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Improving Maintenance Effectiveness

An Evaluation of Plant Preventive and Predictive Maintenance Activities

(continued on back cover)

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REPORT SUMMARY

Effective maintenance programs can ensure reliable performance of plant systems, structures, and components (SSCs). Special performance requirements and increased competition in the utility industry demand a well thought-out maintenance strategy that is supported by a balanced mix of maintenance activities and techniques to achieve reasonable equipment reliability and availability.

Background

Over the past few years, utilities have experimented (with varying levels of success) with changes in the their maintenance practices and programs. A certain level of preventive maintenance (PM) has always been required to operate nuclear power plants; however, achieving an optimal mix of PM activities remains a challenge for some nuclear plant operators. Reliability-centered maintenance (RCM) and other customized versions of this methodology have been used to adjust maintenance practices for certain SSCs. Most nuclear plant operators have recognized that dependence on planned and periodic maintenance alone does not provide the level of performance desired by most nuclear power plants.

Objective

- To provide a picture of maintenance optimization processes used in the nuclear industry
- To present alternative strategies that can be used by power plants to assist the optimization process
- To review and discuss the current predictive maintenance (PdM) tools being used in most nuclear power plants

Approach

Using surveys, site visits, and interviews with key site personnel, the project reviewed the current nuclear industry practices and procedures used in typical nuclear power plants. These plants were selected through peer recommendations and from plant performance ratings. The project attempted to take a fresh look at industry maintenance practices to provide an unbiased review of the status of these practices as understood by the plant personnel responsible for implementing their plant's maintenance program. Previous industry studies were also reviewed.

Results

Current maintenance practices used at most nuclear power plants have incorporated some type of predictive maintenance activity into their maintenance programs. However, predictive maintenance practices for the most part are not the result of a fully developed strategy but are the consequences of trying to use the most current technology. Even with the lack of overall strategic planning, most sites have maintenance programs that function well and have been fairly successful in controlling maintenance costs, while achieving a respectable level of equipment performance. Many of the programs were implemented with the intent to meet prescribed equipment operational and performance goals.

EPRI Perspective

Many of the maintenance programs in the nuclear industry would benefit from a thorough review of the current mix of practices and techniques that make up a site's maintenance strategy. Nuclear plants can benefit from establishing objectives and developing plans on how to better use current industry preventive and predictive maintenance techniques, while continuing to implement new technologies as they become available. By improving their use of current maintenance practices, plants should be able to maintain reliable SSCs and achieve lower maintenance costs through a more effective use of technology.

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Interest Categories

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Maintenance practices

Maintenance evaluations

Engineering and technical support

Key Words

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FOREWORD

The purpose of this guide is to provide recommendations for improving the cost-effectiveness of the maintenance process at nuclear power plants through a balanced mix of maintenance programs. In addition, this guide also proposes a set of measures that may be useful in promoting consistent and uniform assessment of the effectiveness of the maintenance process.

This guide contains six sections and several appendices as follows:

- Section 1 provides a general description of the existing maintenance strategy, programs, and practices.
- Section 2 presents a review of the information gathered and the observations from plant visits and a survey conducted during the development of this guide.
- Section 3 provides a brief overview of the approaches used in the nuclear industry to improve maintenance programs.
- Section 4 proposes a set of recommendations to build on current plant initiatives to improve the overall effectiveness of maintenance programs.
- Section 5 provides a discussion of the current use of PdM technologies in nuclear plants and the opportunities to expand their cost-effective use.
- Section 6 proposes a set of measures to assess the effectiveness of maintenance programs.
- Section 7 contains a list of cited references.

The appendices include a bibliography, a glossary of terms, and related background information. This guide ends with an index that can aid the reader in finding a specific topic of interest.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1

CURRENT MAINTENANCE PROGRAMS AND PRACTICES

Improving maintenance effectiveness presents a multidimensional challenge. To change, the first step is to have a thorough understanding of your current status and the variables involved. Equally important are the usage and meaning of different terms related to maintenance. This section suggests common meanings and usage for some maintenance-related terms. Additionally, a description of maintenance strategy currently adopted by nuclear plants and the programs and practices in support of that strategy are included.

1.1 Introduction

Maintenance is an important part of physical asset management; in a nuclear plant, the physical assets are the systems, structures, and components (SSCs). Maintenance is the process used to preserve functional capabilities of physical assets at specified levels. Functional capabilities are those that directly affect plant load factor and plant or equipment availability and reliability. By itself, preserving physical assets in a certain state does not necessarily guarantee the capability of the system or equipment to perform within specified parameters or to limit the losses caused by their failure.

The maintenance process requires a clear and well-defined policy backed by a sound strategy, which in turn is supported by an organization and programs that ensure the execution of the strategy. In nuclear plants, the maintenance function has evolved from an adjunct role in the 60s and 70s to an important function with its own senior management supported by a team of managers.

Evolutionary development, coupled with reactive management and necessitated by regulatory demands, has led to a collection of maintenance programs and practices that may not be cost-effective. The maintenance functions constitute approximately 40% of the total Operations and Maintenance (O&M) cost, excluding fuel, for most nuclear power plants. As seen in Figure 1-1, O&M cost, excluding fuel, had steadily increased until 1990. Recent utility attention to this area has arrested this increase, and this trend has begun to decline. Today's competitive utility industry operating environment demands further improvements in overall O&M cost at every nuclear plant.

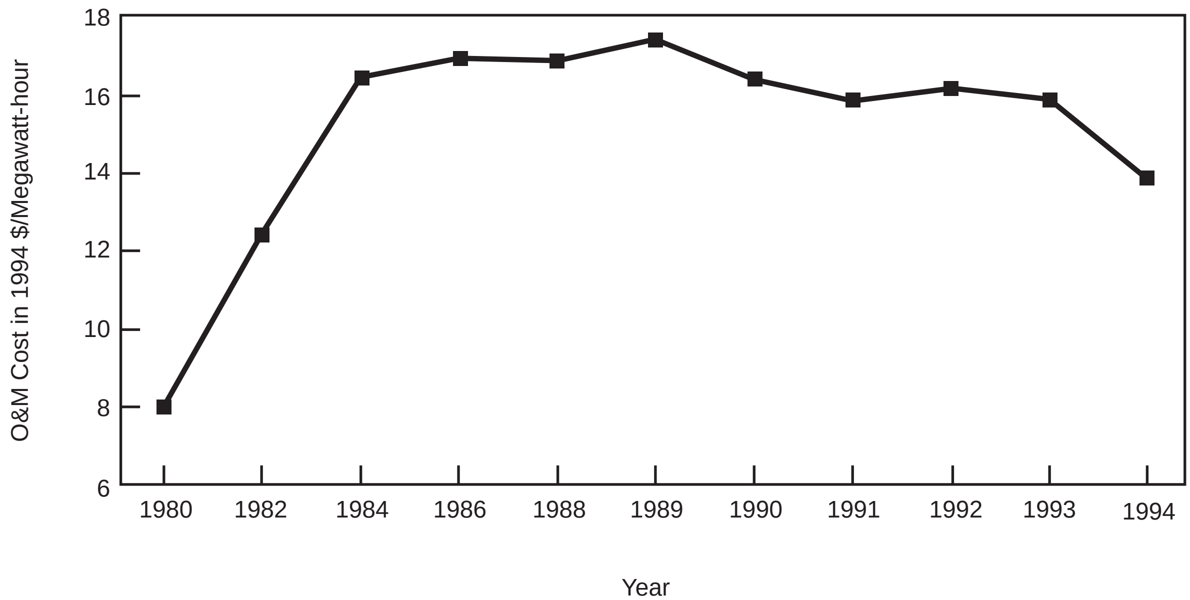

Figure 1-1
Historical Trend of O&M Cost
Source: UDI database 1995 [1]

1.2 Maintenance Terminology

Definitions for the maintenance-related terms used in this document are provided in Appendix B. This subsection discusses a few of the key terms to ensure that their meanings are clearly understood and to promote consistency in their usage. Figure 1-2 illustrates the relationship of maintenance terms and their fit in an overall maintenance scheme or strategy.

1.2.1 Preventive Maintenance

The term *preventive maintenance* (PM) has many definitions or connotations. In this guide, it is used to mean regularly scheduled maintenance activities (such as inspections or routine servicing of equipment) or planned maintenance activities aimed at avoiding or reducing failures. Preventive maintenance actions are directed at known or postulated failure modes to reduce failures. Some view PM as a means to *eliminate* failures. This is not always true because: a) not all failure modes and mechanisms can be anticipated, and b) even if they were anticipated, they may not be addressable by current maintenance practices. In fact, evidence shows that, sometimes, PM activities can increase failure. This class of maintenance is aimed at taking action before the equipment breaks.

Mandatory preventive maintenance activities are those performed to meet nuclear safety, regulatory, and personnel safety requirements. Some of the insurance-driven PM activities are mandatory, while others (for example, infrared thermography of motor control centers) are incentive-driven (that is, the plant receives insurance premium credits for performing them). All other PM activities are discretionary and, generally, are performed only when they are determined to be cost-effective. Preventive maintenance can be divided into two broad categories: periodic maintenance and predictive maintenance.

Time-based (-directed) preventive maintenance is called *periodic maintenance.* Other names for this include planned maintenance, scheduled maintenance, and routine maintenance. In this case, maintenance actions are taken at fixed intervals or at a fixed number of operating hours or operational cycles to eliminate known or expected failure modes/mechanisms. Examples of planned maintenance activities are:

- Changing oil at specified intervals to preclude the potential for bearing failure from contaminated or degraded lubricant
- Replacing motor bearings after a specified number of operating hours to preclude motor failure as result of bearing failure
- Conducting a tear-down inspection and overhaul of certain high-voltage motors once every so many years to preclude failures from causes such as a cracked rotor bar, loose braces or wedges, or high levels of moisture in the winding insulation

Condition-based preventive maintenance is called *predictive maintenance (PdM).* Condition monitoring, assessment, and trending are some of the other names used to refer to it. These terms are used interchangeably although they are not synonymous. Condition-based monitoring is just what it sounds like, that is, monitoring the condition of a piece of equipment through one or more techniques, such as visual inspection, vibration monitoring, or temperature monitoring, and making determinations about its capability to perform as specified.

Condition assessment is the analysis or engineering evaluation part of condition monitoring. Trending is one of the data analysis methods used in condition assessment. Other data analysis methods used in condition assessment are:

- Pattern recognition
- Correlation
- Test against limits or ranges
- Statistical process analysis

Predictive maintenance encompasses condition monitoring, condition assessment, and decisions regarding when and what maintenance should be performed to restore equipment capability to the desired condition. In some cases (for example, pipe wall thickness), remaining useful life predictions are also made. It involves monitoring key design and/or operating parameters, either on-line or periodically, to assess the equipment's ability to perform its specified function reliably. The assessment is generally based on monitored parameters that exceed a pre-established limit or show an abnormal pattern or adverse trend.

Condition monitoring may be done by one or more of the following:

1. Surveillance testing
2. Inservice test (IST) programs
3. Inservice inspections (ISI)
4. Monitoring key design or operating parameters such as operating temperature, vibration levels

Until recently, items 1, 2, and 3 at most nuclear plants have not usually been identified as “condition monitoring” per se. However, when one considers the type of information gathered and the data that are presently or may be collected and evaluated from these activities, it is difficult to escape the conclusion that all the activities constitute “condition monitoring.” Hence, it has been suggested that information obtained during IST and ISI activities may be used for monitoring purposes.

The purpose of the inspections and tests covered by items 1 and 2 above are to verify that SSCs operate within design specifications. The focus is on the required functional performance capability of equipment and not on any specific failure mode or mechanism. The rationale is that most, if not all, dormant failures or degraded conditions can be detected by functional failure or degraded performance during such tests and inspections. Examples of surveillance and IST are:

- Testing of the main steam isolation valves to verify that they can reach the full closed position under load within the required time
- Testing of the diesel generator system to verify that the engine starts and carries the required load and that it is operating within design specifications

Upon detection of an unacceptable or deviant condition, maintenance actions are initiated to troubleshoot and correct the deviant conditions as necessary. Note that these tests and inspections cannot identify all incipient or dormant failures. However, operating experience shows that many equipment failures or incipient failures have been detected during surveillance tests and inspections. For example, one recent study notes that for motor control centers, approximately 50% of all the identified breaker failures were detected during surveillance tests and inspections [2].

ISI and monitoring of key design / operating parameters aim to identify incipient failures by focusing on postulated failure mechanisms. Monitoring and inspecting are directed at parameters indicative of the progression of one or more postulated failure mechanisms. Examples of predictive maintenance that is based on these types of condition monitoring include the following:

- Decision to repair a weld on a pipe based on indications of flaws or cracks from an ultrasonic evaluation of welds
- Decision to replace the bearings of a motor before an elapsed time based on an indication of excessive vibration

- Decision to repair a motor to replace a cracked end-ring based on an indication of an incipient failure condition through motor current signature analysis
- Decision to replace a motor bearing based on high wear metal particle count in the lubricant

Generally, it is more cost-effective to monitor the condition of a piece of equipment and to initiate appropriate maintenance actions only upon detection of a deviant condition. Because of the advance warning of the potential functional failure, it is often possible to plan and execute maintenance, rather than being forced to react after a failure. In other words, maintenance actions are focused where and when they are needed, and usually at the incipient stage, rather than at a specified interval without regard to the condition of the equipment being serviced. Appendix C provides a discussion of how to establish the interval for monitoring based on the I-F interval, that is, the interval between the incipient and the failed condition.

1.2.2 Corrective Maintenance

Corrective maintenance (CM) refers to maintenance actions done after an equipment failure is detected. Not all corrective maintenance is done immediately after the detection of a failure. Generally, corrective maintenance needs are prioritized and performed on a planned basis. They may often take priority over preventive maintenance. When performing CM, it may often be prudent and cost-effective to perform PM activities that are almost due or for which the nature of the CM includes many of the same steps. Throughout this document, planned corrective maintenance is called prioritized corrective maintenance (PCM). Some corrective maintenance requires immediate action because of either a safety concern or an impact on plant operation. Such corrective maintenance is called *emergency maintenance*.

1.3 Maintenance Policy Objectives

Senior maintenance management establishes maintenance policy to support the overall plant, personnel safety, and financial performance goals. A typical set of maintenance policy objectives for a nuclear power plant can be stated as follows:

1. SSC Availability Objectives
   - Ensure that systems, structures, and components required to perform or support safety functions meet the required reliability and availability goals
   - Ensure that systems, structures, and components that affect continued operation of the plant at rated power levels meet the required reliability and availability goals
2. Personnel Safety Objectives
   - Ensure that lost time from personnel injury is as low as practical
   - Ensure that worker radiation exposure is as low as practical and is comparable to industry peers

3. Economic Objectives
    - Ensure that the cost of maintenance as a percentage of the overall plant O&M cost is as low as practical and is comparable to industry peers
    - Ensure that the life cycle of SSCs are managed to obtain the longest practical service life
    - Ensure that the indirect cost of equipment failure is as low as practical

Sites may wish to include additional objectives such as performance goals for SSCs to achieve a certain megawatt performance at the plant level. When setting policy level objectives, one should bear in mind that they should:

- Enable clear and direct accountability evaluation of Maintenance Department performance
- Be limited to those that can be influenced by the Maintenance Department's actions

1.4 Current Maintenance Strategy

The policy objectives stated above are achieved by adopting a maintenance strategy founded on the following two maxims:

- For mission-critical items, perform preventive maintenance. Examples of mission-critical items include: SSCs covered by the plant Technical Specifications, power production systems such as the turbine generator, and certain other items that are important to ensure system reliability or personnel safety.
- For items with considerable economic impact, preventive maintenance should be considered.
- For others, fix after failure, that is, depend only on corrective maintenance.

Figure 1-2 shows the overall maintenance strategy including the supporting programs. Broadly, the strategy consists of preventive and corrective maintenance programs. Preventive maintenance includes periodic and predictive maintenance. Periodic maintenance may be done at calendar intervals or after a specified number of operating cycles or a certain number of operating hours. These intervals are established based on manufacturers' recommendations, and utility and industry operating experience. The equipment population covered by PM was established during the plant startup stage and is refined as experience accumulates. Generally, the equipment population covered, the associated maintenance tasks, and their frequency of performance were established without a systematic evaluation of the related factors such as:

- Importance of equipment failure to the overall plant mission
- Equipment duty cycles, equipment redundancies
- Effectiveness of the maintenance action contemplated in reducing unanticipated failures

The result is too many maintenance tasks, high work backlogs, and an overall maintenance program that may not be cost-effective. There are wide variations in maintenance coverage (that is, the population covered) and practices (that is, the type of maintenance performed) among plants for similar equipment and applications. Sometimes, this is the case even within the same utility.

Predictive maintenance refers to maintenance that is performed based on the detected or observed equipment condition. Condition monitoring based on ISI has been used for many years. The related population and frequencies of inspection are mandated by either the plant Technical Specifications or industry codes and standards. Condition monitoring using key design and / or operating parameters is relatively new (less than 10 years old) in the nuclear industry. Examples include lubricant analysis, vibration monitoring, infrared thermography, and pipe wall thickness monitoring. Because of its evolving nature, the population of equipment covered, the frequency of monitoring, and the organization that does the work varies from plant to plant. Some plants have their system engineers performing data collection and analysis, while others have a team of specially trained technicians and engineers organized as a separate entity under the engineering department doing the work.

Predictive maintenance (PdM) refers to maintenance based on the detected or observed condition of a piece of equipment. PdM consists of two steps:

- Monitoring the condition of the item through either a one-shot measurement or periodic monitoring
- Trending of key design / operating parameters and performing appropriate maintenance upon identifying a specific deviant or suspect condition as indicated by condition monitoring data

Corrective maintenance, as discussed in Section 1.2.2 can be divided into those items that require fairly prompt attention and those that have been determined to be non-critical and can be repaired as needed. This approach has been used by industry for years and can be used advantageously to prioritize work activities.

Generally, plants manage the preventive maintenance tasks using a computerized maintenance management system (CMMS).

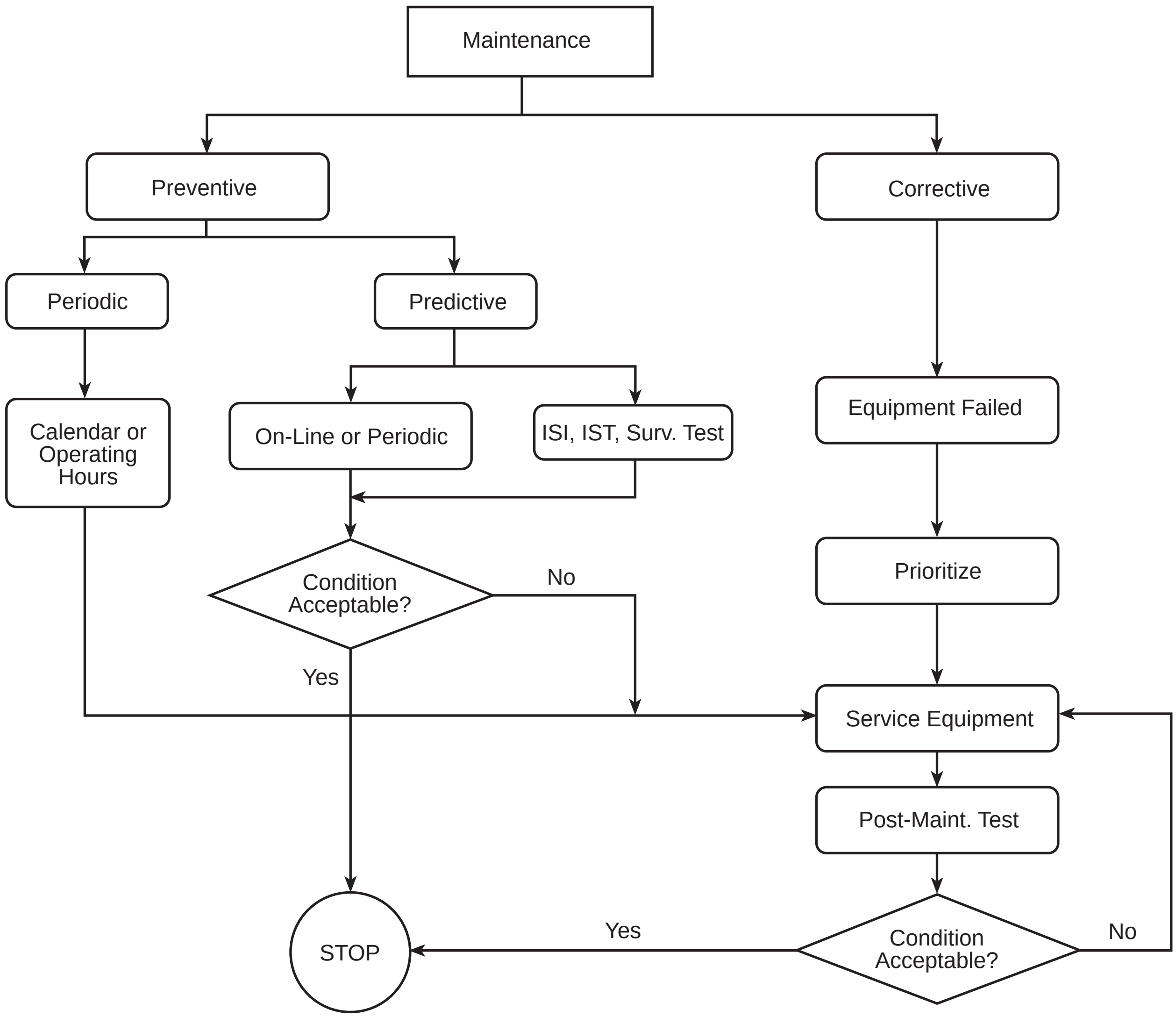

Figure 1-2
Present Maintenance Strategy

Organizationally, in most nuclear plants three (sometimes four) separate departments are involved in executing this maintenance strategy. The Operations (that is, Production) Department is responsible for performing the IST and some of the ISI and surveillance testing. The remaining ISI is performed by a separate department. Surveillance testing that is not performed by the Operations Department usually is done by the

I&C Department. In some plants, surveillance test of radiation monitoring instrumentation is performed by the Rad-Protection Department with I&C support. The Maintenance Department, which generally includes electrical and mechanical maintenance departments only, performs all maintenance work on electrical and mechanical equipment. Exceptions to this are cases where a separate Relay and Metering Department performs all maintenance on protective relays and indicating meters. The I&C Department, which performs all maintenance work on I&C equipment, reports to either the Operations or the Maintenance Department superintendent. The above description of the organizational responsibilities represents the norm, and the organizational breakdowns of individual plants may vary.

