RCM GUIDE

RELIABILITY-CENTERED MAINTENANCE GUIDE

For Facilities and Collateral Equipment

FINAL
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National Aeronautics and Space Administration

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1.0 PREFACE

Reliability-Centered Maintenance (RCM) and variations thereof are employed by thousands of public and private organizations world-wide to address a host of reliability issues in order to improve Overall Equipment Effectiveness (OEE) while controlling the Life-Cycle Cost (LCC) inherent with Asset Management and Facility Stewardship.

With each new RCM practitioner, new ideas and applications for RCM are discovered, which in turn improves the RCM process. Professional organizations have formed or expanded as the number of RCM practitioners has grown. The role of RCM in organizations has expanded past the development of maintenance tasks based on Failure Modes and Effects Analysis (FMEA) to include the following:

- Sustainability
- Energy Efficiency
- Commissioning, Recommissioning, and Retrocommissioning
- Maintainability
- Age Exploration
- Reliability Analysis

1.1 RCM AND NASA

National Aeronautics and Space Administration (NASA) holds a policy to continuously improve the institutional management of capital assets by maintaining the NASA-owned and NASA-operated facilities in safe, environmentally sound, and affordable condition. Facilities and equipment owned by NASA shall be maintained in the most cost efficient fashion to create a hazard-free working environment while protecting and preserving capital investments and their capability.

> It is the policy of the United States to promote the efficient and economical use of America's real property assets and to assure management accountability for implementing Federal real property management reforms. Based on this policy, executive branch departments and agencies shall recognize the importance of real property resources through increased management attention, the establishment of clear goals and objectives, improved policies and levels of accountability, and other appropriate action.[1]

Since the *NASA RCM Guide for Facilities and Collateral Equipment* was implemented in 1996, the uses and capabilities of RCM principles and techniques have increased significantly. NASA applies the NASA-created Reliability-Centered Maintenance (RCM) Guide to successfully employ diverse asset maintenance strategies, varying from “run to failure” to streamlined

[1] Executive Order 13327, Federal Real Property Asset Management: February 4, 2004.

failure mode and effect analysis (FMEA), combined with Predictive Testing and Inspection (PT&I).

Specifically, NASA believes the RCM approach can be a valuable tool in the effort to meet the goals of the Energy Policy Act of 2005.

> The Secretary, in consultation with the Administrator of General Services, shall establish an Advanced Building Efficiency Testbed program for the development, testing, and demonstration of advanced engineering systems, components, and materials to enable innovations in building technologies. The program shall evaluate efficiency concepts for government and industry buildings, and demonstrate the ability of next generation buildings to support individual and organizational productivity and health (including by improving indoor air quality) as well as flexibility and technological change to improve environmental sustainability.[2]

In addition, NASA believes the RCM approach will aid the Centers in complying with the requirements of Executive Order 13423, Strengthening Federal Environmental, Energy, and Transportation and Energy Independence and Security Act of 2007 by:

> …implementing the policy of the United States that Federal agencies conduct their environmental, transportation, and energy-related activities under the law in support of their respective missions in an environmentally, economically and fiscally sound, integrated, continuously improving, efficient, and sustainable manner.

The NASA RCM Logic Tree, which provides a consistent approach to all equipment maintenance, has been modified to address sustainability (see Figure 3-2). NASA team members and contractors are encouraged to adopt the use of the NASA RCM Logic Tree and, where appropriate, perform an FMEA in the development of commissioning Pre-functional and Functional Tests. All Construction of Facilities (CoF) funded projects should include an RCM-based commissioning process to include training on the FMEA.

In addition to the increased awareness of the energy implications in facilities management since 2000, an increased emphasis has been placed on facility security in the wake of the September 11, 2001 attacks. The NASA RCM Logic Tree and accompanying criticality tables have been modified to include security.

Other significant changes to this guide are as follows:

- Information on commissioning has been expanded
- PT&I technology information has been updated
- RCM integration with computerized maintenance management systems (CMMS) and/or Computer Aided Facility Management (CAFM) has been included

[2] Public Law 109–58, Energy Policy Act of 2005: August 8, 2005.

- Wireless data collectors have been integrated with CMMS
- Key Performance Indicators (KPIs) and the President's Management Agenda Scorecard have been included
- RCM as a Quality Assurance (QA) tool
- Statistical Process Control (SPC) and Pareto Analysis
- The role of RCM in the Deferred Maintenance (DM) Model
- Generic FMEAs are provided for all major facilities equipment and systems in Appendix J

RCM principles and techniques have been used by NASA Headquarters, Centers, and Field Activities to improve their stewardship of the more than 44 million square feet of facilities and the associated billions of dollars of collateral equipment contained within by implementing and/or refining the following:

- Energy Management Control Systems
- Predictive Testing and Inspection (PT&I) (See Chapter 6.0 Predictive Testing and Inspection Technologies, page 6-1, and Chapter 7.0 Predictive Testing and Inspection Criteria, page 7-1.)
- Key Performance Indicators (KPIs) (See Chapter 12.0 Key Performance Indicators.)
- Performance Based M&O Contracts (PBC) (See Chapter 10.0 RCM Contract Clauses.)
- Failure Modes and Effects Analysis (FMEA) (See Section 4.2 Failure Modes and Effects Analysis, page 4-13.)
- Age Exploration (AE) (See Section 5.5.7 Age Exploration, page 5-30.)
- Commissioning, Recommissioning, and Retrocommissioning (See Chapter 10.0 Building Commissioning.)
- LEED® Certification

1.2 APPLICABILITY AND USE OF THIS GUIDE

This manual is offered as a tool to assist NASA facility organizations in implementing and institutionalizing an RCM approach to achieve and maintain the world-class facilities required to support the inherent reliability goals at any NASA Center and component facility.

This manual should be utilized by:

- Facility Planners
- Designers
- Equipment Procurement Specialists
- Construction Managers
- Commissioning Agents
- Maintenance and Operations (M&O) personnel
- Contract Planners

2.0 HISTORICAL EVOLUTION OF RELIABILITY-CENTERED MAINTENANCE

The following sections provide a brief overview of the evolution of maintenance practices leading to the development of RCM.

2.1 PREVENTIVE MAINTENANCE

In the past, industrial and facility maintenance organizations commonly used a Preventive Maintenance (PM) program, which is based on the following:

> One of the underlying assumptions of maintenance theory has always been that there is a fundamental cause-and-effect relationship between scheduled maintenance and operating reliability. This assumption was based on the intuitive belief that because mechanical parts wear out, the reliability of any equipment [is] directly related to operating age. It therefore followed that the more frequently equipment was overhauled, the better protected it was against the likelihood of failure. The only problem was in determining what age limit was necessary to assure reliable operation.[3]

PM assumes that failure probabilities can be determined statistically for individual machines and components, and that replacing parts or performing adjustments in time can often preclude failure. For example, a common practice has been to replace or renew bearings after a specified number of operating hours, assuming that bearing failure rate increases with time in service. The introduction of computerized maintenance management systems and the availability of computers solved the problem of when (what age) to overhaul many types of equipment in order to assure required reliability.

Maintenance and operations, failure and reliability data being reported by airlines highlighted problems with this approach. Specifically:

> In the case of aircraft it was also commonly assumed that all reliability problems were directly related to operating safety. Over the years, however, it was found that many types of failures could not be prevented no matter how intensive the maintenance activities. Moreover, in a field subject to rapidly expanding technology it was becoming increasingly difficult to eliminate uncertainty. Equipment designers were able to cope with this problem, not by preventing failures, but by preventing such failures from affecting safety. In most aircraft essential functions are protected by redundancy features which ensure that, in the event of a failure, the necessary function will still be available from some other source. Although fail-safe and "failure-tolerant" design practices have not entirely eliminated the relationship between safety and reliability, they have disassociated the two issues sufficiently that their implications for maintenance have become quite different.

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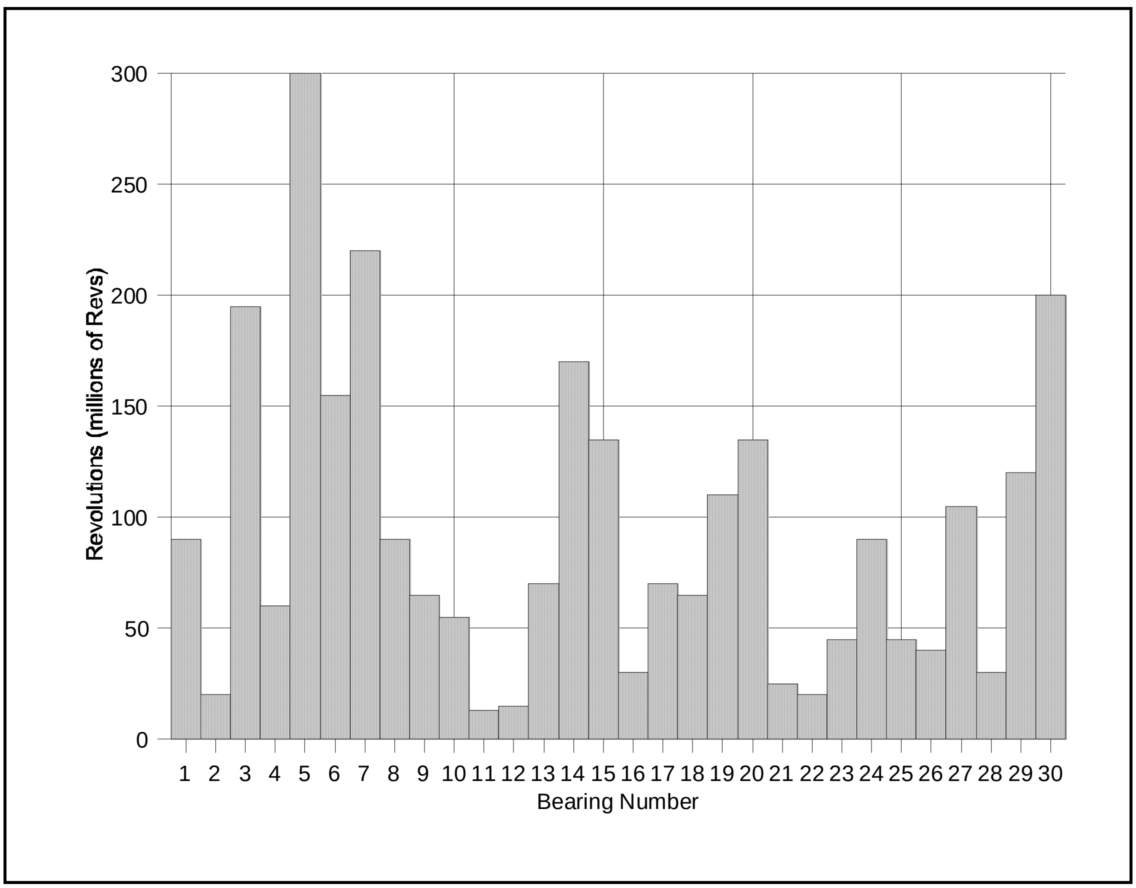
[3] Nowlan, F. Stanley, and Howard F. Heap. Reliability-Centered Maintenance. Department of Defense, Washington, D.C. 1978. Report Number AD-A066579.(Sponsored and published by the Office of Assistant Secretary of Defense, 1978.)

> A major question still remained, however, concerning the relationship between scheduled maintenance and reliability. Despite the time-honored belief that reliability was directly related to the intervals between scheduled overhauls, searching studies based on actuarial analysis of failure data suggested that the traditional hard-time policies were, apart from their expense, ineffective in controlling failure rates. This was not because the intervals were not short enough, and surely not because the tear down inspections were not sufficiently thorough. Rather, it was because, contrary to expectations, for many items the likelihood of failure did not in fact increase with increasing operation[al] age. Consequently a maintenance policy based exclusively on some maximum operating age would, no matter what the age limit, have little or no effect on the failure rate.[3]

Figure 2-1 shows the failure distribution of a group of thirty identical 6309 deep groove ball bearings installed on bearing life test machines and run to failure, using standard test procedures. The X-axis identifies the individual bearing being tested while the Y-axis is the number of revolutions achieved prior to fatigue failure of the individual bearing. The wide variation in bearing life precludes the use of any effective time-based maintenance strategy.

Figure 2-1. Bearing Life Scatter



2.2 CONDITION-BASED MONITORING

By the 1980s alternatives to traditional Preventive Maintenance (PM) programs began to migrate to the maintenance arena. While computer power first supported interval-based maintenance by specifying failure probabilities, continued advances in the 1990s began to change maintenance practices yet again. The development of affordable microprocessors and increased computer literacy in the work force made it possible to improve upon interval-based maintenance techniques by distinguishing other equipment failure characteristics. These included the precursors of failure, quantified equipment condition, and improved repair scheduling.

The emergence of new maintenance techniques called Condition Monitoring (CdM) or Condition-based Maintenance supported the findings of F. Stanley Nowlan, Howard F. Heap, and others, while revealing the fallacy of the two basic principles in traditional PM programs:

- A strong correlation exists between equipment age and failure rate.
- Individual component and equipment probability of failure can be determined statistically, and therefore components can be replaced or refurbished prior to failure.

Subsequently industry emphasis on Condition-based Maintenance increased, and the reliance upon PM decreased. However, Condition-based Maintenance should not replace all interval-based maintenance. Interval-based maintenance is still appropriate for those instances where an abrasive, erosive, or corrosive wear takes place; material properties change due to fatigue, embrittlement, or similar processes; or a clear correlation between age and functional reliability exists.

2.3 RELIABILITY-CENTERED MAINTENANCE

While many industrial organizations were expanding PM efforts to nearly all other assets, the airline industry, led by the efforts of Nowlan and Heap, took a different approach and developed a maintenance process based on system functions, consequence of failure, and failure modes. Their work led to the development of *Reliability-Centered Maintenance*, first published in 1978 and sponsored by the Office of the Assistant Secretary of Defense (Manpower, Reserve Affairs, and Logistics). Additional independent studies confirmed their findings.

In 1982 the United States Navy expanded the scope of RCM beyond aircraft and addressed more down-to-earth equipment. These studies noted a difference existed between the perceived and intrinsic design life for the majority of equipment and components. In many cases, equipment greatly exceeded its perceived or stated design life.

The process of determining the difference between perceived and intrinsic design life is known as Age Exploration (AE). AE was used by the U.S. Submarine Force in the early 1970s to extend the time between periodic overhauls and to replace time-based tasks with condition-based tasks. The initial program was limited to Fleet Ballistic Missile submarines. The use of AE was expanded continually until it included all submarines, aircraft carriers, other major combatants, and ships of the Military Sealift Command. The Navy stated the requirements of RCM and Condition-based Monitoring as part of the design specifications.

Development of relatively affordable test equipment and computerized maintenance management software (CMMS) during the last decade has made it possible to:

- Determine the actual condition of equipment without relying on dated techniques which base the probability of failure on age and appearance instead of condition.
- Track and analyze equipment history as a means of determining failure patterns and life-cycle cost.

RCM has long been accepted by the aircraft industry, the spacecraft industry, the nuclear industry, and the Department of Defense (DoD), but is a relatively new way of approaching maintenance for the majority of facilities outside of these four arenas. The benefits of an RCM approach far exceed those of any one type of maintenance program.

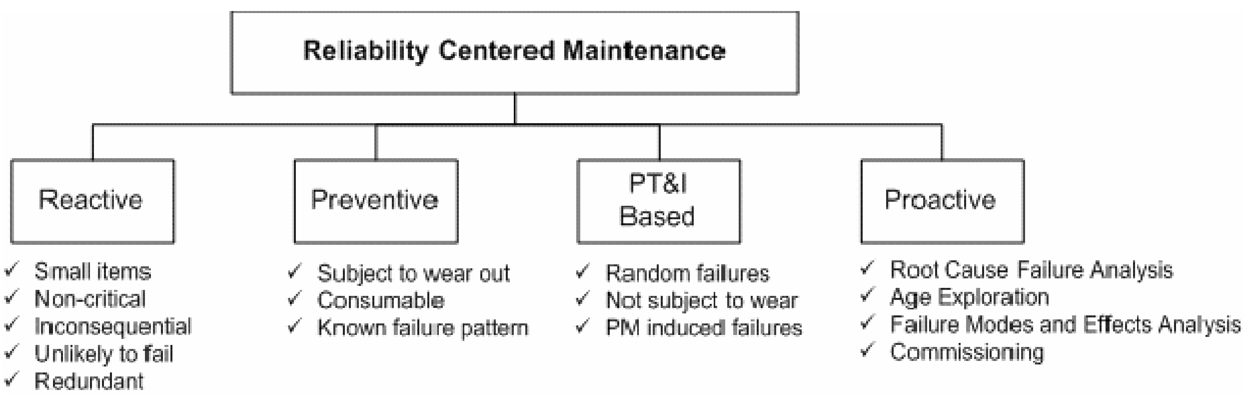
3.0 THE RCM APPROACH

3.1 INTRODUCTION TO RELIABILITY-CENTERED MAINTENANCE

Reliability-Centered Maintenance (RCM) integrates Preventive Maintenance (PM), Predictive Testing and Inspection (PT&I), Repair (also called reactive maintenance), and Proactive Maintenance to increase the probability that a machine or component will function in the required manner over its design life-cycle with a minimum amount of maintenance and downtime. These principal maintenance strategies, rather than being applied independently, are optimally integrated to take advantage of their respective strengths, and maximize facility and equipment reliability while minimizing life-cycle costs. The goal of this approach is to reduce the Life-Cycle Cost (LCC) of a facility to a minimum while continuing to allow the facility to function as intended with required reliability and availability.

The basic application of each strategy is shown in Figure 3-1.

Figure 3-1. Components of an RCM Program



RCM requires maintenance decisions to be supported by sound technical and economic justification. The RCM approach also considers the consequence of failure of a given component. For example, an identical make and model of exhaust fan can be used to support restroom operations or as part of a smoke/purge system. The consequence of failure and the maintenance approach of the two units are different, based on the system used. RCM analysis carefully considers the following questions:

- What does the system or equipment do; what are its functions?
- What functional failures are likely to occur?
- What are the likely consequences of these functional failures?
- What can be done to reduce the probability of the failure, identify the onset of failure, or reduce the consequences of the failure?

The goal of an RCM approach is to determine the most applicable cost-effective maintenance technique to minimize the risk of impact and failure and to create a hazard-free working environment while protecting and preserving capital investments and their capability. This goal is accomplished through an identification of failure modes and their consequences for each system. This allows system and equipment functionality to be maintained in the most economical manner. Specific RCM objectives, as stated by Nowlan and Heap[4], are as follows:

- To ensure realization of the inherent safety and reliability levels of the equipment.
- To restore the equipment to these inherent levels when deterioration occurs.
- To obtain the information necessary for design improvement of those items where their inherent reliability proves to be inadequate.
- To accomplish these goals at a minimum total cost, including maintenance costs, support costs, and economic consequences of operational failures.

3.2 TYPES OF RCM

RCM programs can be implemented and conducted in several ways and use different kinds of information. One technique is based on rigorous Failure Modes and Effects Analysis (FMEA), complete with mathematically-calculated probabilities of failure based on a combination of design data, historical data, intuition, common-sense, experimental data, and modeling. This approach is broken into two categories: Rigorous and Intuitive.

The decision as to how the RCM program is implemented should be made by the end user based on:

- Consequences of failure
- Probability of failure
- Historical data
- Risk tolerance (Mission Criticality)

3.2.1 Rigorous RCM Approach (Also known as Classical RCM)

A Rigorous RCM approach provides the most knowledge and data concerning system functions, failure modes, and maintenance actions addressing functional failures. Rigorous RCM analysis is the method first proposed and documented by F. Stanley Nowlan and Howard F. Heap and later modified by John Moubray, Anthony M. Smith, Jack Nicholas and others. Rigorous RCM produces the most complete documentation, compared to other RCM methods addressed in this guide.

A formal Rigorous RCM analysis of each system, subsystem, and component is normally performed on new, unique, high-cost systems such as aircraft and spacecraft systems and structures. This approach is rarely needed for most facilities and collateral equipment items because their construction and failure modes are well understood.

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[4] Nowlan, F. Stanley, and Howard F. Heap. Reliability-Centered Maintenance. Department of Defense, Washington, D.C. 1978. Report Number AD-A066579.

Rigorous RCM is based primarily on the FMEA and includes probabilities of failure and system reliability calculations but with little or no analysis of historical performance data. Rigorous RCM is labor intensive and often postpones the implementation of obvious PT&I tasks.

A Rigorous RCM approach has been used extensively by aircraft, space, defense, and nuclear industries where functional failures have the potential to result in large losses of life, national security implications, or extreme environmental impact. The analysis is used to determine appropriate maintenance tasks or possible redesign requirements in order to address each of the identified failure modes and their consequences.

A Rigorous RCM approach should be limited to the following three situations:

- The consequences of failure result in catastrophic risk in terms of environment, health, safety, or complete economic failure of the business unit.
- The resultant reliability and associated maintenance cost is still unacceptable after performing and implementing a streamlined-type FMEA.
- The system or equipment is new to the organization and insufficient corporate maintenance and operational knowledge exists on its function and functional failures.

Candidates for Rigorous RCM analysis include, but are not limited to, wind tunnel drive motors, supercomputer facilities, and mission support systems where single points of failure exist. In addition, a Rigorous RCM analysis may be needed for those systems and components where the Intuitive RCM approach has been utilized and the resultant reliability is still unacceptable in terms of security, safety, environmental, life-cycle cost, or mission impact.

3.2.2 Intuitive RCM Approach (Also known as Streamlined or Abbreviated RCM)

An Intuitive RCM approach is typically more appropriate for facility systems due to the high analysis cost of the rigorous approach, the relative low impact of failure of most facilities systems, the type of systems and components maintained, and the amount of redundant systems in place. The Intuitive RCM approach uses the same principles as the Rigorous RCM approach, but recognizes that not all failure modes will be analyzed.

An Intuitive RCM approach identifies and implements obvious, condition-based maintenance tasks with minimal analysis. Low value maintenance tasks are culled or eliminated based on historical data and Maintenance and Operations (M&O) personnel input. The intent is to minimize the initial analysis time in order to help offset the cost of the FMEA and condition monitoring capabilities development.

Errors can be introduced into the RCM process by reliance on historical records and personnel knowledge, creating a possibility of not detecting hidden, low-probability failures. The intuitive process requires that at least one individual has a thorough understanding of the various PT&I technologies.

An Intuitive RCM approach should be applied in the following situations:

- The function of the system/equipment is well understood.
- Functional failure of the system or equipment will not result in loss of life, catastrophic impact on the environment, or economic failure of the business unit.

An Intuitive RCM approach is recommended for NASA facilities and collateral equipment with the understanding that a more rigorous approach may be warranted in certain situations.

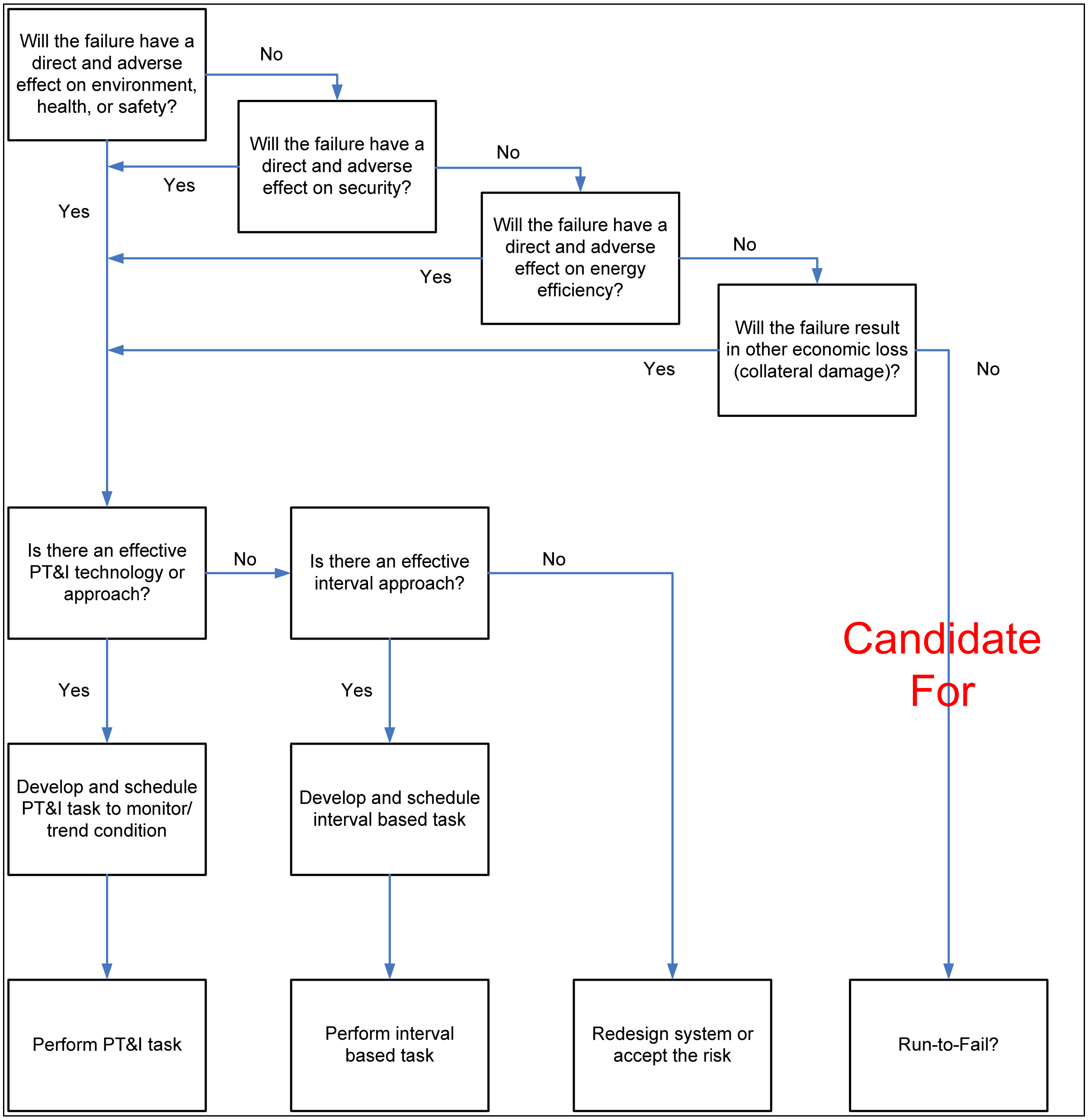
3.3 RCM PRINCIPLES

RCM focuses on the following principles.

- **Function-Oriented:** RCM seeks to preserve system or equipment function, not just operability for operability's sake. Redundancy of function through redundant equipment improves functional reliability but increases life-cycle cost in terms of procurement and operating costs.
- **System-Focused:** RCM is more concerned with maintaining system function than individual component function.
- **Reliability-Centered:** RCM treats failure statistics in an actuarial manner. The relationship between operating age and the failures experienced is important. RCM is not overly concerned with simple failure rate; it seeks to know the conditional probability of failure at specific ages (the probability that failure will occur in each given operating age bracket).
- **Acknowledges Design Limitations:** The objective of RCM is to maintain the inherent reliability of the equipment design, recognizing that changes in inherent reliability are the province of design rather than maintenance. Maintenance can only achieve and maintain the level of reliability for equipment which is provided for by design. RCM recognizes that maintenance feedback can improve on the original design. RCM recognizes that a difference often exists between the perceived design life and the intrinsic or actual design life, and addresses this through the Age Exploration (AE) process.
- **Safety, Security, and Economics:** Safety and security must be ensured at any cost; life-cycle cost-effectiveness is a tertiary criterion.
- **Failure as Any Unsatisfactory Condition:** Failure may be either a loss of function (operation ceases) or a loss of acceptable quality (operation continues). See Figure 3-2.
- **Logic Tree to Screen Maintenance Tasks:** This provides a consistent approach to the maintenance of all equipment. See Figure 3-2.
- **Tasks Must Be Applicable:** Tasks must address the failure mode and consider the failure mode characteristics.

- **Tasks Must Be Effective:** Tasks must reduce the probability of failure and be cost-effective.

Figure 3-2. NASA RCM Logic Tree



3.3.1.1 Three Types of Maintenance Tasks

Tasks are time-directed (PM), condition-directed (PT&I directed), and failure-finding (one of several aspects of Proactive Maintenance). Time-directed tasks are scheduled when appropriate. Condition-directed tasks are performed when conditions indicate they are needed. Failure-finding tasks detect hidden functions that have failed without giving evidence of failure and are normally time directed. Run-to-Failure (RTF) is a conscious decision and is acceptable for some equipment.

3.3.1.2 Living System

RCM gathers data from the results achieved and feeds this data back to improve design and future maintenance. This feedback is an important part of the Proactive Maintenance element of the RCM program.

Note that the maintenance analysis process, as illustrated in Figure 3-3, has only four possible outcomes:

- Perform Interval- (time or cycle) based actions.
- Perform Condition-based (PT&I directed) actions.
- Perform no action and choose to repair following failure.
- Determine no maintenance action will reduce the probability of failure and failure is not the chosen outcome (Redesign or Redundancy).

Regardless of the technique used to determine the maintenance approach, the approach must be reassessed and validated. Figure depicts an iterative RCM process that can be used for a majority of NASA facilities and collateral equipment.

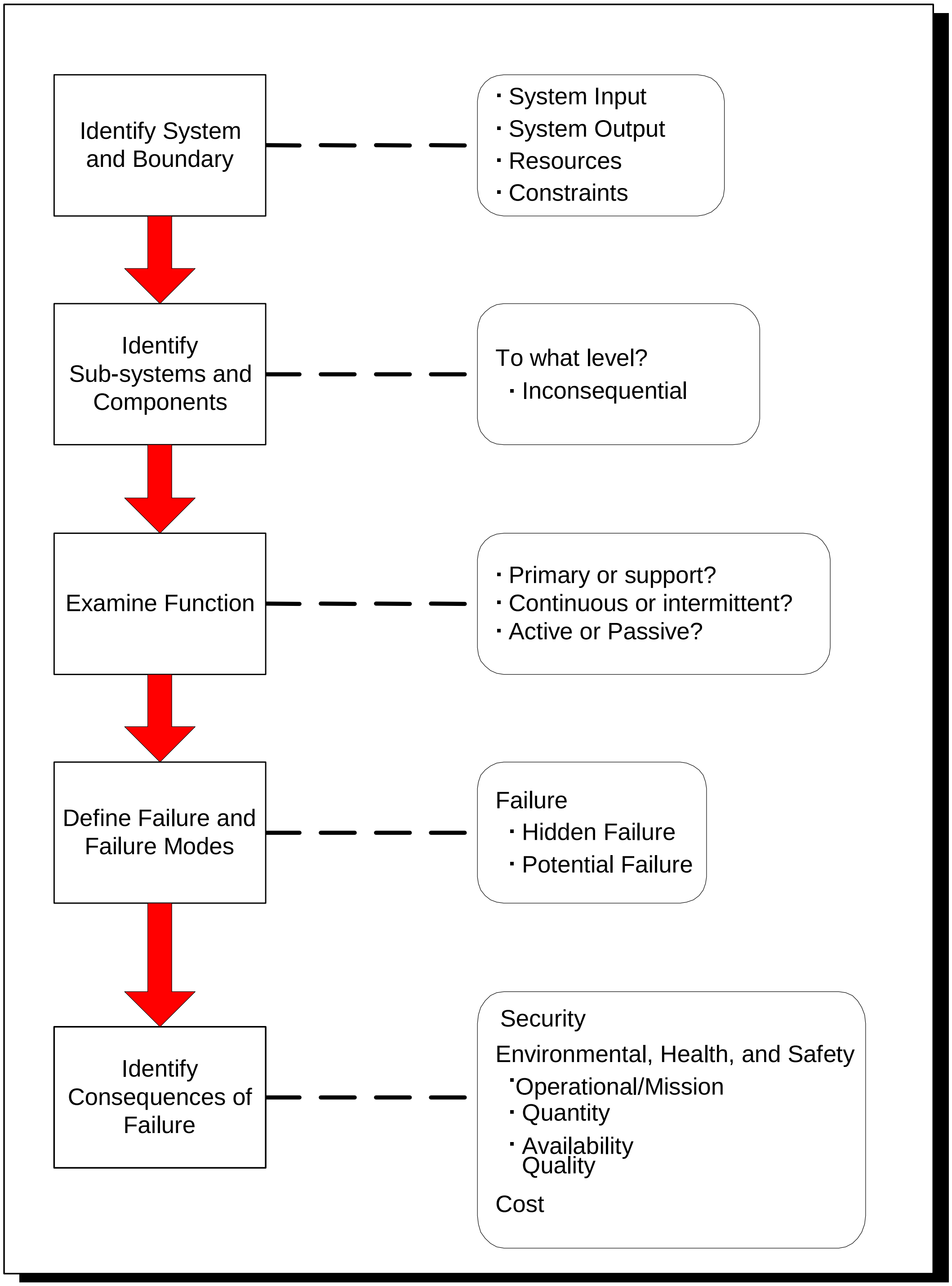
3.4 RCM ANALYSIS

RCM analysis carefully considers the following questions:

- What does the system or equipment do; what are its functions?
- What functional failures are likely to occur?
- What are the likely consequences of these functional failures?
- What can be done to reduce the probability of the failure, identify the onset of failure, or reduce the consequences of the failure?

Figure 3-3 illustrates the RCM approach and the interactive streamlined process.

Figure 3-3. RCM Analysis Considerations



3.5 BENEFITS OF RCM

Some benefits of RCM include safety, security, cost, reliability, scheduling, and efficiency.

3.5.1 Safety

The safety policy of NASA is to avoid loss of life, personal injury, illness, property loss, property damage, and environmental harm, and to ensure safe and healthful conditions for persons working at or visiting NASA facilities. The RCM approach supports the analysis, monitoring, early and decisive action, and thorough documentation that are characteristic of the NASA safety policy.

3.5.2 Security

An RCM approach provides improved reliability of physical barriers (such as celta barriers and motor/hydraulic gates) and emergency power supplies (such as generators and UPS systems) by adding PT&I tasks.

3.5.3 Cost

Due to the initial investment required for obtaining the technological tools, training, and equipment condition baselines, a new RCM Program typically results in an increase in maintenance costs. This increase is relatively short-lived, averaging two to three years. The cost of repair decreases as failures are prevented and preventive maintenance tasks are replaced by condition monitoring. The net effect is a reduction of both repair and total maintenance costs. Often energy savings are also realized from the use of PT&I techniques.

Figure 3-4. Effect on Maintenance and Repair Costs

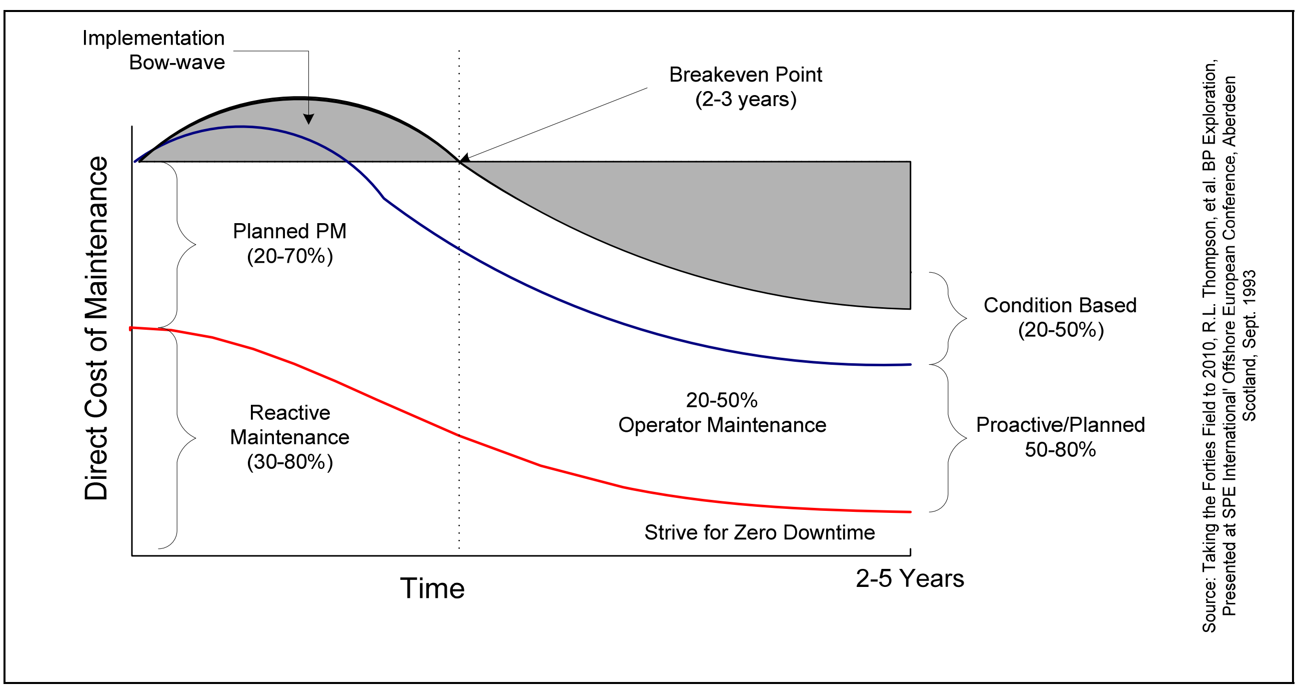


Figure 3-4 depicts the Bow Wave Effect experienced during the RCM implementation life-cycle. Initially, M&O costs increase for two reasons:

- RCM implementation costs include procurement of test equipment, software, training of existing staff, and in some cases the hiring of new personnel and use of consultants. In NASA's case, NASA Headquarters invested $15M over a three year period (1995-1997) in RCM-related activities.

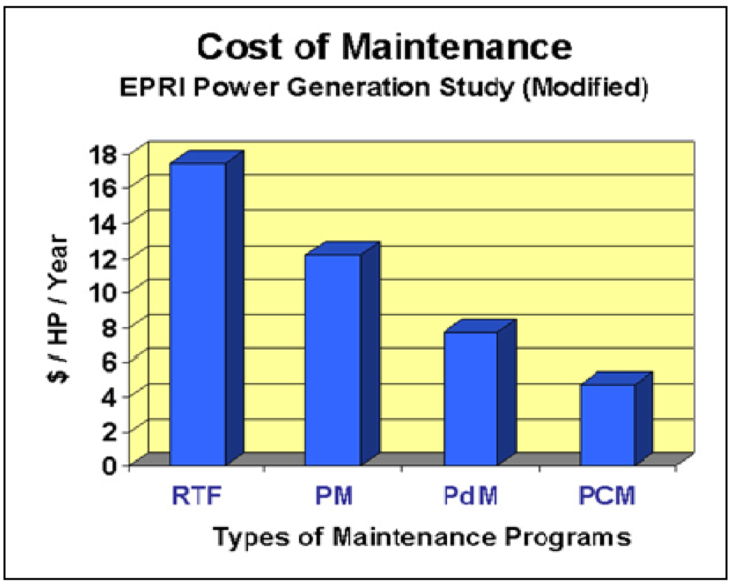
- As more sophisticated testing techniques are used, more faults are detected, resulting in more repairs until all of the potential failures have been addressed and/or mitigated.

As suggested by Figure 3-4 and Figure 3-5, the cost of maintenance per horsepower per year is cheaper as it changes from RTF to condition monitoring (CdM) and finally to an RCM-based practice.

The Return on Investment experienced by NASA during the period from 1996 to 2000 is consistent with that of British Petroleum (and the Electric Power Research Institute). NASA commissioned a study[5] in 2000 to evaluate the impact of their RCM investment. The study stated the NASA-wide Cost Avoidance to be between a reported $26,793,000 and an estimated $33,643,000 for a Return of Investment of 1.75-2.20.

During this period of time, NASA Centers reported[6] approximately 10,000 PT&I finds with average cost avoidance per find of $2,724.

Figure 3-5. Cost of Maintenance Programs by Type



[5] NASA Reliability-Centered Maintenance Center Assessments, EMR, Inc. September, 2000

[6] NASA Centers' Self Assessment Summary Reports for 1996-1999

3.5.4 Reliability

RCM places great emphasis on improving equipment reliability through the feedback of maintenance experience and equipment condition data to facility planners, designers, maintenance managers, craftsmen, and manufacturers. This information is instrumental for continually upgrading the equipment specifications for increased reliability. The increased reliability that comes from RCM leads to fewer equipment failures, greater availability for mission support, and lower maintenance costs.

3.5.5 Scheduling

The ability of a condition-monitoring program to forecast maintenance provides time for planning, obtaining replacement parts, and arranging environmental and operating conditions before the maintenance is done. PT&I reduces the unnecessary maintenance performed by a time-scheduled maintenance program which are driven by the minimum "safe" intervals between maintenance tasks.

A principal advantage of RCM is that it obtains the maximum use from equipment. With RCM, equipment replacement is based on actual equipment condition rather than a pre-determined, generic length of life.

3.5.6 Efficiency/Productivity

Safety is the primary concern of RCM. The secondary concern of RCM is cost-effectiveness. Cost-effectiveness takes into consideration the priority or mission criticality and then matches a level of cost appropriate to that priority. The flexibility of the RCM approach to maintenance ensures that the proper type of maintenance is performed on equipment when it is needed. Existing maintenance that is not cost-effective is identified and not performed.

3.6 IMPACT OF RCM ON THE FACILITIES LIFE-CYCLE

The life-cycle of a facility is often divided into two broad stages: acquisition (planning, design, and construction) and operations. RCM affects all phases of the acquisition and operations stages to some degree, as shown in Figure 3-6.

Decisions made early in the acquisition cycle affect the life-cycle cost of a facility. Even though expenditures for plant and equipment may occur later during the acquisition process, their cost is committed at an early stage. As shown in Table 3-1, planning (including conceptual design) fixes two-thirds of the facility's overall life-cycle costs. The subsequent design phases determine an additional 29 percent of the life-cycle cost, leaving only about 5 percent of the life-cycle cost that can be impacted by the later phases.

The decision to include a facility in an RCM program is best made during the planning phase. An early decision in favor of RCM will allow for a more substantial, beneficial impact on the life-cycle cost of a facility. Delaying a decision to include a facility in an RCM program will decrease the overall beneficial impact on the life-cycle cost of a facility.

RCM is capable of introducing significant savings during the M&O phase of the facility's life. Savings of 30 to 50 percent in the annual maintenance budget are often obtained through the introduction of a balanced RCM program.

Figure 3-6. Life-Cycle Cost Commitment

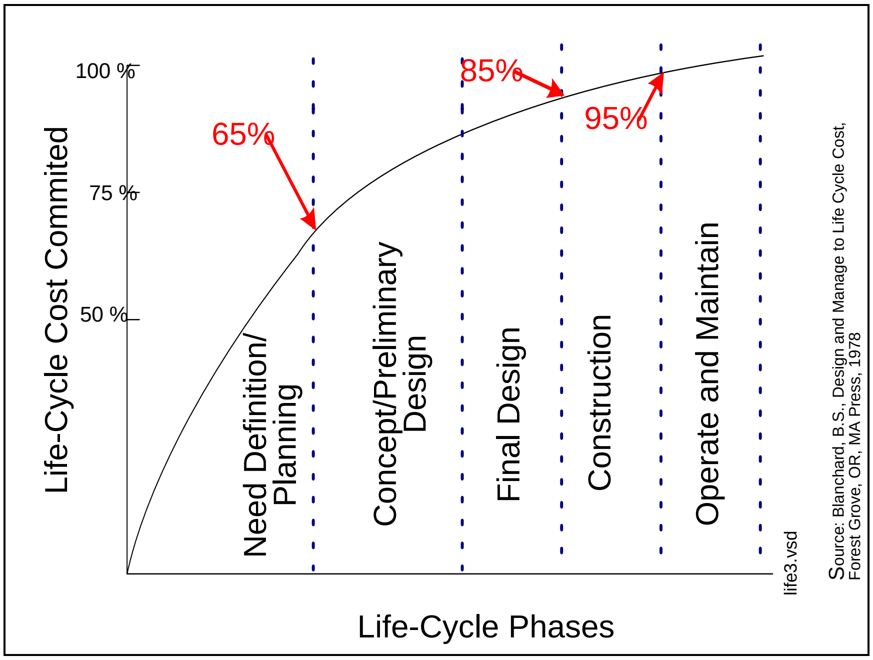


Table 3-1. RCM Facility Life-Cycle Implications

Life-Cycle Phase	Acquisition Implications	Operations Implications
Planning	Requirements Validation Contract Strategy RCM Implementation Policy Funding Estimates Construction Equipment (Collateral/R&D) Labor Training Operations A&E Scope of Work	Requirements Development Modifications Alterations Upgrades A&E Scope of Work Funding Estimates M&O Considerations Annual Cost Labor Spare Parts
Design	A&E Selection Drawings Specifications Acceptance Testing Requirements	A&E Selection Drawings Specifications Acceptance Testing Requirements
Construction	Contractor Selection Mobilization Construction Activation	Contractor Selection Construction Acceptance Testing
Maintenance and Operations (M&O)	Not Applicable	RCM Operations Training/Certification

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4.0 RCM AND FAILURE ANALYSIS

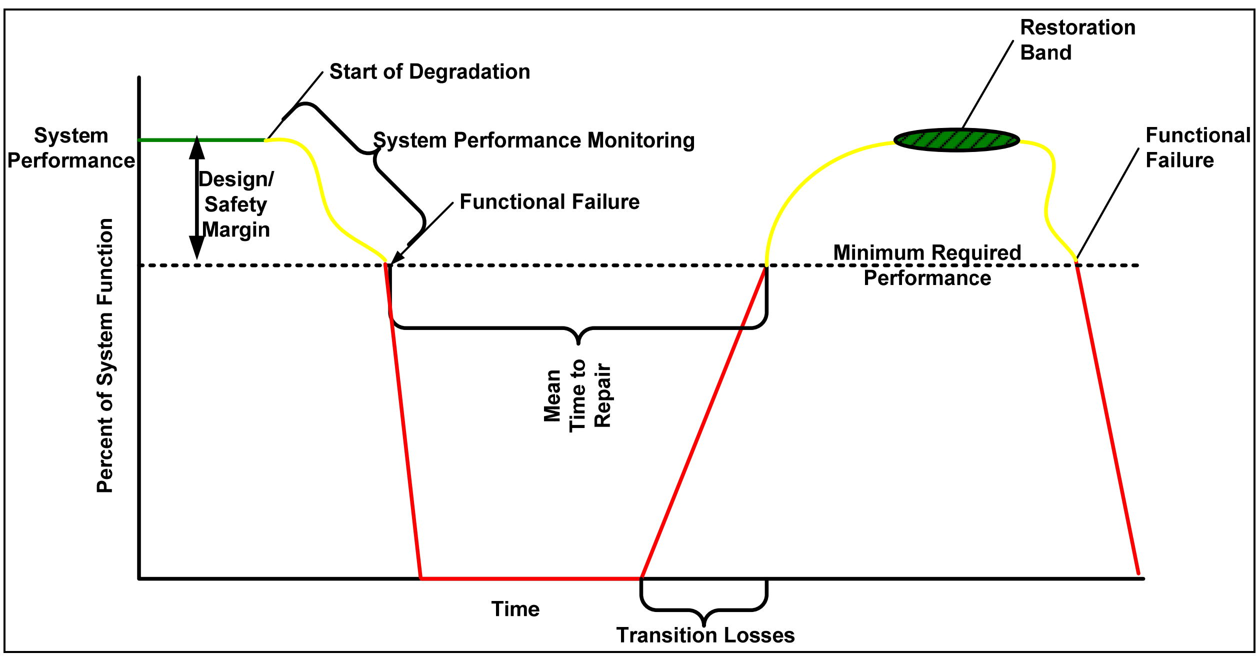
Failure is the cessation of proper function or performance. RCM examines failure at several levels: the system level, subsystem level, component level, and the parts level.

4.1 FAILURE

The goal of an effective maintenance organization is to provide the required system performance at the lowest cost. This means that the maintenance approach must be based upon a clear understanding of failure at each of the system levels. System components can be degraded or even failed and still not cause a system failure. For example, a failed parking lamp on an automobile has little effect on the overall performance of the automobile of the car as a transportation system.

Figure 4-1 depicts the entire life-cycle of a system from the moment of design intent (Minimum Required Performance + Design Safety Margin) through degradation, to Functional Failure, and subsequent restoration. In Figure 4-1, failure occurs the moment system performance drops below the point of Minimum Required Performance. The role of the maintenance and operations (M&O) staff is to recognize the margin to failure, estimate the time of failure, and pre-plan required repairs in order to minimize the Mean Time to Repair (MTTR) and associated downtime in order to achieve the maximum Overall Equipment Effectiveness within budgetary constraints.

Figure 4-1. System Performance Curve



PT&I measures the baseline system, component performance, and the amount of degradation. PT&I forecasts impending failure in a timely manner so repairs can be performed prior to catastrophe. As shown in Figure 4-2, the point of initial degradation and point of initial detection rarely coincide. It is essential that the interval between tasks be initially established conservatively. At least three maintenance tasks should be performed between the point of initial degradation and point of initial detection.

PT&I task intervals are listed in Chapter 6.0 and Chapter 7.0.

Preventive Maintenance (PM) task intervals should be set based on location, application, and operating environment. Maintenance schedules should be modified for remote locations where parts and service are not readily available. Appendix J provides sample maintenance tasks and recommended base intervals.

For PT&I and PM tasks, the difference between actual system performance and Minimum Required Performance should be considered. For example, a fan operating at an overall vibration level of 0.2 inches per second (ips) is closer to the point of functional failure than an identical unit operating at an overall vibration level of 0.1 ips and should be monitored more frequently.

Figure 4-2. P-F Curve (Modified)

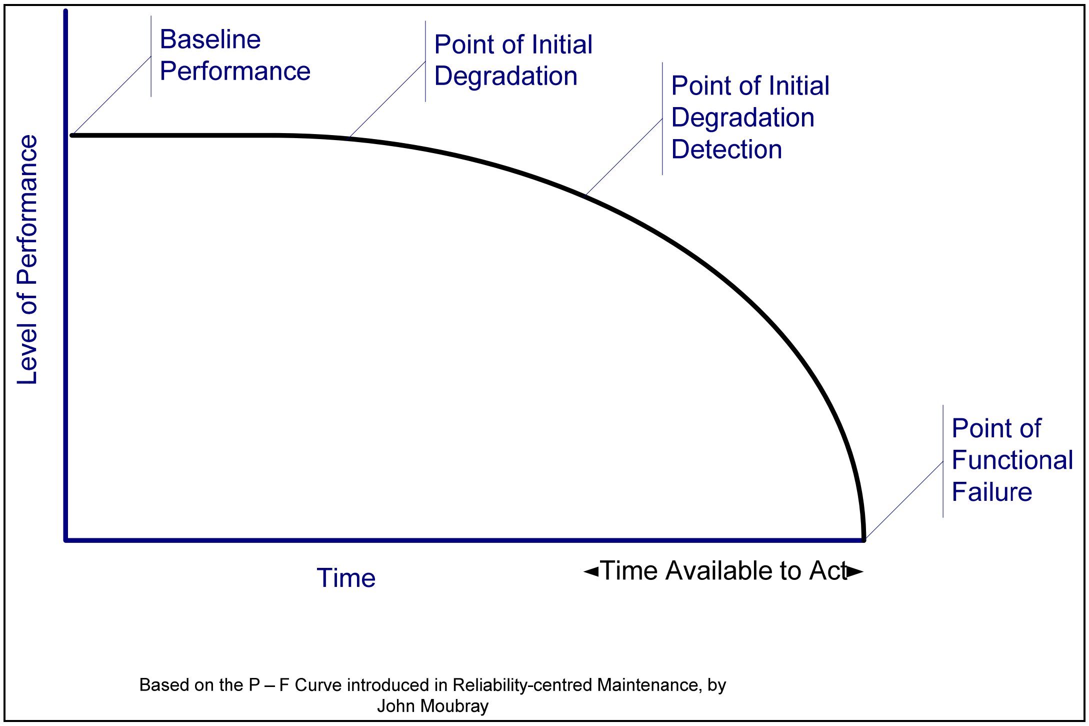


Figure 4-2 and Figure 4-3 provide a Conceptual Degradation Detection Graph which shows the baseline state as well as the onset of degradation from initial detection, to alert status, and to finally remove from service because failure is imminent. Although the actual moment of failure for most systems and components is not known, the fact that failure is imminent is known.

Figure 4-3. Conceptual Degradation Detection Graph[7]

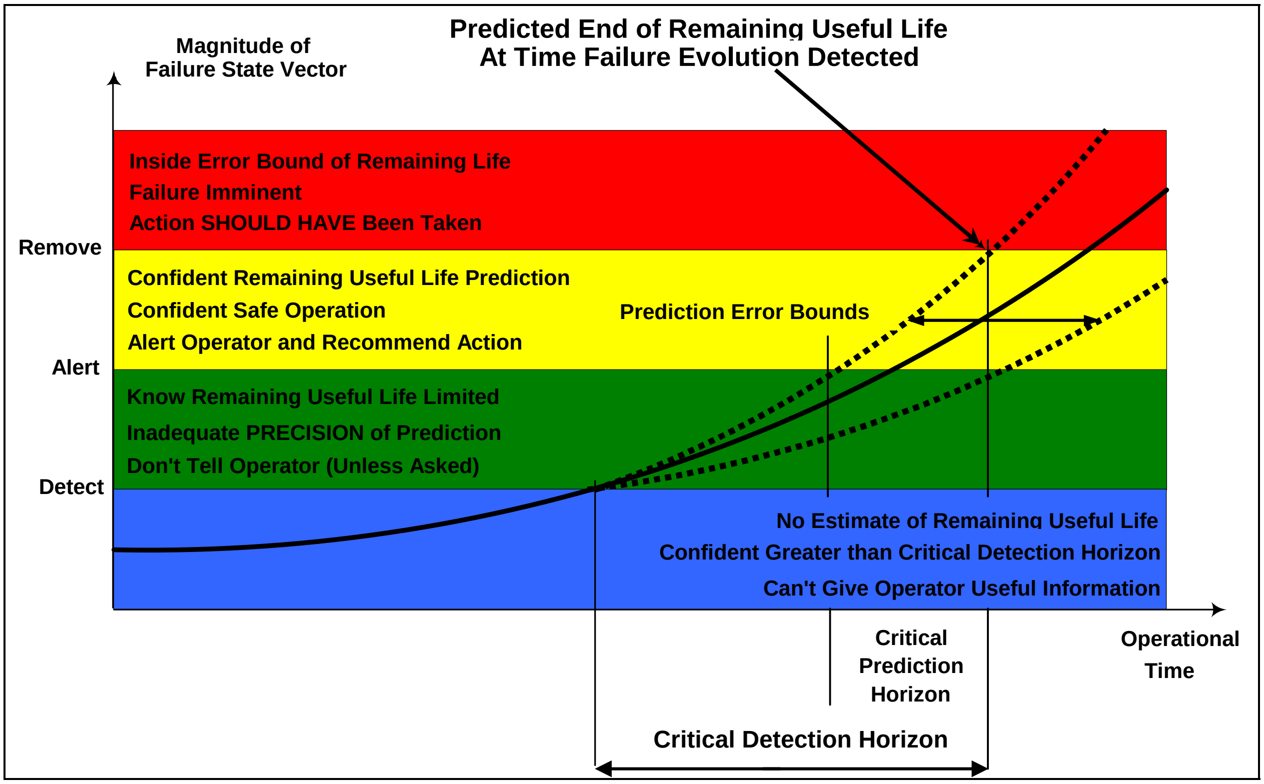


Figure 4-3 suggests there is a steady, non-linear progress from baseline condition until potential failure and recommended removal. Analysis of the data must observe any changes in slope of the plotted data. As the failure point is approached, the resistance of the object to failure often decreases in an exponential manner. In this situation, catastrophic failure occurs almost without warning.

Once the Alert limit has been exceeded, the monitoring interval should be reduced to between one-third and one-quarter of the prior interval. For example, if vibration data was being collected quarterly, the new interval should be between three and four weeks. As the vibration levels continue to rise, the monitoring interval should continue to be reduced. Conversely, if the readings stabilize, the monitoring interval can be increased.

The concepts presented in Figure 4-1, Figure 4-2, and Figure 4-3 must be fully understood and adhered to if the full benefits of RCM and PT&I are to be realized. Condition monitoring activities must occur frequently in order to forecast the potential failure. As shown in Figure 4-3, Prediction Error Bounds do exist and are often referred to as a Probability of Detection (Pd) and Probability of False Alarm (Pfa).

[7] CBM Technology NASA RCM Course 3 - Penn State Applied Research Laboratory.

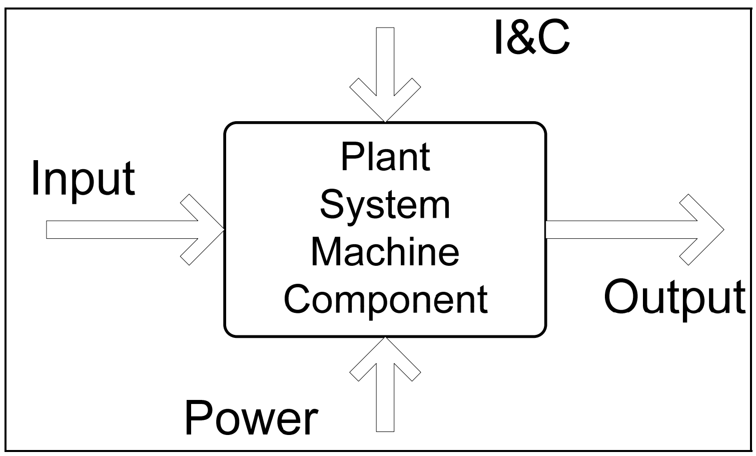
4.1.1 System and System Boundary

A system is any user-defined group of components, equipment, or facilities that support an operational function. These operational functions are defined by mission criticality or by environmental, health, safety, regulatory, quality, or other NASA-defined requirements. Most systems can be divided into unique subsystems along user-defined boundaries. The boundaries are selected as a method of dividing a system into subsystems when its complexity makes an analysis by other means difficult.

As shown in Figure 4-4, a system boundary or interface definition contains a description of the inputs and outputs across each boundary as well as the power requirements and Instrumentation and Control.

The facility envelope is the physical barrier created by a building, enclosure, or other structure plus five feet; e.g., a cooling tower or tank.

Figure 4-4. System Functional Boundaries



4.1.2 Function and Functional Failure

The function defines the performance expectation and its many elements may include physical properties, operation performance (including output tolerances), and time requirements (such as continuous operation or limited required availability). A System Performance curve similar to Figure 4-2 exists for each operating parameter.

Functional failures describe the various ways in which a system or subsystem can fail to meet the functional requirements designed into the equipment. A system or subsystem that is operating in a degraded state but does not impact any of the requirements addressed has not experienced a functional failure.

It is important to determine all the functions of an item that are significant in a given operational context. By clearly defining the functions' non-performance, the functional failure becomes clearly defined. For example, it is not enough to define the function of a pump to move water. The function of the pump must be defined in terms of flow rate, discharge and suction pressure, efficiency, etc.

4.1.3 Failure Modes

Failure modes are equipment- and component-specific failures that result in the functional failure of the system or subsystem. For example, a machinery train composed of a motor and pump can fail catastrophically due to the complete failure of the windings, bearings, shaft, impeller, controller, or seals. A functional failure also occurs if the pump performance degrades such that there is insufficient discharge pressure or flow to meet operating requirements. These operational requirements should be considered when developing maintenance tasks.

Dominant failure modes are those failure modes responsible for a significant proportion of all the failures of the item. They are the most common modes of failure.

Not all failure modes or causes warrant preventive or predictive maintenance because the likelihood of occurrence may be remote or the effect inconsequential.

4.1.4 Reliability

Reliability (R(t)) is the probability that an item will survive a given operating period, under specified operating conditions, without failure. The conditional probability of failure ($P(Dt/t_1)$) measures the probability that an item entering a given age interval will fail during that interval. The item shows wear-out characteristics if the conditional probability of failure increases with age. If the conditional probability of failure is constant with age, the resulting failure distribution is exponential and applies to the majority of facilities equipment. (See Section 4.1.5, Section 4.1.6, and the Engineering Reliability & RCM NASA Course.)

All physical and chemical root causes of failure have time varying hazard rates h(t) and often require time-based tasks, usually inspection and/or measurement.

The conditional probability of failure reflects the overall adverse effect of age on reliability. It is not a measure of the change in an individual equipment item.

Failure frequency, or failure rate, plays a relatively minor role in maintenance programs because it is too simplistic to gauge much. Failure frequency is useful in making cost decisions and determining maintenance intervals, but does not tell which maintenance tasks are appropriate or the consequences of failure. A maintenance solution should be evaluated in terms of the safety or economic consequences it is intended to prevent. A maintenance task must be applicable (i.e., prevent failures or ameliorate failure consequences) in order to be effective.

4.1.5 Failure Characteristics

Conditional probability of failure (P_{cond}) curves fall into six basic types, as graphed (P_{cond} vs. Time) in Figure 4-5. The percentage of equipment conforming to each of the six wear patterns as determined in three separate studies is also shown.

- Type A: Constant or gradually increasing failure probability, followed by a pronounced wear-out region. An age limit may be desirable. (Typical of reciprocating engines.)

- Type B: Infant mortality, followed by a constant or slowly increasing failure probability. (Typical of electronic equipment.)

- Type C: Low failure probability when the item is new or just overhauled, followed by a quick increase to a relatively constant level.

- Type D: Relatively constant probability of failure at all ages.

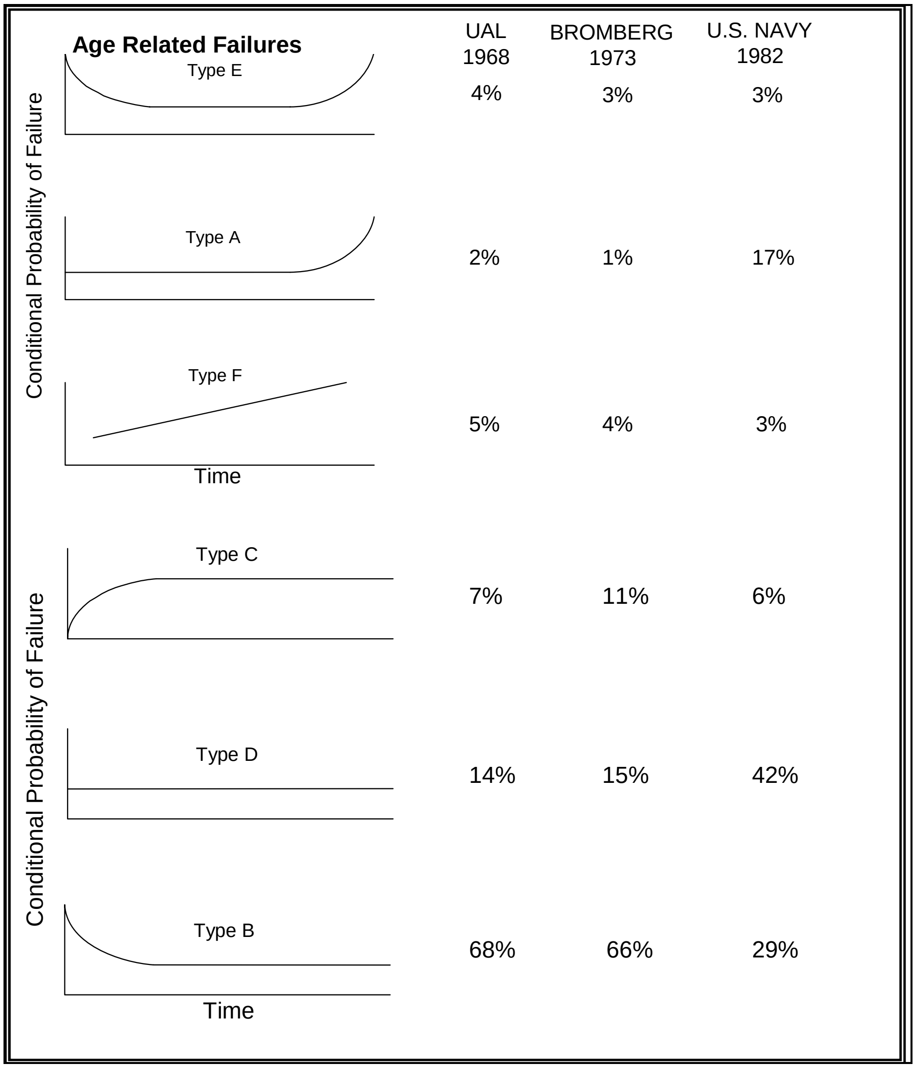
- Type E: Bathtub curve; i.e., infant mortality followed by a constant or gradually increasing failure probability and then a pronounced wear-out region. An age limit may be desirable, provided a large number of units survive to the age where wear-out begins.

- Type F: Gradually increasing failure probability, but no identifiable wear-out age. Age limit usually not applicable. (Typical of turbine engines.)

Types A and E are typical of single-piece and simple items such as tires, compressor blades, brake pads, and structural members. Most complex items have conditional probability curves similar to Types B, C, D, and F.

The basic difference between the failure patterns of complex and simple items has important implications for maintenance. Single-piece and simple items frequently demonstrate a direct relationship between reliability and age. This is particularly true where factors such as metal fatigue or mechanical wear are present or where the items are designed as consumables (short or predictable life spans). In these cases an age limit based on operating time or stress cycles may be effective in improving the overall reliability of the complex item of which they are a part.

