry 2
Diablo Canyon 1	Monticello	Susquehanna 1
Diablo Canyon 2	Nine Mile Point 1	Susquehanna 2
Dresden 2	North Anna 1	Three Mile Island 1
Dresden 3	North Anna 2	Trojan
Duane Arnold	Oconee 1	Turkey Point 3
Farley 1	Oconee 2	Turkey Point 4
Farley 2	Oconee 3	Vermont Yankee
Fitzpatrick	Oyster Creek	Wash. Nuclear 2
Fort Calhoun	Palo Verde 1	Waterford 3
Ginna	Point Beach 1	Wolf Creek
Grand Gulf	Point Beach 2	Zion 1
Haddam Neck	Prairie Island 1	Zion 2
Hatch 1	Prairie Island 2	

selection ensured that the effects from initial plant startup would not bias the failure data reported in the NPRDS. The plant participates in the NPRDS after the unit enters commercial operation.

The total count of maintenance effectiveness indicator flags was compared to the cause code rate using the SAS computer program's procedure named CORR.[18] Scatter plots and distributions of each variable within the NPRDS were reviewed to identify outlier cases. The extreme outliers were removed, and final correlations for the BWRs and PWRs were calculated.

Figure 7 provides the final scatter plot for all mature PWR units combined. The line shown in the figure is a linear regression through the LER cause code and the maintenance effectiveness indicator points. The data for three units were removed, because they were deemed to be outliers. The correlation coefficient with the outliers removed is 0.39, with an observed significance of 0.003. Thus, the maintenance effectiveness indicator and the LER maintenance cause codes were found to be correlated, i.e., plants with higher numbers of maintenance-related operational events will produce higher numbers of maintenance effectiveness indicator flags, and visa versa.

In the AEOD/S804B report, the maintenance effectiveness indicator was found to be correlated for mature BWR plants. As explained previously, the present study considered a slightly different BWR plant population and a different set of systems and components. The relationship found in the AEOD/S804B report was revisited in this study to determine whether the correlation found in the previous work still existed. The results of the present analysis indicated that a positive correlation still exists between the maintenance effectiveness indicator and the LER maintenance cause codes.

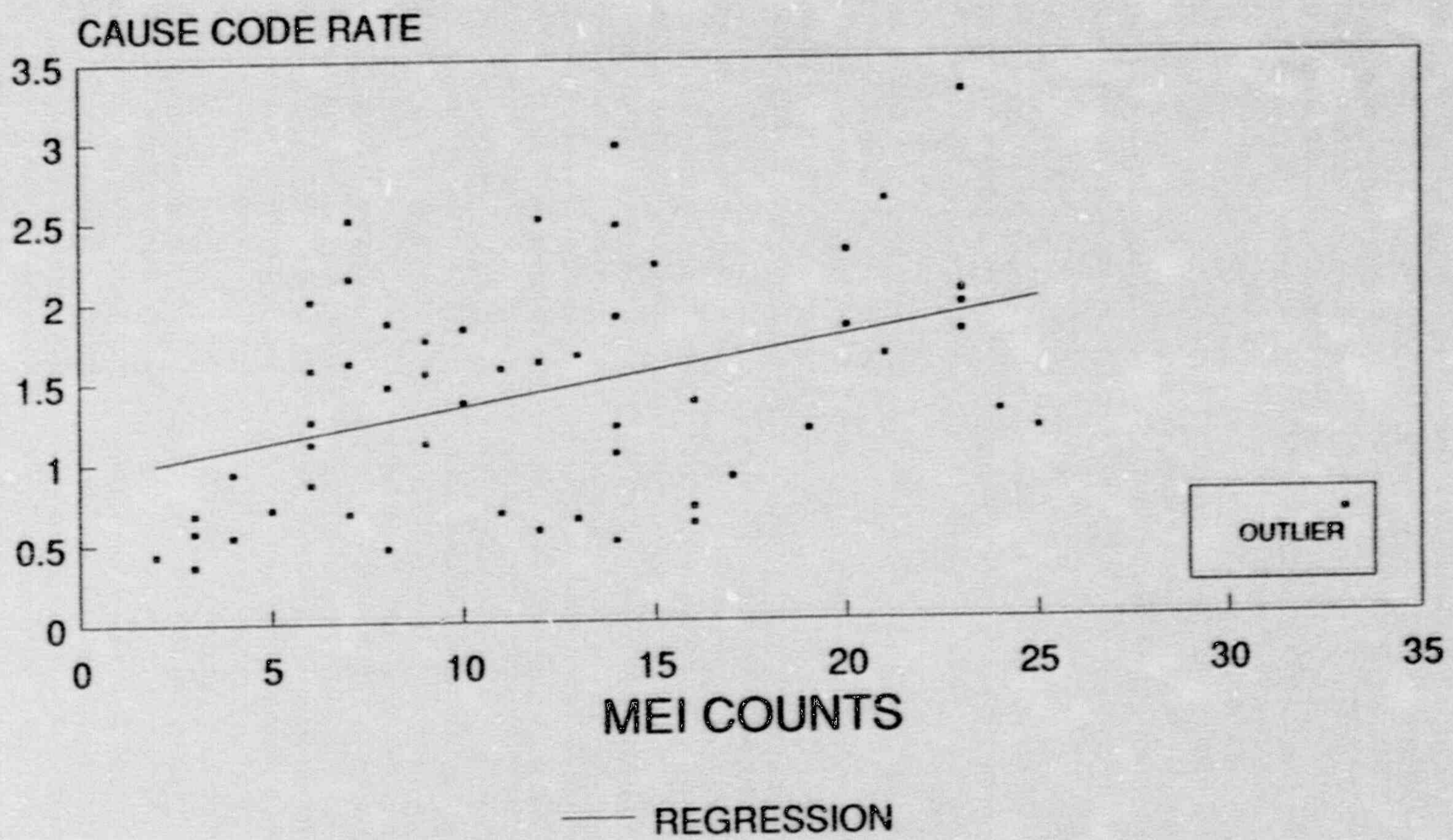


Figure 7. Scatter plot illustrating direct correlation between indicator and LER maintenance-caused operational events for PWRs.

5. RESULTS

Following the validation of the maintenance effectiveness indicator, three studies were conducted to determine the status of maintenance effectiveness for U.S. commercial plants, the influence that plant outage has on the indicator results, and the ability of the indicator to predict system failures. The results of these studies are presented in this section.

The industry trends analysis was conducted first. Overall, a trend of improvement in maintenance effectiveness was noted for the two-year study period (July 1986 through June 1988). The total number of maintenance effectiveness indicator flags decreased. This trend was consistent for all PWR and BWR reactor vendor groups, with some groups showing more improvement than others.

The second analysis addressed the distribution of indicator flags during a fuel cycle based on plant status. As noted in Section 4, the indicator evaluates the NPRDS-reported failures from ODE that supports power generation. The equipment is generally maintained during outages, which is also when failures of the equipment are frequently discovered.

During this analysis, the influence of plant status on the indicator results was also considered. Two major findings were noted. First, the failure discovery rate (number of discoveries per month) does increase during planned outages. About 32% of all discovered failures and 70% of all maintenance effectiveness indicator flags are noted for months inside of plant outages. Thus, the indicator flags are more concentrated during periods of plant outages. However, the plants with the higher number of component failures will also produce a higher number of flags outside of plant outages. Second, and more importantly, the plants with higher numbers of component failures (i.e., less effective maintenance programs) are regularly producing a higher *cumulative* number of indicator flags, regardless of whether or not the plant is in a planned outage. Thus, plants with ineffective maintenance programs will likely be noted by indicator flags throughout the tracking period. Also, the methods to retrieve failure data and to calculate the indicator are valid regardless of plant operational status, such as a plant outage.

A final analysis using plant status and system failure information was performed to address the question, "Do maintenance effectiveness indicator flags precede system failures that result in power outages?" The results showed that for only 12% of the cases, an increase in component failures as noted by the generation of the indicator flag(s) preceded an equipment forced outage.

5.1 Historical Trends

The indicator was used to assess maintenance effectiveness for mature commercial nuclear power plants. The intent was to identify the overall historical trend and the outlier plants for the study period (January 1986 through June 1988). The analyses also identify the most troublesome systems, that is, the systems for which the highest number of indicator flags are noted. The Appendices contain discussions on the last two areas: the proprietary plant-specific data and trends, along with the results from the statistical outlier analysis.

The industry and vendor results are presented below. The operational plants considered for the analysis are those plants listed on Table 5. During the study period, these plants collectively discovered and reported about 11,000 failures for the components monitored by the maintenance effectiveness indicator. These 11,000 failures were generated among 160,000 components monitored for these plants, out of the 520,000 components tracked by the NPRDS.

5.1.1 Pressurized Water Reactors. The maintenance effectiveness indicator was calculated using the component failure data for all mature PWRs. Figure 8 shows the trend in the monthly plant average number of indicator flags for the PWRs. The trend indicates that the number of maintenance effectiveness indicator flags on the average, is *decreasing*, denoting general improvement in maintenance effectiveness over the two-year period of interest. Several individual PWRs were observed to have increasing trends, but these plants were a minority of the total population.