1.5 Assessment of Current Maintenance Strategy

The maintenance strategy and its supporting programs outlined above have generally been successful as evidenced by the gradual reduction in unplanned reactor trips, unplanned engineered safety feature(ESF) actuations, and equipment forced outage rate (Figure 1-3). Similar trends have been noted for low-level waste generation in m^3 / unit and personnel exposure in person-rem / unit. As seen in Figure 1-1, the O&M costs rose until 1990 and have since leveled out and commenced a slow decline. Although not all of the improvements in these indicators can be attributed to the maintenance strategy and programs alone, their trends suggest that the overall strategy is on sound footing and may not require any fundamental change.

However, several factors discussed previously and those that follow point to a need and present an opportunity for further improvement:

- Individual maintenance programs supporting this strategy have evolved over the past two decades in response to various regulatory and management demands, and the cost-effectiveness of each program has not always been the central focus.
- The present utility industry climate demands continued improvements in this area (that is, cost-effectiveness of maintenance).
- Advances in condition monitoring technologies now offer tools that can be used to substitute or supplement current periodic maintenance with condition-directed maintenance that could eliminate unwarranted tasks.
- Experience at some plants with systematic evaluation of maintenance programs using equipment operating experience data and reliability-based tools indicates that many opportunities exist to improve the effectiveness of maintenance programs.
- Experience at some plants with maintenance organizational and process reviews indicates that the potential exists for improving effectiveness by streamlining the administrative processes. This requires the shifting of responsibilities and equipment ownership to more appropriate parties.

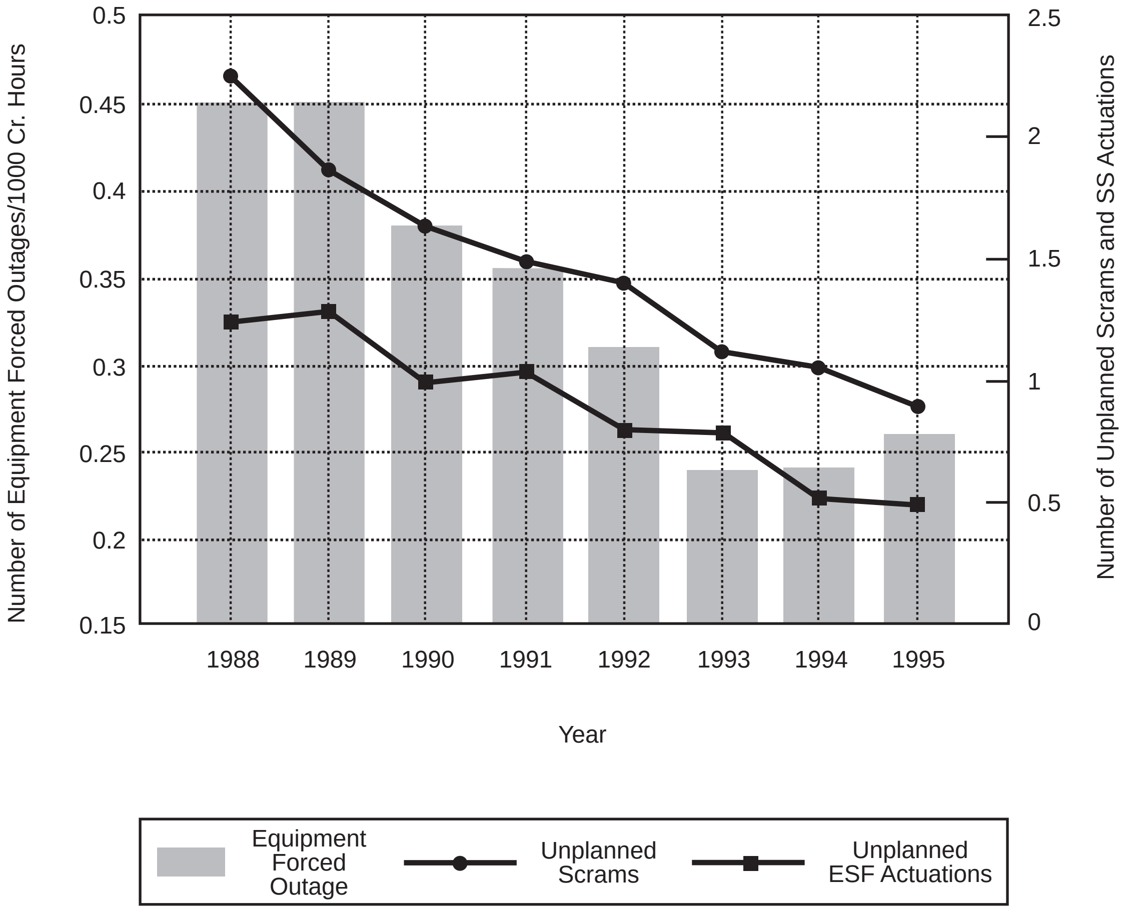

Figure 1-3
Historical Trends of Key Performance Indicators

1.6 Summary

Current maintenance strategy involves performing preventive maintenance for mission-critical items and corrective maintenance for others. This strategy is supported by many discrete and complementary programs such as periodic maintenance, surveillance testing, inservice inspection, inservice testing, root cause evaluation, equipment history trending, and so on. Generally, this strategy has been successful. However, evolutionary development of many of these programs has not always ensured that maintenance is producing the desired results at a practical cost. Experience with many recent initiatives such as reliability-centered maintenance (RCM), PM optimization programs, and increased use of condition monitoring technologies confirm this observation. For example, using RCM or reliability-based maintenance (RBM) or a variant thereof, some plants have trimmed down the population of equipment that gets periodic maintenance and increased the use of condition-directed maintenance, thus eliminating unwarranted maintenance. Further, experience from these initiatives also indicate that there is considerable opportunity for improving the effectiveness of plant maintenance programs through a systematic evaluation and increased use of condition monitoring. The remaining chapters of this guide are devoted to providing information that could assist plants in improving maintenance effectiveness.

2

PLANT SURVEYS AND VISITS

As a part of this study, several plants were surveyed to gain insight into the effectiveness of their current maintenance programs. The focus of the survey was to collect the following information:

- Resources expended (for example, person-hours)
- Total equipment population in the plant
- Breakdown of the population by type of maintenance received
- The use of predictive maintenance
- Experience with condition monitoring technologies

This survey was conducted with a written questionnaire, telephone discussions, and site visits. Responses were received from 10 nuclear sites representing a total of 17 nuclear units in the U.S. and Canada. The responding nuclear sites contained six early vintage (1970s) plants and four recent vintage (post-1970s) plants. Six nuclear sites (11 units) representing all three nuclear steam supply systems (NSSSs) were visited. Three of the sites visited were early vintage plants, and the other three were recent vintage plants. Interviews were conducted with management and staff involved in predictive maintenance (PdM) functions to develop information on the use of condition monitoring and other maintenance technologies. The organizations responsible for PdM and equipment and software being used were also reviewed. Table 2-1 summarizes the information gathered from this effort regarding the use of condition monitoring technologies. Table 2-2 presents the information gathered on maintenance person-hours and the breakdown of the equipment population by the type of maintenance they receive.

Table 2-1
Insights on PdM Technology Use from Plant Surveys and Visits

Plants	A	B	C	D	E	F	G	H	I	J	K	L	M	N	% of Plants using Technology
↓ **Technology**															
Temperature monitoring	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	100
Infrared thermography	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	100
Contact temperature monitoring	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	100
Area temperature monitoring	N	N	Y		Y		N	Y	Y	Y					67
Lubricant analysis	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	93
Spectroscopy	Y		Y		Y	Y	Y	Y	Y	Y					87
Ferrography	N		Y		Y	Y	N	Y	Y	Y					40
Particle CT	Y		Y		Y	Y	N	Y	Y	Y					53
Micro-patch	N		N		N	N	N	N	N	N					0
Transformer oil dissolved gas analysis	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	100
Motor condition monitoring	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	100
MCA	N		N	Y	Y	Y	Y	Y	Y	Y					80
Motor circuit evaluation	N		N		Y	N	N	N	Y	Y					20
Hi-pot	Y	Y	Y		Y	Y	N	Y	Y	Y					87
Surge test	N	Y	Y		Y	Y	Y	Y	Y	Y					87
Winding resistance	Y		Y		Y	Y	N	Y	Y	Y					80
Insulation resistance	Y	Y	Y		Y	Y	N	Y	Y	Y					87
Other electrical condition monitoring	Y		Y		Y	Y	N	N	Y	Y					40
Partial discharge															0
ELCID									Y	Y					13
ECAD for cables															0
Oxidative induction time for cables															0
Indenter for cables															0
Vibration monitoring	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	100
Generator end-turn vibration monitoring															0
Rotating equipment bearing monitoring	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	100
Alignment check using vibration											Y				7
Acoustic	N			Y	Y	Y	Y	Y	N	N	N	N	N	N	33
Ultrasonic	Y			Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	93
Radiography	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	100
Eddy CT probes	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y					60
Optical monitoring															0

Table 2-1 (cont.)
Insights on PdM Technology Use from Plant Surveys and Visits

Plants	A	B	C	D	E	F	G	H	I	J	K	L	M	N	% of Plants using Technology
↓ **Technology**															
Remote visual inspection	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	100
Fiber optic sensors	Y	Y			Y	Y	N	Y	Y						40
Borescope			Y	Y	Y	Y	Y	N	Y						40
CCTV									Y						7
Robots									Y						7
Other technologies						Y	Y			Y					20
MOV motor power monitoring	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	100
Cycle counters for switchgear															
Operating deflection analysis							Y								7
Ultrasound for valve and steam trap leaks										Y					7
Beta analysis diesel generators										Y					7

Table 2-2
Insights from Plant Surveys and Visits

Item or Topic	Values/Range per Unit[1] Person-Hours	Estimated Average Person-Hours
Annual craft person-hours spent on maintenance	35,000–60,000	45,000
% of equipment covered by PM	15–55%	25%
% equipment covered by CM only	45–85%	75%
Equipment included in PdM as % of equipment in PM	5–35%	<20%
Annual work order counts	4,000–10,000	7,000
Annual craft hours expended on maintenance	85,000–240,000	180,000
Annual maintenance support staff hours	26,000–68,000	50,000
Emergency maintenance person-hours as percentage of CM person hours	5%[2]	Not Meaningful

Notes:
1. The low end values represent early vintage (pre-1974) plants.
2. Information was obtained only from two plants, and even they were able to provide only an estimate. Thus, this statistic is not considered reliable or representative. It is believed that a plant with a top-tier maintenance program should have very few, if any, emergency maintenance needs between outages. This measure should be valuable in assessing the effectiveness of plant maintenance programs.

2.1 Observations from Surveys and Visits

The following insights and general conclusions can be drawn regarding the maintenance process at the plants visited or responding to the survey:

1. The maintenance strategy, program, and organization generally conform to the model discussed in Section 1.4.
2. Twenty-five percent of the equipment population on average receives some PM, while the remaining 75% of the equipment population receives only corrective maintenance.
3. Of the equipment that receives PM, approximately 20% receives some form of PdM. It is likely to be on the order of 35% if all plant PdM activities (see item 14 below) are taken into account.
4. As a percentage of total maintenance craft hours, support staff hours average around 35%.
5. All plants perform some level of predictive maintenance.
6. It appears that PdM has a limited connotation such as the use of vibration monitoring (VM), infrared (IR) thermography, lubricant analysis, and motor circuit analysis (MCA) using specialized test and measuring equipment.
7. IR thermography has been very successful in identifying and correcting many incipient failures such as loose electrical connections, overheating coils, cracked high-voltage electrical insulators, and leaking steam traps. After the initial successes, additional “finds” have been few and far between.
8. VM has been successful in providing timely warnings of impending bearing failures and unbalanced conditions.
9. Lubricant analysis has been very successful in reducing the number of oil changeouts and in providing confirmatory indications of incipient failure conditions of rotating equipment bearings.
10. Motor current signature analysis is not widely used and the experience with it is too limited to support any meaningful conclusions.
11. Some sites may be moving in the direction of establishing a PdM center to review, evaluate, and absorb new condition-monitoring technologies as they become commercially available.
12. Sites that have done a comprehensive assessment of their maintenance programs report that they have:
    - Eliminated approximately 15–20% of periodic maintenance tasks
    - Increased the PdM content significantly

    Both should lead to significant economic benefits, that is, reduced direct maintenance costs and indirect costs through avoided unplanned outages, power reductions, and safety system challenges.

13. As shown in Table 2-1, considerable variation exists in the number of technologies used among the sites. Similarly, for any given technology, there is a wide variation among sites (even among sites of the same utility) in the equipment population included, the application, and sophistication (which varies with experience).

14. It appears that sensory (that is, visual and tactile) inspection, albeit its wide use, is almost never associated with PdM. To a lesser extent, this is also the case with other condition monitoring technologies, such as MOV monitoring, transformer oil analysis, check valve programs, and valve leakage monitoring using acoustic monitoring, which have been in use for a long time.

15 Some sites may not be taking full advantage of insurance premium credits available for PdM activities. Insurers' loss control programs provide premium credits for some best practices and penalize for noncompliance with "should" requirements. Some PdMs qualify as best practices. For instance, thermographic surveys on certain equipment are eligible for credits. Additional credits apply for surveys done by certified thermographers. Appendix D contains a typical list of predictive maintenance activities for which insurance credits or penalties may apply.

16. Some sites have completed a systematic review and upgrade of their PM process. Others are in the midst of, or are yet to begin, such an effort. Either reliability-centered maintenance (RCM), reliability-based maintenance (RBM), or other methodology has been used in such systematic reviews. At some plants, this effort was completed as part of implementing the Maintenance Rule, while others performed similar reviews as a process improvement measure before the Maintenance Rule.

17. Three of the sites visited have implemented some level of what is described as PM optimization. Apparently, this has led to a significant shift in the balance between periodic and predictive maintenance and, thus, to an increase in the use of condition monitoring technologies.

18. Vibration monitoring, infrared thermography, and lubricant analysis are generally consolidated within a separate group with a lead engineer supported by one or two engineers and four to five technicians. The responsibilities for other PdM functions are scattered among the system engineers, the Engineering Department, and/or the respective Maintenance Departments.

19. One site reported integrating all PdM functions into the respective Maintenance Departments. Site electrical/mechanical and I&C maintenance technicians collect data and do most of the preliminary data analysis. On-call engineers support the Maintenance Departments.

20. A PdM program description document that establishes the overall PdM strategy, responsibilities, criteria for use of technologies, and so on was not available. Nevertheless, they do have a list (formal or informal) of equipment covered by PdM technology and written procedures for performing vibration monitoring, infrared survey, and oil sample collection. To be sure, all plants stated that they are now considering the development of such a program description document.

21. Some equipment included in the PdM population was added through special programmatic reviews such as PM optimization, Maintenance Rule, insurance credit, and equipment qualification (EQ). Otherwise, the list of equipment covered by PdM was developed using an informal process and engineering judgment. In other words, no written criteria exist for deciding which technologies are to be used for which equipment, how, or why. As a result, there is a wide variation in equipment population covered under any supporting PdM technology and the application of any given technology. The expertise bias of the PdM lead (that is, a leader who may be strong in vibration tends to focus more on that) perhaps contributes to this situation.
22. Personnel involved in PdM programs have received some level of training in related technologies. Some sites may be past the learning curve in application of some technologies such as infrared thermography, vibration monitoring, and lubricant analysis. Site personnel stressed the need for additional and ongoing training to improve data analysis and application of the technologies.
23. Management awareness, support, and commitment to PdM exist at all sites surveyed or visited, but the level of commitment varies.

2.2 Recommendations

Based on an assessment of the information gathered and the observations presented in the previous section, the following recommendations are offered for consideration by plant Maintenance Departments. Where appropriate, Sections 4, 5, and 6 present ways to address them.

- Sites that have already completed a maintenance program review will benefit from a continuing and routine review of the maintenance process to further improve the effectiveness of maintenance. (See Section 4.1 for details.)
- Sites that are presently performing or are yet to begin a review of their maintenance programs should review the experience gained by peer sites. (See Section 4.2 for details).
- Sites should establish a clear set of goals (preferably quantitative and qualitative) to be achieved by adopting each given condition monitoring technology and tracking their progress.
- Sites should consider integrating day-to-day condition monitoring responsibilities into the respective plant maintenance organizations, and to some extent, into the Operations Department. (See Sections 4.1 and 4.2.)
- Sites should begin to focus on the opportunities for streamlining the use of condition monitoring technologies. (See Section 5.)
- Sites should consider establishing a measurement system to monitor the effectiveness of maintenance. (See Section 6.)
- Sites would benefit from a review of the insurance credit and penalty program (see Section 5 and Appendix D) to adjust the PM to maximize the credits and avoid penalties.

3

APPROACHES TO IMPROVE MAINTENANCE EFFECTIVENESS

Improving maintenance effectiveness involves a multidimensional challenge. Success in this endeavor requires identification and balancing of the controllable variables and their interrelationships to maximize value at minimum cost. Utilities have used several approaches to achieve this goal, each with its own advantages and limitations. This section presents a discussion of the variables involved, their interrelationships, and some approaches that have been or may be used. Finally, this section provides recommendations that could ensure maximum value for the maintenance expenses incurred. These recommendations should benefit all sites—no matter where the sites are in their maintenance review process.

3.1 The Challenge

Initiatives to improve maintenance effectiveness involve a process used to maximize the value received for the resource applied. It is not necessarily the least expensive solution to a problem. The effectiveness of a maintenance program is measured by the extent to which it meets the maintenance policy objectives discussed in Section 1 and restated here for convenience.

1. SSC Availability Objectives
   - Ensure that systems, structures, and components required to perform or support safety functions meet the required reliability and availability goals
   - Ensure that systems, structures, and components that affect continued operation of the plant at rated power levels meet reliability and availability goals

2. Personnel Safety Objectives
   - Ensure that lost time from personnel injury is as low as practical
   - Ensure that worker radiation exposure is as low as practical and is comparable to industry peers

3. Economic Objectives
   - Ensure that the cost of maintenance as a percentage of the overall plant O&M cost is as low as practical and is comparable to industry peers
   - Ensure that the life cycle of SSCs are managed to obtain the longest practical service life
   - Ensure that the indirect cost of equipment failure is as low as practical

The resources applied are materials such as replacement parts, consumables, and person-hours. The cost of not achieving policy objectives 1 and 2 include losses from one or more of the following direct and indirect cost elements:

- Direct cost elements
  - Person-hour costs including craft, support staff, administrative salaries and benefits
  - Physical asset losses, for example, a burned transformer requiring major repairs, a seized impeller in a pump requiring replacement of the pump and its burned-out drive motor
  - Spare and replacement parts use and inventory
- Indirect cost elements
  - Additional personnel radiation exposure necessitated by repairs of equipment in radioactive areas
  - Handling and disposal of additional radioactive, chemical, or toxic wastes
  - Lost power production
  - Cost of processing reportable incidents
  - Possible collateral losses, for example, events involving personnel injury, insurance penalties, possible increase in insurance premiums, and rate regulation issues

Policy objective 3 seeks to minimize the cost elements listed. If objectives 1 and 2 are fully met, then objective 3 should be automatically met with one exception:

- Ensuring that maintenance cost is comparable to that of industry peers (objective 3a) will require a set of maintenance effectiveness indicators. Further, these indicators should be periodically collected and compared, and the results of that comparison should be used to adjust the maintenance programs.

Policy objective 1 is expected to be achieved through the maintenance strategy discussed in Section 1. The successful track record of this strategy suggests that fundamental changes in this strategy may not be warranted. Therefore, the challenge here boils down to that of revamping the blend of the various maintenance programs and adjusting the resources and other controllable variables to ensure maximum value at the lowest overall cost. In addition, a set of maintenance effectiveness indicators should be developed and used so that:

- The effectiveness of the programs can be monitored to facilitate course correction as required.
- They can also provide a basis for industry-wide comparison of the maintenance costs and other measures.

Looking at the maintenance effectiveness challenge from the equipment side, it can be stated that an optimal maintenance program is one that delivers 100% equipment availability and reliability at the lowest practical direct maintenance cost. Under this situation, indirect cost becomes zero and is of little concern. However, laws of nature, physics, and chemistry do not permit that luxury and we must settle for something less than 100% reliability and availability, but aim for a value as close to 100% as practical.