Figure 4-5. Conditional Probability of Failure Curves



Complex items frequently demonstrate some infant mortality, after which their failure probability increases gradually or remains constant, and a marked wear-out age is not common. In many cases scheduled overhaul increases the overall failure rate by introducing a high infant mortality rate into an otherwise stable system. The failure characteristics were first noted in the previously cited book, *Reliability-Centered Maintenance*[8]. Follow-on studies in Sweden in 1973, and by the U.S. Navy in 1982, produced similar results. In these three studies, random failures are between 77 and 92 percent of the total failures and age-related failure characteristics for the remaining 8 to 23 percent.

[8] Nowlan, F. Stanley, and Howard F. Heap. Reliability-Centered Maintenance. Department of Defense, Washington, D.C. 1978. Report Number AD-A066579.

4.1.6 Preventing Failure

Every equipment item has a characteristic that can be called *resistance to* or *margin to failure*. Figure 4-6 depicts this concept graphically. The figure shows that failures may be prevented or item life extended by:

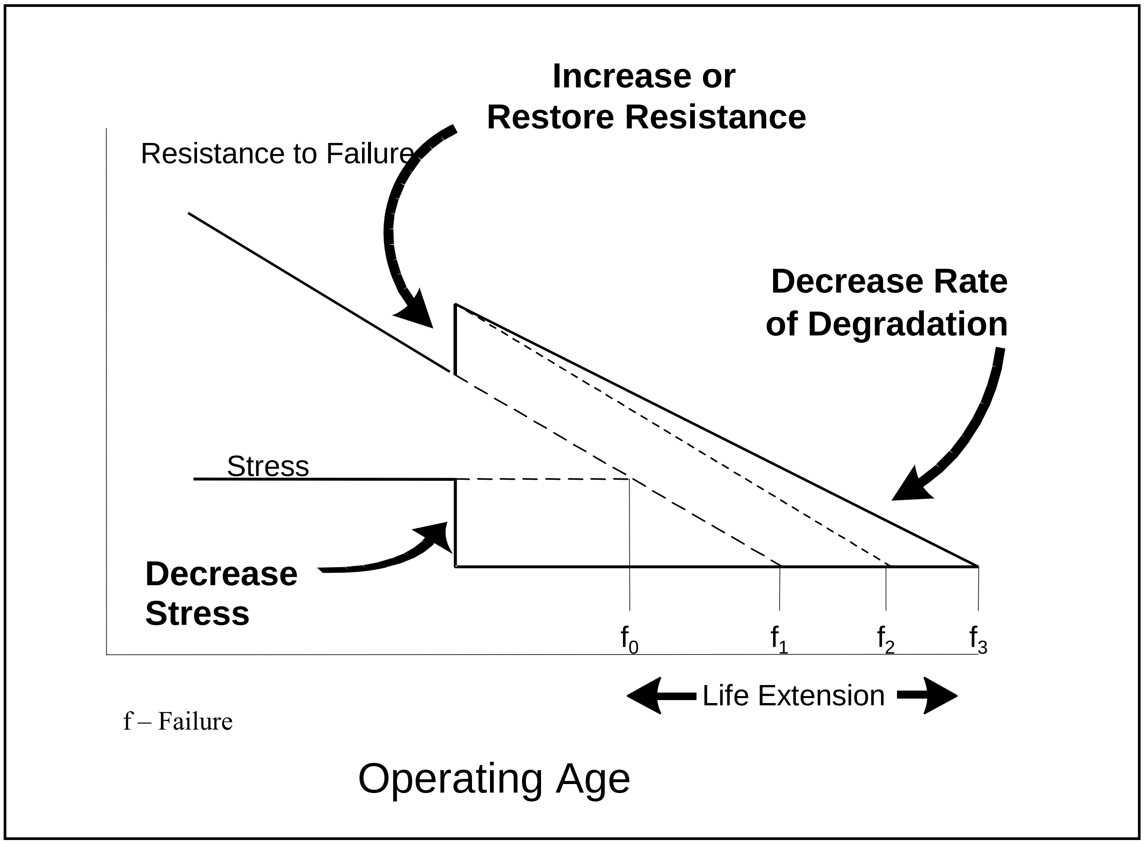
- Decreasing the amount of stress applied to the item. The life of the item is extended for the period f_0-f_1 by the stress reduction shown.
- Increasing or restoring the item's resistance to failure. The life of the item is extended for the period f_1-f_2 by the resistance increase shown.
- Decreasing the rate of degradation of the item's resistance to or margin to failure. The life of the item is extended for the period f_2-f_3 by the decreased rate of resistance degradation shown.

Stress is dependent on use and may be highly variable. A review of the failures of a large number of nominally identical simple items would disclose that the majority had about the same age at failure, subject to statistical variation, and that these failures occurred for the same reason. If preventive maintenance for some simple item is being considered and a way to measure its resistance to failure can be found, then this measurement information can be used to help select a preventive task.

Adding excess material that wears away or is consumed can increase resistance to failure. Excess strength may be provided to compensate for loss from corrosion or fatigue. The most common method of restoring resistance is by replacing the item.

The resistance to failure of a simple item decreases with use or time (age), but a complex unit consists of hundreds of interacting simple items (parts) and has a considerable number of failure modes. In the complex case, the mechanisms of failure are the same, but they are operating on many simple component parts simultaneously and interactively. Failures no longer occur for the same reason at the same age. For these complex units, it is unlikely that one can design a maintenance task unless there are few dominant or critical failure modes.

Figure 4-6. Preventing Failure



4.2 FAILURE MODES AND EFFECTS ANALYSIS

Failure Modes and Effects Analysis (FMEA) is applied to each system, subsystem, and component identified in the boundary definition. For every function identified, there can be multiple failure modes. The FMEA addresses each system function, all possible failures, and the dominant failure modes associated with each failure. The FMEA then examines the consequences of failure to determine what effect failure has on the mission or operation, on the system, and on the machine.

Even though there are multiple failure modes, often the effects of failure are the same or very similar in nature. From a system function perspective, the outcome of any component failure may result in the system function being degraded.

Similar systems and machines will often have the same failure modes, but the system use will determine the failure consequences. For example, the failure modes of a ball bearing will be the same regardless of the machine, but the dominate failure mode, cause of failure, and effects of failure will change from machine to machine.

Figure 4-7 provides an example of a FMEA worksheet. The key elements identified on the worksheet reflect the items identified in the RCM analysis. (See Figure 5-5 Failure Analysis Form for more information.) There are two new terms identified in Figure 4-7: criticality and probability of failure occurrence.

Figure 4-7. FMEA Worksheet

Failure Modes & Effects Worksheet

Area: Center, Building
System: Name
FMEA Number: If Used
Team Members: FMEA Preparers

Date Started:
Date Completed:

Page: ___ of ___
Printed: Date/Time

Control Number	Name & Function/ Performance Requirement	Potential Failure Mode	Potential Failure Effects	Criticality	Probability	Remarks/Continue

4.2.1 Criticality of Occurrence

Criticality assessment provides the means for quantifying how important a system function is relative to the identified mission. Table 4-1 provides a method for ranking system criticality. This system, adapted from the automotive industry[9], provides 10 categories of Criticality/ Severity. It is not the only method available. The categories can be expanded or contracted to produce a site-specific listing.

Table 4-1. Criticality/Severity Categories

Ranking	Effect	Comment
1	None	No reason to expect failure to have any effect on safety, health, environment or mission.
2	Very Low	Minor disruption to facility function. Repair to failure can be accomplished during trouble call.
3	Low	Minor disruption to facility function. Repair to failure may be longer than trouble call but does not delay mission.
4	Low to Moderate	Moderate disruption to facility function. Some portion of mission may need to be reworked or process delayed.
5	Moderate	Moderate disruption to facility function. 100% of mission may need to be reworked or process delayed.
6	Moderate to High	Moderate disruption to facility function. Some portion of Mission is lost. Moderate delay in restoring function.
7	High	High disruption to facility function. Some portion of Mission is lost. Significant delay in restoring function.
8	Very High	High disruption to facility function. All of Mission is lost. Significant delay in restoring function.
9	Hazard	Potential Safety, Health, or Environmental issue. Failure will occur with warning.
10	Hazard	Potential Safety, Health, or Environmental issue. Failure will occur without warning.

[9] Reliability, Maintainability, and Supportability Guidebook, Third Edition, Society of Automotive Engineers, Inc., Warrendale, PA, 1995.

4.2.2 Probability of Occurrence

The Probability of Occurrence (of Failure) is based on work in the automotive industry.

Table 4-2 provides one possible method of quantifying the probability of failure. Historical data provides a powerful tool in establishing the ranking. If historical data is unavailable, a ranking may be estimated based on experience with similar systems in the facilities area. The statistical column can be based on operating hours, day, cycles, or other unit that provides a consistent measurement approach. The statistical bases may be adjusted to account for local conditions.

Table 4-2. Probability of Occurrence Categories

Ranking	Effect	Comment
1	1/5,000	Remote probability of occurrence; unreasonable to expect failure to occur.
2	1/5,000	Low failure rate. Similar to past design that has, in the past, had low failure rates for given volume/loads.
3	1/2,000	Low failure rate. Similar to past design that has, in the past, had low failure rates for given volume/loads.
4	1/1,000	Occasional failure rate. Similar to past design that has, in the past, had occasional failure rates for given volume/loads.
5	1/500	Moderate failure rate. Similar to past design that has, in the past, had moderate failure rates for given volume/loads.
6	1/200	Moderate to high failure rate. Similar to past design that has, in the past, had moderate failure rates for given volume/loads.
7	1/100	High failure rate. Similar to past design that has, in the past, had high failure rates that has caused problems.
8	1/50	High failure rate. Similar to past design that has, in the past, had high failure rates that has caused problems.
9	1/20	Very High failure rate. Almost certain to cause problems.
10	1/10+	Very High failure rate. Almost certain to cause problems.

4.2.3 Cause of Failure

After the function and failure modes are determined, it is necessary to investigate the cause of failure. Without an understanding of the causes of potential failure modes it will not be possible to select applicable and effective maintenance tasks. For example, the type and progression of information collected for a chilled water system could look similar to Figure 3-3 RCM Analysis Considerations.

Each of the individual components that make up the chilled water system would then have a similar analysis performed, as illustrated in Figure 4-8.

Figure 4-8. General HVAC System with Test Points

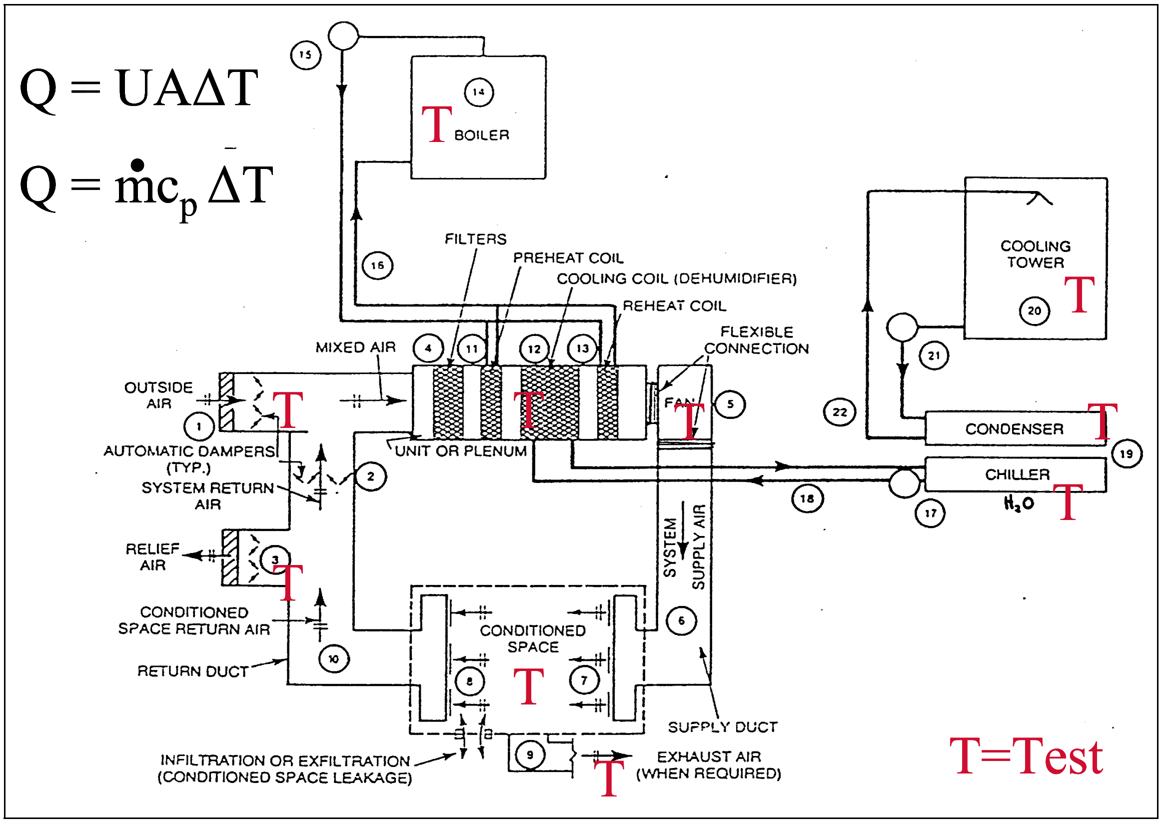


Table 4-3. Chilled Water System Analysis

Function	Functional Failure	Failure Mode	Source of Failure
Provide chilled water at specified: Flow Rate and Temperature (The flow and temperature would be based upon the use requirement. For example, if the chilled water system were supplying a computer room, what would the water flow and temperature range need to be to maintain the room temperature?)	Total loss of flow	Electric Motor Failed	(See Table 4-4.)
		Pump Failed	
		Major Leak	
		Blocked Line	
		Valve Out of Position	
	Insufficient Flow	Pump Cavitation	
		Drive Problem	
		Blocked Line	
		Valve Out of Position	
		Instrumentation Error	
	Water temperature high or low	Chiller Failure	
		Low Refrigerant	
		Cooling Tower Problem	
		Valve out of position.	
		Fouled Heat Exchanger	
		Instrumentation Error	

Table 4-4. Electric Motor Component Analysis

Function	Functional Failure	Failure Mode	Source of Failure
Stator	Motor will not turn.	Insulation Failure	Insulation contamination, excessive current, voltage spike, phase imbalance, excessive temperature.
		Open Winding	
Rotor	Motor will not turn.	Insulation Failure	Insulation, contamination, excessive current, excessive temperature.
	Motor turns at wrong speed.	Excessive Vibration	
Bearings	Motor will not turn.	Bearing Seized	Fatigue, improper lubrication, misalignment, mechanical imbalance, electrical pitting, lube contamination, excessive thrust, excessive temperature.
Motor Controller	Motor will not turn.	Contactor Failed	Contact failure, control circuit failure, cable failure, loss of power.
	Motor turns at wrong speed.	VFD Malfunction	
Power Supply	Motor will not turn.	Loss of Power	Supply failure, excessive current, excessive torque, poor connection.

Table 4-5 focuses on one failure mode: the seized bearing. Similar information will be needed for each failure mode. This information can require a significant amount of effort and expense to compile. Through the iterative, simplified process illustrated above, the engineer or technician performing the analysis is able to determine the root cause of the problem by deducting non-indicative symptoms and conditions.

Table 4-5. Cause of Motor Bearing Failure

Failure Mode	Mechanism	Reason	Cause
Bearing seized (this includes seals, shields, lubrication system, and lock nuts.)	Lubrication	Contamination	Seal Failed
			Supply Dirty
		Wrong Type	Procedure or supply information wrong
		Too Little	Oil leak
			Procedure error
		Too Much	Procedure error
	Fatigue	Metallurgical	Inherent
			Excessive temperature
		Excessive Load	Mechanical imbalance
			Misalignment
			Wrong Application (bearing not sized for the load)
			Poor Fit-up
	Surface Distress	Installation	Procedure error
		Storage	Procedure error
		Electrical	Insulation
			Welding
		Contamination	See Lubrication

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5.0 RCM PROGRAM COMPONENTS

An RCM program includes preventive, predictive, proactive, and reactive maintenance tasks. The actual mix and usage of the various types of maintenance tasks should be driven by the end users based on their risk tolerance and budget. For example, the approach to implementing a RCM process by Wallops Flight Facility will differ significantly from the approach taken by Glenn Research Center. For the former, the facility consists of a flight line and supporting systems, several tenant agencies, and general purpose buildings. The latter is a research center with a very complex and expensive Central Plant supporting the operation of wind tunnels and engine test stands. These specialized facilities require a degree of analysis and Predictive Testing and Inspection (PT&I) not found in a facility such as Wallops Flight Facility.

Another factor that must be taken into consideration when implementing a specific RCM program is how the organization fits into NASA, and the specific program, center, or directorate facility life-cycle. A NASA program, center, or directorate should be defined in terms of an overall facility life-cycle in the macro sense in order to determine the appropriate RCM approach and mix.

There are three macro facility life-cycle scenarios to be considered when choosing the RCM approach and program components. They are as follows:

Scenario 1

NASA, or a specific program, center, or directorate thereof, is engaged in significant construction of new facilities or revitalization of existing facilities. Maintaining the status quo in terms of facility condition where Facility Condition Index (FCI) is constant is not an option due to change in mission, change in threat to mission, or change in mission priority.

Scenario 2

NASA, or a specific program, center, or directorate thereof, is engaged in maintaining the existing facilities and maintaining current facility condition where FCI is constant to support mission. Little or no new construction or major revitalization is in progress. There is minimal budget constraint.

Scenario 3

NASA, or a specific program, center, or directorate thereof, is under significant budgetary pressure to preserve critical functionality within a highly constrained budget. Individual facility and building FCIs are managed to preserve core business while allowing less critical facilities' FCIs to decrease.

The following RCM approaches and component selection have been encountered for each of the three scenarios.

Scenario 1

Construction or revitalization design and construction contracts include the following:

- Commissioning & Sustainability (See Chapter 13.0)
- Maintainability (See Chapter 14.0)

Failure Modes and Effects Analysis (FMEA) used to develop the following:

- Prefunctional and functional tests documentation
- Initial maintenance job plans
- Maintenance and operations (M&O) training requirements
- PT&I requirements and acceptance standards

Scenario 2

A streamlined or intuitive approach to RCM is used to replace existing time-based tasks with PT&I tasks. Age Exploration (AE) is applied to high-cost contracted program maintenance tasks and non-regulatory open and inspect type tasks.

Scenario 3

A streamlined or intuitive approach to RCM is used to replace existing time-based tasks with PT&I tasks. AE is applied to all maintenance tasks. The AE process may be applied in an intuitive manner for all non-regulatory tasks. An arbitrary decision is made to eliminate all time-based monthly or quarterly tasks on a system by system basis. Intervals between PT&I tasks are increased.

A user should understand system boundaries and facility envelopes, functional failures, and failure modes, all of which are critical components of the RCM program. The following sections describe these key RCM components.

Table 5-1 suggests the criteria to be used in determining RCM priorities.

Table 5-1. Maintenance Priority Levels

Priority		Application
Number	Description	
1	Emergency	Safety; mission impact.
2	Urgent	Continuous operation of facility at risk.
3	Priority	Mission support/project deadlines.
4	Routine	Accomplish on “first come, first served” basis.
5	Discretionary	Desirable, but not essential.
6	Deferred	Needed but unable to accomplish until more resources available.

5.1 REACTIVE MAINTENANCE

Reactive Maintenance is also referred to as breakdown, repair, fix-when-fail, or run-to-failure (RTF) maintenance. Trouble Calls (TCs) are a type of reactive maintenance. When applying this maintenance technique, maintenance, equipment repair, or replacement occurs only when the deterioration in the condition of the equipment causes a functional failure. This type of maintenance assumes that failure is equally likely to occur in any part, component, or system and failure is age-related. This precludes the identification of a specific group of repair parts as being more necessary or desirable than others. If the item fails and repair parts are not available, delays ensue. If certain parts are needed to restore a critical machine or system to operation, a premium for expedited delivery must be paid.

There is no ability to influence when the failures occur because no (or minimal) action is taken to control or prevent them. A high percentage of unplanned maintenance activities, high replacement part inventories, and inefficient use of maintenance effort are typical when reactive maintenance is the only type of maintenance practiced.

A purely reactive maintenance program ignores the many opportunities to influence equipment survivability. Reactive maintenance can be used effectively when it is performed as a conscious decision based on the results of an RCM analysis that compares the risk and cost of failure with the cost of the maintenance required to mitigate that risk and cost of failure.

Examples of components where Reactive Maintenance is applicable are non-critical electric motors less than 7.5 HP, comfort cooling, restroom exhaust fans, small, low temperature water heaters, and items where the consequences of failure are negligible. When deciding what items to relegate to Reactive Maintenance, ensure all functions and consequences are fully understood.

5.1.1 Reactive Maintenance Criteria

Table 5-2 suggests criteria to be used in determining the priority for repairing or replacing the failed equipment in the reactive maintenance program.

Table 5-2. Reactive Maintenance/Trouble Call Priorities

Priority		Criteria Based on Consequences of Equipment/System Failure
Number	Description	
1	Emergency	Safety of life or property threatened. Immediate serious impact on mission.
2	Urgent	Continuous facility operation threatened. Impending serious impact on mission.
3	Priority	Degrades quality of mission support. Significant and adverse effect on project.
4	Routine	Redundancy available. Impact on mission insignificant.
5	Discretionary	Impact on mission negligible. Resources available.
6	Deferred	Impact on mission negligible. Resources unavailable.

5.2 PREVENTIVE MAINTENANCE

Preventive Maintenance (PM) consists of regularly scheduled inspection, adjustments, cleaning, lubrication, parts replacement, calibration, and repair of components and equipment. PM schedules periodic inspection and maintenance at pre-defined intervals (time, operating hours, or cycles) in an attempt to reduce equipment failure. It is performed regardless of equipment condition.

Depending on the intervals set, PM can result in a significant increase in inspections and routine maintenance. PM also reduces the frequency and seriousness of unplanned machine failures for components with defined, age-related wear patterns.

Traditional PM is keyed to failure rates and times between failures. It assumes that these variables can be determined statistically and that a part can be replaced before it is due to fail. The availability of statistical failure information leads to fixed schedules for the overhaul of equipment or the replacement of parts subject to wear. PM is based on the assumption that the overhaul of machinery by disassembly and replacement of worn parts restores the machine to a like-new condition with no harmful effects. This renewal task is based on the perception that new components are less likely to fail than old components of the same design.

Failure rate or its reciprocal, Mean Time between Failures (MTBF), is often used as a guide to establishing the interval at which the maintenance tasks should be performed. The major weakness in using these measurements to establish task periodicity is that failure rate data determines only the *average* (arithmetic mean) failure rate. Failures are equally likely to occur at random times and with a frequency unrelated to the average failure rate. Selecting a specific time to conduct periodic maintenance for a component with a random failure pattern is difficult.

For some items with age-related failure, failure is not equally likely to occur throughout the life of the item. The majority of equipment is not subject to wear-out (sharply increasing conditional probability of failure at a specific operating age). Timed maintenance can often result in unnecessary and in some cases harmful maintenance. PM can be costly and ineffective when it is the sole type of maintenance practiced.

5.2.1 Preventive Maintenance Criteria

PM criteria reflect the age-reliability characteristics of the equipment based upon the equipment history. The characteristics are not related to mission criticality. The selection of maintenance tasks is made using the process shown in Table 5-1 and Table 5-2. The selection process guides the determination of the type of task which will be done, but is less helpful in establishing task frequency or periodicity.

5.2.2 Determining PM Task and Monitoring Periodicity

5.2.2.1 PM Tasks

None of the currently proposed ways for determining the correct periodicity of PM tasks is valid unless the in-service age-reliability characteristics of the system or equipment affected by the desired task are known. This information is not normally available and must always be collected for new systems and equipment. PT&I techniques should be used as an aid in determining the relationship between equipment condition and equipment age.

Careful analysis of similar hardware has shown that more than 90 percent of the hardware analyzed showed no adverse age-reliability relationship. The ages at failure are distributed in such a way there is no value in performing a preventive maintenance task. Imposing an arbitrary preventive task often increases the average failure rate through the resetting of "infant mortality."

Mean Time between Failures (MTBF) is often used as the initial basis for determining PM interval. This approach does not provide any information about the effect of increasing age on reliability. It provides only the *average* age at which failure occurs, not the most likely age. A Weibull[10] distribution, as used by the bearing industry to specify bearing life, will provide more accurate information on the distribution of failures.

- The characteristic lifetime eta[11] is related to the median lifetime t_{50}:

$$t_{50} = \text{eta}\,\ln 2^{\frac{1}{\text{beta}}}$$

- The Weibull shape factor is a dimensionless number typically between beta = 0.5 and 7
- For beta <1 the hazard rate decreases

[10] 1-2 Engineering Reliability & RCM NASA RCM Course 1.

[11] The scale perimeter eta determines when, in time, a given portion of the population will fail; in this case, 63 percent. For more information, see http://www.weibull.com/hotwire/issue21/hottopics21.htm.

- For beta >1 the hazard rate increases
- For beta =1 the hazard rate is constant

A constant conditional probability of failure has a limited number of root causes in the physical world of equipment and facilities:

- Random external causes, e.g. lightning, fire, earthquakes, dropping
- Multiple internal physical failure mechanisms, none of which predominates
- Routine maintenance causes time-varying (increasing) conditional probabilities of failure to approach a constant average value

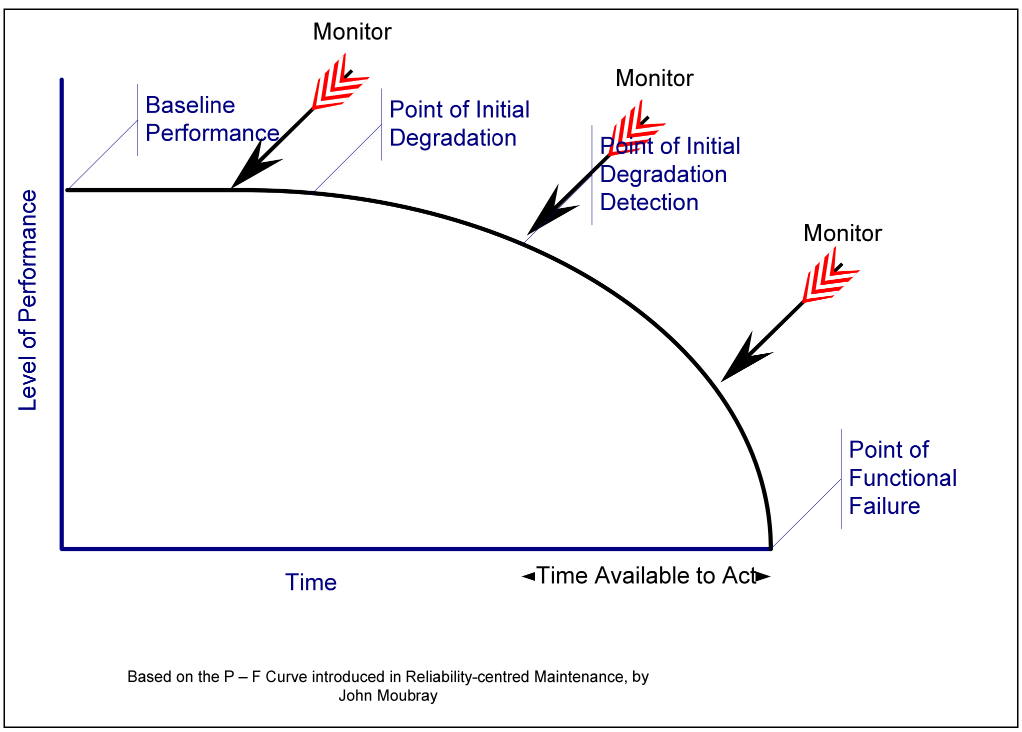
All physical and chemical root causes of failure have time-varying hazard rates f(t).

If good information on the effect of age on reliability is not available, the condition of the equipment should be monitored using the appropriate PT&I technology.

5.2.2.2 Equipment Monitoring

The factors above still apply, but with several important modifications. The goals when monitoring equipment condition are to determine equipment condition and to develop a trend with which to forecast future equipment condition. A minimum of three monitoring points are recommended. These three points should be located before failure is expected. Using three data points, the trend can be established and confirmed. See Figure 5-1 for an example.

Figure 5-1. Monitoring Intervals



The following techniques are recommended for setting initial periodicity.

Anticipating Failure from Experience

Failure history and personal experience can provide an intuitive feel as to when equipment failure may be expected. In these cases, failure is time related. Monitoring periodicity should be selected such that there will be at least three monitoring intervals before the anticipated onset of failures. The monitoring interval should be shortened when the wear-out age is approached or if uncertainty exists regarding the operating condition of the equipment with respect to the point of functional failure.

Failure Distribution Statistics

In using statistics to determine the basis for selecting task periodicity, the distribution and probability of failure should be known. Weibull distributions can provide information on the probability of equipment exceeding a given age. For example, bearings are normally specified by their B_{10} life. Depending on the criticality of the equipment, an initial periodicity is recommended which allows a *minimum* of three monitoring samples prior to the B_{10} life. In less critical cases, the three monitoring samples should occur prior to the MTBF point. In more critical cases the three monitoring samples should occur prior to the B_2 life.

Lack of Information or Conservative Approach

The most common practice in industry is to monitor the equipment biweekly or monthly due to a lack of information and poor monitoring techniques. This often results in excessive monitoring. In these cases, significant increases in the monitoring interval may be made without adverse impact on equipment reliability.

When indications of impending failure become apparent through trending or other PT&I methods, the monitoring interval should be reduced. Additional analysis should then be performed in order to gain more detailed information on the condition of the equipment.

5.3 PREDICTIVE TESTING AND INSPECTION

PT&I, also known as predictive maintenance or condition monitoring, uses primarily non-intrusive testing techniques, visual inspection, and performance data to assess machinery condition. PT&I replaces arbitrarily timed maintenance tasks with maintenance that is scheduled only when warranted by equipment condition. Continuing analysis of equipment condition-monitoring data allows planning and scheduling of maintenance or repairs in advance of catastrophic and functional failure.

The PT&I data collected is used in one of the following ways to determine the condition of the equipment and identify the precursors of failure:

- Trend analysis
- Pattern recognition
- Data comparison
- Tests against limits and ranges
- Correlation of multiple technologies
- Statistical process analysis

PT&I does not lend itself to all types of equipment or possible failure modes and therefore should not be the sole type of maintenance practiced.

Refer to Chapter 6.0 and Chapter 7.0 for information on PT&I technologies.

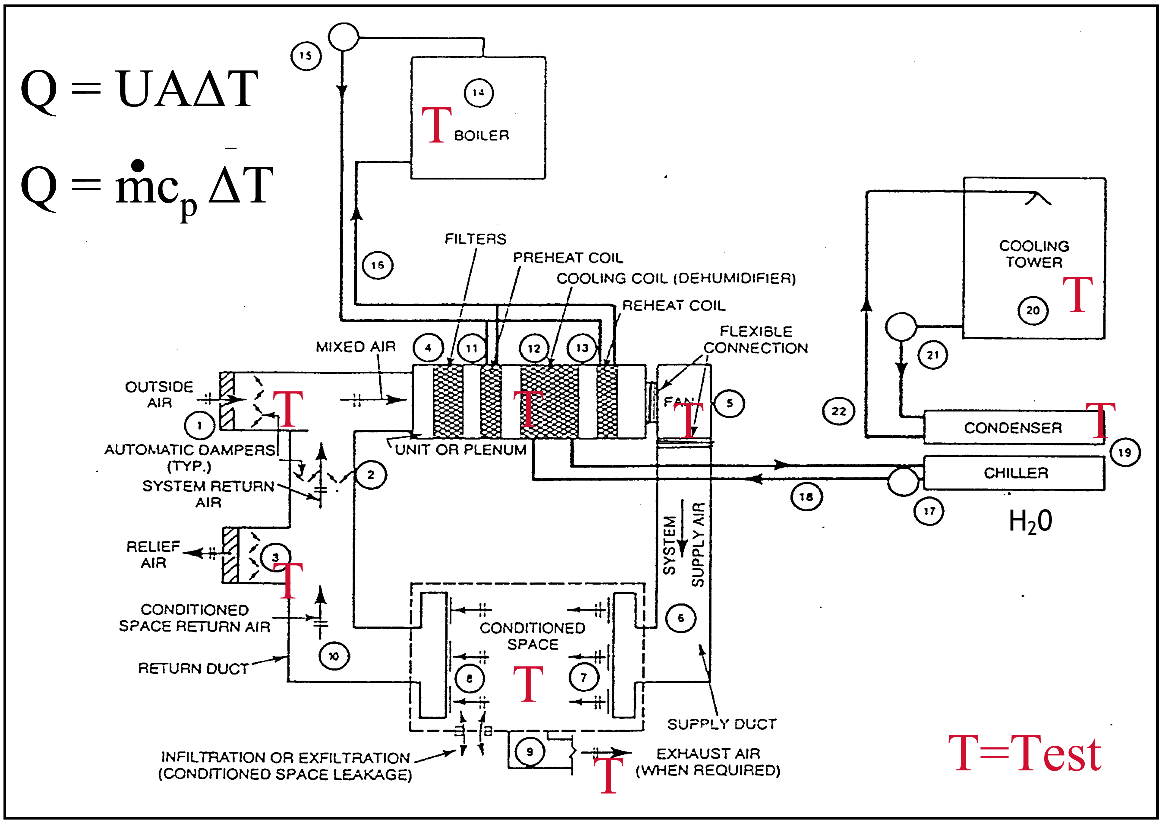
5.3.1 Data Correlation

Data acquired from the various PT&I techniques should be correlated with each other to increase the probability of detection (Pd). The tables in Appendix F provide correlation between the various PT&I technologies.

Figure 5-2 depicts a simplified HVAC System and the various components that can be monitored using the aforementioned correlated PT&I technologies. For example, a chilled water system would require the following PT&I techniques be used for the entire system to be evaluated:

- **Flow Rates:** Measure flow using precision, non-intrusive flow detectors.
- **Temperature:** Differential temperature determines heat transfer coefficients and indicates possible fouling of tubes.
- **Pressure:** Differential pump and chiller pressures determine pressure drops and pump efficiency.
- **Electrical:** Motor power consumption and motor circuit testing assesses the condition of the motor circuits and to correlate with pump efficiencies.
- **Ultrasonic Thickness:** Pipe wall thickness determines erosion and corrosion degradation.
- **Vibration:** Vibration monitoring assesses the condition of the rotating components such as pumps and motors. Resonance and model testing indentifies any structural problems.
- **Lubricant Analysis:** Oil condition and wear particle analysis identifies problems with the lubricant and correlates with vibration when wear particle concentrations exceed pre-established limits.
- **Fiber Optics:** Fiber optic inspections are used in response to indications of component wear, tube fouling, etc.
- **Thermography:** Thermography scans check motor control centers and distribution junction boxes for high temperature conditions. Piping insulation should be checked for porosities.
- **Eddy Current:** Eddy current determines and locates leaking tubes.
- **Airborne Ultrasonics:** Airborne Ultrasonics detects leaking air from control system and compressor leaks.

Figure 5-2. Sample HVAC System



5.4 PROACTIVE MAINTENANCE

Proactive maintenance improves maintenance through better design, installation, maintenance procedures, workmanship, and scheduling. The characteristics of proactive maintenance are:

- Using feedback and communications to ensure that changes in design or procedures are rapidly made available to designers and managers.
- Employing a life-cycle view of maintenance and supporting functions.
- Ensuring that nothing affecting maintenance occurs in isolation.
- Employing a continuous process of improvement.
- Optimizing and tailoring maintenance techniques and technologies to each application.
- Integrating functions that support maintenance into maintenance program planning.
- Using root-cause failure analysis and predictive analysis to maximize maintenance effectiveness.

- Adopting an ultimate goal of fixing the equipment permanently.
- Periodic evaluation of the technical content and performance interval of maintenance tasks (PM and PT&I).

Proactive maintenance employs the following basic techniques to extend machinery life:

- Specifications for new/rebuilt equipment
- Commissioning
- Precision rebuild and installation
- Failed-part analysis
- Root-cause failure analysis
- Reliability engineering
- Rebuild certification/verification
- Age Exploration (AE) and the relationship with Replacement of Obsolete Items (ROI)
- Recurrence Control

5.4.1 Specifications for New or Rebuilt Equipment

The design and fabrication of equipment often fail to provide the capability to obtain reliable equipment condition data while the equipment is operating. Existing standards are often 25 to 30 years old and are not reflective of changes in technology. These existing standards are usually inadequate, addressing only general or minimal performance criteria. The life-cycle costs and failure histories of families of equipment are rarely documented for purchasing and contract personnel who, bound by regulation, procure conforming products based on least cost.

To compensate for these inadequate standards, reliability engineers must write proper specifications, test the equipment of different vendors, and document problems. These specifications should include, minimally, vibration, alignment, and balancing criteria. The basis of the Proactive Maintenance technique is the documentation of historical data. This allows design and procurement personnel to write verifiable and quantifiable purchasing and installation specifications for new and rebuilt equipment. Performance testing is conducted in the factory prior to shipment, as the equipment is installed prior to acceptance, and as the equipment is commissioned to establish a baseline data set.

The use of PT&I for measuring equipment condition is not normally contained in the procurement specifications. For example, it is rare to see a banded-vibration criterion, a quantifiable alignment and balance specification, or complex phase impedance data for an electric motor.

5.5 ACCEPTANCE TESTING

The following sections outline various methods for acceptance testing.

5.5.1 Precision Rebuild and Installation

Equipment requires proper installation to control life-cycle costs and maximize reliability. Maintenance personnel and operators routinely face problems that arise due to poor installation. Rotor balance and alignment, two common rework items, are often poorly performed or neglected during initial installation. The adoption and enforcement of precision standards can more than double the life of a machine. For example, the contract specification for the installation leveling equipment being installed should include a maximum acceptable slope of the base and frame, and the type and accuracy of the instrument used for measuring the slope. After the criteria have been included in the contract specifications, the installation should be checked to ensure that the mechanic has complied with the specification.

5.5.1.1 Balance

Bearings are the machine components that support and transfer the forces from the rotating element to the machine frame. This results in the perception that bearings are inherently a reliability problem due to the fact that only 10 to 20 percent of rolling element bearings achieve their design life. One of the leading causes of premature rolling element bearing failure is parasitic load due to excessive vibration caused by imbalance and misalignment. The resulting parasitic loads result in increased dynamic loads on the bearings. The design formulas (SKF, 1973) used to calculate theoretical rolling element bearing life are:

- Ball Bearings

$$L_{10}\ \text{Life Hours} = \left(\frac{16{,}667}{\text{RPM}}\right) \text{X} \left(\frac{C}{P}\right)^{3}$$

- Roller Bearings

$$L_{10}\ \text{Life Hours} = \left(\frac{16{,}667}{\text{RPM}}\right) \text{X} \left(\frac{C}{P}\right)^{\frac{10}{9}}$$

Where L_{10} is the number of hours 90 percent of a group of bearings should attain or exceed under a constant load (P) prior to fatigue failure. C is the bearing load which will result in a life of one million revolutions. P is the actual bearing load, static and dynamic. C is obtained from a bearing manufacturer’s catalog and P is calculated during equipment design.

Bearing life is inversely proportional to speed and more significantly, inversely proportional to the third power of load for ball and to the 10^{9} power for roller bearings.

5.5.1.2 Balance Calculations[12]

Precision balance of motor rotors, pump impellers, and fans is one of the most critical and cost-effective techniques for achieving increased bearing life and resultant equipment reliability. It is not sufficient to simply perform a single plane balance of a rotor to a level of 0.10 in/sec or 1.0. It is also not sufficient to balance a rotor until it achieves low vibration levels. Precision balance methods should include the calculation of residual imbalance. The following equation can be used to calculate residual imbalance:

$$|U_r| = \frac{V_r}{V_e} \text{ x } |M|$$

Where U_r is the amount of residual imbalance, V_r is the actual imbalance, V_e is the trial mass imbalance, and M is the trial mass. This equation can be expressed as follows:

$$\text{Residual Imbalance} = \frac{(\text{Trial Wt.})\,(\text{Trial Wt. Radius})\,(\text{Amplitude after Balance})}{(\text{Trial Wt. Effect})}$$

$$e_{per} = \frac{U_{per}}{m}$$

Permissible imbalance is related to equipment type and rotor mass. The greater the rotor mass, the greater the permissible imbalance. The following equation can be used to determine the relationship between permissible residual imbalance (U_{per}) based on the rotor mass (m) and a required or target permissible imbalance (e_{per}):

The relationship between speed and imbalance can be expressed by the following equation where ω is the rotor angular velocity at *maximum* operating speed.

$$e_{per} \text{ x } \omega = \text{a constant}$$

5.5.1.3 Effect of Imbalance

Imbalance forces make a major contribution to decreased bearing life. For example, consider a rotor turning at 3600 RPM with 1 oz. of unbalance on a 12" radius.

Calculate the amount of centrifugal force due to imbalance as shown below, where:

$$F = mA = mr\,\omega^2 = \frac{mr(2\pi r)^2}{g} = 0.102\ mrf^2$$

- F = Force
- m = Imbalance (lbs)
- A = Acceleration
- r = Radius of imbalance (in)

[12]The following equations and discussion of permissible imbalance is based on ISO 1940/1, *Mechanical vibration—Balance quality requirements of rigid rotors*. 1986

- f = Rotational speed (Hz)
- g = 386.4 in/sec2

Substitute 1 oz. (1/16 lb.), 12", 3600 RPM (60 Hz):

$$F = 0.102 \text{ x } (\frac{1}{16}) \text{ x } (12) \text{ x } (60)^2 = 275 \text{ lbs.}$$

1 oz. of imbalance on a 12" radius at 3600 RPM creates an effective centrifugal force of 275 lbs. Now calculate the effect of this weight on bearing life. Suppose that the bearings were designed to support a 1000 lb. rotor. The calculated bearing life is less than 50 percent of the design life as shown below.

$$\text{Actual } L_{10} \text{ Life} = (\text{Design } L_{10} \text{ Life}) \text{ x } (\frac{1000}{1000+275})^3 = 0.48 \text{ Design } L_{10} \text{ Life}$$

5.5.1.4 Alignment

The forces of vibration from misalignment also cause gradual deterioration of seals, couplings, drive windings, and other rotating elements where close tolerances exist. The use of precision equipment and methods, such as reverse dial and laser systems to bring alignment tolerances within precision standards, is recommended. Both laser alignment and reverse dial indicator equipment offer equal levels of precision. Laser alignment is considerably easier and quicker to learn and use. Recommended specifications for precision alignment are provided in Table 5-3.

Table 5-3. Recommended Coupled Alignment Tolerances (General Motors, 1993)

Coupling Type	Maximum Speed (RPM)	Tolerance	
		Horizontal & Vertical Parallel Offset (IN.)	Angularity (Inch/10 inch of Coupling Dia.)
Short Coupling	600	0.005	0.010
	900	0.0053	0.007
	1200	0.0025	0.005
	1800	0.002	0.003
	3600	0.001	0.002
	7200	0.0005	0.001
Coupling with Spacer (Measurement is per inch of spacer length)	600	0.005	N/A
	900	0.0018	N/A
	1,200	0.0012	N/A
	1,800	0.0009	N/A
	3,600	0.0006	N/A
	7,200	0.00015	N/A

In addition to the alignment specifications, Table 5-4 contains the following additional tolerance recommendations.

Table 5-4. Alignment Related Tolerances (General Motors, 1993)

Parameter	Tolerance
Soft Foot	0.002" max
Foot Centerline Deformation (No load to full load)	0.001" max
Single Steel Base Plate Thickness	1.0" min
Foot Movement Caused by Pipe Flange Tightening	0.002" max
Total Shim Pack	5
Minimum Shim Pack Size	0.125" min
Axial Shaft Play	0.125" max

5.5.1.5 Alignment Effects

Based on data from a petrochemical industry survey, precision alignment practices achieve:

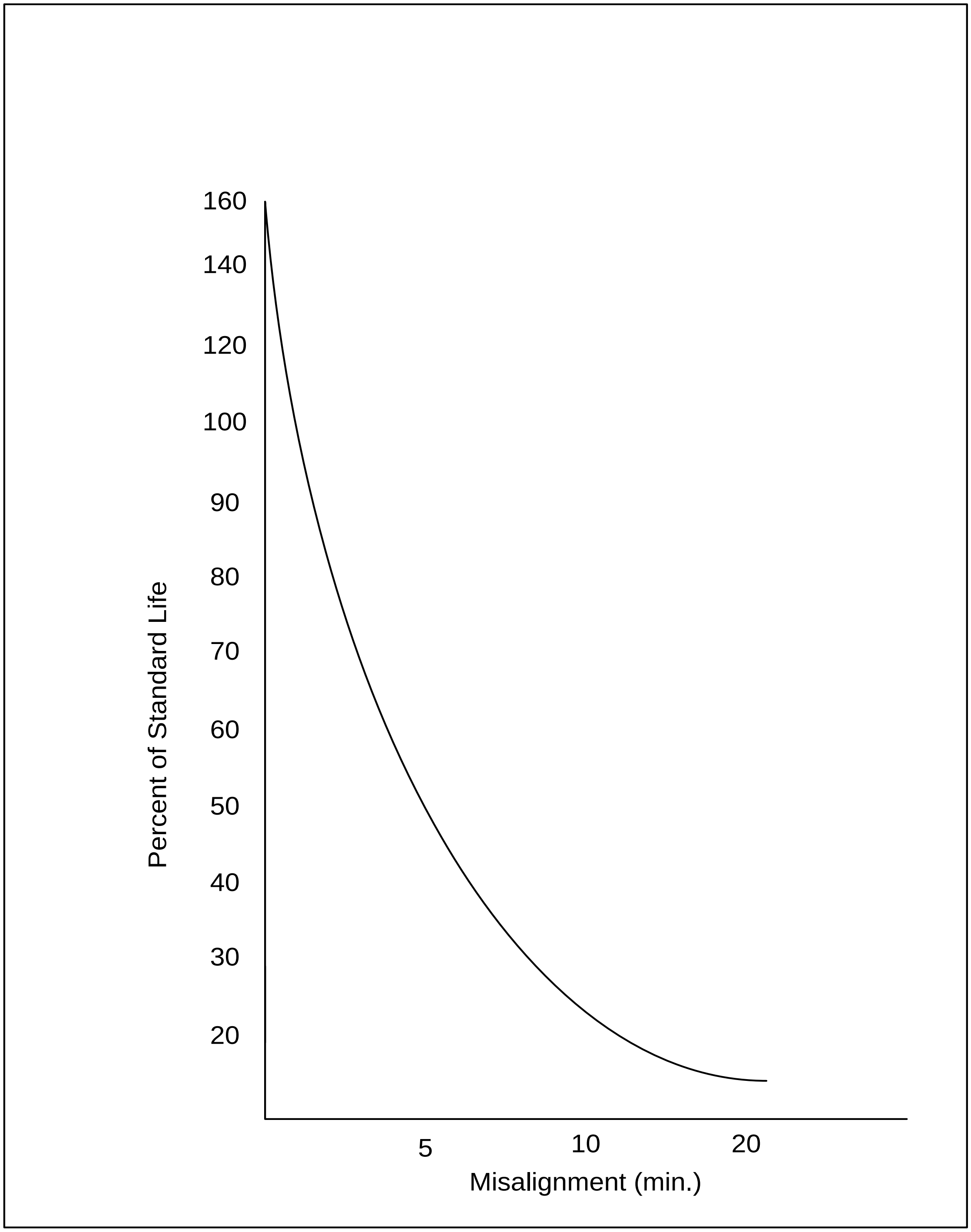
- Average bearing life increases by a factor of 8.0
- Maintenance costs decreases of 7 percent

Machinery availability increases by 12 percent. Table 5-5 and Figure 5-3 provide limitations and effect of misalignment on rolling element bearings. The maximum acceptable misalignment is based on experience data in bearing manufacturer catalogs.

Table 5-5. Limitations on Rolling Bearing Misalignment (Harris, 1984)

Bearing Type	Misalignment Angle	
	Minutes	Radians
Cylindrical Roller	3-4	0.001
Tapered Roller	3-4	0.001
Spherical Roller	30	0.0087
Deep Groove Ball	12-16	0.0035-0.0047

Figure 5-3. Effects of Misalignment on Roller Bearings[13]



[13] Harris, Tedric A. Rolling Bearing Analysis. John Wiley & Sons, New York. 1984

5.5.2 Failed-Part Analysis

This proactive process involves visually inspecting failed parts after their removal to identify the root causes of their failures. More detailed technical analysis may be conducted when necessary to determine the root cause of a failure.

Bearings are generally the weakest equipment components. Only 10-20 percent of bearings achieve their design life. The root causes of bearing failures may relate to improper installation, poor lubrication practices, excessive balance and alignment tolerances, or poor storage and handling techniques. Failed-bearing analysis provides methods to categorize defects such as scoring, color, fretting, and pitting and to relate these findings to the most probable cause of failure.

5.5.2.1 Causes of Bearing Failures

Over a quarter of all bearing problems result from contamination or improper installation. As such, maintenance and operations (M&O) departments should evaluate the equipment in their plants as systems operating in specific environments and supported by specific operational practices. M&O should investigate beyond bearings and employ condition monitoring and predictive maintenance practices as well as corrective maintenance programs. In companies where resource or training limitations exist, outsourcing such services to complement internal competencies can greatly benefit a reliability program.

Causes of bearing failures follow[14].

Poor Lubrication

Poor lubrication practices coupled with errors in specifying bearings cause 36 percent of premature bearing failures. While sealed-for-life bearings can be fitted and forgotten, any bearing deprived of proper lubrication will fail long before its normal service life. Wherever manual maintenance is not feasible, a fully automatic lubrication system can be installed to lubricate a bearing with the right amount of lubricant at the correct lubrication intervals. Failure can be the result of using the wrong lubricant type, mixing lubricants, improper re-lubrication amounts, and improper additives.

Fatigue

Fatigue accounts for 34 percent of early bearing failures. When machines are overloaded, unbalanced, or misaligned, bearings suffer the consequences. These abnormal conditions cause unintended loads on the bearing that quickly cause a dramatic reduction in service life. Premature failures from fatigue may be the result of lubrication problems. Most of these problem conditions can be detected using predictive or condition-monitoring techniques long before failure occurs.

Poor Installation

Poor installation accounts for about 16 percent of all premature bearing failures. Service personnel need to be aware of which tools to use and be trained in using them. Indicators of installation problems generally are evident on both internal and external surfaces. Bearing

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[14] Conyers, Jon. *RCFA: Bearing Failures*. Maintenance World. June 2003 (http://www.maintenanceworld.com/Articles/manufacturing/bearing-failure.htm)

users have the option of securing training for their personnel or contracting to have installations done by outside professionals. Improper installation techniques can lead to failures from load imbalance, misalignment, or improper load distributions within the bearing.

Contamination

Contamination contributes to about 14 percent of premature bearing failures. Bearing users have sealing solutions available that can be tailored to the most arduous operating environments. Typical failures can be the result of excessive wear, abnormal surface stresses caused by debris denting, or corrosion from liquid contamination, such as water. Indicators of contamination normally appear on the internal surfaces of bearings.

5.5.3 Root-Cause Failure Analysis

When plant equipment fails repeatedly, the failures are often accepted as a normal idiosyncrasy of that equipment. Recurring problems such as short bearing life, frequent seal fracture, and structural cracking are symptoms of more severe problems. Maintenance personnel often fix only the symptomatic problems and continue with the frequent repairs. Repeated failures result in high costs for parts and labor and in decreased customer goodwill and mission support reliability. Unreliable equipment may pose a continuing personnel safety hazard.

While a PT&I program can identify most equipment faults at such an early stage that they never lead to an equipment failure, the program often does not include discovering the underlying reason for the faults. For example, a bearing may fail repeatedly because of excessive bearing loads caused by an underlying misalignment problem. PT&I would most likely predict a bearing failure and thus allow the bearing to be replaced before it fails, but if no one recognizes the misalignment and eliminates it, conditions causing the failure will remain and failures will recur and continue to require unnecessary corrective work and downtime.

Root-Cause Failure Analysis (RCFA) proactively seeks the fundamental causes that lead to facility and equipment failure. Its goals are to:

- Find the cause of a problem quickly, efficiently, and economically.
- Correct the cause of the problem, not just its effect.
- Provide information that can help prevent the problem from recurring.
- Instill a mentality of fix forever.

5.5.4 Reliability Engineering

In combination with other proactive techniques, reliability engineering involves the redesign, modification, or improvement of components or their replacement by superior components. Sometimes a complete redesign of the component is required. In other cases, upgrading the type of component metal or adding a sealant is all that is required. Progressive maintenance organizations include a reliability engineer assigned this responsibility on either a full or part time basis depending on the size of the facility.

5.5.5 Reliability Calculations

5.5.5.1 Mean Time between Failure

Mean Time between Failure (MTBF) should be calculated from data collected from machinery history information stored in the computerized maintenance management software (CMMS). Other sources of MTBF data are operator logs, parts usage, and contractor records. Reliability can be expressed by the following reliability function:

$$R(t) = 1 - F(t)$$

F(t) is the probability the system will fail by time t. F(t) is basically the failure distribution function, or the "unreliability" function. If the random variable t has a density function of f(t), then the expression for reliability is:

$$R(t) = 1 - F(t) = f(t)dt$$

Assuming that the time to failure is described by an exponential density function, then

$$f(x) = 1/L(e^{-t/L})$$

L is the mean life, t is the time period of interest and e is the natural logarithm base (*e*). The reliability at time t is:

$$R(t) = 1/L(e^{-t/L}) = e^{-t/L}$$

Mean life (L) is the arithmetic average of the lifetimes of all items considered. The mean life (L) for the exponential function is equivalent to mean time between failures (MTBF).

$$R(t) = e^{-t/M} = e^{-F/t}$$

F is the instantaneous failure rate and M is the MTBF. If an item has a constant failure rate, the reliability of that item at its mean life is approximately 0.37. In other words, there is a 37 percent probability that a system will survive its mean life without failure. Mean life and failure rates are related by:

$$Fr = 1/L$$

5.5.5.2 Failure Rate

The rate at which failures occur in a specified time interval is called the failure rate during that interval. The failure rate (Fr) is expressed as:

$$Fr = \frac{\text{Number of failures}}{\text{Total Operating Hours}}$$

See Table 5-6 for hypothetical failure times.

Table 5-6. Example of Failure Times

Unit	Failed at Time (Operating Hours)
1	75
2	125
3	130
4	325
5	525

All five units operated for 525 hours following failure for a total of 2,625 hours. In addition Unit 1 experienced failure at 75 hours, Unit 2 at 125 hours, Unit 3 at 130 hours, Unit 4 at 325 hours, and Unit 5 at 525 hours. This results in total operating hours as shown in Table 5-7.

Table 5-7. Example of Total Operating Hours Based on Failure Times

Operating Hours	
2,625	Total operating hours after failure.
75	Unit 1 operating hours before failure.
125	Unit 2 operating hours before failure.
130	Unit 3 operating hours before failure.
325	Unit 4 operating hours before failure.
+ 525	Unit 5 operating hours before failure.
3,805	Total operating hours.

Thus the failure rate (Fr) is the reciprocal.

$$\text{Fr} = \frac{5}{3805} = .0001314 \text{ failures/hour}$$

Assuming an exponential distribution, the system mean-life or MTBF is:

$$\text{MTBF} = \frac{1}{\text{Fr}} = \frac{1}{.001314} = 761 \text{ hours}$$

When assuming the negative exponential distribution, the failure rate is assumed to be relatively constant during normal system operation if the system design is mature. A mature system is operating beyond the infant mortality period of decreasing failure rate and before the wear out region of increasing failure rate (if such a wear-out region exists).

5.5.5.3 Reliability Component Relationships

The following are the three types of reliability component relationships.

Series networks

In a series network each component is a single point of failure. For example, there is normally only one labeler for each packaging line. If the labeler fails, the line stops.

$$\text{Reliability (R)} = (RA)\,(RB)\,(RC)$$

If a series configuration is expected to operate for a specified time period, its overall reliability can be derived.

$$R_S = e^{-(l+l+...+1)t}$$

Parallel networks

In a parallel network, multiple redundant pieces of equipment exist. For example, parallel packaging lines and/or redundant chilled water pumps.

$$\text{Reliability (R)} = RA + RB - (RA)(RB) \quad \text{2 component network}$$

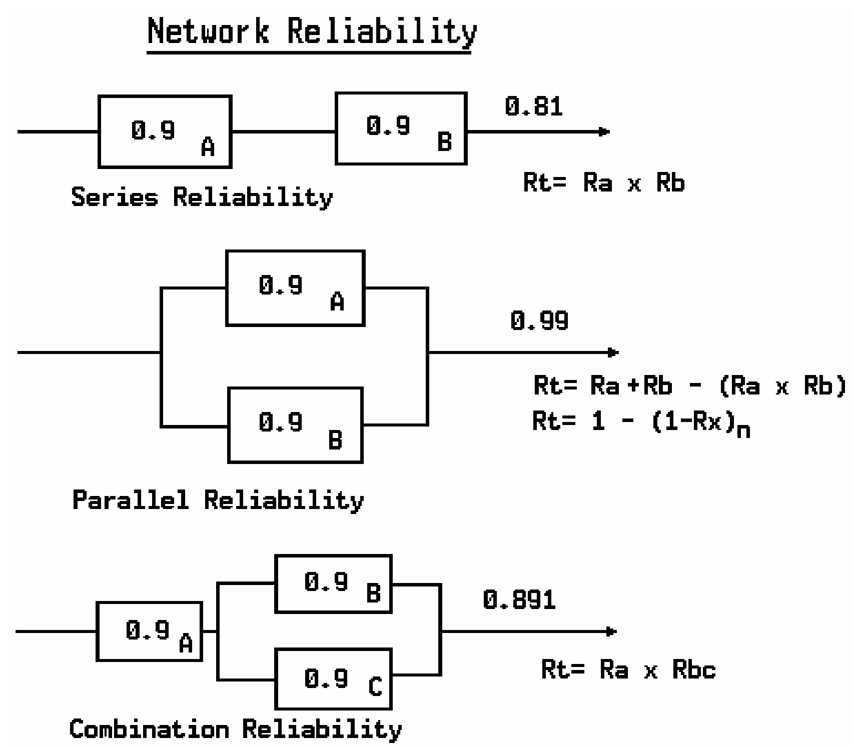
$$(R) = 1 - (1 - RA)(1 - RB)(1 - RC) \quad \text{3 component network}$$

$$(R) = 1 - (1 - R)^n \quad \text{n identical components}$$

Series-parallel networks

Figure 5-4 provides examples of how to calculate network reliability for series and parallel components within a system. As with electrical circuits, analyze the parallel portions to create an equivalent and then complete the analysis by combining all components and equivalents serially.

Figure 5-4. Determining Network Reliability



5.5.5.4 Related Reliability Factors

Availability (A)

- Inherent Availability (A_i)
- The probability that a system or equipment, when used under stated conditions in an ideal support environment, will operate satisfactorily at any point in time as required.
- Excludes preventive or scheduled maintenance actions, logistics delay time and administrative delay time.

Achieved Availability (A_a)

- The probability that a system or equipment, when used under stated conditions in an ideal support environment, will operate satisfactorily at any point in time.
- Preventive (scheduled) maintenance is included.
- Excludes logistics delay time and administrative delay time.

Operational Availability (A_o)

- The probability that a system or equipment, when used under stated conditions in an actual operational environment, will operate satisfactorily when called upon.

- Includes active maintenance time, logistics delay time and administrative delay time.

5.5.5.5 Weibull Distributions

The Weibull distribution determines the probability of failure due to fatigue. The original work was conducted in 1933 and titled, *A Statistical Theory of the Strength of Materials*. The original work was not directly related to bearings. The theories proposed in *A Statistical Theory of the Strength of Materials* were modified in 1947 by Lundberg and Palmgren (Lundberg, 1947) to account for the effectiveness of the lubricant and the fact not all cracks propagate to the bearing surface.

The importance of the Weibull distribution is that the fatigue behavior of a group of identical bearings can be assessed and changes in the failure distribution can be used to identify the introduction of new sources of failure.

The Weibull distribution is:

$$F(t) = 1 - e^{-(t/T)^k}$$

F(t) is the failure probability, T is the point in time at which 63.2 percent of the bearings have failed, and k is corresponds to the gradient. The value of k for bearings is 10/9 for ball bearings and 27/20 for roller bearings. In addition, F(t) for bearings should be in the range of 0.07-0.60.

In order to use the Weibull distribution to determine failure probability for bearings, it is necessary to have a minimum of ten identical bearings operating under as close to identical conditions as possible.

5.5.6 Rebuild Certification/Verification

When new or rebuilt equipment is installed, the equipment should be tested against formal certification and verification standards to avoid unsatisfactory operation and early failure.

5.5.7 Age Exploration

Age Exploration (AE) is a key element in establishing an RCM program. AE provides a methodology to vary key aspects of the maintenance program in order to optimize the process. For example, a vendor recommends open and inspection of a chiller at certain intervals. During the open and inspect, the technician notes the condition of various components of the chiller. The condition evaluation sheet is then correlated with performance data from the Energy Management and Control System (EMCS), vibration data, and oil analysis data. As a result of this analysis, the decision is made to change the interval of the open and inspect until monitored conditions indicate degradation has occurred.

The AE process examines the applicability of all maintenance tasks in terms of the following:

- **Technical Content.** The technical content of the tasks are reviewed to ensure all identified failure modes are addressed and that the existing maintenance tasks produce the desired amount of reliability.
- **Performance Interval.** During the AE process, the task performance interval is continually adjusted until the rate at which resistance to failure declines is determined. For example, identical motors with significantly different amplitudes of vibration could result in different monitoring intervals.
- **Task Grouping.** Tasks with similar periodicity are grouped together to minimize the amount of time spent on the job site and reduce outages.

5.5.8 Recurrence Control

This section provides a systematic approach using technical analysis of hardware or material failures for dealing with repetitive failures. Events warranting RCFA are an end result or product of implementing the following methodology.

Repetitive failures are defined as the recurring inability of a system, subsystem, structure, or component to perform the required function:

- Repeated failure of an individual piece of equipment
- Repeat failures of various equipment within a system or subsystem
- Failures of the same or similar components in several different systems

When analyzing failures:

- Systematically address the failures of systems, structures and components
- Provide a means to evaluate failures
- Contribute to long term improvements in plant operation and safety
- Efficiently allocate resources to the investigation and correction of failures that are most critical

The following process for conducting an analysis of repetitive failures is provided:

- Monitor plant or equipment performance
- Identify repetitive system or component failures using a form similar to Figure 5-5
- Establish priorities for solution and allocation of resources
- Assign problems for analysis

- Analyze problems and determine the root cause
- Recommend corrective action
- Select corrective action
- Implement selected corrective actions
- Evaluate results of implemented corrective actions

A systematic approach similar to the following should be established:

- Monitor performance and identify failures by reviewing trouble calls and machinery history contained in the CMMS and PT&I databases.
- Extend PT&I monitoring activities as widely as possible across the Facility consistent with the concepts of RCM.
- Encompass the facility's critical components as identified by RCM. Include safety-related systems and components and those systems and components that support safety systems.
- Monitor the performance of both systems and components. System monitoring will identify potential loss of equipment due to aging, corrosion, wear, design or operational problems. Component monitoring will identify possible generic failure problems that may affect multiple plant systems.

Sources of repetitive failure data are:

- Number of maintenance man-hours by system or component.
- Number of maintenance work orders by system or component.
- Maintenance backlog (by system).
- Control instruments out of service.
- Failure to achieve maintenance performance goals i.e. safety system unavailability, a number of inadvertent safety system actuations, a number of unplanned facility shutdowns, lost mission or production time, forced outage rate, and a number of Incident Reports.

Establish priorities by performing the following:

- Rank identified problems using Pareto Analysis.
- Provide a framework for the allocation of resources.
- Focus on problems identified as the most important to the achievement of the facility's operational and safety goals.

- Consider the following in the ranking process: overall plant performance goals, RCM studies, plant safety analyses and technical specifications, and costs in hours, dollars, exposure, or lost production due to recurring failures.

Assign problems for analysis based on the following:

- Match the problems to available resources (staffing and money).
- Provide a clear definition of the problem.
- Provide the expected improvement in performance (standard by which to measure possible solutions).
- Select the size and composition of the problem-solving team.
- Provide a schedule which allows for effective feedback and timely completion of the task.

Analyze the problem and recommend corrective action based on the following:

- Collect all relevant data (CMMS, PT&I, etc.).
- Analyze the component or system failure.
- Determine the root cause of failure.
- Develop a list of potential corrective actions.

Select corrective actions for implementation:

- Evaluate and prioritize the possible corrective actions.
- Consider the following: achievement of the improvement goals, ease of implementation, resources required (labor, cost, schedule) to implement the corrective action, time necessary to implement the corrective action, and design bases and regulatory requirements.

Implement selected corrective actions by performing the following:

- Assign corrective actions to individuals, departments, or teams for implementation.
- Establish schedules and milestones.
- Review schedule periodically to ensure adequate progress is being made.
- Adjust schedule or resources if necessary.

Monitor impact of implemented corrective actions by performing the following:

- Monitor system performance (PT&I and process data should be used).

- Determine whether the improvement goals have been met.