For the PWR group evaluated, a total of 695 indications, or flags, were trended. On a per-plant basis, the total number of indications ranged from 2 to 33, with an average of 12.2 indications per plant. The median of this distribution was 12.

It is interesting to note on Figure 8 that the indicator is tracking seasonal variations in maintenance activities. The monthly number of indicator flags reaches a peak twice each year (spring and fall), corresponding to the seasons when most refueling outages and ODE maintenance activities occur. This tracking pattern is also seen for each PWR vendor group and for the BWRs.

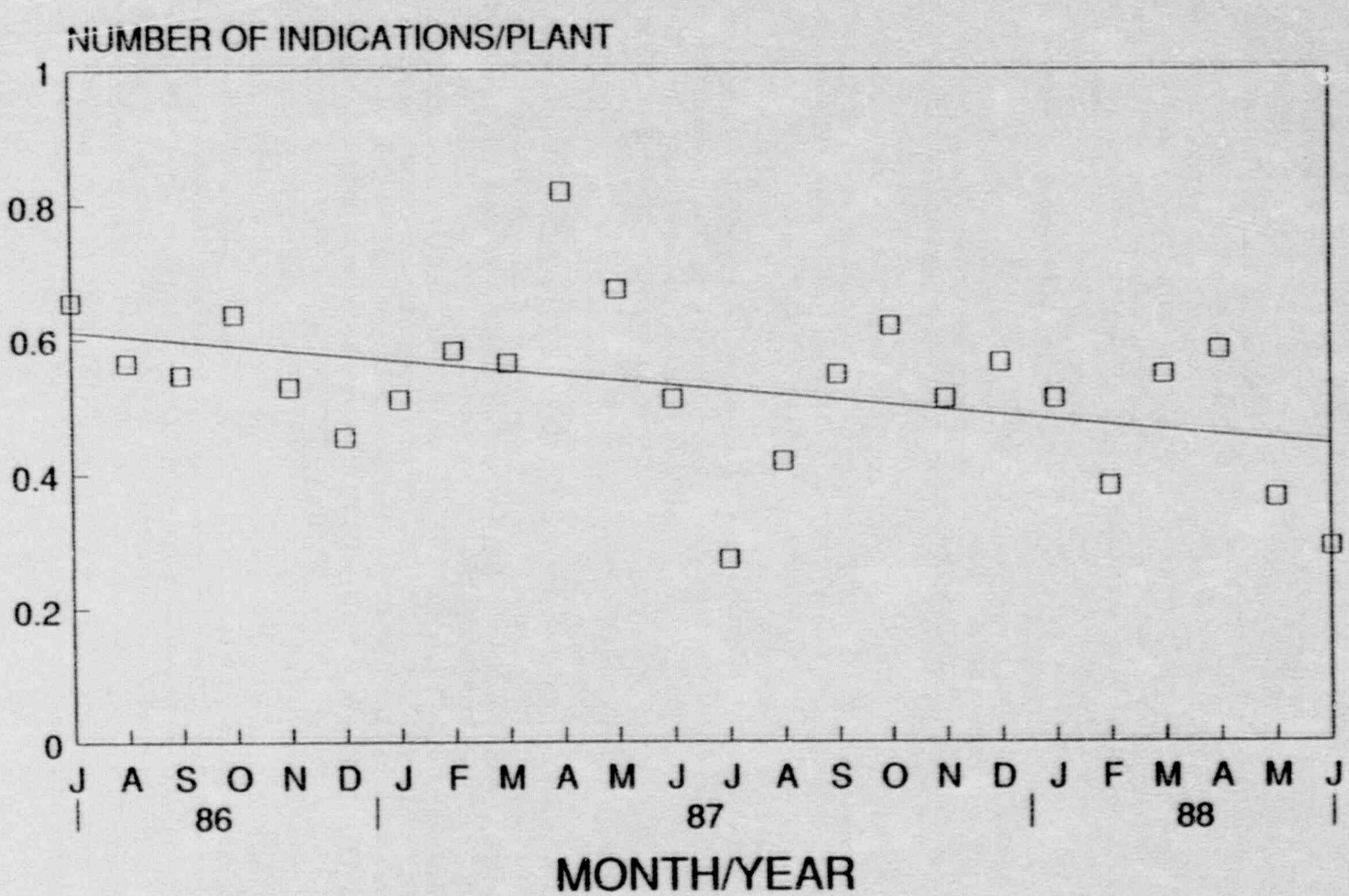


Figure 8. Monthly average number of indicator flags for PWR plants over two-year study period.

Figure 9 shows the distribution of the number of indications tallied on a PWR per–plant basis. The data appear to have a normal distribution. One outlier (greater than two standard deviations from the mean) was identified for the group of PWR plants, with a total of 33 indications.

Looking at the indicator results on a system basis for all PWR NSSS vendors, the reactor protection system (RPS) dominated the distribution for PWRs.

Babcock and Wilcox PWRs. The trend of the average number of maintenance effectiveness indicator flags for Babcock & Wilcox (BW) PWRs is shown in Figure 10. For the study period, a decreasing trend was noted, which indicates that the maintenance effectiveness at BW PWRs had improved. A total of 58 indicator flags were noted for BW PWRs. On a per–plant basis, the number of flags ranged from 4 to 14, with the average being 9.7 per plant and a median of 10. No outliers were observed in this group.

Of the systems monitored for BW PWRS, (see Figure 11 for the distribution), the letdown/purification/charging system was the dominant generator of indicator flags, accounting for more than twice the number of flags as the next highest contributors, the reactor coolant system (RCS), and the RPS.

Combustion Engineering PWRs. Figure 12 shows the trend of the indicator flags for Combustion Engineering (CE) PWRs. This figure clearly shows a decreasing trend, indicating that, on the average, the maintenance effectiveness at CE PWRs improved during the study period. A total of 165 indicator flags were calculated for CE PWRs. The number of indications per plant ranged from 2 to 33, with the latter plant being an outlier for this group and also for the entire PWR population as a whole. The average number of indicator flags per plant was 13.8, with a median of 10.5.

Of the systems monitored for CE PWRs (see Figure 13 for the distribution), the generation of indicator flags was dominated by the control element assembly system, with the chemical and volume control system (CVCS) being the next highest contributor. Out of the 33 indicators flags calculated for the outlier plant, roughly one–third (10) were due to component failures that occurred in the RPS. This number was significantly higher than the next highest contributors, the auxiliary feedwater system (AFW) and the RCS, which were responsible for four indications each.

Westinghouse PWRs. Figure 14 indicates only a slightly decreasing trend for Westinghouse (WE) PWRs, in contrast to the BW and CE cases. A total of 472 indicator flags were noted for the mature WE PWRs. The number per plant ranged from three to 25, with the average being 12.8 per plant and a median of 13. No outliers were observed for this distribution. (See Figure 15 for the distribution.)

The total number of indicator flags on a system basis was dominated by component failures in three systems: the RPS, the main feedwater system, and the CVCS. These systems produced about two–thirds of the total number of indicator flags for this group of plants.

5.1.2 Boiling Water Reactors. The maintenance effectiveness indicator was applied to the component failure data for BWRs. Figure 16 shows the trend in the average number of indicator flags trended per month over the study period for the group of BWR plants. As in the case of the PWRs, the decreasing trend indicates that the effectiveness of maintenance at BWRs, on the average, improved over the study period. These results are consistent with the results published in AEOD/S804B.

For the group of all BWR plants, a total of 330 indicator flags were noted. On a per–plant basis, the total number ranged from 1 to 33, with an average of 14.4 indicator flags per plant. The median of this distribution was 14.

Once again, the data appear to have a normal distribution. Figure 17 shows the distribution of the indicator flags tallied on a per–plant basis. One outlier was observed in this distribution. This plant accumulated a total of 33 indications, with component failures in three systems (the nuclear steam supply shutoff, the neutron monitoring, and the feedwater systems) contributing nearly an equal number (6, 5, and 5 flags, respectively) to this total.

On a system basis, unlike the PWR cases on a system basis, the indicator flag distribution for the BWRs was not dominated by failures in a specific system, or even two or three systems. In fact, out of the 12 BWR systems monitored, 8 accounted for roughly 90% of the total number of indicators flags for this group of plants, with each system contributing almost an equal share. These systems are: feedwater, main steam, nuclear steam supply shutoff, neutron monitoring, control rod drive, reactor recirculation, essential service water, and RPS.