3.2 The Variables and Their Interrelationships

In a typical nuclear plant, the controllable variables involved in improving maintenance effectiveness include:

1. Equipment population covered by preventive maintenance
2. Type of maintenance applied
3. Allocation of maintenance between outage and nonoutage periods
4. Cost of performing a specific type of maintenance on a specific piece of equipment
5. Craft person-hours
6. Maintenance support staff person-hours
7. Health Physics support and radiation work permit process
8. Parts availability and quality
9. Equipment design and application
10. Equipment operating procedure
11. Organizational breakdown of responsibilities
12. Administrative and paperwork process

1. *Equipment population covered by preventive maintenance*: This variable is the number of equipment items that receive some level of preventive maintenance. It can affect the total amount of maintenance person-hours, parts inventory, and the various losses (for example, power production loss, waste disposal cost) identified in Section 3.1. Therefore, a concerted effort must be made to ensure that preventive maintenance is performed only for the equipment where it can be demonstrated to be required for reasons of mission impact or avoiding substantial repair cost. Further, PM should be performed only if it can be effective in addressing the applicable failure modes.

Given the evolutionary development of the maintenance programs, it is well known and accepted that often plant maintenance programs cover a larger population than is perhaps necessary. It is also likely that equipment that needs maintenance may not be getting any maintenance at all. Information on this variable should be available from the plant maintenance management information system (MMIS). Some plants may list each task for an equipment item as a line item. If so, then if using the MMIS to derive equipment population, be careful to avoid multiple counting or undercounting. Similarly, if a task is listed by route (for example, vibration monitoring or lube oil inspection or change-out), ensure that the equipment items included are properly accounted for.

2. *Type of maintenance applied:* This variable involves the type of maintenance applied to each equipment item, which may be any of the following:

   - Corrective maintenance only
   - Periodic maintenance only
   - Predictive maintenance only
   - Periodic and predictive maintenance

   This variable can affect the total amount of maintenance person-hours, the parts inventory, and the cost of the various types of losses (for example, power production loss or waste disposal cost) identified in Section 3.1.

   Example: Take the case of a pump that uses a special lube oil in substantial quantities. Currently, the plant changes oil every *n* months of calendar time. For this item, considerable savings can be achieved by assessing the condition of the oil using oil analysis, and changing the oil only when the condition of the oil is unacceptable. The savings result from:

   - Avoided maintenance craft hours by eliminating unwarranted oil change
   - Avoided disposal cost for the used oil
   - Cost of the oil and other supplies

   Additional cost savings can accrue if the equipment is in a radioactive area. In this case, predictive maintenance instead of planned maintenance would very likely be more cost-effective. Similarly, in some cases, the current preventive maintenance may not be effective in addressing the failure modes of concern. In such cases, consideration should be given to eliminating the PM partially or totally. Depending upon the importance of the function of the equipment, a design modification that could eliminate the failure mode or a surveillance test that would identify the failure condition may be more appropriate.

3. *Allocation of maintenance between outage and nonoutage periods*: This variable involves the plant mode in which preventive maintenance is performed, that is, during a plant outage or during power operation. The preference is to do as much preventive maintenance as practical during nonoutage periods because it can improve system availability and reduce the outage duration, overtime, and / or contract maintenance.

However, this decision should be made after a careful evaluation of the impact on plant and personnel safety, for example, what is the potential for the maintenance itself causing an unplanned plant shutdown, safety system actuation, or personnel injury. It appears that a systematic evaluation of the maintenance currently in place, to determine when it is to be performed and why, could lead to significant cost savings. Plants that have recently performed such a systematic evaluation report moving a significant amount (approximately 10%) of maintenance to nonoutage times.

4. *Cost of performing a specific type of maintenance on a specific piece of equipment:* This variable involves the overall cost of performing maintenance on certain major equipment such as a feedwater pump, diesel generator, or UPS. For example, the cost of doing a full diesel generator overhaul can vary depending upon whether it is performed by in-house maintenance personnel or vendor maintenance personnel. The difference in cost may be attributable to the level of in-house knowledge, skills, and test equipment (KSE) available. An evaluation of the related factors, including those listed below, can show whether it is more cost-effective to outsource this maintenance or have it done by in-house personnel:

   - Cost of maintaining the KSE available
   - Plant experience in maintenance-induced failures of the equipment under consideration
   - Contractor warranty of work done
   - Procedures employed to do the work

   This evaluation may reveal the need for changing in-house procedures for doing the work or a need to improve personnel training. This evaluation can be very useful if comparative data from peer plants are used.

5. *Craft person-hours*: The total number of craft hours spent and their breakdown by maintenance type should be included in any review of maintenance effectiveness. This variable affects the burdened salary cost of craft hours applied to maintenance activity. The actual time spent working on an equipment item, that is, “wrench time,” is a function of the complexity of the task. However, the craft time spent on any given maintenance is influenced not only by the complexity of the task itself, but also by factors such as:

   - Maintenance planning
   - Job staging
   - When the maintenance is done (that is, during outage or nonoutage periods)
   - Built-in maintainability
   - Availability of handling facilities and equipment
   - Timeliness of the QC and Health Physics support
   - Radiation work permit and dosimetry process
   - Operations support

- Availability and quality of parts
- Level of training of the individuals doing the maintenance
- Pre-job briefing they receive

At most nuclear plants, the total time and the "wrench time" for each maintenance task are captured in the MMIS, usually on a work order or task basis. At some plants, the MMIS may capture only the actual craft time spent working on the equipment and may not include the craft time spent on obtaining the radiation work permit, dosimetry, Operations clearance and other related activities.

6. *Maintenance support staff person-hours*: This includes the person-hours of maintenance engineers, planning and scheduling staff, procedure writers, and clerical staff involved in support of maintenance. This variable affects the burdened salary cost of the support staff applied to maintenance activity. Training of the support staff for the job being performed is the primary factor that affects this variable. Unlike the craft hours, this information is generally not captured at either the specific equipment or the work order levels. It may be available only at the department (that is, Mechanical, I&C, or Electrical) level.
7. *Health Physics support and radiation work permit process*: This variable is the craft time spent in obtaining Health Physics support, the radiation work permit, and dosimetry for work on equipment in high radiation areas.
8. *Parts availability and quality*: This variable involves the availability of quality spare parts when needed. A balance must be struck between inventory levels required and the cost of purchasing and storing that inventory. In addition, for engineered spares and those with long lead times, timely engineering support is required to ensure that sufficient stock levels are maintained. The myriad of procurement engineering programs and organizational changes put in place over the last 10 years to address the commercial grade item quality problems justifies a thorough review of this variable.
9. *Equipment design and application*: This variable involves the proper selection of equipment for the application and maintainability of equipment. Two questions to be asked in this regard are:
   - Do the design, the materials of construction, and / or the application of the equipment make it more susceptible to frequent failures?
   - Do equipment application and installation facilitate performing maintenance without recourse to unusual or complicated procedures and maneuvers?

   Example: An air-operated valve is mounted on a pipe carrying hot steam. Its associated solenoid valve mounted on the valve operator may be subject to frequent failures caused by heat. Similarly, if a valve operator is mounted in a location high off the floor and there is no work platform, it may require maintenance personnel to perform work in an unusual and potentially unsafe posture. Such a condition may lengthen the work time, cause errors leading to rework, and in the extreme, cause personnel injury. These types of situations may require design modification.

10. *Equipment operating procedure:* This variable involves the duty rotation of redundant and / or standby equipment.

    Example: Three half-capacity compressors are provided in the service air system. Ensuring that the three compressors share the duty evenly is important. Without even duty rotation, it is likely that the compressor operated the least may experience failure from causes such as lubricant stratification, or the compressor operated the most may experience premature failures (for example, bearing failure).

11. *Organizational breakdown of responsibilities*: This variable involves overall plant organization and how maintenance responsibilities are assigned. A careful review of this aspect can lead to a streamlining of the responsibilities, improved accountability, ownership and teamwork, and thus long run cost savings.

    Approach #1: Operating personnel are the closest to the equipment. They perform daily walkdown inspections. Should they be assigned the responsibility for collecting vibration data on rotating equipment and checking and collecting samples for oil analysis? Should they be asked to do an IR survey of fuses and vital components in cabinets? Should they be required to log oil and bearing temperatures and monitor trends?

    Approach #2: Form a core team of electrical, mechanical, and I&C engineers or technicians within the technical services or sysems engineering groups to perform the functions listed in Approach # 1 above and all other predictive maintenance functions.

12. *Administrative and paperwork process:* This variable involves the administrative system currently in place, the paperwork performed, and documentation generated by all those involved in the maintenance process. The changes resulting from addressing the 11 elements discussed earlier and the advances in information technology demand a review of this variable to ensure that they support the transformation into a more productive way of conducting business. It is quite likely that some of this evaluation would have happened as each of the other 11 variables is addressed. A final comprehensive evaluation of this variable can identify additional areas for improvement.

Addressing all these variables in one broad-based project may be resource-intensive and disruptive to the organization. Therefore, undertaking a maintenance effectiveness improvement project in stages is preferable. The variables that are likely to offer the most benefits in the short and long terms are the ones to address first. The order in which the variables are listed and discussed earlier is based on this philosophy.

3.3 Approaches Used To Improve Maintenance

The site visits and survey discussed in Section 2 and a review of the pertinent literature [3–10] identified that the following approaches have been used by nuclear utilities and other industries to “optimize preventive maintenance”:

- Reliability-centered maintenance (RCM)

- Total productive maintenance (TPM)
- Reliability-based maintenance (RBM)
- Probabilistic-safety analysis based maintenance (PSA)

Some sites have also used other in-house methodologies (usually a modified version of RCM or RBM to optimize preventive maintenance programs. The following subsections provide a brief explanation of each of the above approaches and discuss their advantages and limitations in the context of the challenge of overall maintenance effectiveness improvement.

Users are cautioned that the summary descriptions that follow are intended to summarize these concepts. For a more comprehensive discussion of the topics, users should consult other references, including 11, 12, and 28.

3.3.1 Reliability-Centered Maintenance

Classical RCM has its roots in the airline industry and has been adapted for many industrial applications including nuclear plants. Nuclear power plants have found RCM to be a valuable tool when they are attempting to reduce maintenance costs.

3.3.1.1 Classical RCM

Reliability-centered maintenance is an engineering process (see Figure 3-1) used by some nuclear utilities and other industries to optimize PM. RCM may be defined as “a process used to determine the maintenance requirements of any physical asset in its operating context“ [3]. EPRI reports [11, 12] provide a comprehensive discussion of both the RCM process and implementation guidance. Briefly, it is a top-down approach that begins with establishing system boundaries and developing a critical equipment list. An equipment item is deemed to be critical if it performs a function or if its failure can affect functioning of equipment that ensures:

- Nuclear safety
- Prevention of release of radioactivity to the environment
- Personnel safety
- Continued power production
- Any combination of these items

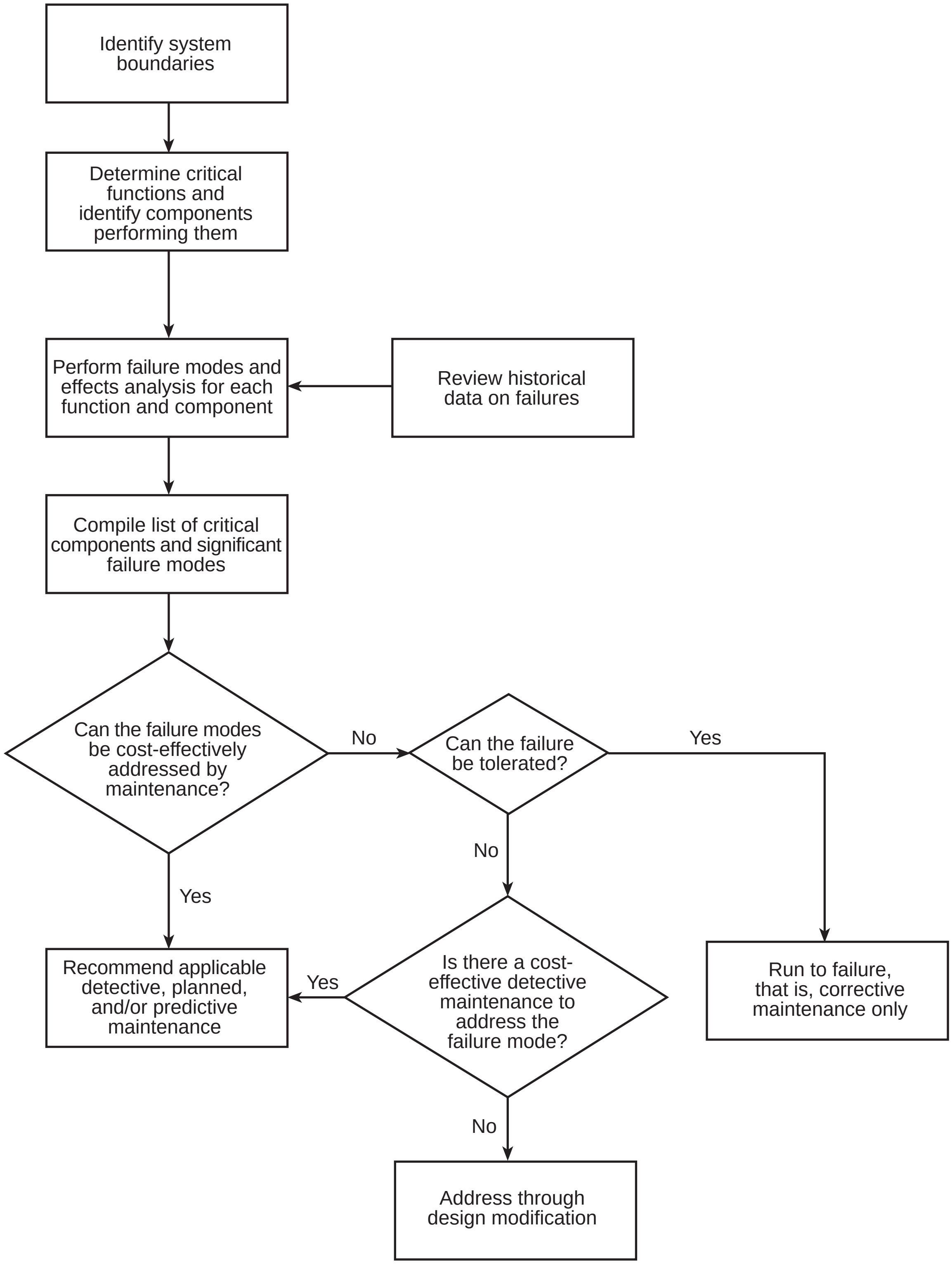

Figure 3-1
Reliability-Centered Maintenance Process Overview

For each equipment item in that list, a failure modes and effects analysis (FMEA) is conducted to:

- Identify each failure mode and its probability of occurrence
- Evaluate the significance of each failure mode according to its impact on equipment function

Functional failures are the only ones considered important in the FMEA. The probability of occurrence of a failure mode is determined (usually on a qualitative basis) based on a review of equipment failure history using databases such as the INPO Equipment Performance Information eXchange (EPIX)[1] . If the probability of a failure mode is determined to be low or if failure mode does not affect the equipment's capability to perform its specified function, then no specific maintenance to address that failure mode is required. For other failures, a logical or other analysis is conducted to determine if a cost-effective maintenance technique is available that can eliminate or reduce their probability of occurrence. Maintenance recommendations are then developed. RCM recognizes that not every failure mode needs to be or can be addressed by a maintenance-based solution. If a maintenance action addressing a significant failure mode is not available or is not cost-effective, and the failure cannot be tolerated, then a design modification is recommended. If the failure can be tolerated, then run-to-failure, that is, corrective maintenance, is recommended. Ideally, this process should ensure that:

- Maintenance is applied only to equipment that must receive it for policy objective 1 (equipment availability and reliability) outlined earlier to be achieved.
- Even in those cases, only those maintenance actions determined to be cost-effective are applied.
- For equipment not in the critical equipment list, run-to-failure, that is, corrective maintenance only, strategy is automatically prescribed.

In the decision logic phase, the cost-effectiveness of periodic maintenance and predictive technologies appropriate to address the failure mode of interest are evaluated. It is this part of the RCM process that ensures a balanced mix of periodic and predictive maintenance. It is presumed that an optimal balance between PM and CM is achieved through the rigorous process of establishing the critical equipment list. This presumption is true if the criteria for determining the criticality of an item are complete and if those criteria are applied objectively.

In summary, RCM answers two questions:

- Is the equipment important to the mission (that is, what is the effect of its failure on the mission)?
- What cost-effective periodic and predictive maintenance can eliminate or significantly reduce the probability of occurrence of the failure modes that affect the functions important to the mission?

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1 EPIX was formerly known as the Nuclear Plant Reliability Data Systems (NPRDS).

Plants that have used RCM report significant reductions in periodic maintenance and increased use of predictive maintenance. When RCM is used as a maintenance optimization tool, factors to consider include the following:

- It is a very costly and time-consuming process.
- Successful implementation requires highly trained engineering resources dedicated for an extended period.
- It leaves room for subjectivity in the decision-making process regarding the type of maintenance that can be effective for a specific situation.
- It must be used as a living program and not as a one-time engineering evaluation process.
- RCM addresses only controllable variables 1 and 2 directly and to some extent variables 5, 6, and 9 indirectly.

3.3.1.2 Streamlined or Simplified RCM

Nuclear power plants have found RCM to be a valuable tool for maintenance costs reduction; however, the initial or nonrecurring costs for RCM implementation proved to be significant and required a rather high level of plant/system understanding in order to perform reliable evaluations.

Various approaches to RCM were developed to deal with the initial costs associated with classical RCM evaluations and to provide technical soundness to the streamlined methods. Three streamlined methods are presented in Reference 28 that are easily implemented and provide the same set of critical components as classical RCM. These approaches are:

- Streamlined classical RCM
- Plant maintenance optimizer (PMO) streamlined process
- Criticality checklist streamlined process

These methods have enabled sites to implemented RCM concepts at reduced initial costs (for example, a factor of 2 less than classical RCM).

RCM has proven to be a tool that helps sites focus on the appropriate level of maintenance activities, regardless of the approach. After there is experience in the development and application of additional tools such as standard templates, the cost of RCM implementation should reach some standard cost level.

To address some of the factors listed above, plants have used various modified versions of RCM such as low cost RCM and reliability-based maintenance. These factors can also be addressed by using things such as joint utility programs and generic templates.

3.3.2 Total Productive Maintenance

Total productive maintenance (TPM) is a maintenance optimization process that promotes preventive maintenance set in the framework of equipment ownership by the operators and maintenance work teams consisting of operators, maintenance personnel, and engineers. TPM attempts to break down the rigorous compartmentalization of work within a plant. The work team concept determines which equipment gets what type of maintenance, at what level, and using what technologies. The decision process used is less formal and uses the model that best fits the specific application and work group. Similar to the RCM process, this process also emphasizes predictive maintenance. Also like RCM, this process addresses only some of the controllable variables listed earlier. Further, prevailing work rules, environment, and plant culture may limit U.S. nuclear sites in using this approach. Some sites are using this concept to some extent now in what are called “Fix It Now” (FIN) or “Work It Now” (WIN) teams. This is a relatively new initiative, and there has been some limited success with this team concept, but the overall impact on the maintenance process is still not known.

3.3.3 Reliability-Based Maintenance

The reliability-based maintenance (RBM) process is a hybrid of the RCM and TPM processes. As shown in Figure 3-2, RBM begins with a benchmarking phase in which an assessment is made of the current maintenance practices, organization, personnel attitudes, technologies used, work flow and practices, costs, and performance measures. Using the information from this assessment, an action plan for transition from the present to the future is developed. At this stage, RCM is used to determine which equipment will get what level and what type of maintenance and what technologies will be used in the maintenance.

Like RCM, RBM also emphasizes predictive maintenance instead of or as a supplement to periodic maintenance. In a parallel effort, the organization, work division responsibilities between departments, and work flow are evaluated to determine if there is a need to recast the departmental responsibilities and work flow process. From this two-pronged review, a set of recommendations for maintenance, organizational changes, and reassigned responsibilities are developed.