Figure 5-5. Failure Analysis Form

Failure Analysis Form
Reliability-Centered Maintenance

Equipment Identification Unit #: __________ Equipment Type: __________

Section #: __________ Location: __________

Name(s) of Person(s) Responding: __________

Equipment Failure Date: __________ Time: __________
Equipment Returned to Service Date: __________ Time: __________

Brief Description of Failure: __________

Probable Cause of Failure: __________

Corrective Action Taken: __________

Parts Replaced: __________

Previous Failures (Review CMMS): __________

Date Last PM Performed: __________ Associated WO#: __________

Direct Cost Data		In-House	Contract	Subtotal
	Labor	$____	$____	$____
	Material	$____	$____	$____
			Total Cost	$____

Failure Analysis Report Completed by: __________ Date: __________

5.5.9 Facilities Condition Assessment

5.5.9.1 Introduction

The purpose of this section is to provide an overview of the facility condition assessment process which is designed for preparing, understanding, and presenting consistent, repeatable, and auditable deferred maintenance estimates for each facility listed in the NASA real property inventory.

Guidelines and procedures are presented to do the following:

- Provide for a common understanding from which to produce consistent facility systems inspections and evaluations.
- Ensure process uniformity in validating and developing real property information.

5.5.9.2 Background

In FY02, NASA-HQ used the DoD[15] Model to develop a NASA-wide, consistent parametric cost estimating method for documenting facility condition and estimating deferred maintenance.

Designed to be a simplified approach using existing empirical data, the method is based on:

- Condition assessments performed at the system level rather than the component level which is consistent with the NASA Reliability-Centered Maintenance approach.
- A limited number of systems to assess (nine).
- Use of generalized condition levels (five).
- Current replacement values (CRV) of the systems and the facility they support.

The Deferred Maintenance (DM) Model uses cost estimating relationships (CERs) based on existing engineering data and associated algorithms to establish cost estimates. A building system (e.g., a plumbing system) can be developed using very precise work measurements. However, if history has demonstrated that repairs normally cost about 25 percent of the original value, then a detailed estimate need not be performed and can be computed at the 25 percent (CER) level.

Different cost models were developed and are applied according to facility type and condition rating to best represent estimated repair costs for the many facility types within the NASA real property inventory.

The DM Method begins with a rapid visual inspection. Assessors rate each of the following nine building systems, from Excellent (5) to Bad (1) for 43 different facility types.

- Structure

[15] PARAMETRIC COST ESTIMATING HANDBOOK, Joint Government/Industry Initiative, Fall 1995

- Exterior
- Roof
- HVAC
- Electrical
- Plumbing
- Conveyance
- Interior Finishes
- Program Support Equipment

When the assessments are complete, the ratings are entered into a database where the ratings are processed through a parametric estimating model that uses the current replacement value (CRV) as its basis. The CRV is apportioned among each of the nine facility systems, using different System CRV Percentage models for each of 43 different facility types.

The DM Model produces the following three sets of metrics:

- **System Condition Index (SCI).** SCI is a rating derived from the condition assessment ratings for one of the nine building systems.
- **Facility Condition Index (FCI).** FCI is the sum of the nine weighted SCIs, providing an overall condition rating for each facility.
- **DM Cost Estimate.** The cost estimate is a measure that indicates the degree of facilities work that has been deferred for budgetary reasons and that is required to restore the facilities to a good, usable condition.

5.5.9.3 Methodology

The following encompass the methodology of facilities condition assessments.

Parametric Estimating

"An estimating technique that uses a statistical relationship between historical data and other variables (for example, square footage in construction, lines of code in software development) to calculate an estimate for activity parameters, such as scope, cost, budget, and duration. This technique can produce higher levels of accuracy depending upon the sophistication and the underlying data built into the model. An example for the cost parameter is multiplying the planned quantity of work to be performed by the historical cost per unit to obtain the estimated cost."[16] Existing NASA Classification Codes were mapped and linked, based on facility similarity, into 43 DM Category Codes.

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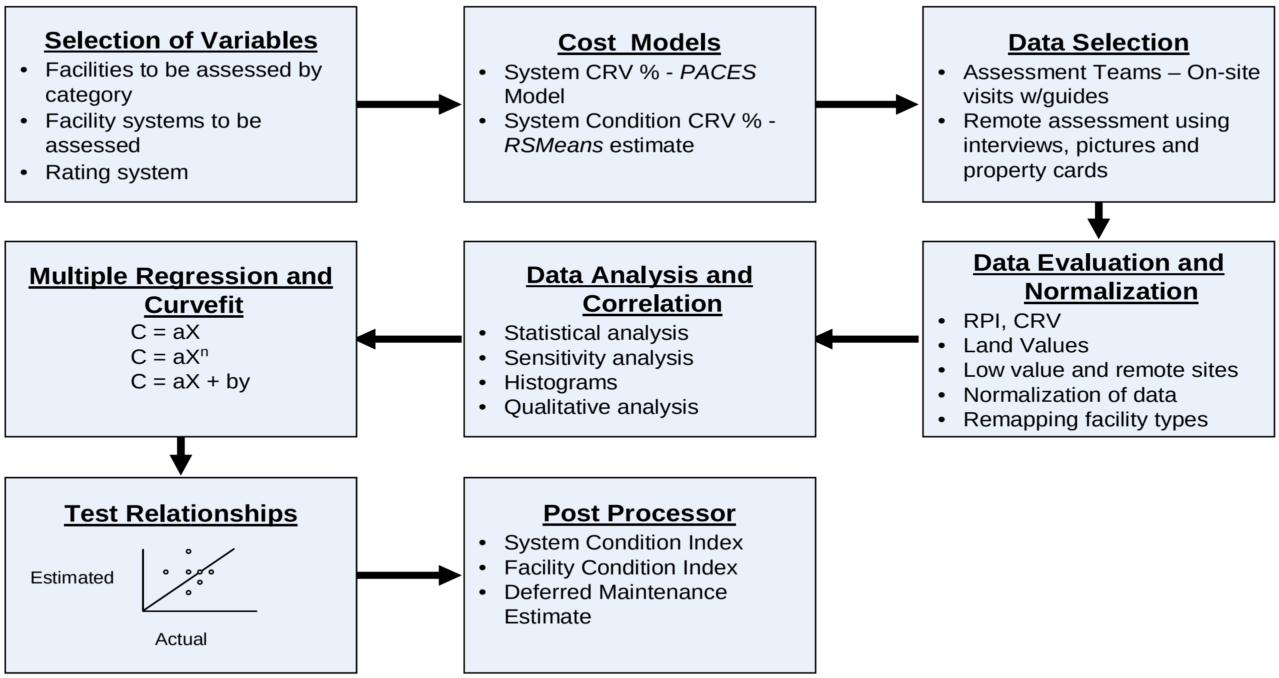
[16] For more information, see www.cit.cornell.edu/computer/robohelp/cpmm/Glossary_Words/Parametric_Estimating.htm .

Parametric cost estimating methods are based on physical or performance characteristics and schedules of the end items. The estimate is derived from statistical correlation of historic system costs with non-cost parameters, such as quality characteristics of performance or physical attributes of the system. Parametric estimating techniques focus on cost drivers. Figure 5-6 provides a generic parametric model.

Figure 5-6. Generic Parametric Model



Parametric estimating relies on simulation models that are systems of statistically and logically supported equations. The impacts of a product's physical, performance, and programmatic characteristics on cost are captured by these equations. The object to be estimated is described by choosing specific values for the independent variables in the equation which represent the characteristics of the object. The equations are then used to extrapolate from past and current experience to forecast future cost.

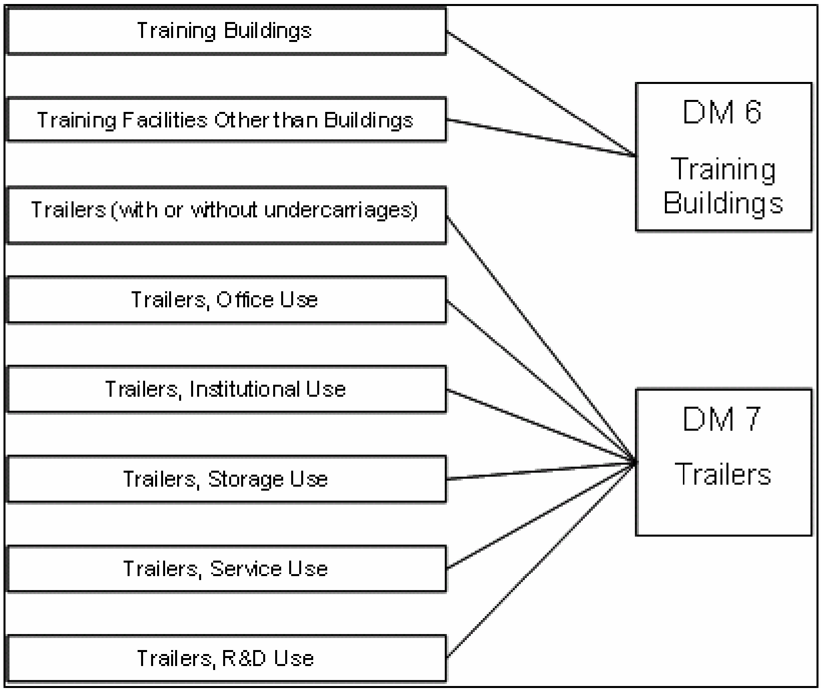
DM Category Codes

The Deferred Maintenance (DM) Category Codes group facilities whose systems are similar and have the approximate relative system CRV percentage values.

The percent contribution to the CRV by each system will be different, so these building types need to be separate in the DM Model Category Codes. Other facilities such as museums, storage, and other structures have different cost models for purposes of estimating DM.

DM Category Codes must be properly assigned to ensure the correct cost model is applied in calculating the deferred maintenance estimate.

Figure 5-7. Sample of Relationship between Classification Codes and DM Category Codes



Facility Systems

Following UNIFORMAT II Classification for Building Elements, each cost model contains nine facility systems.

- **Structure:** foundations, superstructure, slabs, floors, and pavements adjacent to and constructed as part of the facility (e.g., sidewalks, parking lots, access roads).
- **Exterior:** Wall coatings, windows, doors, and exterior sealants.
- **Roofing:** Roof coverings, openings, gutters, and flashing.
- **HVAC:** Heating, ventilating, and air conditioning systems, including controls, balancing devices, and other mechanical equipment associated with indoor air quality.
- **Electrical Systems:** Electrical service and distribution within five feet of the facility, lighting, communications systems (telephone, FAX, LAN), security, and fire protection wiring and controls.
- **Plumbing:** Water, sewer, fire protection piping, piping for steam, gas, and water distribution in specialty systems (e.g., tanks, generation plants).
- **Conveyance:** Elevators, escalators, cranes, and other lifting mechanisms.
- **Interior:** All interior finishes including wall coverings, flooring, and ceilings.

- **Program Support Equipment:** Test, research, and specialty equipment permanently affixed to the facility to provide support for mission programs (e.g., additional ventilation equipment or separate HVAC systems required only to support special testing or programs). This system exists in a limited number of DM Categories.

Facility System CRV Percentage

Each of the DM Categories has different Facility System CRV Percentages based on the estimated percent contribution of the facility system to the total CRV of the facility.

For example, in a simple administrative building the structure may contribute 35 percent to the CRV, the roof 15 percent, the exterior 10 percent, the interior 10 percent, and the mechanical systems 30 percent.

Complex laboratory and testing facilities have the same systems as administrative buildings, but electrical systems make up a larger percentage of the overall building cost. An example breakdown may include 25 percent for structure, 15 percent for the roof, 10 percent for the exterior, 10 percent for the exterior, and the final 40 percent for mechanical systems.

The Facility System CRV Percentages were initially derived from the Parametric Cost Estimating System (PACES), and adjusted as necessary to meet the unique facility types in the NASA real property index. Table 5-8 provides the system CRV percentages by facility type.

Table 5-8. DM Category Facility System CRV Percentages

DM Category	Facility Type	STRUC	EXT	ROOF	HVAC	ELEC	PLUMB	CONV	INT	PROG	SUM
1	R&D and Test Buildings	0.18	0.19	0.04	0.15	0.20	0.04	0.01	0.15	0.04	1.00
2	R&D Structures and Facilities	0.40	0.17	0.01	0.06	0.25	0.02	0.01	0.03	0.05	1.00
3	Wind Tunnels	0.30	0.05	0.01	0.01	0.15	0.01	0.01	0.01	0.45	1.00
4	Engine/Vehicle Static Test Facilities	0.38	0.03	0.01	0.04	0.26	0.01	0.03	0.02	0.22	1.00
5	Administrative Buildings	0.19	0.17	0.06	0.16	0.18	0.05	0.03	0.16	0.00	1.00
6	Training Buildings	0.18	0.20	0.05	0.12	0.21	0.05	0.01	0.18	0.00	1.00
7	Trailers	0.20	0.19	0.06	0.18	0.20	0.02	0.00	0.15	0.00	1.00
8	Storage Buildings	0.60	0.15	0.10	0.04	0.06	0.01	0.00	0.04	0.00	1.00
9	Storage Facilities	0.55	0.22	0.11	0.03	0.04	0.01	0.00	0.04	0.00	1.00
10	Fuel Storage Tanks	0.70	0.13	0.02	0.00	0.10	0.05	0.00	0.00	0.00	1.00
10.1	Specialized Liquid Storage Tanks	0.51	0.13	0.02	0.00	0.14	0.20	0.00	0.00	0.00	1.00
10.2	Fueling Stations & Systems	0.40	0.10	0.05	0.05	0.15	0.20	0.00	0.05	0.00	1.00
11	Magazines	0.33	0.30	0.05	0.06	0.15	0.02	0.00	0.09	0.00	1.00
12	Communication and Tracking Buildings	0.21	0.20	0.05	0.16	0.18	0.05	0.00	0.15	0.00	1.00
13	Communication and Tracking Facilities	0.55	0.10	0.02	0.05	0.26	0.00	0.00	0.02	0.00	1.00
13.1	Large Antennas	0.20	0.20	0.02	0.05	0.15	0.02	0.01	0.02	0.33	1.00
13.2	Small Antennas	0.50	0.30	0.00	0.00	0.10	0.00	0.00	0.00	0.10	1.00
14	Mission Control Operations Buildings	0.22	0.13	0.05	0.15	0.20	0.04	0.02	0.10	0.09	1.00
15	Lighting	0.17	0.00	0.00	0.00	0.83	0.00	0.00	0.00	0.00	1.00
16	Electrical Distribution System	0.39	0.03	0.00	0.00	0.58	0.00	0.00	0.00	0.00	1.00
16.1	Power Generation/Power Plant	0.30	0.10	0.05	0.10	0.39	0.01	0.00	0.05	0.00	1.00
16.2	Electric Substations, Switchgear & Transformer Yards	0.10	0.07	0.00	0.00	0.83	0.00	0.00	0.00	0.00	1.00
17	HVAC Distribution	0.30	0.10	0.00	0.00	0.33	0.27	0.00	0.00	0.00	1.00
17.1	HVAC Generation	0.20	0.10	0.05	0.35	0.10	0.15	0.00	0.05	0.00	1.00
18	Waste Water Collection & Disposal System	0.50	0.02	0.02	0.00	0.05	0.41	0.00	0.00	0.00	1.00
18.1	Waste Water Facilities & Treatment Plants	0.34	0.10	0.05	0.03	0.15	0.32	0.00	0.01	0.00	1.00
18.2	Storm Drains, Ditches, Dams, Retaining Walls	0.90	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.00	1.00
19	Potable Water Distribution System	0.38	0.05	0.02	0.00	0.05	0.50	0.00	0.00	0.00	1.00
19.1	Potable Water Facilities & Treatment Plants	0.25	0.05	0.05	0.03	0.24	0.37	0.00	0.01	0.00	1.00
20	Launch Pads	0.51	0.10	0.03	0.03	0.25	0.04	0.02	0.02	0.00	1.00
20.1	Launch Support Camera Pads	0.80	0.10	0.00	0.00	0.10	0.00	0.00	0.00	0.00	1.00
20.2	Launch Propellant & High Pressure Gas Facilities	0.48	0.05	0.02	0.00	0.20	0.25	0.00	0.00	0.00	1.00
21	Pavement	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
22	Rail	0.95	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.00	1.00
23	Maintenance Facilities and PW Shops	0.20	0.14	0.06	0.13	0.30	0.09	0.00	0.08	0.00	1.00
23.1	Operational Maintenance Facilities	0.20	0.14	0.06	0.13	0.28	0.09	0.02	0.08	0.00	1.00
24	Other Buildings	0.22	0.15	0.12	0.10	0.15	0.11	0.00	0.15	0.00	1.00
25	Other Facilities	0.71	0.10	0.02	0.05	0.10	0.01	0.00	0.01	0.00	1.00
26	Land & Easements	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
27	Compressed Air Distribution	0.50	0.00	0.00	0.00	0.10	0.40	0.00	0.00	0.00	1.00
27.1	Compressed Air Generation	0.25	0.10	0.05	0.05	0.15	0.35	0.00	0.05	0.00	1.00
28	Prefabricated Buildings - various uses	0.18	0.17	0.05	0.15	0.15	0.15	0.00	0.15	0.00	1.00
29	Berthing & Housing	0.15	0.17	0.09	0.16	0.18	0.07	0.02	0.16	0.00	1.00

Condition Rating

NASA uses a five tier condition rating system where “0” denotes that the system does not exist for that particular facility.

Table 5-9 describes the five tiers from Excellent (5) to Bad (1).

Table 5-9. Condition Rating Criteria

Rating	Classification	Description
5	Excellent	Only normal scheduled maintenance required.
4	Good	Some minor repairs needed. System normally functions as intended.
3	Fair	More minor repairs and some infrequent larger repair required. System occasionally unable to function as intended.
2	Poor	Significant repairs required. Excessive wear and tear clearly visible. System not fully functional as intended. Repair parts not easily obtainable. Does not meet all codes.
1	Bad	Major repair or replacement required to restore function. Unsafe to use.
0	Non-Existent	System does not exist.

System Condition CRV Percentage

A significant component of the DM estimate is the application of a System Condition CRV Percentage based on the assigned condition rating for each facility system.

Each condition rating has a corresponding System Condition CRV Percentage which varies based on the facility system.

The System Condition CRV Percentage increases as the condition of the facility system rating decreases, resulting in a larger DM estimate.

For example, if the structure of a facility receives a 5 rating, its contribution to the DM estimate is 0 percent because there is typically no deferred maintenance for this rating. However, if the structure receives a 3 rating, its contribution to the DM estimate will be 10 percent of the CRV of the facility. In the same facility, a 3 rating for the electrical system will contribute 13 percent of the CRV to the DM estimate, or the plumbing system with a 2 rating will contribute 57 percent of the CRV to the DM estimate.

Using RSMeans™, the System Condition CRV Percentage values were developed by comparing cost estimates for various levels of facility system repair work to cost estimates for facility system construction. These comparisons, expressed as percentages, translate into the System Condition CRV Percentage. Table 5-10 provides System Condition CRV Percentage versus Condition Rating.

Table 5-10. System Condition CRV Percentage versus Condition Code

System Condition CRV Percent					
System	Condition Rating				
	5	4	3	2	1
Structure	0	1	10	25	150
Exterior	0	1	10	50	101
Roof	0	9	38	75	150
HVAC	0	2	13	63	133
Electrical	0	2	13	63	133
Plumbing	0	2	10	57	121
Conveyance	0	2	13	50	100
Interior	0	1	10	50	101
Program Equipment	0	2	13	50	100

SCI Calculation

The SCI calculation determines the condition of a facility system across a group of facilities. It can be calculated at the Facility, Installation, Center, Directorate, or Agency level to identify which of the nine facility systems is in the greatest need of repair and to assist in prioritizing facility systems projects for multiple facilities.

To calculate the SCI, first multiply the Facility CRV by the Facility System CRV Percentage based on the DM category of the facility to determine the CRV of the specific facility. Add together the values of the system to obtain the Total System CRV. Divide the System CRV by the Total System CRV to weight the System CRV for each facility. Multiply the quotient by its respective Condition Rating. Finally add the individually weighted System Indices to determine the SCI. Facility systems with a higher CRV contribute more to the overall SCI.

Facility FCI Calculation

The Facility FCI calculation weights each of the nine system condition ratings by its associated Facility System CRV Percentage based on the DM Category of the facility.

For each system, multiply the Condition Rating by its Facility System CRV Percentage to determine the weighted value. The sum of the nine weighted values equals the facility’s FCI.

If a facility system does not exist, the Facility System CRV Percentage for the absent facility system is re-distributed to the Structure System.

Installation FCI Calculation

The Installation FCI is the weighted average Facility FCI for all facilities belonging to an Installation. This calculation is applicable to facility groupings at the Installation, Center, Directorate, or Agency level.

To determine Installation FCI, divide each Facility CRV value by the Total Installation CRV. Multiply the quotient by its respective Facility FCI to produce a weighted FCI value. The sum of the weighted FCI values is the Installation FCI. Facilities with higher CRV contribute more to the overall Installation FCI.

DM Calculation

The facility DM estimate is the sum of the deferred maintenance estimates of the nine facility systems.

To calculate the DM estimate, multiply the Facility CRV by the Facility System CRV Percentage; this determines the Facility System CRV. Based on the Condition Rating for each facility system, multiply the corresponding System Condition CRV Percentage by the Facility System CRV. The product is the DM estimate for each facility system. The sum of all facility system DM estimates is the facility DM estimate.

DM Database

Built from applicable data fields in the NASA Real Property Inventory (RPI) database, the DM database processes facility system condition ratings through a series of calculations to generate facilities metrics for each facility system, facility, Installation, Center, Directorate, and the Agency. The DM database information can be sorted by facility, types of facilities, condition rating, etc., providing a robust management tool with which to more effectively identify needs and focus resources to improve the condition of critical assets.

DM estimates per system and facility, Facility Condition Indexes (FCI) per system and facility, and System Condition Indexes (SCI) are recalculated annually incorporating changes in real property assets, the value of the assets, and the condition of the assets.

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6.0 PREDICTIVE TESTING AND INSPECTION TECHNOLOGIES

This chapter describes the primary Predictive Testing and Inspection (PT&I) technologies in terms of purpose, technique, application, effect, equipment required, operators, training available, and cost.

6.1 INTRODUCTION

A variety of methods are used to assess the condition of systems and equipment to determine the most effective time to schedule and perform maintenance. The information below provides an introduction on how the technologies are currently utilized and their respective benefits. These technologies include both intrusive and non-intrusive methods and the use of process parameters to determine overall equipment condition. The data acquired permits an assessment of system and equipment performance degradation from the as-designed and/or required condition. In addition, these techniques should also be used to assess the quality of new and rebuilt equipment installations and operational checks. The PT&I approaches covered include:

- Vibration Monitoring & Analysis
- Infrared Thermography
- Ultrasonic Noise Detection
- Lubricant and Wear Particle Analysis
- Electrical Condition Monitoring
- Non-Destructive Testing

Table 6-1 provides information on the applicability of the PT&I technologies to various facility and production components. Data should be correlated as described in Chapter 3.0 and Appendix F of this guide.

6.2 ALERTS AND ALARMS

PT&I alert and alarm values should be set to meet specific user requirements. The following are common methods for determining alert and alarm values.

6.2.1.1 Arbitrary Value

Set an arbitrary value for change from a baseline value. An increase in the reading by a predetermined amount over the initial reading is used to determine maintenance requirements. This approach was widely used by the U.S. Navy submarine force until the mid-1980s at which time it was abandoned in favor of more statistical approaches.

6.2.1.2 Alert Value

Set an alert value to indicate a statistically significant deviation (usually 2-sigma) from the mean as a warning or alert level. An alarm value is established at 3-sigma. This approach should allow sufficient time between the alert and alarm levels and failure in order to schedule repairs.

6.2.1.3 Failure Analysis

Refine the alert and alarm values by performing analysis of the failed parts and then correlating the as-found condition to the PT&I data. Changing the alert and alarm values is the mechanism to fine tune the condition monitoring process and should be based on the best information available.

Table 6-1. PT&I Applications

APPLICATIONS / TECHNOLOGIES	Pumps	Electric Motors	Diesel Generators	Condensers	Heavy Equipment/Cranes	Circuit Breakers	Valves	Heat Exchangers	Electrical Systems	Transformers	Tanks, Piping
Vibration Monitoring/Analysis	√	√	√		√						
Lubricant, Fuel Analysis	√	√	√		√					√	
Wear Particle Analysis	√	√	√		√						
Bearing, Temperature/Analysis	√	√	√		√						
Performance Monitoring	√	√	√	√				√		√	
Ultrasonic Noise Detection	√	√	√	√			√	√	√	√	
Ultrasonic Flow	√	√		√			√	√			
Infrared Thermography	√	√	√	√	√	√	√	√	√	√	
Non-Destructive Testing (Thickness)				√				√			√
Visual Inspection	√	√	√	√	√	√	√	√	√	√	√
Insulation Resistance		√	√			√			√	√	
Motor Current Signature Analysis		√									
Motor Circuit Analysis		√				√			√		
Polarization Index		√	√						√		
Electrical Monitoring									√	√	

6.3 VIBRATION MONITORING AND ANALYSIS

Vibration monitoring is an analysis of system and equipment vibration levels. It is the most common PT&I technique. Machinery and system vibration is the periodic motion of a body about its equilibrium position. Vibration monitoring helps determine the condition of rotating equipment and structural stability in a system. It also aids in identifying and localizing airborne noise sources.

Machinery and system vibration refers to the periodic motion of a body about its equilibrium position. For example, imagine driving a car at a constant speed through a series of potholes with each one being larger than the last. The shock and resulting vibration increases with each encounter until the vibration destroys the suspension, wheel, or tire. This is similar to what occurs as bearing and gear defects increase in size with each additional impact.

6.3.1 Applications and Techniques

The following applications and techniques are applicable to all rotating equipment, including but not limited to: motors, pumps, turbines, compressors, engines, bearings, gearboxes, agitators, fans, blowers, and shafts. In addition, modern data loggers support resonance testing, equipment balancing, and airborne noise measurements.

6.3.1.1 Conditions Monitored

The following defects shall be monitored: wear, imbalance, misalignment, mechanical looseness, bearing damage, belt flaws, sheave and pulley flaws, gear damage, flow turbulence, cavitation, structural resonance, and fatigue.

6.3.1.2 Detection Interval

Analyzing narrowband vibration can warn of impending failure several weeks or months in advance. The time interval shall be based on the experience of the analyst and the type, quantity, and quality of collected data.

6.3.1.3 Accuracy

Studies by the U.S. Navy have found probabilities of detection as high as 0.92 and as low as 0.76. The corresponding false alarm rate was found to be 0.08. Selecting the appropriate monitoring intervals and alarm criteria optimizes the probability of detection and false alarm rates.

6.3.1.4 Overall Measurement

Overall measurement is the sum of all vibration energy produced across a filtered bandwidth. Overall measurement provides an easy indicator of the major sources of vibration. It does not provide a complete analysis of a systems condition. A modern maintenance program shall not depend solely on an overall measurement approach to vibration analysis.

6.3.1.5 Spectrum Analysis and Waveform Analysis

Spectrum analysis of the frequency domain is the most common analysis method for machinery diagnostics. The spectrum analysis identifies the majority of rotating equipment failures due to mechanical degradation prior to failure. Waveform analysis, or time domain analysis, is a valuable analytical tool used in conjunction with frequency domain data.

6.3.1.6 Torsional Vibration

Torsional vibration detects gear vibration and shaft torque vibration. It is often used when casing vibration analysis is insufficient due to transmission path attenuation. Measuring torsional vibration is especially useful when unsteady forces excite the resonance of the structure or housing. Torque is measured by using pairs of matched sensors (such as accelerometers) spaced at an interval.

6.3.1.7 Multi-Channel Vibration Analysis

Multi-channel vibration analysis encompasses force-response analysis, cross-coupling phase analysis, resonance-mode characteristics analysis, and multi-plane balancing. Multi-channel analyzers offer coherence functions that allow for the analysis of the quality and linearity of data collected with typical data loggers.

6.3.1.8 Shock Pulse Analysis

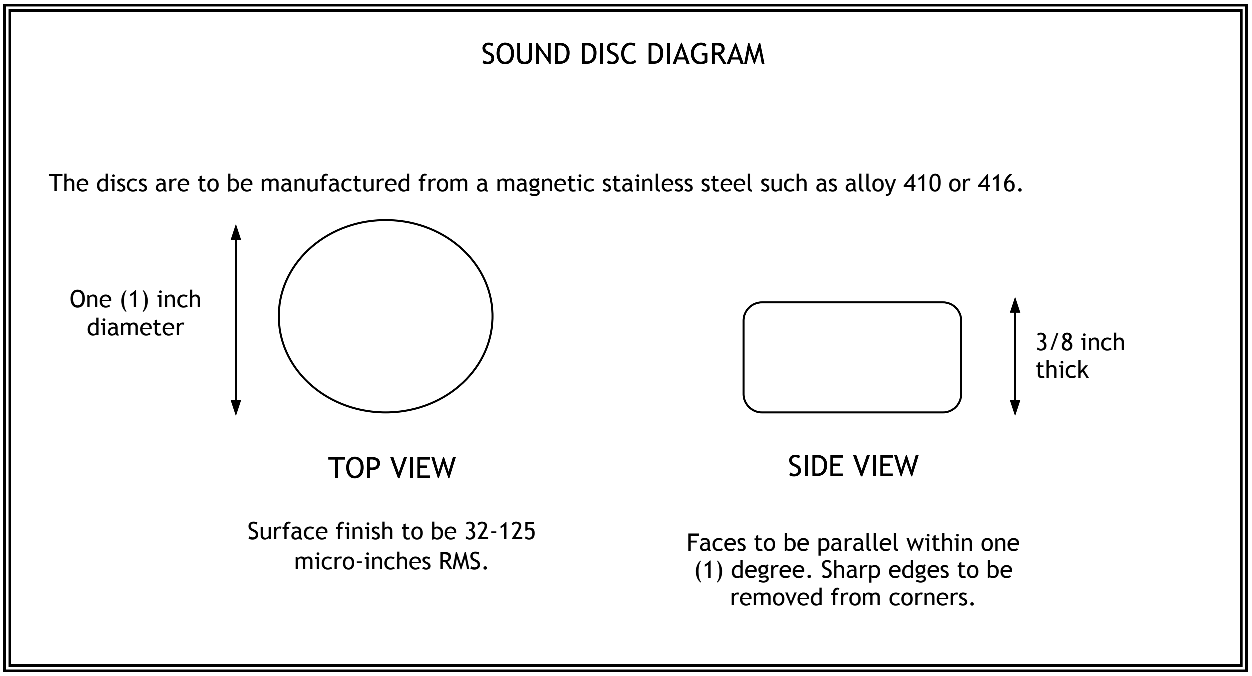
Shock pulse analysis detects impacts caused by contact between the surfaces of the ball or roller and the raceway during rotation of antifriction bearings. The pulse magnitude depends on the surface condition and the angular velocity of the bearing (RPM and diameter). Spike energy is similar in theory to shock pulse.

6.3.1.9 Vibration Sensor Mounting

The use of a low mass accelerometer (minimum of 100mV/g) with an attached rare earth super magnet is recommended to monitor most facilities machinery. The U.S. Navy has proved that using a magnet-mounted accelerometer with a smooth mounting surface provides a usable upper frequency limit of 5 kHz. Accurate measurements to 20kHz are possible by utilizing special purpose accelerometers and a couplant separating accelerometer, magnet, and mounting disc. A permanently mounted accelerometer may be required for high signal transfers, but it is generally a less cost-effective method.

Using a hand-held probe severely limits the upper vibration frequency that can be accurately measured. The repeatability of the vibration data analysis significantly decreases when combined with the failure to mark the measurement points and the use of different individuals to collect data.

Figure 6-1. Sound Disc Diagram



- Identify monitoring points and epoxy magnetic corrosion resistant steel discs (sound discs) at every location. Sound discs should be a minimum of one inch in diameter and between 3/16 and 3/8 inch thick. The discs can be purchased[17] with prices ranging from $0.25 to $6.00 each or can be manufactured by fly cut from 1" alloy 410 or 416 bar stock. The surface finish should be a minimum 63 micro-inch. Figure 6-1 provides a dimensional drawing of a sound disc.

- When using a stud to mount the accelerometer directly to the disk or finished surface, the minimum surface finish is 32 micro-inch. The disk or surface face must be level to prevent the magnet from rocking. The surface must be level within 1 degree or .001 inch.

- Prepare the surface for the epoxy by grinding or spot facing with a portable milling machine and wiping down with a solvent.

- Ensure the face diameter is ¼ inch larger in diameter than the disc diameter if using portable milling machine to spot face the surface.

- Adhere the sound disc to the equipment with a tested epoxy such as Hysol Gray Epoxy Patch™ (available from Structural Adhesives) or Loctite Depend 330™. Superglue adhesives are not recommended as the sound discs adhere unsatisfactorily. Welding is not recommended due to possible machine damage and distortion of the disc surface.

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[17] Michoud Assembly Facility gets inexpensive sound discs from a washer supplier. They simply special order the washers without holes. Supplier is Phoenix Specialty Mfg.. Co., PO Box 418, Bamberg, SC 29003 Phone 800-845-2813, fax 803-245-5734. Be sure to specify "washers with no holes."

- Label the sound disc or machined surface "Vibration data collection point. Do not paint."

As an alternative, the monitoring locations may be the spot faced area machined on the equipment surface. The same conditions identified for the sound disc apply to the machined surface.

6.3.2 Limitations

The effectiveness of vibration monitoring is dependent on sensor mounting and resolution, the analyst's knowledge and experience, machine complexity, and data collection techniques. Complex, low speed (<120 RPM), variable speed, and reciprocating machinery are extremely difficult to monitor effectively.

Single-channel analysis cannot always accurately determine the source of the vibration on complex machines.

6.3.3 Logistics

6.3.3.1 Equipment Required

Vibration analysis systems include micro-processor data collectors, vibration transducers, equipment-mounted sound discs, and computers outfitted with software for analyzing trends, establishing alert and alarm points, and assisting in diagnostics.

6.3.3.2 Operators

While staffing requirements are site-specific, operators shall have a basic understanding of vibration theory, machinery, and failure modes.

6.3.3.3 Training

The Vibration Institute has published certification guidelines for vibration analysts. These guidelines are used by the various vibration equipment vendors and independent trainers. Passing a written examination is required for certification as a Level I, II, or III analyst.

Equipment vendors and independent companies provide training. See Appendix C for training sources.

6.3.3.4 Cost (2008)

Narrowband systems, software, and introductory training can cost between $10,000 and $50,000. The high-priced systems offer a basic multi-channel, installed system which can be outfitted at a cost of $1,000 per additional sensor. Portable analyzers are approximately $2,500 to $32,000, including the necessary hardware, software, and training.

6.4 INFRARED THERMOGRAPHY

Infrared Thermography (IRT) is the application of infrared detection instruments to identify pictures of temperature differences (thermogram). The instruments used are non-contact, line-of-sight, thermal measurement and imaging systems. Because IRT is a non-contact technique, it is especially attractive for identifying hot/cold spots in energized electrical equipment, large surface areas such as boilers and building walls, and other areas where "stand off" temperature measurement is necessary.

Instruments that perform this function detect energy in the short wave (3 to 5 microns) and long-wave (8 to 15 microns) bands of the electromagnetic spectrum. The short wave instrument is the best choice for facilities inspections due to the varied inspections (electrical, mechanical, and structural) encountered. However, the short wave instrument is more sensitive to solar reflections; the inspector should be aware of its effects when performing outdoor inspections. To be effective in facilities applications, the instruments must be portable, sensitive to within 0.2^{o} C over a range of temperatures from -10^{o} C to +300^{oC} , and accurate within ±3 percent. The instrument must be capable of storing an image of the thermogram for later use.

IRT inspections are identified as quantitative or qualitative. The quantitative inspection is interested in the accurate measurement of the temperature of the item of interest. To perform a quantitative inspection requires detailed knowledge and understanding of the relationship of temperature and radiant power, reflection, emittance, environmental factors, and the detection instrument limitations. This knowledge and understanding must be applied methodically to control the imaging system and obtain highly accurate temperature measurements. Quantitative inspections are rarely needed in facilities applications.

The qualitative inspection is interested in relative differences, hot and cold spots, and deviations from normal or expected temperature ranges. A highly accurate temperature recording is less important than the temperature differences (ΔT) between like components. The IRT imaging system identifies any uneven heating, perhaps due to dirty or loose connections. For example, a typical motor control center supplies three-phase power through a circuit breaker and controller to a motor. Current flow through the three-phase circuit should be uniform, meaning the components within the circuit should have similar temperatures, one to the other.

Any uneven heating would quickly be identified with the IRT imaging system. Because the many variables that influence the quantitative inspection (reflection, emittance, etc.) are the same between like components, the thermographer can quickly focus on the temperature differences. The factors which influence the accuracy of temperature measurement have little influence on the measurement of temperature differences between identical or very similar components.

6.4.1 Applications

IRT identifies degrading conditions in facilities electrical systems such as transformers, motor control centers, switchgear, substations, switchyards, or power lines. In mechanical systems, IRT identifies blocked flow conditions in heat exchanges, condensers, transformer cooling radiators, and pipes. IRT verifies fluid level in large containers such as fuel storage tanks and identifies insulation system condition in building walls and roof or refractory in boilers and furnaces. IRT is a reliable technique for locating moisture-induced temperature effects that characterize roof leaks and for determining the thermal efficiency of heat exchangers, boilers, building envelopes, etc.

Deep-probe temperature analysis can detect buried pipe energy loss and leakage by examining the temperature of the surrounding soil. This technique quantifies energy losses and their costs. IRT may serve as a damage-control tool to locate mishaps such as fires and leaks. Unless requested otherwise, the thermographer will typically provide only an exception report consisting of finds and faults.

In-service condition for electrical and mechanical systems can be assessed and work prioritized based upon the temperature difference criteria guideline. IRT criteria are provided in Section 7.2.3 Thermography.

6.4.2 Limitations

Thermography is limited to line of sight. The infrared camera has limited ability to see through material. Most items transparent to the human eye are opaque to the infrared camera. Type of material, material geometry, and environmental factors may introduce errors.

6.4.3 Logistics

6.4.3.1 Equipment Required

- Equipment ranges from simple, contact devices such as thermometers and crayons to full color imaging and computer-based systems that can store, recall, and print thermal images.
- The deep-probe temperature technique requires temperature probes, analysis software, and equipment to determine the location of piping systems.

6.4.3.2 Operators

- Operators and mechanics perform temperature measurements and analyses using contact-type devices requiring minimal training on how to take temperature readings.
- Because thermographic images are complex and difficult to measure and analyze, training is required to obtain and interpret accurate and repeatable thermal data and to interpret the data.

6.4.3.3 Training Available

- Training is available through infrared imaging system manufacturers and vendors.
- The American Society of Non-Destructive Testing (ASNT) has established guidelines for non-destructive testing (Level I, II, or III) thermographer certification (see ASNT Appendix C). These guidelines, intended for use in non-destructive testing, may be useful for thermography in PT&I if appropriately adjusted. General background, work experience, thermographic experience, and thermographic training are all considerations for certification.
- With adequate training (Level I and Level II) and certification, electrical and mechanical technicians and engineers can perform this technique. Level III Certification is not generally required for the type of thermography performed at most NASA Centers. Exceptions include wind tunnels, advanced test cells, and payload support.

- Maintenance personnel can apply deep-probe temperature monitoring after training, although this service is often contracted.

6.4.3.4 Cost (2008)

- Non-contact infrared thermometers/scanners start at approximately $200. Full color microprocessor imaging systems with data storage and print capability range from approximately $10,000 to $60,000.

- Digital Infrared Still Camera technology which operates in the long-wave band is available at approximately 1/4th the cost of a cooled focal plane array camera and provides a good entry-level system.

- Average thermographic system rental is approximately $1,500 per week. Operator training costs approximately $1,250 per week.

- Thermographic contractor services cost approximately $1,000 per day. Contract services for deep-probe temperature analysis cost from $1,500 to $2,000 per day, with $5,000 to $6,000 for the first day.

6.5 ULTRASONIC NOISE DETECTION

Ultrasonic noise detection devices operate in the frequency range of 20-100 kilohertz (kHz) and heterodyne the high frequency signal to the audible range. This allows the operator to be able to hear changes in noise associated with leaks, corona discharges, and other high frequency events such as bearing ring and housing resonant frequency excitation caused by insufficient lubrication and minor defects.

6.5.1 Applications and Procedures

The following methods are applicable to all airborne ultrasonic devices.

6.5.1.1 Gas Pressure and Vacuum Leaks

The most common application of the ultrasonic noise detector is examining in-service gas systems for leaks. The detector is used in the non-contact mode and is effective for both pressure and vacuum systems.

6.5.1.2 Heat Exchangers

Perform a general scan of the equipment with the sensitivity set to maximum in the fixed band mode. As the search area is reduced, attach the rubber probe hood and reduce the equipment’s sensitivity. Heat exchangers may be tested by either of the following methods:

Tone Generator Method

Place an ultrasonic source inside the test area (one tone generator required for each 4,000 cubic feet of volume). Set the instrument on scanning mode, log position, and fixed band. The tone generator can be attached to an adapter at the end of a pipe to flood the pipe, heat exchanger shell, or tube bundle with ultrasonic noises. Perform a scan on the pipe or tubes.

Differential Pressure Method

Establish a differential gas pressure between the inspection area and the scanning location. Perform a general scan of the area. When checking the tubes, block the tubes one at a time and note differences in readings. Mark any tubes suspected of leakage.

6.5.1.3 Boilers

Boiler casing surveys should be performed using the blowdown valves; the test equipment's fixed band, and the contact probe.

6.5.1.4 Steam Traps

Implementation of a steam trap monitoring program often has significant financial benefit. The following method can be used to calculate potential cost avoidance. Initial steam trap[18] surveys in the petrochemical industry revealed that 34 percent of the steam traps inspected had failed, mostly in the open position. Assuming a nominal steam pressure of 100 pounds per square inch (psig) and the back pressure on the trap is atmospheric, the following information can be used to calculate leak rates:

For facilities with a periodic steam trap monitoring program, the following distribution of degradations was discovered during each survey:

- Five steam leaks (other than traps) per 150 traps
- Two leaking valves per 150 traps
- Twenty leaking traps per 150 traps

The numbers above can be used to estimate the number of leaks for a facility and combined with the data in Table 6-2 to approximate the total steam loss due to the steam leaks.

Table 6-2. Estimated Steam Loss

Leak Diameter (inches)	Steam Loss per Month (lbm)
1/64	3,300
1/32	6,650
1/16	13,300
1/8	52,200
¼	209,000
½	833,000

[18] Yarway Technical Note STA-9.

Once the estimated amount of steam loss is calculated, the cost of producing or buying a pound of steam should be calculated. The following should be considered when calculating the cost of producing steam:

- Cost of fuel
- Operator cost
- Maintenance cost
- Chemical treatment cost
- Depreciation of steam plant

Steam traps should be monitored on the downstream side of the trap using the test equipment's contact mode, if applicable, in the 25 kHz band and the log position. Each type of steam trap produces a distinct sound as briefly described below. To gain experience with the difference in the sound produced by steam and condensate, the operator should listen to a condensate and a steam line.

- **Intermittent Traps:** An opening and closing sound will be audible. The trap normally fails in the open position, producing a continuous, rushing sound.
- **Inverted Bucket:** A normal trap sounds as if it is floating; a failed trap sinks, producing a continuous flow noise.
- **Thermostatic:** Ultrasonic testing results of this type of trap vary. The noise produced by these traps can be continuous or intermittent and will produce different sounds accordingly.
- **Float and Thermostatic (Continuous Load):** Flow and noise associated with these traps are usually modulated. Failed traps are normally cold and silent.
- **Continuous Flow:** This type of trap, when operating normally, produces the sound of condensate flow only. If it has failed in the open position, a continuous flow sound should be heard.

6.5.1.5 Corona Discharge

Corona is the polarization of air molecules due to electrical energy and is normally associated with high voltage distribution systems. Corona is produced as a result of a poor connection or an insulation problem. It produces noise in the ultrasonic region and ultraviolet light in the electromagnetic spectrum (normally undetectable with thermography). Because the inspection of high voltage systems is done at a safe distance, a parabolic hood is often attached to the detector to direct and shield other noise sources.

6.5.1.6 Bearings

Airborne ultrasonics detect bearing problems, but it is not the preferred method. Narrowband vibration analysis is recommended because ultrasound detects sound above 20 kHz; the majority of bearing defects produces vibration and structure-borne noise below 5 kHz and is not detectable using an ultrasonic detector.

6.5.2 Limitations

Airborne ultrasonics are subjective and dependent on perceived differences in noises. Use caution when setting test equipment controls for frequency ranges, sensitivity, and scale. The operator should recognize that piping bends and the presence of moisture and solids may dissipate or block the ultrasonic signal.

6.5.3 Logistics

6.5.3.1 Equipment Required

An ultrasonic monitoring scanner for airborne sound or ultrasonic detector for contact mode through metal rod is required.

6.5.3.2 Operators

Maintenance technicians or engineers are appropriate for performing an ultrasonic survey.

6.5.3.3 Training Available

Minimal training is required with the exception of multi-channel Acoustic Valve Leak Detectors (AVLDs).

6.5.3.4 Cost (2008)

Scanners and accessories range from $500 to approximately $10,000. Complex acoustic valve leak detection systems are approximately $100,000.

6.6 LUBRICANT AND WEAR PARTICLE ANALYSIS

6.6.1 Purpose

Lubricating oil analysis is performed to determine the machine mechanical wear condition, the lubricant condition, and whether the lubricant has become contaminated. There are a wide variety of tests that will provide information regarding one or more of these areas. The test used will depend on the test results sensitivity and accuracy, the cost, and the machine construction and application.

Note that the three areas are not unrelated as changes in lubricant condition and contamination, if not corrected, will lead to machine wear. Because of the important relationships, commercial analysis laboratories will often group several tests in cost-effective packages that provide information about all three areas.

6.6.1.1 Machine Mechanical Wear Condition

The criteria for analyzing the lubricating oil to determine the machine's condition include machines with motors of a selected size (for example, 7.5 HP or larger), critical machines, or high-cost machines. The routine sampling and analysis periodicity is similar to the vibration analysis periodicity (when using a portable vibration data collector). For machines that have a condition history (a year or more of data), this is typically performed quarterly or semi-annually.

6.6.1.2 Lubricant Condition

Lubricating oil is either discarded or reconditioned through filtering and replacing additives. Analyzing the oil to determine the lubricant condition is cost-driven. Small reservoirs, usually one gallon or less, have the oil changed on an operating time basis.

An automobile is the most common example of time-based lubricating oil maintenance. The cost to replace the automobile oil (replacement oil, labor, and disposal) is lower, through economies of scale and competition, than the cost to analyze the oil (sample materials, labor to collect the sample and the analysis).

In cases such as this, discard the machine lubricating oil if it is cheaper than analyzing it. When making this decision, keep in mind that the costs for sample materials and collection labor is a cost for each sample collected and that each sample is used to perform many tests.

6.6.1.3 Lubricant Contamination

Lubricating oil may be contaminated due to the machine's operating environment, improper filling procedures, or through mixing different lubricants. The routine sampling and analysis periodicity will be the same as discussed for machine condition. A periodic analysis is recommended following "topping off" or reconditioning the oil. The root cause of any oil contamination must be determined and eliminated to avoid machine damage.

Lubricating oil analysis is performed on in-service machines to monitor and trend emerging conditions, confirm problems identified through other PT&I and observations, and troubleshoot known problems. Lubricating oil analysis is performed for to determine:

- Machine mechanical wear condition
- Lubricant condition
- Whether the lubricant has become contaminated

Specific tests address indicators of these conditions and vary in cost depending on time and materials. The tests selected for use in the PT&I program must balance the need for understanding the lubrication condition and the cost the testing.

6.6.2 Standard Analytical Tests

Lubricating oil and hydraulic fluid analysis should proceed from simple, subjective techniques onto more sophisticated techniques. The more sophisticated techniques should be used when conditions require additional information and the equipment cost or criticality justifies it.

6.6.2.1 Visual and Odor

The equipment operator may perform weekly inspections to see and smell the lubricating oil. A visual inspection looks for changes in color, haziness or cloudiness, and particles. This test is subjective, but the test can indicate recent water or dirt contamination and advancing oxidation. A small sample of fresh lubricating oil in a sealed, clear bottle can be stored for visual comparison. A burned smell may indicate oxidation of the oil; other odors may indicate contamination. The operator must not introduce dirt into the system when taking a sample.

6.6.2.2 Viscosity

Viscosity indicates oil flow rate at a specified temperature. An increase or decrease in viscosity over time measures changes in the lubricant condition or lubricant contamination. Viscosity can be tested using portable equipment or more accurately in a laboratory using *ASTM D445, Standard Test Method for Kinematic Viscosity of Transparent and Opaque Liquids*. Viscosity is measured in Centistokes (cSt) and minimum and maximum values are identified by International Organization for Standardization (ISO) grade. Testing is usually included in a commercial laboratory standard test package.

6.6.2.3 Water

Water in lubricating oil and hydraulic fluid contributes to corrosion and formation of acids. Small amounts of water (less than 0.1 percent) can be dissolved in oil and detected using the crackle test or infrared spectroscopy (minimum detectable is .05 percent or approximately 500 parts per million (PPM) for both methods); the ASTM D95 distillation method (minimum detectable is .01%/100 PPM); or the ASTM D1744 Karl Fischer method (minimum detectable is .001%/10 PPM). Greater than 0.1 percent water, if suspended or emulsified in the oil, will appear cloudy or hazy. Free water in oil collects in the bottom of reservoirs and drains from the bottom.

6.6.2.4 Percent Solids/Water

This simple, inexpensive test provides a gross estimate of solids and water in the oil. A sample is centrifuged in a calibrated tube and the resulting volume is measured. The test is effective for amounts in the range of 0.1 percent to 20 percent of volume and is generally included in a commercial laboratory standard test package.

6.6.2.5 Total Acid Number (TAN)

Total acid is an indicator of the lubricating oil condition and is monitored relative to the total acid number (TAN) of new oil. In some systems the TAN may also indicate acid contamination. TAN is measured in milligrams of potassium hydroxide (KOH) per gram of oil (mgKOH/g). KOH is used in a titration process where the end point is indicated by color change (ASTM D974, *Standard Test Method for Acid and Base Number by Color-Indicator Titration*) or electrical conductivity change (ASTM D664, *Standard Test Method for Acid Number of Petroleum Products by Potentiometric Perchloric Acid Titration*).

6.6.2.6 Total Base Number (TBN)

Similar to TAN, the total base number (TBN) test measures alkalinity (ability to neutralize acid) of the oil sample. The test is used on oil with high detergent additives such as diesel and gasoline engines. KOH is used in a titration process and the end point is indicated by electrical conductivity change (ASTM D664 , *Standard Test Method for Acid Number of Petroleum Products by Potentiometric Perchloric Acid Titration* or ASTM D2896, *Standard Test Method for Base Number of Petroleum Products by Potentiometric Perchloric Acid Titration*). When comparing test results, ensure that the same test method is used, as results can vary between test methods.

6.6.2.7 Spectrometric Metals

Also known as emission spectroscopy, this technique examines the light (spectrum) emitted from the oil sample during testing and identifies up to 21 metals. Metals are categorized as wear, contaminate, or additive metals. The procedure identifies both soluble metal and metal particles up to 5 to 10 microns (5-10 mm). The test is moderate in cost and is usually part of a commercial laboratory standard test package. Other techniques, such as absorption spectroscopy and X-ray spectroscopy, are also used by some laboratories to identify metals.

6.6.2.8 Infrared Spectroscopy

Infrared spectroscopy is also known as infrared analysis, infrared absorption spectroscopy or spectrophotometry, and Fourier Transform Infrared (FTIR) spectroscopy. The technique examines the infrared wavelength that is absorbed by the oil sample. The test is used to identify non-metallic contamination (see 6.6.2.3 Water) and lubricant conditions such as oxidation and anti-oxidant and other additive depletion.

Ongoing work couples computer expert system analysis with known oil spectrums to produce highly accurate diagnosis of small changes in the oil condition. Costs vary depending on the level of sophistication required. Infrared spectroscopy is usually part of a commercial laboratory standard test package.

6.6.2.9 Particle Counting

Particle counting is used to identify metal and non-metal particles between 5 microns and 50 microns. There are two methods (visual and electronic) which both result in particle counts (parts per milliliter) by size category. For example, the ISO size categories are greater than 5, 10, 15, 25 and 50 microns.

The visual method of particle counting is time-consuming and relies on the skill of the analyst. Its benefit is the identification of types of particles such as dirt, seal material, and metal. The electronic counting method is much faster and is independent of the skill of the analyst. It does not identify the particle make up. A commercial laboratory will quote electronic particle count; visual particle counting is more expensive and done by request only and is fiscally more demanding.

6.6.2.10 Direct-Reading Ferrography

Ferrography, the analysis of ferrous material, uses a magnetic technique to separate wear particles from the oil sample. In the direct reading (DR) process the wear particles are further separated into small (5 to 15 microns) and large (greater than 15 microns) categories. This results in a ratio of large to small particles and a total particle concentration. Both values can be tracked and trended to indicate increases in wear and type of wear. This test supplements the spectrometric metals test and identifies large wear particles not identified by spectrometric metals test. The cost of this test is moderate.

6.6.2.11 Analytical Ferrography

Analytical ferrography is typically initiated based on changes in DR, spectrometric metal increases, or increased particle count. The analysis may be performed regularly for high-cost or critical machines. The process is labor intensive, involving the preparation of sample and examination under magnification. The procedure may provide details regarding wear material such as wear type (rubbing, sliding, cutting), color, particle types (oxide, corrosive, crystalline), and other non-ferrous particles. This detailed information can lead to the root cause of wear problems. Costs are moderately high; the test is performed on a fixed price basis (per sample) from a commercial laboratory.

6.6.3 Special Tests

Special tests may be necessary to monitor lubricant conditions on high-cost or critical systems. The special test may monitor a lubricant contaminate, a characteristic, or additive depletion. Special tests are rarely needed for routine monitoring of lubricants. The procedures are constantly being developed and refined; the following are sample current test methods, as described by the annual ASTM Standards.[19]

6.6.3.1 Glycol Antifreeze

Infrared spectroscopy can detect glycol contamination at levels greater than 0.1 percent (1,000 PPM), which is usually adequate for condition monitoring. Additional tests can be specified to identify smaller amounts of glycol. *ASTM D2982, Standard Test Method for Glycol-Base Antifreeze in Used Lubricating Oils* will indicate if trace amounts are present. ASTM D4291, *Standard Test Method for Trace Ethylene Glycol in Used Engine Oils* uses gas chromatography to quantify small amounts of glycol.

6.6.3.2 Karl Fischer Water

Infrared spectroscopy can detect water contamination at levels greater than 0.05 percent (500 PPM) which is usually adequate for condition monitoring. Using a titration process with a Karl Fischer reagent, low levels of water can be quantified. The test, ASTM D1744, *Standard Test Method for Determination of Water in Liquid Petroleum Products by Karl Fischer Reagent* is useful when accepting new oil or evaluating clean up efforts. The cost of the test is moderate.

6.6.3.3 Foaming

Oil may have additive anti-foam agents to improve the lubrication capability in specific applications such as gearboxes or mixers. ASTM D892, *Standard Test Method for Foaming Characteristics of Lubricating* tests the oil foam characteristics by blowing air through an oil sample to measure the foam volume. The cost of the test is moderately high.

6.6.3.4 Rust Prevention

Some systems are susceptible to water contamination due to equipment location or the system operating environment. In those cases, the lubricating oil or hydraulic fluid may be fortified with a corrosion inhibitor to prevent rust. The effectiveness of rust prevention can be tested using ASTM D665, *Standard Test Method for Rust-Preventing Characteristics of Inhebited Mineral Oil in the Presence of Water* (or ASTM D3603, *Standard Test Method for Rust-Preventing Characteristics of Steam Turbine Oil in the Presence of Water (Horizontal Disk Method)*). Results are pass/fail. The cost of the test is high.

6.6.3.5 Rotating Bomb Oxidation Test (RBOT)

Also known as the Rotary Bomb Oxidation Test, ASTM D2272, *Standard Test Method for Oxidation Stability of Steam Turbine Oils by Rotating Pressure Vessel* estimates oxidation stability and, identifies the remaining useful life of oil. The test simulates aging to identify when rapid oxidation takes place indicating that anti-oxidants have been depleted. This test must be performed over time, including a baseline test with new oil, in order to develop a

[19] Annual Book of ASTM Standards, Section 5, Petroleum Products, Lubricants, and Fossil Fuels, American Society for Testing and Materials.

trend line. Because of the high cost and multiple test requirements, this test is generally performed only on large volume reservoirs or expensive oil.

6.6.4 Application

All machines with motors 7.5 HP or larger, and critical or high-cost machines should be evaluated for routine lubricating oil analysis. The analysis schedule should be adjusted similarly to the vibration analysis schedule. It is important that there is a dynamic process for addressing the adjustment of periodicity for all equipment in both the PM and PT&I programs. Analyze more frequently for machines that indicate emerging problems; less frequently for machines that are stable and not run on a continuous basis.

A new baseline analysis is necessary following machine repair or oil change out. All hydraulic systems, except mobile systems, should be analyzed on a quarterly basis. Mobile systems should be considered for analysis based upon the machine size and the cost-effectiveness of performing the analysis. It is generally more cost-effective in mobile equipment to maintain the hydraulic fluid based upon the fluid condition. However, for small systems, the cost to flush and replace the hydraulic fluid on a time basis may be lower than the cost to analyze the fluid on a routine basis.

Grease is not typically analyzed on a regular basis. Although most testing that is done on oil is applicable to grease, it is difficult to obtain a representative sample. The machine may require disassembly to get a representative sample, a homogeneous mixture of the grease, contaminants, and wear.

Keeping dirt and moisture from the system is a concern common of all machines with lubricating oil systems. Common components of dirt, such as silica, are abrasive and promote wear of contact surfaces. In hydraulic systems, particles can block and abrade the close tolerances of moving parts. Water in oil promotes oxidation and reacts with additives to degrade the performance of the lubrication system. The lubricant analysis program must therefore monitor and control contaminants.

Large systems with filters have steady state levels of contaminates. Increases in contaminates indicate breakdown in system integrity (leaks in seals, doors, heat exchangers, etc.) or degradation of the filter. Unfiltered systems can exhibit steady increases during operation. Operators can perform a weekly visual and odor check of lubricating systems and provide a first alert to contamination. Some bearing lubricating systems have such a small amount of oil that a weekly check may be impractical.

6.6.4.1 Motors, Generators, Pumps, Blowers, Fans

The analyst focuses mostly on machine condition for machines selected for monitoring (as discussed in Chapter 3.0) and with less than five gallons of oil in the lubrication system. Lubricant condition and contamination contribute to machine condition. The analyst monitors trends and discards or refreshes the oil when viscosity changes 10 percent from the baseline. Viscosity normally increases above the baseline with the oil service time. If the viscosity decreases below the baseline, it may mean the oil is contaminated, probably from adding the wrong makeup oil. There should be no water present (minimum detectable with the percent solids/water test is 0.1 percent). If water is found, identify and correct the source.

For machines with more than five gallons of oil in the system, add infrared spectroscopy (minimum amount of water detectable is .05 percent) and particle counting. Changes in particle count may indicate increased contamination or increased wear; correlate particle count with spectrometric metals. The rate of particle count change indicates how quickly the lubricant is degrading. Visual particle counting may identify the source of the contamination. Perform DR ferrography for high-cost or critical machines.

In all machines, investigate changes in spectrometric metals or DR using analytical ferrography and correlate with vibration analysis.

6.6.4.2 Gearboxes

The analyst focuses mostly on machine condition for machines selected for monitoring (as discussed in Chapter 3.0) and with less than five gallons of oil in the lubrication system. Lubricant condition and contamination contribute to machine condition. The analyst monitors trends and discards or refreshes the oil when viscosity changes 10 percent from the baseline. Viscosity normally increases above the baseline with the oil service time. If the viscosity decreases below the baseline, it may mean the oil is contaminated, probably from adding the wrong makeup oil. There should be no water present (minimum detectable with the percent solids/water test is 0.1 percent). If water is found, identify and correct the source.

For machines with more than five gallons of oil in the system, add infrared spectroscopy (minimum amount of water detectable is .05 percent) and particle counting. Changes in particle count may indicate increased contamination or increased wear; correlate particle count with spectrometric metals. The rate of particle count change indicates how quickly the lubricant is degrading. Visual particle counting may identify the source of the contamination. Perform DR ferrography for high-cost or critical machines.

In all machines, investigate changes in spectrometric metals or DR using analytical ferrography and correlate with vibration analysis.

For all gearboxes, including those with less than five gallons of oil, perform particle counting. Include DR ferrography for high-cost or critical gearboxes. Monitor trends and correlate with vibration readings.

6.6.4.3 Chillers

The analyst focuses mostly on machine condition for machines selected for monitoring (as discussed in Chapter 3.0) and with less than five gallons of oil in the lubrication system. Lubricant condition and contamination contribute to machine condition. The analyst monitors trends and discards or refreshes the oil when viscosity changes 10 percent from the baseline. Viscosity normally increases above the baseline with the oil service time. If the viscosity decreases below the baseline, it may mean the oil is contaminated, probably from adding the wrong makeup oil. There should be no water present (minimum detectable with the percent solids/water test is 0.1 percent). If water is found, identify and correct the source.

For machines with more than five gallons of oil in the system, add infrared spectroscopy (minimum amount of water detectable is .05 percent) and particle counting. Changes in particle count may indicate increased contamination or increased wear; correlate particle count with spectrometric metals. The rate of particle count change indicates how quickly the lubricant is degrading. Visual particle counting may identify the source of the contamination. Perform DR ferrography for high-cost or critical machines.

In all machines, investigate changes in spectrometric metals or DR using analytical ferrography and correlate with vibration analysis.

Perform TAN and DR ferrography.

6.6.4.4 Diesel Engines

The analyst focuses mostly on machine condition for machines selected for monitoring (as discussed in Chapter 3.0) and with less than five gallons of oil in the lubrication system. Lubricant condition and contamination contribute to machine condition. The analyst monitors trends and discards or refreshes the oil when viscosity changes 10 percent from the baseline. Viscosity normally increases above the baseline with the oil service time. If the viscosity decreases below the baseline, it may mean the oil is contaminated, probably from adding the wrong makeup oil. There should be no water present (minimum detectable with the percent solids/water test is 0.1 percent). If water is found, identify and correct the source.

For machines with more than five gallons of oil in the system, add infrared spectroscopy (minimum amount of water detectable is .05 percent) and particle counting. Changes in particle count may indicate increased contamination or increased wear; correlate particle count with spectrometric metals. The rate of particle count change indicates how quickly the lubricant is degrading. Visual particle counting may identify the source of the contamination. Perform DR ferrography for high-cost or critical machines.

In all machines, investigate changes in spectrometric metals or DR using analytical ferrography and correlate with vibration analysis.

Substitute TBN for TAN when oil has high detergent additives.

A decrease in viscosity below the baseline may indicate fuel contamination. Infrared spectroscopy analysis identifies and coolant leakage (glycol and other characteristics).

6.6.4.5 Compressors

For centrifugal and reciprocating compressors:

- The analyst focuses mostly on machine condition for machines selected for monitoring (as discussed in Chapter 3.0) and with less than five gallons of oil in the lubrication system. Lubricant condition and contamination contribute to machine condition. The analyst monitors trends and discards or refreshes the oil when viscosity changes 10 percent from the baseline. Viscosity normally increases above the baseline with the oil service time. If the viscosity decreases below the baseline, it may mean the oil is contaminated, probably from adding the wrong makeup oil. There should be no water present (minimum detectable with the percent solids/water test is 0.1 percent). If water is found, identify and correct the source.

- For machines with more than five gallons of oil in the system, add infrared spectroscopy (minimum amount of water detectable is .05 percent) and particle counting. Changes in particle count may indicate increased contamination or increased wear; correlate particle count with spectrometric metals. The rate of particle count change indicates how quickly the lubricant is degrading. Visual particle counting may identify the source of the contamination. Perform DR ferrography for high-cost or critical machines.

- In all machines, investigate changes in spectrometric metals or DR using analytical ferrography and correlate with vibration analysis.

For reciprocating compressors, perform TAB and DR ferrography.

6.6.4.6 Hydraulic Systems

The analyst focuses mostly on machine condition for machines selected for monitoring (as discussed in Chapter 3.0) and with less than five gallons of oil in the lubrication system. Lubricant condition and contamination contribute to machine condition. The analyst monitors trends and discards or refreshes the oil when viscosity changes 10 percent from the baseline. Viscosity normally increases above the baseline with the oil service time. If the viscosity decreases below the baseline, it may mean the oil is contaminated, probably from adding the wrong makeup oil. There should be no water present (minimum detectable with the percent solids/water test is 0.1 percent). If water is found, identify and correct the source.

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In all machines, investigate changes in spectrometric metals or DR using analytical ferrography and correlate with vibration analysis.

Monitor particle count by ISO category. Each hydraulic system will have limiting clearances that will determine critical particle sizes. Note that some hydraulic systems use fluids other than oil (water or glycol). Particle control is the same for these systems. See Table 8-9.