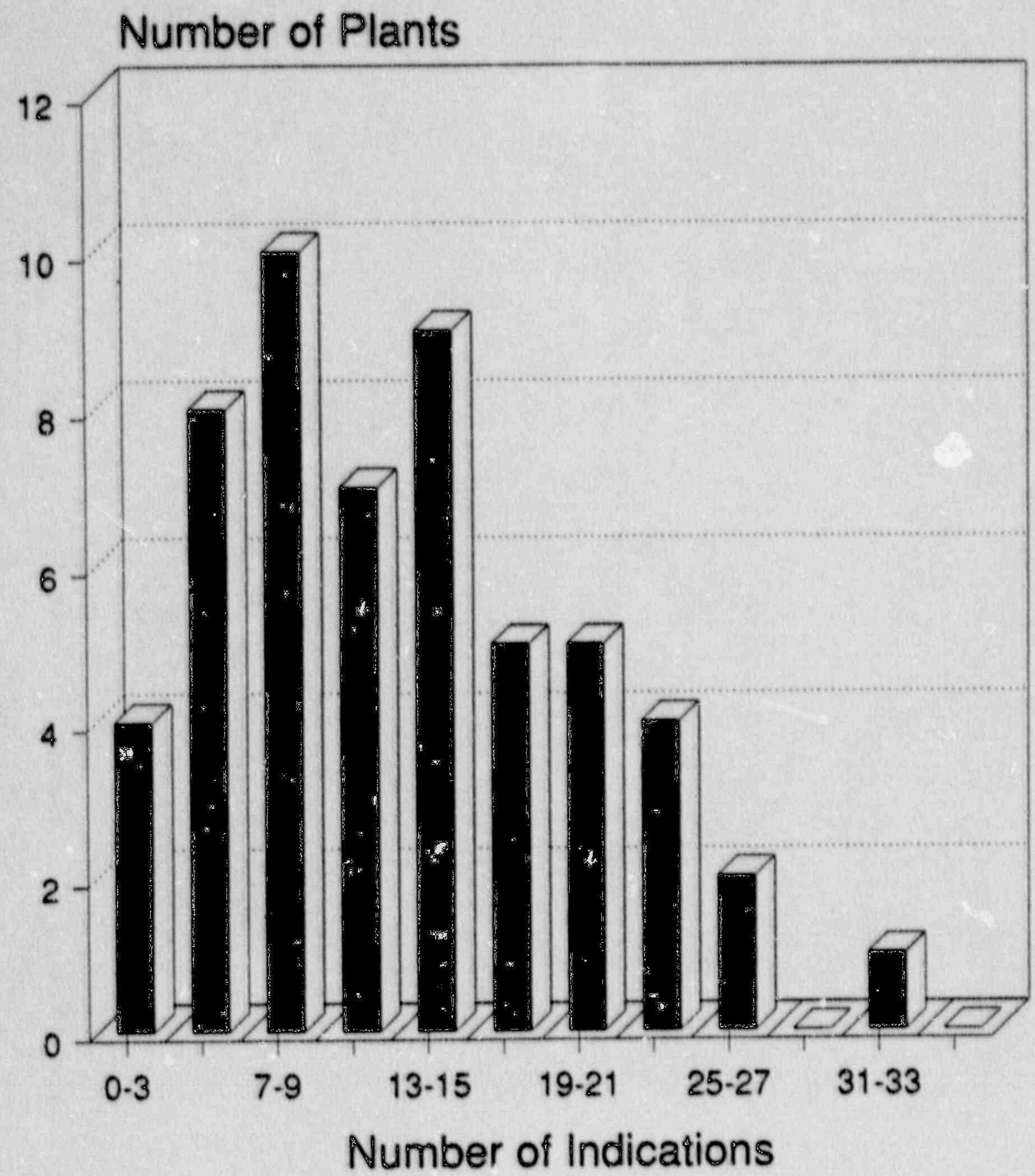


Figure 9. Number of indicator flags accumulated by PWR plants over two-year study period.

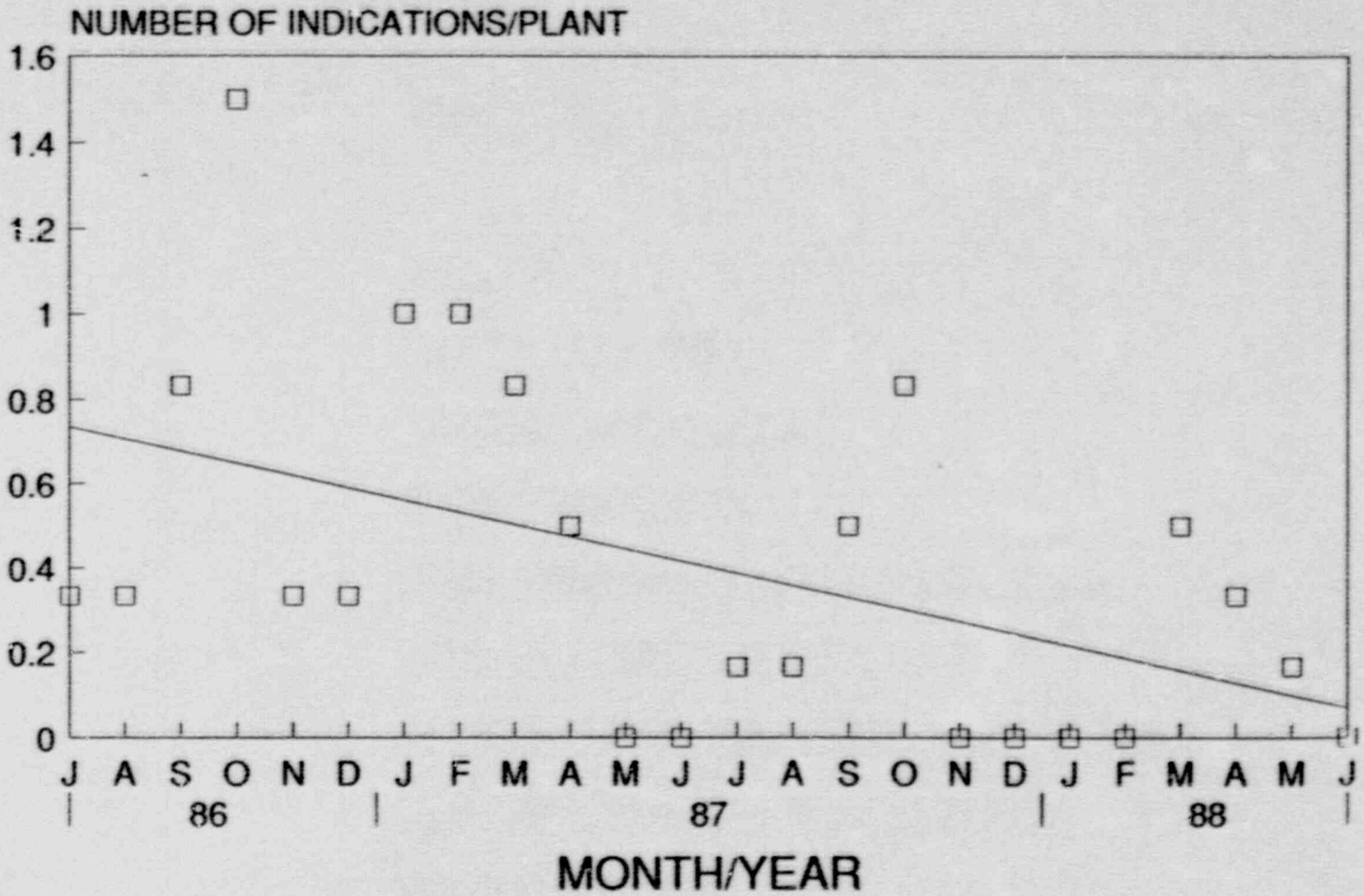


Figure 10. Monthly average number of indicator flags for BW plants over two-year study period.