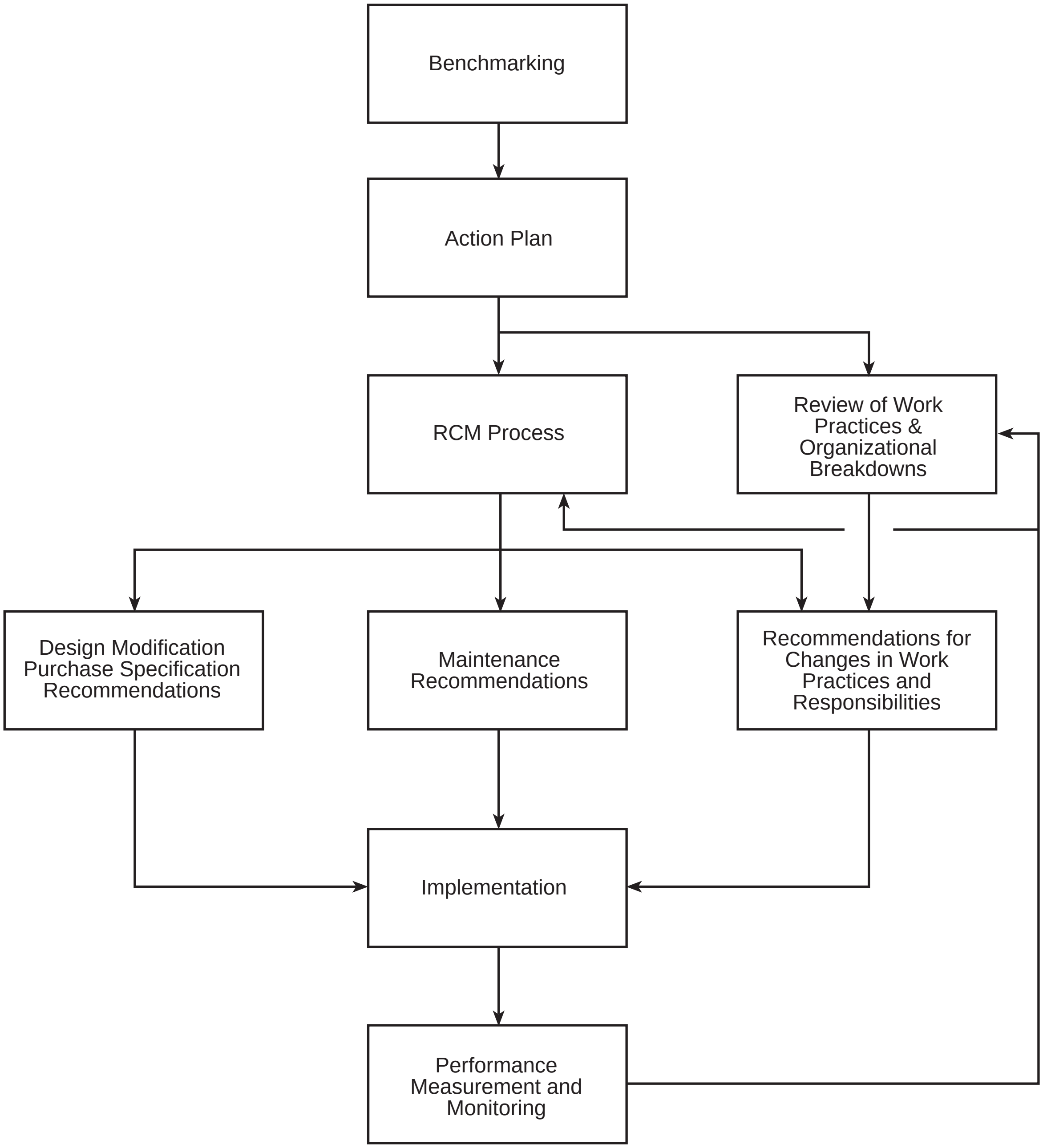

Figure 3-2
Reliability-Based Maintenance Process Overview

Note that there are a few variations of RBM. Specifically, RBM aims to foster equipment ownership by the operators, and teamwork between engineers, operators, and maintenance personnel, similar to the TPM model. RBM encourages redistribution of some predictive maintenance (for example, vibration data gathering and oil sample collection) and routine servicing (for example, oil changes) tasks to the operators who are the ones in close contact with the equipment on a daily basis.

Another feature of RBM is the emphasis on feedback to the engineering and purchasing processes. The intent is to eliminate significant failure modes from currently installed equipment through design modifications wherever practical and in future equipment purchases through changes to design and selection of materials.

RBM addresses controllable variables 1, 2, 8, 9, and to some extent 5 and 6. Some sites have apparently used some form of RBM and the available information is insufficient to evaluate its success.

3.3.4 PSA-Based Maintenance

Probabilistic safety analysis (PSA) is a logical and reproducible methodology that is used to estimate the frequency of events that will lead to some undesirable state (for example, core melt) of the plant. PSA models incorporate plant design, component and system reliability (usually based on prior operating history), operating procedures, human interactions, and physical processes. Sites that have done a full-scope PSA can use it to develop a critical equipment list and equipment reliability goals, and to identify significant failure modes.

Using this information, the decision logic similar to that used in an RCM process (see Figure 3-1) can be applied to develop maintenance recommendations. A PSA-based ranking of equipment and systems can be useful in the analysis and management of maintenance performance risks. Plants may also find such information useful in evaluating potential schedule conflicts, supporting decisions to prioritize periodic maintenance activities, and determining acceptable work scope and duration consistent with station risk. The difficulties that may be encountered in using this methodology for maintenance optimization include but are not limited to the following:

- PSAs may not be sufficiently comprehensive to support the detailed information needs of a comprehensive maintenance optimization effort.
- PSAs do not address equipment and systems that are not directly or indirectly involved in the support of a safety function (for example, power production).
- PSAs do not include considerations such as personnel and occupational safety in working with equipment.

The surveys and site visits performed as a part of this project did not identify any plant that used this methodology by itself for maintenance optimization. However, sites have used the results from PSA in establishing a critical equipment list.

4

RECOMMENDATIONS FOR IMPROVEMENT

At the time of this writing, sites have completed their Maintenance Rule [13] implementation. In addition, some sites have also done some level of maintenance optimization, usually called preventive maintenance optimization (PMO), using one or more of the approaches discussed in Section 3. In developing a set of recommendations for improving maintenance effectiveness, building on what has already been done is important. For this purpose, sites are divided into two groups:

- **Group A**. Sites that have used RCM, RBM, or other methodologies to achieve some level of PM optimization
- **Group B**. Sites that have yet to or are only beginning to focus systematic attention on maintenance improvements.

4.1 Recommendations for Group A Sites

Sites in this group are those that have implemented the Maintenance Rule (MR) and in addition have completed or have undertaken some form of PM optimization effort. Table 4-1 shows the presumed status of these sites in terms of addressing the 12 controllable variables of the maintenance effectiveness challenge identified in Section 3.2. Note that for any given site, the exact status can vary from that shown. When reviewing the recommendations provided in this section, users should modify Table 4-1 to match their site's status with respect to each identified variable.

Table 4-1
Maintenance Process Review Status of Group A Sites

Item	Description	Status
1	Equipment population covered by preventive maintenance	Although between PMO and MR, for the most part this item should have been addressed. For some plants, additional work in this area may be appropriate. See recommendations 1 and 2 for areas suggested for review.
2	Type of maintenance applied	Between MR implementation and PMO, this item should have been addressed. See recommendations 1 and 3.
3	Allocation of maintenance between outage and non-outage periods	This item may not have been addressed in some sites in this group. See recommendation 5.
4	Cost of performing a specific type of maintenance on a specific piece of equipment	This item may not have been addressed in some sites in this group. See recommendation 6.
5	Craft person-hours	To the extent that this item is affected by variables 1 and 2 above, it should have been addressed. See recommendations 1–6.
6	Maintenance support staff person-hours	To the extent that this item is affected by variables 1 and 2 above, it should have been addressed. See recommendations 1–6.
7	Health Physics support and radiation work permit process	This item may not have been addressed in some plants in this group. See recommendation 8.
8	Parts availability and quality	This item should have been addressed. See recommendation 7.
9	Equipment design and application	To the extent that this item is affected by variables 1 and 2 above, it should have been addressed. See recommendation 11.
10	Equipment operating procedure	This item should have been addressed. See recommendation 11.
11	Organizational breakdown of responsibilities	This item should have been addressed. See recommendation 9.
12	Administrative and paperwork process	This item should have been addressed. See recommendations 9 and 10.

Given the above status, most (>50%) of the maintenance optimization and the resultant maintenance cost improvements have been achieved. Attention should now be focused on the variables that remain. For Group A sites, the recommendations listed below are aimed at augmenting the ongoing or completed efforts. The final recommendation addresses monitoring the effectiveness of maintenance to provide a basis course correction.

Note that addressing all the items in one comprehensive project is not necessary. These recommendations may be implemented in steps over a period of time. What is important is to instill and sustain a maintenance effectiveness culture among the O&M personnel.

Recommendations:

1. Review the PdM technology application against Tables 5-1 and 5-2 (see Section 5) to ensure that maximum use of PdM is made. Each application should be evaluated using a payback model similar to the one shown in Table 4-2. For many equipment types, just one failure per year may be enough to pay back the cost of PM, even without the added cost from the losses due to radiation exposure, waste disposal, and lost power production.

Table 4-2
Economic Evaluation of PdM Technology Application
Case: Substituting Run-to-Fail Maintenance with PM

Cost Elements	Value or Unit Cost*	Total Cost
Number of failures of equipment per year = 1, Plant downtime per failure = 5 hrs Plant rated output 1000 Mwe A PM that can be effective in addressing key failure modes is available.		
$ value of lost production per hour**	$1,000.00/MWe/hr	$5,000.00
Person-rem cost @ 1 person-rem per failure	$500.00 per person-rem	$500.00
Cost replacement parts and repair material***	$3,500.00 per failure	$3,500.00
Person-hours (craft + support staff) 10 per failure	$55.00	$550.00
Waste disposal cost	$500.00 per failure	$500.00
Total cost of annual failures	--------	$10,050.00
Cost of PM, two times a year	$400.00 per event	$800.00
Cost of test equipment****	$ 12,000.00	$2,400.00
Total cost of PM*****	--------	$3,200.00
Payback period	--------	< 1 year

Notes:

* Unit costs shown are for illustrative purposes only. Plant-specific numbers should be used.

** Conservatively assumed at $240,000 per day.

*** For high dollar value (>$5,000.00) engineered items, including the cost of procurement and cost to carry inventory using an average inventory turnover based on prior use would be prudent. For example, assuming a $5,000 engineered item, 8 equivalent (Engineering, QA, QC, Expediting, Purchasing) person-hours at $60.00 an hour for procurement, an 18-month inventory turnover, and 8% per annum interest, the real cost to be used would be 5000+480+658 = $6138, computing the interest on a simple interest basis.

**** Assuming five years' useful life and a present value of $12,000 that includes the initial cost of equipment acquisition and its maintenance and training costs for five years, an annualized cost of $2,400 for test equipment is used.

***** When applicable, take into account the present worth of insurance credit/penalty (see Appendix D for details).

2. Consider expanding PM to noncritical equipment (that is, equipment presently run-to-failure only) with a history of repeated failure or equipment whose failure can involve substantial (>$10,000) repair or replacement costs.[1] This can be done by reviewing the plant's corrective maintenance records for the past five years to identify the top 20% of the equipment that required the most CM person-hours (the Pareto principle of 80-20). Additional supporting evidence on equipment failure history may be obtained by reviewing the EPIX[2] database for this class and type of equipment.

   Within this population, focus first on equipment in high radiation areas. Next, for each piece of equipment on this list, identify the dominant failure modes that caused most of the CM needs. Last, evaluate possible periodic and/or predictive maintenance that could be effective in addressing the dominant failure modes, and develop maintenance recommendations. Evaluate the cost-effectiveness of a maintenance action using a payback model similar to the one shown in Table 4-2.

3. Review the results of PdM technologies already in use to improve their cost-effectiveness. Section 5 provides a detailed discussion of the potential for such improvements.

4. Review historical calibration data on instruments to identify opportunities for calibration frequency changes (Note: not just a reduction in frequency) that could eliminate or reduce some of the losses listed in Section 3.1. EPRI report TR-103436 [15], which provides a comprehensive methodology to optimize the calibration frequencies for instrument loops, could be the basis for this evaluation.

5. This recommendation applies only to those plants that may not have completed a systematic review of all PM activities during MR implementation. Review each outage maintenance task to determine why it must be done only during an outage, and move those that do not have any plant impact to be performed during nonoutage periods. Maintenance should be performed during power operation, especially in cases where it would improve plant safety, system reliability, or system availability. However, it is important to ensure that doing so would not:

   - Result in a plant transient and/or trip
   - Result in unwarranted actuation of safety systems
   - Entail entry into a restrictive limiting condition of operation (LCO)
   - Unduly increase personnel exposure
   - Jeopardize personnel safety

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1 By definition, noncritical equipment should not have any power production, personnel safety, or other safety and environmental regulation-related losses. But other losses such as person-rem exposure, waste disposal, etc., can be there, and they should be included.

2 The EPIX database is limited to safety-related equipment. However, operating experience on a similar equipment type (for example, Westinghouse 480 V motor) may be useful for this evaluation.

Results from plant PSA may be useful in performing this review. Some plants have used an expert panel (usually a team of operations, maintenance, and engineering staff) to perform and/or verify this evaluation.

6. Collect and review the history (for example, for the previous five years) of failures, the person-hours spent on PM, and the CM per operating cycle for the following major equipment:[3]

   - Diesel generator
   - Main feedwater pump turbine if applicable
   - Control room chiller
   - Reactor coolant pump
   - UPS and battery charger
   - Other major types of equipment as needed

   Obtain and compare information from three peer plants for similar equipment. If there are major differences, evaluate the causes and initiate corrective measures as necessary. Using this information, evaluate if outsourcing the PM can result in significant cost savings while maintaining the equipment availability at the desired level.

   Example: The cost of performing a full diesel generator overhaul can vary depending upon whether it is done by in-house maintenance personnel or vendor maintenance personnel. The difference may be attributable to other competing priorities and the level of in-house knowledge, skills, and test equipment (KSE) available. Evaluating the cost of maintaining that KSE available, plant experience in maintenance-induced failures of the equipment under consideration, and other related factors can show whether it is more cost-effective to outsource the overhauls or keep them in-house.

7. Review recurring PM and CM rework for the last five years to identify the rework that resulted from parts quality and/or availability. For these cases, initiate engineering resolutions (for example, design or materials change) to correct the parts-related problems.

8. Evaluate the work flow and practices to identify and eliminate waste of craft and support staff person-hours. Items in the work flow that should be evaluated are areas of review such as division of labor, processes for obtaining radiation work permits, and the closing of job packages. Review also the maintenance training for craft personnel to ensure that training is tailored to the job requirements and emphasizes attention to detail so that rework can be reduced.

[3] It is assumed that a similar comparative evaluation has been performed on the turbine generator and the steam generator; therefore, they are excluded from this list. Users may wish to add other major equipment categories in this review.

9. Re-evaluate the breakdown of responsibilities for PdM tasks and routine inspections. Evaluate the feasibility of integrating field data collection and preliminary evaluations within the respective Maintenance Departments and, where practical, within the Operations Department. Consider the feasibility of consolidating all PdM functions (see Table 4-3) under one lead, for example, a PdM group that would report to the maintenance superintendent and function as a cost center for budgeting and reporting purposes. This has the potential to offer the following advantages:

   - Development of an in-house specialized technology capability
   - Avoidance of test equipment duplication
   - Cross-training of personnel
   - Efficient use of personnel
   - Improved coordination of all PdM work performed on the same equipment or in the same location
   - Better accountability

   In addition to managing all PdM activities, this group would:

   - Serve as an in-house service organization to assist in troubleshooting, using advanced technology, for all other maintenance groups
   - Be responsible for annually reviewing all CM work and identifying opportunities for additional PM that can address the loss leaders

   Table 4-3 provides a suggested breakdown of PdM functions for consideration in this review.

10. Establish a set of maintenance effectiveness indicators similar to those discussed in Section 6 for monitoring maintenance performance, and require monthly reporting.
11. Review equipment failure history to identify equipment with frequent or recurring failures. For those cases, perform root cause analysis and determine if changes in equipment design, application, and/or operating procedures can eliminate or minimize recurring failures. Implement appropriate changes in accordance with plant priorities.

Collectively, the recommendations above are intended to address the areas of maintenance that impact effectiveness, but may not have been fully addressed by the PMO or other maintenance process review programs already completed. For the most part, each recommendation stands alone and can be implemented either singly or in groups. The choice of which recommendations to implement, to what extent, when, and in what order depends upon the plant needs and the availability of resources.

Table 4-3
Proposed PdM Responsibilities Matrix

PdM Function	Responsibility
Technology selection	PdM group engineers trained in applicable technology
Selection of equipment application	Same
Purchase of test and diagnostic equipment, tools, and software	Same
Establishing procedure and acceptance criteria	Same
Personnel training	Same as above with assistance from Training Department
PdM budget development, management reporting	PdM group supervisor
Field data collection for technology that does not require equipment cover opening or disassembly, and use simple portable test equipment. For example: • Vibration monitoring of pumps, motor bearings, and housings • IR thermography survey of control panels and fuse assemblies. • Temperature measurement/logging such as bearing temperatures or oil temperatures • Visual inspection of oil and grease • Oil sample collection • Sensory inspection of components such as excessive humming of solenoid coils, arcing contacts, bearing squeals, or noisy belts	Operations Department or integrated with PdM responsibility for a core technical team from Technical Services or Systems Engineering
Field data collection for technologies that require complex setup and test equipment. For example, motor current signature analysis, MOVAT, surge testing.	Respective Maintenance Departments
Preliminary data evaluation for cases where a clear go-no-go acceptance criteria is used. For example, vibration amplitude or temperature exceeding a preset value.	Data collectors, that is, the Operations Department or the respective Maintenance Departments
Final data evaluation for simple go-no-go types, and data evaluation, interpretation, and analysis that requires an in-depth knowledge of technology.	PdM group engineers trained in the applicable technology
Overall PdM program direction and accountability	PdM group supervisor

Table 4-4
Maintenance Process Review Status of Group B Sites

Item	Description	Status
1	Equipment population covered by preventive maintenance	MR implementation should have addressed this item to the extent of identifying system boundaries and equipment for safety systems and certain non-safety systems. Further work is needed to complete the identification of overall PM population and determination of maintenance needs. See Phase I recommendations and Phase II recommendations 1 and 2.
2	Type of maintenance applied	MR implementation should have addressed this item to some extent. See Phase I recommendations and Phase II recommendation 3.
3	Allocation of maintenance between outage and non-outage periods	This item may not have been addressed in some sites in this group. See Phase I recommendations.
4	Cost of performing a specific type of maintenance on a specific piece of equipment	This item may not have been addressed in some sites in this group. See Phase II recommendation 6.
5	Craft person-hours	This item should be addressed. See Phase I recommendations and Phase II recommendations 1-7.
6	Maintenance support staff person-hours	This item should be addressed. See Phase I recommendations and Phase II recommendation 1-7.
7	Parts availability and quality	This item should be addressed. See Phase II recommendation 5.
8	Health Physics support & radiation work permit process	This item should be addressed. See Phase II recommendation 6.
9	Equipment design and application	This item should be addressed. See Phase II recommendation 8.
10	Equipment operating procedure	This item should be addressed. See Phase II recommendation 8.
11	Organizational breakdown of responsibilities	This item should be addressed. See Phase II recommendation 7.
12	Administrative and paperwork process	This item should be addressed. See Phase II recommendation 6.

4.2 Recommendations for Group B Sites

Sites in this group are those that have implemented the Maintenance Rule, but are yet to undertake a PM optimization effort. Table 4-4 shows the presumed status of these plants in addressing the 12 controllable variables of the maintenance effectiveness challenge identified in Section 3.2. Users are cautioned to verify that the assumptions regarding Maintenance Rule implementation shown in Table 4-4 are valid for their sites.

Given the above status, most (>70%) of the maintenance process review and the resultant maintenance cost improvements are yet to be accomplished. Ideally, for these sites, a complete and comprehensive PM optimization effort should be performed using approaches such as RBM supplemented with the recommendations for Group A sites discussed in Section 4.1. However, it would require not only application of a large amount of highly trained resources, but would also be very time consuming and costly. The benefits from such an undertaking would not be seen for at least two years. It would, therefore, be preferable to embark on a project that has the following traits:

- It would build on the work already done for Maintenance Rule implementation.
- Its elements can be implemented as necessary.
- It would not require the total dedication of a large number of highly trained resources.
- It can be carried out by the Maintenance Department support staff with minimal support from the Engineering and Operations Departments.
- It would start showing benefits almost immediately (that is, within six months).

The following recommendations for implementation in two phases are given in the sections that follow.

4.2.1 Phase I Recommendations

These are the recommendations for Phase I:

1. For each item in the PM program except I&C, determine if the maintenance being performed is valid and effective, and if not, develop recommendations for change. I&C equipment is deferred for review in Phase II because it would tax the resources and divert attention from the bigger payoff items. This review may be done by following the steps listed below:

   a. Review each piece of equipment in the current PM list and put each piece into one of three categories as follows:

      - Category A — Required for MR
      - Category B — i) Equipment required to perform a function to ensure (or its failure can affect the functional capability of equipment that ensures):
        - Continued power production (for example, condensate pump, heater drain control system, and valves)
        - Personnel safety (for example, certain protective relays and area radiation monitors)
        - Plant security

        ii) Equipment failure that would lead to repair or replacement costs[4] more than $50,000
      - Category C — Others

      Category A and B equipment together should make up the population of equipment similar to the critical equipment list generated in the beginning of the RCM process.

   b. For each equipment item in categories A and B, review the current PM tasks using a logic similar to one shown in Figure 4-1, and develop recommendations for changes. Justification for maintenance is automatically established after the review following the logic in Figure 4-1 is completed.

   c. Alternatively, the above review may be done at the equipment group level after grouping equipment by types similar to that shown in Table 4-5. In this case, variations in maintenance for individual items within a group should be addressed on a case-by-case basis. A current EPRI project [14] is aimed at developing maintenance templates (that is, recommended preventive maintenance tasks and their frequencies of performance) for various equipment types used in power plants. The results from this project may be useful in completing this review.

[4] When computing repair cost, include the cost of material, person-hours, waste disposal, and personnel exposure costs only.