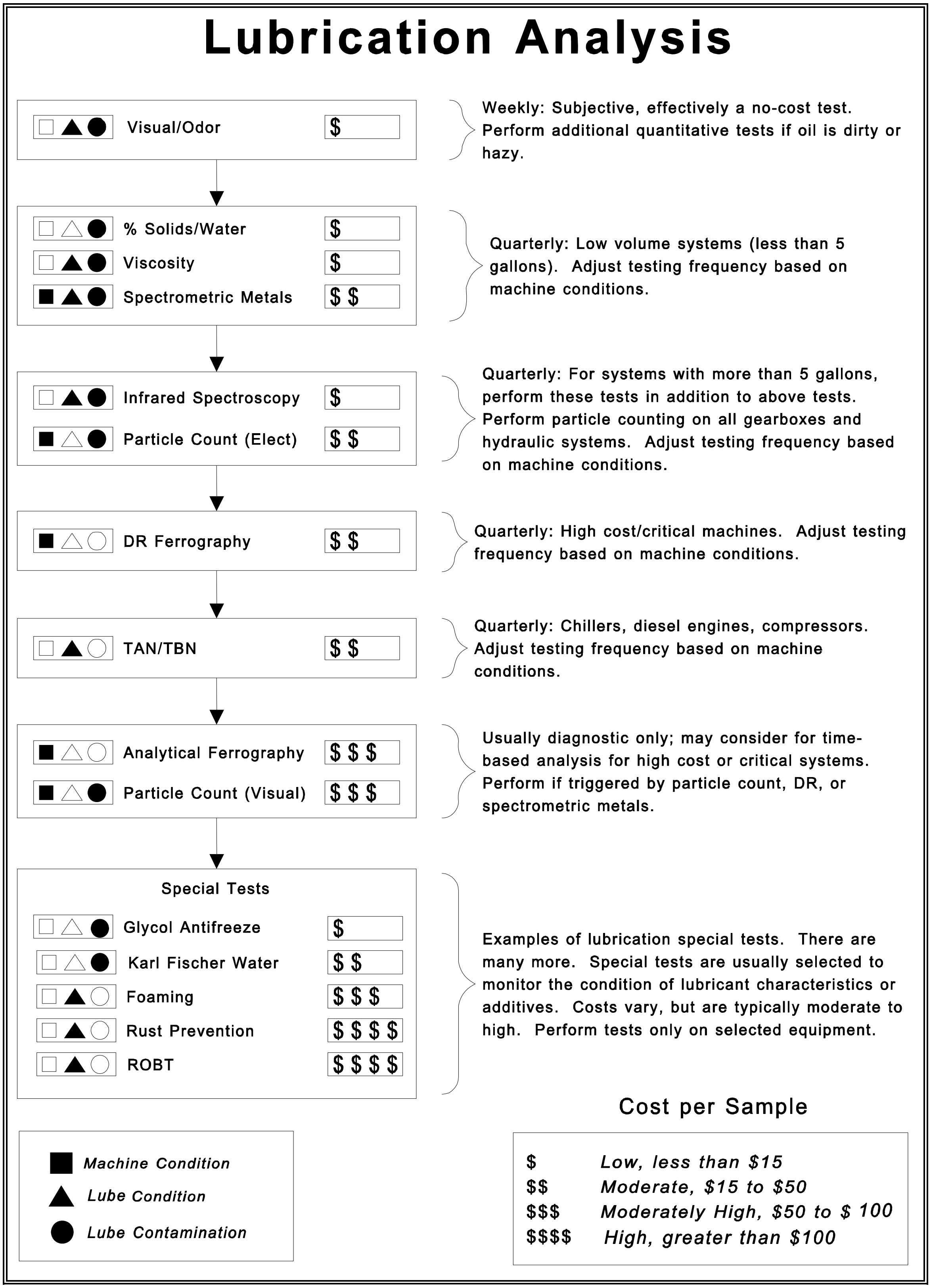
6.6.4.7 Large Reservoirs

For reservoirs over 500 gallons, consider performing an RBOT to assess the oxygen stability. Cost is usually the deciding factor. At least three tests are needed to develop a trend with additional retesting at least once a year. Benefit is derived when replacement or refreshing of a large volume of oil (or smaller volume of expensive oil) can be deferred.

6.6.4.8 Lubrication Analysis

Figure 6-2 summarizes the various lubricant tests, monitoring intervals, and applications.

Figure 6-2. Lubrication Analysis Chart



6.6.5 Sampling

Oil samples must be collected safely and without introducing dirt and other contaminates into the machine, system, or sample. This may require installing permanent sample valves in some lubricating systems.

The sample should be collected from a mid-point in reservoirs, prior to filtering in circulating systems. Sample collection bottles and tubing can be procured through testing laboratories. The testing laboratory may determine the necessary cleanliness level. Avoid contamination by properly using sample pumps to extract oil from reservoirs. Samples must be collected from the same point in the system in order to assure consistency in the test analysis. The maintenance procedure must provide detailed direction on where and how to collect samples.

The equipment operators may collect samples. Each sample is marked with the system/machine name, sample location point (the system may have multiple sample points), date, elapsed operating time for the system/machine, and other comments such as last "topping off" or filtering operation. The analyst will also need to know the amount of oil in the reservoir in order to make recommendations to correct abnormalities.

6.7 ELECTRICAL CONDITION MONITORING

Electrical equipment represents the majority of a facility's capital investment. From the power distribution system to electric motors, the electrical system's efficient operation is crucial to maintaining operational capability. Electrical condition monitoring encompasses several technologies and techniques that provide critical information so a comprehensive system evaluation can be performed.

Monitoring key electrical parameters provides the information to detect and correct electrical faults such as high resistance connections, phase imbalance and insulation breakdown. Since faults in electrical systems are seldom visible, these faults are costly (increased electrical usage) and present safety concerns (fires) and life-cycle cost issues (premature replacement of equipment). According to the Electric Power Research Institute[20], voltage imbalances of as little as 5 percent in motor power circuits result in a 50 percent reduction in motor life expectancy and efficiency in 3-phase AC motors. A 25 percent increase in motor temperatures can be generated by the same 5 percent voltage imbalance accelerating insulation degradation.

6.7.1 Techniques

The following are techniques for monitoring electrical conditions.

6.7.1.1 Infrared Thermography

Infrared thermography has widespread application in electrical systems because of its ability to be used safely on energized equipment and to detect temperature differences and overheating of circuits. See Section 6.4 Infrared Thermography for more information.

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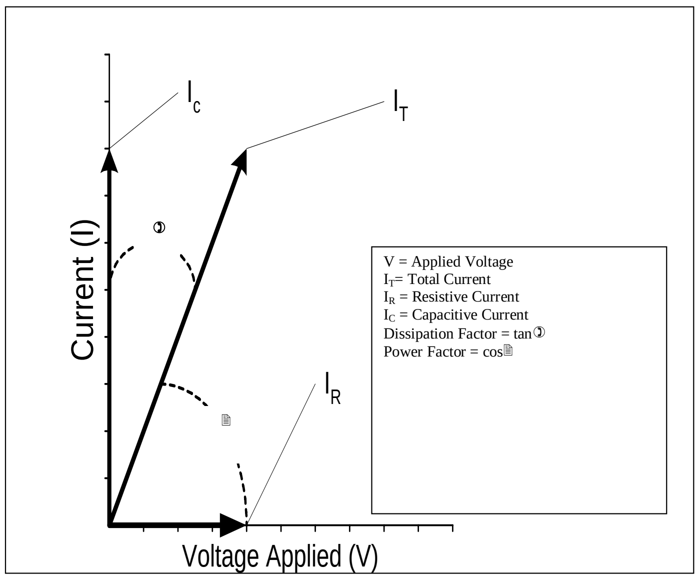
[20] EPRI is a nonprofit membership corporation, established by U.S. electric utilities, to manage a national research program on behalf of its members.

6.7.1.2 Insulation Power Factor

Insulation Power Factor, sometimes referred to as dissipation factor, is the measure of the power loss through the insulation system to ground. It is a dimensionless ratio expressed in percent of the resistive current flowing through insulation to the total current flowing. To measure this value, apply a known voltage to the insulation and measure the resulting current and current/voltage phase angle.

Figure 6-3 shows the phase relationships of the resulting currents.

Figure 6-3. Power Factor Current/Voltage Relationship



- Where I_R is the resistive current
- I_C is the capacitive current
- I_T is the resultant, or total current
- V is the applied voltage

I_R is generally very small compared to I_T because most insulation is capacitive in nature. A capacitor is two current carrying plates separated by a dielectric material. An electrical coil is a current-carrying conductor with an insulation material protecting the conductor from shorting to ground. The conductor of the coil and ground are similar to the two conducting plates in the capacitor, and the insulation of the coil is like the dielectric material of the capacitor. The dielectric material prevents the charge on each plate from bleeding until the voltage level of the two plates exceeds the voltage capacity of the dielectric. The coil insulation prevents the current from flowing to ground until the voltage level exceeds the voltage capacity of the insulation.

Figure 6-3 shows that I_R is in phase with the applied voltage V and I_C is leading the voltage by a phase angle of 90 degrees. The total current is the resultant combination of both I_R and I_C. The tangent of the angle between the applied voltage and resultant current is called the dissipation factor and the cosine of the angle between the resultant current and the capacitive current is called the power factor.

As the impedance of the insulation changes due to aging, moisture, contamination, insulation shorts, or physical damage, the ratio between I_C and I_R will become less. The resulting phase angle between the applied voltage and resultant current decreases and the power factor will rise. Consequently, the power factor test is primarily used for making routine comparisons of the condition of an insulation system. The test is non-destructive and regular maintenance testing will not deteriorate or damage insulation.

6.7.1.3 Insulation Oil Analysis

High and medium voltage transformers, some high and medium voltage circuit breakers, and some medium voltage switches are supplied with mineral oil as an insulation medium. Performing an analysis of that insulating oil can yield operational history and current condition of the equipment.

Below are listed available tests, the ASTM standard number[21] (several were discussed in the lubricating oil section), and a brief description.

- **Karl Fischer, ASTM D-1533-88.** Tests for water in insulating fluids and reveals total water content in oil, both dissolved and free. High readings could indicate a leak in the equipment housing or insulation breakdown.

- **Dielectric Breakdown Strength, ASTM D-877 and D-1816.** Tests for conductive contaminants present in the oil such as metallic cuttings, fibers, or free water.

- **Neutralization Number, ASTM D-974.** Commonly called the acid number test, this measures the amount of acid in the oil. Acidity is a result of oxidation of the oil caused by the release of water into the oil from insulation material due to aging, overheating, or operational stresses such as internal or through faults. Acidity is measured as the number of milligrams of potassium hydroxide (KOH) it takes to neutralize the acid in one gram of oil. An increase in acidity indicates a deterioration of the oil. This process causes the formation of sludge within the windings which in turn can result in premature failure of the unit.

- **Interfacial Tension (IFT), ASTM D-971.** Measures the tension at the interface between oil and water. It is expressed in dynes/centimeter. Good oil will have an IFT of 40 to 50 dynes/cm, and will normally “float” on top of water. As transformer and breaker insulation ages, contaminants such as oxygen and free water are released into the oil. The properties that allow the oil to “float” on top of the water then begin to break down, resulting in a lower IFT. IFT can reveal the presence of sludge in insulating oils.

- **Color, ASTM D-152.** A marked color change from one year to the next could indicate deteriorating oil.

- **Sediment, ASTM D-1698.** This test indicates oil deterioration and contamination.

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[21] Annual Book of ASTM Standards, Section 5, Petroleum Products, Lubricants, and Fossil Fuels, American Society for Testing and Materials.

- **Power Factor, ASTM D-924.** Performed at 25° C, this test reveals the presence of moisture, resins, varnishes, or other products of oxidation or foreign contaminates such as motor or fuel oil. The power factor of new oil should always be below 0.05 percent.
- **Visual Examination, ASTM D-1524.** Insulating oil is normally clear and sparkling. Cloudiness indicates the presence of moisture or other contaminates. This cursory test can trigger a Karl Fischer or Dielectric Breakdown test.

6.7.1.4 Gas-in-Oil Analysis

Gas-in-oil analysis, also called dissolved gas analysis, is a predictive test for oil-filled transformers. As transformers age small amounts of combustible gases are formed; however, when insulation systems are subjected to stresses such as fault currents and overheating, combustible gas generation can change dramatically. Generally these stresses can be detected early; the presence and quantity of the individual gases can be measured and the results analyzed to indicate the probable cause of generation.

A small oil sample (50cc) is drawn from a transformer with a glass syringe[22]. To obtain a reliable reading this must be accomplished with the unit energized. A transformer cools after being taken off-line. As the transformer cools, dissolved gases in the oil will migrate into the windings so the sample must be taken when the transformer is energized and at operating temperature.

The oil is analyzed using ASTM D-3612-90, *Standard Test Method for Analysis of Gases Dissolved in Electrical Insulating Oil by Gas Chromatography*. While there are over 200 gasses present in insulating oils there are only nine that are monitored. They are:

- Nitrogen (N_2)
- Oxygen (O_2)
- Carbon Dioxide (CO_2)
- Carbon Monoxide (CO)
- Methane (CH_4)
- Ethane (C_2H_6)
- Ethylene (C_2H_4)
- Hydrogen (H_2)
- Acetylene (C_2H_2)

[22] ASTM D3613 provides a detailed procedure. D3613, Standard Test Methods of Sampling Electrical Insulating Oils for Gas Analysis and Determination of Water Content, American Society for Testing and Materials.

Different combinations of these gases reveal different conditions. Large amounts of CO and CO_2 indicate overheating in the windings. CO, CO_2, and CH_4 show the possibility of hot spots in the insulation. H_2, C_2H_6, and CH_4 are indicative of corona discharge. C_2H_2 is a sign of internal arcing. Consult industry publications to determine potential problems.

6.7.1.5 Megohmmeter Testing

A hand-held generator (battery powered or hand-cranked) is used to measure the insulation resistance phase-to-phase or phase-to-ground of an electric circuit. Readings must be temperature-corrected to trend the information. Winding temperatures affect test results. An enhanced technique compares the ratio of the Megohmmeter readings after one minute and ten minutes. This ratio is named the polarization index.

6.7.1.6 High Potential Testing (HiPot)

High Potential test (HiPot) applies a voltage equal to twice the operating voltage plus 1000 volts to cables and motor windings to test the insulation system. Industry practice calls for HiPot tests on new and rewound motors and on new cables. This test stresses the insulation systems and can induce premature failures in marginal insulation systems. Due to this possibility, HiPot is not recommended as a routine condition monitoring technique, but as an acceptance test.

An alternative is to start with a lower voltage and increase the applied voltage in steps and measure the change in insulation resistance readings. In repaired equipment, if the leakage current continues to increase at a constant test voltage this indicates the repair is not to the proper standard and will probably fail soon. In new equipment, if the equipment will not withstand the appropriate test voltage it indicates the insulation system or construction method is inadequate for long term service reliability.

(Note: Perform HiPot testing with caution. The high voltage applied may induce premature failure of the units being tested.)

6.7.1.7 Airborne Ultrasonic Noise

Electrical arcing and discharges create noise in the upper, or ultrasonic, frequency ranges, sometimes long before failure. Corona discharges in switchyards, loose switch connections, and internal arcing in deadfront electrical connections can sometimes be heard with an ultrasonic noise detector.

6.7.1.8 Battery Impedance Testing

All batteries have a storage capacity which is dependent on the terminal voltage and internal impedance. A battery impedance test set places an AC signal between the terminals of the battery, measures the resulting voltage, and calculates the impedance. This measurement can be accomplished without removing the battery from service due to the low AC signal and its position on top of the DC voltage of the battery. Two comparisons are then made: first, the impedance is compared with the last reading for that battery and with other batteries in the same bank. Each battery should be within 5 percent of its last reading and within 10 percent of the others. A reading outside of these values indicates a cell problem or capacity loss.

If the battery has an internal short the impedance tends to go to zero. If there is an open circuit, the impedance approaches infinite resistance and causes premature aging due to excessive heat. Discharges will cause the impedance to rise quickly.

There are no set guidelines and limits for this test. Each type, style, and configuration of battery will have its own impedance so it is important to take these measurements early in a battery's life, preferably at installation. Performance should be under an hour for a battery bank of 60 cells.

6.7.1.9 Surge Testing

Surge testing utilizes equipment based on two capacitors and an oscilloscope to determine the condition of motor windings. This is a comparative test evaluating the difference in readings of identical voltage pulses applied to two windings simultaneously. The applied voltage equals two times operating voltage plus 1000 volts. Data is provided as a comparison of waveforms between two phases indicating the relative condition of the two phases with regard to the insulation system. Because of the repeated stress of the insulation system, Surge testing is not recommended for routine condition monitoring.

(Note: Perform surge testing with caution. The high voltage applied may induce premature failure of the units being tested.)

6.7.1.10 Motor Circuit Analysis

The motor circuit analysis technology packages several motor tests into a single unit. The test device performs a polarization index and checks test parameters in a motor circuit including resistance to ground, capacitance to ground, resistive imbalance, inductive imbalance, and rotor influence. De-energize the motor and use low voltage to avoid stressing the insulation system. Data is collected by the unit and enables trending and comparing with similar motors.

The total resistance of a conductor is the sum of its resistance, capacitive and inductive impedance. Accurate measurement of the conductor’s impedance allows minor degradations in a motor to be detected and addressed prior to a failure. The condition of the insulation system can be determined by measuring the capacitance between each phase and ground. The presence of moisture or other conducting substance will form a capacitor with the conductor being one plate, the insulation the dielectric, and the contaminate forming the second plate. Maintaining proper inductive balance is imperative to efficient operation and realizing full lifetime of electrical equipment. An electrical imbalance leads to elevated winding temperatures and reduced insulation life.

6.7.1.11 Motor Current Signature (Spectrum) Analysis (MCSA)

Motor Current Signature (Spectrum) Analysis (MCSA) is a remote, non-intrusive, on-line method of testing motor-driven equipment. Current and voltage probes provide the signal data used for analysis to detect equipment degradation. Motor current spectrums in both time and frequency domains are collected with a clamp-on ammeter and FFT analyzer. Rotor bar problems will appear as side-bands around the power supply line frequency. MCSA allows for diagnosis of power circuit, motor and driven end component.

MCSA can be performed in an indirect manner by measuring the magnetic flux produced by the motor and analyzing the data using the Fast Fourier Transform (FFT) process to identify the presence of electrical fault frequencies.

6.7.1.12 Very Low Frequency (VLF) Testing

A Very Low Frequency (VLF) Test Set is an AC test that operates at 0.1 HZ. The low frequency allows for the portability of a DC test set (light weight, less input current) without the destructive capability of a HiPot. The primary application of VLF testing is for partial discharge and over potential testing of large rotating machines, power cables, and other high capacitance apparatus. The results can be trended to monitor degradation. The high cost of a VLF test set limits its use to facilities with large electrical systems.

6.7.1.13 Circuit Breaker Timing Tests

This is a mechanical test to monitor the speed and position of breaker contacts before, during, and after an operation. The first timing devices, called Drop-Bar Recorders, recorded their results on a rotating drum. Developed in the late 1930s, it was the instrument of choice until the arrival of rotary motion, vacuum, and high-speed breakers in the mid 1970s.

For in-service circuit breakers, a digital contact and breaker analyzer can be used to measure the contact velocity, travel, over travel, bounce back, and acceleration to indicate the condition of the breaker operating mechanism. A voltage is applied to the breaker contacts and a motion transducer is attached to the operating mechanism. The breaker is then closed and opened. The test set measures the timeframe of voltage changes, and plots the voltage changes over the motion waveform produced by the motion transducer.

Analyzing and trending this information allows for adjustments to the breaker operating mechanism when necessary. This test is not applicable to molded case breakers or low voltage breakers.

6.7.1.14 Circuit Breaker Contact Resistance

This test determines the contact condition on a breaker or switch without visual inspection. The results can be trended to help schedule maintenance activities before the contacts degrade significantly.

Most manufacturers of high and medium voltage circuit breakers will specify a maximum contact resistance for both new contacts and in-service contacts. The contact resistance is dependent on the quality of contact area and the contact pressure. The contact quality can degrade if the breaker is called upon to open under fault conditions. The contact pressure can lessen as the breaker springs fatigue due to age or a large number of operations.

To measure the contact resistance a DC current, usually 10 or 100 amps, is applied through the contacts. The voltage across the contacts is measured and the resistance is calculated using Ohms law. This value can be trended and compared with maximum limits issued by the breaker or switch manufacturer. For oil-filled breakers, use a 100 amp test set because oil tends to glaze on contact surfaces and 10 amps may not be enough current to overcome the glaze.

6.7.2 Additional Techniques and Troubleshooting

There are numerous electrical tests that may indicate system conditions.

6.7.2.1 Time Domain Reflectometry

This technology locates faults within a cable run. A voltage spike is sent through a conductor. Each discontinuity in the conductor path generates a reflected pulse. The time between initial pulse and reception of the reflected pulse indicates the location of the discontinuity. The test is performed with the cable de-energized.

6.7.2.2 Power Factor and Harmonic Distortion

Maintaining optimum power factor maximizes the efficient use of electrical power. Power factor is the ratio of real power to reactive power usage. Dual channel data-loggers are used to determine the phase relationship between voltage and current and then calculate the power factor. Addition of power factor enhancing capacitors is then evaluated as a means of improving power system power factor.

Harmonic distortion is a result of having non-linear loads on the power system. These loads include laser printers, desktop computers, and SCRs found in variable speed motor controls. High levels of harmonic current cause excessive heating in transformers and cables, reduce service life, and cause spurious tripping of circuit breakers. A harmonic analyzer is used to measure the harmonic current and identify the source. Place filters on the circuit to minimize the impact. This test is performed with the system energized.

6.7.2.3 Motor Starting Current and Time

Starting current in electric motors can routinely exceed five times full load running current. The amount of starting current combined with the duration of the starting surge can indicate the condition of electrically driven equipment. Higher starting current and longer duration of the surge can indicate mechanical problems such as increased friction due to misalignment of the mechanical components of the equipment. Alternatively, coastdown tests using timing devices and vibration monitoring equipment can verify the presence of magnetically-induced vibrations or mechanical friction.

6.7.2.4 Transformer Turns Ratio

The Transformer Turns Ratio (TTR) test measures the turns-ratio of a transformer and is mainly used as an acceptance test. It can also be used as a troubleshooting tool when other electrical tests reveal a possible problem. During routine maintenance tests a TTR can be performed to identify short circuited turns, incorrect tap settings, mislabeled terminals, and failure in tap changers.

Apply a voltage across the primary windings and measure the resulting voltage across the secondary windings. The ratio of active windings can be calculated. This measurement can determine the condition of the transformer’s inductive capability. The turn ratio measurement can show that a fault exists but can not determine the reason or location of the fault. This test is done with the transformer de-energized.

6.7.3 Applications

6.7.3.1 Equipment to be Monitored

Specific equipment that can be monitored by electrical condition monitoring techniques is listed below:

- **Electrical Distribution Cabling:** Megohmmeter, VLF Testing, Time Domain Reflectometry, HiPot, Infrared Thermography (if visible) and Airborne Ultrasonics.

- **Electrical Distribution Switchgear and Controllers:** Breaker Timing, Insulation Power Factor Testing, Visual Inspection, Infrared Thermography and Airborne Ultrasonics.

- **Electrical Distribution Transformers:** Oil Analysis, Turns Ratio, Power Factor and Harmonic Distortion.
- **Electrical Motors:** Motor Current Signature Analysis, Motor Circuit Analysis, Megohmmeter, HiPot, Surge Test, Starting Current and Coast Down Time, Infrared Thermography, Airborne Ultrasonics.
- **Generators:** Megohmmeter, VLF Testing, and Coast Down Time.
- **Distribution System:** Infrared Thermography, HiPot, Airborne Ultrasonics, Power Factor and Harmonic Distortion.

6.7.3.2 Conditions Monitored

The following conditions are monitored: temperature, voltage, current, resistance, complex impedance, capacitance, insulation integrity, phase imbalance, mechanical binding, and presence of arcing.

6.7.3.3 Detection Interval

Monitoring intervals of several weeks to several years for various technologies will provide sufficient condition information to warn of degrading equipment condition. Specific expectations of the length of warning provided should be factored into developing monitoring intervals for specific technologies. Some monitoring intervals will depend on outage cycles. Some of the electrical condition monitoring can be done with the system energized. Several of the technologies outlined are also effective when used for acceptance testing and certification.

6.7.3.4 Accuracy

Accuracy depends on the applied testing technique and the rating of the instrument.

6.7.3.5 Limitations

The technologies presented can be divided into two categories: energized and de-energized. Each technology requires specific initial conditions to be set prior to conducting the test. For instance, prior to an Infrared Thermography survey, typical equipment powered through the switchboard should be running to bring the distribution equipment to normal operating temperatures. Higher load accentuates problem areas. Conducting the survey at low load conditions may allow a problem to remain undetected.

Energized

Those technologies that can safely provide information on energized systems and require the system be energized and operational. These technologies include Infrared Thermography; Airborne Ultrasonics; Motor Current Readings including Starting Current, Motor Current Spectrum Analysis, VLF Testing, Power Factor and Harmonic Distortion; Battery Impedance Testing; and Insulation Oil Analysis (including Gas-in-Oil).

De-Energized

Technologies that require the circuit to be de-energized include Surge Testing, HiPot Testing, Time Domain Reflectometry (TDR), Megohmmeter, Motor Circuit Analysis, Circuit Breaker Timing, Transformer Turns Ratio, and Insulation Power Factor Testing.

6.7.4 Logistics

6.7.4.1 Equipment Required

A comprehensive electrical testing program includes the following items: Infrared camera, ultrasonic noise detector, multi-meters/volt-ohmmeters, clamp on current transformers, Insulation Power Factor test set, Time Domain Reflectometry test set, Breaker Timing test set, Contact Resistance (micro-ohmmeter) test set, Battery Impedance test set, VLF test set, motor current signature analysis software, and integrated motor circuit analysis testers.

6.7.4.2 Operations

Electricians, electrical technicians, and electrical engineers should be trained in electrical PT&I techniques such as motor current signature analysis, motor circuit analysis including complex phase impedance, and insulation resistance readings and analysis.

6.7.4.3 Training Available

Equipment vendors and independent companies can provide training. See Appendix C for training sources.

6.7.4.4 Cost

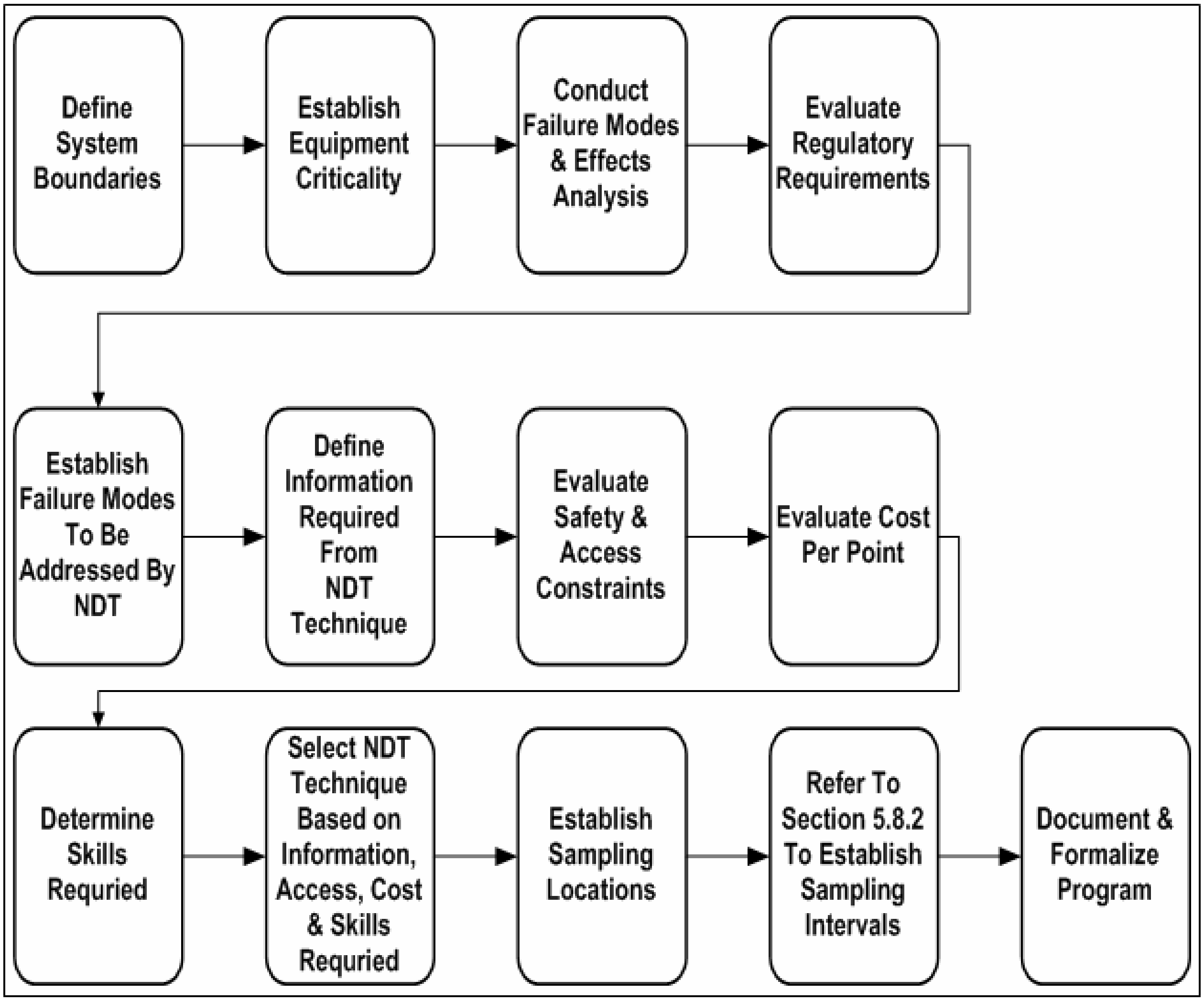
Equipment costs vary from $20 for a simple multi-meter to approximately $80,000 for integrated on-line, motor-circuit/current analysis (MCE/A) testers. A full inventory of electrical testing equipment can cost in excess of $200,000.

Training averages between $750 and $1,000 per week per person per technology.

6.8 NON-DESTRUCTIVE TESTING

Non-Destructive Testing (NDT) evaluates material properties and quality of manufacture for high-value or critical components or assemblies without damaging the product or its function. NDT techniques are used when other testing techniques are cost prohibitive or ineffective (see Figure 6-4). NDT has been associated with welding of large, high stress components such as pressure vessels and structural supports. Process plants such as refineries or chemical plants use NDT techniques to assure integrity of pressure boundaries for systems processing volatile substances.

Figure 6-4. Non-Destructive Testing Selection Process



6.8.1 Techniques

6.8.1.1 <u>Radiography</u>

Radiography detects deep subsurface defects. Radiography or x-ray is one of the most powerful NDT techniques. Depending on the strength of the radiation source, radiography can provide a clear representation (radiograph) of discontinuities or inclusions in material several inches thick. Place the X-ray- or gamma ray-sensitive film on one surface of the material to be examined. Position the radiation source on the opposite side of the material to be examined. The source may be either a natural gamma emitter or a powered X-ray emitter. Align the source to assure the proper exposure angle through the material (see Figure 6-5). When all preparations and safety precautions are complete, energize or unshield the radiation source to let the rays pass through the material to expose the film.

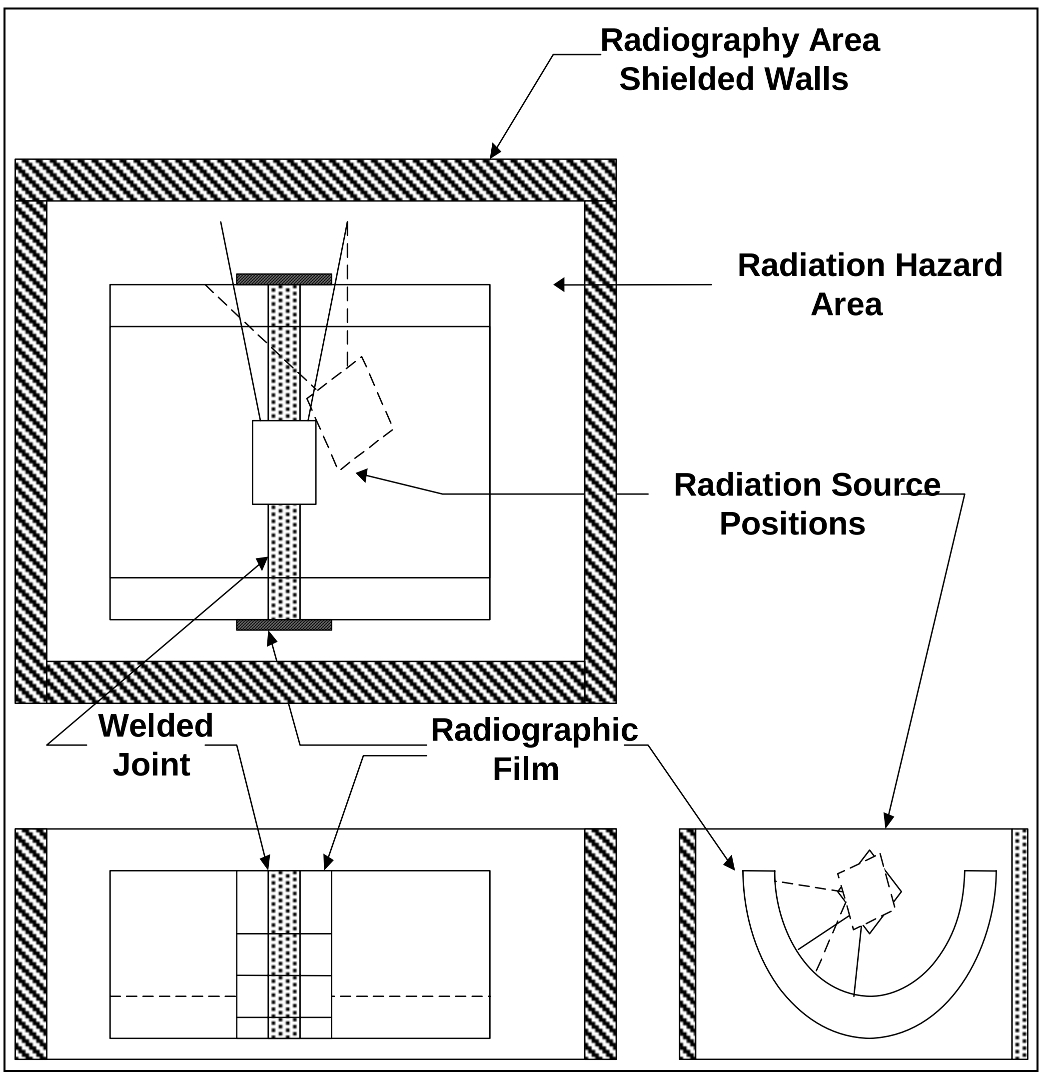
Developing the film in a similar manner to photographic film produces an image of defects or inclusions in the material. More advanced radioluminescent film does not require photographic processing. Varying angles provides a complete picture of the thickness of the material. Dual angles are required to determine the size and orientation of an inclusion.

Once the type, size, and orientation of each inclusion are defined, they can be classified into either acceptable inclusions or unacceptable defects.

Defects in the material must be located for minimal material removal while completely eliminating the defect. Minimizing material removal also supports reduction in repair cost and reduces the likelihood of additional defects created by the repair. The repair is then re-evaluated to assure the defect removal and subsequent repair were conducted properly.

Radiography usually requires that the material be moved to a special shielded area (Figure 6-5) and sometimes requires evacuation of personnel from the vicinity. Temporary shielding may also be installed, but is labor intensive. Radiography technicians are trained in radiation health physics and material properties and can distinguish welding slag inclusions, porosity, cracking and fatigue when analyzing radiographic images.

Figure 6-5. Shielded Radiography Enclosure



6.8.1.2 Ultrasonic Testing (Imaging)

Ultrasonic testing (UT) detects deep subsurface defects and often complements radiography in inspecting welds and base material. UT does not produce the harmful radiation encountered with radiography.

UT inspection is based on the difference in the wave-reflecting properties of defects and the surrounding material. An ultrasonic signal is applied through a transducer into the inspected material. The speed and intensity with which the signal is transmitted or reflected to a transducer provides a graphic representation of defects or discontinuities within the material. A couplant fluid is often used to provide a uniform transmission path between the transducer, receiver, and the material. Transducer configurations differ depending on the type of system used.

Some systems use a single transducer to transmit and receive the test signal. Others utilize a transmitting transducer in conjunction with a separate receive transducer. Dual transducer systems may be configured with both transducers on the same surface of the material or with transducers on the opposite surfaces of the material.

A-Scan, B-Scan, and C-Scan are the most common systems. A-Scan systems analyze signal amplitude along with return time or phase shift as the signals travel between a specific surface and discontinuities. B-Scan systems add signal intensity modulation and capability to retain video images. C-Scan systems include depth gating to eliminate unwanted returns.

UT inspection is a deliberate process covering a small area (four to eight square inches) at each sampling. Consistency in test method and interpretation of results is critical to reliable test results. Surface preparation is also critical to reliable UT results. Surface defects adversely affect the reliability of UT results.

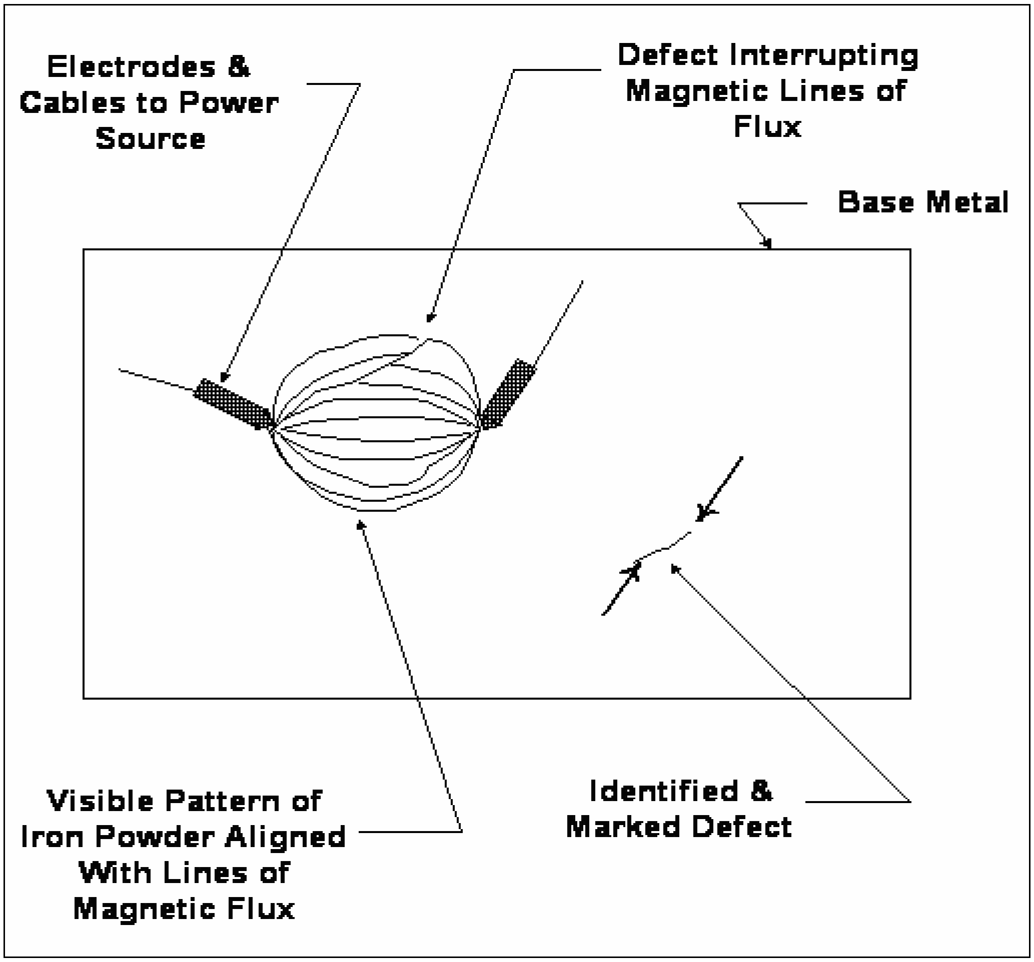
UT inspections are often conducted on representative sites such as high stress, high corrosion areas and large welds. By evaluating the same sites at regular intervals, monitoring the condition of the material can be accomplished. 100 percent UT inspection is typically reserved for original construction of high stress components such as nuclear reactor vessels or chemical process vessels.

6.8.1.3 Magnetic Particle

Magnetic Particle Testing (MT) locates shallow subsurface defects. MT techniques are useful during localized inspections of weld areas and specific areas of high stress or fatigue loading. Two electrodes are placed several inches apart on the surface of the material of interest. An electric current is passed between the electrodes producing magnetic lines. While the current is applied, iron ink or powder is sprinkled in the area of interest. The iron aligns with the lines of flux. Any defect in the area of interest will cause distortions in the lines of magnetic flux, which will be visible through the alignment of the powder, as illustrated in Figure 6-6. Surface preparation is important since the powder is sprinkled directly onto the metal surface and major surface defects will interfere with sub-surface defect indications. Electrode contact and placement assures consistent strength in the lines of magnetic flux.

A major advantage for MT is its portability and speed of testing. The electrodes are hand-held which allows the orientation of the test to be changed in seconds. This allows for inspection of defects in multiple axes of orientation. Multiple sites can be inspected quickly without interrupting work in the vicinity. The equipment is portable and is preferred for on-site or in-place applications. The results of MT inspections are recordable with a high quality photograph or transfer to tape. Fixing compounds are available to "glue" the particle pattern in-place on the test specimen. Interpretation of results is dependent on the experience of the operator.

Figure 6-6. Magnetic Particle Testing



6.8.1.4 Dye Penetrant

Dye Penetrant (DP) inspections detect surface defects in non-porous materials. DP allows large areas to be quickly inspected. Once the surface has been cleaned, a penetrating dye (magenta or fluorescent color) is sprayed liberally on the entire surface. Allow the dye to penetrate for several minutes. Wipe the excess dye, leaving only the dye in surface defects. A developer (usually white) is sprayed on the entire surface. The developer draws the dye from the defects, producing a visual indication of the presence of surface defects. The defective areas are then identified for repair and the remaining dye and developer are removed.

6.8.1.5 Hydrostatic Testing

Hydrostatic testing detects breaches in a system's pressure boundaries. Hydrostatic Testing is an NDT method for detecting defects that completely penetrate pressure boundaries. Hydrostatic tests are typically conducted prior to the delivery or operation of completed systems or subsystems that act as pressure boundaries. As the name implies, hydrostatic tests fill the system to be tested with water or the operating fluid. The system is then sealed and pressure increased to approximately 1.5 times operating pressure.

This pressure is held for a defined period. During the test, inspections are conducted for visible leaks, pressure drop, and water additions. If the pressure drop is out of specification, the leak or leaks must be located and repaired.

The principle of hydrostatic testing can be used with compressed gases. Called an air drop test, it measures the integrity of high-pressure air or gas systems.

6.8.1.6 Eddy Current Testing

Also known as electromagnetic induction testing, eddy current testing provides a portable and consistent method for detecting surface and shallow sub-surface defects. This test inspects metal components for defects or homogeneity. By applying rapidly varying AC signals through coils near the surface of the test material, eddy currents are induced into conducting materials. Any discontinuity that affects the material's electrical conductivity or magnetic permeability will influence the results of this test. Component geometry must also be taken into account when analyzing results from this test.

A set of magnetizing coils induces electrical currents (eddy currents) into the component being tested. The induced currents produce magnetic fields, detected by a set of sensing coils. The two sets of coils are combined into a single probe. In some systems, Hall effect devices are used instead of sensing coils.

The frequency of the AC signals used (5 to 10M Hz) determines the depth of penetration through the material for the eddy currents. Lower excitation frequencies increase the penetration depth and improve the effectiveness in detecting deeper defects. Higher frequencies are utilized to enhance detection of surface defects. Analysis equipment senses several parameters including magnitude, time lag, phase angles and flow patterns of the resulting magnetic fields. Automated analysis methods reduce the reliance on operator experience for consistent results.

6.8.2 Location & Intervals

Prior to implementing an NDT program, develop a formal plan detailing the type of technique to be used, location, frequency, number and orientation of samples, information sought, and failure mode that each sample addresses. This plan will point out excessive testing and omissions from the NDT Program. Two more difficult variables to address are location and interval (time period) between inspections.

6.8.2.1 Intervals

When establishing sample intervals or frequency, several factors must be weighed. Operating cycle of the system, historical failure rate, type of container material, type of contained substance, chemistry control, major corrosion mechanisms, expected corrosion rate, erosion mechanisms, expected erosion rate, proximity of existing material to minimum wall thickness, consequences of system breach, and type of NDT techniques applicable to the situation will affect the inspection interval (Table 6-3). Other factors may enter into consideration, if warranted.

American Petroleum Institute (API 570) recommends the following criteria for establishing intervals for NDT inspection.

Table 6-3. Recommended Maximum Inspection Intervals (API 570)

Piping Circuit Classification	Thickness Measurements	External Visual Inspection
Class 1	5 Years	5 Years
Class 2	10 Years	5 Years
Class 3	10 Years	10 Years
Injection Points	3 Years	By Class
Soil-to-Air Interfaces	—	By Class

In-place corrosion rates affect and are relevant to remaining life calculations.

$$\text{Remaining Life} = \frac{t_{actual} - t_{min}}{\text{annual corrosion rate}}$$

- Remaining life = Number of years until thickness reaches minimum.
- t_{actual} = Actual minimum thickness at time of most recent inspection.
- t_{min} = Minimum allowable thickness for the limiting section.
- Piping circuit classification where Class 1 has the highest potential of resulting in an immediate emergency and Class 3 has the lowest potential if a leak were to occur.

Consider relevant regulatory requirements when determining NDT inspection intervals. Many government regulations provide sufficient leeway for the experts within an organization to set intervals in accordance with technically sound methods. Some regulations require a technically sound plan that the organization follows.

Before accepting an apparently unreasonable interval due to regulatory compliance, investigate the document that originates the requirement. In industry, many regulatory requirements have been needlessly made more stringent by the philosophy, “If a little is good, a lot must be better.” In an effort to avoid falling afoul of regulatory inspectors, inspection costs were significantly increased without a corresponding increase in plant safety or reliability. Investigate basic requirements; if these are unclear ask the originating agency for clarification of their expectations.

After the base inspection intervals have been established based on corrosion rate, class, and regulatory requirements, specific system intervals can be modified based on actual conditions, historical data, and operating parameters. Evaluate intervals based on operating conditions, previous history, current inspection results or other indications of other than normal conditions. By conducting statistical analysis on historical NDT results and failure rates, intervals can be refined with a higher level of confidence. Pareto and Weibull analysis techniques can be applied to indicate systems where unusual failure rates are occurring.

Coupons can be utilized to provide specific information on the corrosion rate, allowing further refinement of inspection intervals.

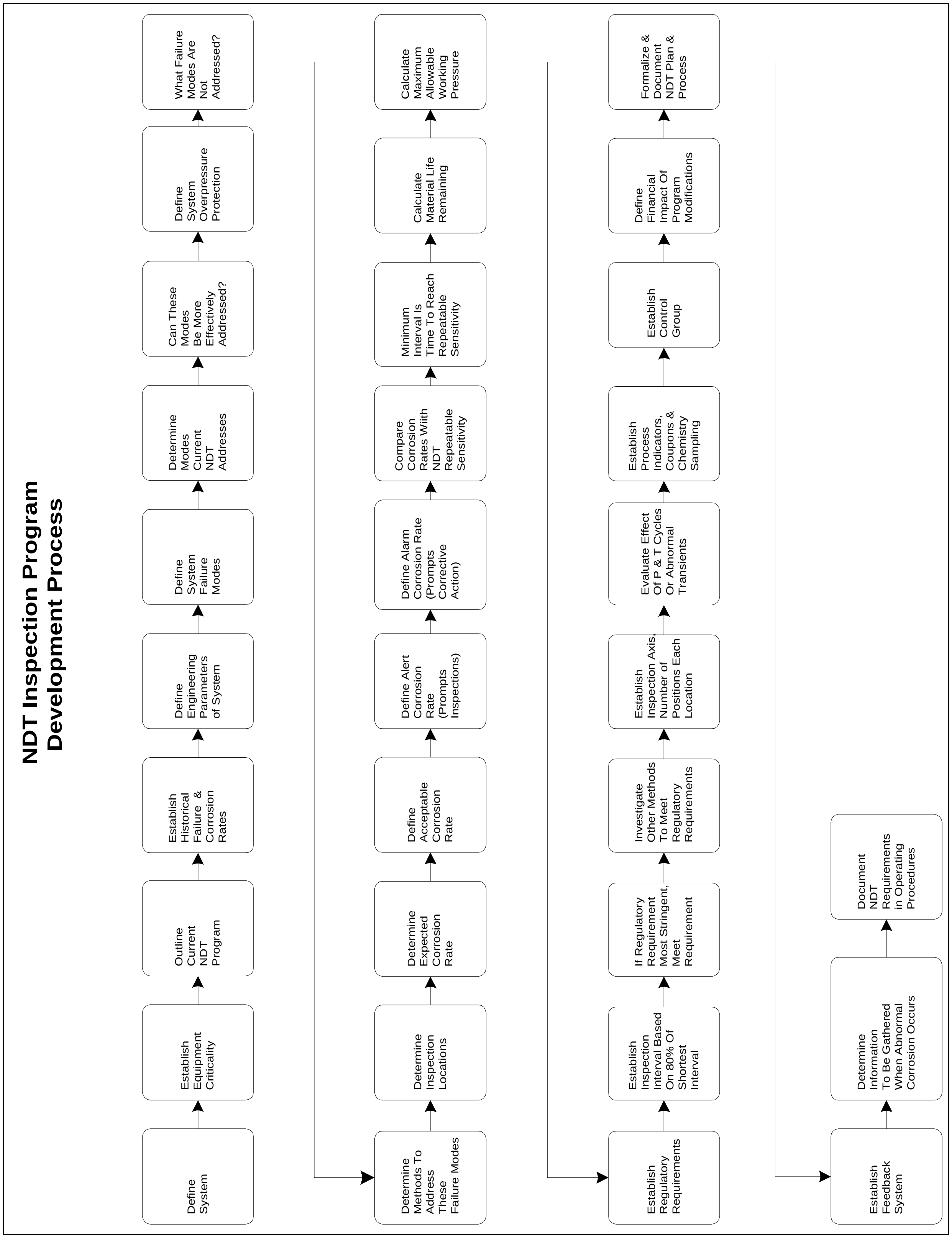
Process parameters can be used as a “trigger” for specific NDT inspections (Figure 6-7). Changing thermodynamic properties indicate increased corrosive product deposits. Analysis of fluids transported within the system can also indicate changes in corrosion activity, allowing NDT inspection schedules to be appropriately adjusted. Procedures for addressing adverse events such as over-pressurization and out-of-specification temperatures should include the requirement for more frequent or immediate NDT inspections. Details of type, location, parameter of concern, and acceptable value should be indicated to facilitate a safe and expeditious recovery from the incident.

6.8.2.2 Locations

The following should act as guidelines for locating NDT sampling points:

- Abrupt changes in direction of flow (elbows) and changes in pipe diameter will cause turbulence that may accelerate many corrosion mechanisms.
- Turbulence or stagnant areas where material may accumulate and set up corrosion cells.
- Junctions of dissimilar metals; galvanic corrosion is prevalent in these areas.
- Stressed areas, welds, high stress fasteners, and areas that undergo cyclic temperature, pressure, or flow changes.
- Some applications may warrant specifying top, middle or bottom of pipe or areas where more than one phase of a substance is present.
- Areas where accelerated corrosion/erosion mechanisms have been identified.
- Areas susceptible to cavitation.

Figure 6-7. Inspection Program Development



6.8.3 Applications

6.8.3.1 Radiography

Radiographic techniques are readily applicable to metal components including weld deposits. Specialized applications for plastics or composite materials are possible, though typically these materials are not most economically inspected with radiography. For thick cross-sections, radiography is often the only reliable method for inspection.

6.8.3.2 Ultrasonics

Ultrasonic techniques are readily applicable to metal components including weld deposits. Specialized applications for plastics or composite materials are common. UT is preferred to radiography for in-place applications due to expense and safety issues. UT is especially useful since it only requires access to one surface of the material. Ultrasonic techniques provide excellent penetrating power for thick cross-sections.

6.8.3.3 Magnetic Particle

Magnetic particle techniques apply only to materials that conduct electric current and magnetic lines of flux; only shallow defects are detectable. These techniques are most effective on welded areas. The speed of testing allows multiple inspections to be conducted along different axes to detect defects in different orientation planes.

6.8.3.4 Dye Penetrant

Dye Penetrant inspections apply to any non-porous material that is chemically compatible with the dye and developer.

6.8.3.5 Hydrostatic Testing

Hydrostatic testing examines the integrity of pressure boundaries for components and completely assembled systems that contain pressurized fluids or gases. Identification of defects that penetrate the entire pressure boundary is the primary application for hydrostatic testing.

6.8.3.6 Eddy Current

Eddy current techniques detect internal defects such as cracks, seams, holes, or lamination separation on flat sheets and complex cross-sections. Eddy currents also monitor the thickness of metallic sheets, plates, and tube walls. Portable systems are used extensively in the condition monitoring of installed heat exchanger and chiller tube wall thickness. Where coating thickness is an important factor, there is sufficient difference in electrical or magnetic properties between the base material and the coating. Eddy current testing can determine the actual coating thickness. In more production-oriented applications, installed systems can determine material composition, uniformity, and thickness of materials being produced.

6.8.4 Limitations

6.8.4.1 Radiography

Effective use of radiography mandates expensive equipment, extensive safety precautions, and skilled technicians to interpret the images. Expensive tracking and security for radiation sources is mandatory. Safety precautions often demand evacuation of areas adjacent to the material being examined or installation of extensive shielding. Radiography is often the most effective method of assuring integrity of critical welds, structural members, and pressure boundaries. As material thickness increases, radiography is often the only acceptable method to achieve a 100 percent penetration.

6.8.4.2 Ultrasonics

Ultrasonic techniques are one-dimensional. Unless special techniques are applied, defects that parallel the axis of the test will not be apparent. Components constructed using laminate techniques or layered construction present special problems for UT techniques because the boundary between each layer may be interpreted as a defect. The thicker the layers of base material, the more likely UT will provide usable results.

6.8.4.3 Magnetic Particle

Magnetic Particle techniques are applicable only to materials that conduct electrical current and influence magnetic lines of flux. The difference in the influence of the lines of flux between base material and the defect is the basis for MT inspection. Only small areas (30 square inches) between the two electrodes can be inspected. Surface preparation is important, though not as critical as with UT. Consistent electrode contact is critical. Loose contact will weaken the magnetic lines of flux to the point where the influence of a defect may not be visible in the filing pattern. Operator skill is important, though this is a relatively simple technique. No historical record is produced for each test, unless specific steps are taken to photograph the result of each test.

6.8.4.4 Dye Penetrant

Minute surface discontinuities such as machining marks are readily apparent. The inspector must distinguish between normal surface discontinuities and defects that require repair. The dye and developer are usually sprayed or painted on the piece to be inspected, so over-spray and protection of internal surfaces are prime concerns for systems with stringent chemistry and cleanliness control. Product cleanliness standards may prohibit the use of Dye Penetrant inspection.

6.8.4.5 Hydrostatic Testing

Cleanliness and chemistry control of the fluid must be consistent with the operating standards of the system. Close attention should be given to controlling system thermodynamic parameters during the test to prevent over-pressurization of the system. Over-pressurization could lead to unintended damage to the system. Individual component hydrostatic tests do not assure system integrity. A final hydro of the completed system is used to assure the integrity of the assembled system’s pressure boundary. Hydrostatic tests will not identify defects that are present, but have not completely penetrated a pressure boundary. The pressure applied to the system is generally not sufficient to enlarge existing defects to the point of detection by the test. Hydrostatic testing requires a pressure source capable of expeditiously filling and pressurizing the system, extensive instrumentation and monitoring equipment along with a sufficient quantity of fluid to fill the system. A method of isolating pressure relief devices and connecting the pressure source to the system must be provided.

6.8.4.6 Eddy Current

Eddy currents flow parallel to the surface to which the exciting field is applied. Some orientations of laminar discontinuities parallel to this surface tend to remain undetected by this method. Eddy Current Testing will not penetrate deeply into the material of interest, so it is limited to shallow sub-surface and surface defects.

6.9 PHOTOGRAPHY

6.9.1 Introduction

This section discusses the uses of photography, including still (normal and high speed), video taping, and other imaging devices such as borescopes. Photography can be used at the microscopic level such as to document material failure due to fatigue, overload, corrosion, and process induced failures. Photography is also applicable on a macroscopic level, such as to document events occurring at the component or system level.

Photography can document operating sequence and abnormal conditions as part of failure analysis. Photographic evidence should maintain the proper perspective and orientation of the incident site. This can be accomplished by taking an overall picture of the system and/or process and then zooming into the areas of interest. When appropriate capture a photographic record of the entire volume of the incident area. Events and the accompanying debris are usually not limited to one plane.

A borescope, for example, can be used to capture images inside components such as piping and ducts, engines, motors, pumps, generators, sewer lines, and in many venues which are inaccessible for reasons beyond geometrical limitations.

6.9.2 Applications of Photography

The following list provides a starting point for using photography in the facilities environment:

- Document before and after conditions at a work site
- Capture sequence of operations
- Internal inspections via borescope of inaccessible components
- Aftermath of incidents – man made and natural
- Preparation of a Request for Proposal bid package
- Document training
- Document maintenance processes

High speed photography can be used to document the start-up, operation, and shutdown of systems and equipment. Specific examples are cranes, elevators, lifts, presses, and equipment programmed with automatic sequencing such as forming, cutting, and packaging machines. Filming the initial start-up of critical systems such as generators, automatic transfer switches and paralleling switchgear allows the event to be used for future training of M&O personnel as well as providing a visual record of the start-up and testing.

In summary, any event occurring at a speed greater than the human eye can resolve is a candidate for high speed photography.

6.9.3 High Speed Photography[23]

Photography with exposure times shorter than 1/1000 second is considered high speed work, often requiring special techniques. To arrest motion in a picture, either (1) use the shortest exposure possible or (2) move the camera in synch with the subject, thereby permitting the background to blur. A formula for the maximum permissible exposure time is:

$$T = \frac{L}{500} \text{ x V seconds}$$

- Where L = the largest subject to be recorded
- V = the subject speed (in the same units as L per second)

For examples, for a car moving at 86 mph (100 feet per second), the longest frame dimension L may be 50 feet. Thus

$$T = \frac{50}{500} \text{ x } 100$$

Or T = 1/1000, just inside the range for a normal shutter with no camera motion. Note that both V and L determine the exposure time; increasing V or decreasing L both demand shorter exposures. Many research subjects are both faster and smaller than a car, requiring more advanced photography.

Another method for determining exposure time is based on the concept of maximum allowable blur based on subject dimensions. A decision on this dimension at the subject may be influenced by several factors, each depending on user-defined criteria. These may include: total absence of blur at a given degree of magnification of the reproduction and size of the smallest object within the subject that requires detailed recording. The formula, which takes into account the direction of subject motion, is:

$$T = \frac{\text{Size of smallest detail within subject}}{(\text{K})(\text{Velocity of subject})(\cos\text{A})}$$

- Where K is a quality constant, generally a number between 2 and 4
- A is an angle between film plane and subject direction

Even a small object requiring detail as minute as 1/200 inch and moving at the relatively slow speed of 100 feet per second requires an exposure as short as four microseconds, or 1/250,000 second.

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[23] This section, used with the author's permission, is based on *High Speed Photography* by Andrew Davidhazy, Imaging and Photographic Technology Department School of Photographic Art and Sciences, Rochester Institute of Technology.

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7.0 PREDICTIVE TESTING AND INSPECTION CRITERIA

7.1 BASELINES

Baseline data is the Predictive Testing and Inspection (PT&I) data representative of equipment in operating condition. Baseline data is used as the comparison for future measurements on similar units. It is the foundation of the PT&I trending analysis required to forecast equipment condition.

Baseline data should be established early in the life of the equipment. The baseline readings and periodic monitoring data should be taken under similar conditions and recorded. Baseline readings should be re-established whenever equipment undergoes major maintenance, repair, or usage changes including the operating environment and input and output parameters.

7.2 CRITERIA BY PT&I TECHNOLOGY

7.2.1 Vibration Monitoring

Vibration amplitude varies with operating speed, load, and mounting arrangement, so criteria should also consider the frequency content of the spectrum. Criteria must consider the differences between reciprocating machines and centrifugal machines.

The following vibration specifications are based on International Organization of Standards (ISO), American Petroleum Institute (API), American Gear Manufacturers Association (AGMA), American National Standards Institute (ANSI), MIL-STD-167-1, MIL-STD 740-2 (Appendix C), General Motors Vibration Specifications, and field data acquired on a variety of machinery.

- **Developing Vibration Criteria**. Specific vibration criteria are provided in this guide where possible. Where specific criteria are not provided, the procedures provided in the above references are recommended in developing the vibration criteria.

- **Vibration Analysis of New Equipment**. For all large or critical pieces of equipment assembled and run at the factory prior to shipment, a narrowband vibration spectrum should be acquired at the locations listed in Section 10.1.17 Vibration Monitoring of this guide while the equipment is undergoing this factory performance testing. A baseline or reference spectrum should be retained for comparison with the post-installation vibration check. Equipment failing the vibration criteria should be rejected by the Government prior to shipment.

7.2.1.1 Vibration Criteria for Electric Motors

Vibration criteria for electric motors are listed below.

Balance

The vibration criteria listed in Table 10-1 Motor Balance Specifications are for the vibration amplitude at the fundamental rotational frequency or one times running speed. This is a narrowband limit; an overall reading is not acceptable.

Additional Vibration Criteria

All testing should be conducted at normal operating speed under full load conditions. Suggested motor vibration criteria are provided in Table 10-2 Motor Vibration Criteria. In addition, Appendix E contains criteria for common machines and an example of how to calculate criteria.

Rewound Electric Motors

Due to the potential for rotor and stator damage incurred during the motor rewinding process, a rewound electrical motor should be checked both electrically and mechanically. The mechanical check should include post-overhaul vibration measurements at the same location as for new motors. The vibration level at each measurement point should not exceed the reference spectrum for that motor by more than 10 percent. In addition, vibration amplitudes associated with electrical faults such as slip, rotor bar, and stator slot should be noted for any deviation from the reference spectrum. (Note: Rewinding motor will not correct problems associated with thermal distortion of the iron.)

7.2.1.2 General Equipment Vibration Standards

If rolling element bearings are utilized in either the driver or driven component of a unit of equipment (e.g., a pump/motor combination), no discrete bearing frequencies should be detectable. If a discrete bearing frequency is detected, the equipment is considered unacceptable.

For belt-driven equipment, belt rotational frequency and harmonics should be undetectable. If belt rotation and/or harmonics are detectable, the equipment is considered unacceptable.

If no specific criteria are available, the ISO 3945 acceptance Class A guidelines (Appendix C) should be combined with the motor criteria contained in Table 7-2 and used as the acceptance specification for procurement and overhaul.

Specific Equipment

Use the criteria shown in Table 10-3 Pump Vibration Limits on boiler feed water, split case, and progressive cavity pumps.

Belt Driven Fans

Use the criteria in Table 10-4 Belt Driver Fan Vibration Limits for belt-driven fans.

Vibration Guidelines (ISO)

Table 10-5 ISO 10816-1: 1995(E) Typical Zone Boundary Limits is based on International Standards ISO 3945 (Appendix C) and should be used as a guideline for determining the acceptability of a machine for service. The vibration acceptance classes and ISO 3945 machine classes are shown in Table 10-6 Vibration Acceptance Classes and Table 10-7 Machine Classifications respectively. The ISO amplitude values are overall measurements in inches/second RMS while the recommended specifications for electric motors are narrowband measurements in inches/second peak.

7.2.2 Lubricant and Wear Particle Analysis

Lubricant analysis monitors the actual condition of the oil. Parameters measured include viscosity, moisture content, flash point, pH (acidity or alkalinity), the levels of additives in lubricants, and the presence of contaminants such as fuel, solids, and water.

Tracking the alkaline nature of the lubricant permits the identification of an undesirable degree of oxidation, gauging the ability of the lubricant to neutralize contaminants, and aids in the verification of the use of the correct lubricant after a lubricant change. Viscosity provides a key to the lubricating qualities of the lubricant. These qualities may be adversely affected by contamination with water, fuel, or solvents or by thermal breakdown or oxidation. The presence of water reduces the ability of the lubricant to effectively lubricate, promotes oxidation of additives, and encourages rust and corrosion of metal parts.

