EPRI

Metrics for Assessing Maintenance Effectiveness

Technical Report

NMAC

TEAM

Metrics for Assessing Maintenance Effectiveness

1007604

Final Report, February 2003

EPRI Project Manager
W. E. Johnson

EPRI • 3412 Hillview Avenue, Palo Alto, California 94304 • PO Box 10412, Palo Alto, California 94303 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

THIS DOCUMENT WAS PREPARED BY THE ORGANIZATION(S) NAMED BELOW AS AN ACCOUNT OF WORK SPONSORED OR COSPONSORED BY THE ELECTRIC POWER RESEARCH INSTITUTE, INC. (EPRI). NEITHER EPRI, ANY MEMBER OF EPRI, ANY COSPONSOR, THE ORGANIZATION(S) BELOW, NOR ANY PERSON ACTING ON BEHALF OF ANY OF THEM:

(A) MAKES ANY WARRANTY OR REPRESENTATION WHATSOEVER, EXPRESS OR IMPLIED, (I) WITH RESPECT TO THE USE OF ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT, INCLUDING MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE, OR (II) THAT SUCH USE DOES NOT INFRINGE ON OR INTERFERE WITH PRIVATELY OWNED RIGHTS, INCLUDING ANY PARTY'S INTELLECTUAL PROPERTY, OR (III) THAT THIS DOCUMENT IS SUITABLE TO ANY PARTICULAR USER'S CIRCUMSTANCE; OR

(B) ASSUMES RESPONSIBILITY FOR ANY DAMAGES OR OTHER LIABILITY WHATSOEVER (INCLUDING ANY CONSEQUENTIAL DAMAGES, EVEN IF EPRI OR ANY EPRI REPRESENTATIVE HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES) RESULTING FROM YOUR SELECTION OR USE OF THIS DOCUMENT OR ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT.

ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

MOS

ORDERING INFORMATION

Requests for copies of this report should be directed to EPRI Orders and Conferences, 1355 Willow Way, Suite 278, Concord, CA 94520, (800) 313-3774, press 2 or internally x5379, (925) 609-9169, (925) 609-1310 (fax).

CITATIONS

This report was prepared by

MOS
25 Piermont Ct.
Melville, NY 11747

Principal Investigator and Author
S. Kasturi

Nuclear Maintenance Applications Center (NMAC)
1300 W. T. Harris Blvd.
Charlotte, NC 28262

Principal Investigator
W. E. Johnson

This report describes research sponsored by EPRI.

The report is a corporate document that should be cited in the literature in the following manner:

Metrics for Assessing Maintenance Effectiveness, EPRI, Palo Alto, CA: 2003. 1007604.

REPORT SUMMARY

Based on performance trends and efforts for continuous improvements, EPRI conducted a study to benchmark metrics (indicators) that can be used in assessing maintenance. The indicators and values/ranges developed from this work provide guidance for plants to assess their internal activities and to compare them industry-wide or with peers.

Background

In 1996 EPRI developed a tech note *Assessing Maintenance Effectiveness*, TR-107759, in order to collect and describe the most commonly used maintenance indicators, what they are supposed to measure, their relevancy, and the expected range/values.

Based on industry trends, increases in self-assessments, and industry forums, the industry would benefit from a set of metrics that could be used to evaluate and compare maintenance performance internally as well as externally.

Objectives

- To collect and evaluate plant data to populate a maintenance metric set
- To determine if metrics can be applied to plants of various ages and geographical locations
- To understand the difficulty, if any, with collecting data from the central maintenance database such as computerized maintenance management systems (CMMS)
- To provide nuclear power plants with metrics that can be compared internally, among peers, and across the industry

Approach

The project team reviewed relevant information from sources (such as research reports, survey results, and industry meetings) to understand the latest trends and practices for gathering and presenting maintenance data.

Site visits were conducted to gather maintenance data and to review maintenance practices and other programs that affect maintenance in order to populate metrics. These visits helped determine what metrics were currently being used by plant personnel in their evaluation processes. In addition, the teams looked for other metrics that might be beneficial to the benchmarking effort. The evaluation process included comparing existing plant metrics to those presented in TR-107759, modifying the metrics set, and developing benchmark values for the metrics.

The project team sought to understand any plant/company issues or work practices in a maintenance program that would affect the data used to populate the metrics.

Results

This report presents a set of metrics that are appropriate indicators for assessing maintenance activities within a power plant. By using the knowledge of plant personnel and existing maintenance data, EPRI has developed a workable set of metrics to provide a basis for follow-on comparison in the area of maintenance. This benchmarking effort provides reference values/ranges that can be used to evaluate maintenance activities.

EPRI Perspective

This effort has benchmarked the metrics that were originally presented by EPRI in 1996. With the implementation of the maintenance rule, probabilistic risk assessment (PRA), and other programs, plants have tended to use more self assessments and peer assessments in an effort to continuously improve practices.

This benchmarking effort has shown that the data required to populate the metrics:

- Are easily retrievable
- Require minimal computer time to run queries
- Can be readily evaluated with standard spreadsheet tools

Plants should be capable of collecting the data from their current MMS to:

- Populate the metrics
- Establish limits and goals for their site
- Conduct more focused self assessments
- Compare their plant to other plants in the industry using these metrics

These metrics are strictly associated with maintenance activities.

Keywords

Metrics
Indicators
Maintenance
Comparison
Assessments

ABSTRACT

Assessing and improving maintenance effectiveness requires a consistent set of metrics that would provide a basis for comparison with industry peers and identify opportunities for improvement. Such a set of metrics should consist of:

- One-time measurements to assess program condition and to achieve an initial comparison with peers and industry
- Ongoing measurements for monitoring, trending, periodic assessment, and identifying opportunities for program improvements

This document proposes a set of metrics for above-mentioned purposes and provides a benchmark for each metric. These metrics were developed to be capable of:

- Being generated from existing data in typical nuclear plant *maintenance management systems*[1] and other existing data systems through queries or reports
- Being complementary to metrics currently used for other purposes/organizations, such as the WANO indicators and/or system health reports that were developed to meet the requirements of the maintenance rule
- Supporting a comprehensive assessment of maintenance effectiveness using objective measurements
- Helping to focus the scope of periodic team-based self-assessments and peer-group assessments currently in use

Use of the information conveyed by these metrics must be tempered with sound judgment. One should also keep in mind that when comparing with peer plants, valid and justifiable deviations could exist. A remedial and/or corrective action plan is warranted only when trends/conditions point to significant opportunities for improvement and/or a potential for adverse consequences.

Benchmarking of the metrics set was performed by collecting data from a representative sample of nuclear plants in the United States. This benchmarking effort established that the input data required to generate the metrics were readily available in existing data systems and could be retrieved through queries. This report summarizes the results from this effort and provides a correlation of the maintenance assessment areas with the metrics set. Finally, a set of recommendations for implementing the metrics system at plants is discussed.

---

[1] First occurrence of words and terms that are defined (see Section 2) in the context of their use in this document are *italicized*.

ACKNOWLEDGMENTS

The author and the EPRI project managers gratefully acknowledge the contributions of many individuals from the six plants that participated in the survey and provided the data to support the development of the benchmarks for the maintenance assessment metrics.

EXECUTIVE SUMMARY

Assessing the effectiveness of a maintenance program as a whole is currently being done periodically (for example, once in two years) through self-assessments and peer-group assessments. Though comprehensive and performed by experienced professionals, the assessments are mostly qualitative evaluations based on subjective judgments. A few objective measurements (also known as indicators) in use include work backlog, rework count, and plant level indicators such as the number of unplanned trips and safety system actuations. With the exception of backlog and rework, most of the other objective measurements being used are not maintenance focused. System health reports instituted to support the maintenance rule have contributed improvements in the use of objective measurements. These are limited in scope and depth because they include only structures, systems, and components (SSCs) under maintenance rule scope and for the most part use plant level indicators.

The purpose of this guide is to present a set of metrics that objectively measures the three Ps of maintenance (that is, *performance, process*, and *productivity*). These metrics could be used to supplement other broad-based indicators currently in use for assessing the effectiveness of maintenance programs and in periodic self-assessments.

It was demonstrated during the benchmarking effort that the metrics set presented in this document could be generated consistently across the industry from data that are currently available and readily retrievable from most maintenance management systems and other plant event/activity/records tracking systems. This set of indicators includes metrics that provide objective indications of strengths/weaknesses and identify opportunities for improvement by measuring items such as:

- Unplanned trips, safety system challenges, and power-loss events attributable to maintenance
- Maintenance coverage and breakdown
- Maintenance work load and its breakdown
- Manpower resource application and its breakdown
- Overdue backlog and rework
- Craft and staff productivity
- Procedure stability and quality

In addition, these indicators include one-time measurements (such as the number of components included in preventive maintenance (PM) and corrective maintenance (CM) programs and breakdown of maintenance by types) that would be useful in initial evaluation/calibration. For each metric, this guide:

- Identifies the data source(s)
- Discusses what it indicates
- Explains how it is calculated
- Provides a benchmark value and, if appropriate, a goal

The metrics are grouped under the three Ps—performance, process, and productivity. If used on an ongoing basis, these metrics have the potential to:

- Support a comprehensive assessment of maintenance program effectiveness
- Support comparison of plant maintenance programs against a reference group or industry
- Supplement portions of the periodic self-assessments and peer-group assessments currently being used

Finally, insights gained about maintenance program/function during the plant visits to develop benchmarks are summarized in Section 7. Examples of such insights include:

- The data required to compute the metrics set discussed in this document were readily retrievable from plant MMS and a few other data systems. Queries were written by the maintenance support staff (on the average, it required a few hours). These data were downloaded into a Microsoft Excel spreadsheet for further processing by the investigators. At each of the surveyed plants, the staff support provided to the investigators was about two fulltime equivalents for one week.
- Overall, maintenance cost was 25% of non-fuel O&M cost based on the data collected
- Only one of the six plants in the survey had a comprehensive system to capture actual person-hours spent on each work order. Each discipline such as craft and maintenance support staff (for example, planners, technicians, work control, and maintenance support engineers/technicians) charges time against work orders. Other plants in the survey did not provide data, nor did it appear that they collected this information. Actual hours can be valuable when improvements in cost effectiveness of maintenance are being sought. For example, monitoring the cost of emergency maintenance can identify opportunities for cost savings. This information can be used to reduce the need for emergency maintenance.
- Plants in the survey appear to have a rather limited view of what constitutes PdM. At most plants, PdM means thermography, oil analysis, and vibration analysis. In reality, more than a dozen other programs, such as electric motor monitoring, MOV diagnostics, and diesel engine (DG) performance analysis, fit into this category. PdM responsibilities and budgets are dispersed under many groups. If a comprehensive view is taken of all the PdM programs in place, it would reveal that substantial resources are expended for PdM within a plant. There may be some opportunities for consolidation. Such a consolidation would improve the level of expertise and enhance management function.
- Rework and backlog, the two widely used indicators in the industry, lack consistent definitions and usage. In addition, determination of what fits these categories depends heavily on human intervention; the data obtained from the plants varied so much that it raised questions about the ability to make meaningful comparisons across the industry. Therefore, this benchmarking effort has posed some definitions that should assist plants in categorizing data and making comparisons across the industry.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1

INTRODUCTION

> *"Any process can be improved, and continuous improvement is necessary to remain competitive." Proverb*

Since the 1990s, nuclear power plants have embarked on various efforts to reduce their power production costs while maintaining an acceptable level of safety, reliability, and capacity factor. Success of these efforts is reflected in the steady improvements in production cost and capacity factor as shown in Figure 1-1.

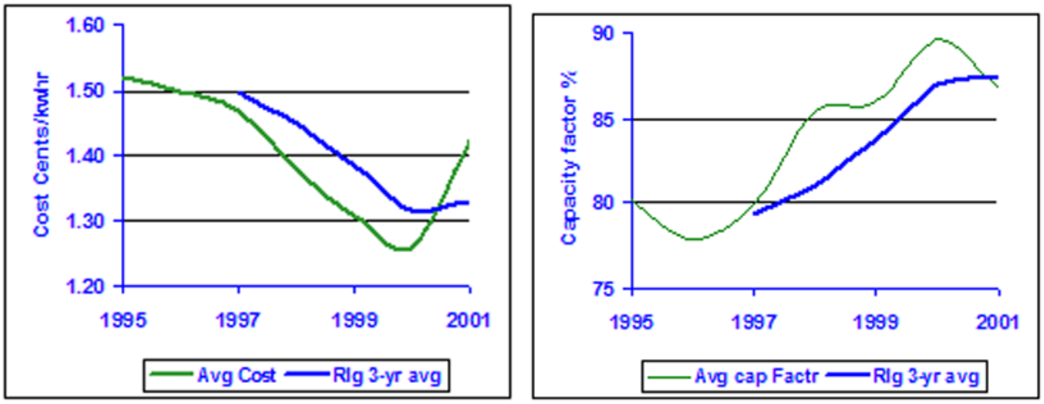

Figure 1-1
Historical Trend in O&M Cost and Capacity Factor (Data Source: NEI)

The cost of maintaining structures, systems, and components (SSCs) is a key contributor to the cost of operating a nuclear plant. Maintenance assures a level of SSC *availability*, *reliability*, and *longevity* that permits safe and continuous plant operation at its highest practical capability level. Maintenance costs amount to roughly 25%[1] of overall non-fuel production costs. Aging of the SSCs could have adverse effects on plant operations unless it is balanced with appropriate countermeasures including effective maintenance. Maintenance programs should focus timely action where needed and minimize unscheduled emergency maintenance. The fact that a maintenance program is effective in ensuring maximum reliability and availability of SSCs does not automatically imply that it is also cost effective. For instance, a Work Control Manager at one plant observed:

---

[1] This estimate was derived by computing the maintenance cost as a percentage of the non-fuel O&M cost for the population surveyed for this report.

> “We are doing a lot of maintenance on systems under the maintenance rule scope. We do whatever preventive maintenance activities are demanded of us by our engineers. Our rolling backlog keeps on increasing forcing an increase in overtime costs. Do we know if we are getting our money’s worth? Would we be better off accepting more of a “fix it when it fails” approach? How are other plants approaching this?”

One must perform an *assessment* to determine if an existing maintenance program is effective. Currently, maintenance program assessments are being done mostly through self-assessments and peer assessments at a frequency not exceeding 24 months. Though comprehensive and performed by experienced professionals, assessments are mostly qualitative evaluations based on subjective judgments. There are a few objective measurements used such as rework counts, backlog counts, plant level indicators (for example, the number of unplanned plant trips), and safety system actuations. Presently, with the exception of backlog and rework, most other objective measurements are generally not maintenance focused. System health reports instituted to comply with the maintenance rule have improved this assessment process, but their scope and depth are limited. Attention has yet to be fully focused on costs and efficiencies in the various process elements of maintenance programs. Thus, there is a need for a set of metrics that will measure performance[2] and productivity of the various elements of maintenance programs in a consistent manner and across a spectrum of nuclear power plants. Such a metrics set should:

- Be complementary to other indicators currently in use
- Aid in assessing a plant’s maintenance program on an ongoing basis
- Provide a basis for comparison across the industry
- Focus exclusively on maintenance activities, resources applied, and the results thereof
- Be capable of being generated consistently across the industry using available data

Section 2 of this document provides definitions of related terminologies. Section 3 discusses what constitutes effective maintenance and aspects of assessing maintenance. Section 4 provides a discussion of the proposed set of metrics, input data elements, calculation algorithms, what they indicate, and how they are generated. A reference benchmark value/range is included for each metric. Section 5 discusses the correlation of maintenance assessment areas to the metrics set presented in this document. Section 6 presents recommendations for implementing a metrics-based monitoring program at plants. Section 7 discusses the insights on plant maintenance program/process gained by the investigators during the benchmarking effort. The appendices provide additional details on specific areas discussed in the report.

The intended audience for the metrics set is plant/corporate maintenance management and their direct reports. The proposed metrics set is designed such that:

- It looks at the maintenance program and process as a whole without any scope or coverage limitations.
- It is complementary and not redundant to those measurements already in use for other purposes such as the maintenance rule, WANO and INPO indicators [4].

---

[2] Plant performance metrics, such as “unit unplanned capability loss factor” and “thermal performance,” have long been used in the nuclear power industry to provide comparative performance metrics at the plant level. They are of limited focus for this document.

- It is based exclusively on data that are currently available in typical plant *maintenance management systems* and other data management systems used in the nuclear industry.
- It can be generated consistently to convey the same information by all participants in the nuclear industry.

To provide a basis for comparison, reference values or benchmarks have been developed for the proposed metrics set. Such reference values were developed by collecting, evaluating, and reducing data across a representative sample of nuclear plants. Optimal[3] values (goals), where provided, were chosen based on what constitutes an effective maintenance program as defined and discussed in Section 3. Where optimal values are given as zero, they should be interpreted as “zero or as close to zero as practical.” Appendix A provides a discussion of the methodology used for developing the benchmark values.

---

[3] Optimal values are what industry goals should be, and they are not the same as reference values, which is an industry average based on evaluating data from a representative sample of nuclear plants.

2

TERMINOLOGY

A discussion of metrics invariably involves the use of terms that are subject to varying interpretations or meanings depending upon the user's vantage point. Therefore, it is imperative that these terminologies with non-standard meanings be listed, defined, and (if necessary) explained in order to ensure that they are consistently understood and used. This section identifies and defines the key terms used in this guide; where appropriate, additional descriptions and illustrative examples are included.

Assessment: A general term that refers to an examination of the processes and contexts that influence learning. Such an examination usually combines objective measurements, comparison with references or benchmarks, and subjective judgments.

Availability: The percentage of time that a system is operating (or is capable of operating for standby systems) satisfactorily at any point in time when used under specified conditions, where the total time considered includes the operating time and down time (unavailability).

Note: Availability is time-related.

Backlog: An accumulation of unperformed tasks.

At some plants, the backlog contains all work that has been scheduled. This practice is more akin to workload. There are other plants that consider backlog to be only overdue work, while some combine overdue work and scheduled work as backlog. It does not distinguish between new work scheduled for that period and missed work items carried over from previous periods. **See more discussion in Section 4.5.8**.

For the sake of consistency, it is suggested that the industry adopt a more standard definition for backlog. Backlog would be a more useful metric if it is thought of as those tasks that are overdue, beyond their grace period, and not rescheduled.

Down Time: The period for which a system/component is not operating or is not capable of operation in a satisfactory manner.

Emergency Work: Work that must be done immediately upon identification to:

- Ensure continued and safe continued operation of the plant
- Preclude unplanned trips or production loss
- Ensure personnel safety
- Ensure regulatory compliance

- Prevent potential for release of radioactivity
- Preclude unplanned challenges to the safety system

Maintenance Management System (MMS): A computerized data management system (CMMS) used to support, monitor, and control plant maintenance work/activities.