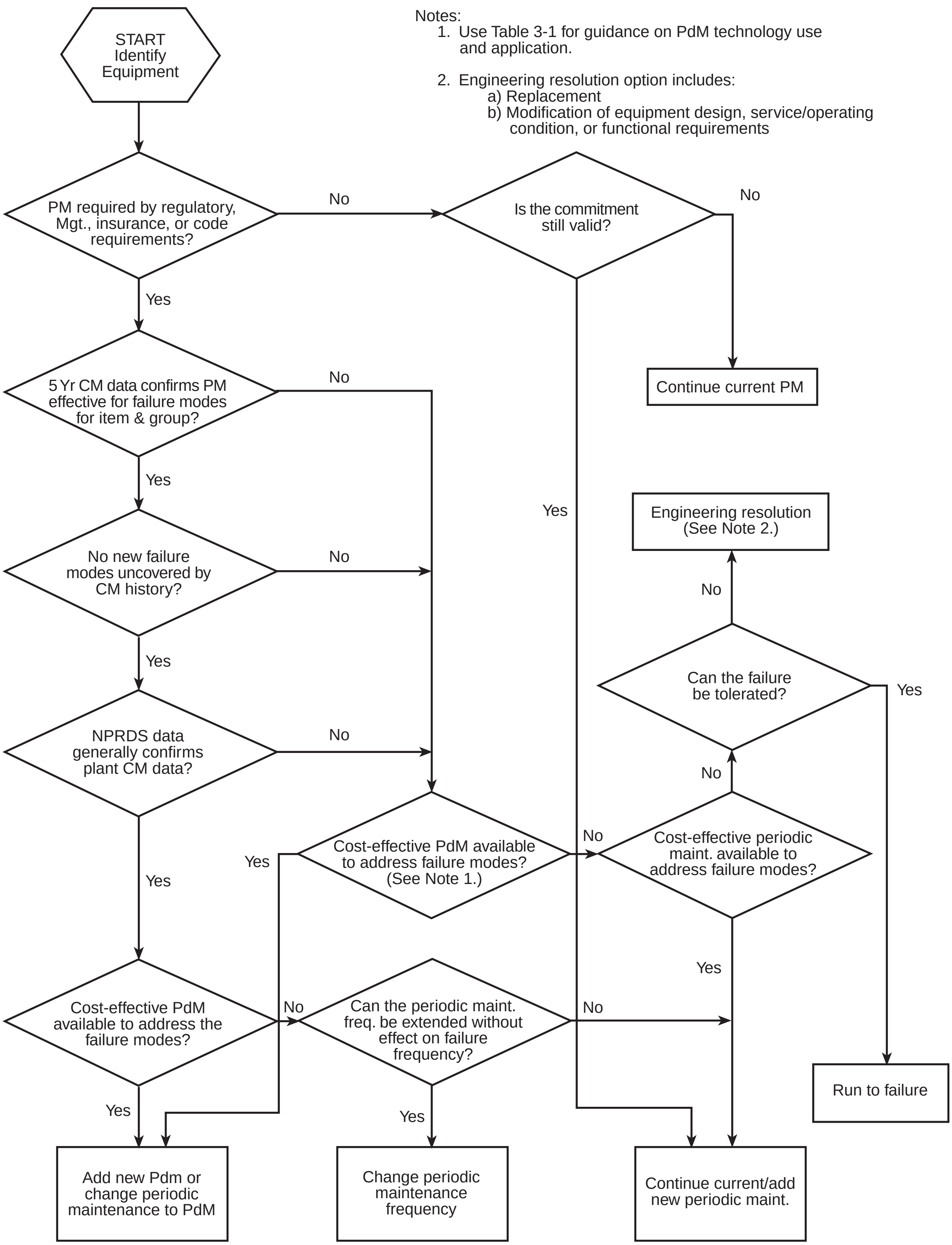

Figure 4-1
Evaluation of Non-MR Equipment

Table 4-5
Equipment Grouping

Item	Equipment Description	Item	Equipment Description
1	Air filter	16	Snubbers
2	Batteries	17	Switchgear
3	Cables	18	Transformers
4	Controllers	19	Turbines
5	Check valves	20	Valves - Manual
6	Centrifugal pumps	21	Valves - Motor operated
7	Compressors	22	Valves - Air operated
8	Diaphragm valves	23	Valves - Check
9	Generators	23	Valves - Solenoid operated
10	Heat exchangers	25	Pumps
11	I&C equipment	26	Steam traps
12	MCC	27	MG sets
13	Large motors	28	Battery chargers
14	Medium motors	29	Batteries
15	Small motors	30	UPS

For this equipment, review each outage maintenance task, determine why it must be performed only during an outage, and move those that have no plant impact to nonoutage periods. The criteria used to decide when a given maintenance task is to be performed may include the following:

A. Performing maintenance during power operation would enhance:

- Equipment and system reliability / availability
- Plant safety
- Personnel safety
- Reduce outage duration

And

B. Performing the maintenance during power operation would not:

- Result in plant transients and / or trip
- Result in unwarranted actuation of the safety systems
- Require entry into a restrictive limiting condition of operation (LCO) required by the plant Technical Specifications
- Unduly increase the personnel exposure
- Jeopardize personnel safety

2. Finalize the maintenance recommendations and implement them.
3. Implement a maintenance effectiveness monitoring system similar to that discussed in Section 6.

4.2.2 Phase II Recommendations

Phase II recommendations are intended to be considered after Phase I has been fully implemented. These recommendations complete the overall maintenance process review.

1. Review historical calibration data on instruments to identify opportunities for calibration frequency changes (Note: not just a reduction in frequency) that could eliminate or reduce some of the losses listed in Section 3.1. EPRI report TR-103436 [15], which provides a comprehensive methodology to optimize the calibration frequencies for instrument loops, could form the basis for this evaluation.
2. Consider expanding PM to noncritical equipment (that is, equipment presently run-to-failure only) with a history of repeated failure or equipment whose failure can involve substantial (>$10,000) repair or replacement costs.[5] This can be done by reviewing the plant CM records for the past five years to identify the top 20% of equipment that required the most CM person-hours (Pareto principle of 80-20).

   Within this population, focus first on equipment in high radiation areas. Next, identify the dominant failure modes that caused most of the CM needs. Additional supporting evidence on equipment failure history may be obtained by reviewing the EPIX database for this class and type of equipment. Last, identify and evaluate possible periodic and / or predictive maintenance that could be effective in addressing the dominant failure modes, and develop maintenance recommendations.

   Evaluate the payback for each action using a model similar to the one shown in Table 4-2. For many equipment types, just one failure per year may pay back the cost of PM, even without the added cost from the losses due to radiation exposure, waste disposal, and lost power production.

[5] By definition, noncritical equipment should not have any power production, personnel safety, or other safety and environmental regulation related losses. But other losses such as person-rem exposure, waste disposal, etc., can be there, and they should be included.

5

PREDICTIVE MAINTENANCE, PRESENT AND FUTURE

Predictive maintenance refers to a set of tasks performed to detect incipient failures of equipment, to determine the maintenance actions required, and to restore equipment to its operable state upon detection of an incipient failure condition. Collectively, the first two parts are called *condition monitoring*. The third part is the performance of preventive maintenance that is determined to be required based on the observed condition.

Condition monitoring may consist of continuous monitoring (for example, on-line diagnostics used in digital instrumentation systems or TG thrust bearing wear monitoring) using permanently installed instrumentation or activities performed at specified intervals to monitor, diagnose, or trend the functional condition of equipment. The results from this activity support an assessment of the current and future functional capability of the equipment monitored and a determination of the nature of and schedule for required maintenance.

Although visual inspection can be very useful, modern condition monitoring generally involves the use of advanced technologies. Nuclear plants have been using predictive maintenance for major structures, systems, and components (SSCs) such as some pressure boundary components, containment structure, main turbine generator, and reactor coolant pumps for more than three decades. Since the late 1980s, heightened focus on O&M cost containment has led to a broader use of predictive maintenance for many other classes of equipment as well. This section reviews the application of predictive maintenance in nuclear plants and discusses opportunities for streamlining and improvements.

5.1 Present Application of Predictive Maintenance

Predictive maintenance relies on monitoring and diagnostic tools. Table 5-1[1] summarizes the uses of key predictive technologies and how they work. The EPRI *Predictive Maintenance Primer* [16] provides a comprehensive discussion of most of these technologies. Where applicable, references that provide application guidance on specific technologies are cited.

1 Note that this table is not a complete listing of all technologies available or used in nuclear plants.

Table 5-1
PdM Technologies, Their Uses, and Applications

Item	Technology [References]	Uses	Applications
1.	Acoustic emission monitoring	Detects incipient failure caused by fatigue and inter-granular structure breakdown. Commonly used to identify the onset of fatigue failures in pressure boundary components, pressure vessels, structural supports, and roller bearings.	Acoustic sensors are used to pick up acoustic emissions caused by the defect. Analysis of the time of arrival of the signal identifies the defect's location. By trending event occurrence and signal strength, analysts can project the progression of the defect.
2.	Acoustic monitoring [17, 18]	Detects internal and external leaks in relief valves, check valves, steam traps, heat exchanger tubes, and pipes used in air, steam, and water applications.	Broadband frequency sound sensors mounted around a pipe or valve. Senses sound in the range of 10 Hz to 100 kHz to detect a leak.
3.	Eddy current testing [19]	Detects surface and slightly subsurface flaws in metallic pipes and tubes in heat exchangers, condensers, and steam generators.	Temporary coils used to produce a magnetic field and an eddy current flow. Distortion of the eddy current suggests the presence of a flaw.
4.	Infrared thermography [20]	Monitors localized hot spots in electrical or mechanical devices, for example, bearings in rotating machines, coils in relays and solenoids, contacts in switching devices, power semiconductors, leakage of valves carrying high temperature fluids, steam traps, and other similar devices.	Detectors sensitive to an infrared frequency spectrum are used with an imager to develop a map of the temperature of the object that is focused on. The image shows the temperature gradient on a screen and can be digitized and processed to calculate the temperature at any given spot in the image. Physical contact with measured/scanned objects is not required.
5.	Liquid penetrant testing	Detects surface defects in welds, pipes, tanks, liners, and so on. Can also be used to detect leaks in tanks or other vessels.	A liquid dye is spread over the surface and wiped off. Viewed under a UV light, sometimes ordinary light, the surface shows where liquid dye has been drawn into the cracks.
6.	Magnetic particle testing	Detects surface cracks on welds, pipes, castings, forgings, and rod and bar stock.	A magnetic field is set up with ac or dc current at or around the object. Magnetic particles spread over the area are attracted to discontinuities that indicate flaws.
7.	Motor current signature analysis	Identifies motor problems such as friction or binding in mechanical parts, broken or cracked rotor bars and end rings, and certain winding irregularities.	A clamp-on current probe is connected to a microprocessor in order to produce and analyze the motor current traces for start, run, and coast down conditions. Spectral analysis consists of scanning for significant sidebands, separation of sidebands, sideband amplitude, breakaway or peak inrush current, and so on. This is a nonintrusive test.
8.	Movement or position monitoring	Detects wear in moving parts with close tolerance. Sensors can be used to recognize out-of-tolerance conditions in bearings, and pipe and snubber movements.	Sensors may be of the eddy current, optical, or ultrasonic type. They are sensitive to the interruption of the signal path by a change in the gap between the moving and stationary parts.

Table 5-1 (cont.)
PdM Technologies, Their Uses, and Applications

Item	Technology [References]	Uses	Applications
9.	Lubricant analysis	a) Identifies bearing and gearing problems in rotating equipment. b) Identifies insulation problems in transformers.	a) A sample of oil is chemically analyzed to identify the degradation of lubricant qualities and/or the presence of contaminants, wear particles, and water. b) A sample of insulating oil is chemically analyzed to identify the presence of various gases and their quantities, which is indicative of the insulation condition.
10.	Radiography	Detects subsurface or internal flaws in welds, castings, and forgings. It can be used on a variety of materials.	A photograph of the item is taken using X-rays or gamma rays. Recent developments include the use of a monitoring screen for live display and easy storage, expert systems combined with digitized imaging, and computed tomography for multi-angle scanning.
11.	Ultrasonic testing	a) Detects flaws in welds, metals, and plastics. b) Measures thickness in pipes and vessels. c) Monitors bearing wear by measuring the gap between two surfaces.	a) Sound waves in the frequency range of 100 kHz to 10 MHz are transmitted through the object being examined, and the reflected or refracted sound is measured and analyzed in a waveform analyzer. b) The same technique as a), but a scanner or imager is used to scan an area. c) A permanently installed ultrasonic transmitter and receiver measure the strength of reflected sound wave signals that vary with the gap size between two surfaces.
12.	Vibration analysis [21]	Identifies unbalanced, out-of-alignment, loose, or broken parts; gear problems, and bearing wear in rotating machinery.	Acceleration, velocity, or displacement sensors mounted on the equipment permanently or temporarily is connected to a microprocessor-based analyzer that can display a frequency spectrum. Pattern recognition is the common method of analysis to analyze vibration signatures. These signatures can be trended to identify abnormal conditions.
13.	Sensory inspection	Identifies abnormal equipment conditions that can be visually observed by the naked eye, heard, or felt. Useful for most equipment.	A checklist of inspection attributes tailored for each equipment category is used.
14.	Visual inspection - remote	Identifies abnormal conditions in equipment that is either in an inaccessible location or dangerous to be near. Used for conditions that can be visually observed by using remote observation aids. Useful for most equipment, specifically fuel pool liners, pipes, vessels and generators.	Optical equipment such as a telescope, periscope, Borescope, fiber optic sensor, or TV camera in tethered or robot-controlled configuration is used to facilitate remote visual inspection.

Table 5-1 (cont.)
PdM Technologies, Their Uses, and Applications

Item	Technology [References]	Uses	Applications
15.	MOVAT, VOTES, and other similar techniques for MOV testing	Identifies abnormalities in motor operator for motor-operated valves.	A set of sensors is used to measure stem thrust, motor current, and actuation points of limit and torque switches. A signature pattern recognition analysis of the stem thrust, current, and switch actuation signatures is done to identify abnormalities in gear box, mechanical condition, grease hardening, and electrical condition of the motor.
16.	Cable indenter	Detects age hardening of cable insulation and jacket materials.	An instrumented anvil indents the external surface of cable insulation or jacket as the case may be. Age hardening and the amount of aging is estimated from the compression modulus (that is, the force per unit of indentation).
17.	Engine analysis for DG	Detects engine problems and localizes it to a specific cylinder in an engine.	An engine analyzer and software that measure peak pressure, compression, horsepower, vibration, and exhaust temperatures assess engine performance and identify cylinders that may be the cause of performance degradation.
18.	Conventional electrical tests	Detects insulation integrity in motors, coils, transformers, and cabling.	Standard electrical test equipment is used to measure and trend parameters such as insulation resistance, high-pot, surge test, and winding resistance.
19.	AOV diagnostics	Air-operated valves	Data acquisition and diagnostic equipment used to test and/or determine valve condition.
20.	Operating deflection and shape analysis	Diesel generator	Measures and trends crank shaft deflection.

Table 5-2 shows the percentage of plants currently using a given technology and equipment applications covered for each predictive technology at nuclear plants. This information is based on the feedback received from 17 units in the U.S. and from 9 units in Canada. Although the table shows that many predictive technologies are used in most of the units, follow-up discussions suggest that the full potential of predictive technology is yet to be realized at most of the sites. Examples include:

- At one site, infrared thermography is used only for monitoring certain electrical power panels and in some troubleshooting applications.
- Infrared thermography is used to detect steam trap leakage at two of the sites in this survey, while others are not using it at all.
- Motor current signature analysis is being used at only one site.
- None of the sites surveyed use any cable condition monitoring.
- Only one site reported using an engine analyzer to monitor and trend the performance of diesel engines.

- The level of use of conventional electrical testing such as measuring winding resistance, insulation resistance, polarization index, and circuit evaluation for motor circuit condition monitoring varies among plants. Some plants use these techniques for all motors above a certain voltage or horsepower rating, or if the motors are mission-critical, these techniques are used, regardless of rating. One plant reports using motor circuit evaluation for all MOVs covered by the Maintenance Rule. Other plants use these tests only sparingly.
- Oil analysis includes particle count and size analysis on a routine basis only at some sites.
- While some sites report that they have eliminated 10–20% of the planned maintenance tasks by shifting over to PdM, others report minimal change. In fact, one site reported an increase in overall preventive maintenance tasks.
- Frequencies of performance for most predictive technologies vary among sites even for similar applications. Examples include the following:
  - The frequency of infrared thermography surveys of electrical components in control panels varies from once a quarter to annually.
  - Oil analysis for DG lube oil varies from once a month to once a quarter.
  - The frequency of vibration data collection on motors varies from monthly to quarterly.

Table 5-2
Current Plant Use of Predictive Technologies

Item	Technology	% Plants Use	Equipment Applications
1.	Acoustic emission monitoring	0	
2.	Acoustic monitoring	33	Check valves, relief valves, pipe wall thickness
3.	Eddy current testing	100	Heat exchangers, steam generators
4.	Temperature monitoring	100	
	Infrared thermography		Overheating in switch gears, bus ducts, coils in relays and solenoid-operated valves (SOVs), current transformers (CTs) motor current, insulators in substations, motor control centers (MCCs), loose terminations, and loose mechanical connections in fuse holders
	Contact temperature measurement		Heat exchangers, bearings of large motors and pumps.
5.	Liquid penetrant testing	100	Welds, containment liners, suppression pool liners, tanks, valve bodies, and pipes
6.	Magnetic particle testing	100	Welds, containment liners, suppression pool liners, tanks, valve bodies, and pipes
7.	Motor current signature analysis (MCSA)	70	All except one report using MCSA for motor-operated valves (MOVs). The one exception apparently uses motor current analysis (MCA) for MOVs and some large motors.
8.	Movement or position monitoring	<10	No data is available.
9.	Lubricant analysis	100	Rotating equipment that uses one or more gallons of lubricating oil, for example, EH fluid for turbines, fuel oil for diesel generators (DGs).
	Spectroscopic analysis	87	
	Particle counting	53	
	Ferrography	40	
	Transformer oil/gas analysis	100	
10.	Radiography	100	Check valves, welds, piping
11.	Ultrasonic testing	100	Piping susceptible to erosion/corrosion, for example, raw water system piping or steam piping.
	Flaws and crack detection in metals	100	
	Thickness monitoring	93	Check valves, air systems
	Leakage monitoring	<10	Large motors and pumps
	Bearing monitoring	<20	Condensers
	Condenser leakage monitoring	<10	
12.	Vibration analysis	100	Safety-related 480 V and higher motors, usually those under Maintenance Rule scope. Some plants also include fans, turbine, compressors, DGs, and a few NSR motors that are critical for power operation or those for which insurance requirements exist or insurance credit is available.
	End-turn monitoring	0	
	Motor and pump bearings monitoring	100	
	Alignment and balancing	<10	

Table 5-2 (cont.)
Current Plant Use of Predictive Technologies

Item	Technology	% Plants Use	Equipment Applications
13.	Sensory Inspection	100	Generally rotating equipment, and control panels during operator rounds
14.	Visual inspection - remote Borescope Fiber optic sensor CCTV Robots	100 40 40 <10 <10	Pipes and heat exchangers, tanks' internal condition, intake structures, spent fuel pool, loose parts in fuel pools, reactor internals, motor starters
15.	MOVAT, VOTES, and other technologies for MOV testing	100	Motor-operated valve actuator
16.	Cable indenter	0	Now in trial use at two U.S. plants and a French plant for low voltage cables and medium voltage power cables
17.	Engine analysis for DG	<10	Diesel generator engines
18.	Conventional electrical tests Insulation resistance High-pot Surge test Winding resistance Partial discharge	100 87 87 87 80 <10	Detection of insulation integrity in motors, coils, transformers, and cabling Large motors covered by Maintenance Rule Motors and cables Motors and cables Large motors Diesel generator
19.	AOV diagnostics	<10	Air-operated valves
20.	Operating deflection and shape analysis	<10	Diesel generators

5.2 Opportunities for Improving Predictive Maintenance

Technologies such as vibration monitoring, infrared thermography, and lubricant analysis are widely used as PdM technologies in most, if not all, nuclear power plants. Review of the experience with these technologies suggests that opportunities for improving their use exist in two distinct ways as follows:

- Scope for wider application
- Elimination or reduction of the frequency of certain tests

Also, new technologies, such as motor current signature analysis, are now available for application on specific equipment types. Use of these technologies can increase equipment availability and lead to cost savings through eliminating previously scheduled periodic maintenance and limiting unexpected equipment failures.

Success breeds success. As with any technology that offers the potential for cost savings, predictive technologies will continue to be applied to more SSCs in power plants. In addition, user experience also reveals useful information on how this technology can be used more cost-effectively and additional maintenance cost savings achieved. The following subsections discuss the potential for improvements in maintenance cost-effectiveness.

5.2.1 Infrared Thermography

Infrared thermography is the technology of measuring infrared radiation and converting that into a temperature map and visual image showing thermal gradient or changes. This technology has been in existence for decades.

Over the last decade, nuclear power plants have been using infrared thermography for troubleshooting and equipment condition monitoring. The EPRI *Infrared Thermography Guide* [20] identifies the potential applications for this technology in power plants and provides comprehensive guidance on its use.

5.2.1.1 Present Use

At present, common use of IR thermography at most power plants includes the following applications:

- Identification of loose or high resistance electrical connections, for example, loose fuse holder, loose terminal screw, loose pin in plug connectors
- Identification of localized hot spots in motor winding
- Identification of hot-running (that is, overheating) electrical devices such as solenoid coils, relay coils, SCRs, transformer coils, and so on

In all these cases, an increase in temperature caused by the excess heat generated by the specific condition (for example, localized hot spot) is identified using an infrared thermal imager.

5.2.1.2 Potential for Improvements in Use

Some plants are using IR thermography for applications other than those listed above. The list below identifies these applications, as well as others that it could be used for:

- Leak detection across normally closed valves carrying hot fluids.[2] This can also include verifying safety relief valve settings.
- Leaks across steam traps.
- Bearing temperature increase due to churning of excess lubricants or inadequate lubrication.
- Misalignment of rotating mechanical equipment as indicated by excessive heating in bearings or couplings.
- Cracked electrical insulators in substations or switch gear compartments.
- Condenser air in-leakage.
- Survey of continuously energized power cables to measure conductor temperatures so that insulation life/condition can be assessed.
- Identification of energized ground cable.
- Undersized electrical cables or connections.
- Open circuits in electrolytic capacitors used in inverters, battery chargers, or other power electronic equipment.
- Phase current imbalance in three-phase equipment.
- High resistance conditions in a cell in a battery bank.
- Hot running components on printed circuit boards and electronic cabinets (for example, thyristors in inverter cabinets).
- Inadequate ventilation in electrical cabinets.