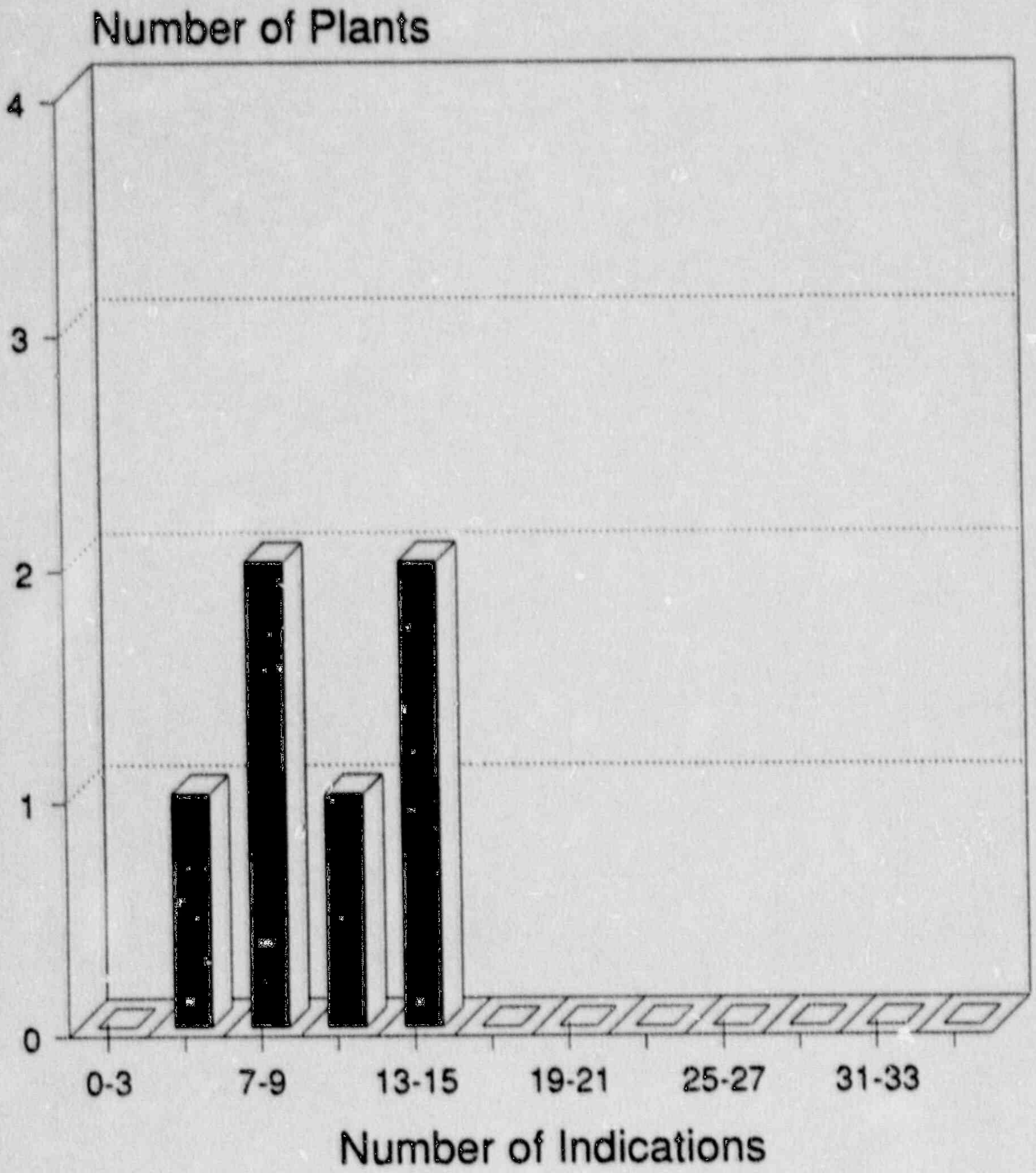


Figure 11. Number of indicator flags accumulated by BW plants over two-year study period.

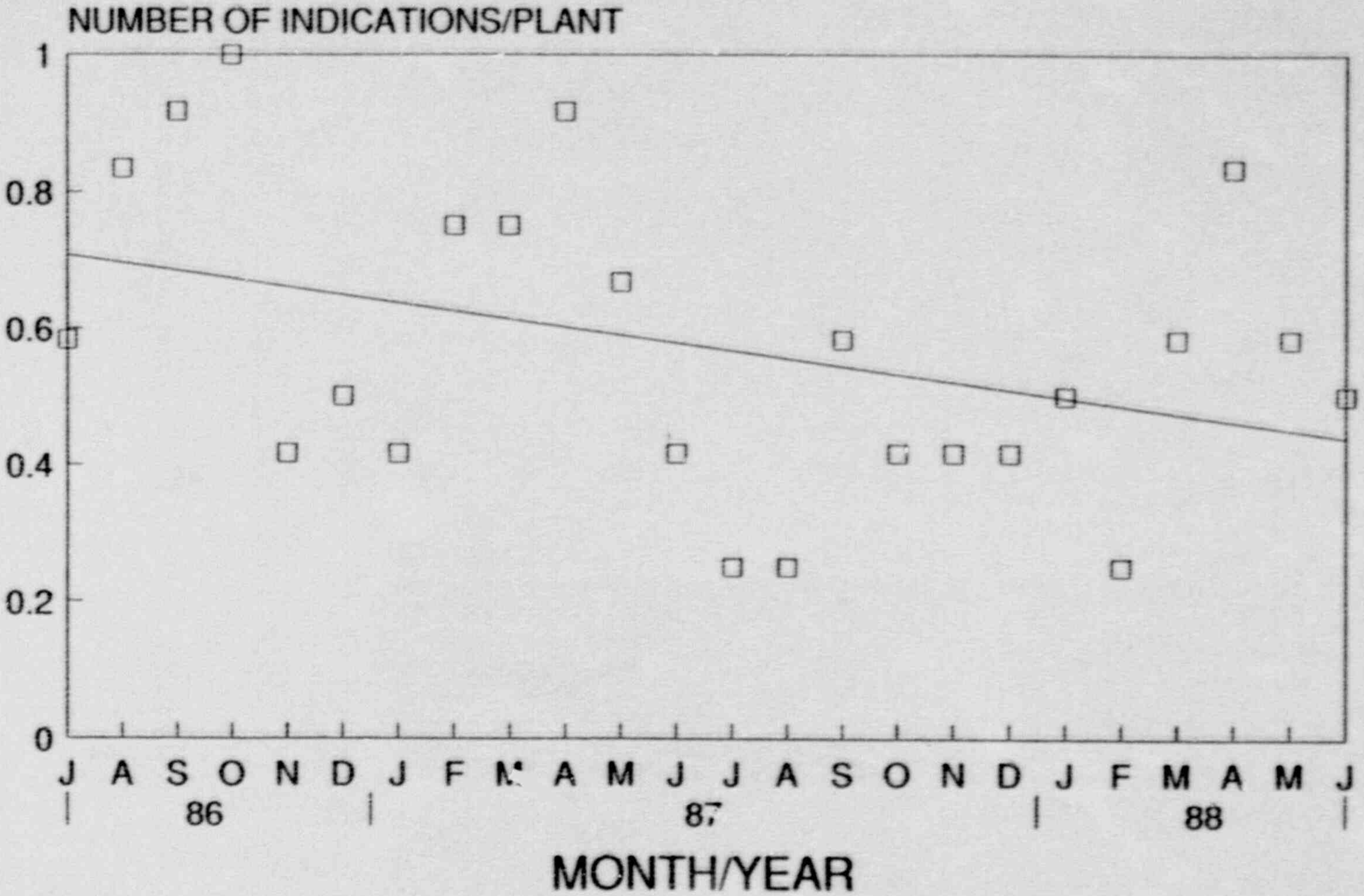


Figure 12. Monthly average number of indicator flags for CE plants over two-year study period.

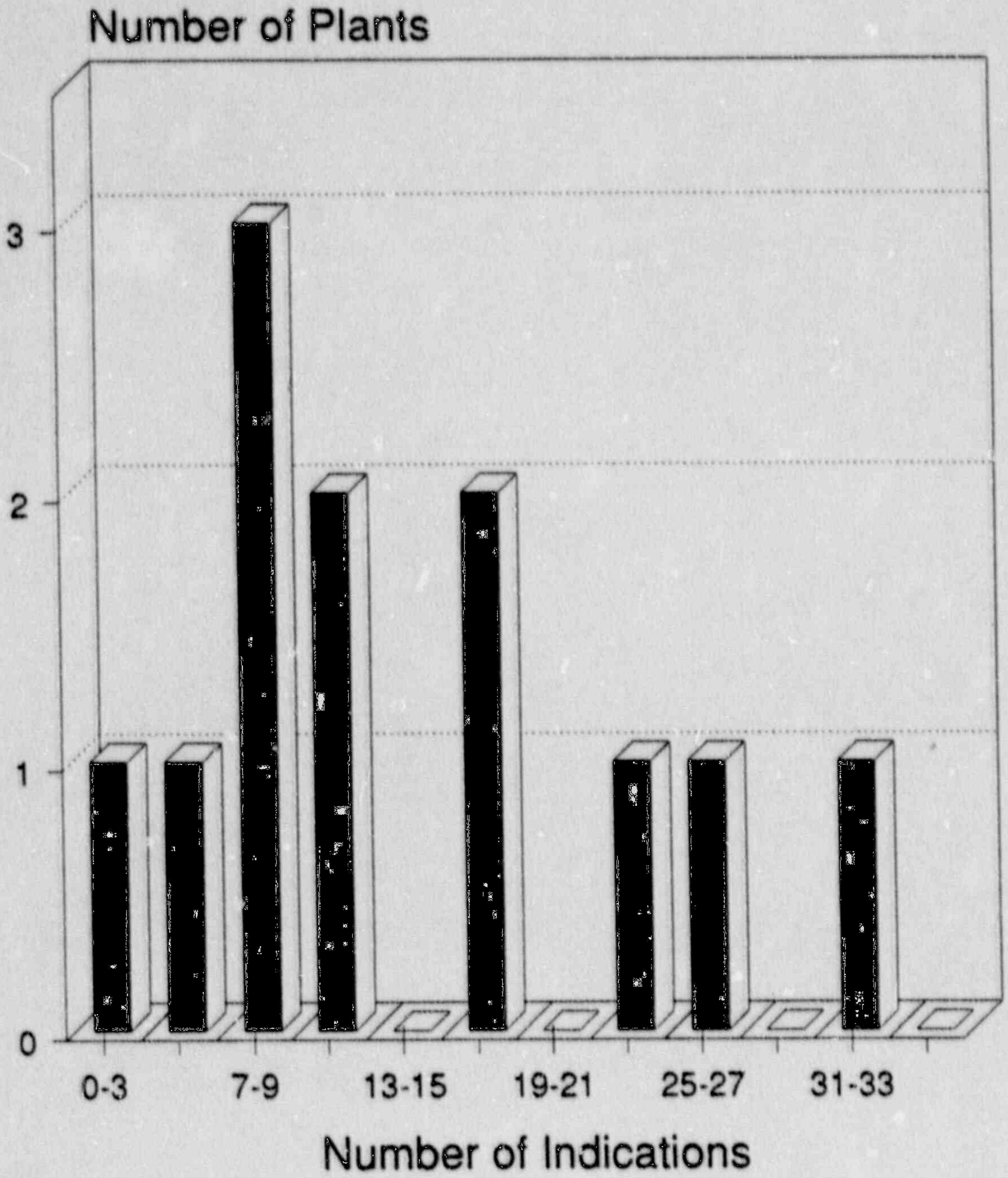


Figure 13. Number of indicator flags accumulated by CE plants over two–year study period.