Maintenance Type: Essentially, maintenance can be classified into two broad types:

1. Maintenance performed to prevent failure
2. Maintenance performed to restore equipment to service after a failure occurs

Item one is usually a planned activity, and the common names used for this type of maintenance include preventive maintenance, planned maintenance, and periodic maintenance. Item two is commonly known as corrective maintenance. Corrective maintenance can be performed on a planned or emergency basis, depending upon the functional importance of the item to ensure safe plant operation. To promote consistent interpretation and use of these terms, this document classifies maintenance type(s) as follows (see Figure 2-1):

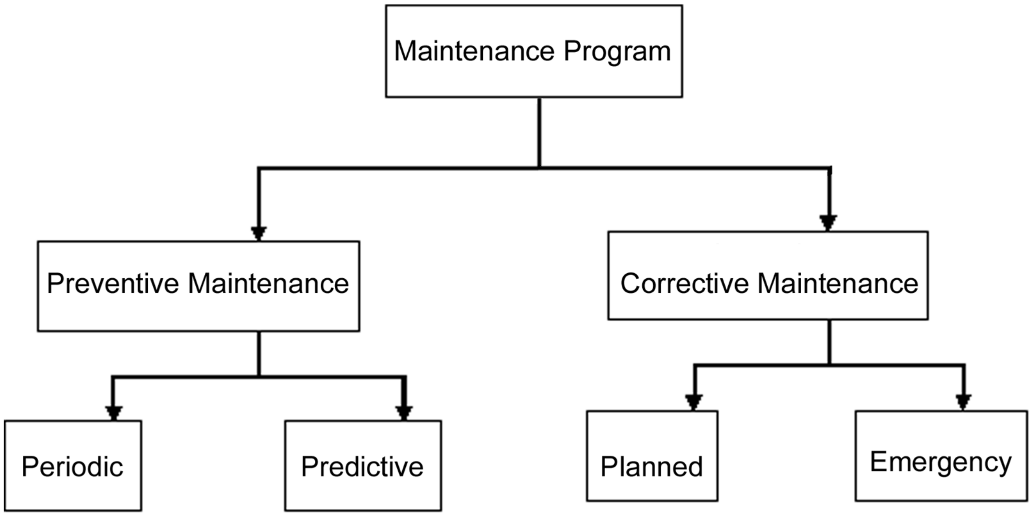

Figure 2-1
Breakdown of Maintenance Types

Preventive Maintenance (PM): Maintenance performed on a planned basis to minimize unexpected failures. It may be subdivided into:

- ***Periodic Maintenance:*** Routine maintenance activities (for example, inspections, tests, lubrication, alignments, balancing, repairs, and parts replacements) performed at preset intervals without regard to equipment condition. The periodic maintenance tasks and their frequencies are established based on vendor recommendations and the plant's operating experience.
- ***Predictive Maintenance (PdM):*** Maintenance activities intended to monitor the condition of the equipment and identify the need for maintenance. Also, they are performed on planned basis. It includes measurements and tests performed to collect data to assess equipment condition and initiate and/or perform maintenance activities. Information obtained from these activities may also be used to adjust the intervals for periodic maintenance and intervals at

which predictive data is obtained. Another term that might be encountered in this context is *condition monitorin*g, which really is the act of applying predictive maintenance. Examples of PdM are vibration analysis to determine the need for balancing rotors, oil analysis to determine the need for replacing lubricants, and gas content analysis to determine activities within a transformer.

Note: *If PdM generates an emergency-maintenance work order, then it is an indication that it is not working as it should.*

Corrective Maintenance (CM): Maintenance performed upon detection of a fault or failure. This type of maintenance can also be subdivided into:

- ***Planned Corrective Maintenance****:* Corrective maintenance that is prioritized and performed according to a schedule or other planning basis. (Also referred to as Expected.)
- ***Emergency Corrective Maintenance:*** Maintenance performed in cases where immediate repair is required to ensure safe and continuous operation of SSCs. (Also referred to as Unexpected.)

Note: *Plants have what is known as a Fix it Now (FIN) or Work it Now (WIN) team. These teams are generally assigned to perform unexpected maintenance.*

Mean Time Between Failures (MTBF): The arithmetic average of operating times between failures of an item.

Operating Time: The time during which the system/equipment is operating in an acceptable manner.

Peer-Group Assessments: Assessments performed by a team consisting of experienced professionals assembled from in-house, from other plants, and/or industry organizations.

Reference Group: Plants that are comparable in vintage, type, balance-of-plant (BOP) design, and other geographical factors that could influence the cost of maintenance. For purposes of comparing maintenance metrics, the reference group should include a minimum of three similar plants.

Reliability: The probability that a system/component will perform satisfactorily when required for a specified duration under specified conditions. For example, a statement that the high pressure core injection (HPCI) system has a reliability of 98% means that:

> The probability that the HPCI system will start, inject water into the core within the required time, and continue to do so until it is no longer required during and following a designed basis event is 98%. In other words, there is a finite (2% in this case) probability that the system might not perform as intended. Plant safety objectives dictate that system reliability is maintained as high as practical. Reliability predictions assist in selecting the courses of action that affect reliability. For example, after a few years in operation, if the HPCI system reliability were estimated to be 86%, then the plant management would want to identify and evaluate the options (for example, enhanced condition monitoring or design modification for the offending component) available to improve that reliability.

Note: Reliability is demand related.

Rework: Work re-performed within a specified time from its first performance because work performed the first time was inadequate, incorrect, or performed using deficient parts and/or materials. Recommended duration for the specified time is six months or ½ of the PM interval of the equipment whichever is shorter. The rework designation clock starts upon return to service after completion of the specified work.

System Health Report: A status report on a system(s) including all its components/structures regarding its ability to perform reliably and its overall availability. These reports are generated by system engineers using inputs from maintenance, operations, and engineering data.

Self-Assessments: Assessments performed by an individual or team consisting of experienced professionals. This type of assessment is typically directed from within a particular organization.

Unavailability: See down time.

Unplanned Automatic Scrams per 7,000 Hours Critical* [1]*: An indicator that tracks the average scram rate per 7,000 hours of reactor criticality (approximately one year of operation) for units operating with more than 1,000 critical hours during the year. Unplanned automatic scrams result in thermal/hydraulic transients in plant systems.

Unplanned Capability Loss Factor* [1]*: The percentage of maximum energy generation that a plant is not capable of supplying to the electrical grid because of unplanned energy losses (such as unplanned shutdowns, forced outages, outage extensions, or load reductions). Energy losses are considered unplanned it they are not scheduled at least four weeks in advance.

Unplanned Safety System Actuations: The actuation of safety system(s) such as emergency core cooling or containment spray without a valid demand. A valid demand is one that is originated automatically or manually by the operator: a) based on plant and/or system conditions that require a safety system actuation or b) for test purposes.

Workload: The amount of work to be completed in a specified period of time (usually 12 or 13 weeks for nuclear power plants). Workload is often used synonymously with backlog, which includes scheduled work and old work from previous planning horizons (overdue-backlog) that was not completed as scheduled and was not rescheduled.

It is suggested that the industry consider the following definition of workload: all work that has been scheduled, is within its grace period, and is waiting to be completed.

3

EFFECTIVE MAINTENANCE AND ASSESSING MAINTENANCE

This section defines and describes what constitutes an *effective maintenance* program, and how to *assess* maintenance effectiveness.

3.1 What Constitutes an Effective Maintenance Program?

A program is said to be effective if it achieves the intended results. Effectiveness refers to doing the right work (that is, doing what needs to be done); whereas, efficiency is doing what is right within the shortest practical time. Effectiveness does not necessarily imply efficiency. In a power plant, the mission of the maintenance function is to deliver services to assure that SSCs have maximum practical reliability, availability, and life. This will assure that production losses attributable to maintenance are minimized, if not eliminated. If this objective is achieved at the lowest practical cost (both direct and indirect), then this indicates effective utilization of resources. Based on this premise, an effective maintenance program may be defined as one that consistently delivers its services *at the lowest practical cost*[1] when compared to its peers and has:

- Zero maintenance-related unplanned safety system challenges, production losses, and plant trips
- Zero regulatory violations
- Zero lost time injuries
- Lowest worker radiation exposure
- Zero breakdowns requiring emergency repairs

The proposition above implicitly captures other significant attributes of an effective maintenance program such as:

- Maximum reliability and availability of SSCs
- Right mix of skills and technology
- High degree of ownership
- Good work culture
- Effective management
- Efficient underlying maintenance processes

---

[1] In this definition used throughout this document, for simplicity, only direct costs labor and materials are included.

3.2 Assessing Maintenance

Assessing maintenance is an examination of the overall maintenance program, its processes, and elements for the purpose of:

- Understanding their relationships and efficiencies
- Categorizing the knowledge/skills and technologies employed
- Identifying opportunities for improvements in technical and economic performance

Several EPRI [5–9,12], NEI [1], INPO [11], WANO [4], and NRC [3] documents discuss various aspects of assessing maintenance effectiveness and propose guidelines. These references propose various performance indicators as shown in Table 3-1 for assessing the effectiveness of maintenance. INPO and WANO documents are focused on overall plant performance. Generally, the NEI, NRC, and EPRI documents[2] focus on reliability and availability aspects of safety systems and certain non-safety power block systems. Some of these indicators were developed to address maintenance rule requirements.

Table 3-1
Performance Indicators Currently Used

Metric	WANO	IAEA	NRC NEI	INPO
Unplanned scrams per 7000 hrs	Yes	Yes	Yes	Yes
Unplanned safety system actuations	Yes	Yes	Yes	Yes
Unplanned power changes	Yes	Yes	Yes[2]	Yes
Unit capacity factor	Yes			
Physical protection	Yes			Yes
Industrial safety				Yes
Lost person-hours due to injury		Yes	Yes	Yes
Annual worker exposure		Yes	Yes	Yes
System health report			Yes	

Except for the system health reports, the remaining indicators are focused on overall plant level performance. System health reports are focused on system performance, but from a single-minded pursuit of implementing and enhancing preventive maintenance programs. Their chief purpose is to deliver maximum reliability and availability for the SSCs in the maintenance rule scope. Cost is a secondary consideration. Finally, the maintenance rule applies to less than 25% of the equipment in a plant.

Determining whether a maintenance program is effective requires an *assessment.* Currently, maintenance program assessments are done through self-assessments and peer assessments at a frequency not exceeding 24 months. Though comprehensive and performed by experienced

---

[2] Reference 5, which is the precursor to this document, is an exception in that it is strictly maintenance focused without any scope limitation.

professionals, they are generally qualitative evaluations based on subjective judgments. A few objective measurements are used such as work backlog, rework[3] counts, and plant level indicators (such as number of unplanned plant trips and unplanned safety system actuations). A comprehensive maintenance effectiveness assessment should address the four major areas without any limitations on scope or coverage:

1. Maintenance programs and process
2. Technologies employed
3. People skills/knowledge
4. Management and work culture

Another equally important area is the cost of maintenance. Of the four areas listed, only maintenance programs and process is amenable to an assessment using a set of objective measurements. Yet, if a set of properly designed metrics is used for assessing maintenance programs and their underlying processes, it can measure the effectiveness of maintenance programs as a whole including areas 2, 3, and 4. The logic behind this position is:

> The mission of maintenance is to deliver services to assure that SSCs have maximum practical reliability, availability, and life. If this mission is fulfilled at the lowest practical cost, then that implies effective utilization of resources, and thus an effective maintenance program. Implicit in this reasoning is that an optimal mix of technologies, processes, and people skills with a properly aligned management and work culture are prerequisites to effectively fulfilling the role of maintenance. A properly designed metrics set would highlight any misalignment of the prerequisites. For example, a low percentage of PM coverage would most likely be accompanied by a high percentage of CM, indicating inadequate maintenance mix and technologies employed. Another example is if the maintenance function fulfils its mission, but at a cost substantially higher than industry/peer group average cost, then it is not cost effective.

The maintenance process consists of work identification, control, execution, close out, as-found reporting, and actions for continuous improvement. Performing a comprehensive and objective ongoing assessment would require measurements that relate performance, productivity, quality of service, and efficiency to cost. Monitoring using the right set of metrics will help focus periodic self/peer assessments. Section 4 contains a discussion of a comprehensive set of metrics that could be used to monitor the various aspects of maintenance and identify opportunities for improvements.

---

[3] Plant visits and data collection performed for this study reveals that the definitions used for backlog and rework vary. Refer to Section 2 for proposed definitions.

4

PROPOSED METRICS AND BENCHMARKS

This section discusses the proposed metrics set, the data input required, algorithms for computing them, and the information that they convey. In addition, a benchmark value is provided for each metric.

4.1 Maintenance Process—Input and Outputs

Designing a set of metrics to assess a maintenance program should begin with an examination of the process and its input and output. As shown in Figure 4-1, elements of a maintenance process consist of the identification of maintenance work (maintenance mix and scope), work order generation, execution of the work (procedures, wrench time, support level), and closeout.

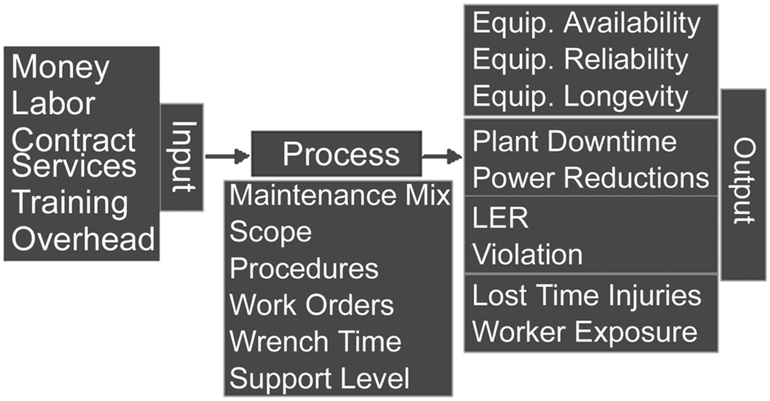

Figure 4-1
Maintenance Process: Its Input and Output

Maintenance mix is based on a review of the SSCs, their function, the vendor's maintenance recommendations, and the utility's own operating experience. The result of this effort is the identification of SSCs to be included under PM, CM, and PdM tasks to be performed and their frequencies. A maintenance process uses written work orders to document and control work, procedures to guide work performance, and support staff to manage the work control process (that is, planning and scheduling the work). Work is performed by trained personnel using written procedures. Maintenance staff may be supplemented by contract service(s) on occasion. The principal output from this process is equipment availability, reliability, and longevity. Other outputs from this process might include items such as plant down time, power reductions, and Licensee Event Reports (LERs). Other outputs that reflect performance are regulatory violations, personnel injuries, and worker exposure to radiation. The latter outputs reflect on performance[1] and usually indicate ineffective processes and/or process management. Inputs consist of labor (craft, staff, and management), materials, parts, and investment in training.

4.2 Developing a Metrics Set

The role of maintenance is to support the overall plant objective of producing electric power safely, reliably, and economically. Plant maintenance programs are developed and implemented to achieve a set of maintenance policy objectives. A typical set of maintenance policy objectives for a nuclear power plant might be stated as follows:

SSCs availability and reliability objectives:

- Ensure that safety SSCs meet the required reliability and availability/unavailability goals
- Ensure that SSCs that affect continued operation of a plant (that is, power block) meet stated reliability and availability/unavailability goals
- Ensure that all other SSCs have the longest practical *Mean Time Between Failures* (MTBF)

Economic and asset management objectives:

- Ensure that the cost of maintenance is as low as practical and is comparable to industry peers
- Ensure that the life cycle of all SSCs are managed to obtain the longest practical service life

Personnel safety objectives:

- Ensure that worker radiation exposure attributable to maintenance function is as low as is reasonably achievable
- Ensure that lost time from personnel injury attributable to maintenance function is as low as practical

Regulatory objectives:

- Ensure that LERs and regulatory compliance violations attributable to maintenance functions are as low as is reasonably achievable

While it is true that assessment tools generally include objective measurements and subjective judgments, the focus of this document is objective measurements that can be used for:

- Monitoring and trending effectiveness of maintenance programs
- Performing comparative evaluations against a reference group of plants and/or the industry
- Setting goals for maintenance function

---

[1] Performance can also be measured using outputs such as SSC availability, reliability, and longevity. They are not used here because it would require an enormous amount of work to calculate these values for tens of thousands of items. Hence, the focus is on the negative outputs that are relatively easier to calculate and reflect performance assessment equally well.

Tools to assess the effectiveness of maintenance programs should therefore measure:

a. The extent to which the stated maintenance policy objectives are met

b. The vital parameters of the underlying processes that provide insights into the various elements of the process, resource consumption, and efficiencies; and identify opportunities for improvement

Item “a” could be achieved by using measurements of SSC reliability, availability/unavailability, and longevity. That would require hundreds of thousands of calculations, and some of the data required are either captured partially or not at all in the plant data systems. To some extent, these indicators are addressed through the system health reports—albeit indirectly at system levels. For a limited scope of SSCs, recurring failure evaluations, and equipment history review programs also help address equipment problems. Limiting ourselves to these three measurements would be ignoring some of the negative outputs that have direct and indirect costs associated with them. Hence, the performance metrics in this document focus on the byproduct results. Performance deficiencies in SSC reliability, availability, and longevity will be reflected in one or more of the performance metrics discussed in detail in this document. For example, if the reliability or availability of the high-pressure safety injection system or a component therein is below acceptable levels, it will be reflected in the number of maintenance-related LERs and/or in the unplanned safety-system challenges metrics.

4.2.1 Criteria for Metrics Design

The following criteria were used in the design of the proposed metrics for assessing and monitoring maintenance effectiveness:

1. Should consist of a minimum number of discrete metrics that can convey required and readily usable information
2. Should be complementary/supplementary to existing metrics or indicators used for other purposes
3. Could focus portions of self/peer assessments, to the extent practical
4. Should use available data from existing data systems and keep demands for new and additional data gathering to a minimum
5. Should be easily calculated from data available in the existing maintenance management systems and other related plant data systems
6. Calculation algorithms should be capable of being incorporated into existing data management and reporting systems
7. Should be based on definitions and terms that are consistently used and understood in the industry. Where that is not the case, definitions should be developed to ensure uniform use
8. Should require minimum amount of manual prescreening of data and/or intervention in the calculation or report generation process

The metrics presented in this document meet the criteria set forth above and are further discussed in Sections 4.3 through 4.5.

4.2.2 Developing Benchmarks

Benchmark values for the metrics set were developed by collecting and analyzing relevant data for a representative sample of nuclear plants in the United States. Data were gathered from six plants consisting of 13 units with capacities ranging from 600 MW to 1350 MW. Both single unit and multi-unit plants were included in the survey population. The methodology used for selecting the survey population and developing the benchmark values is described in Appendix A. At all but one of the surveyed plants, historical data required for all the metrics were collected for years 1999, 2000, and 2001. The benchmark values were calculated by first computing the three-year average of each metric for each plant and then computing an arithmetic average of each metric for all plants. Some of the input data were found to be sensitive to economies-of-scale considerations (for example, cost of maintenance in dollars/MWhr and person-hours expended in maintenance function). Adjustments can be done either at the input data level or at the benchmark level. It was decided that establishing adjustment factors for the benchmarks would ensure consistency in using the metrics.

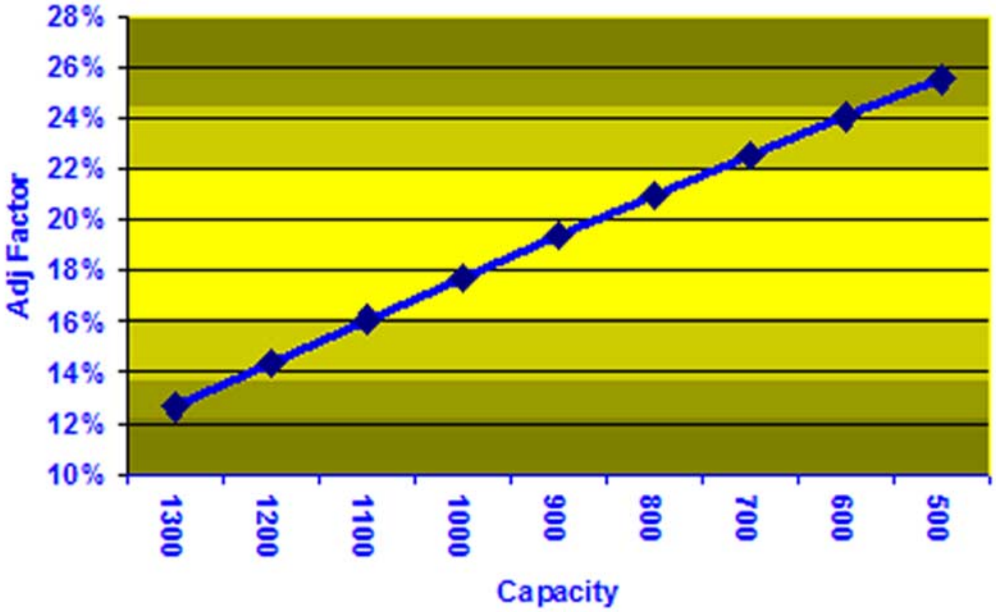

Figure 4-2
Adjustment Factor for Single Unit Plants

The benchmarks given in this document can be applied directly for multi-unit plants with unit capacities ranging from 800 MW to 1350 MW. Figure 4-2 shows the adjustment factor versus installed capacity that can be used for adjusting the benchmark values when required, for single unit plants. This graph was generated by analyzing the historical non-fuel production cost and the maintenance cost for variations between single unit versus multi-unit plants and installed capacity in increments of 100 MW.