At present, power plants use IR thermography mostly as a predictive maintenance tool. Some sites use it as a troubleshooting tool also. As a PdM tool, plants use it to monitor an average of 300 pieces of equipment on a fixed schedule, usually once a quarter. Sites report that approximately one to one and one-half person-years are being spent annually on this application. Utility personnel suggest that the covered population will continue to grow and it is expected to double within the next year or two.

Discussions with plant personnel and review of the IR thermography data show that after the initial finds, ongoing surveys do not show gross variations between surveys. If the initial find was properly evaluated and fixed, the probability of a repeat occurrence of the same overheating condition may be very low. For example, at one site, a survey of control panels was begun to identify loose terminations, fuse holders, and overheating of electrical components such as relays, trip coils, and closing coils. The initial survey four

2 One user indicates that the infrared thermal imager can be used to detect temperature differences as low as 2–5°C.

years ago indicated several loose terminations and fuse holders. Those findings became the justification to survey all the control panels, power panels, and MCCs routinely once every three months. Though subsequent surveys in the three years after the initial survey have not shown any recurrence, the survey continues at the prescribed intervals. A case can be made for decreasing the frequency of surveys for MCCs and control panel terminations to once a year. Such a frequency would still be eligible for insurance credits.

In other cases similar to this one, after the initial finds have been rectified, with two or three follow-up verification surveys, a case can be made for either eliminating or significantly reducing the frequencies of IR surveys. A root cause analysis (a rudimentary one should suffice) would have shown that most of the problems discovered were quite likely the result of one or more of the following:

- Aging degradation
- Inadequate attention to detail when performing maintenance
- Poor installation practices
- Operating environments different from those originally specified
- Improper selection of equipment for the application
- Improper selection of construction materials for the application

If aging degradation was the cause of the overheating condition identified, then a case can be made to continue the survey at the same or even enhanced frequency to identify incipient failure conditions in a timely manner. If the problems are in the next two categories, consider revising the applicable maintenance procedures to require an IR survey after maintenance and before return to service. Few cases have been identified in the last three categories, that is, where there is a generic material or design deficiency that caused the overheating conditions. In such cases, a design modification should have been made to prevent a recurrence. Therefore, after a few follow-up surveys to verify the effectiveness of the fix, frequency reduction or outright elimination of the surveys should be considered.

Insurers provide credit points[3] for thermographic surveys for transformers, motors, motor control centers and associated bus ducts, and pumps including bearings, couplings, and gears. Additional credits are also available for surveys done by certified thermographers who follow certain industry standards.

The survey revealed that not all sites are taking advantage of these credits. Sites should review their IR programs and take advantage of credits wherever it is cost-effective to do so. Appendix D provides a typical list of insurance credits and penalties that are available from one insurer.

3 For purposes of payback evaluation, each credit point may be assumed to be worth an approximate $75.00 reduction in the annual premium.

5.2.2 Vibration Monitoring

Vibration monitoring is the technology of measuring vibration characteristics such as amplitude, frequency, and velocity at specific locations (for example, bearing housings) to identify abnormal conditions or faulty components in rotating machinery. Vibration problems can originate from design, installation, set up, in-service wear, or maintenance.

For over 30 years, vibration sensors have been routinely installed on main turbines and some large pumps to monitor bearing vibration levels. During the last decade, nuclear power plants have begun to use this technology as a predictive maintenance tool for identifying incipient failures in many types of rotating equipment such as fans, pumps, and compressors. The EPRI *Predictive Maintenance Primer* [16] discusses the basics, identifies potential applications, and provides comprehensive guidance on its use. Another EPRI report [21] provides guidance on setting up a machinery vibration monitoring program.

5.2.2.1 Present Use

Current use of vibration monitoring at power plants includes the following applications:

- Identification of incipient failures in rolling element bearings in large pumps, motors, and fans. Determination of which rotating machine receives vibration monitoring is based on its importance to the mission, its failure experience, and / or the cost of repair.
- Excessive wear in sleeve bearings
- Identification of bent, broken, or cracked shafts in rotating machinery
- Loose parts monitoring in reactor vessel, steam generator, and certain key piping (for example, recirculation piping in BWR plants, letdown piping in PWR plants)

5.2.2.2 Potential for Improvements in Use

Some plants are using vibration monitoring (VM) for applications other than those listed above. The list below identifies these applications, as well as others that it could be used for:

- Unbalanced or out-of-tolerance alignment conditions in rotating machinery, specifically large fans
- Generator end turn monitoring
- Loose or broken parts in rotating machinery
- Deterioration of impellers in high speed pumps
- Coupling problems in rotating machinery
- Gear boxes for speed increase / decrease applications

- Anomalies in diesel engine operation

At present, power plants use VM to monitor hundreds of pieces of equipment (200–600 was noted in the plants surveyed) on a fixed schedule, mostly once a quarter. Plants report that approximately one to one and one-half person-years are being spent annually on this application. Utility personnel expect the covered population to grow by 50–100% on the average within the next year or two. None of the plants reported using outside specialists to interpret the data.

Discussions with plant personnel and review of the vibration monitoring data show that after the initial finds, ongoing surveys do not show gross variations between surveys. If the initial find was properly evaluated and fixed, the probability of a repeat occurrence of the same excessive vibration condition on the same equipment may be very low. Further, it appears that the data from the last decade of VM can be used to establish a periodicity for incipient failure condition development, particularly for bearings. If so, it might be prudent to adjust the frequency of bearing replacements accordingly and reduce vibration monitoring of certain bearings. For equipment fitted with bearing temperature monitoring or for those covered under the oil analysis program, this approach could be valuable in reducing the cost of PM. Also, revising the applicable maintenance procedures to require a vibration survey of the equipment after maintenance work and before return to service may be appropriate.

Insurers provide premium credit points for vibration monitoring for several applications including the following:

- On-line vibration analysis for main turbines
- Generator end turn vibration monitoring
- Monthly vibration analysis program that measures, records, and trends vibration signatures for certain rotating machinery

The survey revealed that some sites may not be taking full advantage of these credits. Sites should review their VM programs and take advantage of credits wherever it is cost-effective to do so. Appendix D provides a typical list of insurance credits and penalties available from one insurer.

In the past, plants may have rejected on-line vibration analysis for the main turbine and generator end turn applications on the basis of its cost-effectiveness. Many recent technological advances in vibration monitoring coupled with dramatic reductions in computer hardware and software costs over the last five years may now make this PdM cost-effective. Thus, it may be appropriate to revisit this area now.

5.2.3 Lubrication Analysis

Lubrication analysis involves analyzing samples of grease, lube oil, insulating oil, grease, or motive fluids used in machinery to observe, measure, and trend physical and chemical properties. These analyses provide indications of component (for example, bearings or gears) wear, contamination, and loss or breakdown of the lubricant's functional capabilities (for example, lubrication ability, insulation capability, corrosion protection).

In its simplest form, lubricant analysis can be sensory inspection and spectrometric analysis to obtain gross indications of contaminants, metals particles, and so on. Sophisticated lubricant analysis may involve advanced instrumental chemical analysis, such as infrared spectroscopy, atomic absorption spectroscopy, and gas chromatography. These techniques can be used to identify the exact composition of the lubricant, the presence and quantities of dissolved gases, contaminant particle characterization (size and count), and other information. The changes in lubricant properties usually originate from use, wear, and / or operation under abnormal conditions.

For over 20 years, oil samples from transformers have been routinely analyzed to identify the presence and quantities of various dissolved gases, which are measures of the insulation condition in transformers. Similarly, diesel fuel oil samples are analyzed to identify the presence of water. Over the last decade, nuclear power plants have expanded the use of this technology as a predictive maintenance tool. An EPRI report on predictive maintenance [16] discusses the basics of oil analysis, identifies the potential applications, and provides comprehensive guidance on its use.

5.2.3.1 Present Use

At present, lubricant analysis is used at most power plants for the following applications:

- Identifying incipient failures in rolling element bearings in large pumps and motors. Determination of which rotating machine gets oil analysis is based on the amount oil used, the machine's importance to the mission, its previous operating history, and the cost of repair.
- Detecting excessive wear in sleeve bearings.
- Identifying insulation deterioration in large oil-filled transformers.
- Detecting the presence of water in lube oil and fuel oil for diesel generators.
- Determining turbine EH fluid and lube oil quality.
- Identifying the need to change or recondition oil.

5.2.3.2 Potential for Improvements in Use

Some plants are using lubricant analysis for applications other than those listed above. The list below identifies additional applications:

- Determining lube oil quality for mission-critical equipment such as turbine-driven feedwater pumps and motors for instrument air compressors, chillers, and some fans that use more than a gallon of oil

- Detecting wear particles and contaminants in grease used in MOV gear boxes mounted on hot pipes, located in high temperature zones, or operated infrequently

Currently, power plants use lubricant analysis as a predictive maintenance tool to monitor 200–300 pieces of equipment on a fixed schedule, mostly once a quarter. Sites report that approximately one person-year is being spent annually on this application. More than 75% of sites surveyed do most of the analysis using outside laboratories, and the remaining 25% perform most of the analysis in-house. It appears that performing most of the routine analysis in-house can lead to some cost savings. Also, two sites report that for most of the applications, sensory inspection and basic spectrometric analysis using equipment such as Oil-View is more than sufficient to identify impending problems. Such screening tests enable them to request more sophisticated analysis sparingly. Utility personnel expect the covered population to grow by another 25% over the next two years.

Discussions with site personnel and review of the oil analysis data show that after the initial finds, generally ongoing analysis does not show gross variations between analyses. Further, it appears that the data from the last decade of oil analysis can be used to establish a periodicity for oil changes for most equipment. If so, it might be prudent to adjust the routine oil change frequency accordingly and *reduce* the frequency of oil analysis. For equipment fitted with bearing temperature monitoring and/or included under the vibration monitoring program, this approach could be valuable in reducing the cost of PM. Consideration should be given to revising applicable maintenance procedures to require a sensory inspection of the oil in equipment after maintenance work and to obtain samples for possible analysis. It is also feasible to have experienced maintenance technicians perform the preliminary oil analysis using equipment such as Oil-View.

Insurers provide premium credit points for lubricant analysis for several applications including the following:

- Quarterly full spectrum lubricating oil and control fluid analysis for certain rotating machinery
- Gas-in-oil analyzers on the main generator step-up transformers

The survey revealed that not all sites are taking advantage of these credits. Sites should review their lubrication analysis programs and take advantage of credits wherever it is cost-effective to do so.

5.2.4 Motor Condition Monitoring

Monitoring the condition of motors requires focus on the following:

1. Bearings and the lubrication system
2. Turn-to-turn insulation integrity
3. Ground wall insulation integrity

4. Unequal air gaps
5. Rotor defects

Bearing and lubrication system problems may be monitored effectively through a combination of vibration monitoring, temperature monitoring, and oil analysis. This part of motor condition monitoring is already in place at most nuclear plants and has been successful.

To address the other items above, three distinct technologies are available. The first is an electrical circuit evaluation known as motor circuit analysis (MCA). Motor circuit analysis is accomplished by various methods and equipment; however, all methods attempt to measure similar parameters. The second is on-line partial discharge monitoring, and the third is based on spectral analysis of motor current or magnetic flux.

In MCA off-line, low-voltage testing of the electrical circuit is performed. The premise is that prolonged operation under imbalanced impedance conditions leads to motor failures. The circuit parameters measured include the following:

- Individual phase resistances from the power bus disconnect through the motor winding
- Phase to ground resistance
- Inductance of the motor coils
- Capacitance of each phase to ground

The data are fed into a computer with software capable of trend analysis of the data, which leads to an identification of imbalances in impedance. Numerical limits for imbalances in circuit parameters are used to provide a warning of the need for in-depth evaluation of the motor. One utility surveyed employs this technique for monitoring motor condition and reports favorable results.

Motor current signature analysis (MCSA) employs measurement and Fourier transform analysis of motor current vs. time history during start, run, and coast down. The current is obtained using a clamp-on meter on the feeder cable at the switching equipment or near the motor. The technique is generally very effective in detecting incipient conditions resulting from items 2, 3, and 4 above. One utility reports successful experience with MCSA for motor-operated valves. This technology may be useful for motors on the critical equipment list and rated at >100 hp and/or those that operate at speeds greater than 1800 rpm.

Motor flux monitoring systems employ flux coils mounted on the motor end bell to measure magnetic flux. In addition, the system also measures current using clamp-on meters and temperature using an infrared scanner. Using a computer and appropriate software, the system performs a spectrum analysis of the flux and current to identify anomalies in the rotor and/or stator. Using temperature information, the system identifies potential mechanical and insulation problems. Another version of the flux monitor employs a multi-component sensor that includes a flux coil, temperature probe, and vibration sensor in a compact unit that can be attached to a boss on the motor housing. Both versions can be used to perform on-line evaluation of the motor condition.

A partial discharge (PD) monitoring system monitors the presence and progression of the partial discharges in windings to assess insulation condition. The sensors may be radio frequency (RF) current transformers used in series with surge capacitors, or in cases where surge capacitors are not used, three 80 picofarad capacitors connected to the phases. The sensors detect the high-frequency pulse currents or voltages that accompany PD and noise pulses. The signals are measured and analyzed using spectrum analyzers, a digital oscilloscope, and a specialized instrument called the thermo-gravametric analyzer (TGA). The difference in the magnitude and rise time between noise and PD pulses detected at the motor terminals enables identification of stator winding problems. This technique is particularly useful for motors rated at 4 kV and over.

Instruments incorporating the basic principles discussed above are commercially available and have been field-proven with varying levels of success, though mostly in non-nuclear power plant applications with a few in nuclear plant applications [22–26].

5.3 Organizational Improvements

At present, PdM functions at nuclear plants are organized as follows:

- A separate group exists under the systems engineering or technical support function with responsibilities for IR thermography, vibration monitoring, and lubricant analysis.
- Some PdM functions are dispersed among the respective Maintenance Departments, for example, MOVAT within the Electrical Maintenance Department.
- Other PdM functions are covered under a separate groups called the ISI or ISI/IST group.

Other variations of this dispersed responsibility model were also noted. At some plants, even the responsibility for IR thermography, VM, and lubricant analysis was split between different groups. At one plant, all PdM functions are apparently integrated into the respective Maintenance Departments (I&C, Electrical, and Mechanical). Further, it was noted that the plant Chemistry Department is not generally involved in PdM functions, such as lubricant analysis.

The present organizational model for PdM functions evolved over time according to the strengths of the available people and site needs. Demands for learning and applying new technologies may have also contributed to a somewhat fragmented PdM program. It appears that the present organizational setup may not be conducive to total accountability and the efficient use of manpower and test equipment. Further, PdM responsibility involves making tough judgment calls based on condition monitoring data that may require sites to take immediate to short term actions such as plant shutdown or power reductions. Since this decision may require other departments (Maintenance and/or Operations) to react, there may be a reluctance to make such calls.

With the experience gained in implementing many new technologies, sites may benefit from a review of the assignment of responsibility and accountability for PdM. Two models for streamlining the PdM functions at a site are offered for consideration. It is recognized that other models may be better suited for a specific site environment. Regardless of the model used, the following objectives should be achieved:

- Achieve the best use of available technology at the lowest cost.
- Promote total accountability.
- Minimize duplication of expertise, test equipment, and software.
- Integrate the PdM data collection and preliminary analysis functions into the department with equipment ownership.
- Ensure a vehicle for continual assessment of the condition monitoring technology marketplace to identify and evaluate new technologies, hardware, and software.
- Ensure core competence through training of all personnel involved.

5.3.1 Model A. Totally Centralized PdM Responsibilities

In this model, a new department reporting to the maintenance superintendent is responsible for all PdM functions. This group is on a par with other maintenance functions such as I&C and electrical, and has its own technicians and engineers headed by a group supervisor. This group draws on other on-site and off-site resources as needed. The group supervisor is accountable for the total budget, human resource development, and technical direction.

5.3.2 Model B. Centralized PdM with Technical Support Direction

In this model, the responsibility for all PdM functions that involve technology selection, equipment procurement, overall technical direction, procedures, and training of maintenance and operations personnel in the use of equipment resides within the Technical Support group. Field data collection and preliminary data analysis are integrated into the respective Maintenance Departments. Chemical analysis functions are integrated into the Chemistry Department. In addition, some routine and simple data collection functions, such as vibration data, thermography of control panels and oil sample collection, are assigned to the Operations Department for performance as part of the daily rounds.

5.4 Summary

During the past decade, nuclear sites have made great strides in using PdM technologies for improving maintenance effectiveness. As new technologies have become available, they have been assimilated into site maintenance programs. The use of these technologies has provided big initial payoffs. Several new monitoring programs have been put in place because of the initial finds. Many sites have wholeheartedly adopted some technologies such as IR thermography and vibration monitoring, while others have not reached that point.

Because differences exist among sites, the number of technologies used and the applications also vary. Opportunities exist for improving maintenance effectiveness through enhanced and enlightened applications of PdM technologies. This may be accomplished through a more centralized organization of the PdM functions. Sites may benefit from a comprehensive review of PdM applications and organization as outlined in this section. The application of these new technologies have prompted sites to begin new monitoring programs because of the information that they can provide.

6

MONITORING EFFECTIVENESS

Typically, change is undertaken to achieve a set of objectives. To ensure that the objectives are achieved, the change must be planned and managed. A plan must incorporate in it the organization to support it and the means to monitor its effectiveness. This section discusses the organizational and measurement aspects or maintenance effectiveness.

6.1 Organizational Aspects

In a nuclear plant with an established maintenance programs and practices, an effort to improve maintenance effectiveness further will very likely require a change in the plant culture and the way of thinking about maintenance. Two key themes that permeate throughout the organization are:

- Plant management and maintenance personnel should think of maintenance as a profit center and not a cost center.
- Maintenance effectiveness improvement is an ongoing process, not a one-time exercise.

Senior management must make a commitment to the project to improve maintenance effectiveness, set its objectives in consultation with maintenance management, and communicate it in clear terms to all involved. Examples of six high-level objectives that may be set are listed below:

NOTE: *For Group B sites, the numeric values given in the objectives below should be adjusted based on current plant status at the time of initiating the project. For Group A sites, the numeric values may already exist and may only need to be refined, or they may need to be established anew, based on current plant status.*

- Unplanned scrams that are maintenance-induced should be zero within a given period.
- Maintenance-induced unplanned safety system challenges should be zero within a given period.

- In nominal dollars, maintenance cost as a percentage of O&M budget should be reduced by 2% in each of the next given number of years
- Emergency maintenance, expressed as a percentage of corrective maintenance work orders, should be less than 5% in the first year following full implementation, and each year thereafter the percentage should trend down, reaching <2% within, for example, five years.
- Maintenance Department SALP rating should be a minimum of 2 and shall achieve a 1 rating.
- Annual maintenance cost in nominal cost per MW should be among the lowest third of industry peers.

Senior management should review progress on these objectives at least once a quarter. The choice of a minimum two-year time horizon is based on allowing one year to complete implementation of major portions of the project and one full year of post-implementation period to accomplish the objectives. Maintenance Department management should be held accountable for these goals, and a performance-linked rewards system should be considered.

At the Maintenance Department level, management should communicate these objectives to everyone in the department and seek input on ways to achieve them. A lead manager should be appointed to plan and execute the project. A system of performance measurement should be implemented to monitor progress and to compare plant performance with industry peers.

6.2 Performance Measures and Monitoring

This subsection presents a set of performance measures that could be used to monitor progress on effectiveness improvements. They are intended for use by the plant maintenance management and their staff. Most of the data required may be generated from the computerized maintenance management systems currently used at nuclear plants. Where appropriate, optimal values are proposed for the performance measures. These values were developed from a minisurvey of nuclear power plants and other non-nuclear installations, and provide an initial boundary range of values.

> ***Note:*** *Remember that the real value of a number lies not in its magnitude but in the information it conveys.*

As a first step, users should develop baseline values for the performance measures. These values should be based on historical data accumulated during a significant operating period (for example, two to five years) including a minimum of two refuelings. A corresponding set of values for these data should be developed for a

[1] Reference group refers to plants that are comparable in vintage, type, BOP design, and other locational factors that could influence the cost of maintenance.

reference group[1] of nuclear sites. These should form the basis for making an initial assessment, setting goals, monitoring on an ongoing basis, targeting specific areas, and establishing relative priorities for improvement programs.

A nuclear power plant is an aggregation of systems and structures. Systems are in themselves an aggregation of equipment items or components. Availability of equipment impacts the availability of systems, which in turn may impact the availability of a plant. Maintenance activities as well as effectiveness improvement efforts are primarily focused at the equipment and structure level. Thus, it makes sense to focus related performance measures at the same level. For senior management's evaluation, the measures should permit an assessment of the performance on achieving the stated objectives. For the Maintenance Department staff, the measures should enable them to identify areas of strength and weakness so that they can build on the strengths and work on eliminating the weaknesses. Finally, the measures should facilitate an assessment of how one's own company compares with its peers in the industry.

6.2.1 Broad-Based Performance Measures for Senior Management Use

The seven broad-based measures listed below may be useful for senior management's assessment of overall performance of the Maintenance Department and comparison with peer group plants:

1. Total annual maintenance budget (in nominal dollars) expressed as a percentage of the O&M budget and in cost per MW. Further breakdown of the maintenance budget as listed below can help but is not necessary:
   - Cost of preventive maintenance activities as a percentage of overall maintenance budget
   - Cost of corrective maintenance activities as a percentage of overall maintenance budget
   - Cost of maintenance training as a percentage of overall maintenance budget
2. Percentage of corrective maintenance work orders classified as emergency work orders per 2000 plant operating hours. A monitoring interval of 2000 hours is recommended because it would enable timely identification of adverse trends. This is distinct from the 7000-hour interval currently used for reporting of unplanned scrams.
3. Number of maintenance-induced unplanned scrams per 2000 plant operating hours. See Section 6.2.2 1.
4. Number of maintenance-induced unplanned safety system challenges per 2000 hours (includes both operating and shutdown modes of the plant). See Section 6.2.2 2.
5. Maintenance personnel exposure in person-rems per 2000 hours (includes both operating and shutdown modes of the plant).
6. Lost person-hours due to on-the-job injury per year.