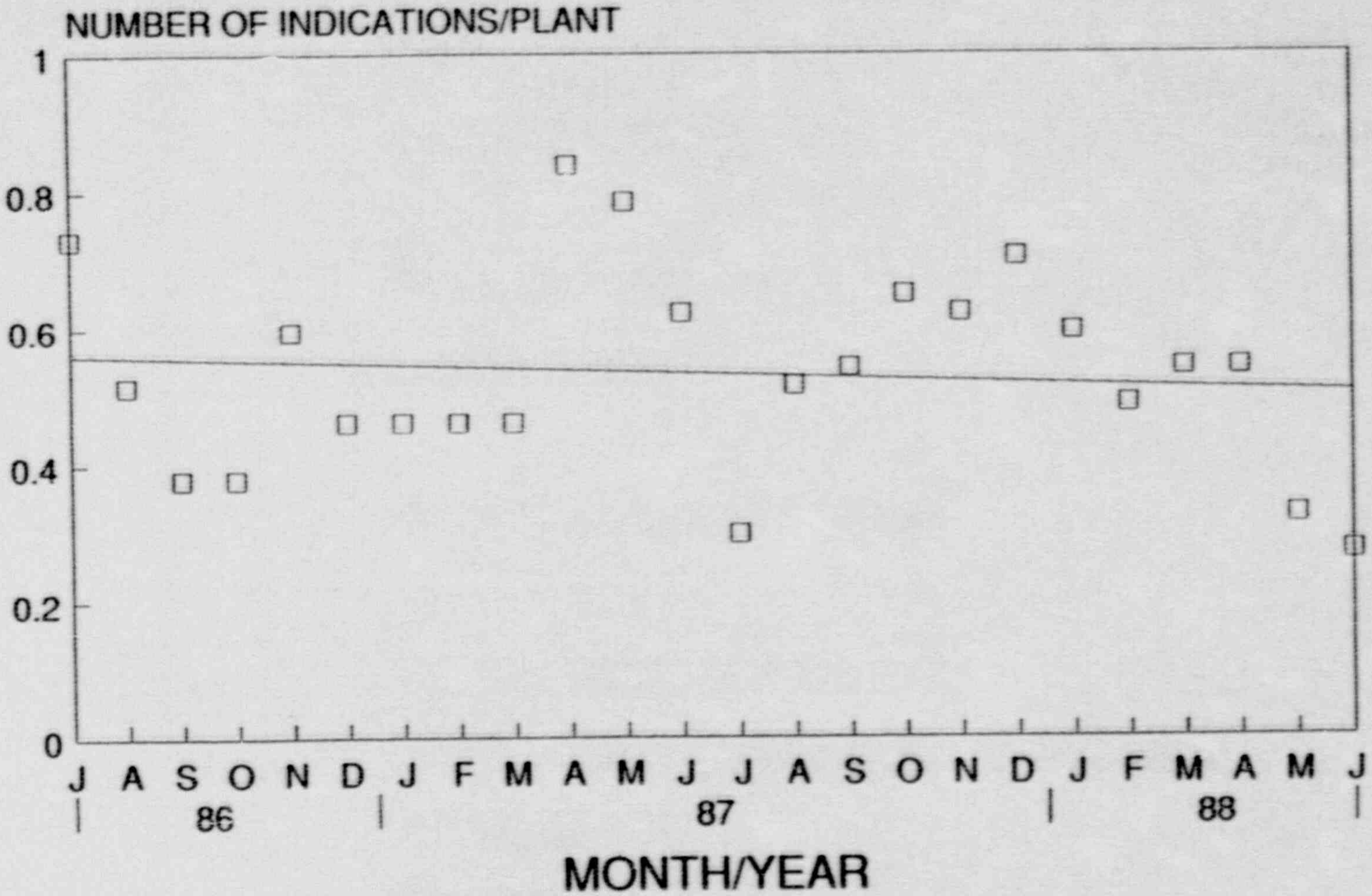


Figure 14. Monthly average number of indicator flags for WE plants over two-year study period.

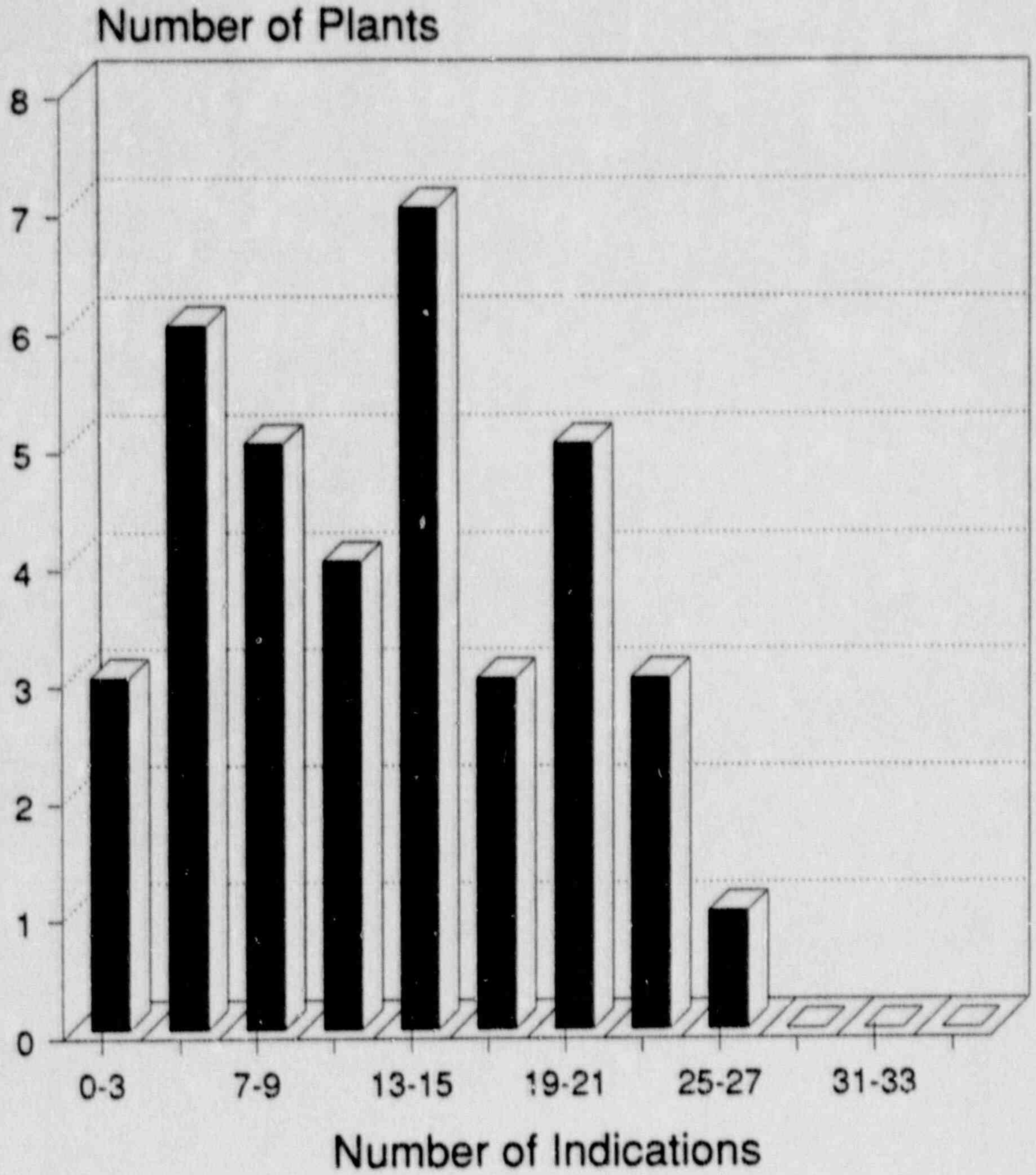


Figure 15. Number of indicator flags accumulated by WE plants over two-year study period.