4.2.3 The Metrics Set

The proposed metrics set for assessing maintenance effectiveness that meets the criteria discussed earlier is shown in Table 4-1. For those metrics that are currently in use and used for maintenance assessment, the table identifies the organizations (for example, WANO, INPO, EPRI, and NRC) that use/recommend them. In addition, the table also identifies the data source(s) for each metric and provides a reference to the section where it is discussed in detail. The metrics are grouped under three categories as follows:

- Performance
- Process
- Productivity

In lieu of current year value, three-year rolling average is recommended for all metrics in order to include outage and non-outage years. For example, maintenance cost in a given year may be unusually high because of:

- Increased number of PMs in that year due to heavy concentration of PMs scheduled on biannual or tri-annual basis or other infrequent activities coming due that year
- Extra cost incurred for special in-service inspections conducted in that year

Sections 4.3 through 4.5 contain a detailed discussion of each metric in each group including how they are calculated, what they indicate, data source, what the benchmark values are and, where appropriate, what the goals should be.

Table 4-1
List of Metrics and Who Uses/Recommends Them

Metric	WANO	IAEA	NRC	INPO	EPRI (1)	Sec. Ref. (2)	Data Source
Performance Metrics							
Total maintenance cost in dollars/MWhr					Yes	4.3.1	Maintenance cost & power generation
Maintenance man-hours input Hrs/million kWhr					Yes	4.3.2	Maintenance cost & power generation
Unplanned scrams per 7000 hrs	Yes		Yes		Yes	4.3.3	Plant trip data, limit to maintenance
Unplanned power changes	Yes		Yes (3)		Yes	4.3.4	Plant power production records, limit to maintenance
Unplanned safety system actuations			Yes		Yes	4.3.5	LER records, limit to maintenance
Maintenance-related LERs and violations					Yes	4.3.6	LER records, limit to maintenance
Lost person-hours due to injury	Yes	Yes	Yes	Yes	Yes	4.3.7	Plant safety records, limit to maintenance
Annual worker exposure	Yes	Yes	Yes	Yes	Yes	4.3.8	Plant safety records, limit to maintenance
System health report			Yes		Yes		CM calls and recurring failures
Process Metrics							
Component/system availability			Yes				System health reports
Work Order statistics and maintenance mix					Yes	4.4.1	MMS, PdM database, PM database
Personnel utilization by maintenance type					Yes	4.4.2	MMS
% time spent in training					Yes	4.4.3	Plant training records
Percentage of contracted maintenance					Yes	4.4.4	Plant administrative records
Person-hours by major systems and components					Yes	4.4.5	MMS
Component count (covered in maintenance programs and their breakdown)					Yes	4.4.6	MMS
Percentage of non-outage maintenance					Yes	4.4.7	MMS
Productivity Metrics							
Craft productivity					Yes	4.5.1, 4.5.4	MMS
Staff productivity					Yes	4.5.2, 4.5.3 4.5.5, 4.5.6	MMS
Rework, emergency work, backlog				Yes	Yes	4.5.7, 4.5.8 4.5.9	MMS
Man-hours input Hrs/100MW installed capacity					Yes	4.5.10	Maintenance cost & power generation
Procedure changes					Yes	4.5.11	Procedure control records
Overall maintenance performance index, human performance index, maintenance process index, and maintenance productivity index					Yes	4.3.8, 4.3.9, 4.4.8, 4.5.12	Computed values from the metrics

1. *Refers to the proposed metrics set present in this report. Specifics of the indicator, data input, computations, assumptions, and monitoring period may vary.*
2. *Review the referenced section present in this report for specific use of each indicator by EPRI.*
3. *Unit capability loss factor is a similar indicator.*

4.3 Performance Metrics

The performance metrics set focuses on the output and the input variables shown in Figure 4-3. The equipment availability, reliability, and longevity areas are excluded as discussed in Section 4.2 to avoid redundancy.

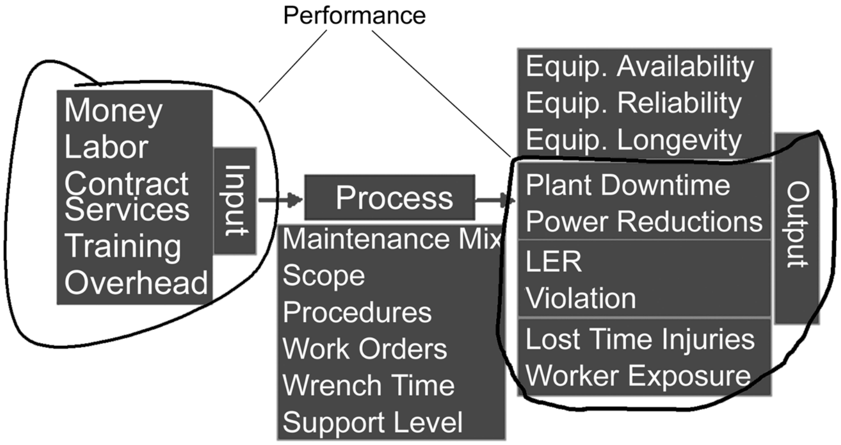

Figure 4-3
Focus of Performance Metrics

This set consists of eight (two input and six output) metrics and two composite indices, maintenance performance index (MPI) and human performance index (HPI). MPI is indicative of the overall performance of the maintenance department, and HPI is indicative of human performance that takes into account human performance issues such as work culture, training, and adequacy of procedures. This information can assist in budgetary and resource allocation decisions, support regulatory demands for data justifying power production costs and rate making, identify areas needing improvements at the department level, or just provide relative points of comfort. A maintenance process index, which is a composite of the individual process metrics, is also included. The composite index provides a quick look at the overall performance of the maintenance function. The specific metrics in this group consists of:

1. Maintenance cost in dollars/MWhr
2. Maintenance man-hours input per million kilowatt-hours
3. Number of plant trips attributable to maintenance
4. Number of power loss events attributable to maintenance
5. Number of LERs attributable to maintenance
6. Number of regulatory violations attributable to maintenance
7. Maintenance personnel exposure
8. Lost time injuries attributable to maintenance
9. Maintenance performance index, which is a composite of the eight metrics above
10. Human performance index

4.3.1 Maintenance Cost in Dollars/MWhr

Maintenance cost is that portion of the overall plant non-fuel production (also known as O&M) cost incurred in delivering maintenance services. Generally, it should be the cost that the maintenance superintendent/manager is held accountable for. If maintenance support is a separate cost center, be it on-site or offsite, then that should also be included. In addition, PdM engineering man-hour costs[2] for thermography, vibration analysis, and oil analysis programs are also included since engineers, usually in a separate and dedicated group with their own budget, are integrally tied into these activities. The craft man-hour costs for these programs and all other PdM programs are fully included since the work is performed under the maintenance department budget. Costs for contract services such as laboratory services and equipment rental for all PdM programs are included because they are part of the overall maintenance budget. If procedure and scheduling support for maintenance is not included under maintenance management, then an estimate of the associated cost should be included.

In order to get a complete picture of all maintenance costs, engineering support for maintenance and other indirect costs, such as costs incurred by the training department in providing training to maintenance personnel, should be included. However, in order to ensure consistency of data among plants, the benchmark values provided in this document exclude these items. One-time unplanned (unanticipated) costs for special activities, such as vessel head inspections performed to meet regulatory demand, may be excluded to avoid distortion of even the three-year rolling averages.

Data Source

Annual maintenance cost data were obtained from the plant financial organization’s records. Annual generation was obtained from the plant monthly (or weekly) generation records.

Calculation:

$$\frac{\text{Maintenance Cost in Dollars}}{\text{MWhr}} = \frac{\text{Total Annual Cost of Maintenance}}{\text{Annual Generation in MWhrs}}$$

Multi-unit plants with a common maintenance department should use average per unit values of the total cost and associated unit annual generation. Multi-unit plants with separate maintenance departments, each with its own management and budget, should use the respective unit’s values of the total cost and annual generation.

Benchmark Value = 2.80 dollars/MWhr

Recommended Goal = to be consistently in the low end of lowest quartile of the industry

The benchmark value given above is based on typical multi-unit plants with unit capacities ranging from 800 MW to 1350 MW. For a single unit plant, the benchmark value should be increased by a factor based on installed capacity using the graph shown in Figure 4-2. For example, for a 700 MW single unit plant, the benchmark value will be = (2.80 × 1.23) = 3.40 dollars/MWhr.

---

[2] Based on analysis of the information that could be collected on other PdM programs, it is concluded that the effect of not including all PdM engineering support costs (see Section 4.4.5) would understate the total maintenance cost by less than 2%.

4.3.2 Maintenance Man-Hours Per Million Kilowatt-Hours

This metric on labor input is calculated using all the direct employees in the maintenance department including those in maintenance support. It includes craft, supervision, management, and administrative personnel within the maintenance function. If procedure and scheduling support for maintenance is not included under maintenance management, then an estimate of the associated man-hours should be included. PdM engineering man-hour costs for thermography, vibration analysis, and oil analysis programs are also included since engineers, usually in a separate and dedicated group with their own budget, are integrally tied into these activities.

Data Source

Organization charts of the maintenance and maintenance support departments were used to determine the total man-hours applied. Annual generation was obtained from the plant monthly (or weekly) generation records. The benchmark includes PdM engineering man-hours only for thermography, vibration analysis, and oil analysis programs obtained through interviews with cognizant engineers for these programs. The craft man-hours for these programs and all other PdM programs are fully included since the work is performed under the maintenance department budget. Based on analysis of the information that could be collected on other PdM programs, it is concluded that the maintenance man-hours in the benchmark given below would be understated by less than 3% by not including the engineering man-hours for these programs.

Calculation:

$$\frac{\text{Man-Hours}}{\text{million kwhr}} = \frac{\text{Total Man-Hours Available}}{(\text{Annual Generation in kwhrs} \div 10^{6})}$$

$$\text{Total Man-Hours Available} = \left(365 \times \frac{\text{Work Hours}}{\text{Day}} \times \#\text{of Employees}\right) - \text{Vacation} - \text{Holidays and Weekends} - \text{Other Scheduled Time Off}$$

For benchmarking calculations, available annual man-hours of 1840/year/person were used. Multi-unit plants with a common maintenance department should use average per unit values of the total man-hours and associated unit annual generation. Multi-unit plants with separate maintenance departments, each with its own management, should use the respective unit’s values of the total man-hours and annual generation.

Benchmark Value: = 42 hrs/million kWhrs

Recommended Goal = to be consistently in the low end of lowest quartile of the industry

The benchmark value given above is based on typical multi-unit plants with unit capacities ranging from 800 MW to 1350 MW. For a single unit plant, the benchmark value should be increased by a factor based on installed capacity using the graph shown in Figure 4-2. For example, for a 700 MW single unit plant the benchmark value will be = (42 × 1.23) = 52.9 hrs/million kWhrs.

4.3.3 Maintenance-Related Plant Trips

This metric is a modified subset of the "*unplanned automatic scrams*" indicator currently used by plants. Modification to the currently used indicator involves capturing the annual value rather than 7000 hrs of criticality and focusing only on those trips attributable to maintenance-related causes. A trip is unplanned if it is not scheduled four weeks in advance. This includes all auto and manually initiated scrams that are not planned trips such as a planned maintenance outage or refueling outage. Data on the number of trips are obtained from plant trip records or operating performance data. Only those unplanned trips directly attributable to a maintenance function should be included. An example would be miscalibration of a reactor protection system (RPS) trip unit resulting in an unplanned plant trip.

Care should be taken to avoid including plant trips attributable to indirect maintenance-related causes. For example, a trip caused by a part subsequently determined to be defective, installed during a maintenance activity in an uninterruptible power supply (UPS), should not be charged as a maintenance-related plant trip. All trips determined to be attributable to a maintenance-related cause, whether or not they are reportable to the Nuclear Regulatory Commission (NRC), should be included.

Data Source

During the development of the benchmark value, at some plants the number of trips attributable to maintenance-related causes was taken directly from the monthly operating report submitted to the NRC (cause code "B"). It is assumed that any trip, be it automatic or manual, is included in the monthly operating report and a cause is assigned. At other plants, the trip and power loss events log and the corresponding LERs were reviewed to determine the number of maintenance-related trips.

Benchmark = 0.22/year

Multi-unit plants should use unit-specific values for the number of trips.

Recommended Goal = zero

An increasing trend or a constant value other than zero for this metric in any two consecutive periods is indicative of sub-par maintenance performance. More often than not, an adverse trend in this metric is due to inadequate procedures, improper practices, and/or inadequate training.

4.3.4 Maintenance-Related Power Loss Events

This metric is a subset of the "*unplanned capability loss*" indicator currently used by plants. Modification to the currently used indicator involves capturing the annual value rather than 7000 hrs of criticality and focusing only on those events attributable to maintenance-related causes. Capability loss is unplanned if it is not scheduled four weeks[3] in advance [1]. This metric is the number of such events and is obtained from plant records on unplanned power reductions. Only those events directly attributable to a maintenance action/activity should be included. An example would be a misaligned pump bearing leading to a loss of one train of a safety system that required entering a limiting condition for operation (LCO) requiring power reduction. Care should be taken to avoid including events attributable to indirect maintenance-related causes. In the previous example, if the loss of one train was caused by the failure of a defective bearing that

---

[3] WANO uses four weeks as does NEI, but ROP uses 72 hours.

was replaced during a maintenance activity, then it should not be charged as a maintenance-induced power loss event. All power loss events determined to be attributable to a maintenance-related cause, whether or not they are reportable to the Nuclear Regulatory Commission (NRC), should be included.

Data Source

During the development of the benchmark value, at some plants the number of power-loss events attributable to maintenance-related causes was taken directly from the monthly operating report submitted to the NRC (cause code "B"). It is assumed that any power-loss event, be it automatic or manual, is included in the monthly operating report and a cause is assigned. At other plants, the trip and power loss events log and the corresponding LERs were reviewed to determine the number of maintenance-related events. In the later case, chargeability determination of the investigators was reviewed and concurred with by the plant licensing staff.

Benchmark = 0.13/year

Multi-unit plants should use respective unit values for the number of power loss events.

Recommended Goal = zero

An increasing trend or a constant value other than zero for this metric in any two consecutive periods is indicative of sub-par maintenance performance. More often than not, an adverse trend in this metric is due to inadequate procedures, improper practices, and/or inadequate training.

4.3.5 Maintenance-Related Licensee Event Reports (LERs)

This metric is a modified subset of the "number of safety system challenges" indicator currently used by plants. Modification to the currently used indicator involves capturing the annual value rather than 7000 hrs of criticality, capturing all LERs including those for "number of safety system challenges," and focusing only on those events attributable to maintenance-related causes. Only those LERs generated as a direct result of a maintenance action/activity should be included. Examples include the improper setting of a safety relief valve resulting in an unplanned challenge to a safety system or the subsequent discovery of a condition deviant from plant technical specifications caused by a maintenance activity. Note that this metric includes LERs reporting a plant trip or power loss event from maintenance-related causes, and it is intended to be so. The rationale is that an LER represents a cost element; attempts to separate those from others would require unwarranted additional effort and could lead to inconsistency.

Care should be taken to avoid including LERs attributable to indirect maintenance-related causes. For example, an LER resulting from a diesel generator failure to start per specification limits due to a malfunction of an under-voltage relay installed during a maintenance activity and subsequently determined to be defective should not be charged to maintenance function.

Data Source

During the development of the benchmark value, this number was determined by gathering and reviewing the LERs submitted to the NRC. Those attributable to a maintenance-related cause were identified from this review. LER listing was obtained from the utility's regulatory record keeping systems. For the most part, the chargeability determinations made by the investigators were reviewed by the utility licensing staff.

Benchmark = 1.76/year

Multi-unit plants should use respective unit values of the number of LERs.

Recommended Goal = zero

An increasing trend or a constant value other than zero for this metric in any two consecutive periods is indicative of sub-par maintenance performance. More often than not, an adverse trend in this metric is due to inadequate procedures, improper practices, and/or inadequate training.

4.3.6 Maintenance-Related Regulatory Violations

This metric is a count of regulatory compliance violations (for example, NRC or EPA regulations) attributable to a maintenance-related cause. Note that while some of the violations may have been captured in the LER metric discussed in Section 4.3.5, no attempt is made to separate and eliminate them to ensure consistency in counts because not all violations may result in LERs. For example, a Notice of Violation issued by the NRC after a discovery of systemic maintenance program deficiency or a series of missed contingent EQ maintenance without adequate engineering justification may not generally result in an LER.

Data Source

The relevant data were obtained from the plant regulatory compliance records kept by the department responsible for nuclear regulatory affairs. It is assumed that they effectively capture the nuclear as well as environmental regulatory compliance deviations. During the development of the benchmark value, the number of violations attributable to maintenance action/activity was determined by reviewing the actual documents at the plant. For the most part, the chargeability determinations made by the authors were reviewed by the utility licensing staff.

Benchmark = 0.11/year

Multi-unit plants should use respective unit values for the number of violations.

Recommended Goal = zero

An increasing trend or a constant value other than zero for this metric in any two consecutive periods is indicative of sub-par maintenance performance. More often than not, an adverse trend in this metric is due to inadequate procedures, improper practices, and/or inadequate training.

4.3.7 Maintenance-Related Lost-Time Injuries

This metric is a modified subset of the “Lost person-hours from injuries” indicator currently used by plants. Modification to the currently used indicator involves capturing only those events attributable to a maintenance activity and/or involving maintenance personnel. It can be obtained from the plant safety records database used for reporting to OSHA. It is assumed that they effectively capture all personnel safety events that involve lost work time. Lost-time events resulting from contract services work that do not involve or affect direct employees are excluded.

Data Source

During the development of the benchmark value, the number of lost-time injury events was obtained from plant safety departments that kept such records including categorization of the events by department affected and/or involved.

Benchmark = 1.11/year

Multi-unit plants should use respective unit values for the number of lost-time injuries.

Recommended Goal = zero

An increasing trend or a constant value other than zero for this metric in any two consecutive periods is indicative of sub-par maintenance performance. More often than not, an adverse trend in this metric is due to inadequate procedures, improper practices, and/or inadequate training.

4.3.8 Maintenance Personnel Exposure

This metric is a modified subset of the “personnel exposure” indicator currently used by plants. Modification to the currently used indicator involves capturing only person-rems to maintenance personnel. No distinction is made as to the cause of the exposure. It may or may not be attributable to a maintenance activity. Only those events that result from a maintenance activity and/or involve maintenance personnel should be included. It may be preferable to exclude such events resulting from contract maintenance services work that do not involve or affect direct employees in the maintenance department.

Data Source

The relevant data are gathered from the plant radiation exposure records database used for reporting to regulatory bodies. It is assumed that they effectively capture all personnel exposure events. During the development of the benchmark value, the total radiation exposure in person-rems was obtained from plant departments that kept such records including categorization of the events and doses by department affected and/or involved.

Benchmark = 56 person-rems/year (5.6 ksieverts/year)

Multi-unit plants should use respective unit values for personnel exposure.

Recommended Goal = To be consistently in the low end of lowest quartile of the industry

Barring any special situations such as the recent regulatory driven vessel head inspection, an increasing trend for this metric in any two consecutive periods may be indicative of inadequate training and/or control of work in high radiation areas.