7. Percentage of plant equipment population covered by PM (breakdown by planned and predictive) and CM.

The information on items 1 to 6 above should be presented as a trend plot and should include data starting three years before to discern the trend. An example of such a trend plot with peer group data is shown in Figure 6-1. Item 7 may be a table revised initially after two years and may be discontinued after five years. A report consisting of the above mentioned plots and tables should be issued once a quarter updating those that changed in the interval with explanation for variances as applicable. Although updating peer group data also on a quarterly basis would be desirable, for logistical and economical reasons, doing so only annually may be practical.

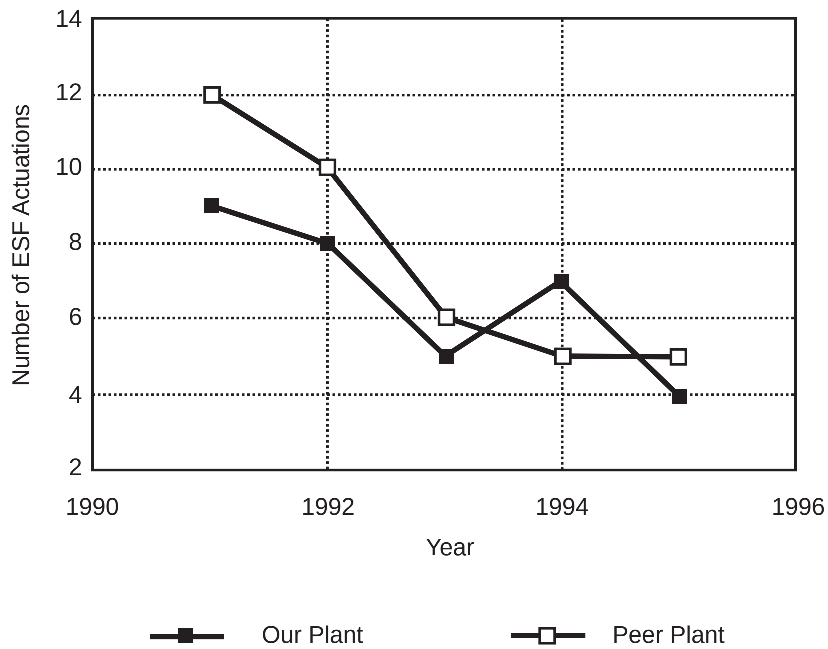

Figure 6-1
Trend of Maintenance-Induced ESF Actuations

6.2.2 Performance Measures for Maintenance Staff Use

Maintenance management and staff need a more in-depth assessment of the maintenance activities. A set of maintenance performance measures that may be used for an in-depth assessment are listed and discussed in the following paragraphs. Most of the plant-specific data for the proposed measures can be obtained from the MMIS or other plant databases, and further calculations required can be automated with minimal incremental effort.

6.2.2.1 Maintenance-Induced Plant Trips

This data is extracted from one of the plant reporting system databases such as the LER database. Only those trips that are directly attributable to a maintenance action should be included. An example would be miscalibration of a reactor protection system 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 defective replacement part in an uninterruptible power supply (UPS) installed during a maintenance activity should not be charged as a maintenance-induced plant trip. All trips determined to be attributable to a maintenance-related cause, whether they are reportable to the NRC or not, should be included. To ensure objectivity in the collection of this type of data, consideration should be given to having an independent entity (for example, the Nuclear Assurance Department) determine the chargeable items.

The optimal value for this indicator is zero. Even one trip during any given monitoring period warrants a root cause analysis and corrective action. An increasing trend or a constant value other than zero in any two consecutive periods may suggest ineffectiveness of maintenance.

6.2.2.2 Maintenance-Induced Unplanned Safety System Challenges

This data is derived from the plant LER database. Only those LERs generated as a direct result of a safety system challenge initiated by a maintenance action should be included. An example would be the improper setting of a safety relief valve resulting in an unplanned challenge to a safety system or a later discovery of a condition deviant from Technical Specifications. If a plant trip is experienced, that should already have been included in item A discussed in the previous section, and hence, it should be excluded from this.

Care should be taken to avoid including LERs attributable to indirect maintenance-related causes. For example, an LER resulting from a safety system actuation caused by a defective spring installed in a relief valve during a maintenance activity should not be charged to this item. Only those determined to be attributable to a maintenance-related cause and reportable to the NRC should be included. To ensure objectivity in the collection of this type of data, consideration should be given to having an independent entity (for example, the Nuclear Assurance Department) determine the chargeable items during the review process for the LERs or cited violations.

The optimal value for this indicator is zero or near zero. An increasing trend or a constant value other than zero in this indicator for any two consecutive periods may suggest ineffectiveness of maintenance.

6.2.2.3 Key Component Availability

This measure provides information about whether maintenance is focused on where and when it is needed. It also conveys information about the adequacy of component selection and maintenance (that is, focus on the proper failure modes, maintenance practices, allocation between maintenance types, and frequencies). While looking at all components in the PM system may be desirable, looking at the data for only some key components is sufficient. Others can be evaluated on an exception basis.

Plant-specific operating experience should be taken into account when determining the specific components for which availability calculations are monitored. The availability for each component can be calculated at the required intervals from the data contained in a typical plant computerized maintenance management information system. It may be tempting to maintain that the system level availability calculations performed for the Maintenance Rule are sufficient. It may not be sufficient because that statistic can mask the component level problems for a long time. A look at the component level availability data indicates the effectiveness of the maintenance improvements put in place, and provides advance warnings of impending problems at the system level.

Consider the HPCI system as an example. The term *system* is used for ease of reference, but the discussion would apply at any SSC level. In a given monitoring period, the HPCI system remains in a standby condition for most of the time. For a few hours, it is tested to verify operability. In addition, during a given monitoring period, the system may be out of service for periodic and / or corrective maintenance activities. The formula to be used and the two cases that arise in determining the operating time and downtime for use in availability calculations are discussed below:

Case I. There was no discovery of a failed condition during a periodic maintenance or surveillance test in the monitoring period.

The system can be assumed to be in an operable condition and capable of performing its mission successfully between tests. Therefore

$$t_u = \Sigma\left(t_{si} - t_D\right)$$

$$t_D = \Sigma\left(t_{pmi} + t_{emi}\right)$$

Availability = (Operating time ÷ Total time in the period) * 100%

Where

t_u = total operating time

t_D = total downtime

t_{si} = duration between successful tests

t_{pmi} = time for periodic maintenance in the period

t_{emi} = time for corrective maintenance in the period

***Notes**: All times are in hours. The time in a surveillance test is assumed to be operating time unless a failure results. The time in corrective maintenance should include the elapsed time from the discovery of a failure to the time when the system is returned to service.*

Case II. A failure occurred during a surveillance test or a failed condition was discovered during a planned maintenance activity.

If a failure occurs or is discovered during a test or a periodic maintenance activity, then a determination should be made as to whether the system was in an operationally ready status until discovery, and if not, when it became unsatisfactory. If an evaluation of the defect reveals that the system could not have performed its mission satisfactorily, then an allowance must be made to the operating time. Except in rare cases, it is impractical to determine the time of failure. To resolve this indeterminate condition, for purposes of availability calculations used for maintenance effectiveness assessment, the following approach is suggested:

$$t_o = \Sigma\, t_{si} - t_D + \left(t_{sui} \div 2\right)$$

$$t_D = \Sigma\, t_{pmi} + \Sigma\, t_{cmi} + t_{pmsui}$$

Availability = (Operating time ÷ Total time in the period) * 100%

Where

t_o	=	total operating time
t_D	=	total downtime
t_{si}	=	duration between successful tests
t_{sui}	=	duration between successful and unsuccessful tests
t_{pmi}	=	time for periodic maintenance in the period up to the last surveillance test or PM whichever occurred last
t_{cmi}	=	time for corrective maintenance in the period up to the last surveillance test or PM whichever occurred last
t_{pmsui}	=	time for periodic maintenance in the first half of the period between successful and unsuccessful tests

> ***Note:*** *"Unsuccessful tests" as used above should be interpreted to mean either a surveillance test or planned maintenance, whichever leads to the discovery of an unacceptable condition.*

Note that the period used for purposes of maintenance performance measurement may not generally be synonymous with that between surveillance tests. There may be one or more surveillance tests in this period.

The optimal value for this indicator may vary from 85–95% over a period of 8760 hours. The required value depends upon the component type, its parent system configuration (including redundancies and sparing), the frequency of the surveillance test, and the maintenance types to which it is subject. For example, the availability for the reactor trip portion of the plant protection system at the train level may be set at 95%, whereas for the diesel generator, a train level availability of 85% may be sufficient.

The availability goals should initially be set taking into account relevant factors including the frequency of surveillance tests and the system configuration. The MMIS should be programmed to calculate component availability at a preset interval. Trending the component availability semi-annually may provide early warning of the potential for system level availability degradation.

6.2.2.4 Craft Productivity

Craft productivity measures are intended to provide information on the effectiveness of the use of craft resources. Specifically, this set consists of the following:

- Work order count and breakdown
- Craft resource utilization ratio
- Work orders per wrench week
- Person-hours for selected equipment type

Work Order Count and Breakdown

Tracking the total number of work orders serviced over a quarter and their breakdown provides information about the work load handled by the Maintenance Department, department productivity, and how the department compares with peer group plants. Specific data to be included under this category are:

- Total number of work orders serviced
- Percentage of work orders attributable to rework
- Percentage of work orders attributable to emergency work

Note that though the total component count may be comparable to a peer plant, the work order count and breakdown may not be. Some plants do not initiate a work order for certain maintenance activities such as predictive maintenance and minor maintenance items. In these cases, each equipment item included in such activities should be counted as a work order. These data may suggest one or more of the following:

- Frequent breakdown of certain equipment indicative of a need for replacement
- Excessive periodic and / or predictive maintenance activities
- Inadequate training and / or procedures

Although used by many sites, work order backlog count is not included as an indicator of maintenance effectiveness because it strictly depends on resource management. Sites attempt to keep this backlog as low as practical. Further, unless specifically excluded, the total backlog count can include those that have no impact on safety or continued safe operation (for example, service calls to repair a sump pump or a level indicator on a waste storage tank). High backlog on mission-critical or safety-related items should affect plant performance and would, therefore, be reflected in one or more of the following indicators:

- Maintenance-induced unplanned safety system challenges
- Maintenance-induced unplanned plant trips
- High percentage of emergency repairs
- High rework percentage

Thus, by itself, work order backlog is not considered to be a valid indicator of maintenance effectiveness, but tracking that variable can be useful in managing resources.

Craft Resource Utilization Ratio

The craft resource utilization ratio is a measure of how effectively maintenance craft resources are utilized. It shows how much of the craft time is spent on actual hands-on work. Interviews with maintenance staff indicate that less than a third of the craft time is spent on actual hands-on work. The rest of the time apparently goes into administrative and preparatory tasks such as dressing out, waiting for proper clearances, obtaining the appropriate permits, and so on. This data should be generated at the Maintenance Department level and for each discipline.

$$\text{Craft resource utilization ratio} = 100 * \frac{\text{(Sum of the reported actual on the job hours for the period, that is, the wrench time)}}{\text{(Total craft person-hours available for the period) (see note)}}$$

The optimal value for this indicator is greater than or equal to 40%.

> ***Note:*** *Total craft person-hours available should include only the hours that craft personnel are in attendance at work, that is, time off such as holidays, sick time, or vacation should be excluded.*

Work Orders per Wrench Week

Work orders per wrench week is a measure of Maintenance Department productivity.

$$\text{Work orders per wrench week} = \frac{\text{Total of work orders processed in the monitoring period} * 40 \text{ (see note)}}{\text{(Sum of the reported actual on the job (wrench time) hours for the period)}}$$

> ***Note:*** *The average work week is assumed to be 40 hours. If overtime is used, the average work week should be adjusted accordingly.*

An increasing trend or low absolute values in comparison to peers may indicate the need for better job staging and / or an examination of the procedures, job-specific training, or the administrative processes.

Person-Hours for Selected Equipment Type

These data relate to the breakdown of craft person-hours expended on selected equipment types during a monitoring period. Specific types of equipment for which these data may be useful include the following:

- Main turbine generator
- Diesel generator
- Reactor coolant pump
- Feedwater pumps
- Main and feedwater isolation valves
- Main and auxiliary transformers
- Plant protection system
- Nuclear instrumentation system
- Radiation monitoring system
- Security system

Note that though the total person-hours spent in maintenance may be comparable to peers, analysis of the breakdown of hours spent by major equipment categories may identify opportunities for improvements. Excessive person-hours spent on a piece of equipment in comparison with peers may indicate one or more of the following:

Aging of equipment

Excessive periodic/predictive maintenance activities

Poor maintainability conditions

Need for more training in maintaining the equipment

Overly complex procedures

6.2.2.5 Staff Productivity

Staff productivity measures are intended to assist in gauging the efficiency of use of support staff resources. These measures consist of:

- Craft to support staff person-hour ratio
- Work orders per staff week
- Procedure change percentage per period

The first two are measures of efficiency of support resource use in a plant. Typically, the maintenance craft is supported by a staff of planners, schedulers, procedure writers, and other administrative and supervisory staff. Given that the plants have a set of procedures in place, the two most important variables that can affect craft productivity are job scheduling and staging, both of which are planners' functions. This set of data should be calculated at the department level.

$$\text{Craft to support person-hour ratio} = 100 * \frac{\text{Total craft person-hours expended for the period}}{\text{Total staff support person-hours}}$$

$$\text{Work orders per staff week} = \frac{\text{Total number of work orders processed in the monitoring week (see Note 1)} * 40}{\text{Sum of the support staff hours for the period (see Note 2)}}$$

> ***Note 1**: The average work week is assumed to be 40 hours. If overtime is used, the average work week should be adjusted accordingly.*

> ***Note 2**: Total staff person-hours should include only the hours that personnel are in attendance at work, that is, time off such as holidays, sick time, or vacation should be excluded.*

Procedure change percentage per period provides information on systemic problems in procedures and / or their inadequacy. Ideally, by now, plants should have a stable system of procedures for performing maintenance. Changes, if any, should be minimal and directed at either correcting errors and omissions or addressing areas previously unaddressed by procedures. High procedure change counts on a continuing basis may suggest a weak procedure system. These data may be treated as a temporary indicator if the historical data show an acceptable level such as <5% or less.

$$\text{Procedure change \% per period} = 100 * \frac{\text{Number of procedures subject to change during the period}}{\text{Total number of maintenance and surveillance procedures}}$$

When counting the number of procedures that were subject to change during a monitoring period, if a procedure was changed more than once during the period, then each occurrence should be counted as an individual procedure change.

6.3 Summary

Improving maintenance effectiveness is a slow and ongoing process with steady progress over time. Expectations of quantum leaps are unrealistic. This process should be viewed as a journey. It requires long-term commitment of the senior plant management, strong organizational support, and a dynamic system of measurements to monitor progress and apply course correction as required. A maintenance effectiveness improvement project should have a strong leader and a well thought-out plan. The set of performance measures proposed in this section can be useful in monitoring at the senior management and at the department management or staff levels.

Plants are encouraged to obtain a copy of *Assessing Maintenance Effectiveness* [27] for a further discussion of the maintenance performance measures presented in this section.

7

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B

GLOSSARY

availability. The portion of time that an equipment item is actually capable of performing its intended function. It is the ratio of operating time divided by the total time which is the sum of operating time and down time.

calibration. Making adjustments that are necessary to bring operating characteristics into substantial agreement with standardized scales or marking.

Class 1E. The safety classification of the electric equipment and systems that are essential to emergency reactor shutdown, containment isolation, reactor core cooling, and containment and reactor heat removal, or that are otherwise essential to prevent significant release of radioactive material to the environment.

condition. State or level of those characteristics of an item that can affect its ability to perform its specified function.

condition assessment. Technical evaluation leading to the determination of the inherent capability of an item to perform its specified function.

condition indicator. Characteristic that can be observed or trended to infer or directly indicate the current and future ability of an item to perform its specified function.

condition monitoring. Observation, measurement, or trending of condition or functional indicators with respect to some independent parameter (usually time or cycles) in order to infer or directly indicate the current and future ability of an item to perform its specified function.

corrective maintenance. The maintenance carried out after a failure has occurred and intended to restore an item to a state in which it can perform its specified function.

defense-in-depth. A term generally used in the context of nuclear plant design. It refers to the multiple layers of defense employed in the plant design to protect the health and safety of plant personnel and the public.

degradation. Immediate or gradual deterioration of characteristics of an item that could impair its ability to perform as specified.

degraded condition. Marginally acceptable condition of an unfailed item that could lead to a decision to perform planned maintenance.

downtime. The time period during which the system is not operating or not capable of operating in a satisfactory manner.

equipment qualification. The generation and maintenance of evidence to ensure that an equipment item will meet the performance requirements.

failure. The termination of the ability of an item to perform a specified function.

failure mechanism. The physical, chemical, or other process that results in failure.

failure mode. The effect by which a failure is observed.

failure modes and effects analysis. A systematic, documented process of identifying the failure modes of an equipment item and assessing the consequences of those failures on the functional capability of the item.

failure rate. The expected number of failures of a given type, per item, in a given time interval or a given number of operating cycles.

failure analysis. Systematic process of determining and documenting the mode, mechanism, causes, and root cause of the failure of an item.

functional failure. Inability of an equipment item or system to perform its specified functions. (See *failure*.)

infrared thermography. A nonintrusive method of determining surface temperature by measurement of radiated heat.

incipient failure. A failure that is about to occur.

maintenance. The combination of all technical and corresponding administrative actions intended to retain an item in, or restore it to, a state in which it can perform its specified function.

monitoring period. A suggested period for collecting data for the purpose of ongoing assessment of maintenance effectiveness.

operating time . The time during which the system is operating in an acceptable manner.

periodic maintenance. A form of preventive maintenance carried out at predetermined intervals of calendar time, operating hours, or number of cycles.

planned maintenance. A form of preventive maintenance such as refurbishment, overhaul, or replacement that is scheduled or performed prior to failure of an item.

Note: The nuclear industry appears to use the terms *periodic maintenance* and *planned maintenance* synonymously, justified perhaps by the notion that periodic maintenance is generally established to avoid or reduce the probability of a failure from postulated or known modes.

predictive maintenance. A form of preventive maintenance performed continuously (that is, on-line) or at intervals governed by observed conditions in order to monitor, diagnose, or trend the performance or condition of a piece of equipment.

preventive maintenance. The maintenance carried out at predetermined intervals or corresponding to prescribed criteria, and intended to reduce the probability of failure or the performance degradation of an item.

qualified life. The period of time for which satisfactory performance can be demonstrated for a specific set of service conditions.

random failure. Any failure whose cause or mechanism, or both, make its time of occurrence unpredictable.

reliability. The ability of an item to perform a required function under stated conditions for a stated period of time.

reliability-centered maintenance(RCM). A process employed to develop a maintenance strategy and a supporting equipment preventive maintenance program composed of required and effective tasks that can ensure equipment reliability at specified levels.

reliability-based maintenance. A variation of RCM that attempts to integrate other organizational functions (for example, equipment/system modification, changes to future equipment and replacement parts purchase specifications, and profitability impact evaluation) in the development of an overall maintenance strategy.

remaining design life. A period from a stated time to planned retirement of an item.

remaining life. The actual period from a stated time to retirement of an item. (Also known as *remaining service life*, *remaining useful life*, *residual life.*)

repair. Actions (usually maintenance actions) to restore a failed item to an acceptable condition.

root cause analysis. Process of determining and documenting the most fundamental cause (usually the basic one about which something can be done) of the failure of an item, which, if corrected, will prevent recurrence of the failure.

set point. A predetermined point within the range of an instrument where protective or control action is initiated.

stressor. An agent or stimulus that stems from pre-service and service conditions and can produce immediate or aging degradation.

surveillance. Observation or measurement of condition or functional indicators to verify that an item can perform its intended function.

time-based preventive maintenance. See *periodic maintenance*.

total productive maintenance (TPM). A concept based on preventive maintenance that includes planned and predictive maintenance programs developed and implemented by the equipment operators and maintenance personnel working as a team.

C

ESTABLISHING MAINTENANCE INTERVALS

Establishing the intervals for periodic maintenance or condition monitoring tasks requires an insight into the item's failure patterns and modes and into the progression of the underlying failure mechanisms. This appendix illustrates a concept that may be useful for establishing PM intervals.

C.1 Failure Patterns

The traditional view of equipment failures is that they follow the bathtub curve, Pattern A as shown in Figure C-1. That is during the initial stages of life, equipment fails at a high rate, followed by a long period of relatively failure-free service. As it ages, the failure rate increases again. Not all equipment failures follow this failure pattern. Studies have shown that there may be as many as six failure patterns, as shown in Figure C-1 [8].