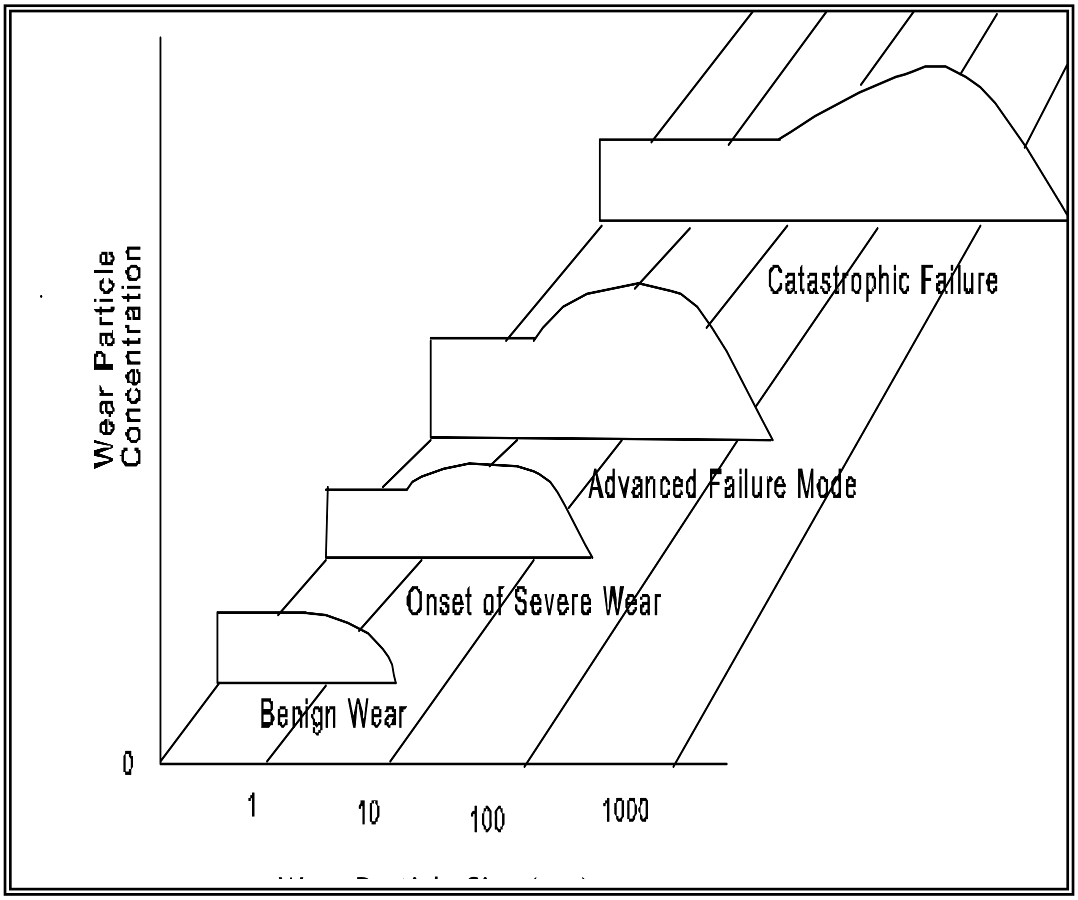
A spectrometric analysis can detect the presence of water in lubricants. To perform a spectrometric analysis, burn a small amount of the fluid sample and analyze the resulting light frequencies and intensities to determine the type and amount of compounds present based on their absorption of characteristic light frequencies. Compare sample results to the characteristics of the same new lubricant to measure changes reflecting the lubricant's reduced ability to protect the machine from the effects of friction.

The continued presence of desirable lubricant additives indicates lubricant quality. Infrared spectrometry is also capable of detecting and measuring the presence of organic compounds such as fuel or soot in the lubricant sample.

In wear particle analysis, analysts examine the amount, makeup, shape, size, and other characteristics of wear particles and solid contaminants in the lubricants as indicators of internal machine condition. Analyzing and trending the amount, size, and type of wear particles in a machine's lubrication system can pinpoint how and where degradation is occurring. With experience and historical information, degradation rates and estimated time until machine failure can be projected. Wear particle analysis includes ferrography, a technique that analyzes metal wear products and other particulates. Elemental spectrographic analysis is used to identify the composition of small wear particles and provide information regarding wear sources.

Figure 7-1 illustrates the relationship between wear particle size, concentration, and equipment condition.

Figure 7-1. Conceptual Wear Particle Size and Equipment Condition



7.2.3 Thermography

There are two basic criteria for evaluating temperature conditions: differential temperature (ΔT) and absolute temperature.

7.2.3.1 Differential Temperature

Temperature difference (ΔT) criteria provide a simple and adequate qualitative screening system to identify thermal exceptions and problems. Temperature difference criteria compare component temperature to the ambient temperature and may be used for electrical equipment and mechanical components.

Typical ΔT criteria, which may be modified to allow for variance in environmental and operating conditions, are shown in Table 7-1.

Table 7-1. Actions Required Based on Temperature Rise under Load

Temperature Rise	Action
10-25°F	Repair at Convenience
25-40°F	Repair Next Scheduled Availability
40-80°F	Repair at First Availability
> 80°F	Repair Immediately

7.2.3.2 Absolute Temperature

Absolute temperature criteria are generally specific to an equipment model, type of equipment, class of insulation, or service use. Thus absolute temperatures are suited to quantitative infrared thermography and critical temperature applications. The mechanical temperature specifications come primarily from manufacturer's manuals. Electrical temperature specifications are set by the following three principal electrical standards organizations:

- National Electrical Manufacturers Association (NEMA), Appendix C.
- International Electrical and Electronic Engineers (IEEE), Appendix C.
- American National Standards Institute (ANSI), Appendix C.

Table 7-2 provides absolute temperature limits for materials commonly found in government plants.

Table 7-2. Temperature Limits for Selected Components

Component	Temperature (°C)
Bearings, Roller Element Type	
Races/Rolling Elements	125
Retainers (plastic)	120
Cages/Retainers/Shields (metal)	300
Bearings, Plain Type	
Tin/Lead Based Babbitt	149
Cadmium/Tin-Bronze	260
Seals, Lip Type	
Nitrile Rubber	100
Acrylic Lip	130
Silicone/Fluoric	180
PTFE	220
Felt	100
Aluminum (lab)	300
Mechanical Seal Materials	
Glass Filled Teflon	177
Tungsten Carbide	232
Stainless Steel	316
Carbon	275
V-Belts	60

7.2.4 Airborne Ultrasonics

The use of a passive ultrasonic instrument as a leak detector (listening for the ultrasonic noise characteristic of a pressure/vacuum leak) is qualitative. There are no numerical thresholds. Many common passive ultrasonic devices operate on a relative absolute scale. However, by using relative changes in intensity from baseline readings, the degradation process may be trended and tracked.

Volumes containing different gases with a flow path will cause a high frequency (usually greater than 20kHz) noise emanating from the location of the leak. However, there are no set guidelines to correlate leak rates to frequency or amplitude, similar to measuring corona discharge and high frequency bearing tones where a lack of lubrication and/or presence of hard particle contamination will cause the bearing to resonate at the natural frequency of the outer ring.

7.2.5 Motor Circuit Analysis

Motor circuit analysis (MCA) measures natural electrical motor circuit characteristics such as:

- Individual phase resistance from bus disconnect through the motor windings (milli-ohms)
- Inductance of the motor coils (millihenries)
- Capacitance of each phase to ground (picofarads)

During the same test series, one can measure resistance to ground of each phase (megohms) through the use of low voltages (both AC & DC) and low currents, which are not harmful to the motor or motor circuits. The following procedures are recommended when performing MCA:

- De-energize the circuit (comply with safety instructions)
- Eliminate stray currents/voltages
- Do not disconnect/exclude components except:
  - Power factor correction capacitors
  - Solid state controllers
- Place as much of the circuit under test as possible, including:
  - Disconnects
  - Motor controller contactors
  - Circuit breaker(s)

A motor circuit analysis test set indicates circuit problems in electrical terms for maintenance personnel to pinpoint and correct faults. This test can also measure post-repair performance.

7.2.5.1 <u>MCA Resistance Imbalance Guidelines</u>

Conductor Path Resistance Imbalance Guidelines

- Less than 2 percent: Expected and acceptable when new.
- Greater than 5 percent: Plan troubleshooting to locate cause of increased resistance when convenient.
- Greater than 10 percent: Schedule effort to locate and eliminate problem in order to preserve motor life.

$$\text{Where: } R_{avg} = \frac{(R_1 + R_2 + \cdots R_n)}{n}$$

$$\% \ Imbalance = \frac{R_{high} - R_{avg}}{R_{avg}} X \ 100$$

- Where R_{high} is the highest of the phase resistances
- R_{avg} is the average of the phase resistances
- R_1, R_2, … R_n refer to the number of electrical phases

Inductive Imbalance Guidelines

- Less than 10 percent: Acceptable from OEM or rewind shop.
- Between 10-15 percent: Acceptable in service.
- Greater than 15 percent: Isolate cause(s), increase monitoring frequency.
- Greater than 25 percent: Begin planning for motor repair or replacement.
- Greater than 40 percent: Be prepared for failure, within weeks.

$$Where: \ X_{avg} = \frac{(X_1 + X_2 + \ldots X_n)}{n}$$

$$\% \ Imbalance = \frac{X_{high} - XR_{avg}}{X_{avg}} X \ 100$$

7.2.5.2 <u>MCA Capacitance Imbalance Guidelines</u>

Capacitance imbalance is reflective of moisture and dirt in the vicinity of motor circuit components. Analysis is performed by trending and by making relative comparisons as follows:

- Take initial reading.
- Compare readings for similar motor circuits.
- Compare follow-on readings, watch for upward trends.
- Identify significant differences and schedule inspection to resolve differences.

7.2.6 Motor Current Signature Analysis

Mechanical and electrical interactions associated with magnetic forces in and around the rotating element of a motor are “reflected” in and around AC power supply cables. They are readily identifiable and display repetitious flux field characteristics centered at the electrical power line frequency (F_L) of 60 Hz (3600 CPM). By analyzing the AC power line frequency and its motor generated sidebands, motor current signature analysis may be used to detect:

- Broken rotor bars or high resistance joints (braze, crack).
- Defective rotor shorting rings (alignment, porosity, integrity).

- Rotor and stator (air gap) eccentricity (dynamic and static).
- Unbalanced magnetic pull.

As the difference between the amplitude of the power line frequency and the pole pass sideband frequencies decreases in magnitude, the greater concern is for the condition of the rotor. Results indicate:

- A slight decrease may trigger increased monitoring.
- A moderate decrease may indicate increasing resistance between the rotor bars and the end ring or that a crack is developing in either.
- Further decreasing values indicate rotor bar breaks.

7.2.7 Insulation Resistance

There are several forms of insulation resistance measurement.

7.2.7.1 Megohmmeter Testing

Megohmmeter testing measures phase-to-phase and phase-to-ground resistance. While it provides an overall indication of insulation condition, reliable trending requires temperature correction.

7.2.7.2 Dielectric Absorption Ratio and Polarization Index

Insulation resistance ratios are frequently used to evaluate insulation-to-ground conditions in order to avoid compensating for temperature. A single DC voltage, usually slightly higher than the motor rated voltage, is impressed continuously on a winding. The current induced by the DC voltage has three components:

- Capacitive charging of the circuit, which fades quickly.
- Leakage current to ground, a constant value.
- Current, which polarizes the molecules of the insulation surrounding the motor circuit conductor path and fades slowly from its initial value.

The ratio of readings taken at two different times indicates the condition of the insulation, as follows:

$$\frac{\text{Megohm Reading at 1 Minute}}{\text{Megohm Reading at 30 Seconds}} = \text{Dielectric Absorption RatioA}$$

- Greater than 1.5 = OK
- Less than 1.25 = Danger

$$\frac{\text{Megohm Reading at 10 Minutes}}{\text{Megohm Reading at 1 Minute}} = \text{Polarization Index}$$

- Greater than 2 up to ~4 = OK
- Less than 2 insulation = Weak
- Greater than 5 insulation = Possibly too dry and brittle

7.2.7.3 Leakage Current

Leakage current indicates insulation condition and cleanliness of the equipment. The accumulation of dirt and moisture provides a path for leakage current. There are no absolute values to gauge the deterioration of insulation using leakage current. The comparison of successive values permits the comparison and trending of leakage current.

7.2.8 Surge Testing

A surge test uses high voltage, high energy discharge pulses inserted into two windings of a polyphone motor simultaneously. The pulses cycle between motor windings and the test set. The test indicates the voltage level at which the insulation breaks down. Current waveform analysis may indicate problems.

When using surge testing, the Electric Power Research Institute notes the following:

- The surge test could be destructive, inducing failure in weakened turn to turn insulation. For this reason, test impulse voltage levels and rise times should be carefully selected.
- The surge test does not provide information that will allow making an assessment of remaining life.
- Experience is required to perform the test and to interpret its results, especially if complete windings rather than individual coils are tested.

7.2.9 Start-Up Tests

7.2.9.1 Coast-down time

This test records and trends the time for the motor to coast to a full stop when the power is removed. This data details the mechanical condition of the motor bearings over the life of the machine.

7.2.9.2 Peak starting current

This test involves periodically recording the peak starting current of a motor and provides an indication of the mechanical condition of the motor.

8.0 RCM REQUIREMENTS DURING FACILITIES ACQUISITION

This chapter discusses RCM requirements during the acquisition stage of the facilities life-cycle.

8.1 PLANNING

The planning stages of a new facility should decide the extent of RCM analysis and Predictive Testing and Inspection (PT&I) techniques to maintain a facility and its equipment. These decisions cross organizational lines (i.e., operations, maintenance, and engineering) and should be addressed in the Standard Operating Procedures (SOP) with prior commitment from managers in those organizations.

The amount of built-in condition monitoring, data transfer, and sensor connections to be used are vital decisions. It is more economical to install this monitoring equipment and connecting cabling during construction than later. Planning, designing, and building in the condition monitoring capability ensures it will be available for the units to be monitored. Continuously monitored equipment tied into performance analyzers allows for the controlling of functions and monitoring of degradation. On-line monitors will become increasingly capable and important. Installed systems also reduce manpower requirements when compared to the process of collecting data with a portable data collector. However, for many uses, portable condition monitoring equipment does provide advantages of lower initial cost and flexibility of application when compared to post-acquisition-installed systems.

8.2 PREDESIGN

The Owner's Project Requirements (OPR) and Design Intent documents should address required system and equipment availability, acceptable maximum downtime by system, and overall facility and infrastructure performance.

8.3 DESIGN

The following points should be considered during the design phase.

8.3.1 Maintainability and Ease of Monitoring

In recent years equipment has been designed increasingly to ensure a high level of reliability. By extending this approach to the maintainability and ease of monitoring of equipment during design, reliability is enhanced and maintainability is improved for the full life-cycle of the equipment. Chapter 14.0 contains a detailed discussion on maintainability.

8.3.1.1 <u>Maintainability Factors</u>

- **Access.** Equipment, its components, and facilities should be accessible for maintenance and repairs.
- **Material.** Choose materials for durability, ease of maintenance, availability, and value (life-cycle cost (LCC) vs. special requirements trade-offs).

- **Standardization.** Minimize use of special or one-of-a-kind materials, fittings, or fixtures. Maximize commonality of equipment component parts. Choose standard equipment for multiple uses where feasible.

- **Quantitative Maintenance Goals.** Use quantitative measures of maintenance (i.e., mean-time-between-failure (MTBF), mean time to repair (MTTR), Operational Availability (A_o), and Overall Equipment Effectiveness) to set goals for maintainability which will influence design.

8.3.1.2 Ease of Monitoring Factors

- **Access.** Provide clear access to collect equipment condition data with portable data loggers or fluid sample bottles.

- **On-line Data Collection.** Installed data collection sensors and links (wire, fiber optics, or radio frequency (RF) links are possible) may be justified for high-priority, high-cost equipment or inaccessible equipment.

- **Metrics.** Management or key performance indicators (KPIs/Metrics) are discussed in Chapter 12.0. For an RCM program, the KPIs and the analysis methods are incorporated into the system design. Often the performance parameters monitored for equipment or system control may be used to monitor equipment condition. For example, trending of thermal performance and efficiency for boilers, chillers, and heat exchangers by the BAS can indicate reduced heat transfer capability due to fouling, low refrigerant charge, or burner problems.

- **Performance Measures.** RCM performance measures such as operating time or equipment loading are equipment related. The data to be used and the collection method are incorporated into the system design.

8.3.2 Technology Review

The technology review should be a part of the SOP for new facilities and equipment. Design and acquisition and should address the following six areas.

8.3.2.1 PT&I Review

Conducting a PT&I technology review at an early stage of the design is necessary to establish which technologies are to be used in the RCM program.

8.3.2.2 Maintenance Review

A continuing review of other maintenance programs for new and emergent predictive technologies assists in keeping the program current by incorporating the latest technological developments.

8.3.2.3 Feedback

Update or improve the design based on feedback, prior experience, and lessons learned.

8.3.2.4 Scope of Work

Clearly establish in the Architect & Engineering (A&E) contract scope of work that RCM maintainability and ease of monitoring requirements must be met.

8.3.2.5 Qualification

Contractor qualifications should provide for a demonstration of familiarity and understanding of the PT&I technologies planned for the RCM program.

8.3.2.6 Specifications and Drawings.

The designer should incorporate the RCM lessons learned from the history of similar or identical equipment for optimum life-cycle cost of the equipment and consider the use of condition-based maintenance in lieu of interval-based maintenance and its effect on manufacturer warranties.

Specifications for equipment procurement should incorporate maintainability and ease of monitoring requirements. Maintainability requirements should be specified in terms of an appropriate combination of measurements. It should be made clear that meeting these requirements is an important aspect of equipment performance.

Construction contracts should specify the type of acceptance testing to be performed on building materials and equipment prior to shipment to the building site. The designer should specify the PT&I technologies and related acceptance criteria as part of the post-installation acceptance testing for all collateral equipment and structures. These specifications should be used when determining if a building is ready for occupancy.

Commissioning Plans, pre-functional tests, and functional tests should be written to include RCM requirements.

8.4 CONSTRUCTION

During the construction phase, the progress and quality of construction shall be monitored to ensure that the planning and design work from earlier phases is effectively implemented. This includes monitoring for conformance to specifications, drawings, bills of material, and installation procedures. The following important steps should be taken during construction:

8.4.1.1 Training

The training of personnel in the use of PT&I technologies and equipment should start during construction.

8.4.1.2 RCM Analyses

During the construction phase, the Failure Modes and Effect Analysis (FMEA) should be completed, the maintenance program tasks should be chosen, and maintenance procedures and instructions should be written. See Appendix J for examples of generic FMEA worksheets.

8.4.1.3 Criticality and Probability of Failure

Criticality of equipment and probability of failure for equipment should be determined as well as any single points of failure.

8.4.1.4 Maintenance and Operations

Maintenance and Operations (M&O) personnel should use the construction phase to become familiar with the details of construction which will no longer be easily accessible after the facility is completed. M&O personnel should ensure adequate training is provided on new systems and equipment, and fully participate in all Prefunctional Testing and Functional Testing.

8.4.1.5 Commissioning Agent

The Commissioning Agent should assure the construction contractor properly installs, aligns, and checks the equipment in accordance with the contract specifications and the equipment manufacturer recommendations. The Commissioning Agent should validate the construction contractors Quality Assurance Plan. Incorrect installation can void the manufacturer warranty and lead to premature equipment failure.

8.4.1.6 Equipment

When equipment is specified by performance rather than proprietary name (which is preferable), the contractor should be required to submit catalog descriptions of the intended equipment to provide for approval by the Government. The equipment should be approved by the Government (including the RCM technologists) to ensure it satisfies the requirements of the contract specifications and the design intent. If the contract specifications require that the contractor establish a vibration and thermographic baseline for the equipment, the Government should ensure this is done and the baseline information is properly documented and turned over to the Government with the equipment technical manuals and other information required from the contractor.

8.4.1.7 Turnover

The deliverables required for the turnover to M&O should be set forth in the following manner and addressed in the following contract specifications, as listed by Department of State:

- 01771 Closeout Procedures
- 01781 Operations & Maintenance Data
- 01811 Start-up & Commissioning
- 01821 Demonstration & Training

The M&O related deliverables are divided into the following major categories:

- Maintenance Plan Structure
- Material for Repair and Operations (MRO) Plan Structure
- Table of Equipment
- Training
- M&O Manuals
- Computerized Maintenance Library

8.5 MAINTENANCE AND OPERATIONS

How the facility and its equipment will be operated and maintained to meet the Design Intent must be considered during the planning, design, and construction phases. During these phases, M&O needs are best served by carefully and realistically identifying and defining the PT&I requirements as well as the necessary acceptance testing (commissioning activities), and training and demonstrations to be provided at closeout.

Although the performance of the majority of M&O tasks occur during the operations stage of the life-cycle of the equipment or facility, the following preparatory activities should be carried out during the latter part of the acquisition stage. The tasks listed are usually determined by the specific model number of equipment and cannot normally be performed until the equipment submittals have been finalized.

- Personnel selection
- Training
- Operating procedures preparation
- Maintenance task development
- Special tools requirements
- Review of specifications
- Validation of nameplate data
- Review of the maintenance performed by the construction contractor prior to substantial completion

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9.0 RCM CONSIDERATIONS DURING FACILITIES OPERATION

9.1 RCM PROGRAM DATA

Maintaining an adequate level of funding is a continuous requirement during the life-cycle of a facility. Therefore RCM program data must be input periodically into the Annual Work Plan (AWP), the Five Year Work Plan, and other budgetary planning documents. The collection of data to support these requirements must be scheduled and completed frequently.

Maintenance personnel shall employ modern computerized maintenance management systems (CMMS), Building Automation Systems (BAS), and Energy Management and Control Systems (EMCS) to document RCM maintenance costs, cost avoidance, and program savings. These systems can track building data such as systems and equipment performance, efficiency, uptime, maintenance costs, etc. The introduction of wireless technology allows for two-way data entry, collection and loading, and continuous dynamic connectivity between wireless data collectors and CMMS, BAS, and EMCS.

Because analyzing data regarding performance, cost, availability, failure rates, and energy efficiency requires multiple analytical techniques, the following are recommended for use by the Centers:

- Pareto Analysis
- Statistical Process Control
- Six-sigma (with reservations)

Maintenance personnel shall recognize and document direct maintenance program savings and the less obvious “costs avoided.” This data is vital to the Continuous Improvement (CI) process.

9.1.1 Pareto Analysis

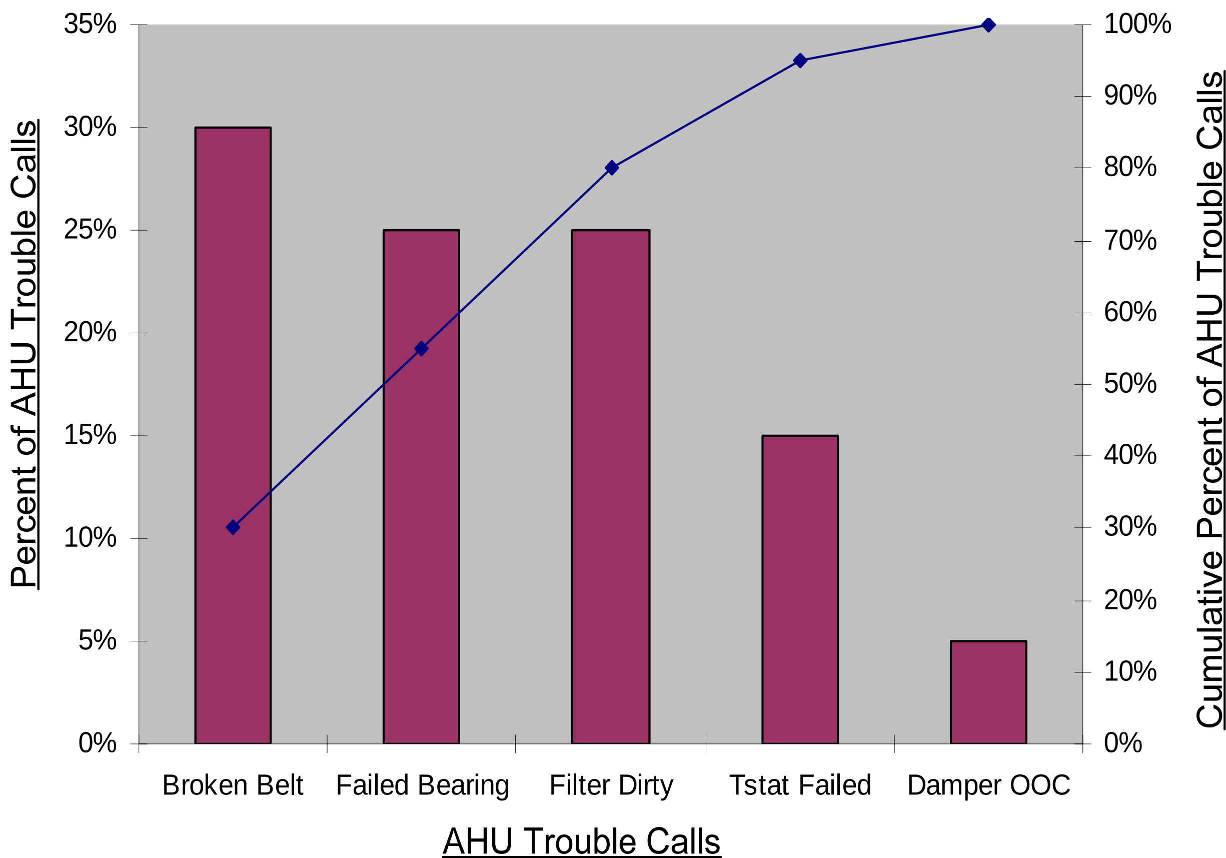
Pareto[24] Analysis tracks the “maintenance burden” which includes the man-hours and labor costs expended on a particular piece of equipment. By identifying where, when, and how (i.e., RM, PM or PT&I) the maintenance occurs, the maintenance burden may be optimally allocated. With labeled maintenance man-hour expenditures, both the high burden items and the distribution of the burden within the facility can be tracked over time. The Pareto analysis uses this data to identify equipment that requires attention or modification to improve effectiveness and reliability. Figure 9-1 provides the seven basic steps for performing a Pareto Analysis.

[24] Vilfredo Federico Damaso Pareto: In 1906 he made the famous observation that twenty percent of the population owned eighty percent of the property in Italy. Joseph M. Juran and others later dubbed it the Pareto principle (also known as the 80-20 rule) and further explored the concept of a Pareto distribution.

Figure 9-1. Seven Steps for Performing a Pareto Analysis

Seven steps to identifying the important causes using Pareto Analysis:

1. Form a table listing the causes and their frequency as a percentage.
2. Arrange the rows in the decreasing order of importance of the causes, i.e. the most important cause first.
3. Add a cumulative percentage column to the table.
4. Plot with causes on x -axis and cumulative percentage on y - axis.
5. Join the above points to form a curve.
6. Plot (on the same graph) a bar graph with causes on x - axis and percent frequency on y -axis.
7. Draw a line at 80% on y -axis parallel to x -axis. Then drop the line at the point of intersection with the curve on x - axis. This point on the x - axis separates the important causes on the left and less important causes on the right.



9.1.2 Statistical Process Control (SPC)

Statistical process control (SPC) is a monitoring process that uses control charts.[25] By collecting data from samples at various points during the process, variations in process that may affect the quality of the end product can be detected and corrected. Unlike quality methods that address problems at end product, SPC emphasizes the early detection and prevention of problems.

SPC can reduce the time required to produce the product or service from end to end. This is due to two factors:

- A diminished likelihood that the final product will have to be reworked.
- SPC data identifies bottlenecks, wait times, and other sources of delays within the process. Process cycle time reductions coupled with improvements have made SPC a valuable tool from both a cost reduction and a customer satisfaction standpoint.

SPC indicates whether an action in a process should occur. For example, heating or cooling the temperature in a room is a process that has the specific, desired outcome to reach and maintain a defined temperature (e.g. 72°F ±4°F) to be kept constant over time. The temperature serves as both the controlled variable and the input variable since it is measured by a thermometer and used to decide whether to heat. The desired temperature is the setpoint. The state of the control valve is the manipulated variable since it is subject to control actions.

A programmable logic controller (PLC) reads a set of digital and analog inputs, applies a set of logic statements, and generates a set of analog and digital outputs. First the room temperature, as the controlled variable and the input variable, is entered into the PLC. Then the logical statements compare the setpoint to the input temperature to determine what action is necessary to maintain a constant temperature. Finally a PLC output either opens or closes the control valve to release the necessary hot water to reach the desired temperature.

In practice, process control systems can be characterized as one or more of the following forms:

- **Discrete.** Found in many manufacturing, motion and packaging applications. Most discrete manufacturing involves the production of discrete pieces of product, such as metal stamping.

[25] Dr. Walter A. Shewhart created the basis for the control chart and the concept of a state of statistical control by carefully designed experiments. While Dr. Shewhart drew from mathematical statistical theories, he understood that data from physical processes seldom produces a "normal distribution curve" (a Gaussian distribution, also commonly referred to as a bell curve). He discovered that observed variation in manufacturing data did not always behave the same way as data in nature (for example, Brownian motion of particles). Dr. Shewhart concluded while every process displays variation, some processes display controlled variation that is natural to the process (common causes of variation), while others display uncontrolled variation that is not present in the process causal system at all times (special causes of variation).

- **Batch.** Some applications require that specific quantities of raw materials be combined in specific ways for particular durations to produce an intermediate or end result. One example is the production of adhesives and glues, which normally requires the mixing of raw materials in a heated vessel for a period of time to form a quantity of end product.

- **Continuous.** Often a physical system is represented via variables that are smooth and uninterrupted in time. An example is the control of the chilled water temperature.

A thermostat is an example of a closed control loop: it constantly measures the current room temperature and controls the heater's valve setting to increase or decrease the room temperature according to the user-defined setting. The drawback to this method is that the control valve is fully open or fully shut which will lead to an over-shoot or under-shoot of the controlled temperature.

The more common and applicable method varies the amount of heating or cooling depending on the difference between the required temperature (the "setpoint") and the actual temperature. This minimizes any over- or under-shoot. See Figure 9-2.

Figure 9-2. Sample Control Sequence

COOLING

AN ELECTRONIC ANALOG TEMPERATURE SENSOR LOCATED IN THE SUPPLY AIR DUCT SHALL, THROUGH THE DDC CONTROLLER, CONTROL A CHILLED WATER VALVE TO MAINTAIN THE SUPPLY AIR TEMPERATURE AT SETPOINT.

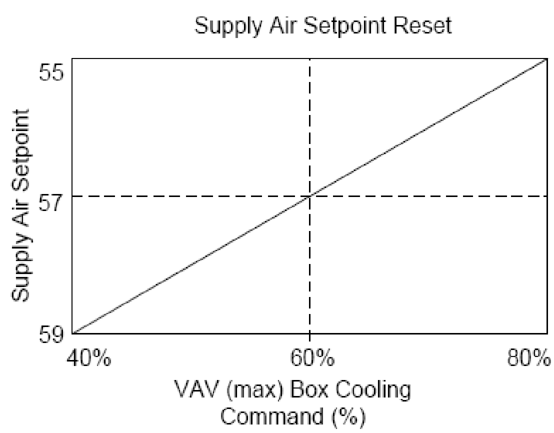
IN THE EVENT THE SUPPLY AIR TEMPERATURE RISES ABOVE COOLING SETPOINT, THE DDC CONTROLLER SHALL MODULATE THE CHILLED WATER VALVE TO MAINTAIN THE SUPPLY AIR TEMPERATURE AT SETPOINT.

THE SUPPLY AIR TEMPERATURE SETPOINT SHALL BE 58 DEG F / 14.4 DEG C (ADJUSTABLE).

SUPPLY AIR COOLING TEMPERATURE SETPOINT RESET

WITH THE SYSTEM OPERATING UNDER NORMAL MODE, THE SUPPLY AIR COOLING TEMPERATURE SETPOINT SHALL BE RESET IN RESPONSE TO VAV BOX COOILING COMMAND.

THE BAS SHALL MONITOR THE COOLING COMMAND EACH VAV CONNECTED TO THE AIR HANDLING SYSTEM. THE BAS SHALL, THROUGH THE DDC CONTROLLER, RESET THE SUPPLY AIR TEMPERATURE SETPOINT BASED ON THE MAXIMUM COOLING COMMAND (SEE THE RESET SCHEDULE BELOW).



ROUTINE ADJUSTABLE LIMITS:

- LOW: 55 DEG F / 12.8 DEG C
- HIGH: 59 DEG F / 15.0 DEG C

THE RESET ROUTINE SHALL BE EASILY ENABLED AND DISABLED BY THE BAS OPERATOR THROUGH A SOFTWARE TOGGLE ON THE SYSTEM GRAPHIC.

Process capability is a specific measurement of a process. The output of this measurement is usually illustrated by a histogram and calculations that predict how many parts will be produced out of specification. There are two parts to process capability:

- Measure the variability of a process.
- Compare variability with a proposed specification or product tolerance.

9.1.2.1 Measure the Process

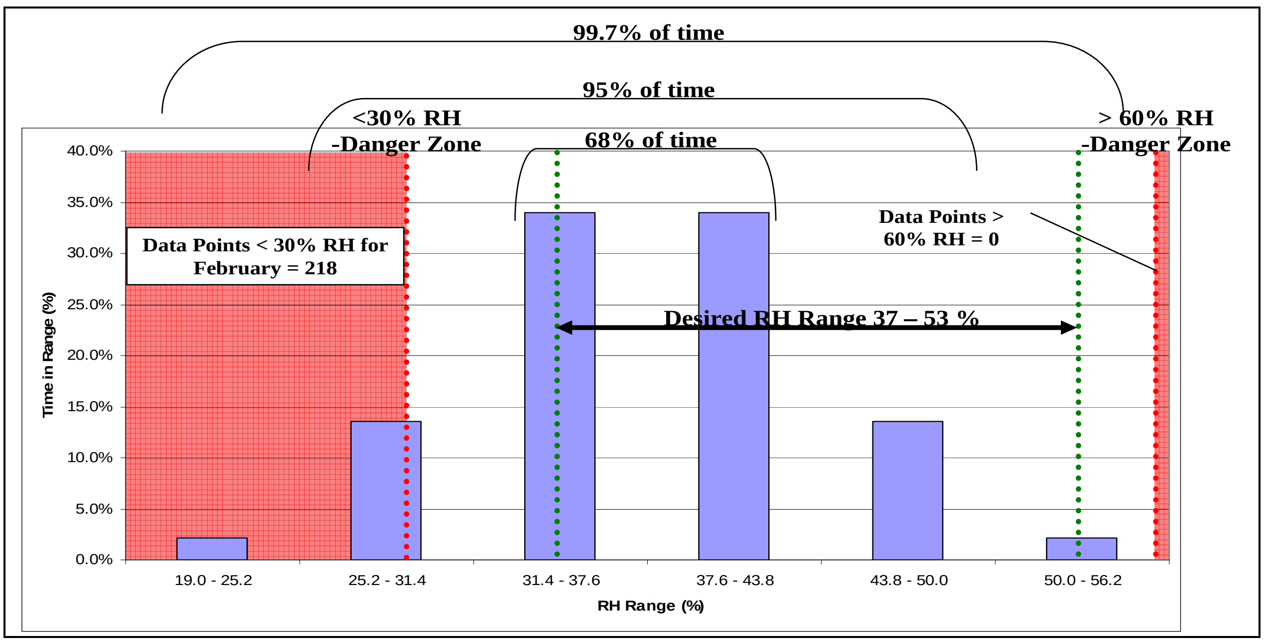
The output of a process usually has at least one measurable characteristic used to specify outputs. These can be analyzed statistically, where the output data shows a normal distribution the process can be described by the process mean (average) and the standard deviation.

A process needs to be established with appropriate controls in place. A control chart analysis determines whether the process is in statistical control. If the process is not in statistical control then capability has no meaning. Therefore the process capability involves only common cause variation and not special cause variation.

Sufficient data quantifying the normal variety of conditions, materials, and involved personnel must be obtained from the measured output of the process. The preferred data minimum is 30 data points but an estimate can be determined with as few as 17 data points.

Once the data has been entered, the process mean (average) and standard deviation are calculated. With a normal distribution, the "tails" can extend well beyond plus and minus three standard deviations, but this interval should contain about 99.73 percent of production output. Therefore for a normal distribution of data the process capability is often described as the relationship between six standard deviations and the required specification. Figure 9-3 provides an example of SPC being used to determine whether RH was controlled between the lower control limit of 37 percent and the upper control limit of 53 percent. There were 3,360 data points in a one-month period.

Figure 9-3. Sample of RH Control



9.1.2.2 Process Capability Study

A process capability study (Cpk) is performed to predict future capability of the process to produce within specification, and to identify process improvement opportunities. Process improvements are classified as follows:

- Human factors
- Training
- Tools
- Design
- Materials
- Inherent reliability
- Random, external

The output of a process is expected to meet customer requirements (72˚F) and tolerances (±4˚F). A review of design documentation and system performance analysis can determine the extent to which the process can meet temperature and RH expectations.

The ability of a process to meet specifications can be quantified in two ways:

- A single number using a process capability index
- Control charts

Both cases require running the process to obtain enough measurable output to establish confidence in the estimates.

SPC defines techniques to properly differentiate stable processes, drifting processes (those experiencing a long-term change in the mean of the output), and more varied processes. Process capability indices are meaningful only for stable processes.

9.1.2.3 Six Sigma

Sigma (the lower-case Greek letter σ) is used to represent standard deviation of a population. The widely accepted definition of a six sigma process is one that produces no more than 3.4 defective per million opportunities (DPMO). The term “six sigma process” derives from the notion that if one has six standard deviations between the mean of a process and the nearest specification limit, there will be practically no items that fail to meet the specifications. This is the basis of the process capability study.

In a process capability study, sigma refers to the number of standard deviations between the process mean and the nearest specification limit. (In a Cpk, sigma should not be confused with the sigma of the standard deviation of the process.)

9.2 MAINTENANCE FEEDBACK

During the life of the facility and its equipment, operators and maintenance personnel gain experience with the facility, and new methods and tools may become available to accomplish the mission and tasks in a more efficient or cost-effective manner. Personnel shall document these changes and modifications and submit them to the designers as feedback to improve and optimize the performance of the equipment. The RCM organization can be tasked with maintaining and developing this feedback function.

The feedback that the designer integrates into each successive generation yields lower overall failure rates and extended equipment life. These improved characteristics reduce maintenance costs thus contributing to a lower life-cycle-cost, one of the goals of the RCM and Continuous Improvement process.

Facility documentation and feedback shall be included in the SOP.

9.3 MAINTENANCE AND OPERATIONS CONSIDERATIONS

The following are RCM considerations during the Maintenance and Operations (M&O) activity.

9.3.1 Labor Force

The RCM program requires a labor force with the specific skills necessary to accomplish the program's reactive, preventive, and PT&I tasks successfully. The quality of the maintenance accomplished is reflected in the equipment post-maintenance mortality rate. The quality of maintenance is influenced by:

- The skill of the maintenance technicians
- The workmanship of the maintenance technicians
- The quality of supporting documentation and procedures
- The technologies in use

9.3.2 System Experts

For technical consistency and availability, a single person unlikely to be reassigned should be responsible for condition monitoring, predictive analysis, and maintenance planning for a given equipment or group of similar equipment. The system expert is responsible for monitoring and analyzing the maintenance data. The system expert should review, analyze, and file relevant data, work requests, and test documents. The system expert is expected to be a member of the facility maintenance team who is conversant with the maintenance history of their assigned equipment and systems. The system expert is also involved with integrating maintenance support from facility resources outside of the normal maintenance organization.

The system expert is not intended to replace or supplant the technical expertise found within the design organization of the original equipment manufacturer (OEM), facility, center, or NASA headquarters.

9.3.3 Training

Training is vital in reaching and maintaining the required RCM workforce skill level. The training is both technology- and equipment-specific and more general. Training for management and supervisory personnel includes an overview of the RCM process, its goals, and methods. Technician training includes the training on specific equipment and technologies, RCM analysis, and PT&I methods. See Table 9-1.

Table 9-1. Maintenance Training

Position/Title	Maintenance Overview	RCM/ PT&I	Root Cause/ Predictive Analysis	Technology/ Equipment
Managers/Supervisors	X	X	X	
System Experts	X	X	X	X
Maintenance Technicians	X	X	X	X
Support Personnel (Logistics)	X			

9.3.4 Equipment

During the operation of the facility and its equipment, operators and maintenance personnel shall document equipment modifications and alterations. This function helps improve the performance of the facility and its equipment as well as future designs. As shown in Figure 9-4, design improvements from one generation of equipment to the next have a significant effect on operability, maintainability, and reliability.

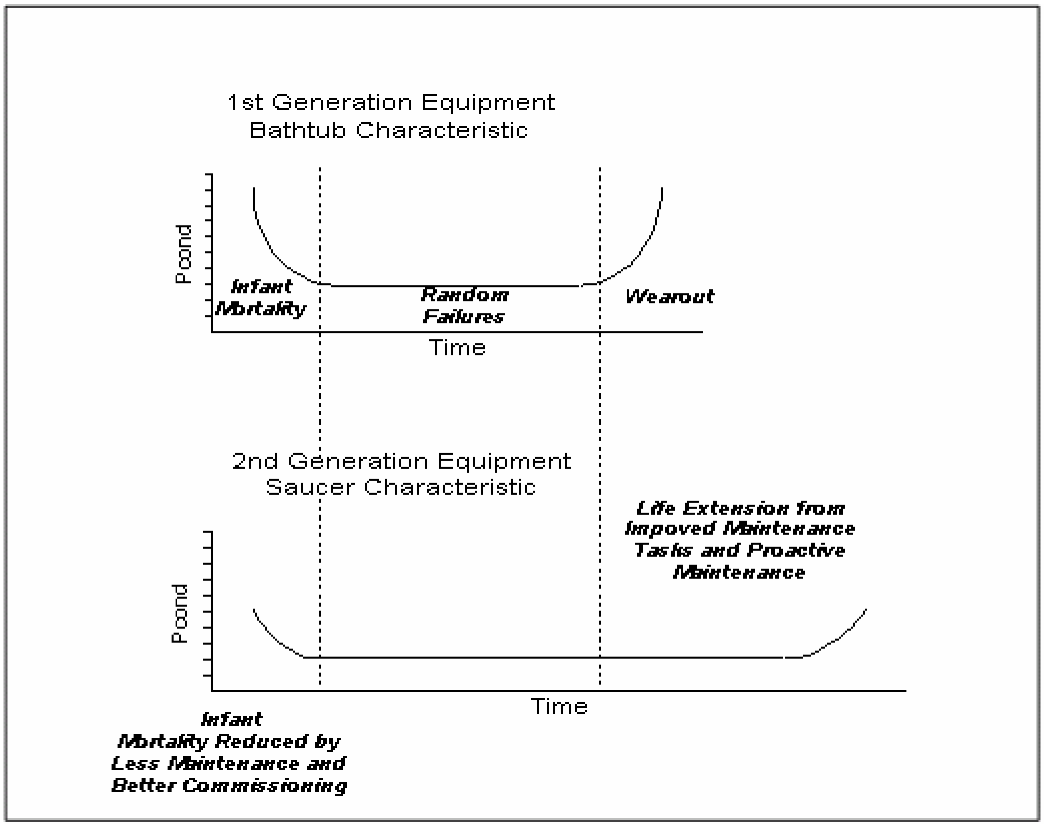
9.3.5 Maintenance History

Maintenance history, as captured in the CMMS, is critical to the success of the RCM program because it aids in:

- Establishing whether an age-reliability relationship (wear-out) exists for equipment, and if so, determining the critical failure-onset age.
- Analyzing long-term equipment and system performance trends.
- Forecasting equipment failures (which influence spare part stock levels).

Figure 9-4 provides a conceptual impact the RCM can have on the equipment life-cycle by providing design feedback, improved or enhanced commissioning, and a continuous improvement process.

Figure 9-4. Design Improvements through Maintenance Feedback



10.0 RCM CONTRACT CLAUSES

There are four basic contract types involved in the facility and equipment life-cycle.

- Architect & Engineering (A&E) Contracts
- Construction Contracts
- Equipment Procurement Contracts
- Maintenance and Operations (M&O) Contracts

These contracts occur during the following life-cycle phases:

Life-Cycle Phase	Contract Type
Planning	A&E
Design	A&E
Construction	Construction
Maintenance & Operations	Equipment Procurement

There is a need for RCM-related clauses in each of these contracts. This section recommends standard RCM contract clauses. Clauses are grouped by equipment and by the applicable technology. Table 10-1 through Table 10-10 provide criteria specific to the technology being offered. Table 10-11 through Table 10-16 identify and cross-reference the applicability of each RCM contract clause, component, and type of contract for each phase of the contract as follows:

A&E Contracts	Table 10-11
Construction Contracts	Table 10-12
Equipment Procurement Contracts	Table 10-14
Maintenance and Operations Contracts	Table 10-16

The applicable RCM contract clause and criteria should be included in all Requests for Proposals (RFPs), Requests for Quotation (RFQs), and in the contracts. The clauses may be used without modification; however, they and any referenced Table or illustration will have to be renumbered to fit the organization of the specification in which they are used.

10.1 GENERAL CONTRACT CLAUSES

This section contains standard contract clauses that may apply to all phases in the facility life-cycle. The specific clauses used in each phase are suggested in Sections 10.2through 10.5.

For example, the vibration data listed in Section 10.1.7, Vibration Monitoring, through Section 10.1.8, Vibration Monitoring Locations, should be included in contract specifications if vibration analysis is to be performed as part of the RCM program.

10.1.1 Measurements and Measurement Data

When measurements or surveys are required by a contract clause, the contractor shall furnish to the procuring organization the following information concerning the equipment used to make the specified measurements:

- **Test Equipment**. The contractor shall provide a list of all test equipment used including manufacturer, model number, serial number, calibration date, certificate of calibration, and special personnel qualifications required.

- **Equivalency.** If the contractor uses an equivalent test or procedure to meet the requirements of the contract specification, the contractor shall provide to the procuring organization proof of equivalency.

The contractor shall submit to the procuring organization Preventive Maintenance and Condition Monitoring and Inspection schedules with instructions that state when systems should be retested.

10.1.2 Bearing Information

The contractor shall use sealed bearings, where possible. Ball or roller bearings shall have an L-10 rated life of not less than 40,000 hours as specified.

- **Drawings**. The contractor shall provide to the procuring organization section drawings that show the component arrangement for all rotating equipment supplied under the contract. The section drawings shall accurately depict the bearing support structural arrangement, be drawn to scale, and show the dimensions to the centerline of all rotating shafts.

- **Bearing Data.** The contractor shall provide to the procuring organization the bearing manufacturer and part number for all bearings used in all rotating equipment supplied under this contract. The information shall be included on the sectional drawings for each bearing location.

- **Operating Data.** The contractor shall provide to the procuring organization equipment data that shall include the operating speed for constant speed units and the normal operating speed range for variable speed equipment.

10.1.3 Gearbox Information

The contractor shall provide to the procuring organization a description of the type and number of teeth on each gear used in the gearbox, the input and output speeds, and gear ratios. This information shall be included on the sectional drawings, which must be to scale and be specific to gear location.

10.1.4 Pumps

The contractor shall provide to the procuring organization the following information on all pumps supplied under the contract:

- Number of pump stages
- Number of pump vanes per stage
- Number of gear teeth for each pump gear
- Type of impeller or gear(s)
- Rotating speed
- Number of volutes
- Number of diffuser vanes

Bearings on vertical-shaft pumps shall be self-lubricating and permanently sealed.

10.1.5 Centrifugal Compressors

The contractor shall provide to the procuring organization the following information on all centrifugal compressors supplied under the contract:

- Number of compressor sections
- Number of blades per section
- Number of diffusers
- Number of vanes per diffuser
- Number of gear teeth on drive gear
- Number of driven shafts
- Number of gear teeth per driven shaft
- Rotating speed of each rotor

10.1.6 Fans

The contractor shall provide to the procuring organization the following information on all fans supplied under the contract:

- Type of fan or blower
- Number of rotating fan blades or vanes
- Number of stationary fan blades or vanes
- Rotating speeds

The contractor shall provide to the procuring organization the following additional information if the fans or air handlers are belt-driven:

- Number of belts
- Belt lengths
- Diameter of the drive sheave at the drive pitch line
- Diameter of the driven sheave at the drive pitch line

For all fans supplied under the contract, the contractor shall ensure sufficient access to the fan to allow for cleaning and in-place balancing of the fan.

10.1.7 Vibration Monitoring

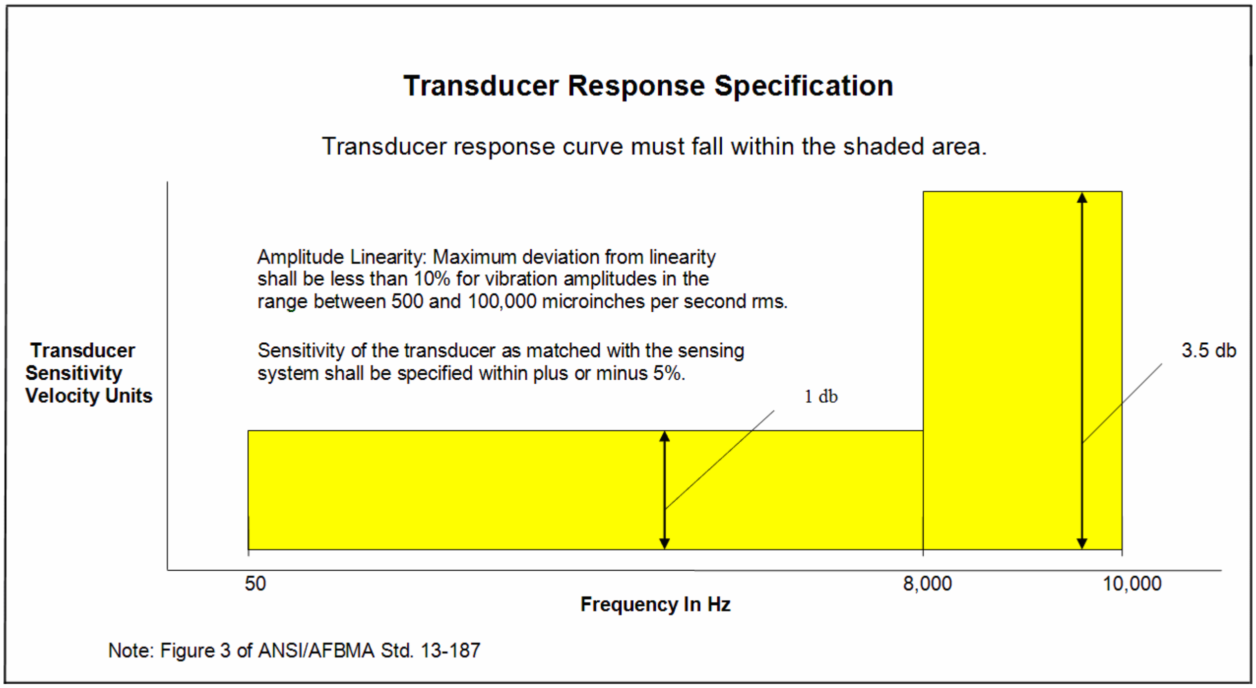
The contractor shall provide to the procuring organization the following information for all equipment where a vibration specification is included in the contract.

10.1.7.1 Instrumentation and Sensors

The contractor shall use the type of instrumentation and sensors specified. For example, a 3,600 RPM machine requires an accelerometer with a sensitivity of 100 mV/g and a resonant frequency of at least 15,000 Hz. Use a rare earth super magnet and a sound disc in conjunction with any vibration data collector that has the following characteristics:

- A minimum of 800 lines of resolution
- A dynamic range greater than 70 dB
- A frequency response range of 5Hz-10kHz (300-600,000 cpm)
- The capability to perform ensemble averaging; i.e., average the data collected
- The use of a hanning or hamming window
- Autoranging
- Sensor frequency response shall conform to Figure 10-1.

Figure 10-1. Transducer Response



The contractor shall provide to the procuring organization narrowband spectral vibration data for all machines as follows:

- For machines operating at or below 1,800 RPM, the frequency spectrum provided should be in the range of 5 to 2,500 Hz.
- For machines operating greater than 1,800 RPM, the frequency spectrum provided should be in the range of 5 to 5,000 Hz.
- Two narrowband spectra for each point shall be obtained in the following manner:
  - For all machines regardless of operating speed, a 5 to 500 Hz spectrum with 400 lines of resolution shall be used to analyze balance, alignment, and electrical line frequency faults.
  - An additional spectrum of 5 to 2,500 or 5 to 5,000 Hz must be acquired for machines operating at or below 1,800 RPM or greater than 1,800 RPM, respectively. The higher frequency range allows early detection of rolling element bearing, gear rotor, and stator problems.
- The contractor reports vibration data in velocity (inches/second). If proximity probes are installed, the contractor acquires and analyzes vibration and phase data.
- The contractor ensures that the equipment provided meets the acceptable vibration amplitudes for each machine.

- The contractor collects vibration data at normal operating load, temperature, and speed.
- The contractor supplies all critical speed calculations and should perform a check for machine resonance following installation and correlate it with all known forcing frequencies; i.e., running speed, bearing, gear, and impeller frequencies.

10.1.7.2 Vibration Analysis of New Equipment

For all large or critical pieces of equipment assembled and run at the factory prior to shipment, the contractor shall acquire a narrowband vibration spectrum at the locations specified below while the equipment is undergoing this factory performance testing. Retain a baseline or reference spectrum for comparison with the post-installation vibration check. Equipment failing the vibration criteria will be rejected by the procuring organization prior to shipment.

Vibration tests shall be performed under the following situations if the equipment fails the initial test or if problems are encountered following installation:

- Motor cold and uncoupled
- Motor hot and uncoupled
- Motor and machine coupled, unloaded and cold
- Motor and machine coupled, unloaded and hot
- Motor and machine coupled, loaded and cold
- Motor and machine coupled, loaded and hot

The contractor shall investigate any significant change in the vibration signature under each condition, which may indicate a problem with thermal distortion or bearing overloading due to failure of one of the bearings to float.

10.1.7.3 Vibration Criteria for Electric Motors

The contractor shall analyze all motor vibration spectra at the following forcing frequencies:

- One times running speed (1X) for imbalance
- Two times running speed (2X) for misalignment
- Multiples of running speed (NX) for looseness, resonance, plain bearing defects
- Electric line frequency and harmonics (60 or 120 Hz for AC motors) for stator and rotor problems
- Rolling element bearing frequencies for:
    - Outer race defect

- Inner race defect
- Ball defect (ball spin frequency)

- Fundamental train frequency

- Harmonics of running speed and at the frequency corresponding to 0.4 - 0.5 of running speed for plain or journal bearing faults.

- Other vibration signatures that are dependent on the number of motor rotor bars and stator slots, the number of cooling fan blades, the number of commutator bars and brushes, and on the silicon controlled rectifier (SCR) firing frequencies for variable speed motors, and sidebands spaced at two times the slip for broken rotor bars.

Balance

The contractor shall ensure that the vibration criteria listed in Table 10-1 complies with the vibration amplitude at the fundamental rotational frequency or one times running speed (1X). This is a narrowband limit; an overall reading is not acceptable.

Additional Vibration Criteria

The contractor shall conduct all testing at normal operating speed under full load conditions. Acceptable motor vibration criteria guidelines are provided in Table 10-2.

Rewound Electric Motors

The contractor shall check all rewound electrical motors both electrically and mechanically. The mechanical check includes measuring post-overhaul vibration at the same location as new motors. The vibration level at each measurement point may not exceed the reference spectrum for that motor by more than 10 percent. Any deviation from the reference spectrum for vibration amplitudes associated with electrical faults such as slip, rotor bar, and stator slot must be documented.

Table 10-1. Motor Balance Specifications

Motor Speed (RPM)	Maximum Vibration (in/sec, Peak)	Maximum Displacement (mils, Peak-to-Peak)
900	0.02	0.425
1200	0.026	0.425
1800	0.04	0.425
3600	0.04	0.212

Table 10-2. Motor Vibration Criteria

Frequency (X RPM) Motor Component	Maximum Amplitude (in/sec Peak)
0.4 - 0.5	Not detectable
1X	See Motor Balance Specifications
2X	0.02
Harmonics (NX)	Not detectable
Roller Element Bearings	Not detectable
Side Bands	Not detectable
Rotor Bar/Stator Slot	Not detectable
Line Frequency (60 Hz)	Not detectable
2X Line Frequency (120 Hz)	0.02

General Equipment Vibration Standards

- The contractor shall ensure that discrete bearing frequencies are not detectable. Detection of any discrete bearing frequency is unacceptable.
- The contractor shall ensure that belt rotational frequency and harmonics are not detectable. Detection of any belt rotation or harmonics is unacceptable.
- If no specific vibration criteria are available for the type of equipment tested, the ISO 10816-1: 1995 (E) Class A guidelines Table B-1, Typical Boundary Limits, (found in Table 10-5) can be combined with the motor criteria contained in Table 10-2 and used as the acceptance specification for procurement and overhaul.

Specific Equipment

The criteria in Table 10-3 determine the maximum acceptable vibration of boiler feed water, split case, and progressive cavity pumps. Pump impeller assemblies shall be statically and dynamically balanced to ISO 1940/2-1997, G2.5, or G1.0 as specified.

Table 10-3. Pump Vibration Limits

Frequency Band	Maximum Vibration Amplitude (in/sec Peak)
Overall (10-1000 Hz)	0.06
1X RPM	0.05
2X RPM	0.02
Harmonics	0.01
Bearing Defect	Not detectable

Belt Driven Fans

The criteria in Table 10-4 determine the maximum acceptable vibration of belt-driven fans.

Table 10-4. Belt Driver Fan Vibration Limits

Frequency Band	Maximum Vibration Amplitude (in/sec Peak)
Overall (10-1000 Hz)	0.15
1X RPM	0.1
2X RPM	0.04
Harmonics	0.03
Belt Frequency	Not detectable
Bearing Defect	Not detectable

Vibration Guidelines

Table 10-5 is based on Appendix B of ISO 10816-1: 1995 (E) and serves as a guideline for determining the acceptability of a machine for service. The vibration acceptance classes and ISO 10816 machine classes are shown in Table 10-6 and Table 10-7. The ISO amplitude values are overall measurements in inches/second RMS, but the recommended specifications for electric motors are narrowband measurements in inches/second Peak.

Table 10-5. ISO 10816-1: 1995 (E) Typical Zone Boundary Limits

<table>
<tr><th colspan="2">RMS Vibration Velocity</th><th colspan="4">Quality Judgment for Separate Machine Classes</th></tr>
<tr><th>Range mm/sec</th><th>Range in/sec</th><th>Class I</th><th>Class II</th><th>Class III</th><th>Class IV</th></tr>
<tr><td>0.28</td><td>0.011</td><td rowspan="3">A</td><td rowspan="4">A</td><td rowspan="5">A</td><td rowspan="6">A</td></tr>
<tr><td>0.45</td><td>0.018</td></tr>
<tr><td>0.71</td><td>0.028</td></tr>
<tr><td>1.12</td><td>0.044</td><td rowspan="2">B</td></tr>
<tr><td>1.80</td><td>0.071</td><td rowspan="2">B</td></tr>
<tr><td>2.80</td><td>0.110</td><td rowspan="2">C</td><td rowspan="2">B</td></tr>
<tr><td>4.50</td><td>0.180</td><td rowspan="2">C</td><td rowspan="2">B</td></tr>
<tr><td>7.10</td><td>0.280</td><td rowspan="5">D</td><td rowspan="2">C</td></tr>
<tr><td>11.20</td><td>0.440</td><td rowspan="4">D</td><td rowspan="2">C</td></tr>
<tr><td>18</td><td>0.710</td><td rowspan="3">D</td></tr>
<tr><td>28</td><td>1.10</td><td rowspan="2">D</td></tr>
<tr><td>45</td><td>2.80</td></tr>
</table>

Table 10-6. Vibration Acceptance Classes

Class	Condition
A	Good
B	Satisfactory
C	Unsatisfactory
D	Unacceptable

Table 10-7. Machine Classifications

Machine Classes for ISO 3945	
Class I	Small size machines up to 15 KW (20 HP).
Class II	Medium size machines 15KW – 75KW (20-100 HP) without special foundations, rigidly mounted engines, or machines (up to 300 KW) on special foundations.
Class III	Large Prime-Movers and other large machines with rotating masses mounted on rigid and heavy foundations which are relatively soft in the direction of vibration measurements.
Class IV	Large Prime-Movers and other large machines with rotating masses mounted on foundations which are relatively soft in the direction of vibration measurements. For example, turbo generator sets and gas turbines with outputs greater than 10 MW.

10.1.7.4 Vibration Monitoring Locations

Monitoring Discs

For all rotating equipment provided under the contract, the contractor shall install vibration monitoring discs using the following guidelines:

- Sound discs shall be a minimum of 1" in diameter, manufactured of a magnetic material, have a surface finish of 32 micro-inches RMS, and attached by welding or stud mounting. The contractor may manufacture the equipment case to achieve a flat and smooth spot that meets the same tolerances as the sound disc if the equipment case is manufactured from a magnetic material.

- The contractor shall ensure monitoring locations are positioned on structural members. The installation of sound discs on bolted cover plates or other non-rigid members is unacceptable.

Centrifugal Pumps, Vertically Mounted

The contractor shall install sound discs in the radial direction as close to the bearings as possible. Accelerometers shall be mounted to solid structures. Mounting locations shall be in line and perpendicular to the pump discharge, and located at the free end, the coupled end of the motor and pump, and in the axial direction on the pump and motor.

Centrifugal Pumps, Horizontally Mounted

The contractor shall install sound discs in the horizontal and vertical planes radial to the shaft at the free and coupled ends of the motor and pump as close to the bearings as possible. Accelerometers should be mounted to solid structures. Mounting locations should be in line and perpendicular to the pump discharge and located at the free and coupled end of the motor and pump, and in the axial direction on the motor and pump.

Positive Displacement Pumps

The contractor shall install sound discs in the horizontal and vertical planes radial to the shaft at the free and coupled ends of the motor and pump as close to the bearings as possible. Accelerometers shall be mounted to solid structures and not on drip shields or other flexible structures. Mounting locations shall be in line with each other, perpendicular to the pump discharge, and located at the free end, coupled end of the motor and pump, and in the axial direction on the pump and motor. An exception may be granted if the pump is sump-mounted.

Generators

The contractor shall install sound discs in the horizontal and vertical planes on the free ends of the motor and generator bearing assemblies. Pedestal bearings between the motor and generator should be monitored in the vertical direction radial to the shaft. Thrust bearings should be monitored in the axial direction.

Gear Boxes

The contractor shall install sound discs radial to the input and output shafts in the horizontal and vertical directions. Additional discs shall be installed in the axial direction close to the input and output shafts.

Compressors

The contractor shall install sound discs radial to the input and output shafts in the horizontal and vertical directions. Additional discs should be installed in the axial direction close to input and output shafts. Centrifugal compressors may be monitored effectively in this manner, but reciprocating air compressors need only be monitored for balance and alignment problems.

Blowers and Fans

The contractor shall install sound discs in the radial and axial directions on motors. The contractor monitors fan bearings radially in the vertical direction.

Chillers

- **Centrifugal**. The contractor shall mount sound discs in the horizontal and vertical planes radial to the shaft at the free and coupled ends of the motor and compressor as close to the bearings as possible. Accelerometers should be mounted to solid structures, not on drip shields or other flexible structures. Mounting locations shall be in line with each other, perpendicular to the compressor discharge, and located at the free end, the coupled end of the motor and compressor, and in the axial direction on compressor and motor.

- **Reciprocating**. The contractor shall install sound discs radial to the input and output shafts in the horizontal and vertical directions. The contractor shall install additional discs in the axial direction as close to the input and output shafts as possible.

10.1.7.5 Lubricant and Wear Particle Analysis

The contractor shall provide to the procuring organization the following information on all lubricants supplied in bulk or contained within equipment supplied under the contract.

Liquid Lubricants

- Viscosity grade in ISO units.
- AGMA or SAE classification, as applicable.
- Viscosity in Saybolt Universal Seconds (SUS) or centipoise at the standard temperature and at designed normal operating temperature.
- The contractor shall use the following formula to calculate SUS and absolute viscosity:

$$Z = p_t(0.22s-180/s)$$

  - Where Z = absolute viscosity in centipoise at test temperature
  - s = Saybolt Universal Seconds
  - pt = specific gravity at test temperature
  - t = temperature (°F)

Grease Lubricants

- National Lubrication and Grease Institute (NLGI) Number
- Type and percent of thickener
- Dropping point
- Base oil viscosity range in SUS or centipoise
- The contractor shall use the following formula to calculate SUS or absolute viscosity:

$$Z = pt(0.22s-180/s)$$

  - Where Z = absolute viscosity in centipoise at test temperature
  - s = Saybolt Universal Seconds
  - pt= specific gravity at test temperature
  - t = temperature (°F)

Lubricant Tests

The contractor shall draw lubricants and perform the lubricant tests listed in Table 10-8 on all lubricants supplied by the contractor and submit the results to the procuring organization.

Table 10-8. Lubricant Tests

Lubricant Tests					
Test		**Testing For**	**Indicates**	**Correlates With**	**When Used**
Total Acid No. (TAN) Total Base No.		pH	Degradation, oxidation, contamination	Visual, RBOT	Routine
Rotating Bomb Oxidation Test (RBOT)		Anti-oxidants remaining	Lubricant resistance to oxidation	TAN	Periodic (long term)
Solids		Solids	Contamination or degradation	TAN, RBOT, spectro-metals	Routine and post repair
Visual for color and clarity		Cloudiness or darkening	Presence of water or particulates. Oxidation of lubricant.	TAN	Routine
Spectrometals (IR spectral analysis)		Metals	Presence of contaminants, wear products and additives	Particle count	Routine
Particle count		Particles >10 µm	Metal & wear product particles	Spectro-metals	Routine
Ferro-graphy	Direct	Ferrous particles up to 250 µm	Wear rate	Particle count, spectro-metals	Case basis
	Analytical	Ferrous particles	Microscopic examination. Diagnostic tool.	Particle count, spectro-metals	Case basis
Micropatch		Particles, debris	Microscopic examination. Diagnostic tool	Particle count, spectro-metals, ferrography	Periodic or case basis
Water Content		Water	Degradation, leak, oxidation, emulsion	Visual, RBOT	Routine
Viscosity		Lubricating quality	Contamination, degradation	Water	Routine

Hydraulic Fluid

The contractor shall ensure that all bulk and equipment-installed hydraulic fluids supplied under the contract shall meet the cleanliness guidelines in Table 10-9. The procuring organization will specify System Sensitivity. The particle counting technique utilized shall be quantitative. Patch test results are not acceptable.