4.3.9 Maintenance Performance Index

This metric is indicative of overall maintenance performance. It is derived by comparing the plant-specific individual performance metrics discussed in Sections 4.3.1 through 4.3.8 against the respective benchmarks. The benchmarks are deemed to be the industry averages. This index is based on a scoring system that weights each metric equally and assigns a score relative to its benchmark. Table 4-2 lists the scoring system. In essence, if a given metric for a given plant is equal to the benchmark, it scores 0.75 for that metric. If the same metric is better than the benchmark by 50% or more, it will score 1. Similarly, for a negative comparison of –100% or more with the benchmark, it will score 0. The composite maintenance performance index is the sum of the individual scores expressed as a percent. Under this method of scoring, negative comparisons offset positive comparisons by like amounts. The maximum a plant can score is 8 out of 8 (which is equal to 100%), indicating an excellent or flawless performance by the maintenance function (that is, an optimal mix of maintenance type and technologies, excellent human performance, and management) at the lowest cost in comparison to the industry.

Table 4-2
Metric Scoring Table

% Delta	Score
-100.00%	0.00
-80.00%	0.15
-60.00%	0.30
-40.00%	0.45
-20.00%	0.60
0.00%	0.75
20.00%	0.85
40.00%	0.90
50.00%	1.00

Figure 4-4 below shows the performance metrics for one of the surveyed plants in a radar chart. As seen from this chart, for Plant F, the number of unplanned trips attributable to maintenance is 0.3 whereas the benchmark is 0.2. Plant F is therefore 50% worse than the benchmark. For the number of LERs attributable to maintenance function, Plant F has 0, whereas the benchmark is 0.1. Plant F is 100% or better than the benchmark for this metric.

Figure 4-5 shows the maintenance performance index for the surveyed plants and the reference or benchmark.

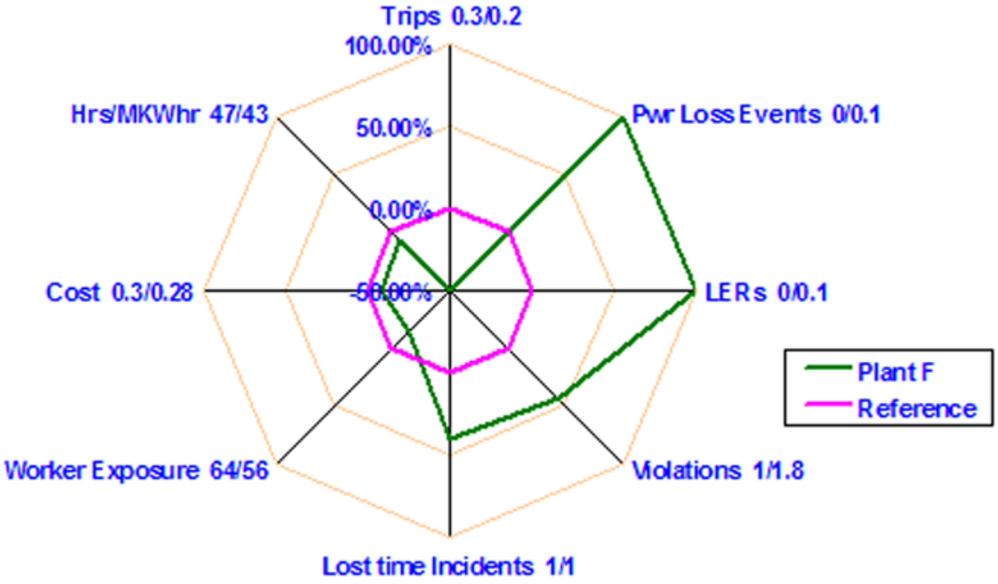

Figure 4-4
Radar Chart of Performance Metrics for Plant F

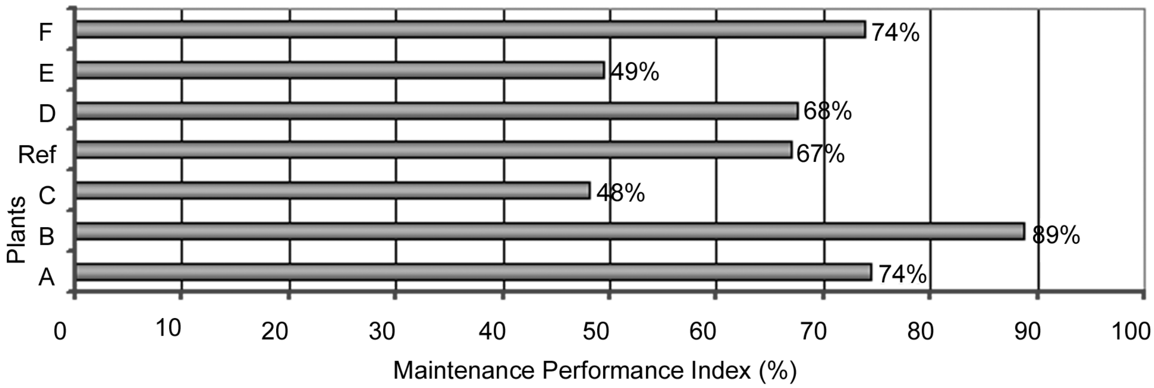

Figure 4-5
Comparison of Maintenance Performance Index for Surveyed Plants

Table 4-3 shows the calculation of the maintenance performance index (MPI) for Plant F using the scoring system shown in Table 4-2 with the metric values shown in Figure 4-4. Figure 4-5 depicts the maintenance performances metrics for the surveyed plants and the reference benchmark.

Table 4-3
Maintenance Performance Index for Plant F

Area	Plant F	Reference	What is Good	Plant B	Score	MPI
Trips 0/0.2	0.33	0.22	< industry	-50.00%	0.30	
Power Loss Events 0/0.1	0.00	0.13	< industry	100.00%	1.00	
LERs 0/0.1	0.00	0.11	< industry	100.00%	1.00	
Violations	1.00	1.76	< industry	43.16%	0.90	
Lost Time Events	0.67	1.11	< industry	40.05%	0.90	
Worker Exp NA/56.3	64.33	56.29	< industry	-14.29%	0.60	
Cost $/MWhr 3.0/2.8	3.0	2.80	< industry	-8.89%	0.60	
Hrs/Million kWhr 32.7/41.7	45.63	41.73	< industry	-9.35%	0.60	
Total					5.90	74%

4.4 Process Metrics

The set of process metrics focuses on the input and process variables shown in Figure 4-6.

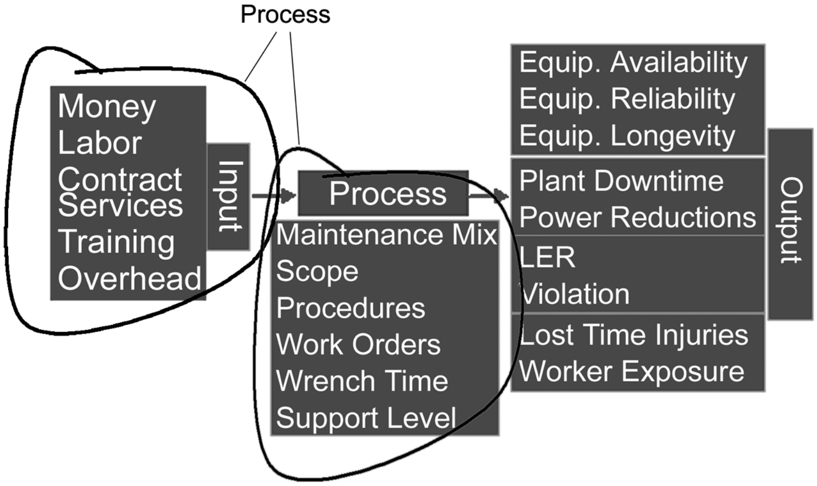

Figure 4-6
Focus of Process Metrics

This metric set consists of 10 metrics that provide a numbers-based view of the maintenance programs and the underlying processes. A maintenance process index, which is a composite of the individual process metrics, is also included. The composite index provides a quick look at the overall process. Process metrics are grouped under the following categories:

1. Work order count and breakdown
2. Person-hours by maintenance type
3. Person-hours expended in training
4. Contract service as a percentage of maintenance cost
5. Person-hours expended on maintaining selected components and systems
6. Equipment count and breakdown
7. Percentage of non-outage on-line maintenance
8. Maintenance process index

Together, this set indicates program scope, mix, resource allocation/use, and workload in the various elements of the maintenance process. At a specific component level, it should identify areas that warrant special attention. It can assist in the comparison of a plant’s maintenance program scope, workload, resource allocation between maintenance types, and maintenance mix with its peers. Such an assessment would identify opportunities for improvements in maintenance performance (see Section 4.3). For example, a variation in the cost of maintenance may be evaluated by looking at the total number of work orders serviced and its breakdown by maintenance type. If the percentage of CM is high in comparison to the industry, it may explain some of the variations and point to a need to find ways to reduce CM demands. Taken individually or as small groups, the metrics in this set provide information about:

- Whether maintenance is focused (that is, on components) where it is needed
- Adequacy of component selection
- Adequacy of the maintenance mix
- Resource allocation consumption between maintenance types
- Maintenance practices

Further, comparative evaluation against the industry and/or reference group plants could identify opportunities for desirable changes in practices and improvement.

4.4.1 Work Order Count and Breakdown

The total number of work orders serviced per year and their breakdown between CM and PM provide information about the annual workload handled by the maintenance department and how it compares with the industry as a whole and/or with the reference group plants. Specific metrics under this category and their benchmark values are shown in Table 4-4.

Table 4-4
Work Order Count and Breakdown

Item	Benchmark	Goal
Total number of work orders serviced	12008	NA
Percent of work orders designated PM	70%	NA
Percent of work orders designated CM	30%	NA
Percent of work orders designated safety-related	30%	NA
Percent of work orders designated non-safety	69%	NA
Percent of work orders designated high risk	TBD	NA
Percent of work orders designated medium risk	TBD	NA
Percent of work orders designated low or no risk	TBD	NA

Notes:

1. Work order count may range from 8000 for a 500 MW early vintage plant to 16000 for a 1300 MW late vintage plant.
2. Multi-unit plants should use average per unit values for the number of work orders.

Note that even though the total component count could be comparable to a peer plant, the work order count and breakdown might not be. Some plants do not initiate a work order for certain routine periodic and/or predictive maintenance items. Examples include performing lubrication work under task cards and performing IR scans using schedules established in a separate database maintained by the cognizant engineer. In such cases, each periodic/predictive maintenance line item that is performed without the work order should be counted as a work order assigned to that item, and the corresponding annual work order counts should be established using the frequency of such work. For example, if oil samples are drawn once in six months for motor XYZ, then that should be counted as two PM work orders per year against that motor and included in the total work order count.

Risk-based categorization of work orders would be another useful metric for comparative evaluation of the maintenance programs among plants. Since utilities are currently in the process of establishing such categorization, benchmarks could not be developed at this time.

Further breakdown of the work order counts such as the number of PdM versus periodic maintenance work orders and the number of CM work orders by their quality class may be useful in spotting specific areas requiring attention.

Data Source

The number of work orders and their breakdown by maintenance type were obtained from the plant maintenance management system. A query was initiated by the maintenance support staff to download the work order sequence number and related information including equipment ID, work type, performing department code, work category, work complete date, work quality classification, estimated man-hours, estimated duration, actual hours, crew size, and work priority. This download was exported into an Excel spreadsheet for further processing and analysis to obtain/calculate the relevant metric values. When routes are used for PdM work orders, a route is considered as one work order. In the survey population, one plant did not perform IR, oil analysis, and vibration-related PdM tasks under their work order management system. For that plant, an estimate of the annual work order counts was established using data on the number of equipment items included in the scope, number of touches per year, and number of routes. Multi-unit plants with a common maintenance department should use average per unit values for the variables. Multi-unit plants with separate maintenance departments, each with its own management, should calculate the metric for each unit using unit-specific values for the variables.

4.4.2 Person-Hours by Maintenance Type

The total number of hours expended in PM and CM provides insight into the relative demand for resources. When used together with the workload (see Section 4.4.1), it could identify opportunities for improvements for optimizing maintenance mix. Specific metrics and the respective benchmarks included under this category are shown in Table 4-5.

Table 4-5
Person-Hours By Maintenance Type

Item	Benchmark
% of person-hours expended on PM	56%
% of person-hours expended on CM	44%
% of PM person-hours expended on PdM as % PM	4%

Data Source

Data on actual hours spent on PM and CM were available from only one of the six plants in the survey population. Actual hours data were obtained from the MMS at this plant. At the remaining plants, either the actual hours were not captured or the available data were incomplete. The breakdown of hours by maintenance type was established for these plants by allocating the available hours less training hours between PM and CM. This was done by using the breakdown of work order counts and a difficulty factor of two for CM compared to PM. That is, on the average, it takes twice as many person-hours to do corrective work as it does for preventive work. Appendix B provides a complete discussion of how the difficulty factor was arrived at and how it is used in the calculations. Multi-unit plants with a common maintenance department should use average per unit values for the variables. Multi-unit plants with separate maintenance departments, each with its own management, should calculate the metric for each unit using unit-specific values for the variables.

4.4.3 Person-Hours in Training

This metric gives information about the investment in training of maintenance personnel as a percentage of total maintenance hours expended. Comparative evaluation among plants helps in calibrating a plant’s training expenditures. This is a leading indicator (that is, if the right training was provided to the right segment); then benefits can be expected over a period of time in the form of avoided mistakes, improved maintenance performance, and improved efficiencies such as low rework counts, low backlog counts, and reduced man-hours/work order completed.

Calculation:

$$\%\text{ of Training Hours} = \frac{100 \times \#\text{of Hours Spent in Training by Craft and Maintenance Staff per Year}}{\#\text{ Total Number of Hours Expended in Maintenance Function}}$$

Benchmark: 5%

Data Source

Historical data on the number of hours spent in training per year for craft and staff were obtained from the training department database/logs for three of the six plants in the survey. The training hours were those spent in classroom training for general orientation, badging, job-specific functions, industry experience review, general administrative and safety procedures, and leadership courses for supervision. For the other three plants, estimates of 100 hrs/person/year for craft and 50 hrs/person/year for staff were used to calculate the total hours spent in training. These estimates were obtained through interviews of the maintenance support manager and maintenance supervisors for the mechanical, I&C, and electrical functions. Further corroboration of these estimates was obtained through discussions with foremen, technicians, and support staff. These estimates were found to be comparable to the actual hours obtained at the other three plants.

4.4.4 Contract Service as Percent of Maintenance Cost

Most plants use some level of contract maintenance to meet specialized personnel needs and/or to support additional short-term demands during outages. Percent contracted maintenance is a useful metric for comparing a plant’s maintenance program with its peers. It is calculated as:

$$\%\text{ Contracted Services} = \frac{100 \times (\text{Total Expenditure for Contracted Services})}{\text{Total Annual Cost for Maintenance}}$$

Only regularly contracted maintenance items such as inverter and battery charger maintenance, power-operated relief valve (PORV) testing, turbine generator overhaul, and outage staff augmentation support should be included in this calculation. Special infrequently contracted maintenance expenditures such as those for steam generator retubing or condenser overhaul should be excluded. Looking at this metric by department may be useful during initial implementation stages. Expressed as a percentage of the total maintenance cost, this metric indicates the effectiveness of in-house resource utilization and control of maintenance.

Data source: Plant financial department records

Benchmark: 5%

This benchmark applies directly to multi-unit sites. For single unit sites, the benchmark may need adjustment upward by the factor established from Figure 4-2. This is based on the premise that multi-unit plants tend to have an economy of scale advantage in procuring such services. However, the data collected in this benchmark effort are insufficient to establish the extent of such advantage with a reasonable degree of certainty since the survey included only one single unit plant.

4.4.5 Equipment Count and Breakdown

This group of one-time metrics provides a view of the scope of maintenance coverage and maintenance mix. It looks at the total number of components included in the plant maintenance program and their breakdown based on safety classification and maintenance type. Specific metrics included under this category and the respective benchmarks are shown in Table 4-6.

Table 4-6
Component Count Included in Maintenance Program

Item	Benchmark
# of equipment items in the plant	69,795
% of equipment safety related (SR)	22%
% of equipment non-safety-related (NSR)	77%
% of equipment covered under PM	11%
% of equipment covered under CM	89%
% of equipment items covered under PdM	1%
% of SR equipment items covered under PM (incl. PdM)	21%
% of NSR equipment items covered under PM (incl. PdM)	8%

The total number of components included under a plant maintenance program might vary with plant type and vintage. The same will be true for the breakdown of the total by their classification (that is, safety, non-safety, and augmented-safety classes) or by maintenance type. Also, the component count may vary based on whether the plant equipment list includes items such as circuit breakers, fuses, penetrations, and other items that are not usually tagged and included in typical equipment lists. Typically, depending upon plant vintage and type, if they are tagged and listed, they would add 8,000 to 12,000 components to the equipment list. Four of the six plants in the survey population included these items in their equipment lists. For the other two, 10,000 items were added to the total count to account for these items.

This one-time metric provides information to compare the scope of the maintenance program against the industry or reference group plants. This metric may identify areas (for example, variations in component counts covered in PM programs between similar plants, growth of component counts covered in PM) that may warrant further review. Generally, a substantive change as a function of time is not expected in this metric. However, it might be appropriate to revisit this metric once in five years to ensure that changes, if any, in the intervening period are consistent with the maintenance program goals. Such a review should provide a supporting basis for budgetary adjustments. For example, reviewing this data for the 1994 to 1998 period should show the growth of the PM program due to maintenance rule and PdM implementation. Since the survey period for this benchmarking work included 1999–2001, a period after the maintenance program adjustments were largely completed, there was no discernible change in the scope of maintenance coverage.

Data Source

Except for PdM scope information, the remaining data input for this metric was available from the MMS and the plant equipment list. The equipment list was used to get the total component count and breakdown by quality class. The MMS was used to obtain scope of maintenance coverage and breakdown by maintenance type and equipment quality class. Some plants maintained a separate PM basis database that provided a ready source for PM scope, excluding PdM. Multi-unit plants should use average per unit values for equipment count, and common plant equipment should be divided and added equally among the number of units. Data from a larger sample of single unit plants would be needed to establish a factor to adjust the benchmark to compensate for shared equipment situations in multi-unit plants. However, the benchmarks as shown in the table are reasonably close for single unit plants, since the margin of error is estimated to be no more than 5%.

The scope data for PdM program(s) could not be established[4] from the equipment list or the MMS. It was found to be available in a separate database usually maintained by the engineer(s) responsible for these programs. Generally, the surveyed plants apparently designate only thermography, vibration analysis, and oil analysis as PdM (see Section 7 for a detailed discussion of this). The scope of PdM shown in Table 4-6 is therefore limited only to these three subprograms. Although a few plants included motor monitoring in PdM, that was excluded because the data could not be uniformly obtained from all the surveyed plants.

4.4.6 Percentage of On-Line Maintenance

This group of one-time metrics provides a view of the amount of PMs performed with the unit on-line. It is generally accepted that performing as much maintenance as practical with the unit on-line should result in cost-efficient maintenance mainly because of the reduced impact in outage duration and the load leveling flexibility it offers. Factors that influence decisions on

---

[4] Data collection and diagnostic testing work on PdMs are performed by the maintenance craft. Hence, while we have a good idea of the annual PdM workload handled, the component count for each of these programs could not be established. If the work order system included a separate category "PdM" for this work instead of lumping them under PM, then the scope for all PdM activities could be easily established.

when to perform maintenance include risk of impacting plant/system availability, personnel safety, radiation exposure, and in-house staffing. A comparative assessment using this metric would enable comparison of a plant's maintenance program against its peers or the industry. Specific metrics included under this category and the respective benchmarks are shown in Table 4-7.