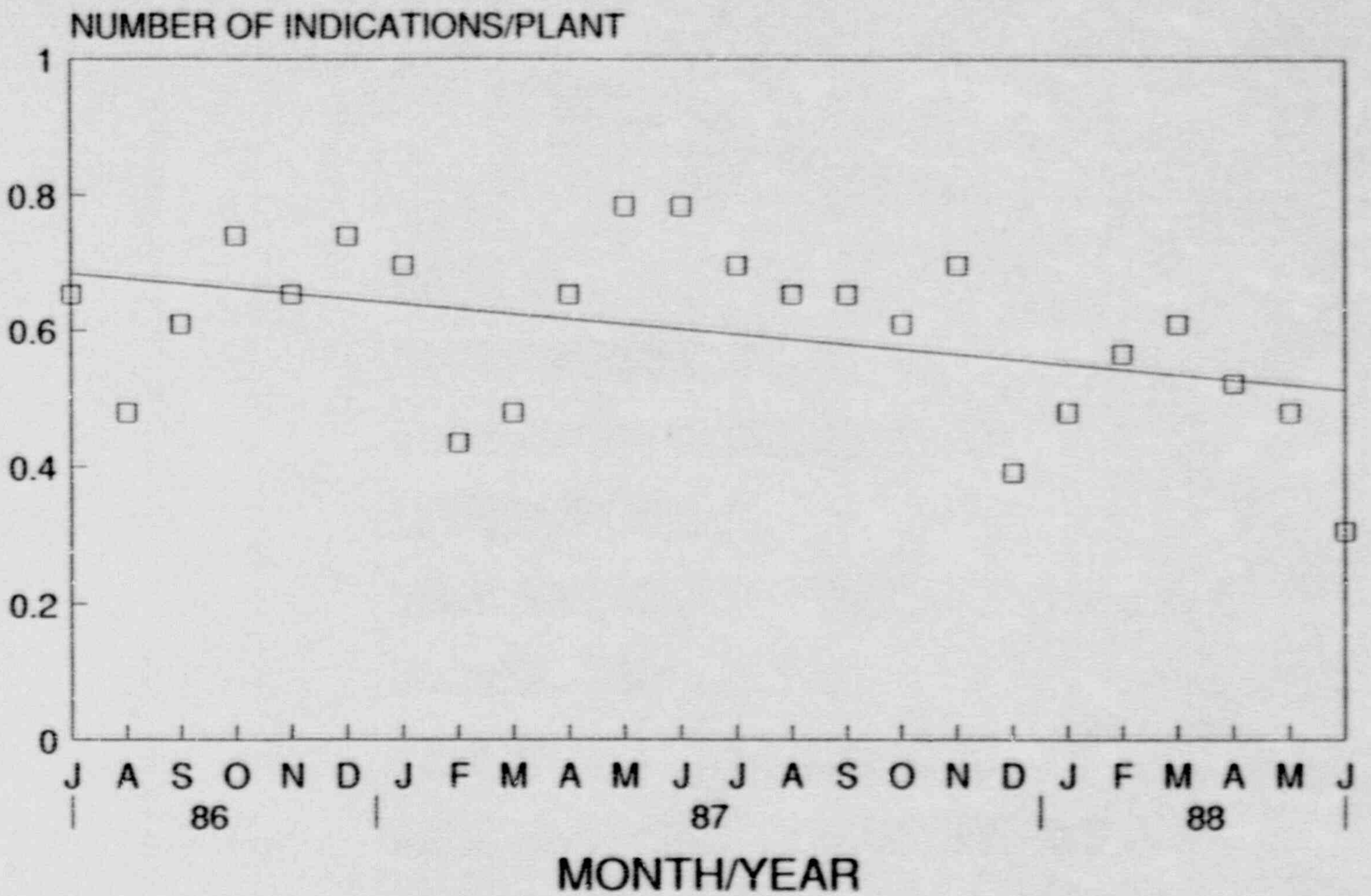


Figure 16. Monthly aveage number of indicator flags for GE plants over two-year study period.

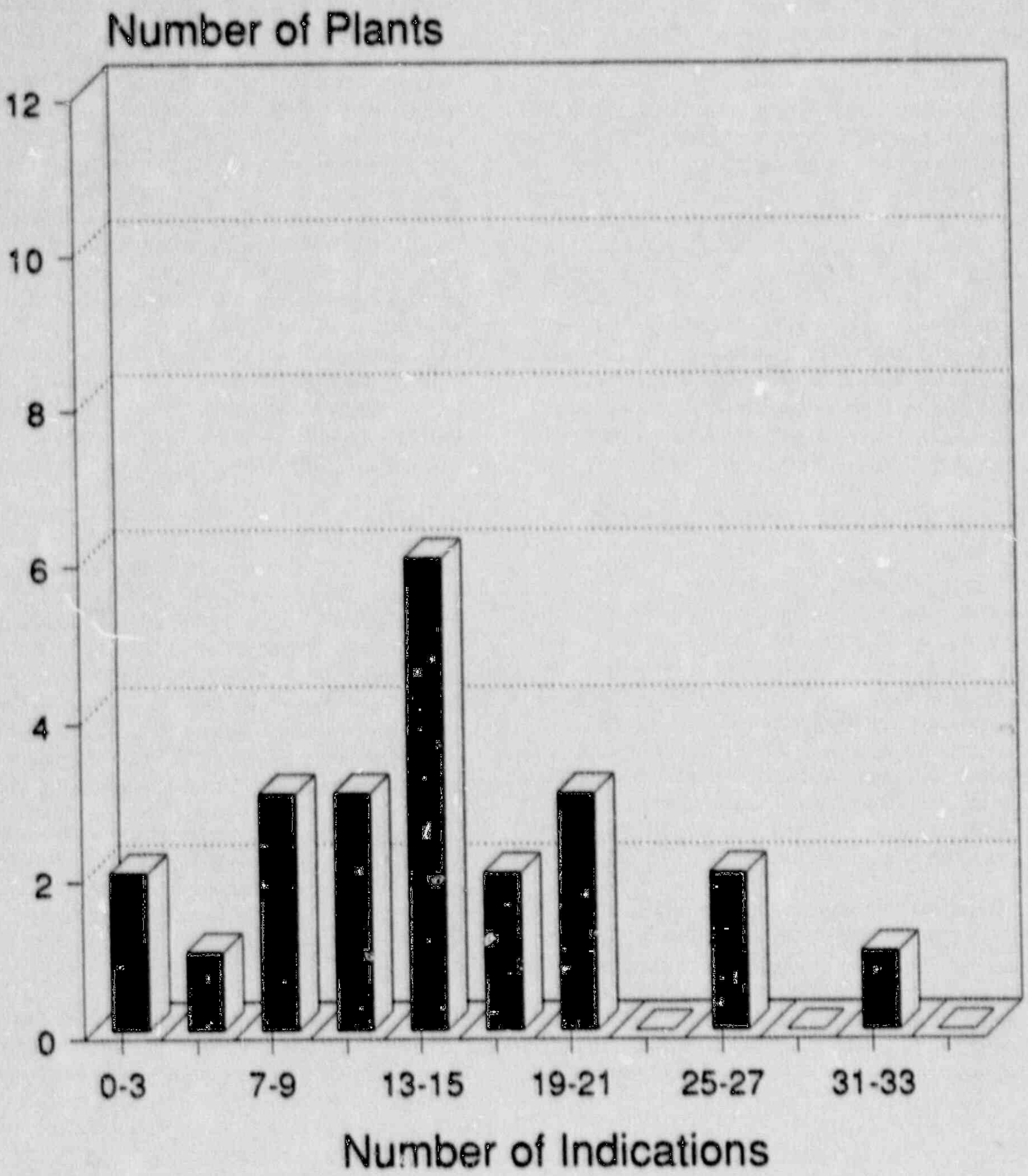


Figure 17. Number of indicator flags accumulated by GE plants over two-year study period.

5.1.3 Example Uses. The historical trends analysis was evaluated to provide more plant specific results. Because these results are proprietary, only two anonymous examples will be discussed.

Figure 18 illustrates the history of the cumulative number of indicator flags generated during the most recent fuel cycle (lower curve) in comparison with the cumulative number generated during the previous 18-month fuel cycle (upper curve). This plant appears to be performing more effectively through the first 12 months of the most recent fuel cycle. Both the magnitude and slope of the flag histories have decreased.

A comparison of cumulative flag histories for five PWRs of comparable design power output and time-in-life (i.e., fuel cycle) is shown in Figure 19. All results are very comparable through the first 15 months of the fuel cycle. After that time, one plant is possibly becoming an outlier as noted by its steep curve slope.

5.2 Retrospective Analysis

Further, more detailed analyses of the industry historical trends were performed to gain additional insight on the influence of plant status. It is known that the indicator has an inherent sensitivity to outages, because the components whose failures are tracked by the indicator are most likely to be discovered while being maintained during outages. To conduct this analysis, the maintenance effectiveness indicator data and the component failure data from the study period (January 1986 to July 1988) were compared against the periods of power outages.

The source of the plant outage information was the NRC's Gray Book (NUREG-0020),[6] which is issued on a monthly basis. Both scheduled (e.g., refueling) and forced system outages were extracted from these reports. The Gray Books were used to (a) identify periods when the plant outage occurred and (b) obtain data when the outage was caused by a component or system failure.

The periods of scheduled outages were first compared with the component failure histories and the indicator flag histories. A tally for each plant was constructed with the number of failures and flags that occurred inside and outside of the plant outages.

The results from this process showed that, on the average, 32% of the component failures are discovered within periods of plant outages and 68% are discovered outside of outages. In contrast, about 70% of the maintenance effectiveness indicator flags are generated for periods within outages and about 30% are generated outside of outages. Thus, the intense maintenance activities that occur during the early periods of scheduled plant outages will produce a large portion of the indicator flags.