In Table 10-8, the numbers in the 5 micron and 15 micron columns are the number of particles greater than 5 microns and 15 microns respectively in a 100-milliliter sample.

Table 10-9. Sperry Vickers Table of Suggested Acceptable Contamination Levels for Various Hydraulic Systems

Type of System	System Sensitivity	Suggested Maximum Particle Level (Particles per 100 milliliters)		
		5 microns	15 microns	ISO
Silt sensitive control system with very high Reliability. Laboratory or Aerospace.	Super Critical	4,000	250	13/9
High performance servo and high pressure long life systems. Machine tools.	Critical	16,000	1,000	15/11
High quality reliable systems. General machine requirements.	Very Important	32,000	4,000	16/13
General machinery and mobile systems. Medium pressure & capacity.	Important	130,000	8,000	18/14
Low pressure heavy industrial systems. Long life not critical.	Average	250,000	16,000	19/15
Low pressure systems with large clearances.	Main Protection	1,000,000	64,000	21/17

Insulating Fluids

The contractor shall identify the type of oil used as an insulating fluid for all oil-filled transformers supplied under the contract. The manufacturer shall certify that the insulating oil contains no PCBs and label the transformer tank and all applicable oil drums.

The contractor shall test the insulating oil using the American Society for Testing Materials (ASTM) test listed in Table 10-10, Typical Properties of Transformer Oils and provide the results to the procuring organization. The contractor corrects any deviation from the typical properties listed before NASA may accept the transformer.

Sampling Points

The contractor shall install sampling points and lines in accordance with Method No.1 as recommended by the National Fluid Power Association (NFPA). The primary method is published as NFPA T2.9.1-1972 titled *Method for Extracting Fluid Samples from the Lines of an Operating Hydraulic Fluid Power System for Particulate Particle Contamination Analysis* as follows:

- **For Pressurized Systems.** The contractor shall place a ball valve in the fully opened position with a downstream capillary tube (ID> 1.25 mm) of sufficient length to reduce downstream pressure and control flow in the desired range. The sampling point should be located in a turbulent flow region and upstream of any filters.

- **For Reservoirs and Non-Pressurized Systems.** The contractor shall place a 1/8" stainless steel line and ball valve in the side of the oil sump or tank. The line should be located near the midpoint of the structure. The sample line should extend internally to and as close to the center of the tank as possible.

Table 10-10. Typical Properties of Transformer Oils

Test (Units)	Silicone	Mineral	Asakrel
Dielectric Breakdown ASTM D877-87 (kV)	30+	30+	30+
Power Factor ASTM D924-99el (%)	0.01	0.05 max	0.05
Neutralization Number ASTM D974-97 (mg KOH/g)	<0.03	<0.03	<0.03
Interfacial Tension ASTM D2285-97 (dynes/cm)	N/A	35 min	N/A
Specific Gravity ASTM 1298-99	0.96	0.88	1.55
Flash Point ASTM D92-98a(c)	>305	160	N/A
Fire Point ASTM D92-98a(c)	360	177	None to Boiling
Pour Point ASTM D97-96a(c)	-55	-51 max	-30 max
Water Content ASTM D1533-00 (ppm)	30 max	30 max	30 max
Viscosity at 40C ASTM D445-97 (SUS)	232	57.9	55.8-61.0
Color & Appearance	clear/water like	pale yellow clear	pale yellow clear

10.1.7.6 Thermography

Thermographic inspections are qualitative or quantitative. Unless otherwise indicated, the contractor shall perform qualitative inspections to detect relative differences, hot and cold spots, moisture, voids, and deviations from normal or expected temperature ranges.

Electrical

The contractor shall perform a thermographic survey on all electrical distribution equipment, motor control centers, and transformers during the start-up phase of the installation unless the thermographic survey is waived by the procuring organization. The contractor corrects any defects noted by an observable difference in temperature of surveyed components or unexplained temperature rise above ambient at no additional expense to the procuring organization. The contractor resurveys repaired areas to assure proper corrective action has been taken.

Piping Insulation

The contractor shall perform a thermographic survey on all insulated piping during the start-up phase of the installation unless the thermographic survey is waived by the procuring organization. The contractor corrects any voids in the piping insulation at no additional cost to the procuring organization. The contractor resurveys repaired areas to assure proper corrective action has been taken.

Building Envelope

The contractor shall perform a thermographic survey of the building envelope as part of the pre-beneficial occupancy to check for voids in insulation, the presence of damp insulation, and the presence of air gaps in building joints. Appropriate procedure and specifications are described in the following:

ASTM C1060-90el	Standard Practice for Thermographic Inspection of Insulation Installations in Envelope Cavities of Wood Frame Buildings
ASTM C1153-97	Standard Practice for Location of Wet Insulation in Roofing Systems Using Infrared Imaging
ISO 6781	Thermal Insulation-Qualitative Detection of Thermal Irregularities in Building Envelopes-Infrared Method
ASTM E1186-98	Standard Practices for Air Leakage Site Detection in Building Envelops and Air Retarder Systems

The contractor shall document by photograph, scale drawing, or description all voids or gaps found during the thermographic scan.

For areas with suspect moisture content, the contractor shall use either destructive or non-destructive testing techniques that confirm the amount of moisture.

Boilers, Furnaces, and Ovens

The contractor shall perform a thermographic survey during the start-up phase of the installation of all furnaces, boilers, and ovens as a means of determining voids in insulation or refractory materials. The contractor shall correct any voids detected at no expense to the procuring organization. The contractor shall perform a thermographic survey of all repaired areas prior to final acceptance by the procuring organization.

10.1.7.7 Airborne Ultrasonics

The contractor shall perform an airborne ultrasonic survey during the start-up phase of the installation (unless waived by the procuring organization). The survey includes checking electrical equipment for indications of arcing or electrical discharge, including corona and piping systems for leakage. The contractor shall correct any defects or exceptions at no additional expense to the procuring organization. The contractor should re-survey repaired areas to assure proper corrective action has been taken.

10.1.7.8 Pulse Echo Ultrasonics

The contractor shall perform material thickness measurements on a representative sample of all material with a contract-specified thickness. Thickness measurements occur at the fabricator’s place of business prior to shipment of any material to the project site. Material that does not meet the specified requirements of the contract may not be shipped without the prior approval of the procuring organization.

10.1.7.9 Motor Circuit Analysis (Complex Phase Impedance)

Following completion of the motor installation, the contractor shall take and provide to the procuring organization the following acceptance/baseline readings and measurements, first for the motor alone, then for motor and circuit together:

- Conductor path resistance
- Inductive imbalance
- Capacitance to ground

10.1.7.10 Motor Current Spectrum Analysis

With the motor installed and operational, the contractor shall conduct an acceptance/baseline spectral analysis on the loaded motor at 75 percent or greater load when specified by the procuring organization.

Insulation Resistance

Following completion of the motor installation, the contractor shall provide to the procuring organization the following acceptance/baseline readings and measurements; first, for the circuit or for the motor alone, then for motor and circuit together:

- Polarization Index (Motors of 500 HP or more only).
- Dielectric Absorption Ratio (for all motors).
- Leakage current at test voltage.

Surge Testing

The contractor shall perform surge testing and high potential resistance testing of motor(s) prior to installation and acceptance by the procuring organization. The contractor shall provide to the procuring organization documentation of test results, including test voltage, waveforms, and high potential leakage current.

Start-Up Tests

With the motor installed and operational, the contractor shall collect and provide the coast-down time and peak starting current data to the procuring organization.

10.1.7.11 Maintainability and Ease of Monitoring

The contractor shall provide a design that is cognizant of facility and equipment maintainability and ease of monitoring. The design shall provide for the ability to open and remove access panels and provide access to inspect the device while circuits are energized. Minimum distances to energized circuits shall be as specified in Occupational Safety and Health Administration (OSHA) Standards Part 1910.333 (Electrical-Safety-Related Work Practices.).

No installation shall be permitted which blocks or otherwise impedes access to any existing machine or system. Except as otherwise indicated, emergency switches and alarms shall be installed in conspicuous locations. All indicators, to include gauges, meters, and alarms shall be mounted in order to be easily usable by people in the area. Insulation shall not impede access to covers/doors used for cleaning or maintenance.

Equipment Pads

The contractor shall ensure that equipment bases and foundations, when constructed of concrete or grout, shall cure a minimum of 14 or 28 days as specified before being loaded.

Leveling of Installed Equipment

The contractor shall level all installed rotating electrical and mechanical machinery. After installation, the equipment shall not exceed a maximum slope of the base and the frame of 0.001 inch per foot. The contractor shall report to the procuring organization the type and accuracy of the instrument used for measuring the level; e.g., a 12-inch machinist's level graduated to 0.0002 inch per foot.

10.2 ARCHITECT AND ENGINEERING CONTRACTS

Table 10-11 identifies the clauses that are appropriate for use in A&E contracts. The numbers refer to the paragraph numbers presented in Section 10.1 General Contract Clauses.

Table 10-11. RCM Clauses for A&E Contracts

Contract Clause in Chapter 10	Element	CdM Technology
10.1.7.17	Facility	Maintainability and ease of monitoring
10.1.7.17	Equipment	Maintainability and ease of monitoring

10.3 CONSTRUCTION CONTRACTS

Table 10-12 identifies the clauses for use in construction contracts. The numbers refer to the paragraph numbers previously presented in Section 10.1.

Table 10-12. RCM Clauses for Construction Contracts

Contract Clause in Chapter 10	Equipment Type	CdM Technology
10.1.1	Measurements/surveys	N/A
10.1.2, 10.1.4, 10.1.7, 10.1.7.2, 10.1.7.4	Pump	Vibration
10.1.7.5	Pump	Lubricant & wear particle analysis
10.1.2, 10.1.6, 10.1.7, 10.1.7.2, 10.1.7.4	Compressor	Vibration
10.1.7.5	Compressor	Lubricant & wear particle analysis
10.1.2, 10.1.6, 10.1.7, 10.1.7.2, 10.1.7.4	Blower/fan	Vibration
10.1.7.5	Blower/fan	Lubricant & wear particle analysis
10.1.2, 10.1.3, 10.1.7, 10.1.7.2, 10.1.7.4	Gearbox	Vibration
10.1.7.5	Gearbox	Lubricant & wear particle analysis
10.1.7.9	Boiler, furnace	Infrared thermography
10.1.7.10	Piping	Passive ultrasound
10.1.7.11	Piping/pressure vessel	Pulse echo ultrasound
10.1.7.9	Piping insulation	Infrared thermography
10.1.7.9	Chiller/refrigeration	Infrared thermography
10.1.7.5	Chiller/refrigeration	Lubricant & wear particle analysis
10.1.2, 10.1.7, 10.1.7.2, 10.1.7.4	Chiller/refrigeration	Vibration
10.1.7.10	Electrical switchgear/ circuit breakers	Passive ultrasound
10.1.7.9	Electrical switchgear/ circuit breakers	Infrared thermography
10.1.7.14	Electrical switchgear/ circuit breakers	Insulation resistance
10.1.7.14	Motor & Motor Circuit	Insulation resistance
10.1.7.12	Motor & Motor Circuit	Motor circuit analysis

Table 10-13. RCM Clauses for Construction Contracts (Continued)

Contract Clause in Chapter 10	Equipment Type	CdM Technology
10.1.7.16	Motor & Motor Circuit	Start up tests
10.1.7.9	Building envelope	Infrared thermography
10.1.7.9	Heat exchanger/condenser	Infrared thermography
10.1.7.10	Heat exchanger/condenser	Passive ultrasound
10.1.2, 10.1.7, 10.1.7.2, 10.1.7.4	Electric motor	Vibration
10.1.7.15	Electric motor	Surge testing
10.1.2, 10.1.3, 10.1.4, 10.1.7, 10.1.7.2, 10.1.7.4	Electrical generator	Vibration
10.1.7.12	Electrical generator	Motor circuit analysis
10.1.7.14	Electrical generator	Insulation resistance
10.1.7.9	Transformer	Infrared thermography
10.1.7.7	Transformer	Oil analysis
10.1.7.18	All pad mounted equipment	Equipment stability for operations
10.1.7.19	Rotating Equipment Electrical Mechanical	Equipment leveling upon installation

10.4 EQUIPMENT PROCUREMENT CONTRACTS

Table 10-14 identifies the clauses for use in equipment procurement contracts. The numbers refer back to the paragraph numbers previously presented in Section 10.1.

Table 10-14. RCM Clauses for Equipment Procurement Contracts

Contract Clause in Section VII	Equipment Type	CdM Technology
10.1.2, 10.1.4, 10.1.7, 10.1.7.2, 10.1.7.4	Pump	Vibration
10.1.7.5	Pump	Lubricant & wear particle analysis
10.1.2, 10.1.5, 10.1.7, 10.1.7.2, 10.1.7.4	Compressor	Vibration
10.1.7.5	Compressor	Lubricant & wear particle analysis
10.1.2, 10.1.6, 10.1.7, 10.1.7.2, 10.1.7.4	Blower/fan	Vibration
10.1.7.5	Blower/fan	Lubricant & wear particle analysis
10.1.2, 10.1.3, 10.1.7, 10.1.7.2, 10.1.7.4	Gearbox	Vibration
10.1.7.5	Gearbox	Lubricant & wear particle analysis
10.1.7.9	Boiler, furnace	Infrared thermography
10.1.7.10	Piping	Passive ultrasound
10.1.7.11	Piping/pressure vessel	Pulse echo ultrasound
10.1.7.9	Piping insulation	Infrared thermography
10.1.7.9	Chiller/refrigeration	Infrared thermography
10.1.7.5	Chiller/refrigeration	Lubricant & wear particle analysis
10.1.2, 10.1.7, 10.1.7.2, 10.1.7.4	Chiller/refrigeration	Vibration
10.1.7.10	Electrical switchgear/ circuit breakers	Passive ultrasound
10.1.7.9	Electrical switchgear/ circuit breakers	Infrared thermography
10.1.7.14	Electrical switchgear/ circuit breakers	Insulation resistance
10.1.7.14	Motor & motor circuit	Insulation resistance

Table 10-15. RCM Clauses for Equipment Procurement Contracts (Continued)

Contract Clause in Section VII	Equipment Type	CdM Technology
10.1.7.12	Motor & motor circuit	Motor circuit analysis
10.1.7.13	Motor & motor circuit	Motor current spectrum analysis
10.1.7.16	Motor & motor circuit	Start-up tests
10.1.7.9	Heat exchanger/condenser	Infrared thermography
10.1.7.10	Heat exchanger/condenser	Passive ultrasound
10.1.2, 10.1.7, 10.1.7.2, 10.1.7.4	Electric motor	Vibration
10.1.7.15	Electric motor	Surge testing
10.1.2, 10.1.7, 10.1.7.2, 10.1.7.4	Electrical generator	Vibration
10.1.7.12	Electrical generator	Motor circuit analysis
10.1.7.14	Electrical generator	Insulation resistance
10.1.7.9	Transformer	Infrared thermography
10.1.7.7	Transformer	Oil analysis
10.1.1	Measurements/surveys	N/A

10.5 MAINTENANCE AND OPERATIONS CONTRACTS

Table 10-16 identifies clauses for use in M&O contracts involving RCM features. The numbers refer back to the paragraph numbers previously presented in Section 10.1.

Table 10-16. RCM Clauses for M&O Contracts

Contract Clause in Section VII	Equipment Type	CdM Technology
10.1.2, 10.1.4, 10.1.7, 10.1.7.2, 10.1.7.4	Pump	Vibration
10.1.7.5	Pump	Lubricant & wear particle analysis
10.1.2, 10.1.5, 10.1.7, 10.1.7.2, 10.1.7.4	Compressor	Vibration
10.1.7.5	Compressor	Lubricant & wear particle analysis
10.1.2, 10.1.6, 10.1.7, 10.1.7.2, 10.1.7.4	Blower/fan	Vibration
10.1.7.5	Blower/fan	Lubricant & wear particle analysis
10.1.2, 10.1.3, 10.1.7, 10.1.7.2, 10.1.7.4	Gearbox	Vibration
10.1.7.5	Gearbox	Lubricant & wear particle analysis
10.1.7.9	Boiler, furnace	Infrared thermography
10.1.7.10	Piping	Passive ultrasound
10.1.7.11	Piping/pressure vessel	Pulse echo ultrasound
10.1.7.9	Piping insulation	Infrared thermography
10.1.7.9	Chiller/refrigeration	Infrared thermography
10.1.7.5	Chiller/refrigeration	Lubricant & wear particle analysis
10.1.2, 10.1.7, 10.1.7.2, 10.1.7.4	Chiller/refrigeration	Vibration
10.1.7.10	Electrical switchgear /circuit breakers	Passive ultrasound
10.1.7.9	Electrical switchgear /circuit breakers	Infrared thermography
10.1.7.14	Electrical switchgear /circuit breakers	Insulation resistance
10.1.7.14	Motor & motor circuit	Insulation resistance

Table 10-17. RCM Clauses for M&O Contracts (Continued)

Contract Clause in Section VII	Equipment Type	CdM Technology
10.1.7.12	Motor & motor circuit	Motor circuit analysis
10.1.7.13	Motor & motor circuit	Motor current spectrum analysis
10.1.7.16	Motor & motor circuit	Start-up tests
10.1.7.9	Building envelope	Infrared thermography
10.1.7.9	Heat exchanger/condenser	Infrared thermography
10.1.7.10	Heat exchanger/condenser	Passive ultrasound
10.1.2, 10.1.7, 10.1.7.2, 10.1.7.4	Electric motor (new and rewound)	Vibration
10.1.7.15	Electric motor (new and rewound)	Surge testing
10.1.2, 10.1.7, 10.1.7.2, 10.1.7.4	Electrical generator	Vibration
10.1.7.12	Electrical generator	Motor circuit analysis
10.1.7.14	Electrical generator	Insulation resistance
10.1.7.9	Transformer	Infrared thermography
10.1.7.6	Transformer	Oil analysis
10.1.1	Measurements/surveys	N/A
10.1.7.18	All pad mounted equipment	Equipment stability for operations
10.1.7.19	Rotating Equipment – Electrical & Mechanical	Equipment leveling upon installation

11.0 CHECKLISTS FOR RCM QUALITY ASSURANCE

The quality assurance checklists provided here should be used in conjunction with the material contained in Chapter 13.0 on Building Commissioning and Chapter 14.0 Maintainability.

11.1 PLANNING

Table 11-1 contains some factors to be considered in the planning phases of facilities acquisition.

Table 11-1. RCM Quality Assurance Planning Considerations

Planning Quality Assurance Checklist	✓
Do the Owner's Project Requirements and Design Intent documentation include RCM elements where appropriate?	
Is an online monitoring system planned where cost-effective?	
Has the use of performance data for PT&I been considered and planned?	
Is the collection of cost, cost avoidance, and cost savings data incorporated into the life-cycle cost model?	
Does the CMMS allow PT&I data input?	
Does the Independent Design Review process provide for maintenance and operations feedback/review?	
Have appropriate PT&I technologies for the equipment been selected?	
Does the Commissioning Plan include PT&I acceptance criteria?	
Do warranty requirements address PT&I monitoring?	
Will an FMEA be used to determine commissioning test and maintenance task development?	
Are single points of failure identified and mitigated?	

11.2 DESIGN

Table 11-2 lists factors to consider for quality assurance during the design phase of facilities acquisition.

Table 11-2. RCM Quality Assurance Design Considerations

Design Quality Assurance Checklist	✓
Are maintainability factors (access, material, standardization) considered? (See Chapter 14.0 for details.)	
Are quantitative goals set, such as Mean Time to Repair?	
Are ease of monitoring factors (access and online data collection) considered?	
Are there performance indicators for measuring system performance and reliability?	
Are PT&I technologies specified and incorporated?	
Do the contractor qualifications match the RCM requirements?	
Has a PT&I analysis capability been provided by the contractor?	
Has the distribution of raw test and PT&I data been incorporated into the turnover process?	
Are construction phase test and maintenance results distributed to users?	
Are maintenance personnel included as part of the Independent Design Review process?	
Do the Owner’s project requirements address availability in a quantifiable manner?	
Is enhanced commissioning part of the design intent?	
Has sustainability been included in the design intent?	

11.3 CONSTRUCTION

Table 11-3 lists factors to consider during the construction phase of facilities acquisition.

Table 11-3. RCM Quality Assurance Construction Considerations

Construction Quality Assurance Checklist	✓
Were acceptance testing requirements established (prior to construction mobilization)?	
Do the contractor’s qualifications indicate an adequate understanding of RCM?	
Is the contractor conforming to specifications and drawings?	
Is the contractor conforming to bills of material?	
Is the contractor conforming to installation procedures?	
Has a surveillance plan been developed for overseeing the maintenance being performed prior to turnover?	
Has the training of maintenance personnel been initiated?	
Is the selection of maintenance tasks in progress based on the FMEA and local criticality and probability of failure?	
Has the writing of maintenance procedures and instructions been initiated?	
Are baseline condition and performance data recorded and made available for equipment as it is installed?	
Are spare parts and material requirements based on results of FMEA and logistical issues?	
Have the contractor equipment submittals been reviewed and approved by the RCM group?	
Is test equipment of sufficient quality and accuracy to test and measure the system performance within the tolerances required?	
Is test equipment calibrated at the manufacturer's recommended intervals with calibration tags permanently affixed to the instrument?	
Is test equipment maintained in good repair and operating condition?	
Is test equipment immediately re-calibrated or repaired, if damaged in any way during project system testing?	

11.4 EQUIPMENT PROCUREMENT

Table 11-4 lists factors to consider during the equipment procurement phase of facilities acquisition.

Table 11-4. RCM Quality Assurance Equipment Procurement Considerations

Equipment Procurement Quality Assurance Checklist	✓
Are performance specifications determined to meet reliability and maintainability RCM requirements?	
Are acceptance testing requirements including criteria specified in the procurement documents?	
Are contractor qualifications matched to RCM requirements?	
Is a feedback system in place for continuous equipment improvement?	
Has a provision been made for PT&I, if applicable?	
Are baseline performance and PT&I data required?	
Are equipment life-cycle costs calculations required/provided?	
Are embedded (on-line) sensors required/provided?	

11.5 MAINTENANCE AND OPERATIONS

Table 11-5 lists factors to consider during the M&O phase of a facility life-cycle.

Table 11-5. RCM Quality Assurance Maintenance and Operations Considerations

Maintenance and Operations Quality Assurance Checklist	✓
Does the existing skills inventory support the RCM program?	
Is training planned to compensate for skill and technical shortcomings?	
Does the training support the development of predictive analytical skills?	
Does the training support RCM management and supervisory skills?	
Are the documentation, procedures, and work practices capable of supporting RCM?	
Are the responsibilities for systems and equipment maintenance defined and assigned?	
Are the maintenance history data and results distributed to proper users?	
Is there a feedback system in place for continuous maintenance program improvement?	
Is root-cause failure analysis in place?	
Are failed components subject to post-failure examination and results recorded?	
Are predictive forecasts tracked and methods modified based on experience?	
Are PM tasks and CM monitoring periodicities adjusted based on experience?	
Does the CMMS fully support the maintenance program?	
Are maintenance cost, cost avoidance, and cost savings data collected, analyzed, and disseminated?	
Is baseline condition and performance data updated to reflect major repair or replacement of equipment?	
Are appropriate measures of maintenance performance (metrics) in use?	

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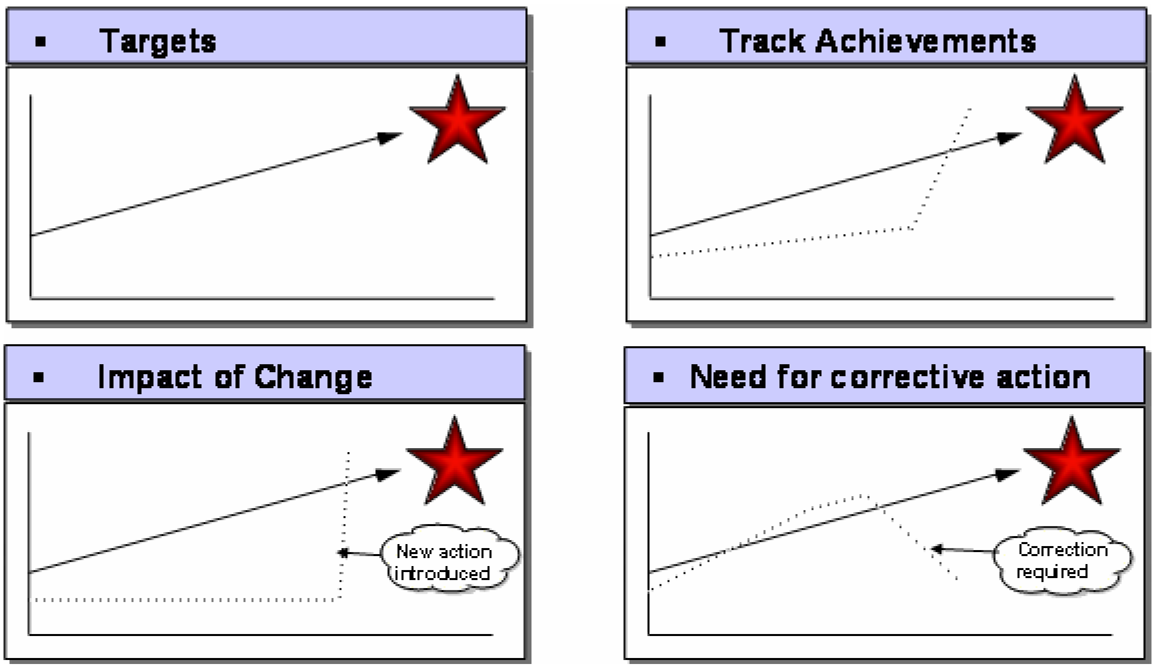
12.0 KEY PERFORMANCE INDICATORS

12.1 GENERAL

There are many management indicators used to measure the effectiveness of an RCM program, the most useful of which are numerical. The numerical, or quantified indicators, are referred to as metrics or key performance indicators (KPIs). KPIs can be expressed as goals and objectives, measured and displayed to analyze and assist in management decision making. See Figure 12-1 for examples.

Figure 12-1. Presentation and Use of KPIs



This chapter addresses the description, benefits, and methods for using KPIs as an integral part of the RCM implementation process. These quantifiable KPIs can be expressed as goals and objectives, measured and displayed in several ways for the purpose of analyzing the effectiveness of the RCM program and to support the decision making process.

RCM is described as a maintenance strategy that logically incorporates the optimum mix of reactive, preventive, predictive, and proactive maintenance practices. These maintenance practices, rather than be applied independently, are integrated to take advantage of their respective strengths in order to maximize facility and equipment operability and efficiency while minimizing life-cycle costs, KPIs therefore must be in place to measure how well the following are achieved:

- Maintenance integration
- Maintenance optimization

- Maximized operability and efficiency
- Life-cycle cost control

Each of these areas requires a method to manage and to describe the effectiveness of implementing RCM; KPIs are the key to measuring, managing and benchmarking all phases of the RCM implementation process.

12.2 PURPOSES OF KEY PERFORMANCE INDICATORS

KPIs are benchmarks to measure performance and effectiveness. With many maintenance processes and technology changes, a system to layout goals, measure implementation progress, and benchmark with others is necessary. KPIs can be used to support the functions of staffing, budget formulation, training, and contracting and to ensure compliance with certain regulatory requirements. Supervisors, engineers, technicians, and crafts use these KPIs to support optimization and continuous improvement of the maintenance program.

Management uses KPIs in the strategic planning process for the development, optimization, and direction of management objectives. KPIs should reveal the effectiveness of the management program and measure costs. Management is responsible for the translation of technical level KPIs into overall facilities maintenance management KPIs, which support NASA goals and objectives.

12.2.1 Ownership of KPIs

Managers and workers at all levels of the organization need to participate in the development and refinement of KPIs in their functional areas, thereby generating a sense of ownership. KPIs must reflect results which managers and workers can effectively change through job performance.

12.2.2 Definitions of KPIs

KPIs are relationships used to indicate the effectiveness of an operation and to compare performance with goals and objectives. KPIs are tangible performance indicators that are preferred for their quantitative, precise, and trendable benefits. KPIs can be event-based or more global. KPIs shall consist of a descriptor and a benchmark.

12.2.2.1 <u>Descriptor</u>

A descriptor is a word or group of words describing the unit(s), function(s), or process(es) to be measured. Examples include: corrective actions developed by the Predictive Testing and Inspection (PT&I) program, hours of equipment run-time, and the equipment availability (expressed as a ratio of equipment hours available to equipment hours required).

12.2.2.2 <u>Benchmark</u>

A benchmark is a numerical expression of a goal or objective to achieve. It can be an absolute number or a range. For example, the benchmark for equipment availability may be 90 percent. The metric (descriptor and benchmark) would therefore be:

$$\frac{\text{Equipment Available (Hours)}}{\text{Equipment Required (Hours)}} = 90\%$$

12.3 SAMPLE KPIS

The following are sample KPIs. The proposed benchmarks are averages taken from approximately 50 major corporations surveyed in the early 1990s and updated in 2008 to reflect the work performed by the Society of Maintenance and Reliability Professionals[26].

Table 12-1. Sample KPIs

Metric	Benchmark	KPI
Equipment Availability	96%	$\% = \frac{\text{Hours Each Unit of Equipment is Available to Run at Capacity}}{\text{Total Hours During the Reporting Time Period}}$
Maintenance Overtime Percentage	5% or less	$\% = \frac{\text{Total Maintenance Overtime Hours During Period}}{\text{Total Regular Maintenance Hours During Period}}$
Emergency Percentage	10% or less	$\% = \frac{\text{Total Hours Worked on Emergency Jobs}}{\text{Total Hours Worked}}$
Percent of Candidate Equipment Covered by PT&I	100%	$\% = \frac{\text{Number of Equipment Items in PT \& I Program}}{\text{Total Equipment Candidates for PT \& I Program}}$
Percent of Emergency Work to PT&I and PM Work	20% or less	$\% = \frac{\text{Total Emergency Hours}}{\text{Total PT \& I Preventive Maintenance Hours}}$
Percent of Faults Found in Thermographic Survey	3% or less	$\% = \frac{\text{Number of Faults Found}}{\text{Number of Devises Surveyed}}$
Percent of Faults Found in Steam Trap Survey	10% or less	$\% = \frac{\text{Number of Defective Steam Traps Found}}{\text{Number of Steam Traps Surveyed}}$
Ratio of PM/PT&I Work to Reactive Maintenance Work	A = 70% PM/PT&I	$A\% = \frac{\text{Manhours of PM/PT \& 1 Work}}{\text{Manhours of Reactive} + \text{PM/PT \& I Work}}$
	B = 30% Reactive Maintenance	$B\% = \frac{\text{Manhours of Reactive Work}}{\text{Manhours of Reactive} + \text{PM/PT \& IWork}}$
	A% + B% = 100%	

[26] For more information, see http://www.smrp.org/body_of_knowledge/best_practices_metrics.htm .

12.4 TRENDING INDICATORS

The following indicators are considerations for trending as maintenance program management tools:

- Equipment (by classification) percentage out-of-service time for repair maintenance.
- Mean time between equipment overhauls and replacement.
- Number of vibration-related problems found and corrected per month.
- Number of vibration-related work orders open at the end of the month.
- Number of vibration-related work orders over three months old.
- Number of problems found by other PT&I techniques (i.e., infrared thermography, ultrasonics, lube oil analysis) and corrected per month, work orders open at the end of the month, and work orders over three months old. A monthly record of the accumulated economic benefits or cost avoidance for the various PT&I techniques.
- Number of spare parts eliminated from inventory as the result of the PT&I program.
- Number of overdue PM work orders at the end of the month (Total number of PM actions should decrease).
- Aggregate vibration alert and alarm levels (trending down).

A NASA inter-center working group led by Kennedy Space Center and Langley Research Center, with input from the other Centers, has recommended to NASA-HQ[27] that the following four KPIs be used to track Facilities Maintenance.

12.4.1 Requirements, Funding, and Actuals

The purpose of this metric is to demonstrate the variance between identified needs, approved funding levels, and actual expenditures. The funding should be broken down by Facility Classification.

The recommended terms are Annual Maintenance Requirement (AMR), Annual Maintenance Funding (AMF), and Annual Maintenance Actual (AMA). These include the labor and material for PM, PT&I, Programmed Maintenance (PGM, Repair, TC, and ROI as defined by latest edition of NHB 8831.2 (Appendix A)).

[27] KSC letter IM-FEO-A from Nancy Bray dated June 7, 1996, Final Recommendation of Agency wide Facilities Maintenance KPIs.

12.4.2 Backlog of Maintenance and Repair

The Backlog of Maintenance and Repair (BMAR) metric tracks changes by fiscal year. This metric includes Construction of Facilities (CoF) as well as center-level funded projects that are identified but not funded. BMAR does not include routine recurring work with a frequency of less than one year.

12.4.3 Facility Reliability

This metric identifies the reliability of facilities and systems based on the level of unplanned work that must be applied to the facility or system. This metric is the ratio of planned AMA to total maintenance performed. Planned maintenance includes PM, PT&I, PGM, and planned repairs, and ROI. Planned maintenance does not include design engineering, planning and estimating, scheduling, and supervision.

12.4.4 Log of Unplanned Failures and Avoided Failures

This metric demonstrates the impact of the overall maintenance program effectiveness by tracking failures and avoided failures by detection of the failure precursor through either PM or PT&I.

12.5 METRIC SELECTION

The owners of processes shall be involved in selecting the KPIs to promote continuous data collection for maintenance support. When selecting KPIs, identify the goals and objectives of the organization. The goals the KPIs will measure should be attainable. Issues of concern should also be identified when selecting KPIs. Owners should also consider the cost of obtaining data for the KPIs as well as the relative value the KPIs add to the program.

12.6 BENCHMARKING BACKGROUND

No single benchmarking process has been adopted universally. The wide appeal and acceptance of benchmarking has led to the emergence of various benchmarking methodologies. The most prominent methodology is the 12-stage methodology by Robert Camp[28]. The 12 stages are:

- Select subject early
- Define the process
- Identify potential partners
- Identify data sources
- Collect data and select partners
- Determine the gap
- Establish process differences

[28] Robert Camp wrote the first book on benchmarking in 1989.

- Target future performance
- Communicate
- Adjust goal
- Implement
- Review/recalibrate

The following is an example of a typical shorter version of the methodology:

- Identify the program's functions and problem areas before comparing with other organizations. Baselining performance provides a point against which improvement effort can be measured. Benchmarking may be applied to any business process or function so a range of research techniques are available. These include:
  - Informal conversations with customers, employees, or suppliers.
  - Exploratory research techniques such as focus groups.
  - In-depth marketing research, quantitative research, surveys, questionnaires, reengineering analysis, process mapping, quality control variance reports, or financial ratio analysis.
- Identify other industries that have similar processes. For instance if a program's goal was to improve transitions in addiction treatment, identify other programs with transition challenges such as controlling air traffic, switching cell phone towers, and transferring patients from surgery to recovery.
- Identify organizations that are leaders in these areas. Consult customers, suppliers, financial analysts, trade associations, and magazines to determine field leaders.
- Survey companies for measures and practices.
- Visit the "best practice" companies to identify leading edge practices. Companies often agree to mutually exchange information beneficial to all parties in a benchmarking group and share the results within the group.
- Implement new or improved business practices.

12.7 BENCHMARK SECTION

After selecting appropriate KPIs establish benchmarks to characterize the organizations' goals and progress points. Benchmarks may be derived from the organizational goals and objectives or selected from a survey performed with similar organizations. Benchmarks should target growth and evaluate risk associated with non-achievement of progress.

12.8 UTILIZATION OF KPIS

Once benchmarks are established and data is collected, owners and personnel should act in a timely manner to maintain continuity among the processes. KPIs should be included in any team charter to track team productivity. KPIs can be placed in public areas for widespread knowledge.

12.9 EXAMPLES OF BENCHMARKS

Table 12-2, Table 12-3, and Table 12-4 provide examples of benchmarks. All data derives from the upper quartile of chemical and process industrial plants.

When analyzing benchmarks, focus on patterns instead of individual data points. For example, if the maintenance budget as a percent of Current Replacement Value (CRV) is below 1 percent it may be due to two factors:

- An effective maintenance program
- An indicator that the facility is being consumed

Table 12-2. Financial Benchmarks

Data Source		Maint. Cost as % of CRV	Maint. Cost as % of Controllable Cost	Training Cost/Maint. Hourly ($US)	Maint. Cost as % of Total Sales	Contractor Cost as % of Total Maint. Cost
Private Industry	High	6.0	26.1	1,990	14.1	46
	Mean	3.1	18.0	1,010	7.7	21
	Low	1.5	8.4	210	0.5	0
Best High (H)/ Low (L)		L[1]	L	H	L	L or H[2]

If a maintenance budget is below 2 percent of the CRV, the overall condition of the facility should be evaluated to determine if the infrastructure is slowly degrading or whether an excessive number of projects are required to maintain the facilities.

Either High or Low is acceptable depending on the strategic plans for the facility, i.e., if the decision has been made to out source either a portion or all of the maintenance function.

Table 12-3. Organizational Benchmarks

Data Source		Reporting Levels	Maint. Hourly/ Maint. Support Staff	Maint. Hourly/First Line Supervisor	Maint. Hourly/ Maint. Planner	Maint. Hourly/ Store-Room Employee	Maint. Hourly/ Maint. Engineer	Maint. Hourly/ as % of Total
Private Industry	High	6.0	6.5	28	62	25.0	77	51
	Mean	4.5	4.1	15.7	41	18.5	32	24
	Low	3.0	2.4	7.6	19	8.6	24	4
BEST High (H)/ Low (L)		L	H	H	H	H	L	L

Table 12-4. Work Practices Benchmarks

Data Source		Emergency Work Orders (%)	PM/PT&I Work Orders (%)	Work Order Coverage (%)	Planned Repair Compliance (%)	PM Schedule Compliance (%)	Average Work Week (Hours)
Private Industry	High	22.2	27.3	100	89	100	50.5
	Mean	7.8	13.4	88	65	91	44.3
	Low	2.1	5.4	78	50	77	41.3
BEST High (H) / Low (L)		L	H	H	H	H	L

12.10 PLANNING AND SCHEDULING KPIS

12.10.1 Backlog of Ready to Work Jobs

- Target = 3 to 5 Crew Weeks

$$\text{Crew Weeks} = \frac{\text{Total Estimated Labor Hrs. for All Ready to Work Jobs}}{\text{Actual Hours Available to Schedule Each Week}}$$

12.10.2 Backlog of All Open Work Orders

- Target = 4 to 6 Crew Weeks

$$\text{Crew Weeks} = \frac{\text{Total Estimated Labor Hrs. for All Open Work Orders}}{\text{Actual Hours Available to Schedule Each Week}}$$

12.10.3 Schedule Compliance

- Target = 90 percent or better

$$\% = \frac{\text{Total Labor Hrs. Worked on Scheduled Jobs}}{\text{Total Labor Hrs. Scheduled}}$$

12.10.4 Estimated Manhours versus Actual Manhours in Completed Jobs

- Target = ± 15 percent

$$\% = \frac{\text{Total Estimated Labor Hrs. for Completed Work Orders for Week}}{\text{Total Actual Labor Hrs. for Completed Work Orders for Week}}$$

12.10.5 Backlog of Logbook Jobs

- Target = Less than half the number of Logbook jobs competed in a single week.
- Number of open jobs in the Electronic Logbook at the end of the month.

12.10.6 Average Labor Hours Spent on Logbook Jobs

- Target = 2 Labor Hours or less

$$\text{Labor Hrs./Logbook Job} = \frac{\text{Total Labor Hrs. spent on Logbook Jobs}}{\text{Total Logbook Jobs completed for the Week}}$$

12.10.7 Indirect Manhours Percentage

- Target = 2 percent or less

$$\% = \frac{\text{Total Indirect Hours}}{\text{Total Hours Worked}}$$

12.10.8 Total Unplanned Repair Work Orders over 30 Days Old

- Number of Unplanned Repair Work Orders over 30 days old at the end of the month per Planner.

12.10.9 Total Number of Open and Closed Work Orders

- Total number of open Work Orders at the end of the month. (Trending down or level.)
- Total number of closed Work Orders during the month. (Trending up or level.)

12.11 RCM KPIS

12.11.1 Percent of Production Line Availability

- Target = 96 percent

$$\% = \frac{\text{Hours each Critical Facility is Available to Run at Capacity}}{\text{Total Hours During the Reporting Time Period}}$$

12.11.2 Maintenance Cost per Unit of Production

- Target = Declining Annually

$$\text{Cost/Unit} = \frac{\text{Total Maintenance Cost per Time Period}}{\text{Total Finished Units Produced per Time Period}}$$

12.11.3 Maintenance Overtime Percentage

- Target = 5 percent or less

12.11.4 Emergency Percentage

- Target = 10 percent or less

$$\text{Labor Hrs.}\,\% = \frac{\text{Total Hours Worked on Emergency Jobs}}{\text{Total Hours Worked}}$$

$$\text{Jobs}\,\% = \frac{\text{Total Emergency Jobs Worked}}{\text{Total Jobs Worked}}$$

12.11.5 Percent of Equipment Covered by Condition Monitoring

- Target = 100 percent

$$\% = \frac{\text{Number of Equipment Items in Predictive Maintenance Program}}{\text{Total Equipment Candidates for Predictive Maintenance}}$$

12.11.6 Percent of Emergency Work to PT&I and PM Work

- Target < 20 percent

$$\% = \frac{\text{Total Emergency Hours}}{\text{Total Predictive \& Preventive Maintenance Hours}}$$

12.11.7 Percent of Faults Found in Thermographic Survey

- Target < 3 percent

$$\% = \frac{\text{Number of Faults Found}}{\text{Number of Devices Surveyed}}$$

12.11.8 Percent of Faults Found in Steam Trap Survey

- Target = 10 percent or less

$$\% = \frac{\text{Number of Defective Steam Traps Found}}{\text{Number of Steam Traps Surveyed}}$$

12.11.9 Ratio of PM/PT&I Work to Corrective Maintenance Work

- Target = 70 percent PM/PT&I work
- Target = 30 percent Corrective Maintenance work

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13.0 BUILDING COMMISSIONING

This chapter discusses Building Commissioning and its relationship to RCM. Together they provide a quality and reliable facility for the owner, user, and maintainer.

13.1 BUILDING COMMISSIONING OVERVIEW

Building commissioning has its roots in the Quality Control programs of the 1970s and is a direct product of the Total Quality Management programs of the 1980s. While commissioning has historically been associated with static, individual systems, modern building commissioning is a systematic, documented, and collaborative process to ensure that a building and its components systems will:

- Have high quality, reliability, functionality, and maintainability
- Meet energy and operational efficiency goals
- Operate and function as the owner intended and as designed
- Meet cost and quality expectations of the owner

Commissioning is usually associated with dynamic and integrated mechanical, electrical, security, life-safety, conveyance and other systems and their controls. Top concerns are security, indoor air quality, and integrated life-safety. Commissioning takes a proactive approach toward the maintenance and operations of the installed system. For example, in addition to ensuring that a system is delivering the required flow and pressure, commissioning tests the interoperability between systems; tests the condition and operation of key components; ensures the completeness and quality of M&O manuals and skills training; considers maintainability, accessibility, supportability, and reliability issues; and documents the entire process.

Commissioning is results-oriented, comprehensive, and emphasizes communication, inspection, testing, and documentation. When properly executed, new building commissioning begins with pre-design planning, continues into post-occupancy, and is heavily involved in the planning, design, construction, and acceptance stages in between. For existing buildings, retroactive commissioning, recommissioning, or ongoing commissioning plans allow users to make low- or no-cost adjustments to building systems to improve efficiency while developing strategies for long-term capital improvements to building systems.

13.2 TYPES OF COMMISSIONING

13.2.1 Total Building Commissioning

Total Building Commissioning should be completed for new construction, beginning at project conception, to ensure that facility systems are planned, designed, installed, tested, and capable of being operated and maintained to perform according to the design intent and the owner's needs. Total Building Commissioning should continue through the length of the construction project, from program planning through design, construction, installation, acceptance, and occupancy.

The commissioning team involvement begins at the earliest stages of project planning and includes the following:

- Applying team expertise to design, including system sizing, code compliance, maintainability, user friendliness, product quality and reliability, ergonomics, and projected life-cycle costs.
- Verifying the quality of the construction for workmanship and compliance with specification and code.
- Monitoring the installed system, following acceptance, to ensure that there are no latent installation defects or degradation of system performance and operational quality.

The benefits and goals of the total building commissioning process include:

- Ensuring that a new facility begins its life with systems at optimal productivity.
- Ensuring system interoperability, as intended.
- Improving the likelihood that the facility will maintain this initial level of performance.

13.2.2 Retrocommissioning

Retrocommissioning is the commissioning of completed or nearly complete buildings that have never been commissioned. The retrocommissioning process confirms that all building systems are functioning as appropriate according to the equipment schedule for the building.

Retrocommissioning may improve performance in many non-commissioned existing buildings, but is specifically recommended in situations where existing buildings are not meeting the expectations of the owner. This is often the case with heavily used facilities or when a building mission has changed. The Oregon Department of Energy[29] suggests retrocommissioning buildings with the following:

- An unjustified, high energy-use index
- Persistent failure of equipment or control system (old equipment should be replaced before the commissioning begins).
- Tenant complaints
- Indoor air quality problems

Retrocommissioning buildings of any age may reduce energy consumption; improve maintainability, indoor air quality, humidity, and temperature control; validate system

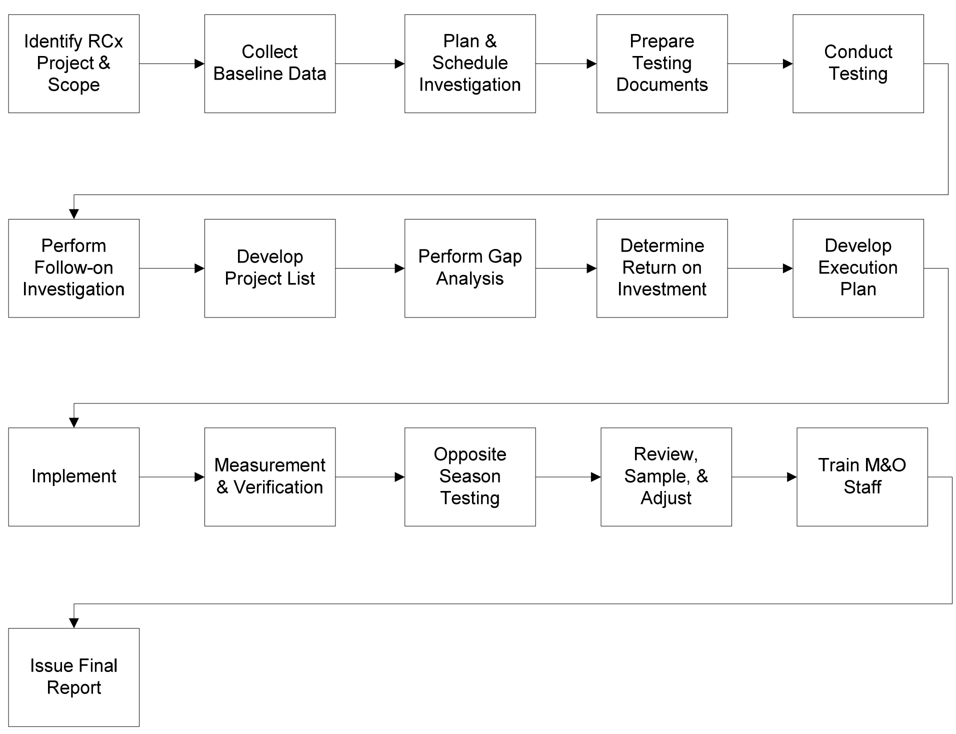
[29] Oregon Department of Energy Retrocommissioning Handbook for Facility Managers prepared by Portland Energy Conservation, Inc. (PECI) March 2001

interoperability; and balance distribution systems. Primary objectives for retrocommissioning projects include:

- Bringing equipment to its proper operational state.
- Reducing tenant complaints.
- Reducing energy and demand costs.
- Increasing equipment life.
- Improving indoor air quality.
- Increasing tenant satisfaction.
- Improving facility maintenance and operations.
- Reducing staff time spent on emergency calls.

Figure 13-1 provides an example of the Retrocommissioning process.

Figure 13-1. The Retrocommissioning Process



13.2.3 Recommissioning

Recommissioning applies only to buildings that have been previously commissioned or retro-commissioned. Recommissioning is used for two purposes:

- To verify that systems continue to operate at their peak efficiencies, particularly after changes to the building or building use have taken place.
- To ensure that the benefits of the original commissioning process endure.

Recommissioning involves revisiting the systems at regular intervals, using prior checklists, and rechecking and retesting the systems following the same procedures as those used originally.

13.2.4 Ongoing Commissioning

Ongoing (continuous) commissioning is a continuation of the initial building commissioning or retrocommissioning that, like recommissioning, verifies that building systems continue to meet current and evolving owner requirements for building performance. Unlike recommissioning, which evaluates building performance over a set timeframe, ongoing commissioning process activities occur throughout the life of the facility, some of which are close to continuous in implementation. Other activities will be less frequent, either scheduled on a routine basis or completed on an as-needed basis.

Ongoing commissioning requires the establishment of a written, long-term plan for evaluating building performance. Components of an ongoing commissioning plan include:

- Expectations for system testing, performance verification, corrective action response, ongoing measurement, and documentation.
- A schedule of the overall commissioning cycle for the building by equipment or system group (with a maximum 24-month cycle).
- A building equipment list, performance measurement frequency for each equipment item, and steps to respond to deviations from expected performance parameters.

13.3 COMMISSIONING GOALS

13.3.1 Maintainability

Maintainability is the ability to retain or restore function within a specified time. Variables to consider include time, parts, tools, training, and maintenance procedures. The impact of future changes such as organizational and mission changes, facility additions, and the political environment should also be considered.

Principal maintainability factors include access, visibility, simplicity, interchangeability, ease of monitoring and testing, and ergonomics.

- **Access.** Access is the ability to reach machines and malfunctioning components. Adequate space immediately around mechanical equipment units should be provided to allow for inspection, maintenance and repair, and the ability to reach and pull malfunctioning components without having to remove functioning components.

- **Visibility.** Visibility refers to the clear and accessible placement of performance or condition indicators. Indicators, including gauges, meters, alarms, test points, and valves, should be both visible and accessible.

- **Simplicity.** The system design should reduce the complexity of subsystems and parts and use common parts in order to improve maintainability. High quality, reliable, low maintenance materials and components such as stainless steel, sealed bearings, watertight units, and special coatings are preferred.

- **Interchangeability.** Interchangeability refers to installing like-functioning machines and replacing worn parts without major readjustment or calibration.

- **Monitoring and Testing.** Components should have easily accessible test points without having to disconnect component parts. Design should include the ability to isolate components for testing, inspection, repair, removal, or replacement by installing valves, disconnects, and switches.

- **Human Factors (Ergonomics).** Human factors considers a person's physical ability to perform the required operation, maintenance task, or repair task, as well as visual and physical accessibility, handling, temperature, weight, communications, and other human characteristics that may reduce maintainability. Designs should account for human factors limitations by incorporating accommodations for:

  - Large, heavy or otherwise awkward units, such as equipment room access doors capable of passing oversized equipment.
  - The installation of built-in cranes, hoists, or chainfalls to enable the hoisting of large or heavy components.
  - The provision of special lighting in areas where installed lighting is obstructed by equipment or other structures.

13.3.2 Supportability

Supportability builds upon reliability and maintainability, and relates to the life-cycle support elements necessary for effective availability. Supportability factors include parts availability, off-site repair capability, special tooling and skills, and technical data.

- **Parts Availability.** When possible, standard parts should be specified to minimize parts stocking and to avoid mixing incompatible parts. Just-in-Time capability should be used whenever possible.

- **Repair Capability.** Consider whether components can be repaired locally or overseas, whether the service is widely available, and whether there is a single vendor. Also consider costs, and turn-around time issues.

- **Special Tooling and Skills.** System design should include a tool and skills analysis that examines the expected tasks to be performed and identifies the needed tools, materials, skills, and skill levels for the task.

- **Technical Data.** Technical data is required to develop maintenance procedures, perform repair, and analyze equipment performance and condition. Technical data includes information in the M&O Manual, engineering and assembly drawings of the machines, schematics and wiring diagrams, control sequences, as-builts, safety notices, and test certifications.

13.4 COMMISSIONING AND SUSTAINABILITY

Sustainability is an increasing priority for facility and equipment design and maintenance. The synergy of sustainability, maintainability, and “green design” practices increase energy and water efficiency while improving the work quality of building occupants by increasing their productivity, health, safety, security, and comfort.

Federal agencies are responsible for addressing sustainability goals pursuant to Executive Order 13423, Energy Independence Security Act (EISA) 2007, the Energy Policy Act of 2005 (EPACT 2005), and the Federal Leadership in High Performance and Sustainable Buildings Memorandum of Understanding (MOU), all which require federal agencies to consider sustainable principles and resource management in the acquisition, planning, design, and construction of federal facilities. Goals for improving the sustainability of facilities and equipment include:

- Using resources efficiently and minimizing material resource consumption, including energy, water, land, and materials, during the design process, the construction process, and throughout the life of the facility.

- Maximizing resource reuse while maintaining financial stewardship.

- Maximizing equipment life while minimizing downfalls and avoiding hazardous conditions.

- Creating a healthy and productive work environment for the building occupants.

- Building and maintaining facilities for long-term use.

- Protecting and, where appropriate, restoring the natural environment.

- Attaining LEED® certification.

Sustainability is a fundamental goal of the commissioning process. Commissioning promotes cost-effective methods of reducing energy and water use, maximizing equipment life-cycles, improving indoor environmental quality for occupants, and reducing demands for building system maintenance. Critical to the sustainability of any building system is information collection, analysis, and education of building maintenance staff as well as occupants.

13.5 THE COMMISSIONING TEAM

The commissioning team is responsible for the preparation of a commissioning plan for fundamental total building commissioning, retrocommissioning, recommissioning, or ongoing commissioning.

A commissioning team is led by a commissioning authority (CxA). In general, the commissioning authority should be an independent, certified, impartial third party with the responsibility to develop and coordinate the execution of the commissioning plan, observe and document performance, and ensure that installed systems are functioning in accordance with the documented design intent and contract documents. The CxA may be a qualified employee of the building maintenance staff, although an independent CxA is preferred. For buildings seeking LEED® New Construction certification, an independent CxA is required for large projects (over 50,000 square feet).

The CxA coordinates the commissioning team which includes representatives of the following stakeholders:

- Owner representatives
- Building occupants and users
- Safety, security, and biohazard personnel
- Facilities maintenance and operations personnel

For new construction projects, the commissioning team is formed during the project planning stage. Additional commissioning team members for new construction projects include:

- All involved contractors (e.g., general, controls, sheet metal, test and balance, mechanical, electrical, HVAC, life safety, etc.)
- Architects and engineers involved from each specialization

Members of the commissioning team are formally assigned with clearly defined roles and responsibilities to be accountable for all decisions. Members must be prepared to commit the time required to fulfill these responsibilities.

13.6 THE COMMISSIONING PROCESS

13.6.1 Owner Needs

The commissioning team should have awareness of the owner's vision of the facility, its use and operation requirements, and the owner's performance goals and objectives. This vision should consider budget constraints, schedules, and other limitations. In both new construction and existing buildings, the commissioning process should meet the owner's expectations for timeliness and professionalism.

New construction projects require additional detail regarding design intent. A clear basis of design provides direction regarding the facility's functional needs, the intended levels and quality of environmental control, environmental needs, biohazard and security requirements, and schedules. The design intent serves as the basis for the contract documentation and as a reference to clarify uncertainties. The final design intent becomes part of the systems manual.

13.6.2 The Commissioning Plan

A commissioning plan should be developed based on the owner's needs for building efficiency and functionality. The plan may be broadly applied to a diverse set of buildings, systems, and equipment but customized requirements should be developed for each building. The plan should address, at a minimum, the heating system, cooling system, humidity control system, lighting system, safety systems, and the building automation controls. The commissioning plan:

- Is a comprehensive document that details how each system will be tested and inspected for conformance to the owner's design intent or goals for building systems.
- Defines the scope and detail of all systems to be commissioned.
- Identifies all relevant stakeholders and team members.
- Identifies the role and authority of all team members.
- Defines the methods and procedures that will be used for the verification, functional performance, and condition acceptance tests.
- Defines the sampling strategy that will be used for the verification and testing.
- Identifies the maintenance and operations (M&O) manuals, warranties, and training requirements.
- Develops the commissioning schedule.

The plan may be enacted for a set time frame (total building commissioning, retrocommissioning, or recommissioning) or for long-term building maintenance and operations (ongoing commissioning).

13.6.3 Building System Investigation and Analysis

Testing and analysis should be conducted to ensure that building systems and equipment are functioning correctly and as intended to meet current owner needs and sustainability requirements.

13.6.3.1 <u>New Construction</u>

For new construction, commissioning should be a fundamental part of construction from the design phase through full building occupancy. In the design phase, the commissioning process seeks to match equipment to occupancy needs, considering factors such as comfort, safety, and health. Through reviews and testing, commissioning will confirm that each building system meets the design intent during peak and partial loads and during various seasons while optimizing reliability and energy efficiency.

A primary responsibility of the commissioning authority is to review the building design relative to the owner's efficiency goals and identify potential flaws, oversights, and insufficient detail. Deficiencies that the commissioning authority routinely detects include life-cycle availability issues, hidden defects (often caused during installation), specification errors, and substitution by suppliers. These frequently result in oversizing and inefficiency, incompatibility with other components or material, and difficulty with maintainability and sustainability.

Commissioning requirements should be written into building specifications. The construction specifications define the scope of the contractor's participation in commissioning, provide general requirements for quality and condition testing, assign the test engineer to coordinate all commissioning requirements for the contractor, and detail the responsibilities of mechanical and electrical subcontractors and vendors during commissioning. Construction specifications should address the following issues:

- Measurement and measurement data requirements.
- Piping and duct system cleaning and flushing requirements.
- Bearing data, support structure diagrams, and configuration requirements.
- Equipment configuration, operating parameters, sequence of operations, operational set-points, and line-diagram requirements.
- Test instrumentation and sensor requirements.
- Vibration test procedures and frequency spectrum and amplitude requirements.
- Lubrication, hydraulic, and insulating oil condition and quality requirements.
- Lubricant sampling point locations.
- Infrared thermographic survey requirements for electrical systems, piping insulation, roofs, furnaces, boilers, motors, bearings, and standards.
- Airborne ultrasonic survey requirements for electrical systems (for arcing), compressed air piping (for leakage), and steam traps (for operation).
- Electrical testing requirements.

Throughout the construction process, the CxA should perform quality construction checks to assure compliance with design specifications. Additionally, the CxA directs the M&O training during the construction phase, reviews submittals of high-risk components, and conducts partnering sessions with the construction team to establish a trust relationship between all parties.

After installation of building components, baseline data must be gathered by the CxA during the testing and balancing (TAB) process. TAB procedures follow recognized standards such as the American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) and should be done concurrently on mechanical equipment, electrical equipment, duct, pipe, and control systems to verify that pressure and flow rates meet design requirements. During the TAB evaluation, the CxA will witness and verify all equipment startup, testing, balancing, and calibration activities and verify all equipment warranties, special tools, and spare parts lists.

After equipment is installed and balanced, a verification and pre-functional test may be completed. The CxA ensures that all systems, associated systems, and control systems are completed, calibrated, and in accordance with the contract documents. This includes all operating modes, interlocks, control responses, and specific responses to abnormal or emergency conditions. With building systems fully installed and verified, functional performance testing can occur.

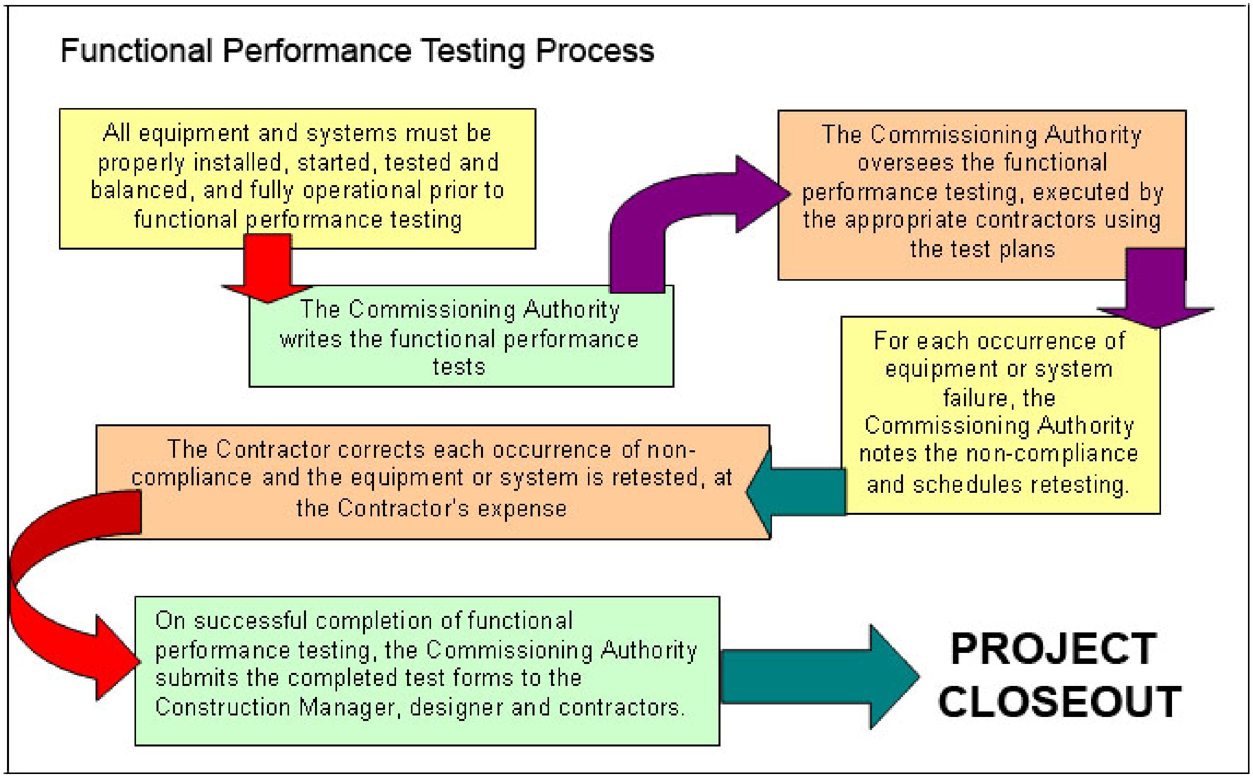
13.6.3.2 Existing Buildings

For existing buildings that do not yet have continuous monitoring capabilities, some form of field test is required to commission building systems. While building owners can determine the most suitable methods for their needs, the suggested approach is to conduct functional performance testing. Functional performance testing allows for both the establishment of baseline performance data and a method of determining which systems fail to meet owner needs and requirements.

13.6.3.3 Functional Performance Tests

Functional performance tests are used in both new construction and existing buildings to demonstrate and document the performance of the systems. Each functional performance test should be performed under conditions that simulate actual operating conditions. Maintenance and operations personnel observe the verification and performance testing. The process is illustrated in Figure 13-2.

Figure 13-2. Functional Performance Test Process



In new construction, the testing progresses from individual components through subsystems to complete systems. Where errors occur, the contractor shall correct any conflicts and deficiencies to the satisfaction of the owner. At the satisfactory completion of all verified tests, the building equipment and systems shall meet the condition required by the contract documents as a complete and operational system.

In existing buildings the opposite approach is recommended. Testing should begin with complete systems. When systems fail, individual subsystems or components may be tested. This process assumes that an integrated system that does not pass a performance test must have one or more subsystems, equipment, or components not in compliance with goals for efficiency established in the commissioning plan. If this is the case, specific testing and improvement for subsystems, equipment, or components must be conducted to bring the overall system into compliance.

The required tests vary based on the type and size of the system, the number of systems, the relationship among building systems, and the specific owner requirements. For completion, every mode of system operation, all system equipment, components, zones, and all items in the control sequence must be proven operational under partial and full loading, abnormal conditions, and emergency conditions. If deficiencies are found, they should be corrected and retested in accordance with the commissioning plan requirements.

13.6.3.4 Document Review

In addition to system testing, all M&O manuals for building systems should be reviewed as part of the commissioning process. Any relevant equipment warranties should also be reviewed to verify that all requirements to keep warranties valid are clearly stated. The M&O manuals should be organized by major systems.

Properly prepared M&O manuals should include the following:

- Detailed description of systems and components
- Wiring and control diagrams
- Control sequence of operation
- Procedures for starting, operating, and shutting-down
- Installation instructions
- Maintenance plan and schedule
- Condition monitoring plan and schedule
- Parts lists and sources of supply
- List and contact information on manufacturers and vendors
- Emergency instructions and safety procedures
- Environmental concerns
- Approved certifications and laboratory test results
- Test and balance reports
- As-built drawings
- Performance test results
- Test procedures
- Performance curves, rating data, baseline data
- Warranties and guarantees
- The CxA should report any deficiencies that are found in the M&O manuals. Manuals should be corrected and maintained by facilities maintenance personnel.