Table 4-7
Percent of Non-Outage Maintenance

Item	Benchmark
% of online PM	69%
% of PM on SR equipment performed at power	65%
% of PM on NSR equipment performed at power	73%

These are expressed as a percentage of the component count. The data will be sensitive to plant type and vintage. In addition, it may be useful to segregate these data by major equipment types (for example, motor-operated valves [MOVs], motors, etc.)[5] and review them. A close review of these data can reveal specific inefficiencies that might exist in a plant maintenance program. It should be noted that a higher percentage in a certain category in comparison to a reference plant group does not necessarily indicate need for change. For example, the plant-specific equipment configuration and built-in maintainability considerations can justify a higher percentage. However, some conditions might be correctable through appropriate plant modifications to improve maintainability. Multi-unit plants with a common maintenance department should use average per unit values for the variables. Multi-unit plants with separate maintenance departments, each with its own management, should calculate the metric for each unit using unit-specific values for the variables.

4.4.7 Person-Hours on Maintaining Major Components and Systems

This metric relates to the breakdown of craft person-hours expended on selected major equipment types or systems. Specific types of equipment or systems for which this metric might be useful include those shown in Table 4-8.

---

[5] Existing special plant programs, such as the MOV program or check valve program, might already provide this information.

Table 4-8
Maintenance Hours Expended for Major Components and Systems

Equipment	Person-Hours
Person hours for selected equipment	6348
Main turbine	15139
Main generator	7185
Diesel generator	482
Reactor coolant pumps	1410
Feedwater pumps	1795
Main steam and feedwater isolation valves	1233
Plant protection system	2590
Nuclear instrumentation system	11553

The person-hours shown in Table 4-8 are based on just one plant since at the remaining plants, the actual hours data were either not captured or were not captured consistently and accurately. Hence, this is not considered a valid benchmark. In this plant, for the radiation monitoring system, a steadily increasing trend was noted for three years in row. Such a trend is indicative of a need for an evaluation of the underlying causes and what portion of the cost is CM based and whether the system might have reached the point in life where it is economical to replace the system rather than continuing to incur disproportionate maintenance costs. Multi-unit plants with a common maintenance department should use average per unit values for the variables. Multi-unit plants with separate maintenance departments, each with its own management, should calculate the metric for each unit using unit-specific values for the variables.

Note that, although the total person-hours spent in maintenance could be comparable to a reference group or the industry, analysis of the breakdown of hours spent by select high-impact equipment categories and maintenance types may identify areas where improvements might be warranted. Adverse comparisons or trends in this metric might indicate one or more of the following:

- Aging of equipment
- Excessive periodic/predictive maintenance activities
- Poor maintainability conditions
- Need for better training in equipment maintenance
- Overly complex procedures

Data Source

Data required to derive this metric were available from the MMS at the one plant where actual hours on each work order were captured. At this plant, all craft, planning, and work control personnel charged their time to the relevant work orders. Hence, deriving this metric was a straightforward summation of hours accumulated based on equipment ID. It is recommended that plants consider instituting a system to capture actual hours for all persons working on a task related to a maintenance work order. It would enable analysis of labor resource consumption down to an equipment item/system level, and offer other benefits including:

- Analyzing the hours expended and cost of CM, PM, and PdM
- Assisting in the replacement or design modification decision making
- Refining estimated hours required to do the same job again
- Improving work scheduling to avoid build up of backlog

4.4.8 Maintenance Process Index

This metric provides a composite view of a plant's maintenance process for comparison against its peers or the industry. It is derived by comparing the plant-specific individual process metrics discussed in Sections 4.4.1 through 4.4.6 against the respective benchmarks in the same manner as explained in Section 4.3.9. Note that the metric on person-hours expended on maintaining selected equipment is not included in composite process index. Table 4-9 lists the process metrics included in computing the Process Index and what is considered better for purposes of scoring. Figure 4-7 shows the maintenance performance index for the surveyed plants and the reference or benchmark.

Table 4-9
List of Process Metrics and What Is Good

Metric	What's Good
% PM wo	> industry
% CM wo	< industry
% SR wo	> industry
% NSR wo	> industry
% PM Mhrs	< industry
% CM Mhrs	< industry
% equipment in PM	> industry
% equipment in CM	< industry
% Mhrs in trng	> industry
% online maint	> industry

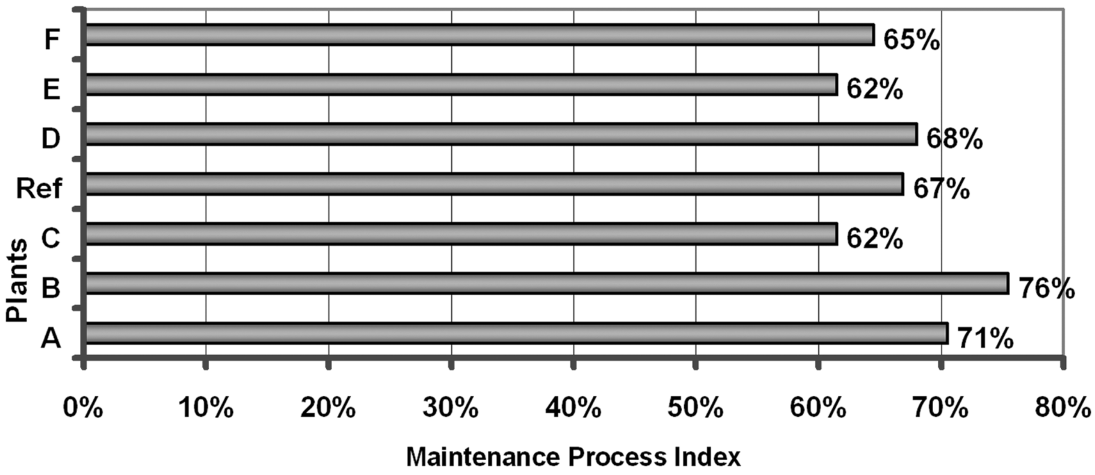

Figure 4-7
Maintenance Process Index for Surveyed Plants

4.5 Productivity Metrics

The productivity metrics set focuses on the input and process variables shown in Figure 4-8.

This set consists of 10 metrics that look at the process and input parameters that would enable assessing the efficiency and productivity of the maintenance process. A maintenance productivity index, which is a composite of the individual productivity metrics, is also included. The composite index provides a quick look at the overall productivity of the maintenance process.

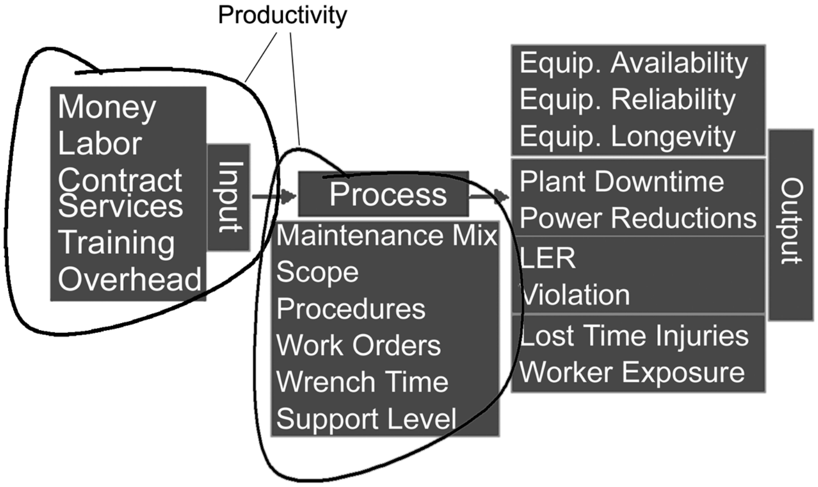

Figure 4-8
Focus of Productivity Metrics

Specific metrics included are:

1. Wrench time
2. Work order turnover per craft week
3. Planner-to-craft ratio
4. Work orders per planner week
5. Staff-to-craft ratio
6. Rework count
7. Emergency work count
8. Backlog and days overdue-backlog
9. Hours per 100 MW installed capacity
10. Procedure changes
11. Productivity index

4.5.1 Wrench Time

This metric indicates how effectively maintenance craft resources are utilized. It shows how much time is spent in performing actual hands-on work, commonly known as “wrench time.” This document defines wrench time as:

> *The time a worker/crew actually spends doing physical work on equipment after arriving at the work site until leaving the work site.*

It includes time spent on:

- Troubleshooting when needed
- Performing the assigned/required tasks on the item
- Independent verification when required
- Post-maintenance testing
- Restoring the item
- Cleaning up

The rest of the time in any given day apparently goes into related administrative and preparatory tasks, such as pre-job and post-job briefs, post-job documentation, dressing out, waiting for proper clearances, obtaining permits (for example, radiation work permit), breaks, and so on. Thus, it is calculated only for the days the craft is available for work at the site and is not in training.

This metric should be generated at the maintenance department level and for each discipline or work category.

Calculation:

$$\text{Wrench Time} = \frac{100 \times \left(\text{Average \# of Hours Doing the Physical Job}/\text{Day}\right)}{\text{Total Craft Person Work Hours per Day}}$$

For plants with five × eight-hour work days/week, the total work hours/day is 8 + 0.5 hrs for lunch.

Average number of hours per day doing the physical job was established as follows:

Step 1: Through interviews, a breakdown of times for the various tasks involved in taking a work order after it is assigned to a crew from start to finish was established. Interviewees included I&C, Electrical, and Mechanical foremen at three of the six surveyed plants. This was done for both one-day and multi-day jobs as shown on Table 4-10. Estimates for the percentage of multi-day jobs and jobs requiring dress out and walk down for each of three disciplines were also obtained in the same interviews. The fractional hours and percentage estimates shown in the table are averages for the three disciplines.

Table 4-10
Breakdown of Job Task Hours

One-Day Job	**Average Hours**
Pre-job Rev	0.75
Walk down adjusted for % requiring walk down (2)	0.13
Dress out for % of job requiring dress-out (2)	0.04
Travel to job	0.25
Tooling up	0.53
Return tools	0.36
Sign off and ECO	0.39
Travel back	0.25
Package write up	0.92
Breaks and lunch	1.50
Do job—includes working on the equipment, post-maintenance testing, cleanup (DJ_S) (3)	5.38 (1)
Multi-Day Job	**Average Hours**
Pre-Job Rev	0.28
Dress out for % of job requiring dress out	0.04
Travel to job	0.25
Travel back	0.25
Post job briefing	0.39
Breaks and lunch	1.50
Do job—includes working on the equipment, post-maintenance testing, cleanup (DJ_M) (4)	7.79 (1)
Estimated % jobs requiring dress out	20
Estimated % jobs requiring walk down	20
Estimated % multi-day jobs	20

Notes:

(1) This computation is based on a 4 × 10 week (that is, 10.5 hrs per person per workday including lunchtime).

(2) These are the weighted values to account for the percentages of jobs requiring dress out or walk down as applicable.

(3) DJ_S = One-day job

(4) DJ_M = Multi-day job

Step 2: Using the estimated hours contained in the work order downloads obtained from each plant, an average value for one-day and multi-day jobs was developed. This was to corroborate the estimates obtained through the interviews.

Step 3: Wrench time is calculated as follows for each of the surveyed plants. Then the average of the six plant values is used as the benchmark.

$$\begin{aligned}
\text{Average Time Doing the Physical Job per Day} &= \%\text{ One-Day Job} \times \text{DJ}_s + \%\text{ Multi-Day Jobs} \times \left(\text{DJ}_s + \text{DJ}_m\right) \\
&= 0.08 \times 5.38 + 0.20 \times \left(5.38 + 7.79\right) \\
&= 6.93 \\
\text{Wrench Time} &= \frac{6.93}{10.5} \qquad = 0.66 \text{ or } 66\%
\end{aligned}$$

Benchmark: 61% for the maintenance department as a whole

Wrench time significantly below the benchmark indicates a need to review task breakdowns in performing the work to identify areas where improvements are needed. Note also that plants that are on a 5 × 8 work week will have a lower wrench time since the number of one day jobs and the hours per day doing the physical job become less than those for 4 × 10 workweek plants.

It has been a common belief in the industry that the time spent by craft doing hands-on work is around 40%. That would be true under an alternate definition of wrench time used in some plants. Under this definition, as shown in Table 4-11, the annual time spent turning wrench is calculated as percentage of the annual hours being paid for, which includes holidays, vacation, sick, and other time off.

Table 4-11
Alternate Method of Calculating Wrench Time

Row#	Item Description	Hours
1	Total hours paid	2088
2	Holidays	64
3	Vacation	120
4	Other time off (for example, jury duty)	24
5	ERO duty and drills	24
6	Other non-job related meetings (for example, all-hands meeting, outage celebration)	16
7	Safety meetings	32
8	Other non-maintenance-related activities (for example, apprenticeship program, LAN administration, training support, procedure reviews)	120
9	Time available for maintenance work Row 1—sum (Rows 2-8)	1688
10	Time spent in non-hands-on work, pre-job brief, getting document, dress out, etc. assumed at 50% of Row 9	844
11	Wrench time as a % of hours paid for = Row 10/Row 1	40%
12	Wrench time as a % of hours available for work = Row 10/Row 9	50%

This method of calculating wrench time understates the wrench time and gives a false impression of dramatic underutilization of craft resources. The deductions (rows 2 through 8) in calculating the total annual hours available for work are applicable to all employees in a nuclear utility. A periodic examination of those activities applicable to all employees in the organization is desirable in order to verify that they continue to be required and that the time spent is appropriate to the job function. However, they should not be included in the calculation of wrench time. It is recommended that the wrench time be calculated (row 12) as a ratio of the hours that the craft personnel are available to perform maintenance work in the plant.

4.5.2 Work Order Turnover Per Craft-Week

This metric indicates the average weekly production capacity of the maintenance craft with no overtime use. Comparative evaluation of this metric may be more useful than the absolute count of the work orders. It should be comparable among various plants in the industry because, on the average, weekly production rate for maintenance craft should be approximately the same.

Calculation:

Since almost all work in a nuclear plant is performed with a minimum crew size of two, this calculation should take into account distribution of work orders by crew size. The benchmark calculation was done by using a distribution of 80% of work orders performed with two-man crews and 10% each requiring three- and four-man crews. The total number of work orders serviced in a year is then converted into an equivalent number of two-man crew work orders. If the distribution of work orders by crew size is significantly different, the formula should be modified appropriately.

$$\text{Turnover}\Big/\text{Craft Week} = \frac{[\text{Number of Two-Man Crew Equivalent Work Orders Processed Per Year}]}{\#\ \text{of Two-Man Crews}}$$

$$\#\,\text{of Two-Man Crew Equivalent Work Orders} = \#\,\text{of WO Serviced in a Year} \times \left(0.8 + 0.1 \times 2/3 + 0.1 \times 2/4\right)$$

$$\#\,\text{of Two-Man Crew Equivalent Work Orders} = \frac{\text{Total Number of Craft Persons}}{2}$$

Data Source

Number of craft persons is from the organization charts of the maintenance and maintenance support departments. The number of craft persons includes all craft personnel from Mechanical, I&C, Electrical, and other support crafts such as insulators, scaffolding, and welders. The number of work orders processed per year and the percentage distribution based on crew size are from the MMS.

Benchmark: 248 work orders/craft-week for the maintenance department as a whole

It would be useful to calculate this metric both at the maintenance department level and at the individual discipline level. Significant variations from the benchmark and adverse trends would be cause for further review. If the resource availability has not changed, a very likely cause is high number of CMs and/or a large number of CMs with complicated evolutions. If actual hours are captured, this can be easily identified using queries from the MMS. Other causes include:

- Craft mix tilted more in favor of new recruits and/or less experienced
- Poor planning and staging

Multi-unit plants with a common maintenance department should use average per unit values for the variables. Multi-unit plants with separate maintenance departments, each with its own management, should calculate the metric for each unit using unit-specific values for the variables.

4.5.3 Planner-to-Craft Ratio

Planners support the maintenance craft by planning and staging the work to be performed. It includes examining the work site, physically or via remote means such as surrogate tour photographs, as appropriate, to identify special work conditions (such as restricted access, confined space, or high radiation) or needed support such as scaffolding. This metric indicates the efficiency of the planner resource utilization.

Calculation:

$$\text{Planner to Craft Ratio} = \frac{100 \times (\text{Total Planner Person-Hours per Year})}{(\text{Total Craft Person-Hours per Year})}$$

Total planner/craft person-hours should be calculated using only the available hours excluding sick days, holidays, vacation, and other time off. Total craft hours available per week are calculated using 1840 hours per person per year.

Data Source

Organization charts for the maintenance and maintenance support department.

Benchmark: 10% for the maintenance department (that is, one planner for every 10 craft persons)

It should be calculated at the maintenance department level and at the individual maintenance discipline (for example, I&C and Mechanical) level. Ratios significantly higher than the benchmark and/or an adverse trend would be cause for an examination of the planning and work-request screening function. Multi-unit plants with separate maintenance departments, each with its own management, should calculate the metric for each unit using unit-specific values of the variables.

4.5.4 Work Orders Per Planner Week

This metric indicates the productivity of the planning function. Over a monitoring period, this metric should be comparable among various plants because, on the average, barring any significant differences in organizational or other environmental variables, productivity should be approximately the same.

Calculation:

Total planner/craft person-hours should be calculated using only the available hours excluding sick, holidays, vacation, and other time off. As a rule of thumb, it is 1840 × the number of planners/craft. Only 60% of the total number of work orders serviced annually are planned since the other 40% are usually screened out for performance by FIN/WIN teams or are routine work such as lubrication, oil sampling, and vibration data collection that does not require planning.

$$\text{Work Orders per Planner Week} = \frac{(\text{Total Number of Work Orders Processed Annually}) \times \text{N}}{[\text{Total Planner Hours Available per Week} \times (1 - \%\text{ of Time in Training})]}$$

$$\text{N} = \text{Number of Work Hours in a Normal Work Week}$$

$$\text{Number of Work Orders Processed Annually} = \text{Total Number of Work Orders} \times 60\%$$

Data Source

Maintenance and maintenance support department organization charts

Benchmark: 15 work orders/planner-week

It would be useful to calculate this metric both at the maintenance department level and at the individual discipline level. Multi-unit plants with a common maintenance department should use average per unit values for the variables. Multi-unit plants with separate maintenance departments, each with its own management, should calculate the metric for each unit using unit-specific values for the variables.

4.5.5 Staff-to-Craft Ratio

The staff that supports the maintenance function includes work control staff, engineers in the maintenance department, planners, schedulers, procedure writers, and other administrative, supervisory, and management staff. This metric is indicative of the efficiency of the support resource utilization in a plant.

Calculation:

$$\text{Staff to Craft Ratio} = \frac{100 \times [\text{Total Staff Person-Hours per Year}]}{\text{Total Craft Person-Hours per Year}}$$

Total staff/craft person-hours should be calculated using only the available hours excluding sick, holidays, vacation, and other time off. Total staff/craft hours available per week are calculated using 1840 hours per person per year.

Data Source

Maintenance and maintenance support department organization charts

Benchmark: 33% (that is, at the maintenance department level, there is a staff person supporting every three craft persons).

Goal: 25%

Multi-unit plants with a common maintenance department should use average per unit values for the variables. Multi-unit plants with separate maintenance departments, each with its own management, should calculate the metric for each unit using unit-specific values for the variables.