Further research of the data revealed two noteworthy results. First, even though the majority of component failures are discovered and indicator flags are noted during outages, the plants with the higher number of component failures will also produce a higher number of indicator flags *outside* of plant outages. Second, the plants with higher numbers of component failures regularly produce a higher *cumulative* number of indicator flags, regardless of whether or not the plant is in a planned outage. Thus, plants with ineffective maintenance programs will likely be notable by indicator flags throughout the tracking period. Also, the methods to retrieve failure data and to calculate the indicator are valid regardless of plant operational status, such as a plant outage.

The maintenance effectiveness indicator flags, the plant outage histories, and the system failure histories were then compared with component failure histories that were tracked by system. An example of such a comparison is shown on Figure 20. The intent was to note whether a discernible increase in component failures, as noted by the generation of an indicator flag or flags, preceded a failure within that system that led to an equipment forced outage. This comparison was made to answer the question, "Could the maintenance effectiveness indicator by used to predict an outage?"

To address the question, the data were reviewed in two steps. First, a sample of 34 plants was selected for study, with essentially equal representation of plants for all four vendors. Within each vendor group, plants with high, average, and low number of failures were represented.

Second, the data for each plant were reviewed in two ways. Initially, each time an equipment forced outage occurred within a system, the history of indicator flags for that system was reviewed to determine whether a flag or flags could be observed during a four-month period before the outage. A tally of results was maintained for each plant. Then, the remaining indicator flags for each system were reviewed to note the number of times that no subsequent outage occurred during the four-month period after these flags were generated. These results were added to the tally.

The results indicated that in about 12% of the cases where an indicator flag was noted, a subsequent system failure occurred; and for all other cases, no system failure was noted. Thus, the indicator flags were a poor predictor of equipment forced outage.

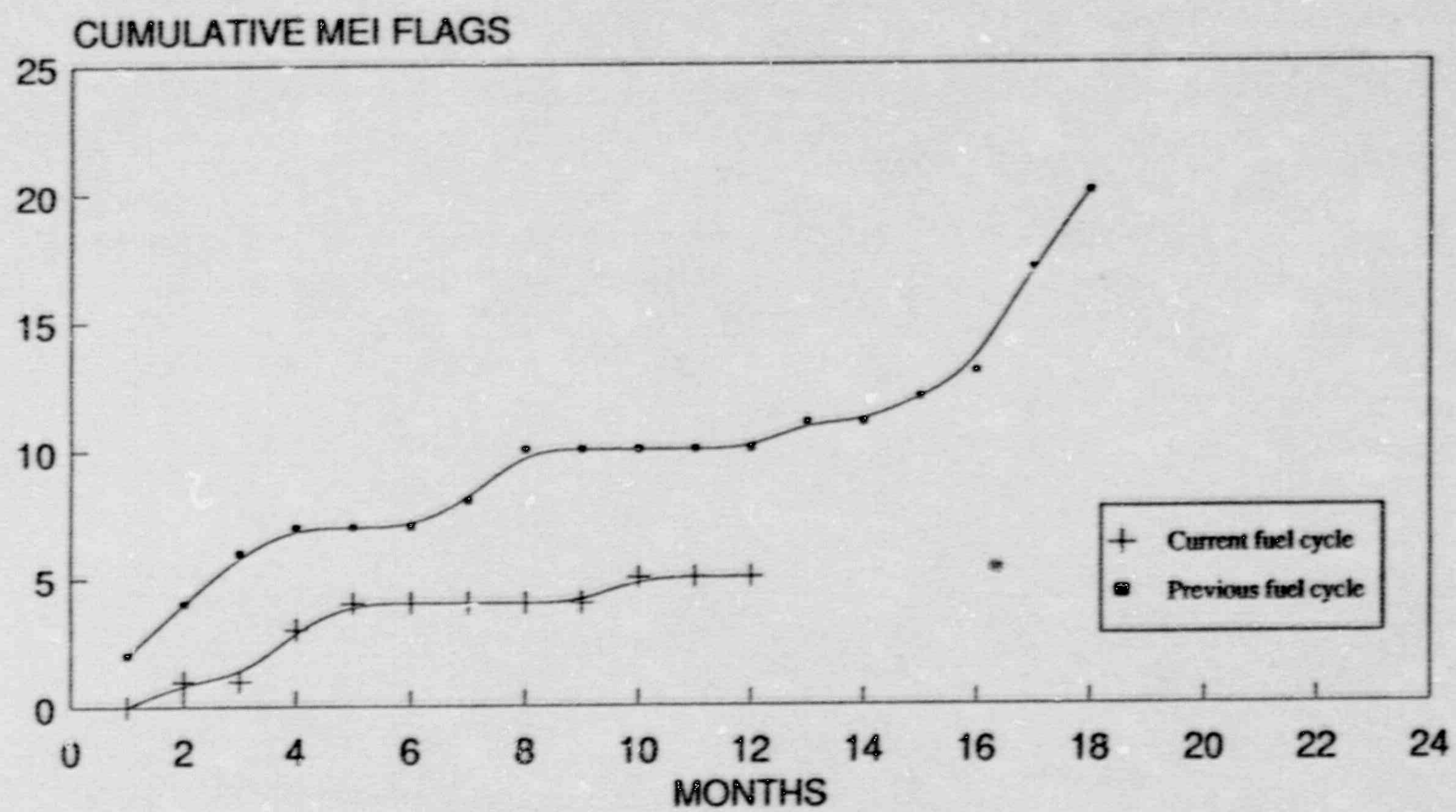


Figure 18. Comparison of an individual plant's cumulative indicator flag histories during two successive fuel cycles.

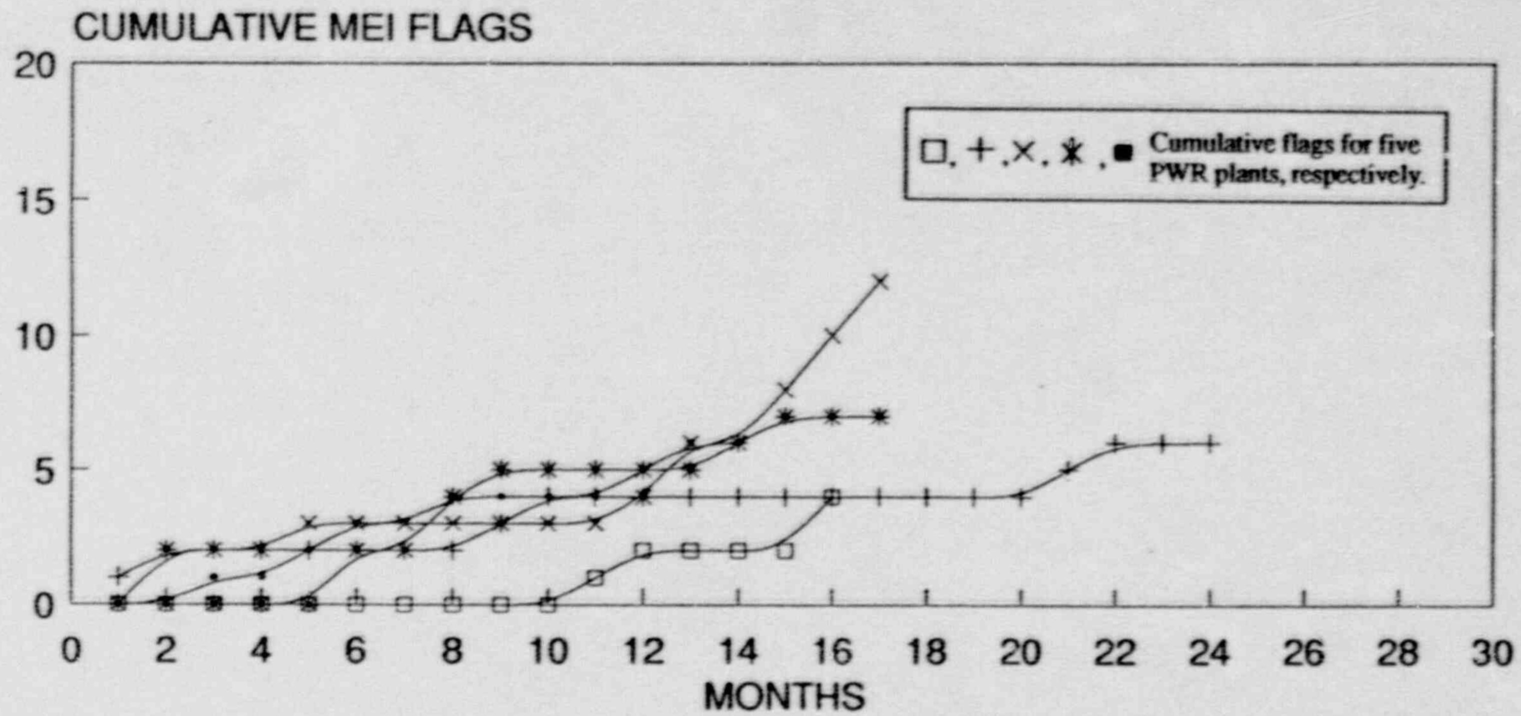


Figure 19. Comparison of cumulative indicator flag histories for five PWRs with comparable power ratings in their eighth fuel cycle.