13.6.3.5 Warranty Enforcement

Warranties and maintenance records should be archived and tracked in the M&O manuals and the CMMS. In the event of a warranty dispute, the warranty, testing, and historical documentation shall be used to assess liability.

13.6.4 Implementation of Efficiency-Related Projects

Based on documented performance discrepancies, facilities staff should perform a savings and cost analysis of all practical measures to meet the constraints and economic criteria of the owner, along with a discussion of any effect on M&O procedures. Necessary building repairs, improvements, or upgrades should be prioritized based on the needs and constraints of the owner. Opportunities to make no- or low-cost capital improvements to enhance building performance should be noted. Long-term goals for system upgrades should be established and incorporated into facility capital improvement plans.

As part of facility upgrades, automated building systems and system-level metering for various building components should be considered, if not already in place. Automated building systems provide information to support the ongoing accountability and optimization of building energy performance and help identify opportunities for additional energy savings investments. Building automation systems can be used to automatically control key building systems including but not limited to: heating, cooling, ventilation, and lighting. A preventive maintenance program should be established to ensure that automation system components are repaired or replaced according to manufacturer specifications. Building automation systems should be used to inform decisions regarding ongoing building system improvements.

Building and system-level advanced metering will provide accurate energy-use information for various building systems and support active energy management policies. Metering can be used to capture information regarding the most significant building loads. The output from metering data can be used to identify changes in consumption and opportunities for energy saving improvements. Both metering and building automation systems greatly assist in the commissioning process and are critical components of buildings using an ongoing commissioning strategy to maintain peak efficiencies.

13.6.5 Training

Training of facilities managers is critical for optimizing building performance. Training for facilities management staff should build awareness and skills in a broad range of sustainable building operations topics. M&O personnel should be involved in the commissioning process. The facility manager and lead engineer determine in which areas and how rigorous training should be for all commissioned equipment. The operator training should provide a complete overview of all equipment components, subsystems, and systems with emphasis on:

- Documentation in the M&O manuals
- How to use the M&O manuals
- System operation procedures for all modes of operation-warm up, cool down, occupied, unoccupied, etc.
- Acceptable tolerances for system adjustments in all operating modes

- Procedures for abnormal and emergency conditions

For newly-installed systems, vendors are responsible for providing training on their own equipment. Prior to training, the vendor should submit for review and approval a written plan addressing the following elements:

- Equipment (included in training)
- Intended audience
- Location of training
- Objectives
- Subjects covered
- Duration of training on each subject
- Instructor for each subject and qualifications
- Methods (classroom lecture, video, site walk-through, actual operational demonstrations, written handouts, etc.)

Participants may include the owner, operators, building manager, and any project team members or contracts for new construction projects. The training should be thorough and of a reasonable length. The training may be recorded for refreshing, training, and reference purposes.

Table 13-1 provides a format to use in tracking specific equipment pieces through the commissioning process.

Table 13-1. Pumps Schedule #M-1

DESIGN CRITERIA	SPECIFIED	SUBMITTED	BALANCED	COMMISSIONED
Pump Number				
Serving				
Type				
Flow (GPM)				
Fluid				
Head (ft.)				
Efficiency (%)				
Suction/Discharge Conn. (In.)				
Motor HP				
Motor RPM				
Power Source (V/PH/HZ)				
Manufacturer				
Model Number				
Serial Number				
Starter Type (X-line, Red. V, AFD)				
Manufacturer				
Size				
Starter By (Div. 15 or Div. 16)				
Alternator Required (yes)(no)				
Manufacturer				
Model				
Pump Flow % System Flow				

Table 13-2. Pumps Schedule #M-1 (Continued)

DESIGN CRITERIA	SPECIFIED	SUBMITTED	BALANCED	COMMISSIONED
Type Base (Interia)(housekeeping)				
Isolation Required (yes)(no)				
Flow Control Valve Required (yes)(no)				
Base Grouted				
Floor Drains in Vicinity				
Alignment Checks				
Gauges Installed/Isolation Valve				
At Suction Flange				
At Discharge Flange				
Across Strainer				
Isolation Valves Installed				
Check Valve Installed				
Strainer Clean				
Flow Control Device Installed				
Flexible Connectors Installed				
Pump Rotation Check				
The following data will be used as a base. It shall be the final reading after strainer is cleaned and system is balanced at 100% speed.				
Strainer Inlet Pressure (PSIG)				
Pump Suction Pressure (PSIG)				
Pump Discharge Pressure (PSIG)				
Pump Head (PSIG/Ft.)				
Motor Amps (each phase)				
Motor Volts (each phase)				

Table 13-3. Pumps Schedule #M-1 (Continued)

DESIGN CRITERIA	SPECIFIED	SUBMITTED	BALANCED	COMMISSIONED
Motor HZ				
Control Signal to AFD				
Pump Shut-off Head (PSIG/Ft.)				
Pump Curve Shut-off Head (Ft.)				
Pump Shut-down Pressure (PSIG)				
Pressure at Highest Point (PSIG)				
Pump Accessories				
Air Separator @ Pump Suct.				
Air Vent with Shut-off				
Drain with Valve				
COMMISSIONING CHECK	COMMISSIONED			
Relief Valve				
Pipe to Drain				
City Water Make-up				
PRV				
Strainer				
Isolation Valves				
Quick Fill Bypass				
Backflow Preventer				
Pre-Pressurized Exp. Tank				
Air Eliminator				
Lock Shield Isolation Valve				
Gauge & Shut-off				

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14.0 MAINTAINABILITY

14.1 INTRODUCTION

Maintainability is emphasized because an estimated 38 percent of life-cycle cost is directed toward maintainability issues.[30] The term maintainability has the following meanings:

- A characteristic of design, construction, and installation, expressed as the probability that an item will be retained in or restored to a specified condition within a given period of time. This probability is based on the assumption that maintenance is performed in accordance with prescribed procedures and resources.

- The ease with which maintenance of a functional unit can be performed in accordance with prescribed requirements.

Maintainability is described in MIL-HDBK-470A dated 4 August 1997, *Designing and Developing Maintainable Products and Systems* (based on Blanchard[31]) as:

> The relative ease and economy of time and resources with which an item can be retained in, or restored to, a specified condition when maintenance is performed by personnel having specified skill levels, using prescribed procedures and resources, at each prescribed level of maintenance and repair. In this context, it is a function of design.

Design for maintainability requires a product that is serviceable (i.e., easily repaired) and supportable (i.e., able to be kept in or restored to a usable condition in a cost-effective manner). Supportability has a design subset involving testability. Testability is a design characteristic that allows verification of the status to be determined and faults within the item to be isolated in a timely and effective manner. Testability can be achieved through the use of build-in-test equipment so the new item can demonstrate its status for routine trouble shooting. Testability also allows for verification that the equipment has been restored to useful condition following maintenance.

Maintainability was defined as "the ability to maintain in the least amount of time at the lowest cost." Doing nothing with respect to equipment and system maintenance was not considered to be a great plan. Design for maintainability is not too expensive if it is considered early in the design process. Failure to provide for maintainability can be very expensive as retrofits to correct problems are notoriously expensive; emergency repairs brought about by poor maintenance are often done in a non-competitive environment; and equipment failure can lead to disruption of operations, system damage, and/or building damage. Poor maintenance can also result in increased day-to-day equipment loads.[32]

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[30] US Army Materiel Systems Analysis Activity (AMSAA).

[31] Benjamin S. Blanchard: Maintainability: A Key to Effective Serviceability and Maintenance Management (1995).

[32] John Rydzewski: Stupid Things We Do to Mess up Maintainability (27 June 2000).

Inaccessible equipment is a common maintainability problem. Examples of poor accessibility include but are not limited to the following:

- Equipment installed above inaccessible ceilings
- Hard-wired electrical switches mounted on access panels
- Access panels on the wrong side of equipment (no space for access)
- Air-handling units with no coil access
- Electrical panels with clearance not in compliance with the National Electric Code (NEC)
- Equipment with electrical (control) panels which do not have clearance in compliance with the manufacturer's recommendations and NEC

Maintainability should be considered during original design, during renovations, and during equipment and system replacement. Inadequate detailing for access, inadequate detailing for installation, and improper specifications (indoor equipment being used outside) are common problems.

A University of Wisconsin-Madison report on the results of a research project[33] to document the cost-effectiveness of design for maintainability used the following design review questions:

- Value engineering asks whether the design is correct.
- Constructability asks whether this design can be built cost-effectively.
- General contracting asks whether the installed equipment complies with all applicable codes and manufacturer guidelines.
- Commissioning asks whether the design and installation meet design intent.
- Maintainability asks whether the design can be maintained and operated cost-effectively.

The research project identified three primary barriers to design for maintainability:

- Inadequate communications
- The existence of two distinct cultures:
    - Focused on building facilities
    - Focused on using or maintaining facilities

[33] Blanchard: Maintainability. Wiley, New York (1995).

- A misunderstanding of the relationship between cost and value

Greg Sibley, with Vanderweil Engineers of Princeton, New Jersey, describes[34] an activist approach to design for maintainability. He strongly endorses the idea of the design engineer reviewing project goals and strategies with other members of the design team. Sibley recommends that a pre-construction document be assembled which collects owner maintenance criteria, operation criteria, capabilities, wants, needs, and preferences.

This information leads to a Project Basis of Engineering that, in detailed outline form, provides system descriptions, design criteria, an expanded program, and specifications. The Project Basis of Engineering serves as a means of facilitating understanding and buy-in on the part of all members of the design team. Sibley recommends that construction documents show all balancing and test points on the drawings, provide for maintenance access and isolation of all equipment, and provide electrical outlets and lighting for maintenance operations.

14.2 SUMMARY

For success in safely and securely maintaining and operating complex NASA facilities, NASA must continually examine the life-cycle management strategies it uses. NASA is incorporating technology to streamline processes to be more efficient and cost-effective, while simultaneously demanding high quality results. In this environment, design must expand beyond short-term goals which overlook life-cycle costs of maintenance and operations. Ignored life-cycle cost factors will negatively impact equipment productivity and availability. Accordingly, maintainability strategies must be further examined.

The Construction Industry Institute (CII) Maintainability Research Team has developed a model process for maintainability implementation consisting of the following six milestones:

- Commit to implementing maintainability
- Establish a maintainability program
- Obtain maintainability capabilities
- Plan a maintainability implementation
- Implement maintainability
- Update design program

The goal of a maintainability program is to design systems and facilities for optimal long-term availability. Maintenance considerations should drive the project planning and design. NASA hopes to achieve optimal long-term availability by performing the following:

- Plan and design for reliability, maintainability, availability, and sustainability at the beginning of the project. The maintainability program manual states,

[34] Greg Sibley: Design for Maintainability: A Consulting Engineer's View (27 June 2000).

"the true cost effectiveness of a design project is reflected through the life-cycle performance and cost." Early consideration of reliability, maintainability, and availability allows for the greatest opportunity to affect initial and long-term costs to return maximum benefits.

- Establishing ownership early in the project builds responsibility and accountability among the team members.
- Testing for compliance with design specifications before installation will ensure run-time-ready projects. A smooth transition from product development to the end-users (operators and maintainers) requires proper maintenance and operations training with complete equipment documentation.

The maximum benefits of a maintainability program are achievable if the entire life-cycle of the system becomes a consideration during project design or project planning. The design for maintainability will contribute to the following results:

- Improved equipment reliability
- Increased equipment availability
- Improved equipment performance through commissioning
- Control of maintenance costs
- Application of innovative technology such as condition monitoring and RCM
- Improved capability and use of human resources
- Increased safety
- Smooth project transition with compressed start-up time

14.3 MAINTAINABILITY, RELIABILITY, AND AVAILABILITY

Maintainability has true design characteristics. Attempts to improve the inherent maintainability of a product or item after the design is frozen is usually expensive, inefficient, and ineffective.

Poor maintainability results in unavailable equipment which is expensive and results in an irritable state for all parties involved with the equipment.

Reliability and maintainability are considered complementary disciplines from the inherent availability equation. Inherent availability looks at availability from a design perspective:

$$A_i = \frac{MTBF}{(MTBF + MTTR)}$$

- Where A_i = Inherent Availability
- MTBF = Mean Time Between Failure (also, Mean Time to Failure)

- MTTR = Mean Time to Repair or Replace

If MTBF is very large when compared to MTTR, availability will be higher. As reliability decreases (i.e., MTBF becomes smaller), better maintainability (i.e., shorter MTTR) is needed to achieve the same A_i. As reliability increases then there is not as urgent a need to improve maintainability in order to achieve the same A_i. Tradeoffs can be made between reliability and maintainability to achieve the same A_i. Reliability and maintainability must work together closely to achieve NASA maintainability goals. A_i is the largest observable availability value assuming no system or process misuse.

Operational availability looks at availability by collecting all of the abuses in a practical system:

$$A_o = MTBM / (MTBM + MDT)$$

- Where A_o = Operational Availability
- MTBM = Mean Time Between Maintenance
- MDT = Mean Down Time

The MTBM includes all corrective and preventive actions; MTBF only accounts for failures. The MDT includes all time associated with the system being down for corrective maintenance including delays (MTTR only addresses repair time) and self-imposed downtime for preventive maintenance (PM). A_o is a smaller availability number than A_i because of naturally occurring abuses.

The following should be included in the time-to-repair calculations:

- Time to successfully diagnose the cause of the failure.
- Time to procure or deliver the parts necessary to perform the repair.
- Time to gain access to the failed part or parts.
- Time to remove the failed components and replace them with functioning ones.
- Time to bring the system back to operating status.
- Time to verify that the system is functioning within specifications.
- Time to “to close up” a system and return to normal operation.

Table 14-1 provides standard definitions for reliability and maintainability terms.

Table 14-1. Maintainability Metrics

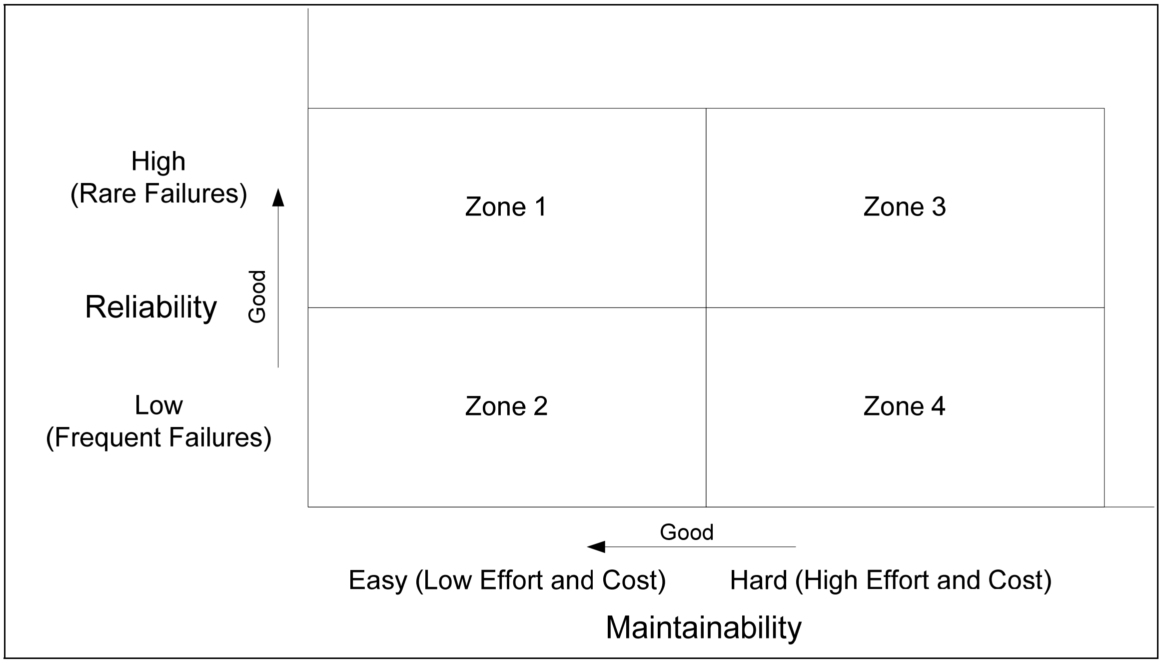
Measure	Description
Mean Time to Repair (MTTR)	The arithmetic average of the maintenance cycle times for the individual maintenance actions of a system (excludes preventive maintenance).
Mean Preventive Maintenance Time	The arithmetic average of the maintenance cycle times for the individual preventive maintenance actions of a system (inspection, calibration, planned replacement, etc.).
Median Active Corrective Maintenance Time	The value of corrective maintenance time that divides all downtime values for corrective maintenance so that 50 percent are equal or greater than the median.
Mean Active Maintenance Time	The arithmetic average elapsed time needed to perform maintenance (both preventive and corrective) excluding logistic and administrative delays.
Maximum Active Corrective Maintenance Time	That value of downtime below which one can expect a specified percent of all corrective maintenance to be completed; must be stated at a given percentile, usually 90 or 95; primarily related to a lognormal distribution.
Mean Time to Restore System	For highly redundant systems, this is the time need to switch to a redundant backup unit.
Mean Down Time	The arithmetic average time that a system is not operational due to repair or preventive maintenance. This includes logistic and administrative delays.
Maintenance Labor Hours per Hour/Cycle/Action/Month	A measure of labor hours expended (based on operating or calendar time, maintenance actions, or operating cycles).

14.4 THEORY OF MAINTAINABILITY

The advances in reliability and maintainability (R&M) over the past 50 years have largely been achieved through practice and empiricism, rather than through "theory." Unlike aerodynamics or structural analysis, there are no laws that govern R&M, but there is a significant body of knowledge that influences design for R&M. Design for R&M has always been pragmatic, experience-driven, and evolutionary. Because performance (speed, agility, payload) is typically considered first, R&M testing and analysis usually follows performance analysis in the design process and relies on past experience with similar designs during the initial stages of development.

Reliability and maintainability experts assert that inherent R&M is created by the design of a system and factors such as training, equipment, and supply support cannot compensate for a poorly designed product. The importance of R&M in design is also confirmed by studies that show that the opportunity to affect life-cycle cost impact is early in the design process with 60 to 70 percent of the life-cycle cost defined by the time preliminary design studies are complete. Decisions regarding R&M and other aspects of performance are dynamic and iterative throughout the design process. As initial estimates of reliability are modified, maintainability considerations are also affected. The relationship between reliability and maintainability for effective life-cycle design is shown below in Figure 14-1.

Figure 14-1. Reliability and Maintainability Matrix



For most components of a system in a design, the ideal method to hold life-cycle costs to a minimum is to have high reliability and easy maintainability (Zone 1 in Figure 14-1; that is a component that fails infrequently, requires little attention, and causes no major effort when it does fail (circuit breakers, switches, etc.). A component in Zone 2 fails frequently, but requires little attention when operating and is easily replaced (light bulbs, air filters, etc.). A reliable component that rarely fails, but could require significant attention during operation and major effort to replace would be assigned to Zone 3 (engines, generators, pumps, etc.). A component that fails frequently requires major effort in operation and major efforts to replace it would be in Zone 4. Systems with components in Zone 4 are typically not successful.

The job of the design team is to ensure that the components are matched to the right zone and right purpose, so that resources are used effectively. Designing a headlight for an automobile to last 30 years is probably inappropriate, as is mounting a headlight with a 2 year life to the fender of the car in such a way that the car requires major disassembly to service it.

To illustrate the relationship between reliability, maintainability, and life-cycle, consider two highly specialized and unique cases: the Space Shuttle and a NASCAR racer. For the Shuttle, reliability is essential because the costs of each mission are high and the psychological impact of failure makes it unacceptable. Thus the components of the Shuttle are generally high cost; extensive testing and high reliability requirements increase the cost to produce the items. The Shuttle also poses unique maintainability challenges: fixing components during a mission is difficult and transferring tools and parts reduces mission payload. The ideal situation is to have few maintainability tasks during missions, even for the components with high reliability. For the purposes of mission success, the objective is to have as many items in Zone 1 as possible. The Shuttle is designed for re-use, so performing maintenance between missions is integral to its design. As a system, the Shuttle is in Zone 3, and trying to migrate to Zone 1.

Parameters of its initial design limit the ability to make maintenance between missions easier, and the effects of age on the platform also tend to make it more difficult to maintain.

A NASCAR racer of 2005 is far different than the "stock cars" of the 1950s and 1960s. A modern NASCAR racer also puts a premium on reliability. The costs of the components in the racer reflect the effort to make the components durable enough to survive the demanding environment they are used in. The design of a racer is also heavily altered from generic automotive configurations to enable rapid servicing (20 gallons of gas in seconds, changing tires in seconds, etc.) and replacement (changing an engine or other major assembly during the race is rare, but it can and does happen). The design of the racer and its components is optimized to achieve mission success at what most people would consider high cost. With millions of dollars in prize money at stake, these costs are relatively reasonable.

Designers for most mass-produced products are typically tasked to develop items that are reliable and that require as little effort to maintain them as feasible within cost, weight, and other performance requirements. If the history or test experience of a product shows it to have a high failure rate or need for frequent maintenance, the objective of the designer must emphasize maintainability by placing that item in such a way as to minimize time and effort to restore the item.

14.5 BACKGROUND

Executive Order 13423 requires federal agencies to consider sustainable principles in the acquisition planning, design and construction of federal facilities. This report reviews this order and other laws, regulations, technology improvements, and industry trends that are driving advances in Sustainable Design, Design for Maintainability, and Total Building Commissioning (TBC).

The study reviewed Sustainable Design, Design for Maintainability, and TBC practices at 10 federal agencies: General Services Administration (GSA), Department of Energy (DOE), Environmental Protection Agency (EPA), Department of State (State), Department of Defense (DOD), Department of the Navy (Navy), Department of the Army (Army), Department of the Air Force (Air Force), Veterans Administration (VA), and National Parks Service (NPS). Seven industry organizations were consulted regarding their efforts to advance one or more of these practice areas, including: National Institute of Standards and Technology (NIST), National Institute of Building Standards (NIBS), American Society of Heating, Refrigeration Air Conditioning Engineers (ASHRAE), The Construction Industry Institute (CII), U.S. Green Building Council (USGBC), the Sustainable Buildings Industry Council (SBIC) and the Federal Facilities Council (FFC). The University of Wisconsin, State of Pennsylvania, New York City, the Washington Metropolitan Airport Authority, and several Architecture and Engineering firms were also contacted regarding their TBC programs and/or experience.

The most significant maintainability initiative is the work by CII, which identifies opportunities for and provides an implementation strategy for maintainability. This initiative produced four publications:

- Design for Maintainability Research Reports RR142-11 and RR142-12
- Design for Maintainability
- Improving Project Return on Investment Research Summary 142-1

- Design for Maintainability Guidebook Implementation Resource 142-2

The CII initiative recommends the following approach to maintainability:

- Secure corporate commitment.
- Assign a corporate champion for implementation and commit the resources required for implementation.
- Conduct a self audit to document the current level of maintainability practice.
- Prepare and publish a corporate policy.
- Prepare implementing procedures (procedural checklists, model specifications, measurable metrics, lessons learned database, etc.).
- Develop and conduct an internal staff training program.
- Implement a pilot project.
- Expand implementation to all projects.
- Periodically measure results achieved and revise program appropriately.

14.6 MAINTAINABILITY AT OTHER FEDERAL AGENCIES

Other federal agencies are embracing maintainability concepts to a limited extent. None has identified goals as comprehensive as those recommended by the CII research discussed above. Agencies in the lead include Navy, State, and GSA. State and GSA initiatives involve inserting sustainability requirements into A&E scopes of work. The Navy initiative is comprehensive and tied to development of the Whole Building Design Guide. Navy requires architects and engineers to produce Operations and Maintenance Service Instructions (OMSI) for all significant projects. These OMSI manuals are intended to improve the transition of ownership from construction contractors to maintenance and operations staffs. Navy invests from one half to one percent of the construction cost for the OMSI manuals and acknowledges the need to develop a more comprehensive policy on maintainability.

Army and Air Force also acknowledged a need for policy on maintainability issues. Other agencies contacted are not doing anything formally, nor do they have policies regarding maintainability.

Building Maintainability is not understood as well as sustainability. Although owners recognize the value of designing and constructing facilities to improve maintenance and operations, they lack a formal methodology for doing so. Generally, owners who value maintainability have focused primarily upon the following limited initiatives:

- Timely acquisition of building system and equipment M&O documentation for building M&O manuals.

- Maintenance and operations staff involvement in the design review process (often during final design review, when opportunity to improve the design is minimal).
- Creating lessons-learned files documenting startup and M&O problems to avoid repeating mistakes on subsequent projects.

Until now, maintainability initiatives occurred during the construction and start up phases, and were reactive. These reactive initiatives missed the opportunity for significant improvements which could have been realized, had alternatives been considered prior to facility design completion.

Maintainability proponents advocate applying maintainability concepts at the beginning of the facility acquisition process, starting with the concept development phase. Maintainability should be a significant project objective. Maintainability experience should factor into A&E selection. Maintainability should influence the design approach and drive material and equipment selection. Maintainability is fundamental to all building commissioning activities. Documents required for maintenance and operations, and appropriate training, should be identified and acquired prior to facility startup.

The following recent developments have gained maintainability more visibility:

- Technology advances, including RCM practices such as vibration sensing, thermal imaging, and oil analysis.
- Business practices that solicit participation of all project stakeholders, including the maintenance and operations staff.
- Material science advances with resultant impact on maintenance requirements.
- Public policy changes, such as greater emphasis on life-cycle costing.
- Increased use of metrics to measure facility performance.
- Owners who demand higher operating reliability and more effective maintenance practices.
- More sophisticated electrical and mechanical building systems that require more intensive maintenance support.
- Greater emphasis on sustainability and green building practices that increase the requirements for facility operating efficiencies

14.7 FIRST PRINCIPLES OF MAINTAINABILITY DESIGN

The following is adapted from the National Institute for Occupational Safety and Health website[35].

Maintainability is often confused with maintenance. *Maintenance* is a series of specific actions taken to restore a machine to full operational status. These actions may include servicing, troubleshooting, inspection, adjustment, removal and replacement, or in-place repair of components or systems on a machine. *Preventive maintenance* refers to the actions taken to retain a machine at a specified level of performance. It includes routine servicing and replacement of parts that are likely to fail during the next operational cycle. *Corrective maintenance* represents actions taken to restore a machine to an operational state after it is disabled due to a part or system failure. *Reliability* is the probability that the machine will perform its intended function for a specified interval of time under stated operating conditions.

With the above definitions in place, introducing the following first principles (see Table 14-2) of maintainability design is possible.

[35] For more information, see http://www.cdc.gov/niosh/mining/topics/topicpage22.htm .

Table 14-2. First Principles of Maintainability Design

FP✓	Maintainability should be a designed-in capability and not an add-on option.
FP✓	Great maintenance procedures cannot overcome poor equipment design.
FP✓	A complex design solution is often easier than a simple solution until you have to maintain it. Given the choice, opt for the simpler design.
FP✓	Every point where two or more components come together or where you mount a component on the chassis represents a maintenance point.
FP✓	Every maintenance point should be directly visible and fully accessible to the maintainer.
FP✓	All parts or components are replaced eventually, so design for these eventualities.
FP✓	Do not design for the "average" or 50th percentile person. To do so could exclude up to 60% of the users. Design for the user population, which includes the 10th-90th percentile person.
FP✓	Troubleshooting is not a form of gambling. Design maintenance and troubleshooting procedures to reduce the odds in the maintainer's favor. Provide specific indicators of pending or actual failures for all systems and major components.
FP✓	In order for the maintenance person to remember maintenance instructions, write them down and post them on the machine where he/she will make the decision while maintenance is being done. Label key components, show flow direction, and provide other decision-making information.
FP✓	Design interfaces so that the component or connection can only go together correctly.
FP✓	Design every interface so that you can install only the correct replacement part or component, by using unique bolting patterns, guide pins, or other features.
FP✓	Design each interface so that you can install acceptable alternative components without modifications. If two different components can serve the same function, design the mounting interface such that you can mount both units without modification.
FP✓	Since the unexpected can occur at any time, ensure that you sufficiently derate all mechanical, electrical, hydraulic, and pneumatic systems to withstand unexpected overloads without failures, degradation in performance, or negative safety consequences.
FP✓	Design line-of-sight visibility for all maintenance tasks that require visual inspection, servicing, adjustment, alignment, in-place repair, or removal and replacement of components.

Table 14-3. First Principles of Maintainability Design (Continued)

FP✓	Because the easiest decision to make is often a go/no-go decision, design all maintenance decisions to be go/no-go decisions.
FP✓	Design all systems and subsystems to fail to a safe mode or state so that a component or subsystem failure will not result in additional damage or employee injury.
FP✓	Because it is sometimes difficult to see what is right in front of you, design all systems so that failures are obvious.
FP✓	Special tools are rarely available when maintainers need them, so design all maintenance tasks to eliminate the need for special tools.
FP✓	Design and locate all components and interfaces so that they are directly and easily accessible or reached for maintenance.
FP✓	Do not force fit standard parts as a substitute for reliability, maintainability, performance, and design innovation.
FP✓	Modularization of components reduces maintenance guess work, which in turn reduces maintenance downtime.
FP✓	Maintenance errors add to the maintenance burden, so reduce the maintenance burden by eliminating or reducing the opportunity for human error.
FP✓	Because equipment operators sometimes cause equipment failure and damage, design the machine to be operator-proof by designing operator-controlled systems with emergency relief valves, overload safety devices, and other precautionary features.
FP✓	Do not design maintenance tasks that rely on personnel to lift or maneuver heavy components.
FP✓	To save time, design repair tasks, alignments, and adjustments so there minimal need to tear down or remove components.
FP✓	Because a person's effective work envelope is determined by his or her reach, do not put maintenance or service points where they are effectively out of arm reach.
FP✓	Because a person's visual acuity decreases with age, viewing distance, and task complexity, do not locate visual inspection points more than 36 in (91.44 cm) away from where the maintainer's head is going to be while doing the inspection. Do not put visual inspection points behind components, under protective covers, or at other points that require work to reach them.

14.8 REVIEW FOR DESIGN MAINTAINABILITY CONSIDERATIONS

The following maintainability factors should be considered and reviewed:

- **Non-Interference of Preventive Maintenance.** Preventive maintenance should be minimized and require as little time as feasible.

- **Flexible Preventive Maintenance Schedule.** Preventive maintenance schedules should be sufficiently flexible to accommodate changes in the schedule of other mission activities.

- **Redundancy.** If maintenance is necessary and system operations will be interrupted, redundant installations should be considered in order to permit maintenance without interrupting system operation.

- **Goals of Designing for Maintainability.** The following are goals for optimizing involvement in both preventive and corrective maintenance:

  - Reduce training requirements.
  - Reduce certain skill requirements.
  - Reduce time spent on preventive and corrective maintenance.
  - Increase overall maintenance capabilities (especially corrective maintenance).

- **Corrective Maintenance.** The following maintainability factors should be considered:

  - The benefit gained from repair should be worth the time and effort expended on repair.
  - The time and effort involved in corrective maintenance should be weighed against the cost and feasibility of carrying replacement units.
  - Required calibration, alignment, or adjustment should be easily and accurately accomplished.
  - Automate fault detection and isolation tasks whenever possible.

14.8.1 Equipment Design Requirements

The following general requirements should be checked as part of the maintainability review:

- **Growth and Update.** Facilities, equipment, and software design shall allow for reconfiguration and growth during the planned life-cycle.

- **Independence.** Systems and subsystems shall be as functionally, mechanically, electrically, and electronically independent as practical to facilitate maintenance.

- **Maintenance Support Services.** Maintenance support services (e.g., electrical outlets) shall be accessible at potential problem locations or at a designated maintenance location.

- **Reliability.** Equipment design shall reduce to a minimum the incidence of preventive and corrective maintenance.

- **Simplicity.** Equipment design shall minimize maintenance complexity.

- **Time Requirements.** Equipment design shall minimize the time requirements for maintenance.

- **Equipment.** Maintenance equipment and tools shall be kept to a minimum.

- **Hazardous Conditions.** System design shall preclude the introduction of hazardous conditions during maintenance procedures. Hazardous substances shall be monitored and controlled through dedicated systems.

- **Critical Operations.** Critical systems shall be capable of undergoing maintenance without the interruption of critical services and shall be maintained.

- **Non-Critical Operations.** Non-critical systems shall be designed to operate in degraded modes while awaiting maintenance. Degraded mode operation shall not cause additional damage to the system or aggravate the original fault.

- **Redundancy Loss.** Notification of loss of operational redundancy shall be provided immediately.

- **Connectors.** Quick-disconnect connectors shall be used.

- **Plug-In Installation.** Plug-in type hardware installation and mounting techniques shall be employed.

- **Quick Release Fasteners.** Quick release fasteners shall be used where consistent with other requirements (e.g., strength, sealing).

- **Replacement Capabilities.** Capacity of replaceable or re-serviceable items (filters, screens, desiccant units, battery power supplies, etc.) shall be higher than the minimum functional requirements of the system.

- **Automation.** Fault isolation, inspection, and checkout tasks shall be automated to the extent practical.

- **Restraints:** Personnel and equipment mobility aids and restraints shall be provided to support maintenance.

- **Special Skills.** Maintenance requiring special skills shall be minimized.

- **Soldering, Welding, and Brazing.** Soldering, welding, brazing, and similar operations during maintenance shall be minimized.

14.8.2 Physical Accessibility Design Requirements

Design requirements for physical access to equipment for the purpose of maintainability are provided below.

- **Relative Accessibility.** Items most critical to system operation and which require rapid maintenance shall be most accessible. When relative criticality is not a factor, items requiring most frequent access shall be most accessible.
- **Access Dimensions**. The minimum sizes for access openings for two hands, one hand, and fingers are shown in Table 14-4.
- **Access**. Access to inspect or replace an item shall not require removal of more than one access cover.
- **Mounted Components**. When feasible, components shall be no more than one deep in a bay or rack.
- **Shape**. Accesses shall be designed to the shape that will enable the maintainer to do his or her job and not be limited only to conventional shapes.
- **Number of Accesses**[36]. Whenever possible, one large access shall be provided rather than a number of small ones.
- **Protective Edges**. Protective edges or fillets shall be provided on accesses that might injure maintainers or their tools.
- **Covers**. Where physical access is required, one of the following practices shall be followed, with the order of preference as given.
  - Provide a sliding, translating, or hinged cap or door where debris, moisture, or other foreign materials might otherwise create a problem.
  - Provide a quick-opening cover plate in a cap that will meet stress requirements.
- **Self-Supporting Covers.** All access covers that are not completely removable shall be self-supporting in the open position.
- **Rear Access.** Sliding, rotating, or hinged equipment to which rear access is required shall be free to open, translate, or rotate its full distance.
- **Damage Inspection and Repair.** Where feasible, the design of structures and equipment, including their interfaces and all portions of the pressure shell, bulkheads, and seals shall be accessible for damage inspection and repair. This shall apply to exterior as well as to interior surfaces.

[36] NASA Spacecraft Accessibility Program.

- **Use of Tools and Test Equipment.** Check points, adjustment points, test points, cables, connectors, and labels shall be accessible and visible during maintenance. Sufficient space shall be provided for the use of test equipment and other required tools without difficulty or hazard.
- **Fold-Out/Pull-Out Drawers and Cabinets.** Fold-out/pull-out drawers and cabinets shall be used where possible to provide ease of access.
- **Slide-Out Stop.** Limit stops shall be provided on racks and drawers which are required to be pulled out of their installed positions for maintenance. The limit stop design shall permit convenient overriding of stops for unit removal.
- **Service Points for Fluid System.** Service points for filling, draining, purging, or bleeding shall be in accessible locations.
- **Plug Connectors.** Full access shall be provided to plug connectors.
- **Cables.**
    - Cables shall be routed so as to be readily accessible for inspection and repair.
    - Wire harness and fluid lines mounted in cable trays shall be located for ready access.
    - Panel, console, and rack mounted components shall have slack cable lengths or maintenance loops sufficient for removal of the connectors after the component has been extracted from its installed location, unless adequate internal access (physical and visual) is provided.
    - Cables shall not be routed external to the face of the equipment rack.
- **Fuses and Circuit Breakers.** Fuses and circuit breakers shall be readily accessible for removal, replacement, and resetting. The condition of fuses (good or blown) shall be readily discernible without having to remove the fuse.
- **Structural Members.** Structural components of units or chassis shall not prevent access to or removal of equipment.
- **Hazardous Conditions.** If a hazardous condition exists behind an access, a safety indictor shall be provided. The access shall be equipped with an interlock that will de-energize the hazardous conditions when the barrier is opened or removed, and a manual override shall be provided.
- **Arc Flash.** Improperly designed, installed or maintained equipment, improper work procedures, loose connections, or unsuccessful interruption of a fault could cause an arc flash. (Just an example: 10,000 A arc at 480V can be compared to 8 sticks of dynamite).

Table 14-4. Access Dimensions

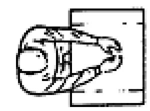
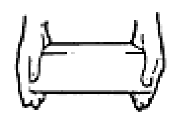
Minimal Two-Hand Access Openings without Visual Access		
Reaching with both hands to depth of 150 mm (5.0 in) to 490 mm (19.25 in)		
Light clothing:	Width: 200 mm (8.0 in) or the depth or reach	
	Height: 125 mm (5.0 in)	
Reaching full arm's length (to shoulders) with both arms		
Light clothing:	Width: 200 mm (8.0 in) or the depth or reach	
	Height: 125 mm (5.0 in)	
Inserting box grasped by handles on the front		
13 mm (0.5 in) clearance around box, assuming adequate clearance around handles		
Inserting box with hands on the sides		
Light clothing	Width: Box plus 115 mm (4.5 in)	
	±Height: 125 mm (5.0 in) or 13 mm (0.5 in) around box*	
* Whichever is larger ± If hands curl around bottom, allow an extra 38 mm (1.5 in) for light clothing.		
Minimal one-hand access openings without visual access		
	Height x Width	

Table 14-5. Access Dimensions (Continued)

Empty hand, to wrist		
Bare hand, rolled	95 mm (3.75 in) sq or dia	
Bare hand, flat	55 mm (2.25 in) x 100 mm (4in) or 100 mm (4 in) dia	
Clenched hand, to wrist		
Bare hand	95 mm (3.75 in) x 125 mm (5.0 in) or 125 mm (5.0 in) dia	
Arm to elbow		
Light clothing	100 mm (4.0 in) x 115 mm (4.5 in)	
Arm to shoulder		
Light clothing	125 mm (5.0 in) sq or dia	
Minimal Finger-Access to First Joint		
Push button access		
Bare hand	32 mm dia (1.26 in)	
Gloved hand	38 mm dia (1.5 in)	
Two finger twist access		
Bare hand	object plus 50 mm (1.97 in)	
Gloved hand	object plus 65 mm (2.56 in)	

14.9 REPLACEMENT AND MODULARITY DESIGN REQUIREMENTS

- **Removal.** Systems and subsystems shall be designed so that failed units can be removed without damaging or disturbing other components.

- **Independence.** Where feasible, it shall not be necessary to remove or disable an operable unit to obtain access to a defective replaceable unit.

- **Component Labeling.** Each removable component and its position on the unit shall be labeled with corresponding numbers or other identification.

- **Isolation Valves.** Subsystems that contain liquids or high pressure gases (pressures exceeding 125 psia) and require maintenance shall be provided with isolation or disconnect valves to permit isolation and servicing and to aid in leak detection.

- **Spillage Control.** Replaceable units shall be designed to control spillage and the release of gases during removal or replacement.

- **Fastener Coatings.** Paint or coatings shall not adversely affect removal or installation of fasteners.

- **Short Life Components.** Easy replacement shall be provided for components that fail frequently (e.g., lamps and fuses).

- **Guide Pins.** For mounting and replacement of replaceable units, guides and guide pins shall be provided for alignment.

- **Replacement Specificity.** All replaceable items shall be designed so that it will be physically impossible to insert the unit incorrectly.

- **Related Items.** Items of the same or similar form which have different functional properties shall be readily identifiable and distinguishable and shall not be physically interchangeable. This indication shall be readily discernible with the component in its installed position.

14.10 FAULT DETECTION AND ISOLATION DESIGN REQUIREMENTS

Design requirements for fault detection and isolation are as follows:

- **General.** Equipment design shall facilitate rapid and positive fault detection and isolation of defective items.

- **Diagnostic Capability.** Mission-critical and life safety system equipment shall have an integrated diagnostic capability for all functional failures identified as known or expected to occur.

- **Manual Override.** A manual override capability for all automatic control functions shall be provided.

- **Portable Equipment.** When built-in test equipment is not available, diagnostic tools or portable equipment shall be provided for fault isolation to the replacement unit level.

- **Critical Malfunction Alarm.** If critical equipment is not regularly monitored an alarm (auditory, visual, or both) shall be designed to ensure detection.

- **Troubleshooting Sequence.** A sequence of troubleshooting checks shall be specified to maximize trouble-shooting efficiency.

- **Test Equipment Accuracy.** The accuracy of all test equipment shall exceed that of the equipment being tested.

- **Adjustment Controls.** Appropriate feedback shall be provided for all adjustment controls and shall be readily discernible to the person making the adjustment while making the adjustment. Adjustment controls shall be reversible without dead band, slop, or hysteresis.

14.10.1 Advantages of Improved Maintainability[37]

Maintainability engineering seeks to increase efficiency and safety while reducing the cost of equipment maintenance. To this end, significant cost reductions in maintenance must begin with improved equipment design. Maintainability engineering will not eliminate the need for service and repair on equipment, but it does provide the following advantages:

- Reduction of the time required to complete scheduled and unscheduled maintenance.

- Minimization of the frequency of unscheduled maintenance by improving accessibility for inspection and servicing.

- Reduction of maintenance errors and incorrect installations.

- Improvement of post maintenance inspection.

- Reduction of maintenance-related injuries.

- Minimization of maintenance personnel training requirements.

- Improved troubleshooting performance.

The following list contains typical design problems on underground mobile equipment that are addressed by incorporating maintainability design.

- Inadequate access opening size.

[37] For more information, see http://www.cdc.gov/niosh/mining/topics/topicpage22.htm .

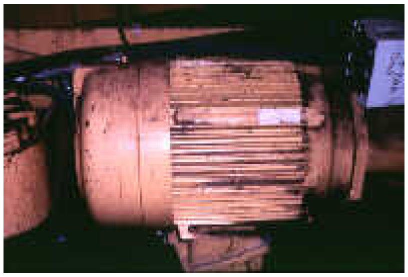
- Poor layout of components in a compartment, necessitating removal and replacement of non-affected parts to access the failed units.
- Inability to access mounting bolts or connectors or to use required tools.
- Installing components in inaccessible interior cavities.
- Inaccessible cables that run inside the frame or chassis.
- Inaccessible fasteners and mechanical interfaces that require partial or complete disassembly.
- Inadequate component handling capability and component machine interface design.
- Inadequate design for routine maintenance, such as the inability to quickly remove and replace leaking hydraulic hoses and water lines, remove and replace failed hydraulic valves, do routine lubrication, and perform visual and physical inspections.
- Inadequate fault isolation capability, such as difficulty determining the precise cause and location of a failure, reaching components to do visual inspections and to perform checks, limited or no designed-in fault diagnostic capabilities, or lack of effective failure indices.
- Increased maintenance burden resulting from poor design and placement of components, subjecting them to damage.
- Poor design regarding available resources, such as the need for maintenance personnel to build tools or handle 100 to 1,000 pound (45.36 to 453.59 kg) components.
- Equipment complexity resulting from poor layout, such as the crowding of components into compartments with no regard to maintenance or replacement of individual items, overlaying hoses and power cables, making removal and replacement difficult.
- Multiplying the number of valves, connectors, and other high-frequency replacement components as a design convenience.

The successful application of maintainability design principles could reduce preventive maintenance and corrective maintenance time by 40 percent to 70 percent, maintenance labor costs by 10 percent to 25 percent, and maintenance risk significantly.

14.10.2 Accessibility Examples

See Table 14-6 for examples of accessibility issues.

Table 14-6. Examples of Accessibility Issues

	Large components, such as this motor, should have lift points clearly marked. Access opening should be large enough to accommodate materials handling equipment.
	Workers had to cut their own opening to access a maintenance point.
	Welding structural members over areas where hydraulic hoses and electrical conduit are run makes it difficult for the maintainer to gain access. Do not crowd components into compartments without regard for the need to maintain or replace individual items.
	There are many examples of good maintainability design. This module swings out from its cabinet to allow easy access to all maintenance points.

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APPENDIX A: GLOSSARY

Acceptable Performance (Commissioning): Performance of systems, subsystems, and components that meet specified design performance parameters under actual load and responds to changing conditions and parameters appropriately as expected and specified.

Age Exploration: The process of determining the most effective intervals for maintenance tasks. It is called age exploration because it is often associated with identifying age related maintenance actions, such as overhaul and discard tasks, and then extending the interval between tasks. Age Exploration techniques are also applicable to PT&I tasks.

Availability: (1) Informally, the time a machine or system is available for use. (2) From the Overall Equipment Effectiveness (OEE) calculation, the actual run time of a machine or system divided by the scheduled run time. Note that Availability differs slightly from Asset Utilization (Uptime) in that scheduled run time varies between facilities and is changed by factors such as scheduled maintenance actions, logistics, and/or administrative delays.

B-Life. The time at which a set percentage of failures are expected. For example, the B1 life is the elapsed time since putting into service when 1 percent of the units being examined will have failed; B10 is the elapsed time when 10 percent of the units will have failed.

Basis of Design: A document that records the design criteria and assumptions upon which the design is based.

Benchmarking: To seek out the best examples of methods, processes, procedures, and products in order to establish a standard and assess ones own performance in terms of quality, productivity, or cost.

Building Commissioning: The systematic process for achieving, verifying, and documenting that the performance of NASA facilities and its equipment meet the design intent. The process extends through all phases of a project and culminates with occupancy and operation. The process includes the testing and accepting of new or repaired building, system or component parts to verify proper installation.

Calibration: A scheduled maintenance task characterized as an Inspection. See Inspection.

Collateral Equipment: Encompasses building-type equipment, built-in equipment, and large, substantially affixed equipment/property and is normally acquired and installed as part of a facility project as described below (also see Non-installed Equipment):

- **Building-Type Equipment:** That equipment normally required to make a facility useful and operable. It is built in or affixed to the facility in such a manner that removal would impair the usefulness, safety, or environment of the facility. Such equipment includes elevators; heating, ventilating and air conditioning systems; transformers; compressors; and other like items generally accepted as being an inherent part of a building or structure and essential to its utility. It also includes general building systems and subsystems such as electrical, plumbing, pneumatic, fire protection, and control and monitoring systems.

- **Built-In or Large, Substantial Affixed Equipment:** That equipment (other than building-type equipment) that is to be built in, affixed to, or installed in a facility in such a manner that the installation cost, including special foundations or unique utilities service, or the facility restoration work required after its removal is substantial.

Commissioning: The process of testing and accepting a system, line, building and/or other plant component. It is often the first (and sometimes last) opportunity for the "maintenance department" to identify a design or build defect. Also see Building Commissioning.

Commissioning Plan: A document that outlines the organization, scheduling allocation of resources, and documentation pertaining to the overall commissioning process.

Computerized Maintenance Management System (CMMS): A set of computer software modules and equipment databases containing facility data with the capability to process the data for facilities maintenance management functions. They provide historical data, report writing capabilities, job analysis, and more. The data describe equipment, parts, jobs, crafts, costs, step-by-step instructions, and other information involved in the maintenance effort. This information may be stored, viewed, analyzed, reproduced and updated with just a few keystrokes. The maintenance-related functions typically include:

- Facility/Equipment Inventory,
- Facility/Equipment History,
- Work Input Control,
- Job Estimating,
- Work Scheduling and Tracking,
- Preventive and Predictive Maintenance,
- Facility Inspection and Assessment,
- Material Management, and
- Utilities Management.

Condition Assessment: Condition assessment is the inspection and documentation of the material condition of facilities and equipment, as measured against the applicable maintenance standard. It provides the basis for long-range maintenance planning as well as annual work plans and budgets.

Condition-Based Maintenance (CBM): Facility and equipment maintenance scheduled only when the condition of the facility or equipment requires it. CBM replaces maintenance scheduled at arbitrary time or usage intervals. It usually involves the application of advanced technology to detect and assess the actual condition

Condition Monitoring (also known as Predictive Maintenance): The continuous or periodic monitoring and diagnosis of systems and equipment in order to forecast failure. Condition Monitoring is a Time- or Cycle-Based Maintenance Action In condition monitoring advanced technology is used to assess machinery condition. The data obtained allows for planning and scheduling preventive maintenance or repairs in advance of failure.

Corrective Maintenance: See repair.

Cost Effective: An economic determination of the Maintenance Approach and entails evaluation of maintenance costs, support costs, and consequences of failure. Also see Effective Maintenance Task.

Critical Failure: A failure involving a loss of function or secondary damage that could have a direct adverse effect on operating safety, on mission, or have significant economic impact.

Critical Failure Mode: A failure mode that has significant mission, safety or maintenance effects that warrant the selection of maintenance tasks to prevent the critical failure mode from occurring.

Current Replacement Value (CRV): Approximate cost to replace an existing facility in its present form. The CRV is calculated by escalating facility and its equipment acquisition cost, and any incremental book value changes of $5,000 or more, to present-year dollars using the Engineering News Record (ENR) Building Cost Index (BCI).

Deferred Maintenance (DM): "Deferred maintenance" is maintenance that was not performed when it should have been or was scheduled to be and which, therefore, is put off or delayed for a future period. For purposes of Federal Accounting Standard 6, maintenance is described as the act of keeping fixed assets in acceptable condition. It includes preventive maintenance, normal repairs, replacement of parts and structural components, and other activities needed to preserve the asset so that it continues to provide acceptable services and achieves its expected life.58 Maintenance excludes activities aimed at expanding the capacity of an asset or otherwise upgrading it to serve needs different from, or significantly greater than, those originally intended.

Design Intent: A narrative description of systems equipment and their intended modes and sequences of operation.

Dominant Failure Mode: A single failure mode that accounts for a significant portion of the failures of a complex item.

Effective Maintenance: The application of the maintenance approach that will produce the required availability, at the lowest cost, without compromising human safety or health, the environment, or any other conditions the organization specifies.

Effective Maintenance Task: A task that is characterized as performing its defined function with a high degree of success for a specified cost. A maintenance task must be both applicable and effective. The benefit of performing the task must be evaluated against the cost. Cost includes many elements; the cost of the task, repair costs when failure occurs, collateral damage caused by failure, and the cost of lost mission (such as production, space and flight operations, research, and administrative support) due to loss of the facilities and installed equipment function.

Facilities Condition Index (FCI): A unitless number which or percentage which expresses the amount of Deferred Maintenance divided by the Current Replacement Value of the facility being evaluated. A FCI can exist for a single property or a collection of properties. FCI can be expressed on a scale of 1 to 5 (where 5 is excellent, no DM) as reported by NASA to the opposite where 1 is excellent. Other agencies and organizations report FCI on a scale of 0 – 100 percent.

Facilities Maintenance: The recurring day-to-day work required to preserve facilities (buildings, structures, grounds, utility systems, and installed equipment) in such a condition that they may be used for their designated purpose over an intended service life. It includes the cost of labor, materials, and parts. Maintenance minimizes or corrects wear and tear and thereby forestalls major repairs. Facilities maintenance includes Preventative Maintenance, Condition Monitoring, Grounds Care, Programmed Maintenance, Repair, Trouble Calls, Replacement of Obsolete Items, and Service Request (Not a maintenance item but work performed by maintenance organizations). Facilities Maintenance does not include new work or work on non-installed equipment.

Failure: A cessation of proper function or performance; inability to meet a standard; nonperformance of what is requested or expected.

Failure Effect: The consequences of failure.

Failure Mode: The manner of failure. For example, the motor stops is the failure, the reason the motor failed was the motor bearing seized, which is the failure mode.

Failure Mode and Effects Analysis (FMEA): Analysis used to determine what parts fail, why they usually fail, and what effect their failure has on the systems in total. The phase of RCM that identifies maintenance tasks.

Failure Mode, Effects, and Criticality Analysis (FMECA): An extension of Failure Mode and Effects Analysis (FMEA). In addition to the basic FMEA, it includes a criticality analysis, which is used to chart the probability of failure modes against the severity of their consequences. The result highlights failure modes with relatively high probability and severity of consequences, allowing remedial effort to be directed where it will produce the greatest value.

Failure Rate: The number of failures divided by an interval such as time or cycles. The failure rate will change over time and can be greater than one (but will never be less than zero).

Fiscal Year: In the Federal Government, it is the 12-month period from October 1 of one calendar year through September 30 of the following year.

Function: Defined performance standard. Usually quantitative in nature (e.g., flow rate, cooling capacity).

Functional Performance Test: A full range of checks and tests carried out to determine if all systems, subsystems, and components function in accordance with the design intent.

Inspection: A time- or cycle-based action performed to identify hidden failure or potential failure.

Infant Mortality Rate: The first stage of the product life cycle in use, characterized by high but declining failure rate.

Infrared Thermography: A PT&I technique that uses infrared imaging to identify defects in electrical and electro-mechanical devices such as fuse boxes, circuit breakers, and switchgear. It also can be used effectively in a non-predictive manner to detect thermal cavities and leaks in walls, ceilings, and rooftops, the correction of which can result in sizeable reductions in heating and air conditioning expenses. Thermal imaging is extremely sensitive, and since it evaluates the heat an object emits, emittance and reflective factors of the object and environment must be considered.

Key Performance Indicator (KPI): Critical few (key) indicators aligned throughout the organization that measure controllable performance and contribute towards achieving the organization objectives.

Life Cycle: The successive stages of development that a facility passes through during its life time until it is disposed of or the process begins over again in its next generation. Typically, facilities pass through the following stages in their lifetime: planning, design, construction, commissioning, occupancy, operation and maintenance, renewal/revitalization, and disposal.

Maintainability: The ability to retain or restore function within a specified period of time, when provided with an identified level of tools, training, and procedures. Maintainability factors include machine and systems access, visibility, simplicity, ease of monitoring or testing, special training requirements, special tools, and the capability of the local work force

Maintenance: Action taken to retain function (i.e., prevent failure). Actions include Preventive Maintenance, Condition Monitoring, lubrication and minor repair (such as replacing belts and filters), and inspection for failure. Also see Preventive Maintenance and Condition Monitoring.

Maintenance Approach: The plan to prevent failure and, when failure occurs, perform repair.

Mean Time Between Failures (MTBF): The reciprocal of the failure rate; the average time to fail. The MTBF is sometimes called the Mean Time to Fail (MTTF).

Mean Time To Fail (MTTF): See Mean Time Between Failure.

Mean Time to Repair: The avergae time to restore functionality to a failed system or component.

Mission Critical: A building, area, or system that is critical to the site's mission or is essential for the site's performance to meet its goals. Also see Mission Support and Site Support.

Mission Support: A building, area, or system that provides support to the site's primary mission or assignment. Also see Mission Critical and Site Support.

Motor Circuit Analysis (MCA): A CM technique whereby the static characteristics (i.e.; impedance, capacitance to ground, inductance) of a motor or generator are measured as indicators of equipment condition.

Motor Current Spectrum Analysis (MCSA): A CM technique whereby motor current signatures provide information on the electro-mechanical condition of AC induction motors. It detects faults such as broken rotor bars, high resistance joints, and cracked rotor end rings by collecting motor current spectrums with clamp-on sensors and analyzing the data.

Non–Collateral Equipment: All equipment other than installed equipment. Such equipment, when acquired and used in a facility or a test apparatus, can be severed and removed after erection or installation without substantial loss of value or damage thereto or to the premises where installed. Non-installed equipment imparts to the facility or test apparatus its particular character at the time, e.g., furniture in an office building, laboratory equipment in a laboratory, test equipment in a test facility, machine tools in a shop facility, computer in a computer facility, and it is not required to make the facility useful or operable as a structure or building. (See also Installed Equipment.)

Pareto Analysis: A problem solving tool that breaks data down into manageable groups and identifies the greatest opportunity for return on investment. The analysis is based on the Pareto Principle, also known as the 80:20 Rule. Simply stated, the principle says that 20 percent of a population will cause 80 percent of the problems associated with the population.

Performance Standards: Those standards that an item is required to meet in order to maintain its required function. The performance standard defines functional failure for the item.

Potential Failure: An identifiable condition that indicates a failure is imminent.

Preventive Maintenance: (1) Also called time-based maintenance or interval-based maintenance. PM is the planned, scheduled periodic inspection, adjustment, cleaning, lubrication, parts replacement, and minor (no larger than Trouble Call scope) repair of equipment and systems for which a specific operator is not assigned. PM consists of many checkpoint activities on items that, if disabled would interfere with an essential site's operation, endanger life or property, or involve high cost or long lead time for replacement. In a shift away from reactive maintenance, PM schedules periodic inspection and maintenance at predefined time or usage intervals in an attempt to reduce equipment failures. Depending on the intervals set, PM can result in a significant increase in inspection and routine maintenance; however, a weak or nonexistent PM program can result in safety and/or health risks to employees, much more emergency work, and costly repairs. (2) Time- or cycle-based actions performed to prevent failure, monitor condition, or inspect for failure.

Predictive Maintenance: See condition monitoring.

Predictive Testing & Inspection (PT&I): The use of advanced technology to assess machinery condition. The PT&I data obtained allows for planning and scheduling preventive maintenance or repairs in advance of failure. Also see Condition Monitoring and Condition-Based Maintenance.

Proactive Maintenance: The collection of efforts to identify, monitor and control future failure with an emphasis on the understanding and elimination of the cause of failure. Proactive maintenance activities include the development of design specifications to incorporated maintenance lessons learned and to ensure future maintainability and supportability, the development of repair specifications to eliminate underlining causes of failure, and performing root cause failure analysis to understand why in-service systems failed.

Programmed Maintenance (PGM): Those maintenance tasks whose cycle exceeds one year, such as painting a building every fifth year. (This category is different from PM in that if a planned cycle is missed the original planned work still remains to be accomplished, whereas in PM only the next planned cycle is accomplished instead of doing the work twice, such as two lubrications, two adjustments, or two inspections.)

Reactive Maintenance: See repair.

Recommissioning: Revisiting previously commissioned or retro-commissioned systems at regular intervals and checking/retesting systems using the same checklists and test procedures used during the original commissioning to help ensure that the benefits of the initial commissioning process endure.

Reliability: The dependability constituent or dependability characteristic of design. From MIL-STC-721C, reliability: (1) The duration or probability of failure-free performance under stated conditions. (2) The probability that an item can perform its intended function for a specified interval under stated conditions.

Reliability-Centered Maintenance (RCM): The process used to determine the most effective approach to maintenance. It involves identifying actions that, when taken, will reduce the probability of failure and which are the most cost effective. It seeks the optimal mix of Condition-Based Actions, other Time- or Cycle-Based actions, or Run-to-Failure approach.

Repair: That facility work required to restore a facility or component thereof, including installed equipment, to a condition substantially equivalent to its originally intended and designed capacity, efficiency, or capability. It includes the substantially equivalent replacements of utility systems and installed equipment necessitated by incipient or actual breakdown. Also, restoration of function usually, after failure.

Retro-Commissioning: Commissioning completed or nearly complete buildings that have never been commissioned before and, for whatever reason, are not performing to the owner's satisfaction.

Root Cause Failure Analysis (RCFA): The process of exploring, in increasing detail, all possible causes related to a machine failure. Failure causes are grouped into general categories for further analysis. For example, causes can be related to machinery, people, methods, materials, policies, environment, and measurement error.

Run-to-Failure: A Maintenance Approach where no action (Time- or Cycle-Based actions) to prevent failure is taken following installation. Candidate systems or machines for Run-to-Failure are usually low-cost, easily repaired, and non-critical.

Site Support: A building, area, or system that supports the overall operation of the site but does not meet the Mission Critical or Mission Support criteria.

Statistical Process Control: A statistical method used to determine if a process is being controlled within the required band of variance where the mean and standard deviation are used to express the distribution of outcomes and their conformance to goal(s).

Sustainability: Meeting the needs of the present without compromising the ability of future generations to meet their own needs – EPA.

System Condition Index (SCI): A unitless number which or percentage which expresses the amount of Deferred Maintenance divided by the Current Replacement Value of a system being evaluated. SCI can be expressed on a scale of 1 to 5 (where 5 is excellent, no DM) as reported by NASA to the opposite where 1 is excellent. Other agencies and organizations report SCI on a scale of 0 – 100 percent.

Time- or Cycle-Based Actions: Maintenance activities performed from time-to-time that have proven to be effective in preventing failure. Items such as lubrication and restoration of wear fit this description. Other items that are Time- or Cycle-Based are inspection and condition monitoring. Also see Condition Monitoring.

Verification: The full range of checks and tests carried out to determine if all components, subsystems, systems, and interfaces between systems operate in accordance with the contract documents. In this context, operate includes all modes and sequences of control operation, interlocks, and conditional control responses, and specified responses to abnormal or emergency conditions.

Vibration Analysis: The technique used in condition monitoring. Uses noise or vibration created by mechanical equipment to determine the equipment's actual condition. Uses transducers to translate a vibration amplitude and frequency into electronic signals. When measurements of both amplitude and frequency are available, diagnostic methods can be used to determine both the magnitude of a problem and its probable cause. Vibration techniques most often used include broadband trending (looks at the overall machine condition), narrowband trending (looks at the condition of a specific component), and signature analysis (visual comparison of current versus normal condition). Vibration analysis most often reveals problems in machines involving mechanical imbalance, electrical imbalance, misalignment, looseness, and degenerative problems.

Weibull Analysis: An equipment life distribution widely used in reliability engineering life cycle analysis.

APPENDIX B: ABBREVIATIONS AND ACRONYMS

A&E	Architect and Engineering
AE	Age Exploration
AGMA	American Gear Manufacturers Association
AMA	Annual Maintenance Actual
AMF	Annual Maintenance Funding
AMR	Annual Maintenance Requirement
ANSI	American National Standards Institute
API	American Petroleum Institute
ASHRAE	American Society for Heating, Refrigeration, and Air-Conditioning Engineers
ASNT	American Society of Non-Destructive Testing
ASTM	American Society for Testing Materials
AVLD	Acoustic Valve Leak Detectors
AWP	Annual Work Plan
BAS	Building Automation Systems
BMAR	Backlog of Maintenance and Repair
BWE	Bow Wave Effect
CAFM	Computer Aided Facility Management
CbM	Condition-based Monitoring
CdM	Condition Monitoring
CdT	Condition-directed Tasks
CER	Cost Estimating Relationship
CI	Continuous Improvement
CII	Construction Industry Institute
CMMS	Computerized Maintenance Management Systems
CoF	Construction of Facilities
Cpk	Process Capability Study
CPM	Cycles per minute
CRV	Current Replacement Value
CR&R	Commissioning, Recommissioning & Retrocommissioning
cSt	Centistokes
CxA	Commissioning Authority
ΔT	Differential Temperature

dB	Decibel
DoD	Department of Defense
DOE	Department of Energy
DOS	Department of State
DM	Deferred Maintenance
DP	Dye Penetrant
DPMO	Defective per Million Opportunities
DR	Direct Reading
DSM	Design Safety Margin
EISA	Energy Independence Security Act
EMCS	Energy Management and Control Systems
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
F(t)	Failure probability
FCI	Facility Condition Index
FFC	Federal Facilities Condition
FFT	Fast Fourier Transform
FMEA	Failure Mode and Effect Analysis
FTIR	Fourier Transform Infrared
GSA	General Services Administration
HiPot	High Potential Testing
HP	Horsepower
Hz	Hertz (Cycles per second)
IEEE	Institute of Electrical and Electronic Engineers
ips	Inches per second
IRT	Infrared Technology
ISO	International Organization for Standardization
kHz	Kilohertz
KOH	Potassium Hydroxide
KPI	Key Performance Indicator
LCC	Life-Cycle Cost
LEED®	Leadership in Energy and Environmental Design
M&O	Maintenance and Operations

MCA	Motor Circuit Analysis
MCE/A	Motor-Circuit/Current Analysis
MCSA	Motor Current Signature (Spectrum) Analysis
MDT	Mean Down Time
MRO	Material for Repair and Operations
MRP	Minimum Required Performance
MT	Magnetic Particle Testing
MTBF	Mean Time between Failure
MTBM	Mean Time between Maintenance
MTTR	Mean Time to Repair
NASA	National Aeronautics and Space Administration
NASA-HQ	National Aeronautics and Space Administration – Headquarters
NDT	Non-Destructive Testing
NEMA	National Electrical Manufacturers Association
NFPA	National Fluid Power Association
NIBS	National Institute of Building Standards
NLGI	National Lubrication and Grease Institute
NPS	National Parks Service
OEE	Overall Equipment Effectiveness
OEM	Original Equipment Manufacturer
OMSI	Operations and Maintenance Service Instructions
OSHA	Occupational Safety and Health Administration
PACES	Parametric Cost Estimating System
PBC	Performance Based (M&O) Contracts
PCB	Polychlorinated biphenyl
Pd	Probability of detection
Pfa	Probability of false alarm
PGM	Programmed Maintenance
PLC	Programmable Logic Controller
PM	Preventive Maintenance
PMA	President's Management Agenda
PPM	Parts per Million
PT&I	Predictive Testing and Inspection

QA	Quality Assurance
OPR	Owner's Project Requirements
R&M	Reliability and Maintainability
RBOT	Rotating Bomb Oxidation Test
RCFA	Root-Cause Failure Analysis
RCM	Reliability-Centered Maintenance
RF	Radio Frequency
ROI	Replacement of Obsolete Items
RPI	Real Property Inventory
RPM	Revolutions per Minute
RRCM	Rigorous Reliability-Centered Maintenance
(R(t))	Reliability
RTF	Run-to-Failure
SBCI	Sustainable Buildings Industry Council
SCI	System Condition Index
SOP	Standard Operating Procedures
SPC	Statistical Process Control
SUS	Saybolt Universal Second
TAB	Testing and Balancing
TAN	Total Acid Number
TBN	Total Base Number
TBC	Total Building Commissioning
TDR	Time Domain Reflectometry
Tdt	Time-directed tasks
TTR	Transformer Turns Ratio
USGBC	United States Green Building Council
UT	Ultrasonic Testing
VLF	Very Low Frequency
VM	Vibration Monitoring
WD	Weibull Distribution

APPENDIX C: BIBLIOGRAPHY

American Society of Non-Destructive Testing, *Recommended Practice Number SNT-TC-1A*, Columbus, OH, 1992.