4.5.6 Rework Count

Rework is additional maintenance (usually repeating the work done) that is required to be performed on the same equipment for the same problem or failure. Associating the warranty period after original work performance would enable consistent and correct determination of what is rework and what is not. Generally, work done by maintenance personnel should have an associated warranty time. For normally operating equipment, inadequate or improper workmanship will most likely result in a failure during post-maintenance testing or shortly thereafter. For standby equipment, if it does not fail during post-maintenance testing, the condition would be discovered only during a subsequent operational test. Therefore, the warranty period should consider both cases. For PMs, the warranty time is inherent in the PM frequency. However, for PMs with long intervals, for example, more than a year, setting the warranty time equal to the PM interval would be unreasonable since other things can go wrong in the intervening period. Warranty times longer than a reasonable period, about six months, are not recommended since failures after that duration will more than likely be associated with other things going wrong. Thus, it would be a waste of time tracking and evaluating such repeat work since equipment history and recurring failures review programs should capture them. Similarly for CMs, a warranty time of six months is recommended. This document defines rework as follows:

> *Work re-performed within a specified period because work performed the first time was inadequate, incorrect, or performed using deficient parts and/or materials. Recommended period is six months or ½ of the PM interval, whichever is shorter.*

That raises the question of when does the warranty period start. The warranty clock should start when the specified maintenance work is completed and the equipment is returned to service. Some plants consider that if a failure occurs during post-maintenance testing or before return to service and requires redoing substantially all of the work, then that should also be included in the rework count. While this position is logically correct, considering that it is subject to human bias, the return on investment in tracking and evaluating such repeat work items would not make it worth the cost including worker morale. Craft supervision should be able to deal with such situations in the normal course of business.

This metric indicates the number of work orders that were re-performed because of inadequate or improper workmanship or use of deficient parts and materials when the work was done the first time.

The term “rework” is not consistently defined and used in the industry. Current practice is for a screener to determine and keep a log of whether a work request is a rework item based on his/her determination of what went wrong. Tracking rework count should be automated by including a suitable algorithm in the MMS. A monthly report of rework counts should be generated and evaluated to determine the cause and take appropriate remedial and corrective actions. A higher rework count in comparison to peers or constant/increasing rework count would demand determination of the underlying cause(s). If the evaluation indicates deficient parts or materials, it should be referred to the appropriate engineering department for follow-up. Otherwise, such a situation is normally indicative of inadequate training, procedures, and/or poor work culture.

Data Source

The benchmark was established by gathering the rework count data from maintenance support personnel who kept track (mostly manually) of the same. As noted before, the data are not considered fully reliable since, within the survey population, a consistent definition of rework and a documented framework for its collection and evaluation could not be established. Therefore, the benchmark established is a conservative estimate.

Benchmark: 24 work orders/year for the maintenance department as a whole

Multi-unit plants with a common maintenance department should use average per unit values for the rework count. Multi-unit plants with separate maintenance departments, each with its own management, should calculate the metric for each unit. Tracking and reviewing the rework count both at the maintenance department level and at the individual discipline level is recommended.

Goal: Zero

4.5.7 Emergency Work Count

If planned maintenance work costs $1 a unit, it is established that maintenance performed upon failure, that is, CM, usually costs $2. If maintenance after a failure has to be performed on an emergency basis (that is, an immediate response), then it will more likely cost $3 or more per unit since it is very disruptive in nature, could require overtime till the job is done, and even demand parts and service personnel to be flown in. Thus, to control maintenance costs, it makes sense to monitor the amount of work that is classified and performed on an emergency basis. This metric is the annual count of emergency work orders.

Data Source

The data input for this metric is available from the MMS. All plants in the survey had a field in the MMS that captured work priority. Usually, Priority 1 or Priority "E" meant emergency work. However, it was noted that some plants did not capture work performed by Fix It Now (FIN) or Work It Now (WIN) teams in their work order system; for this reason, the data input gathered may not reflect the true picture. Note however, that FIN/WIN work is not necessarily emergency work. The data from the surveyed plants indicated that the definitions of "Priorities" vary from plant to plant or that the definitions are not being used consistently. Therefore, the benchmark given below is a conservative estimate based on data from the plants that were most consistent.

Benchmark: 50 work orders/year

Multi-unit plants with a common maintenance department should use average per unit values for the number of emergency work orders. Multi-unit plants with separate maintenance departments, each with its own management, should calculate the metric for each unit using unit-specific data.

Goal: < 10

4.5.8 Backlog Count and Days Overdue-Backlog

Backlog Count

Backlog count is a widely used indicator in the nuclear industry, but it has varying definitions from plant to plant. As currently used, it could mean either workload[6] at any given time or for a planning horizon, or overdue work of varying ages, or both. The intent of tracking backlog is to identify, monitor progress, and eliminate the accumulation of overdue work. If plants would like to make comparisons, this requires that the term "backlog" have a single meaning and consistent usage among plants.

---

[6] The Merriam-Webster dictionary meaning of the term "backlog" is *an accumulation of unperformed tasks*. The same dictionary defines "workload" as *the amount of work performed or capable of being performed within a specified period*.

Therefore, it is recommended that:

- The term “backlog” be defined as: *Overdue work that has missed its work window, is beyond its grace period, and has not been rescheduled.*
- Plants should consider monitoring backlog items by their age and by department on a weekly basis.

It is also recommended that the industry consider using the term “workload” to mean: *All work that has been scheduled, is within its grace period, and is waiting to be completed.*

Backlog, as now used by some power plants, consists of two parts, that is, current workload and overdue workload, hereafter referred to as “backlog.” Current workload is the amount of work scheduled for performance for the current planning horizon. Backlog is work not completed as scheduled in the previous planning horizon(s) that could not be or was not rescheduled and is carried over. Accumulation of backlog should be monitored closely to avoid continuous build up of work items.

Ensuring a reasonable service level by the maintenance department(s) requires assigning a threshold age after which backlog becomes critical. The recommended threshold age for backlog is 30 days since not performing scheduled work that could not be or was not rescheduled and remains undone past 30 days represents poor service level. The rationale is that, when the work was originally scheduled, it took into account the prerequisites (for example, parts arrival, window opportunity to do the work, access to equipment, availability of personnel, and so on) to get that work done. If that work was not performed as scheduled, it could not be or was not rescheduled and is more than 30 days past due; this condition raises questions such as:

- Why was it scheduled when it was?
- Is the work even required now?
- Was the criticality of the work and availability of personnel taken into account when it was scheduled?
- Is the department charged with getting the work done adequately staffed?
- Does the concerned department have a systematic program to track and complete overdue work?

To serve the purpose of monitoring and eliminating the accumulation of backlog, this document defines “backlog” as:

> *Work scheduled for performance during a specified time/window that was not done, could not be done, or was not rescheduled for whatever reason and is more than 30 days overdue.*

Backlog should be tracked automatically by incorporating a suitable algorithm in the MMS and generating weekly reports. Currently, it is not tracked in the MMS at any of the surveyed plants. Some plants manually download the required data from the MMS into a spreadsheet and process it to generate an aged backlog report. At three of the surveyed plants, the backlog > 90 days and ranged from 50 to 60 work orders. The remaining three did not track backlog by age and/or did not distinguish between current workload and backlog.

Data Source

The benchmark was established by gathering the backlog count from maintenance support personnel who kept track (mostly manually) of it at the surveyed plants. As noted before, the data are not considered fully reliable since a consistent definition of backlog and a documented framework for its collection and evaluation could not be established within the survey population. Therefore, the benchmark established is a conservative estimate based on a review of the relevant data from all the surveyed plants.

Benchmark: 50 work orders overdue > 30 days at any given time

Based on the average weekly work order turnover for the survey population, it represents about one week of work for a typical maintenance department with one fourth of its personnel dedicated only to clearing the backlog[7].

Multi-unit plants with a common maintenance department should use average per unit values for backlog. Multi-unit plants with separate maintenance departments, each with its own management, should calculate the metric for each unit using unit-specific values for the variables.

Goal: < 20

Days Overdue-Backlog

"Days overdue-backlog" would be a more useful metric than the count of backlog. It is defined as the number of days it would take 25% of the craft in the concerned maintenance department working only on backlog to clear it. This metric would give a clear and direct indication of any serious misalignment of resources The underlying causes for a high number or adverse trend in this metric include:

- Chronic understaffing
- Poor estimation of the time required to perform work
- Poor planning
- Scheduling problems

This metric should be computed for the maintenance department as a whole and for each discipline. This metric could be calculated as shown here.

Calculation:

$$\text{Days Overdue-Backlog} = \frac{(\text{\# of Work Orders Overdue} > 30 \text{ Days}) \times 4 \times 7}{\text{Work Orders Completed per Week}}$$

Example :

$$\text{Work Orders Overdue} > 30 \text{ Days} = 121$$

$$\text{Average \# Workorders Completed per Week} = 192$$

$$\text{Days Overdue-Backlog} = \frac{121 \times 4 \times 7}{192} = 17.6 \text{ days}$$

---

[7] Half of the survey population tracked backlog by age. At these plants, the average backlog aged 90 days or more was approximately 100 work orders.

Benchmark: Less than one week

This benchmark is an estimate based on the relevant data collected from the six surveyed plants. Multi-unit plants with a common maintenance department should use average per unit values for the number of emergency work orders. Multi-unit plants with separate maintenance departments, each with its own management, should calculate the metric for each unit.

Goal: Zero

4.5.9 Hours Per 100 MW Rated Capacity

This metric enables comparison of personnel used in providing maintenance function based on the installed capacity of each unit. It includes person-hours of:

- All personnel in maintenance and the maintenance support function including administrative and management personnel
- Scheduling support for the maintenance function
- Procedure support for the maintenance function
- PdM engineering support for IR, vibration, and oil analysis programs

Calculation:

$$\text{Person-Hours/100 MW} = \frac{(\#\text{ of Persons in the Maintenance Function} \times 1840) \times 100}{\text{Unit Rated Capacity}}$$

Benchmark: 31278 Person-hours/100 MW

The benchmark is directly applicable to multi-unit plants with per unit capacity ranging from 800 MW to 1300 MW. Single unit plants should adjust the benchmark by a factor obtained from Figure 4-2. Multi-unit plants with a common maintenance department should use average per unit values for person-hours and installed (that is, licensed full power rating) capacity. Multi-unit plants with separate maintenance departments, each with its own management, should calculate the metric for each unit using unit-specific values for the variables.

Goal: To be the lowest among those in the lowest quartile in the industry/reference group

4.5.10 Procedure Stability and Quality

Given that the nuclear plants in the United States have been operating for more than 15 years on the average, one should expect that the procedure system for performing maintenance work on equipment should be stable and high in quality. Changes should be minimal for correcting technical errors or omissions and mainly driven by the need to:

- Address areas previously not addressed by the procedures
- Incorporate changes to equipment/systems
- Address additions/deletions of systems/equipment

Since the industry is now beyond the learning curve and the era of regulatory-driven plant modifications, if a plant experiences a high percentage of procedure changes on a continuing basis, it is indicative of a weak procedural system and will reflect in the productivity of craft personnel. Two metrics that are indicative of the quality and stability of procedures included are:

1. Number of procedure changes expressed as a percentage of all active procedures
2. Number of procedures changed expressed as a percentage of all active procedures

Continuing high levels of either or both metrics can increase the cost of providing the maintenance function and affect the productivity of the maintenance department.

Percent of Procedure Changes

This metric looks at the number of procedure changes processed as a percent of the total number of active procedures. Total number of active procedures includes maintenance procedures and surveillance procedures performed by the maintenance department. For multi-unit plants, since all or a substantial number of the procedures are usually separate and distinct for each unit, this metric should be calculated for each unit using unit-specific values for the variables.

Calculation:

$$\%\ \text{Procedure Change per Year} = \frac{100 \times (\#\ \text{of Procedure Change Requests Processed in a Year})}{\text{Total Number of Active Procedures}}$$

Only procedure change requests processed that resulted in a procedure change should be included. When counting the number of procedure changes processed, if a procedure was changed more than once during the monitoring period, then each occurrence should be counted as an individual procedure change. The intent is to identify systemic problem(s) so that corrective action can be taken.

Benchmark: = 70%

Note that this benchmark is quite high.

Goal: ≤ 20%

Percent of Procedures Changed

This metric looks at the number of procedures affected by the procedure changes discussed earlier. It is also calculated as a percentage of the total number of active procedures. For multi-unit plants, since all or a substantial number of the procedures are usually separate and distinct for each unit, this metric should be calculated for each unit using unit-specific values for the variables.

Calculation:

$$\%\ \text{Procedure Change per Year} = \frac{100 \times (\#\ \text{of Procedures Affected by Change Requests in a Year})}{\text{Total Number of Active Procedures}}$$

Benchmark: = 44%

Goal: ≤ 20%

4.5.11 Maintenance Productivity Index

This metric provides a composite view of a plant's maintenance productivity for comparison against its peers or the industry. It is derived by comparing the plant-specific individual productivity metrics discussed in Sections 4.5.1 through 4.5.10 against the respective benchmarks in the same manner as explained in Section 4.3.9. Table 4-12 provides a list of productivity metrics and what is considered better for each metric for purposes of scoring. Figure 4-9 shows the maintenance performance index for the surveyed plants and the reference or benchmark.

Table 4-12
List of Productivity Metrics and What is Good

Metric	What is Good
Wrench Time	> industry
Craft WO Turnover	> industry
Planner-to-Craft	< industry
WO/Planner-Wk	> industry
Staff-to-Craft	< industry
WO/Staff Wk	> industry
Rework WO Ct	< industry
Emergency WO Ct	< industry
% Procedure Changes	< industry
% Procedures Changed	< industry
Hrs/100 MW	< industry
Days Overdue-Backlog	< industry

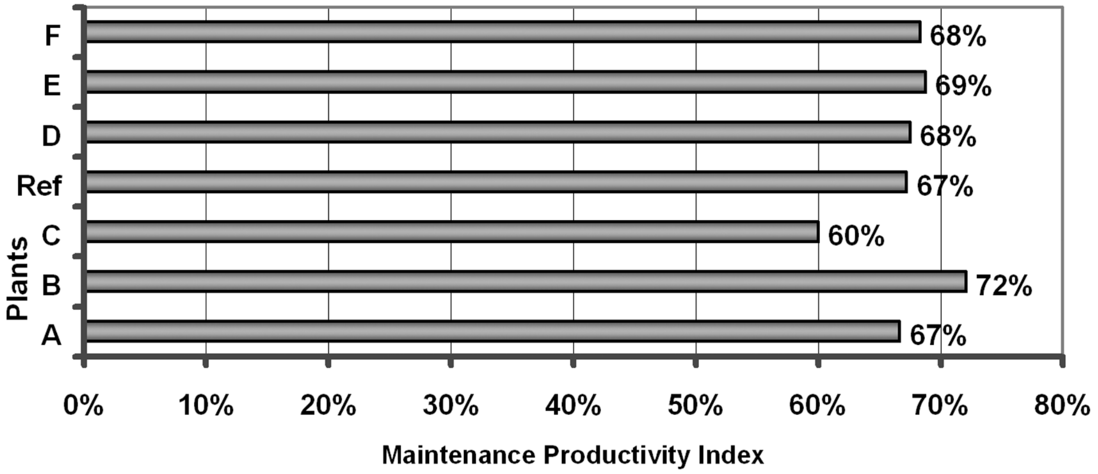

Figure 4-9
Maintenance Productivity Index for Surveyed Plants

4.6 Maintenance Effectiveness Index

An effective maintenance program is one that consistently delivers *at the lowest practical cost* when compared to its peers:

- Zero maintenance-induced safety system challenges, unplanned production losses, and unplanned plant trips
- Zero regulatory violations
- Zero lost time injuries
- Lowest worker radiation exposure

The list above is predominantly performance (that is, results) oriented. The term *at the lowest practical cost* demands that we look at the cost in terms of dollars and person-hours employed, the underlying processes and productivity, together with the results listed above. This can be done by computing a composite index called the "maintenance effectiveness index," which is an arithmetic average of the three-Ps indices:

- Performance index (see Section 4.3.9)
- Process index (see Section 4.4.8)
- Productivity index (see Section 4.5.11)

The maintenance effectiveness index would be indicative of performance, comprehensiveness of the maintenance programs employed, and the underlying process efficiencies. Figure 4-10 shows a bar chart of the overall maintenance effectiveness index and its components for all six plants included in the survey and their average.

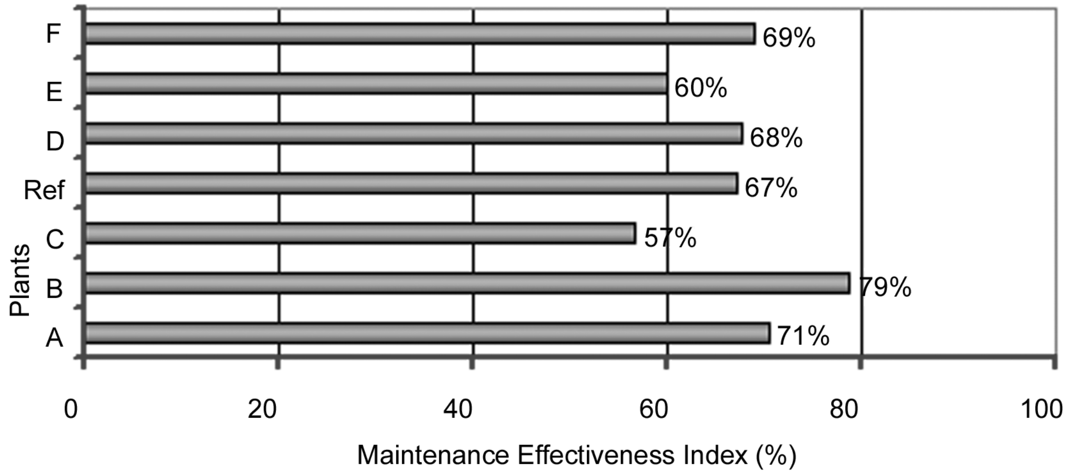

Figure 4-10
Maintenance Effectiveness Index for Surveyed Plants

4.7 Human Performance Index

An index of human performance can be calculated by combining the following seven metrics:

1. Maintenance-related trips (see Section 4.3.3)
2. Maintenance-related power loss events (see Section 4.3.4)
3. Maintenance-related LERs (see Section 4.3.5)
4. Maintenance-related regulatory violations (see Section 4.3.6)
5. Maintenance-related lost time events (see Section 4.3.7)
6. Rework count (see Section 4.5.8)
7. Days overdue-backlog (see Section 4.5.8)

Using the same comparison and scoring methods as outlined in Section 4.3.8, a human performance index (HPI) is calculated. The maximum a plant can score is 7 out of 7 (which is equal to 100%), indicating excellent human performance, that is, excellent work culture, skills/knowledge levels, and procedure systems that minimize human errors that lead to high levels of rework and backlog. Figure 4-11 shows the HPIs for the surveyed plants and the benchmark.

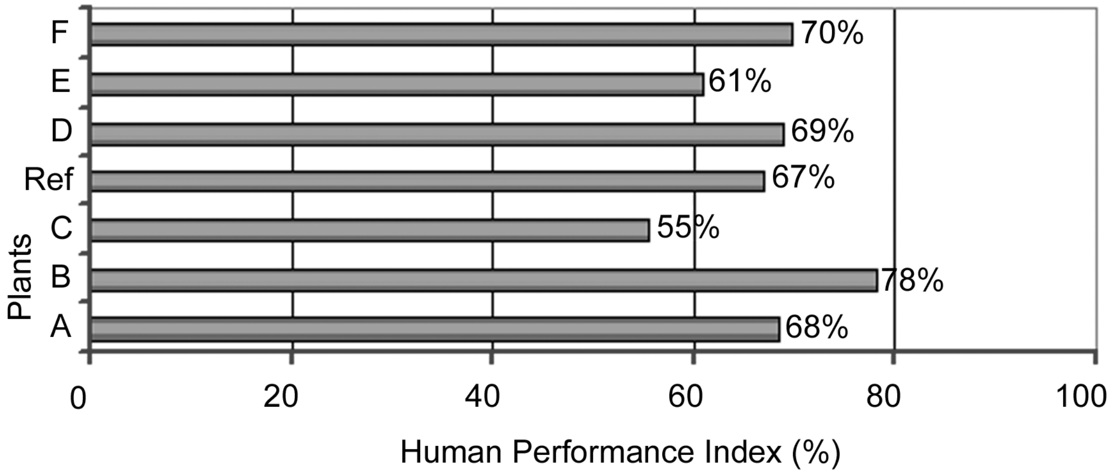

Figure 4-11
Comparison of Human Performance Index for Surveyed Plants

5

CORRELATING THE METRICS TO ASSESSMENT AREAS

Typical peer/self assessments focus on five major areas (that is, work identification, work control, work execution, work closeout, and overall maintenance program) of the maintenance process. Each of these major areas can be subdivided into several sub-areas. Table 5-1 presents a line up of these major areas, sub-areas, and the metric(s) that addresses them individually or as a group.