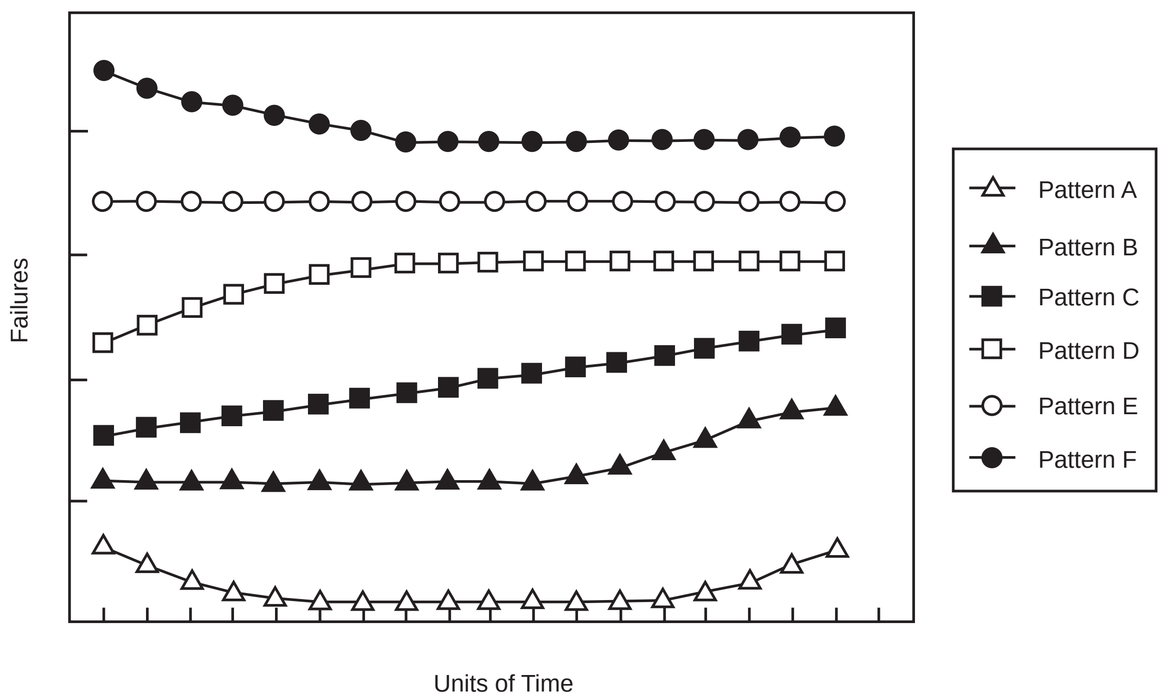

Figure C-1
Six Known Failure Patterns for Equipment

Typically, age-related failures, which are the result of fatigue, oxidation, corrosion, etc., follow patterns A to C. Failures that are not age-related, that is, random failures, follow patterns D to F. Component failures that exhibit these patterns show little or no relationship between age and failure rates. Complex equipment such as electronics and hydraulic controls appear to exhibit these patterns. Rolling element bearings follow pattern E.

In the case of random failures, periodic maintenance can increase the probability of a failure. Studies have shown that for most plant equipment, non-age-related failures follow Pattern F, and age-related failures follow pattern B. Therefore, pattern A, which may be viewed as a combination of patterns B and F, is normally associated with equipment failures.

Generally, preventive maintenance is directed only on those failures (for example, age-related failures) that have a measure of predictability. Further, preventive maintenance should be done only if the maintenance is effective in reducing the probability of a failure from that failure mode. Therefore, the choice of the type of preventive maintenance (periodic or predictive) and its frequency clearly depends upon an understanding of the failure modes and the progression of the underlying failure mechanisms. A more detailed discussion of failure patterns may be found in reference 3.

C.2 The I-F Curve

Whatever pattern of failure an equipment category conforms to during relatively failure-free performance, most equipment begins deterioration or degradation in performance as time progresses, as shown in Figure C-2. This deterioration is mostly the result of inservice wear and aging of equipment. The predominant mechanisms that cause age-related failure are fatigue, oxidation, corrosion, erosion, and vibration. Wear-out failures are caused by changes in clearances or alignment that result primarily from friction forces. If left unattended, a functional failure results.

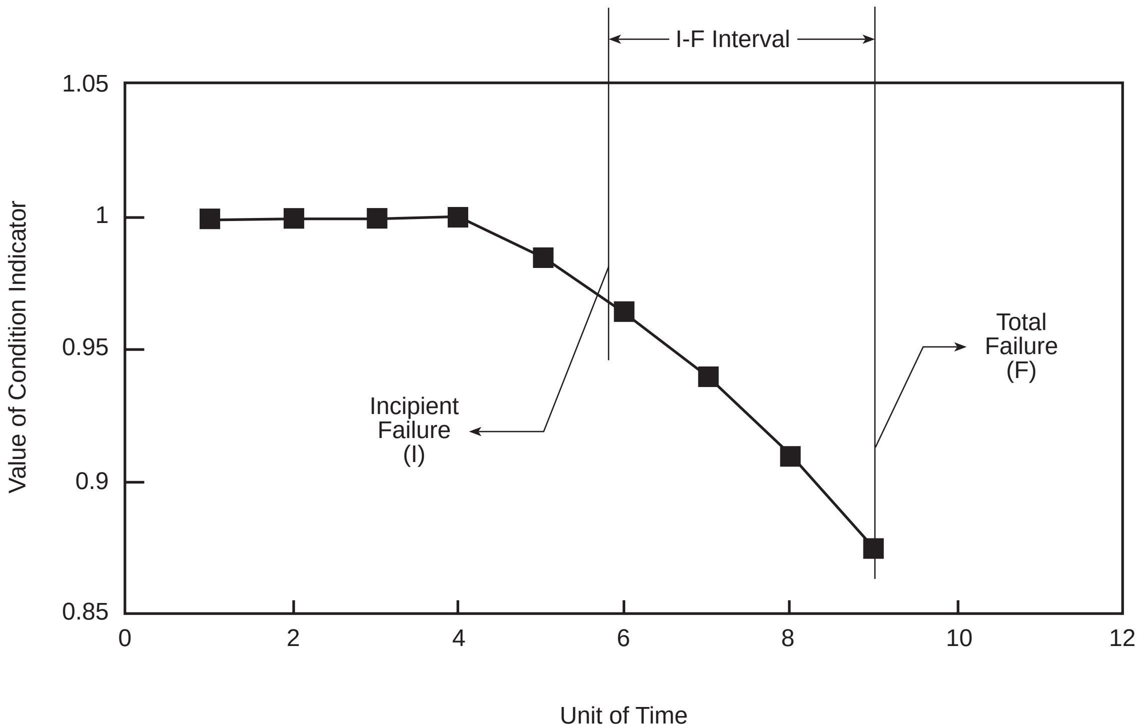

Figure C-2
Curve Showing Approach to Failure

Point I on the curve shown in Figure C-2 is when the incipient condition begins, that is, when a measurable degradation of a parameter that is indicative of impending performance problems takes place. Point F is when total functional failure takes place. The interval between the points I and F, the "I-F interval," may vary depending upon many factors including the underlying physical or chemical mechanism, materials of construction, application environment, and operating duty.

If the degradation is purely age-related, it is likely that the I-F interval will be weeks or months, even years. For instance, polymer insulation of cables ages very slowly and the I-F interval can be several years. Similarly, loss of pipe wall thickness usually results from erosion and corrosion, which takes years to reach point F. It is possible to measure the pipe wall thickness periodically, identify point I, and initiate actions to replace the pipe before a functional failure occurs, that is, when the thickness reaches unacceptable levels.

If the degradation is due to certain types of wearout mechanisms, the I-F interval can range from minutes to days, or in some cases, weeks. For example, if the lubricant in a bearing is lost or badly contaminated, the time between incipient and complete failure is likely to be minutes for large motors and may be somewhat longer for small motors. Very little can be done if the loss of lubricant was due to random failure such as a trip out of the lube oil pump or other similar causes. To address the lubricant contamination problem, one can choose to replace the lube oil periodically or to monitor the condition of the lubricant and initiate change-out in time to avert a failure.

C.3 Using the I-F Curve to Set PM Intervals

The purpose of preventive maintenance is to arrest the degradation process and restore full functional capability. Preventive maintenance can take one of three forms: periodic restoration, periodic replacement, or on-condition restoration. The first two are called periodic maintenance, whereas the third is predictive maintenance.

Periodic restoration can range from minor activities such as cleaning and changing lube oil to an overhaul performed at specified intervals. Periodic replacement can range from replacing affected parts such as a bearing or coil to replacing the whole equipment item at specified intervals. On-condition restoration entails monitoring one or more parameters indicative of the progress of the failure mode deemed to be responsible for performance degradation at specified intervals, and initiating maintenance action when the indicators reach specified limits.

For the first two, the frequency must be established for performing the maintenance work and, for the third, a frequency for performing condition monitoring tasks. Generally, vendor recommendations form the basis for the periodic maintenance and its frequency. Sometimes, historical data on failures are used to estimate failure intervals, also known as mean time between failures (MTBF). Periodic restoration or replacement is established at intervals short of the failure intervals. Some trial-and-error process is involved in determining the optimum interval.

It is expected that the periodic maintenance will address the relevant failure modes and that they occur before a functional failure. On the other hand, condition monitoring is usually based on an analysis of the failure modes of interest, and the frequency of condition monitoring tasks is based on engineering judgment.

The I-F curve can be used to establish these intervals. For the failure mode of concern, if the point I and the I-F interval can be established, then a frequency for condition monitoring can be established, taking into account the following considerations:

- Does the interval ensure that the approach to failure can be identified in time to prevent a functional failure?
- Does the interval result in performing condition monitoring tasks too frequently?
- Does the interval provide the lead time needed to plan and execute restorative maintenance, taking into account system / plant operational needs?

For example, assume that the point I is indicated by a bearing vibration reading that exceeds an alert limit L and that it is estimated, based on knowledge of equipment design and experience, that the I-F interval is three months. Assume that it takes a maximum of three days to schedule and perform a bearing replacement. In this case, the monitoring frequency can be set to once a month or even once in 45 days, and it will still catch any failure before it happens. Monthly may be an appropriate interval, and an interval shorter than once a month may be too frequent.

For the same example, if the I-F interval is less than a month, a weekly or biweekly monitoring would be required. This interval may be too frequent, yet justifiable for a few cases. An on-line monitoring may be economically justifiable for this item. Where the I-F interval is short, on-condition maintenance may not be desirable. If the consequence of a failure is tolerable and can be accepted, a run-to-failure maintenance approach is preferred. Otherwise, consider design options to change either the conditions that promote the failure mechanism or the equipment design.

As a rule of thumb, condition monitoring frequency may be set at one half the I-F interval or less.

From this discussion, it should be clear that predictive maintenance should be chosen only when the following conditions are met:

- Failure modes and mechanisms are known.
- There is clear and consistent indication of the point I.
- Progress of the failure mode can be monitored using simple techniques that can be performed by plant personnel.
- I-F intervals are long enough to permit condition monitoring at reasonable frequency and initiate corrective action to prevent a failure
- It can be shown that performing condition monitoring is cost-effective.

D

INSURANCE CREDITS AND PENALTIES

Insurers establish equipment monitoring requirements under their loss control and prevention programs. On critical items (usually those with high dollar value), they establish both “should” and “shall” requirements. The “should” requirements are more frequent than the “shalls.” To ensure that the “should” requirements are met, insurers assess premium penalty points for noncompliance. To encourage compliance using the best practices, they also provide premium credit points for using certain advanced PdM technologies.

This appendix provides a listing and description of typical monitoring requirements for which premium credits are available and for which premium penalties are assessed for noncompliance. This list is intended to serve only as an example. Users should consult their site insurance coordinator or those responsible for company insurance functions to obtain complete and accurate credit / penalty information applicable to their site.

Three salient points worth noting regarding the use of PdM technologies within the context of the insurance requirements are:

- In addition to premium credit, data from the use of PdM technologies may provide a basis for justifying the extension of the intervals for dismantle inspection required by the insurers. For example, full spectrum vibration analysis and prescribed oil analysis can provide data that are required to justify extending the full dismantle inspection intervals for some parts of the main turbine generator.
- Using PdM technologies can, in some cases, avoid the premium penalties for noncompliance with “should” monitoring requirements. For example, one insurer states that dissolved gas in oil should be monitored once in six months for main step-up transformers. The premium penalty for not performing this “should” monitoring item at the prescribed frequency can be avoided by the use of continuous gas-in-oil analyzers. Users of this guide are encouraged to consult their insurance manual for details.
- Payback calculations (see Table 4-2) for justifying the use of any given PdM technology should take into account the present worth of the credits to be earned and / or penalties to be avoided. As a rule of thumb, $75.00 per credit or penalty point may be used in such calculations. When applicable, the economic worth of any extensions in dismantle inspections that could be gained by using a given PdM

technology should also be taken into account. This may be particularly useful in justifying the use of on-line gas-in-oil analysis for large transformers or full spectrum vibration monitoring analysis for the main turbine generator.

It is likely that the current premium rating by the insurer is based on outdated information regarding a site's use of advanced PdM technologies. Therefore, it may be prudent to perform a periodic review of the current premium rating with the insurer. The aim of this review is to ensure that any unwarranted penalties that are being assessed for noncompliance with "should" requirements are eliminated, and where practical, unwarranted dismantle inspections are eliminated or their frequencies extended.

D.1 Credit Items

Table D-1 lists the PdM technology applications for which one insurer offers premium credit points. Note that this table is not an exhaustive listing and the site-specific insurance manual should consulted to obtain complete and accurate information.

Table D-1
Insurance Credit Items for PdM Technology Application

Equipment Item	PdM Tasks
Reactor coolant pumps and motors	Full spectrum vibration analysis once per fuel cycle Lube oil analysis for sludge, particulates, wear metals, acidity, and moisture content once per fuel cycle
Turbine	On-line vibration monitoring and analysis
Generator	On-line vibration monitoring and analysis End-turn vibration monitoring using fiber-optic technology to provide advance warning of cracks or loose wedges On-line monitoring of shorted rotor turns On-line diagnostic system that continuously monitors trends in generator internal conditions
Transformers, main, startup, station auxiliary, and others over 100 MVA	Thermographic surveys of bushings, disconnect switchgear, and associated bus ducts every six months On-line gas-in-oil analysis
Mechanical drive turbines	Annual full spectrum vibration analysis of all bearings

Table D-1 (cont.)
Insurance Credit Items for PdM Technology Application

Motor, motor-generator sets and pumps	Those that are operated continuously and that are on the "Critical Object" list: Quarterly full spectrum vibration analysis. Quarterly oil analysis for sludge, particulates, wear metals, acidity, and moisture content. Thermographic surveys at steady state operating conditions once every six months. Surveys should include associated MCCs and busses. Performance monitoring that includes trend analysis of winding temperature, bearing temperature, current signature analysis once every six months; **and** electrical testing that includes trend analysis of meggar data, winding resistance, and step voltage test data once every fuel cycle. Those that are operated only during surveillance testing and that are on the "Critical Object" list: Annual full spectrum vibration analysis. Quarterly oil analysis for sludge, particulates, wear metals, acidity, and moisture content. Thermographic surveys at steady state operating conditions once every six months. Surveys should include associated MCCs and busses. Performance monitoring that includes trend analysis of winding temperature, bearing temperature, current signature analysis once a year; **and** electrical testing that includes trend analysis of meggar data, winding resistance, and step voltage test data once every fuel cycle.

D.2 Penalty Items

Table D-2 provides a typical list of "should" monitoring requirements by one insurer for which they assess a noncompliance penalty. The table also identifies PdM technologies that, if used, may help in avoiding the penalties for noncompliance. Note that this table is not an exhaustive listing and a plant-specific insurance manual should be consulted to obtain complete and accurate information.

Table D-2
Insurance Penalty Items List

Penalty Item	Description
Mechanical drive turbine 1000 hp and over	Bearing and casing vibration should be monitored weekly. Noncompliance carries a penalty that can be avoided by periodic vibration monitoring.
Driven pumps over 1000 hp	Bearing metal temperature should be monitored once a week. Noncompliance carries a penalty that can be avoided by a periodic thermography survey.
Motors over 1000 hp	Casing and bearing should be monitored for excessive vibration once a week. Noncompliance carries a penalty that can be avoided by periodic vibration monitoring. Penalties for noncompliance with the dismantle inspection required for bearing distress can very likely be eliminated or its frequency can be extended using a combination of oil analysis and vibration monitoring.

E

ABBREVIATIONS

AEOD	Office of Analysis and Evaluation of Operational Data
ANSI	American National Standards Institute
BWR	boiling water reactor
CCTV	closed circuit television
CM	corrective maintenance
CMMS	computerized maintenance management system
CT	current transformer
DG	diesel generator
ECCS	emergency core cooling system
EPRI	Electric Power Research Institute
EQ	equipment qualification
ESF	engineered safety feature
ESFAS	engineered safety features actuation system
EMI	elector-magnetic interference
EPIX	Equipment Performance Information eXchange
FMEA	failure modes and effects analysis
hp	horsepower
HPCI	high pressure core injection
I&C	Instrumentation and Controls
IEEE	Institute of Electrical & Electronic Engineers
INPO	Institute of Nuclear Power Operations
ISI	inservice inspections
IST	inservice tests
IR	infrared
KSE	knowledge, skills, and test equipment
LER	Licensee Event Report
LCO	limiting condition of operation
LOCA	loss of coolant accident
LOOP	loss of offsite power
MBTF	mean time between failures
MCA	motor circuit analysis
MCC	motor control center
MCE	motor circuit evaluation
MCSA	motor current signature analysis
MMIS	maintenance management information system

MOV	motor-operated valve
MR	Maintenance Rule
MVA	megavolt ampere
MWe	megawatts electric
NEMA	National Electrical Manufacturers Association
NFPA	National Fire Protection Association
NMAC	Nuclear Maintenance Application Center
NPRDS	Nuclear Plant Reliability Data System
NPAR	nuclear plant aging research
NRC	Nuclear Regulatory Commission
NSAC	Nuclear Safety Analysis Center
NSR	non-safety related
NSSS	nuclear steam supply system
OA	oil analysis
O&M	Operations and Maintenance
PD	partial discharge
PdM	predictive maintenance
PM	preventive maintenance
PMO	preventive maintenance optimization
PSA	probabilistic safety analysis
PWR	pressurized water reactor
QA	quality assurance
QC	quality control
RBM	reliability-based maintenance
RCIC	reactor core isolation cooling
RBM	reliability-based maintenance
RCM	reliability-centered maintenance
RF	radio frequency
RPS	reactor protection system
SALP	Systematic Assessment of Licensee Performance
SCR	silicon-controlled rectifier
SOV	solenoid-operated valve
SSC	structures, systems, and components
TG	turbine generator
TGA	thermo-gravametric analyzer
TPM	total productive maintenance
UPS	uninterruptible power supply
UV	ultraviolet
VM	vibration monitoring

3. Collect and review the history (for example, for the previous five years) of failures, the person-hours spent on PM, and the CM per operating cycle for the following major equipment:[6]

   - Diesel generator
   - Main feedwater pump turbine if applicable
   - Control room chiller
   - Reactor coolant pump
   - UPS and battery charger
   - Other major types of equipment as needed

   Obtain and compare information from three peer plants with similar equipment. If there are major differences, evaluate the causes and initiate corrective measures as necessary. Using this information, evaluate if outsourcing the PM can result in significant cost savings while maintaining the equipment availability at the desired level.

   Example: The cost of performing a full diesel generator overhaul can vary depending upon whether it is performed by in-house maintenance personnel or vendor maintenance personnel. The difference may be attributable to other competing priorities and the level of in-house knowledge, skills, and test equipment (KSE) available. Evaluating the cost of maintaining that KSE available, plant experience in maintenance-induced failures of the equipment under consideration, and other related factors can show whether it is cost-effective to outsource the overhauls or keep them in-house.

4. Review recurring PM and CM rework in the last five years to identify the rework that resulted from parts quality and/or availability. For these cases, initiate engineering solutions (for example, design or materials change) to correct the parts-related problems.

5. Evaluate the work flow and practices to identify and eliminate waste of craft and support staff person-hours. Items in the work flow that should be evaluated are areas of review such as division of labor, processes to obtain radiation work permits, and the closing of job packages. Review also the maintenance training for craft personnel to ensure that training is tailored to the job requirements and emphasizes attention to detail so that rework can be reduced.

6. Re-evaluate the breakdown of responsibilities for PdM tasks and routine inspections. Evaluate the feasibility of integrating field data collection and preliminary evaluations within the respective Maintenance Departments and, where practical, within the Operations Department. Consider the feasibility of consolidating all PdM functions (see Table 4-3) under one lead, for example, a PdM

[6] It is assumed that a similar comparative evaluation has been performed on the turbine generator and the steam generator; therefore, they are excluded from this list.

group that would report to the maintenance superintendent and function as a cost center for budgeting and reporting purposes. This has the potential to offer the following advantages:

- Development of an in-house specialized technology capability
- Avoidance of test equipment duplication
- Cross training of personnel
- Efficient use of personnel
- Improved coordination of all PdM work performed on the same equipment or in the same location
- Better accountability

In addition to managing all PdM activities, this group would:

- Serve as an in-house service organization to assist in troubleshooting, using advanced technology, for all other maintenance groups
- Be responsible for annually reviewing all CM work and identifying opportunities for changes to existing PM, or adding new PM that could lower the CM workload

7. Establish a set of maintenance effectiveness indicators similar to those discussed in Section 6 for monitoring maintenance performance, and require monthly reporting.
8. Review equipment failure history to identify equipment with frequent or recurring failures. For those cases, perform root cause analysis and determine if changes in equipment design, application, and/or operating procedures can eliminate or minimize recurring failures. Implement appropriate changes in accordance with plant priorities.

Collectively, the Phase II recommendations above are intended to address the areas of maintenance that have not been effectively addressed in Phase I. For the most part, each recommendation stands alone and can be implemented either singly or in groups. If the available resources permit, it may be cost-effective to perform some of these Phase II tasks as part of Phase I. The choice of which recommendations to implement, to what extent, when, and in what order depends upon the plant needs and the availability of resources.