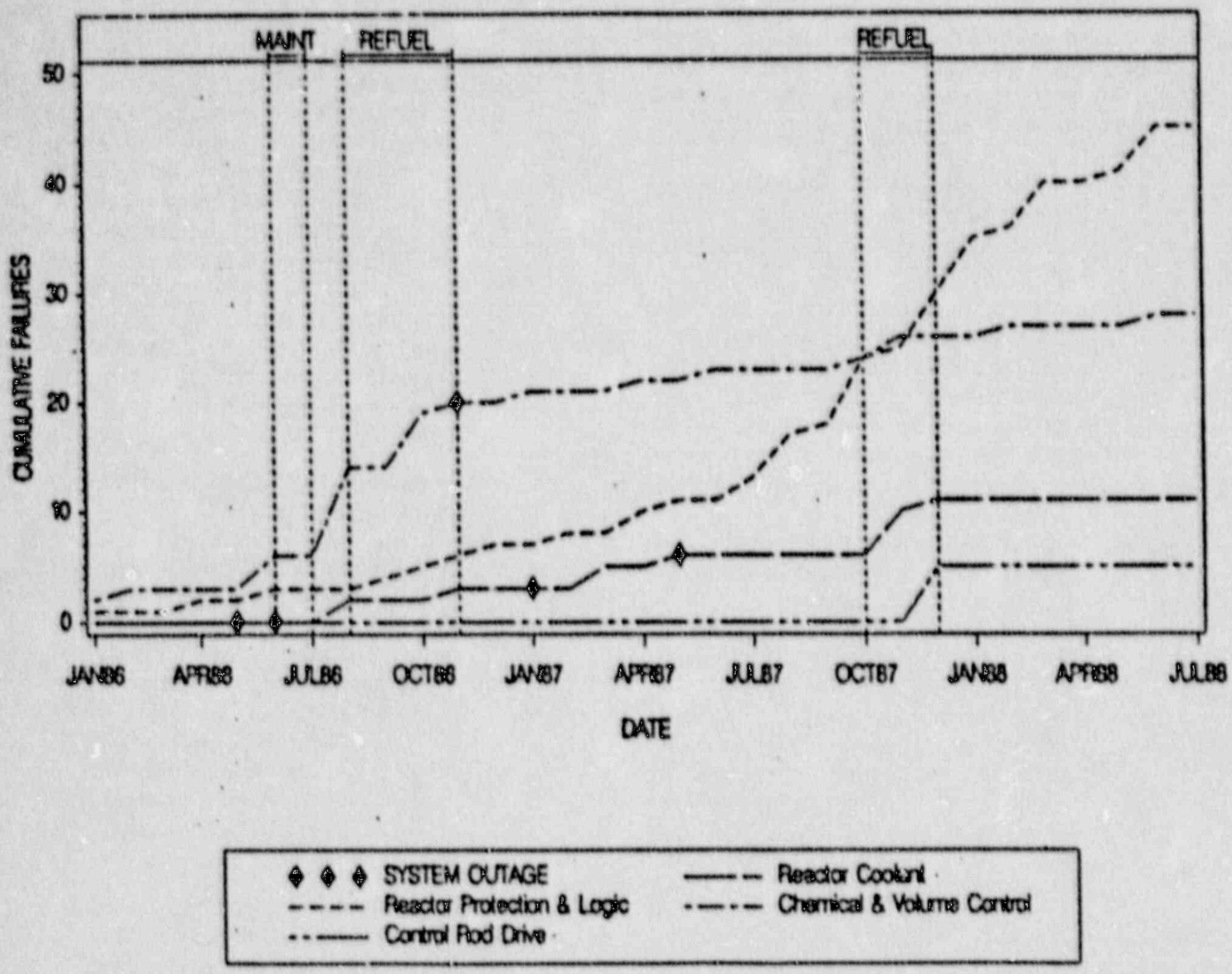


Figure 20. Example of overlay of plant outage history on system and component failure histories.

6. CONCLUSIONS

This section summarizes the results of the development, validation, and use of the indicator to monitor maintenance effectiveness in both PWR and BWR plants. Each conclusion is described below, together with the pertinent findings and references to the appropriate section of the report. The appendices contain material to support these findings and conclusions.

1. *The maintenance effectiveness indicator was validated for monitoring the maintenance effectiveness for both PWR and BWR plants.*

   - The present task verified that the assumptions underlying the earlier indicator development were still valid for the BWRs. Much of the methodology used to develop, validate, and perform the calculations for a maintenance effectiveness indicator for this study was borrowed from the previous efforts in the AEOD/S804A and S804B reports and shown to be valid for the PWR plants. (See Sections 2, 3, and 4.)

   - The results of the root cause analyses and LER correlation analyses satisfied the NRC Staff Requirements Memorandum criteria[2] for validation of performance indicators, i.e., the indicator measured maintenance effectiveness, was useful in revealing maintenance–related trends of equipment performance, and was consistently applied across plants. (See Sections 4.2 and 4.3.)

   - A significant correlation was demonstrated between the maintenance effectiveness indicator and maintenance ineffectiveness. The results of reviewing 3881 narrative descriptions from NPRDS failure records found that about 80% of the component failures that produced indicator flags for the equipment monitored by the indicator, involved ineffectively performed maintenance. (See Section 4.2.)

   - The component failure data used by the indicator were verified to be consistently obtained across plants. The number of failures reported to the NPRDS and tracked by the indicator were compared with the number of maintenance–related events reported through the mandatory LER system. A direct correlation was noted. (See Section 4.3.)

   - The indicator formula was verified as a methodology that highlights degrading maintenance effectiveness. Analysis indicated that a correlation exists between statistical control charts based on NPRDS failure reports and the maintenance effectiveness indicator. When the control charts indicated that the number and rate of component failures was beyond a random level, the maintenance effectiveness indicator also illustrated that in 87% of the cases there was a noticeable increase in the cumulative number of indicator flags. (See Section 3.5.)

2. *The maintenance effectiveness indicator is ready for implementation.*

   - Selected components from systems traditionally causing outages have been identified for use in monitoring maintenance. The list of systems and components was expanded above what was presented in AEOD/S804A and S804B for the BWR plants to more fully track the BOP systems. A comparable list of systems and components was developed for monitoring all PWR plants. (See Section 3.)

   - The maintenance effectiveness indicator display method was expanded to include PWR plants. The maintenance effectiveness of a plant and its vendor peers is depicted by cumulative trend lines on the indicator display. (See Section 2.)

   - The NPRDS methodology for obtaining the failure data for monitoring maintenance effectiveness was confirmed. The download method was confirmed as being effective for both BWR and PWR plants. (See Section 3.3.)

3. *Historically, on the average, commercial PWRs and BWRs showed an improving trend in maintenance effectiveness over the two-year study period.*

   - On the average, each PWR NSSS group (WE, CE, and BW) showed an overall improvement in maintenance effectiveness for the two-year study period. Some vendor groups showed more improvement than others. On a plant-specific basis, some plants showed a worsening trend, while others showed noticeable improvement. (See Section 5.1.)

- The average plant from the BWR reactor vendor group (General Electric) showed an overall improvement in maintenance effectiveness for the two-year study period. On a plant-specific basis, some plants exhibited a worsening trend, while others showed noticeable improvement. (See Section 5.1.)

4. *Plants with ineffective maintenance programs consistently produce a higher-than-average number of indicator flags, regardless of whether or not a plant is in an outage.*

   - Based on the evaluation of Gray Books for 34 plants, about 70% of all maintenance effectiveness indicator flags were noted for months inside of plant outages. A direct relationship was verified between plants that produce a higher-than-average number of indicator flags during outage periods and the plants with ineffective maintenance programs. (See Section 5.2.)

   - Based on the evaluation of the same NPRDS reports, about 68% of all component failures were noted for months outside of plant outages. During these non-outage periods, plants that experience a higher-than-average number of component failures, i.e., plants with ineffective maintenance programs will also produce a higher-than-average number of indicator flags. Therefore, plants with ineffective maintenance programs will be notable by indicator flags throughout the tracking period, i.e., during *both* outages and non-outages. (See Section 5.2.)

5. *The maintenance effectiveness indicator does not have a consistent ability to predict operational events or system forced outages.*

   - System failures were predicted by the maintenance effectiveness indicator about 12% of the time. (See Section 5.2.)

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11. ABSTRACT (200 words or less)

The U.S. Nuclear Regulatory Commission's (NRC's) Office for Analysis and Evaluation of Operational Data (NRC/AEOD) has been pursuing the development of measurement systems to ascertain the effectiveness of maintenance programs in commercial U.S. nuclear power plants. The previous reports AEOD/S804A, *Preliminary Results of the Trial Program for Maintenance Performance Indicators*, and S804B, *Application of the NPRDS for Maintenance Effectiveness Monitoring*, documented the development and validation of a maintenance effectiveness indicator for selected boiling water reactor (BWR) plants and components. The present effort extends the earlier AEOD findings and validates the maintenance effectiveness indicator for use with both BWR and pressurized water reactor (PWR) commercial nuclear power plants.

The development and validation of the maintenance effectiveness indicator are discussed in this report, along with the results of applying the indicator to component failure data for PWR and BWR plants over a two-year study period. The appendices are issued under a separate volume, because they contain proprietary information. For more information regarding the appendices contact Ms. B. M. Brady of NRC/AEOD at (301) 492-4499.

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