Table 5-1
Correlating Metrics to the Maintenance Process Elements

Assessment Area • **Sub-area(s)**	**Related Metrics**
Work Identification • Maintenance basis • PM program • CM program	1. Total number of equipment items covered under all types of maintenance program 2. Percentage of total included in PM 3. Percentage of total included only under CM 4. PdM as percentage of total included in PM 5. Percentage of safety-related equipment included in PM 6. Percentage of non-safety equipment included in PM 7. Percentage of PM performed at power
Work Control • Prioritization • Risk assessment • Planning • Scheduling • Work/crew assignment • Contracted work	1. Total number of work orders serviced 2. Percentage of WOs in PM and CM 3. Percentage of procedure changes 4. Percentage of procedures changed 5. Percentage of contracted maintenance 6. Backlog, overdue-backlog, and days overdue-backlog 7. Staff to craft ratio 8. Planner to craft ratio

Table 5-1 (continued)
Correlating Metrics to the Maintenance Process Elements

Assessment Area • **Sub-area(s)**	**Related Metrics**
Work Execution • Tools and materials management and staging • Pre-job briefing • Risk management • Use of work procedures • Perform tasks • Work quality control/management • Safety program implementation	1. Number of unplanned trips, power loss events 2. Number of LERs and regulatory violations 3. Percentage of procedure changes 4. Percentage of procedures changed 5. Rework counts 6. Backlog, overdue-backlog, and days overdue-backlog 7. Wrench time 8. Work order/wrench week 9. Work order/planner week 10. Lost person-hours due to injury 11. Annual worker exposure
Work Closeout • Post-maintenance testing • Post-job critique • Data capture and documentation • Return to service	1. Work order turnover/week 2. Work orders/staff week 3. Wrench time
Maintenance Program • Ownership • Department expectations • Performance • Productivity • Self-assessments	Maintenance effectiveness index, its three-Ps components, and human performance index

The metrics in Table 5-1 are intended to provide insights that should help focus the peer/self assessment activities. With the metrics in hand, the assessors should have some indication of potential gaps in the maintenance program.

6

RECOMMENDATIONS FOR USING THE PROPOSED METRICS

The set of metrics proposed in this document consists of some that are intended for one-time use and others intended for ongoing use. Recommended steps for initiating the use of the metrics are:

- Start by establishing snapshot values for the one-time metrics. For some one-time metrics, it may be advantageous to collect and evaluate historic data for three to five years to see how the maintenance program has varied. For instance, looking at the historic data for the number of components included in the predictive maintenance program could indicate the rate of growth of the program. It may warrant either using that metric as an ongoing metric until the program stabilizes or revisiting this metric again, for example, at the end of the next monitoring period.
- Collect historic data for the ongoing metrics for the selected historic duration (preferably five years or a minimum of three years). Benchmarking was done based on three years of data, 1999–2001.
- Compute a three-year rolling average (that is, the average of years 1, 2, and 3; 2, 3, and 4; 3, 4, and 5) annual values for the ongoing metrics using historic data. Compute the baseline values as the average of the three 3-year rolling averages. If only three years of historical data are used, then baseline values will be the three-year average. Examine the baseline values and the historic data for any distortion. For instance, if the percentage of procedure changes in year 3 of a set of five yearly values was 30% whereas the others were in the range of 5% to 10%, the reason for the high value in year 3 should be examined, and the appropriate discount applied or the value should be thrown out. If year 3 was the year when a major procedure revision project was performed to change the formats of all I&C procedures, then a discount to reflect that special one-time effort may be appropriate.
- Compare the snapshot values for one-time indicators and baseline values for ongoing metrics against the benchmarks in this document and, if available, against corresponding metrics for a reference group of plants. Analyze the differences to identify any significant variations (for example, delta > 25% in the adverse direction) for further examination. In addition, flag any adverse trend in the plant metric values for the selected historical duration for further examination.
- Examine the deviations and, if appropriate, identify remedial or corrective actions that might be required.

- Store these baseline values for ongoing metrics and the snapshot values for the one-time metrics for future use.
- Decide on the periodic report generation needs (that is, monthly, quarterly, and so on), and implement the software changes required to generate the reports automatically. Alternately, a set of queries may be used for downloading the relevant data input from the respective data systems (for example, MMS) into a Microsoft Excel spreadsheet. All metrics computation and report generation can be set up to run on Excel. This method (used by the investigator on this project) would perhaps be more expedient and easier to accomplish. In addition, it will have the benefit of local control to permit easier modifications in the future.
- Establish a procedure assigning the responsibilities for chargeability determination where required (for example, data input, report generation, and distribution).

7

OBSERVATIONS AND RECOMMENDATIONS

This section lists and discusses the insights gained about the maintenance function at the surveyed plants during the process of collecting the data required to support the benchmark development.

1. The data required to compute the metrics set discussed in this document were readily available in the plant MMS and a few other data systems such as the equipment list, event tracking, plant operating history, worker radiation exposure tracking, and OSHA reportable events. Queries were written by the maintenance support staff relatively easily (on the average, it required a few hours) to download the data into an Excel spreadsheet for further processing by the investigators. At each of the surveyed plants, the support staff that provided all data collection was about two full-time equivalents for one week.

2. There is a fair degree of commonality among the surveyed plants in their MMS and other data systems used. It is reasonable to assume that, with very few exceptions, the same degree of commonality may be expected throughout industry. It indicates that implementing a metrics system for monitoring maintenance as discussed in this document should be feasible with minimal resource expenditure and disruption to existing systems and practices.

3. Overall, based on cost data for the surveyed plants, maintenance cost was about 25% of the non-fuel O&M cost. This applies to single and multi-unit plants.

4. During the survey period, 1999–2001, the data did not indicate any trend of growth or reduction in annual maintenance workload or its breakdown. That is, there has been no growth or reduction in the number of PM or CM work orders serviced during the survey period.

5. Only one of the six plants in the survey had a comprehensive system to capture actual person-hours spent on each work order by the craft and other support staff such as planners, work control and maintenance support engineers/technicians. Others did not do so, either fully or partially. Actual hours are a valuable data set to mine for opportunities for improvements in cost effectiveness of maintenance. For example, three of the six plants in the survey had emergency work order counts in the hundreds. Those plants also had high maintenance costs relative to others in the survey. While the high cost of maintenance may be due to any number of reasons, looking at the work order prioritization and hours spent on emergency work execution may lead to cost savings.

6. At the surveyed plants, PdM apparently means thermography, oil analysis, and vibration analysis. This narrow view seems to be prevalent throughout the industry as shown by the discussions the investigators had with PdM engineers gathered at a recent User Group meeting. In reality, more than a dozen other programs such as motor monitoring, MOV diagnostics, transformer monitoring, DG performance analysis, and flow accelerated corrosion fall into this category.

7. The responsibilities and budgets for PdM are dispersed under many plant groups in the engineering and the plant O&M organizations. If a comprehensive view were taken of all the PdM programs in place at a plant, it would reveal an activity of substantial scope and budget that could benefit from consolidation under one organization. Together, the total annual expenditure for all PdM programs together is estimated to exceed 3 million dollars and 25000 person-hours. Such a consolidation could potentially reduce cost and improve the efficiency of managing and delivering this function, level of expertise, and data management.

8. Generally, PdM-related field data collection is performed mostly by the maintenance craft. In some plants, some of the IR and vibration data collection is apparently performed by system engineers. It would be preferable to transition to a situation where all PdM data collection, diagnostic testing, and first level screening of the data are performed routinely by maintenance craft as some plants have done. Besides freeing up the engineers, it would have the benefit of having large cadre of trained personnel capable of doing this work and permit integrating PdM data collection as part of the maintenance routine.

9. Generally, it was noted that PdM engineering analysis expertise for each PdM is concentrated in an individual, often with no backups. This situation is not conducive to smooth functioning and transition for the long run. Consolidation of PdMs under one roof would offer opportunities to develop and maintain backup capabilities.

10. At some plants, some PdM tasks (IR survey, oil analysis sample collection) are not performed under the work order system. It would be preferable to perform all PdM work under the work order system. Currently, PdM work is coded under the “PM” category in the MMS. PdM work orders should be uniformly coded under their own category such as “PdM-OI” for oil analysis. That would permit monitoring the cost of PdM and its benefits. A larger question that needs to be addressed is, are PdMs living up to their expectations, (that is, reduce PM and/or reduce/eliminate CM). This question can be answered from the work order system if all the PdM tasks, affected equipment ID numbers, and actual hours can be tracked.

11. Rework and backlog, the two widely used indicators in the industry lack consistent definitions. In addition, because the data capture depends heavily on human intervention, the data obtained from the plants varied so much that that it raised questions about the true value of these indicators as used today (that is, the ability to draw meaningful conclusions about the maintenance process and make meaningful comparisons across the industry). See Sections 4.5.6 and 4.5.8 for a detailed discussion.

12. At three of the six surveyed plants, the number of emergency work orders per year ranged in the hundreds per unit per year. One had two emergency work orders per unit per year. The wide disparity in these numbers raises the question of whether the prioritization of work in plants is based on uniform criteria. If it is true (investigators believe otherwise) that three

plants with the counts in the hundreds are correctly prioritizing their work orders, then it points to an opportunity for substantial cost saving through improvements in PM.

13. Other metrics that can be computed from the data available in a typical plant MMS include the following:
    - Days to close out work order documentation—indicates staff service level
    - Response time for CM work requests—indicates maintenance response level
    - Mean time to repair for all components with a CM work order—indicates maintenance response level, provides a basis for refining estimated durations for CM work, and improves work scheduling
    - Maintenance improvement index—Indicates improvement, or lack thereof, for selected maintenance metric(s)
    - Mean time to failure for all components with a CM work order—Indicates service level, provides a basis for replacement decisions
    - Cost of servicing emergency work orders—identifies opportunities for reducing cost of maintenance function

8

SUMMARY

Effective maintenance programs are those that can deliver reliable performance of systems, structures, and components with maximum availability and life at the lowest practical cost in comparison to peers/industry. Special performance requirements and increased competition in the utility industry demand a well-thought-out maintenance strategy supported by a balanced mix of maintenance programs. Current maintenance strategies include a mix of maintenance activities that have evolved over the years. Although maintenance programs have been generally successful in ensuring an adequate level of system and equipment availability, the programs are composed of an assorted mix of preventive and corrective maintenance activities that are not necessarily cost effective. Learning curve considerations and evolutionary responses to operating experience, management requirements, and regulatory demands have relegated cost effectiveness to a secondary consideration.

Over the past decade, utilities have also experimented (with varying levels of success) with preventive maintenance optimization programs using reliability-centered maintenance (RCM), customized versions of RCM, or other in-house methodologies. Recognition that periodic maintenance alone may not be sufficient to arrest/reduce age-induced failures has broadened the use of *predictive maintenance* (PdM) technologies or condition monitoring. Unfortunately, PdM efforts have also evolved randomly. PdMs were introduced to address specific needs or to better operate within resource constraints. Further, the maintenance rule, which became effective in 1996, caused plants to implement steps to strengthen various aspects of maintenance programs including significantly expanding the scope of *preventive maintenance* (PM) programs.

A set of metrics that looks at the three Ps of maintenance (performance, process, and productivity) can be useful in assessing maintenance effectiveness. Such a set of metrics along with the respective benchmarks is presented and discussed in Section 4 of this document. The work performed to develop the benchmarks given in this document for each of the metrics involved six plants, which represents a total of 13 units. This work also established that the metrics could be generated using data available in the existing plant data systems. If used on an ongoing basis, this set of metrics can:

- Identify potential areas of concern in maintenance before they become a problem
- Provide a basis for calibrating a plant maintenance program against its peers or the industry
- Focus or reduce the level of effort to conduct peer/self assessments currently being performed at nuclear power plants

Some examples of the key insights gained about maintenance programs/functions during this benchmarking effort are as follows:

- The data required to compute the metrics discussed in this document were available and readily retrievable from most plants' MMS and a few other data systems. Queries were written by the maintenance support staff (on the average, required a few hours) to download the data into a Microsoft Excel spreadsheet for further processing. At each of the surveyed plants, the staff required to support the project was about two fulltime equivalents for one week.
- In general, maintenance cost as a percentage of non-fuel O&M cost was about 25%.
- Only one of the six plants in the survey had a comprehensive system to capture actual person-hours spent on each work order by the craft and other support staff such as planners, work control, and maintenance support engineers/technicians. Others did not do so, either fully or partially. Actual hours can be a valuable data set when looking for improvement opportunities in cost effectiveness of maintenance. For example, monitoring the cost of emergency maintenance can identify opportunities for cost savings by implementing steps to eliminate or reduce the need for emergency maintenance.
- A more comprehensive view of what constitutes PdM and how that those activities can be more effectively implemented could improve efficiency. At most plants, PdM means thermography, oil analysis, and vibration analysis. In reality, more than a dozen other programs, for example, motor monitoring, MOV diagnostics, and diesel engine performance analysis to name a few, fall into this category. The responsibilities and budgets are dispersed under many groups. If a comprehensive view is taken of all the PdM programs in place, it would reveal a substantial scope and budget that deserves consolidation under one organization. Such a consolidation, offers the potential to improve the efficiency of managing and delivering this function, the level of expertise, and data management.
- Rework and backlog were two of the most widely used indicators in the industry; however, both lack consistent definitions and use. In addition, because the data capture depends heavily on human intervention, the data obtained from the plants varied so much until it raised questions about the true value of these indicators and the ability to make meaningful comparisons across the industry. This report offers definitions that, if used, could bring consistency and allow plants to compare values for these and other indicators or metrics.

9

REFERENCES

1. *Nuclear Energy Institute Industry Guideline for Monitoring the Effectiveness of Maintenance at Nuclear Power Plants*, NEI (NUMARC) 93-01, April 1996.
2. *Aspects of Setting Performance Criteria for Systems, Structures, and Components Within the Scope of 10 CFR 50.65, The Maintenance Rule for Nuclear Power Plants*, D. Worledge, EPRI, September 1, 1994.
3. *NRC Regulatory Guide 1.160—Monitoring the Effectiveness of Maintenance at Nuclear Power Plants*, Rev. 2 March 1997
4. *WANO Performance Indicators for the U.S. Nuclear Utility Industry*, 2000 Year-End Report, April 2001.
5. *Assessing Maintenance Effectiveness*, EPRI, Palo Alto, CA: December 1996. TR-107759.
6. *Plant Maintenance Optimization Assessment Guideline*, EPRI, Palo Alto, CA: December 2000. 1000321.
7. *Predictive Maintenance Self-Assessment Guideline for Nuclear Power Plants*, EPRI, Palo Alto, CA: December 2000. 1001032.
8. *Improving Maintenance Effectiveness Guideline*, EPRI, Palo Alto, CA: March 1998. TR-107042.
9. *Guideline for System Monitoring by System Engineers*, EPRI, Palo Alto, CA: March 1997. TR-107668.
10. *Equipment Reliability Process Description*, INPO AP-913, March 2000.
11. *Work Management Process Description*, INPO AP-928, December 2000.
12. *Guideline for Assessing the Effectiveness of Maintenance*, EPRI, Palo Alto, CA: December 2002. 1002932.

A
SURVEY AND ANALYSIS METHODOLOGY

Early in the project, it was decided that the benchmarks for the proposed metrics set would be developed based on actual data gathered through site visits to a representative sample of nuclear plants. This appendix describes the criteria used for selecting the representative sample, the data gathered from the plants, and the analysis performed.

A.1 Survey Population

Currently, in the United States, there are 69 nuclear plants with 102 units, dispersed geographically. This population includes four different reactor types[1] with installed capacities ranging from 500 MW to 1300+ MW. To ensure that the data for developing the maintenance metric benchmarks are representative of the industry as a whole, the following criteria for selecting plants were established:

- Single plant and multi-plant owners should be included.
- Single unit and multi-unit plants should be included.
- Plants should be geographically dispersed.
- Early vintage and recent vintage plants should be included.
- The range of installed capacities should be adequately covered.
- All four reactor types should be included.
- At least 15% of the population in both unit counts and installed capacities should be included.
- Investor-owned and government-owned plants should be included.
- To the extent practical, plant designs by at least three different architect-engineers (AEs) should be included.

---

[1] Boiling water reactors from General Electric Co. and pressurized water reactors from Westinghouse, Combustion Engineering, and Babcock and Wilcox.

The survey population consisted of six plants, referred to throughout this report only as plants A–F[2], and together had the following characteristics:

- Six plants of the total 69 plants operating are represented.
- Thirteen units of the 106 units operating are represented.
- Installed capacities ranged from 600 MW to 1350 MW.
- Total installed capacity included 13,000+ MWs of the 102,000 total MWs.
- Single plant and multi-plant owners are represented.
- Single, two and three unit plants are represented.
- All four reactor types are represented.
- Designs from two different AEs are represented.
- Plants are geographically dispersed across the United States.
- Early vintage and recent vintage plants are represented.

Thus, the population selected met eight of the nine criteria listed; the exception was criterion 7. Early in the project, it was acknowledged that, since participation was voluntary, it might be difficult to meet all of the criteria. Therefore, the population sample is believed to be representative of the entire installed nuclear plant population in the United States. As a crosscheck, historical data on non-fuel O&M costs for the surveyed plants were reviewed. As shown in Figure A-1, they are evenly spread around the average, indicating that the population is reasonably representative of the industry.

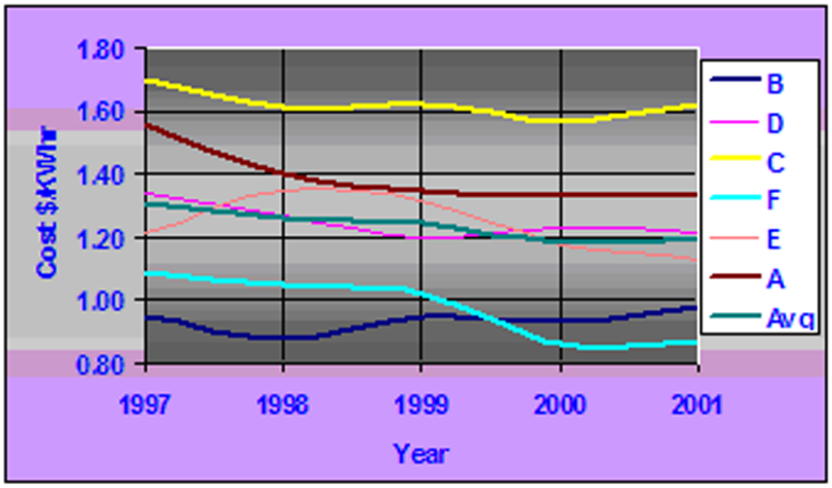

Figure A-1
Non-Fuel O&M Cost for Surveyed Plants

---

[2] In accordance with the confidentiality agreement with the individual plants, throughout this report, plants are referred to only as plants A through F.

A.2 Data Gathered

The metrics set for monitoring and assessing maintenance effectiveness consists of 42 metrics. The total number of data elements collected from the plant databases was 91. Most of these data came from three databases: maintenance management system, equipment list, and the PM basis. Table A-1 lists each data element and its source.

Table A-1
Source of Data Elements

Row #	Data Element	Source of Data
1	Number of maintenance-induced unplanned trips	LER database and actual LERs
2	Number of maintenance-induced unplanned power loss events	LER database and actual LERs
3	Number of maintenance-induced violations	LER database and actual LERs
4	Number of maintenance-induced LERs	LER database and actual LERs
5	Lost time incidents - maintenance injuries only	Plant safety records database
6	Worker exposure (maintenance dept.) in rems	Plant exposure records database
7	Total annual maintenance cost in $	Calculated
8	Annual cost in $ under maintenance dept. control	Plant financial records and FERC account reports
9	Annual PdM cost calculated for various programs	Individuals responsible for the specific program
10	Contracted maintenance/services in dollars	Plant financial records
11	Annual production in MWhrs	Plant production reports
12	Person-hour cost allocated to PM	Calculated with data from MMS
13	Person-hour cost allocated to PdM	Individuals responsible for the specific program
14	Person-hour cost allocated to CM	Calculated with data from MMS
15	Cost allocated to maintenance craft training	Estimates provided by training dept or actual data from training records database
16	Annual person-hours spent on maintenance including PdM	Calculated from organization charts supplemented with data from MMS
17	Person-hours expended on PM	Calculated from organization charts supplemented with data from MMS
18	Person-hours expended on CM	Calculated from organization charts supplemented with data from MMS
19	Person-hours expended on PdM	Individuals responsible for the specific program
20	Total work orders serviced incl. PdM	Calculated with data from MMS
21	Number of work orders serviced	Calculated with data from MMS
22	Number of PM work orders serviced including PdM	Calculated with data from MMS
23	Number of CM work orders serviced	Calculated with data from MMS
24	Number of PdM work orders serviced	Calculated with data from MMS
25	Number of RS work orders serviced = HR + MR	Calculated with data from MMS
26	Number of NRS work orders serviced = LR + NRS + n/a	Calculated with data from MMS

Row #	Data Element	Source of Data
27	Number of SR work orders serviced	Calculated with data from MMS
28	Number of NSR work orders serviced	Calculated with data from MMS
29	Number of work orders attributable to rework	Calculated with data from MMS
30	Number of work orders attributable to emergency work	Calculated with data from MMS
31	Backlog count	
32	Backlog count – I&C	Maintenance support staff records
33	Backlog count – Electrical	Maintenance support staff records
34	Backlog count - Mechanical	Maintenance support staff records
35	Periodic maintenance	Calculated from MMS data where actual hours data are available
36	Predictive maintenance	Calculated from MMS data where actual hours data are available
37	Corrective maintenance	Calculated from MMS data where actual hours data are available
39	Mechanical	Calculated from organization charts
40	Electrical	Calculated from organization charts
41	I&C	Calculated from organization charts
42	Other craft	Calculated from organization charts
43	Total craft hours available	Calculated from organization charts
44	Craft wrench time	Calculated from data gathered through interviews
45	Person hours for selected equipment	
46	Main turbine	Calculated from MMS data where actual hours data are available
47	Main generator	Calculated from MMS data where actual hours data are available
48	Diesel generator	Calculated from MMS data where actual hours data are available
49	Reactor coolant pumps	Calculated from MMS data where actual hours data are available
50	Feedwater pumps	Calculated from MMS data where actual hours data are available
51	Main steam and feedwater isolation valves	Calculated from MMS data where actual hours data are available
52	Plant protection system	Calculated from MMS data where actual hours data are available
53	Nuclear instrumentation system	Calculated from MMS data where actual hours data are available
54	Radiation monitoring system	Calculated from MMS data where actual hours data are available
55	Security system	Calculated from MMS data where actual hours data are available
56	Number of tagged components in the plant	Equipment list
57	Number of SR equipment items	Equipment list
58	Number of NSR equipment items	Equipment list
59	Number of RS equipment items	Equipment list

Row #	Data Element	Source of Data
60	Number of NRS equipment items	Equipment list
61	Number of equipment items covered under PM (incl. PdM)	Equipment list
62	Number of equipment items covered under CM	Equipment list
63	Number of equipment items covered under PdM	Equipment list
64	Number of SR equipment items covered under PM (incl. PdM)	Equipment list
65	Number of SR equipment items covered under CM	Equipment list
66	Number of SR equipment items covered under PdM	Equipment list
67	Number of NSR equipment items covered under PM (incl. PdM)	Equipment list
68	Number of NSR equipment items covered under CM	Equipment list
69	Number of NSR equipment items covered under PdM	Equipment list
70	Number of RS equipment items covered under CM only	Equipment list
71	Number of RS equipment items covered under PM incl. PdM	Equipment list
72	Number of RS equipment items covered under PdM	Equipment list
73	Number of NRS equipment items covered under CM only	Equipment list
74	Number of NRS equipment items covered under PM incl. PdM	Equipment list
75	Number of NRS equipment items covered under PdM	Equipment list
76	Number of PMs performed at power	PM basis database and/or MMS
77	Number of PMs performed during outage only	PM basis database and/or MMS
78	Number of PMs on SR equipment performed at power	PM basis database and/or MMS
79	Number of PMs on SR equipment performed during outage only	PM basis database and/or MMS
80	Number of PMs on NSR equipment performed at power	PM basis database and/or MMS
81	Number of PMs on NSR equipment performed during outage only	PM basis database and/or MMS
82	Number of PdMs on SR equipment performed at power	PdM database maintained by cognizant engineers
83	Number of PdMs on NSR equipment performed at power	PdM database maintained by cognizant engineers
84	Staff person-hours	Calculated from organization charts
85	Number of mechanical planner hours available	Calculated from organization charts
86	Number of electrical planner hours available	Calculated from organization charts
87	Number of I&C planner hours available	Calculated from organization charts
88	Number of other planner hours available	Calculated from organization charts
89	Total number of procedures	Procedure database
90	Number of procedure changes	Procedure database
91	Number of procedures affected	Procedure database

For informational purposes, the data collection took approximately, two person-weeks of work by the EPRI team and two person-weeks of support from the plant maintenance support staff.

A.3 Data Analysis

Mostly, the data downloads were received from the plants in either comma-separated values format or direct Excel spreadsheets. The benchmark values provided in Section 4 were derived from standard Excel spreadsheet operations performed on the data downloads. Data analysis consisted of the following:

- Exporting the data downloads if necessary, into Excel spreadsheets.
- Reviewing the data downloads to ensure data integrity. With very few exceptions, the data downloads from the plants were readily usable and required only a few adjustments, mostly deletions of a few corrupt records.
- Deleting records that were non-maintenance responsibility. For example, in some plants, surveillance tests performed by maintenance personnel and operations were listed with the same category. That required identifying and deleting records using performing craft code.
- Rearranging the data in a standard format so that data from all plants could be used to perform standard Excel operations such as consolidation, pivot calculations, Dcount, and Dsum. Pivot tables were used to obtain counts and sums. Consolidation operations were used to obtain unique counts.
- When required, adjusting the counts for work performed without work orders. For instance, in one plant, minor and routine maintenance work such as lubrication was performed under task cards that were not recorded in the work order management system.
- Adjusting the counts for the PdM work not performed under the work order management system.

A.4 Summary of Plant Metrics

Table A-2 presents a summary of the metrics calculated for the surveyed plants and their averages. For multi-unit plants, the values in the tables for the metrics are per unit. Because the plants surveyed are believed to be representative of the industry as a whole, these averages are considered reasonable benchmarks for the respective metrics.

Table A-2
Metrics Values for Surveyed Plants and Benchmarks

Metrics	Plant A	Plant B	Plant C	Plant D	Plant E	Plant F	Benchmark
Performance metrics							
Number of maintenance-induced unplanned trips	0.00	0.00	0.67	0.00	0.33	0.33	0.22
Number of maintenance-induced unplanned power loss events	0.00	0.00	0.33	0.00	0.44	0.00	0.13
Number of maintenance-induced violations	0.67	0.00	0.00	0.00	0.00	0.00	0.11
Number of maintenance-induced LERs	2.00	1.00	2.00	4.00	0.56	1.00	1.76
Lost time incidents - maintenance injuries only	NA	1.33	1.06	1.50	1.00	0.67	1.11
Worker exposure (maintenance department) in person-rems	12	NA	64	48	93	64	56
Annual direct maintenance cost in cents/KWhr	0.21	0.12	NA	0.33	0.47	0.30	0.28
Annual person-hours expended on maintenance in hrs/MILLION KWhr	37	33	43	47	45	46	42
Performance Index	**74%**	**89%**	**48%**	**68%**	**49%**	**74%**	**67%**
Process Metrics							
Total number of work orders serviced including PdM	8752	10227	6280	18081	10986	17724	12008
Percentage of work orders designated PM	68%	72%	57%	81%	73%	70%	70%
Percentage of work orders designated CM	32%	28%	43%	19%	27%	30%	30%
Percentage of work orders designated safety-related	44%	39%	28%	27%	23%	21%	30%
Percentage of work orders designated non-safety-related	56%	60%	72%	73%	77%	79%	69%
Percentage of person-hours expended on PM	53%	57%	46%	65%	59%	50%	55%
Percentage of person-hours expended on CM	46%	40%	57%	30%	46%	44%	44%
Percentage of person-hours expended on PdM as percentage of PM	8%	6%	5%	2%	1%	1%	4%
Percentage of person-hours expended on training as percentage of maintenance mhrs	5%	5%	4%	5%	5%	5%	5%
Contracted maintenance as percentage of maint cost	5%	NA	13%	NA	NA	NA	9%
Number of equipment items in the plant	86238	63721	54111	89393	57542	67764	69795
Percentage of equipment safety-related	19%	18%	23%	29%	17%	29%	22%
Percentage of equipment non-safety-related	81%	79%	77%	71%	83%	71%	77%
Percentage of equipment covered under PM	13%	18%	12%	6%	5%	9%	11%
Percentage of equipment covered under CM	87%	82%	88%	94%	95%	91%	89%
Percentage of equipment items covered under PdM	2%	1%	2%	1%	1%	1%	1%
Percentage of SR equipment items covered under PM (incl PdM)	26%	57%	19%	5%	12%	10%	21%
Percentage of NSR equipment items covered under PM (incl PdM)	10%	9%	9%	5%	3%	9%	8%
Percentage of online PM	75%	70%	58%	76%	64%	73%	69%
Percentage of PM on SR equipment performed at power	74%	73%	54%	65%	58%	66%	65%
Percentage of PM on NSR equipment performed at power	76%	65%	72%	80%	66%	77%	73%
Process Index	**71%**	**76%**	**62%**	**68%**	**62%**	**65%**	**67%**
Productivity metrics							
Wrench time	66%	66%	52%	60%	62%	58%	61%
Craft work order turnover/week	102	142	180	200	163	198	164
Planner/craft ratio	8%	9%	23%		7%		10%

Metrics	**Plant A**	**Plant B**	**Plant C**	**Plant D**	**Plant E**	**Plant F**	**Benchmark**
Work orders per planner-week (3)	19	11	6	19	15	19	15
Staff to craft ratio of person-hours	22%	25%	41%	36%	35%	38%	33%
Work orders per staff week	17	7	6	7	5	6	8
Number of work orders attributable to rework	43	35	24	12	18	9	24
Number of work orders attributable to emergency work	2	7	47	400	121	338	153
Backlog count (1)	574	673	456	67	46	52	55
Days overdue-backlog (2)	15	11	10	9	8	7	10
Person-hours/100Mw of installed capacity	26857	23913	25817	36949	36332	37798	31278
Percentage procedure change	72%	80%	52%	NA	76%	NA	70%
Percentage of procedures affected	47%	50%	28%	NA	50%	NA	44%
Human Performance Index	**72%**	**77%**	**66%**	**81%**	**65%**	**84%**	**74%**
Productivity Index	**67%**	**72%**	**60%**	**68%**	**69%**	**68%**	**67%**
Maintenance Effectiveness Index	**71%**	**79%**	**57%**	**68%**	**60%**	**69%**	**67%**

Notes:

1. Backlog benchmark is the average of Plants D, E, and F only, and it is based on > 90 days overdue-backlog.
2. Days overdue-backlog is calculated using > 90 days overdue-backlog benchmark for plants A, B, and C where the relevant data are not available.
3. Work orders/planner-week is calculated based on 60% of the work orders subject to planning.

B

BREAKDOWN OF MAINTENANCE PERSON-HOURS

Breakdown of maintenance person-hours by maintenance type was established using a "difficulty factor" (DF) because the actual person-hours spent on maintenance were not captured in the work order system by all plants in the survey population. In one of the surveyed plants, actual person-hours spent by craft, planning, work control, and administrative staff were captured against each work order and were readily retrievable from the maintenance management system. As a first step, using actual hours data, a difficulty factor for CM activities was established as shown in Table B-1.

Table B-1
Calculation of CM/PM Difficulty Factor

Row #	Allocation of Person-Hours Between PM and CM	Value
1	Number of PM work orders	14527
2	Number of CM work orders	5632
3	PM hours based on actual hours	256758
4	CM hours based on actual hours	254143
5	Hrs/PM WO	18
6	Hrs/CM WO	45
7	Difficulty factor (DF) for CM compared to PM = row 6/row 5	2.55

For plants that did not have actual hours captured, the total available maintenance person-hours were allocated between CM and PM by using the hours/equivalent PM WO as shown in rows 8–10 in the example in Table B-2.

Table B-2
Allocation of Available Hours Between PM and CM

Row #	Description	Value
1	Total craft + staff hours available = # persons × 1840 hrs/yr/person	778320
2	Training hours @100hr/craft/yr and 50/staff/year	32000
3	Hours available for work	746320

Table B-2 (continued)
Allocation of Available Hours Between PM and CM

Row #	Description	Value
4	Number of PM work orders	14527
5	Number of CM work orders	5632
6	Difficulty factor for CM compared to PM	2.00
7	Number of PM equivalent of CM work orders = row 6 × row 5	11264
8	Total PM equivalent WO = row 7+ row 4	25791
9	Hours/PM WO = row 3 / row 8	29
10	PM hours = row 9 × row 4	420367
11	CM hours = row 9 × row 7	325953

C

ABBREVIATIONS

CM	corrective maintenance
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
EQ	environmental qualification
FIN	Fix-It-Now Team
IAEA	International Atomic Energy Agency
I&C	instrumentation and control
INPO	Institute of Nuclear Power Operations
kWhr	kilowatt-hour
LCO	limiting conditions of operation
LER	Licensee Event Report
MMS	maintenance management system (computerized or CMMS)
MOV	motor-operated valve
MTBF	mean time between failures
MWhr	megawatt-hour
NEI	Nuclear Energy Institute
NRC	Nuclear Regulatory Commission
O&M	operations and maintenance
OSHA	Occupational Safety and Health Administration
PM	preventive maintenance
PdM	predictive maintenance
RCM	reliability-centered maintenance
SSC	structures, systems, and components
WANO	World Association of Nuclear Operators
WIN	Work-It-Now Team

Target:
Nuclear Power

About EPRI

EPRI creates science and technology solutions for the global energy and energy services industry. U.S. electric utilities established the Electric Power Research Institute in 1973 as a nonprofit research consortium for the benefit of utility members, their customers, and society. Now known simply as EPRI, the company provides a wide range of innovative products and services to more than 1000 energy-related organizations in 40 countries. EPRI's multidisciplinary team of scientists and engineers draws on a worldwide network of technical and business expertise to help solve today's toughest energy and environmental problems.

EPRI. Electrify the World

SINGLE USER LICENSE AGREEMENT

THIS IS A LEGALLY BINDING AGREEMENT BETWEEN YOU AND THE ELECTRIC POWER RESEARCH INSTITUTE, INC. (EPRI). PLEASE READ IT CAREFULLY BEFORE REMOVING THE WRAPPING MATERIAL.

BY OPENING THIS SEALED PACKAGE YOU ARE AGREEING TO THE TERMS OF THIS AGREEMENT. IF YOU DO NOT AGREE TO THE TERMS OF THIS AGREEMENT, PROMPTLY RETURN THE UNOPENED PACKAGE TO EPRI AND THE PURCHASE PRICE WILL BE REFUNDED.

1. GRANT OF LICENSE

EPRI grants you the nonexclusive and nontransferable right during the term of this agreement to use this package only for your own benefit and the benefit of your organization. This means that the following may use this package: (I) your company (at any site owned or operated by your company); (II) its subsidiaries or other related entities; and (III) a consultant to your company or related entities, if the consultant has entered into a contract agreeing not to disclose the package outside of its organization or to use the package for its own benefit or the benefit of any party other than your company.

This shrink-wrap license agreement is subordinate to the terms of the Master Utility License Agreement between most U.S. EPRI member utilities and EPRI. Any EPRI member utility that does not have a Master Utility License Agreement may get one on request.

2. COPYRIGHT

This package, including the information contained in it, is either licensed to EPRI or owned by EPRI and is protected by United States and international copyright laws. You may not, without the prior written permission of EPRI, reproduce, translate or modify this package, in any form, in whole or in part, or prepare any derivative work based on this package.

3. RESTRICTIONS

You may not rent, lease, license, disclose or give this package to any person or organization, or use the information contained in this package, for the benefit of any third party or for any purpose other than as specified above unless such use is with the prior written permission of EPRI. You agree to take all reasonable steps to prevent unauthorized disclosure or use of this package. Except as specified above, this agreement does not grant you any right to patents, copyrights, trade secrets, trade names, trademarks or any other intellectual property, rights or licenses in respect of this package.

4. TERM AND TERMINATION

This license and this agreement are effective until terminated. You may terminate them at any time by destroying this package. EPRI has the right to terminate the license and this agreement immediately if you fail to comply with any term or condition of this agreement. Upon any termination you may destroy this package, but all obligations of nondisclosure will remain in effect.

5. DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

NEITHER EPRI, ANY MEMBER OF EPRI, ANY COSPONSOR, NOR ANY PERSON OR ORGANIZATION ACTING ON BEHALF OF ANY OF THEM:

(A) MAKES ANY WARRANTY OR REPRESENTATION WHATSOEVER, EXPRESS OR IMPLIED, (I) WITH RESPECT TO THE USE OF ANY INFORMATION, APPARATUS, METHOD, PROCESS OR SIMILAR ITEM DISCLOSED IN THIS PACKAGE, INCLUDING MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE, OR (II) THAT SUCH USE DOES NOT INFRINGE ON OR INTERFERE WITH PRIVATELY OWNED RIGHTS, INCLUDING ANY PARTY'S INTELLECTUAL PROPERTY, OR (III) THAT THIS PACKAGE IS SUITABLE TO ANY PARTICULAR USER'S CIRCUMSTANCE; OR

(B) ASSUMES RESPONSIBILITY FOR ANY DAMAGES OR OTHER LIABILITY WHATSOEVER (INCLUDING ANY CONSEQUENTIAL DAMAGES, EVEN IF EPRI OR ANY EPRI REPRESENTATIVE HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES) RESULTING FROM YOUR SELECTION OR USE OF THIS PACKAGE OR ANY INFORMATION, APPARATUS, METHOD, PROCESS OR SIMILAR ITEM DISCLOSED IN THIS PACKAGE.

6. EXPORT

The laws and regulations of the United States restrict the export and re-export of any portion of this package, and you agree not to export or re-export this package or any related technical data in any form without the appropriate United States and foreign government approvals.

7. CHOICE OF LAW

This agreement will be governed by the laws of the State of California as applied to transactions taking place entirely in California between California residents.

8. INTEGRATION

You have read and understand this agreement, and acknowledge that it is the final, complete and exclusive agreement between you and EPRI concerning its subject matter, superseding any prior related understanding or agreement. No waiver, variation or different terms of this agreement will be enforceable against EPRI unless EPRI gives its prior written consent, signed by an officer of EPRI.

Printed on recycled paper in the United States of America

1007604

EPRI • 3412 Hillview Avenue, Palo Alto, California 94304 • PO Box 10412, Palo Alto, California 94303 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com