American Society for Testing and Materials, Philadelphia, PA.

ASTM D877	Dielectric Breakdown Voltage of Insulating Liquids Using Disk Electrodes, April 1987.
ASTM D924	*Power Factor*, June 1993.
ASTM D974	Acid Neutralization by Color Indicator, March 1994.
ASTM D2285	Interfacial Tension of Electrical Insulating Oils of Petroleum Origin against Water by the Drop-weight Method, November 1985.
ASTM 1289	Test Method for Density, Relative Density (Specific Gravity or API Gravity) of Crude Petroleum and Liquid Petroleum Products by Hydrometer Methods, February 1991.
ASTM D92	Flash and Fire Point by the Cleveland Open Cup, May 1991.
ASTM D97	Pour Point of Petroleum Oils, February 1994.
ASTM D1533	Water and Insulating Liquids, November 1989.
ASTM D445	Kinematic Viscosity of Transparent and Opaque Liquids, April 1989.
ASTM C1060-90	Thermographic Inspection of Insulation in Envelope Cavities In Wood Frame Buildings, December 1990.
ASTM C1153-90	Standard Practice for the Location of Wet Insulation in Roofing Systems Using Infrared Imaging, September 1990.
ASTM E1186-87	Standard Practices for Air Leakage Site Detection in Buildings, May 1993.
ASTM E1149-90	Standard Terminology Relating to NDT by Infrared Thermography, 1993

American Petroleum Institute, New York, NY

API 670	Vibration, Axial-Position Bearing-Temperature Monitoring System, November 1993.

American National Standards Institute, New York, NY.

ANSI S2.19	1999 – Pt. 1 – Balance Quality of Rigid Rotors, Determination of Permissible Residual Imbalance

Annual Book of ASTM Standards, Section 5 (for lubricating oil tests), American Society for Testing and Materials, Philadelphia, PA.

Chemistry & Technology of Lubricants, editors R.M. Mortier and S.T. Orszulik, VCH Publishers, New York, NY, 1992.

Contamination Control For The Fluid Power Industry, Second Edition, Fitch, E.C. and I.T. Hong, Pacific Scientific Company, 1990, Silver Spring, MD.

Fuchs, Sheldon J. *Complete Building Equipment Maintenance Desk Book*, Second Edition, Prentice-Hall, Englewood, NJ, 1992.

General Motors Specification A 1.0-1993, Laser Alignment Specification for New and Rebuilt Machinery and Equipment, 1993.

Guideline for Infrared Inspection of Building Envelopes and Insulated Roofs, Infraspection Institute, Shelburne, VT.

Guideline for Infrared Inspection of Electrical and Mechanical Systems, Infraspection Institute, Shelburne, VT.

Guideline for Measuring and Compensating for Reflected Temperature, Emittance and Transmittance, Infraspection Institute, Shelburne, VT.

Guideline for Measuring Distance/Target Width Ratios for Quantitative Thermal Imaging Cameras, Infraspection Institute, Shelburne, VT.

Handbook of Lubrication, several volumes, Society of Tribologists and Lubrication Engineers, Park Ridge, IL (contact at 840 Busse Highway, Park Ridge, IL 60068, (708) 825-5536).

Harris, Tedric A., *Rolling Bearing Analysis*, John Wiley & Sons, New York, NY, 1984.

Hewlett Packard Application Note 243-1, Effective machinery Measurement using Dynamic Signal Analyzers, 1990.

Hewlett Packard Application Note 243, *The Fundamentals of Signal Analysis*, 1991.

Infraspection Institute, Guidelines for Infrared Inspection of Electrical and Mechanical Systems, Shelburne, VT, 1993.

International Standards Organization, American National Standards Institute, 1430 Broadway, New York, NY 10018.

ISO 10816-1	Evaluation of Mechanical Vibration by Measurement of Non-rotating Parts – General Guidelines
ISO 10816–3	Evaluation of Mechanical Vibration by Measurement of Non-rotating Parts – Part 3: Industrial machines with nominal power above 15kW and nominal speeds between 120r/min and 15,000 r/min when measured in situ
ISO 13372–1	Condition Monitoring and Diagnostics Machine Vibration Monitoring – Pt 1, General Procedures

ISO 13372–2	Condition Monitoring and Diagnostics Machine Vibration Monitoring – Pt 2, Processing analysis and presentation of vibration data
ISO 14694	Industrial Fans – Specifications for Balance Quality and Vibration Levels
ISO 3945	Mechanical Vibration of Large Rotatin Machines with Speed Range from 10 to 200 r/s
ISO 6781	Thermal Insulation-Qualitative Detection of Thermal Irregularities in Building Envelopes-Infrared Method, 1983.
ISO 6781	Thermal Insulation- Qualitative Detection of Thermal Irregularities in Building Envelopes - Infrared Method

International Electrical and Electronic Engineers, New York, NY.

Jackson, Charles, *The Practical Vibration Primer*. Gulf Publishing Company, Houston, Texas. 1979.

Lundberg, G. and Palmgren, A. Dynamic Capacity of Rolling Bearings, Acra Polytech, Mechanical Engineering Series 1,R.S.A.E.E., No.3,7 (1947)

Machinery Oil Analysis, Larry A. Toms, Pensacola, FL, 1995. (Contact at 5018 High Pointe Dr., Pensacola, FL 32505-1825).

MIL-STB-2194 (SH)	Infrared Thermal Imaging Survey Procedure for Electrical Equipment.
MIL-STD-167-1	Mechanical Vibrations of Shipboard Equipment, May 1974.
MIL-STD-740-2	Structureborne Vibratory Acceleration Measurements and Acceptance Criteria of Shipboard Equipment, December 1986.

Mitchell, John S., *Machinery Analysis and Monitoring*, Penn Well Books, Tulsa, OK, 1981.

Moubray, John, *Reliability-Centered Maintenance*, Butterworth-Heinemann Ltd. Oxford, England, 1991.

Moubray, John, *Reliability-Centered Maintenance II*, Aladon Press 1997.

National Electrical Manufacturers Association, Washington, DC.

National Fluid Power Association, NFPA T2.9.1-1972, Method for Extracting Fluid Samples from the Lines of an Operating Hydraulic Fluid Power System for Particulate Particle Contamination Analysis, 1992.

NETA MTS-2003	Acceptance Testing Specifications for Electric Power Distribution Equipment and Systems, International Electric Testing Association.

NETA MTS-2003 Maintenance Testing Specifications for Electric Power Distribution Equipment and Systems, International Electric Testing Association.

Nowlan, F.S. and Heap, H.F. *Reliability-Centered Maintenance*, Dolby Access Press, San Francisco, CA 1978.

Oil Analysis Seminar Coursebook, PdMA Corporation, Tampa FL, 1990.

Proceedings of the 44th Meeting of the Mechanical Failures Prevention Group, *Current Practices and Trends in Mechanical Failure Prevention,* Vibration Institute, 1990.

SKF Engineering Data, SKF Industries, Inc. Philadelphia, PA, 1973

Smith, Anthony M. and Hinchcliffe, Glenn R. RCM--Gateway to World Class Maintenance, 2004

A selection of WWW Sites as of January 2008:

IEEE—Institute of Electrical and Electronics Engineers

http://www.ieee.org/

ISO—International Organization for Standardization

http://www.iso.ch/

CIE—International Commission on Illumination

http://www.hike.te.chiba-u.ac.jp/ikeda/CIE/home.html

ANSI—American National Standards Institute

http://www.ansi.org/

NIST—National Institute of Standards and Technology

http://www.nist.gov/welcome.html

JIS—Japanese Industrial Standards

http://www.hike.te.chiba-u.ac.jp/ikeda/JIS/index.html

MFPT – Mechanical Failures Prevention Technology

SMRP – Society of Maintenance and Reliability Professionals

WBDG – Whole Building Design Guideline

RCM Related Sites:

CSI	http://www.compsys.com
Datastream	http://www.dstm.com
Entek/IDR	http://www.entekird.com
Flir Systems	http://www.flir.com
HSB ReliabilityTech.	http://www.hsbrt.com
Inframetrics	http://www.inframetrics.com
Infraspection Institute	http://www.infraspection.com
JB Sysytems	http://www.jbsystems.com
Ludeca Inc.	http://www.ludeca.com
Maintenance Technology Mag.	http://www.mt-online.com
MIMOSA	http://www.hsb.com/pcm/mimosa/mimosa.com
National Reliability Eng. Center	http://www.enre.umd.edu/mainnojs.html
Monarch Monitoring	http://www.easylaser.com
Penn State University	http://wisdom.arl.psu.edu/
Plant Engineering Online	http://www.manufacturing.net/magazine/planteng
PdMA	http://www.pdma.com
Predict	http://www.predict.com/
Raytek	http://www.raytek.com
Reliability Center	http://www.reliability.com
Reliabilityweb	http://www.reliabilityweb.com
SPM Instrument	http://www.spminstrument.se
UE Systems	http://www.uesystems.com
Vibra-Metrics	http://www.vibrametrics.com
VibrAlign, Inc.	http://www.vibralign.com/
Vibration Specialty	http://www.vib.com/

Additional Resources - Magazines:

Reliability	(423) 531-2193	www.reliability-magazine.com	$49/yr
Maintenance Technology	(847) 382-8100	www.mt-online.com	Free
P/PM	(702) 267-3970		$42/yr
Vibrations	(630) 654-2340		$40/yr
Engineered Systems	(248) 362-3700	www.esmagazine.com	Free
Engineering Digest	(708) 291-5222		Free
Plant Engineering		www.planteng.com	Free
Hydrocarbon Processing			Free
Pumps and Systems	(818) 885-6279	www.pumpzone.com	Free
UE Service Partners	(914) 347-5473	www.uesystems.com/service	Free

Note: For additional information, please contact any RCM Team member.

APPENDIX D: SOURCES OF PT&I EQUIPMENT, SERVICES, AND TRAINING

The following web site contains contact information for all aspects of facility maintenance.

http://shopper.mro-zone.com/listing/

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APPENDIX E: VIBRATION CRITERIA[1]

E.1 FOREWORD

The following appendix offers the vibration standard for new and rebuilt machinery and equipment. It is recommended that Vibration Certification of all new and rebuilt machinery and equipment be a part of implementation of Reliability Centered Maintenance. Vibration analysis and certification, as a part of machine performance evaluation will:

- Maximize part quality, machine productivity, tooling and machine life
- Minimize machine installation and set-up time
- Allow verification of machine performance and condition throughout the machine's life

This appendix provides engineering performance guidelines for use by Facilities Maintenance and Operations as well as machinery and equipment builders during the design, development, and building of new equipment and the rebuild of existing equipment. The vibration limits specified by the user and acknowledged by the contractor establish a common goal of acceptability by both parties. Such limits also enable contractors to provide evidence of the superiority and build integrity of their product.

[1] Acknowledgments: We wish to thank General Motors for the free use of their alignment and vibration specifications, which are included in this document. This document may be copied in whole or in part for the use of providing standards for maintainability of equipment.

E.2 TABLE OF CONTENTS

E.3 LIST OF FIGURES

E.4 LIST OF TABLES

1.0 PURPOSE

The purpose of this standard is to:

- Reduce operating costs by establishing acceptable vibration levels for new and rebuilt rotating machinery and equipment.
- Improve the life and performance of rotating machines and equipment.
- Provide a uniform procedure for evaluating the vibration characteristics of a machine for certification and acceptance.

2.0 SCOPE

This standard establishes:

- Acceptable limits for vibration levels generated by new and rebuilt rotating machinery and equipment.
- Measurement procedures—including standardized measurement axis directions and locations, calibration and performance requirements of instrumentation, and procedures for reporting vibration data for machine certification and acceptance.

3.0 INSTRUMENTATION REQUIREMENTS

Vibration measurements will be made with an FFT analyzer. The type, model, serial number(s) and latest certified calibration date of all equipment used in the measurement of vibration levels for machine certification, shall be recorded and made available upon request.

3.1 FFT ANALYZER

The FFT Analyzer shall be capable of a line resolution bandwidth Δf = 300 CPM for the frequency range specified for machine certification unless this restriction would result in less than 400 lines of resolution, in which case the requirement defaults to 400 lines of resolution. (Higher resolution may be required to resolve "Side Bands," or in Band 1 to resolve machine vibration between 0.3X and 0.8X Running Speed.)

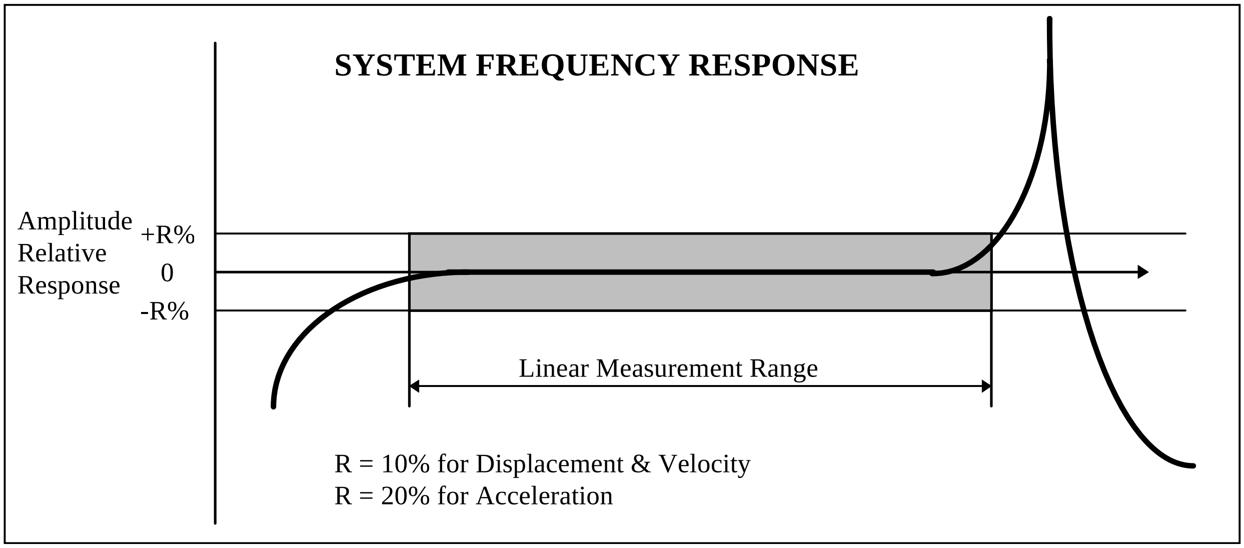
- The Dynamic Range shall be a minimum of 72 dB.
- The FFT analyzer shall be capable of applying a Hanning window.
- The FFT analyzer shall be capable of linear non-overlap averaging.
- The FFT analyzer shall have anti-aliasing filters.

3.2 MEASUREMENT SYSTEM ACCURACY

The measurement system (FFT analyzer, cables, transducer and mounting) used to take vibration measurements for machine certification and acceptance shall have a measurement system. Amplitude accuracy over the selected frequency range is as follows:

- For displacement and velocity measurements ±l0 percent or ±1 dB.
- For acceleration measurements ±20 percent or ±1.5 dB.

Figure E-1. Measurement System Frequency Response



3.3 MEASUREMENT SYSTEM CALIBRATION

Vibration equipment (transducer, preamplifier, FFT analyzer, recorder and connecting cable) used to take vibration measurements for machine certification and acceptance must be calibrated by a qualified instrumentation laboratory in accordance with Sections 5.1 and 5.2 of ANSI S2.17-1980 "Technique of Machinery Vibration Measurement" within one (1) year prior to the date of machine certification.

Calibration shall be traceable to the National Institute of Standards and Technology (NIST) in accordance with ISO 10012-1/1992 "Quality assurance requirements for measuring equipment - Part 1: Metrological confirmation systems for measuring equipment."

3.4 VIBRATION TRANSDUCERS

An accelerometer shall be used in the collection of data for machine certification and acceptance. The accelerometer must be selected and attached to the machine in such a way that the minimum frequency (Fmin) and maximum frequency (Fmax) as specified in Section 9 or specified otherwise by the purchaser, are within the usable frequency range of the transducer and can be accurately measured (reference recommendations of pickup manufacturer and/or Section 6.3, ANSI S2.17-1980).

The mass of the accelerometer and its mounting shall have minimal influence on the frequency response of the system over the selected measurement range. (Typical mass of accelerometer and mounting should not exceed 10 percent of the dynamic mass of the structure upon which the accelerometer is mounted.) Reference Appendix for Dynamic Mass definition and Procedure to Determine Mass Effect

Integration is acceptable as a means of converting acceleration measurements to velocity or displacement, or for converting velocity measurements to displacement.

4.0 VIBRATION MEASUREMENT AXIS DIRECTIONS

- Axial Direction shall be parallel to the rotational axis of the machine (reference Figures 2 and 3).
- Radial Directions shall be 90° (perpendicular) relative to the shaft (rotor) centerline.
- Vertical Direction shall be in a radial direction on a machine surface opposite the machine mounting plate (reference Figure 2).For motors or pumps that are end mounted, vertical readings shall be taken in a radial direction relative to axial readings on a surface opposite the machine to which the motor or pump is attached (reference Figure 3).
- Horizontal Direction shall be in a radial direction:
    - At a right angle (90°) from the vertical readings; and
    - In the direction of the shaft (rotor) rotation (Reference Figure 2 and 3).
- Any radial direction other than Horizontal or Vertical as defined in Sections 4.3 and 4.4.

Figure E-2. Vibration Measurement Axes Directions - Foot Mounted

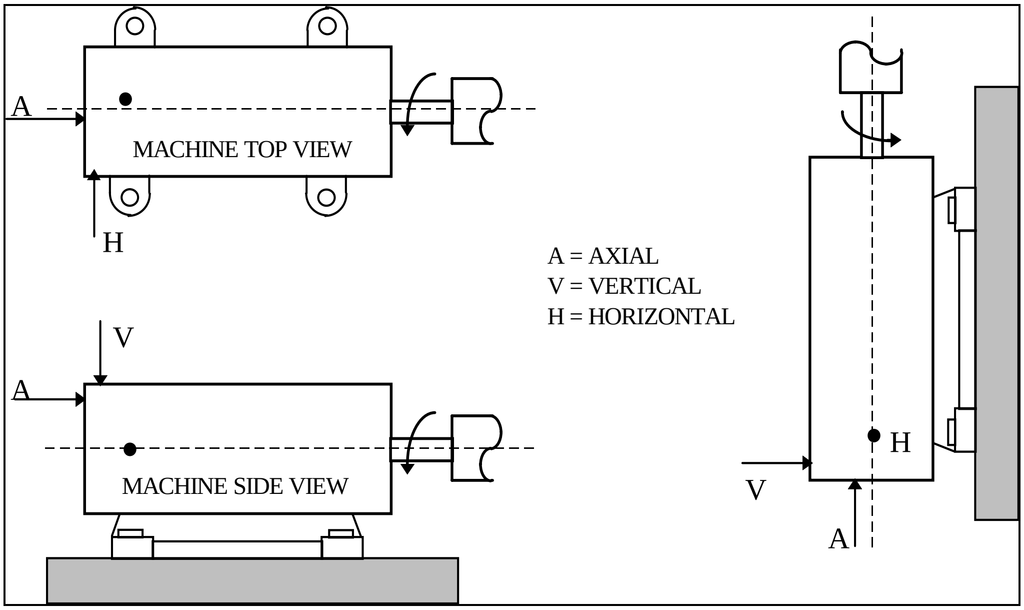
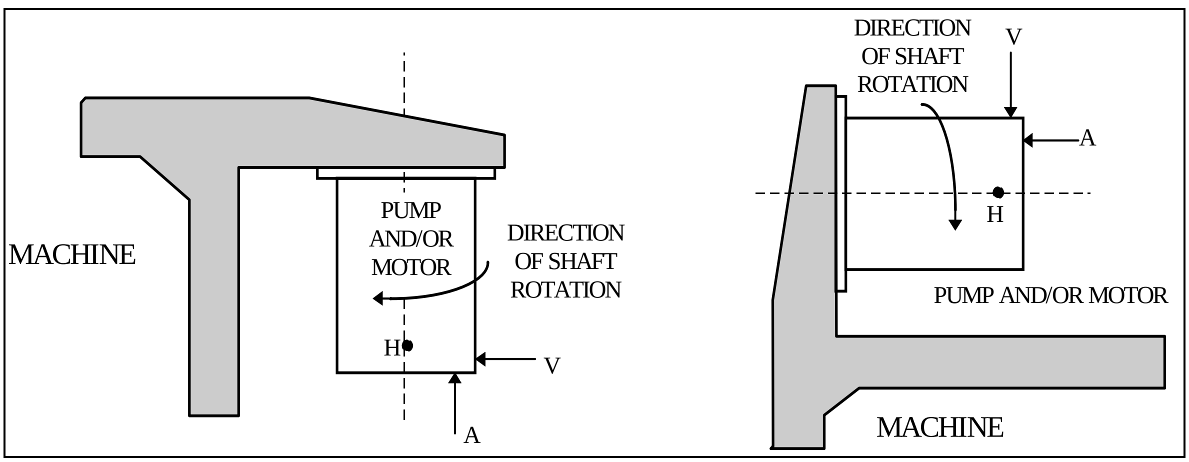


Figure E-3. Vibration Measurement Axes Directions - End-Mounted



5.0 VIBRATION MEASUREMENT LOCATIONS

Required measurement positions and orientations on a machine's surface at which vibration measurements are to be taken shall be determined by mutual agreement of the purchaser and t Required measurement positions and orientations on a machine's surface at which vibration measurements are to be taken shall be determined by mutual agreement of the purchaser and the contractor, and shall meet the following requirements:

5.1 CONVENTIONS

Follow the conventions specified in Sections 4.0 and 5.0, unless specified otherwise by the purchaser.

- If an obstruction or safety prevents locating a transducer as specified, locate as close as possible to the standardized position.
- Measurement locations used for machine certification and acceptance shall be identified on the machine layout drawing and/or machine as mutually agreed upon by the purchaser and the contractor.
- Vibration measurement locations shall be on a rigid member of the machine, as close to each bearing as feasible. Bearing housings, bearing pedestals, machine casings or permanently mounted pickup mounting blocks are examples of suitable mounting locations.
- Vibration measurement location shall NOT be on a flexible cover or shield such as the fan cover on an electric motor or a sheet-metal belt guard.

5.2 ACCESSIBILITY

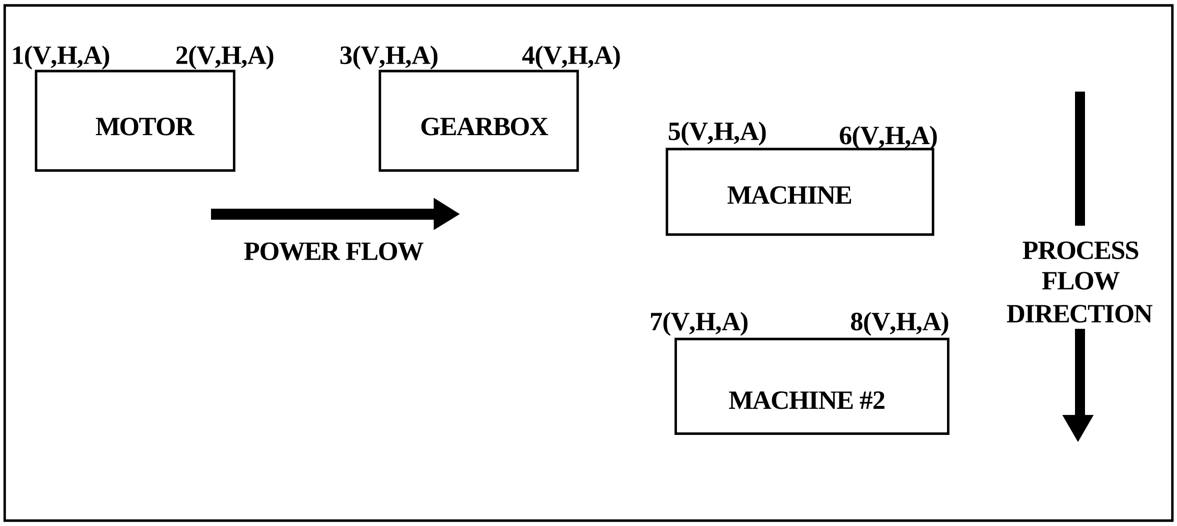
- Guarding must be designed to allow accessibility to all measurement locations (Reference Section 5.7).
- In the event that vibration monitoring points will be rendered inaccessible after the machine is built or access to the measurement points would present a safety problem during measurement, the purchaser shall be contacted to determine if permanently mounted transducers are to be installed.

5.3 LOCATION IDENTIFICATION

Measurement locations shall be numbered consecutively from 1 to N in the direction of power flow per the following:

- Position 1 designates the "out-board" Starting Power Point bearing location of the driver unit of the machine.
- Position N designates the bearing location at the "terminating" Power Point bearing location of the driven machine. (Reference Figure 4)

Figure E-4. Order and Consecutive Numbering Sequence



5.4 DOCUMENTATION

Measurement locations documented for certification and acceptance on the machine layout drawing and on any vibration data submitted shall follow the following convention as shown in Figure 5:

- Station or Machine
- Component (Reference Table 1)
- Position
- Orientation

Figure E-5. Measurement Location Documentation Convention

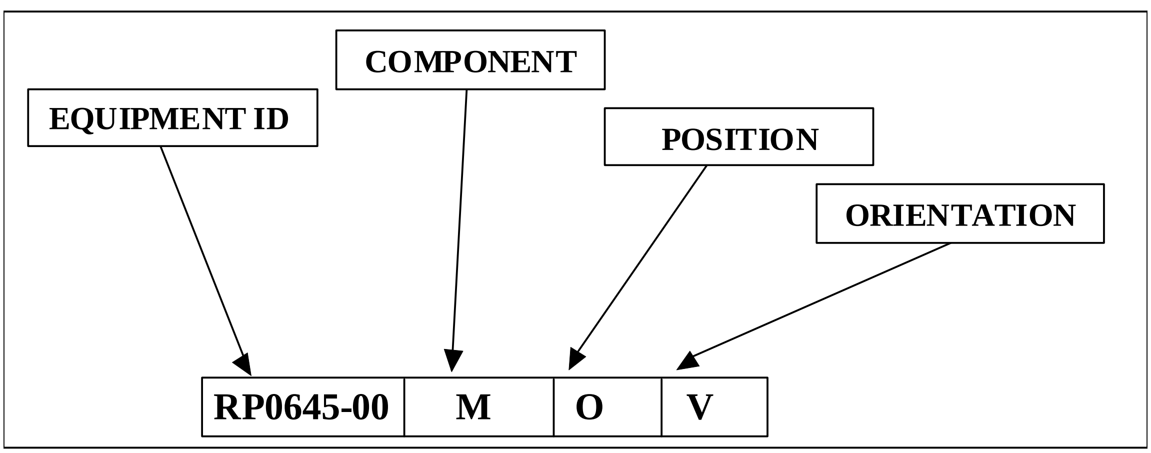


Table E-1. Recommended Component Identification Symbols

GBX = Gear Box	BSH = Bushing	MTR = Motor
FAN = Fan	PMP = Pump	JS = Jackshaft
IP = Idler Pulley	CL = Clutch	
Other Component Symbols not listed above should be agreed upon by the machine tool builder and the purchaser on an as-needed basis		

6.0 TRANSDUCER & MACHINE MOUNTING CONDITIONS

6.1 VIBRATION TRANSDUCER MOUNTING

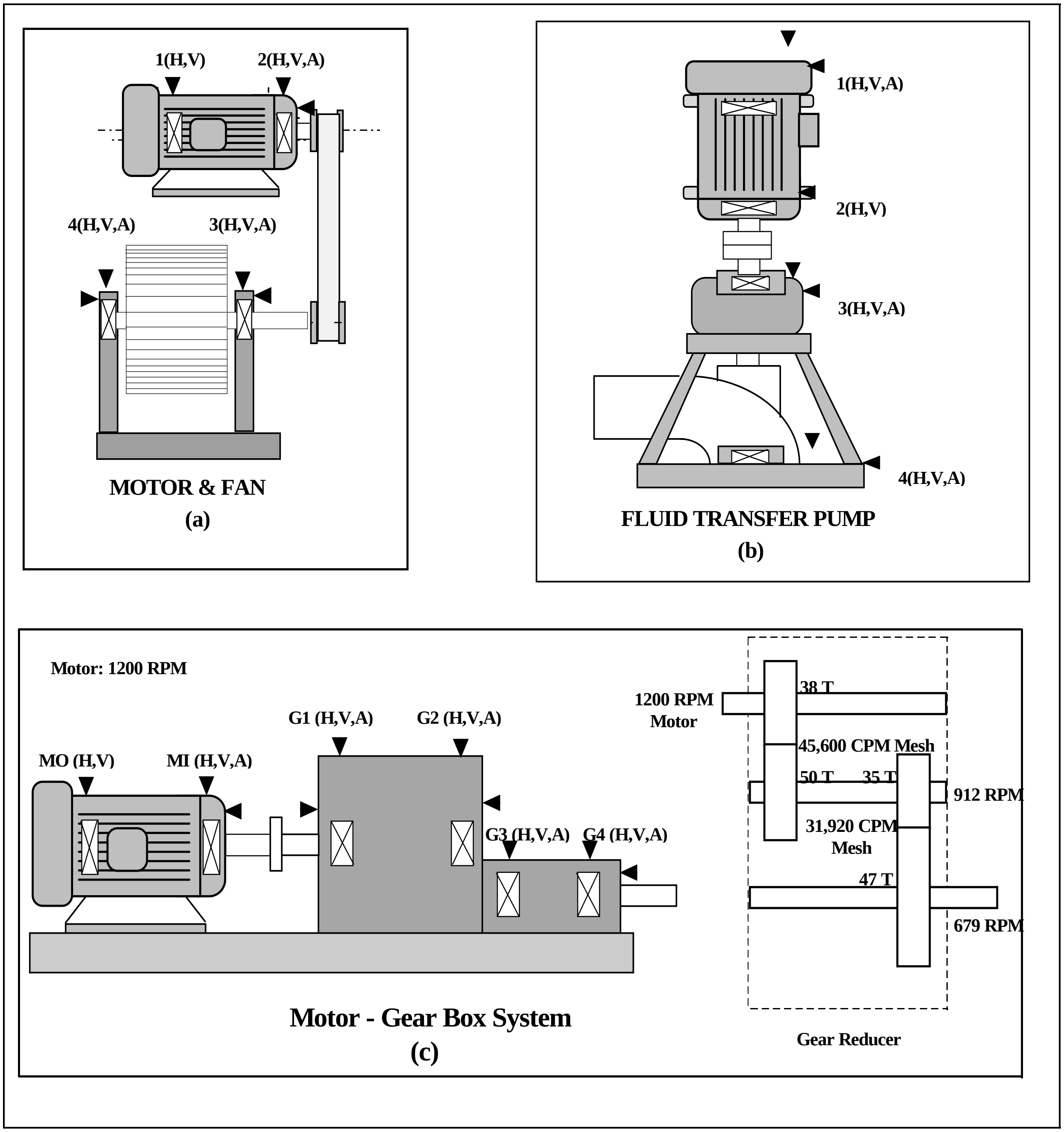
At the designated measurement positions, suitable surfaces shall be provided such that the mounted transducer will attach securely.

- Hand-held pickups are not acceptable for measurement by this specification.
- For a magnetic base mounted transducer the location on a machine's surface at which vibration measurements are to be taken shall be machined, if necessary, such that the magnet base can be attached firmly without "rocking."
- For a stud mounted transducer the machine's surface at which vibration measurements are to be taken shall be in accordance with that specified by the transducer manufacturer (torque, grease, etc.) Designated transducer type to be specified by the purchaser.
- If an adhesive is used to attach either the transducer or a magnetic mounting pad, the upper frequency limit of the transducer shall be reduced by 20 percent of the manufacturer's stated resonance for "hard" adhesives and by 50 percent of the manufacturer's stated resonance for "soft" adhesives. Transducer manufacturer's specifications should be consulted.
- The vibration transducer as mounted must be such that the measurement system Amplitude accuracy over the selected frequency range equals or exceeds the requirements specified in Section 3.1.

6.2 MACHINE MOUNTING

- Where a machine can be tested as an individual unit (e.g. motor, spindle, etc.) the machine must be mounted as specified in Section 9.
- Where an individual machine can be tested only as an assembled unit (e.g. motor/pump, motor/fan, etc.), the machine mounting conditions shall be as equivalent as possible/feasible to those to be encountered upon installation at the purchaser's site. (Figure 6 on next page.)

Figure E-6. Vibration Measurement Locations



7.0 TECHNICAL REQUIREMENTS

7.1 VIBRATION MEASUREMENT UNITS

Vibration data for machine certification and acceptance shall be expressed in the following measurement units.

Table E-2. Vibration Measurement Units

Frequency	Hertz (cycle/sec) or Cycle/Minute (CPM)	
Rotational Speed	Revolutions per Sec (RPS) or Revolutions per Minute (RPM)	
Amplitude	**METRIC**	**ENGLISH**
• Displacement (Peak-to-Peak)*	Micrometers	Inch (Also Mil in U.S.)**
• Velocity (Peak)*	Millimeter/sec	Inch/sec
• Acceleration (Peak)*	Meter/sec^2	g's
*** Can also use Root-Mean-Square (RMS)**		** 1 "Mil" = 0.001 inch

The "Peak" and "Peak-to-Peak" Vibration Amplitude Measurements will be a Calculated Peak not a True Peak. The Calculated Peak will be derived from the RMS level based on the following equations:

- Peak (P) = 1.414 x RMS
- Peak-to-Peak (P-to-P) = 2 x (P) = 2 x 1.414 x RMS

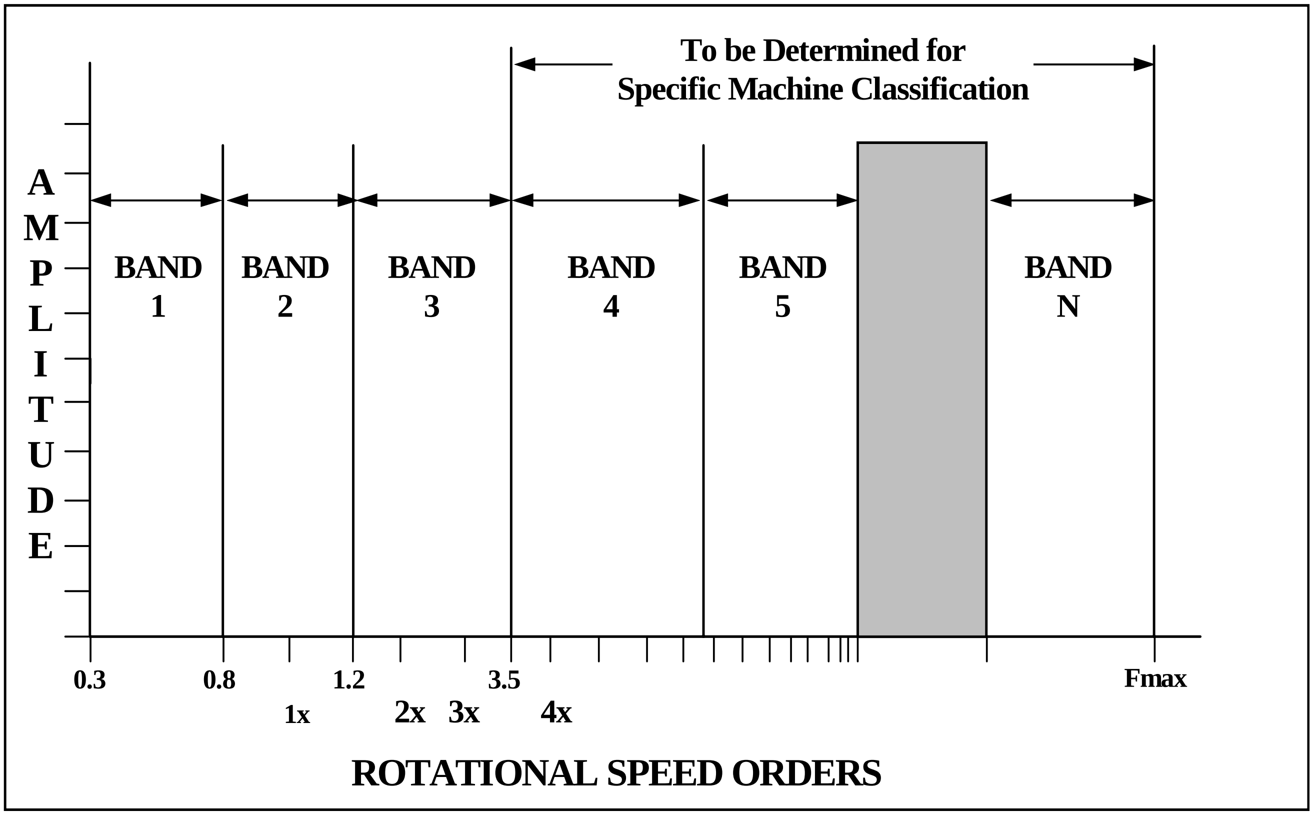
If a "True Peak" is required, the units of vibration measurement will be designated by the words "True Peak".

7.2 FREQUENCY BANDS

The frequency range of measurement shall be divided into sub-groups called bands. The Fmin and Fmax for each band will be defined in units of frequency or orders of running speed of the machine. (Reference Figure 7.)

- Mandatory Bands Band 1 shall be (0.3 - 0.8) X Running Order. Band 2 shall be (0.8 - 1.2) X Running Order. Band 3 shall be (1.2 - 3.5) X Running Order
- Bands 4 through N shall be defined by the specific machine application.

Figure E-7. Frequency Bands



7.3 LINE AMPLITUDE ACCEPTANCE LIMITS

For vibration level limits specified in terms of "LINE AMPLITUDE ACCEPTANCE LIMITS":

- A line of resolution will have a band width Δf = 300 CPM unless specified otherwise (Reference Section 7.4 requirement for total energy in a peak), or unless the Δf = 300 CPM restriction would result in less than 400 lines of resolution over the frequency range specified for certification, in which case the resolution requirement will default to 400 lines. (Greater resolution may be required to resolve "Side Bands," or in Band 1 to resolve machine vibration between 0.3X and 0.8X Running Speed.

- The maximum amplitude of any line of resolution contained within a band shall not exceed the Line Amplitude Acceptance Limit for the Band.

7.4 BAND-LIMITED OVERALL AMPLITUDE ACCEPTANCE

For vibration level limits specified in terms of "BAND-LIMITED OVERALL AMPLITUDE ACCEPTANCE LIMITS" the Total vibration level "A" in a band, as defined by the following equation, shall not exceed the Overall Amplitude Acceptance Limit specified for the Band

$$A = \sqrt{\frac{\sum_{i=1}^{N} A_i^2}{1.5}}$$

- A = Overall vibration level in the Band
- A_i = Amplitude in the i^{th} line of resolution in the Band
- (I=1) = The first line of resolution in the Band
- (i=N) = The last line of resolution in the Band
- N = The number of lines of resolution in the Band

If the total energy in a peak is to be measured, a minimum of 5 lines of resolution must be used and the peak must be centered in the band.

If a line of resolution is coincidental with the F_{min}/F_{max} Of two adjacent bands, that line of resolution will be included in the band having the lowest acceptance level limit. The amplitude range sensitivity of the FFT Analyzer shall be set to the maximum input sensitivity possible without overloading such that the actual measurement uses at least 60 dB of the Dynamic Range.

Certification will be based on:

- Hanning Window[2], and
- Four (4) averages (Linear non-overlapping).

The transducer mounting shall be such that the measurement system Amplitude accuracy over the selected frequency range equals or exceeds the requirements specified in Section 3.1. This may require the use of more than one accelerometer where potentially high frequencies might occur (such as gear mesh or harmonics of gear mesh) along with lower frequencies (such as due to unbalance, misalignment, looseness, etc.).

7.5 ALIGNMENT

All coupled rotating machines consisting of consecutive shafts connected through a coupling (whether rigid or flexible) shall be aligned within the tolerances specified by the purchaser in the "Request for Quote." If the Purchaser does not specify an alignment tolerance, the requirements of this Standard defaults to the tolerance limits specified in Specification No. A 1.0-199X, LASER ALIGNMENT SPECIFICATION FOR NEW AND REBUILT MACHINERY AND EQUIPMENT."

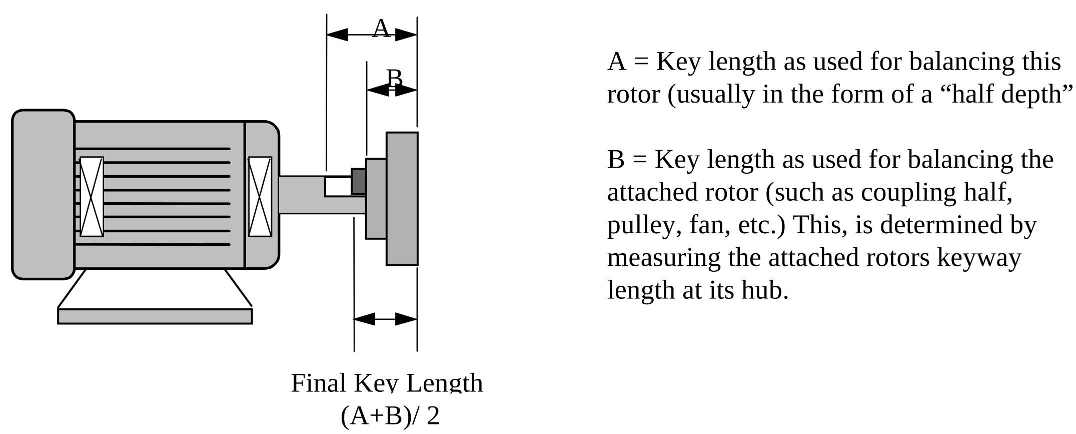
2 The Hanning Window has the shape of a one cycle cosine wave with 1 added to it so it is always positive. The sampled signal values are multiplied by the Hanning function to force the time record to zero at the beginning and end of each bin in order to minimize bleed over between the bins. It is not appropriate for transient analysis.

Consideration shall be given to any "thermal growth" that may occur during the normal operation of the machine that would cause the machine to "grow out of alignment" to the extent that the alignment tolerances of this specification would not be met.

7.6 BALANCING

For rotating machines and machine components with a keyed shaft, balancing will achieved using a standard one-half key in the key seat in accordance with ISO 8821-1989. If a full key, corresponding to the half key used for balancing, is not provided with the rotating machine, a tag, as shown in Figure 8, will be attached to the machine indicating the dimension of the key used to perform the balance test.

Figure E-8. Balance Test Key Dimension



The use of solder or similar deposits to achieve rotor balance is not acceptable. Any parent metal removed to achieve dynamic or static balance shall be drilled out in a manner which will maintain the structural integrity of the rotor.

8.0 MACHINE QUOTATION, CERTIFICATION, AND ACCEPTANCE

8.1 QUOTATION

The Quotation shall specify that the equipment will meet the applicable vibration level limits in Section 9 of this Specification - or the vibration level limits (if different from Specification V1.0 (Latest Version) specified by the purchaser in the "Request for Quote."

The Quotation shall state the applicable specification vibration level limits being quoted.

Any additional costs required to meet the specification limits shall be grouped in a separate section of the Quotation and titled "VIBRATION LIMITS." Costs must be itemized and sufficiently detailed to permit a complete evaluation by the Purchaser.

8.2 MEASUREMENT REQUIREMENTS FOR MACHINE CERTIFICATION

Vibration measurements shall:

- Be the responsibility of the supplier unless specified otherwise by the purchaser.
- Be performed by technically qualified person who is trained and experienced in vibration measurement. The technical qualifications of the person doing the

vibration certification shall be submitted as a part of the machine vibration certification data.

- Be taken with the machine operating as specified in Section 9. Where "no load" is specified, no actual work is to be taking place during collection of machine vibration data. Where "rated load" is specified, rated operating load (actual or simulated) will be applied during collection of machine vibration data.

- Prior to taking vibration measurements, the machine will be "run-in" until it reaches operating speed and thermal stability

- Vibration Signatures as required by Section 9 of this specification shall be submitted to the Maintenance organization or other authorized representative before acceptance of the machinery or equipment being purchased will be authorized.

- Vibration data for machine certification shall be measured during "run-off' at the vendor's facility. Where it is impractical to set-up and test a complete machine at the vendor's facility, arrangements shall be made to perform the test at the purchaser's facility. Under this circumstance, shipment of the equipment does not relieve the vendor of the responsibility for meeting the specified vibration level limits.

- The purchaser shall have the option to verify vibration data of equipment during machine "run-off' at the vendor's test site prior to shipment or at the plant site (per Section 8.2.3) prior to final acceptance authorization.

- The machine layout drawing shall be submitted as a part of the Machine Vibration Certification. Vibration measurement locations on the machine's surface at which vibration measurements are taken shall be designated on the drawing per Section 5.7 requirements. At the option of the purchaser, Shaft speeds (RPM), gear type and number of gear teeth, gear mesh frequencies (CPM), bearing manufacturer's name, bearing type number and class, shall be identified on the machine layout drawing. Where gearboxes are involved, an insert such as illustrated in Figure 6 - c shall be included on the machine layout drawing.

8.3 ACCEPTANCE

Authorization for machine/equipment acceptance based on the vibration limits of this specification requires signature by the purchaser's authorized representative. A copy of the acceptance must be sent to the plant's Purchasing department before final acceptance is authorized.

9.0 VIBRATION LEVEL LIMITS

- Electric Motors: Refer to Section 9.1, “Vibration Standards for Electric Motors."
- Fans: Refer to Section 9.2, “Vibration Standards for Fans."
- Pumps: Refer to Section 9.3, “Vibration Standards for Pumps."
- Gearboxes: Refer to Section 9.4, “Vibration Standards for Gearboxes."
- Default Vibration Level Limits: Refer to Section 9.5, “Vibration Standard Default Limits."
- Complete Machine Assembly

A complete machine is defined as the entire assembly of components, sub-components, and structure, which is purchased to perform a specific task(s). On a Complete Machine Assembly with all individual components operating in their normal operating condition, mode, and sequence, the Component Vibration Level Limits for the complete machine acceptance are the same as when the component is tested individually. Where assembled component levels exceed the acceptable limits, the cause will be identified, if possible, and a decision to correct or accept mutually agreed upon by purchaser and contractor.

9.1 VIBRATION STANDARDS FOR ELECTRIC MOTORS

9.1.1 Electrical Motor Requirements

a. Motors will be defined by four (4) categories:

- Standard motor: Utility Operations (DOS non-essential application)
- Special motor: Semi-Finish Operations (DOS essential application)
- Precision motor: Finish Operations (N/A DOS)
- Other motor: Per agreement by vendor and the Government (N/A DOS)

b. The frequency range for motor certification will be from F_{min} = 0.3 X Running Speed (synchronous speed) to F_{max} = 120,000 CPM (2,000 Hertz).

c. Alternating current motors will be tested at rated voltage and frequency, and no load. Single speed alternating current motors will be tested at synchronous (running) speed. A multi-speed alternating current motor will be tested at all its rated synchronous (running) speeds. Direct current motors will be tested at their highest rated speed. Series and universal motors will be tested at operating speed.

d. Method of Motor Isolation for Measuring Vibration

- Place the motor on elastic mounting so proportioned that the up and down natural frequency shall be at least as low as 25 percent of the test speed of the motor. To accomplish this it is required that the elastic mounting be deflected downwards at least by the amounts shown in the Following table due to the weight of the motor.

- When a flexible pad is used the compression shall in no case be more than 50 percent of the original thickness of the flexible pad; otherwise the supports may be too stiff.

Table E-9.1.1. Motor Isolation Requirements

MOTOR SYNCHRONOUS SPEED (RPM)	ISOLATION PAD COMPRESSION (INCHES)
900	1
1200	9/16
1800	1/4
3600	1/16
7200	1/64

e. All new and rebuilt motors shall conform to the vibration limits specified in Table 9.1 when tested in accordance with this specification.

f. Critical Speed

- Completely assembled motors shall have a percentage separation between the rotor shaft first actual critical speed and the rated motor speed as specified in Table 9.1.2.

Table E-9.1.2. Critical Speed Offset Requirement

ROTOR DESIGN	FIRST ACTUAL CRITICAL SPEED LOCATION
Rigid Shaft	At least 25% Above Rated Motor Speed
Flexible Shaft	Maximum of 85% of Motor Speed

g. Limits

All electrical motors defined by NEMA Standard MG-1-1993 Section I "Classification According to Size," Small (fractional), Medium (integral) and Large Machines, shall meet the following requirements:

- The Velocity Amplitude (Inch/sec-Peak) of any line of resolution, measured at bearing locations (ref. Section 5) in any direction (ref. Section 4) shall not exceed the Line-Amplitude Band Limit values specified in Table 9.1 and graphed in Figure 9.1 when determined in accordance with Section 7.2.1 using the frequency range defined in Section 9.1.1.2.
- The Acceleration Overall Amplitude (g's Peak) at bearing locations (ref. Section 5) in any direction (ref. Section 4) shall not exceed the Band-Limited Overall Amplitude Acceptance Limit values specified in Table 9.1 and graphed in Figure 9.1, when determined in accordance with Section 7.2.2 using the frequency range defined in Section 9.1.1.2.

Table E-9.1.3. Maximum Allowable Vibration Levels For Electric Motors

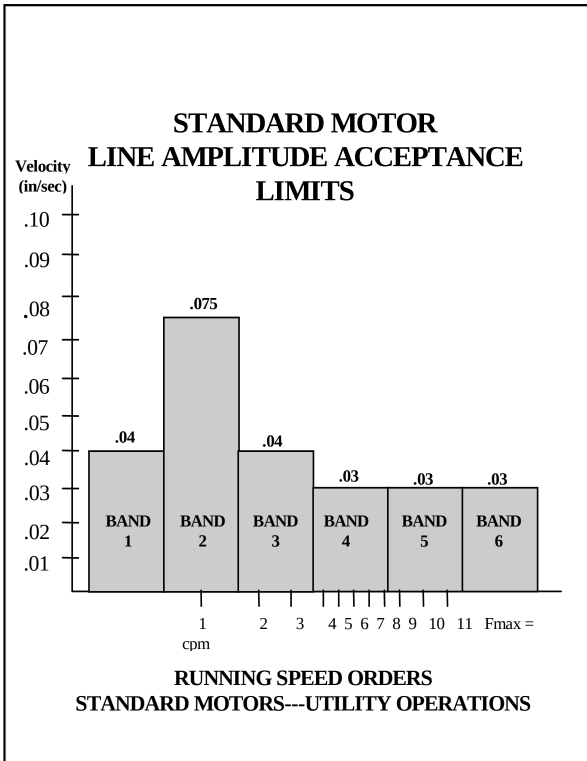
VELOCITY LINE-AMPLITUDE BAND LIMITS				
BAND	FREQUENCY RANGE (CPM)	STANDARD (INCH/SEC - PEAK)	SPECIAL (INCH/SEC - PEAK)	PRECISION (INCH/SEC - PEAK)
1	0.3 x RPM 0.8 x RPM	0.04	0.04	0.02
2	0.8 x RPM 1.2 x RPM	0.075	0.04	0.02
3	1.2 x RPM 3.5 x RPM	0.04	0.04	0.01
4	3.5 x RPM 8.5 x RPM	0.03	0.03	0.01
5	8.5 x RPM 60,000 CPM	0.03	0.03	0.005
6	60,000 CPM 120,000 CPM	0.03	0.03	0.005
ACCELERATION BAND-LIMITED OVERALL AMPLITUDE LIMITS				
BAND	FREQUENCY RANGE (CPM)	STANDARD (g's PEAK)	SPECIAL (g's PEAK)	PRECISION (g's PEAK)
1	0.3 x RPM - 120k	0.5	0.5	0.25

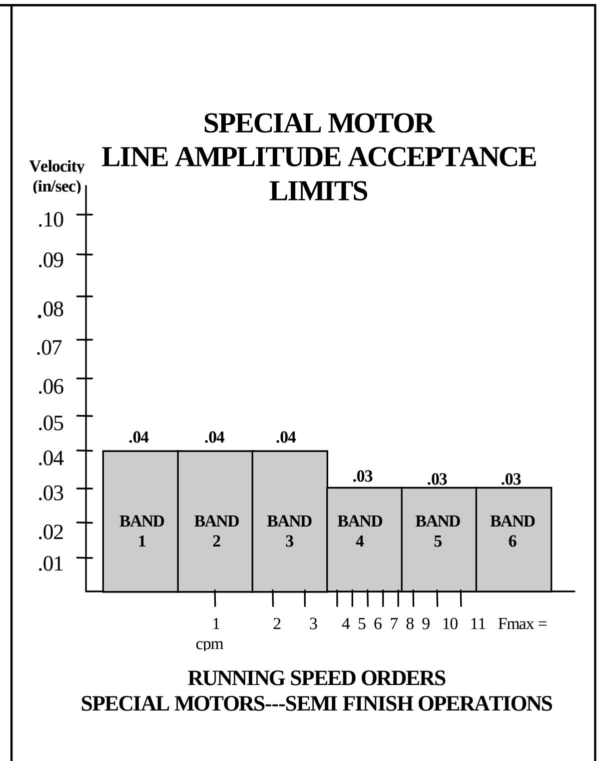
9.1.2 Electrical Motor Certification

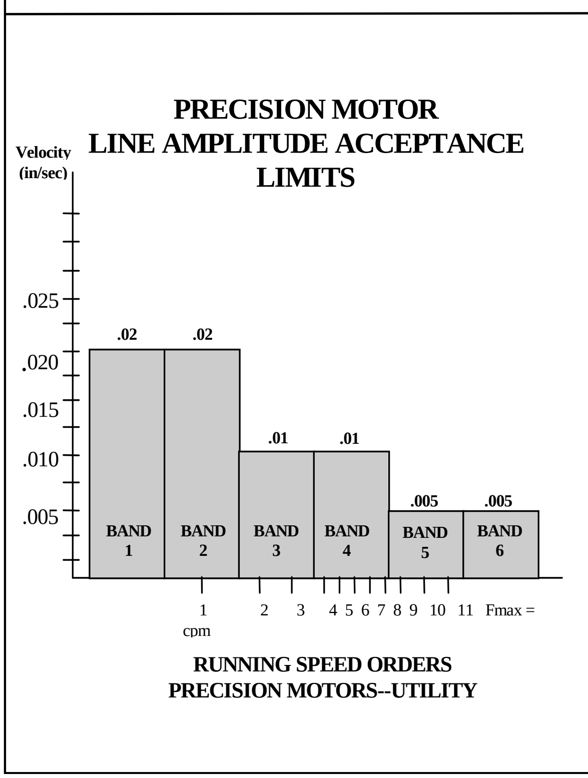
a. The amplitude of vibration at bearing locations (Ref. Section 5) in any direction (radial and axial as defined in Section 4) shall not exceed the values listed in Table 9.1.

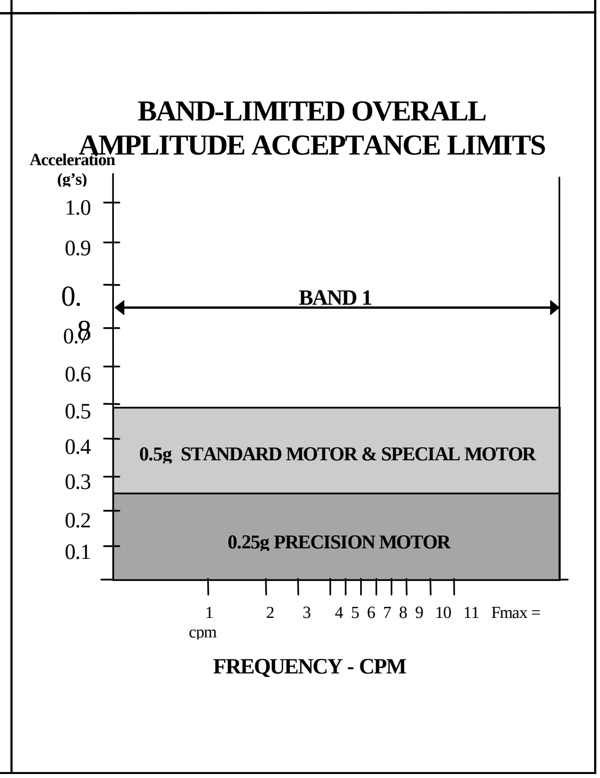
b. Vibration signatures of velocity and acceleration, and a listing of the maximum peak velocity in each band for vibration measurements taken at position 1 horizontal, position 2 vertical, and position 3 axial shall be submitted as part of the motor certification. The data shall be identified with the Motor Serial Number, Frame Number, Model Number, Horsepower and Synchronous speed.

Figure E-9. Maximum Allowable Vibration Limits for Electric Motors


STANDARD MOTOR
LINE AMPLITUDE ACCEPTANCE
LIMITS
Velocity (in/sec)
.10
.09
.08
.07
.06
.05
.04
.03
.02
.01
.04
.075
.04
.03
.03
.03
BAND 1
BAND 2
BAND 3
BAND 4
BAND 5
BAND 6
1 2 3 4 5 6 7 8 9 10 11 Fmax =
cpm
RUNNING SPEED ORDERS
STANDARD MOTORS---UTILITY OPERATIONS


SPECIAL MOTOR
LINE AMPLITUDE ACCEPTANCE
LIMITS
Velocity (in/sec)
.10
.09
.08
.07
.06
.05
.04
.03
.02
.01
.04
.04
.04
.03
.03
.03
BAND 1
BAND 2
BAND 3
BAND 4
BAND 5
BAND 6
1 2 3 4 5 6 7 8 9 10 11 Fmax =
cpm
RUNNING SPEED ORDERS
SPECIAL MOTORS---SEMI FINISH OPERATIONS


PRECISION MOTOR
LINE AMPLITUDE ACCEPTANCE
LIMITS
Velocity (in/sec)
.025
.020
.015
.010
.005
.02
.02
.01
.01
.005
.005
BAND 1
BAND 2
BAND 3
BAND 4
BAND 5
BAND 6
1 2 3 4 5 6 7 8 9 10 11 Fmax =
cpm
RUNNING SPEED ORDERS
PRECISION MOTORS--UTILITY


BAND-LIMITED OVERALL
AMPLITUDE ACCEPTANCE LIMITS
Acceleration (g's)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
BAND 1
0.5g STANDARD MOTOR & SPECIAL MOTOR
0.25g PRECISION MOTOR
1 2 3 4 5 6 7 8 9 10 11 Fmax =
cpm
FREQUENCY - CPM

c. The motor nameplate shall carry the following designation.

Table E-9.1.4. Motor Nameplate Vibration Data Requirements

FOR STANDARD	“0.075 IN/S MAX VIB 1X”
FOR SPECIAL	“0.04 IN/S MAX VIB 1X”
FOR PRECISION	“0.02 IN/S MAX VIB 1X”
FOR OTHER *	“____ IN/S MAX VIB 1X”

* per agreement by vendor and DOS

d. Vibration data and signatures must be submitted with the motor to the DOS maintenance organization or other authorized representative before acceptance of the motor will be authorized.

e. Motors not meeting the certification shall be rejected.

9.2 VIBRATION STANDARDS FOR FANS

9.2.1 Fan Definition

All non-positive displacement air handling units including Induced Draft (ID) Fans, Forced Draft (FD) Fans, Overhung Fans, Centerhung Fans, Centrifugal, Vaneaxial, Tubeaxial, Blowers, etc.

9.2.2 Balancing

a. Permanently attached balancing weighs must be secured by welding, bolting, pop-riveted, or of a "clip-on" design.

- If bolted, a hardened bolt must be used in conjunction with a mechanical locking device (e.g. lock washer or lock nut).
- Clip-on" balancing weights can only be used on centrifugal type fans and must be located and attached on the ID pitch of the blades such that the rotational motion of the fan creates a positive seating of the "clip-on" weight against the fan blade.
- Balancing weights and method of attachment must be stable at fan operating temperature, and of a material compatible with the parent material of the fan to which the balancing weight is attached. Note: The use of stick-in lead weights is not acceptable.

b. Any parent metal removed to achieve dynamic or static balance shall be drilled out in a manner which, will maintain the structural integrity of the rotor or sheave.

c. Access to the fan rotor for field balancing shall be designed in to the system. (Note: It is recommended that components (rotor, shafts, sheaves) be balanced individually and then trim balanced as a total assembly.)

9.2.3 Shaft Tolerance

Fan shaft diameter shall meet bearing manufacturer specifications for shaft tolerances.

9.2.4 Resonance

Natural frequencies of the completely assembled fan unit shall not be excited at the operating speed. (Running speed should be at least 25 percent removed from a natural frequency of the system.)

9.2.5 Limits

a. New and Rebuilt/Repaired Fans shall conform to the vibration limits specified in Table 9.2 when operating at specified system CFM and Fan Static Pressure.

b. The frequency range for fan certification shall be from F_{min} = 0.3 X Running Speed of Fan to 60,000 CPM for velocity and to 120,000 CPM for acceleration.

c. For fan speeds up to 3600 RPM, the maximum velocity amplitude (inch/sec-Peak) of vibration at bearing locations (ref. Section 5) in any direction (as defined in Section 4) shall not exceed the Line Amplitude Band Limit values specified in Table 9.2 and graphed in Figure 9.2.1 when determined in accordance with Section 7.2.1 using the frequency range defined in Section 9.2.5.2.

d. For fan speeds up to 3600 RPM, the Band-Limited Overall vibration level of acceleration (g's Peak) at bearing locations (ref. Section 5) in any direction (as defined in Section 4) shall not exceed the Band-Limited Overall Amplitude Acceptance Limit values specified in Table 9.2 and graphed in Figure 9.2.2, when determined in accordance with Section 7.2.2 using the frequency range defined in Section 9.2.5.2.

e. Acceptance limits for fans running over 3600 RPM shall be specified by the purchaser.

Table E-9.2. Maximum Allowable Vibration Levels for Fans

BAND	FREQUENCY RANGE	VELOCITY LINE AMPLITUDE BAND LIMITS (INCH/SEC PEAK)
1	0.3 x RPM min 0.8 x RPM fan	0.04 DIRECT COUPLED 0.075 BELT DRIVE
2	0.8 x RPM fan 1.2 x RPM fan/motor	0.075
3	1.2 x RPM fan/motor 3.5 x RPM fan/motor	0.04
4	3.5 x RPM fan/motor to Fmax = 60,000 CPM	0.03
		ACCELERATION BAND LIMITED OVERALL AMPLITUDE LIMITS (g's PEAK)
1	0.3 x RPM min to Fmax = 120,000 CPM	0.5
RPM min = Lowest system speed (e.g. Belt speed if Belt Driven, Fan speed if direct drive coupled RPM fan/motor = Fan or motor speed whichever is greater (IN/SEC)		

Figure E-10. Line Amplitude Acceptance Limits for Fans

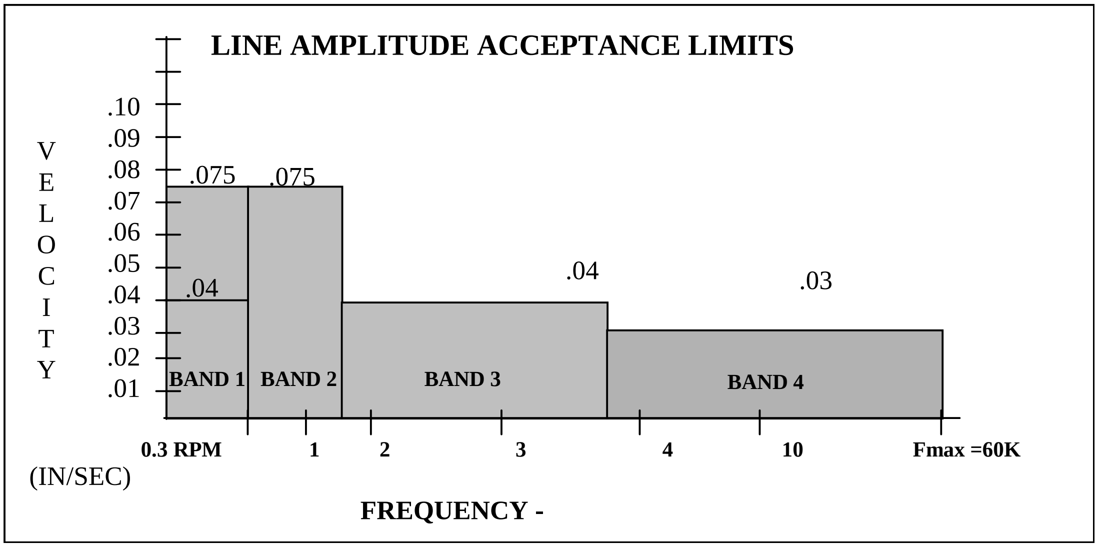
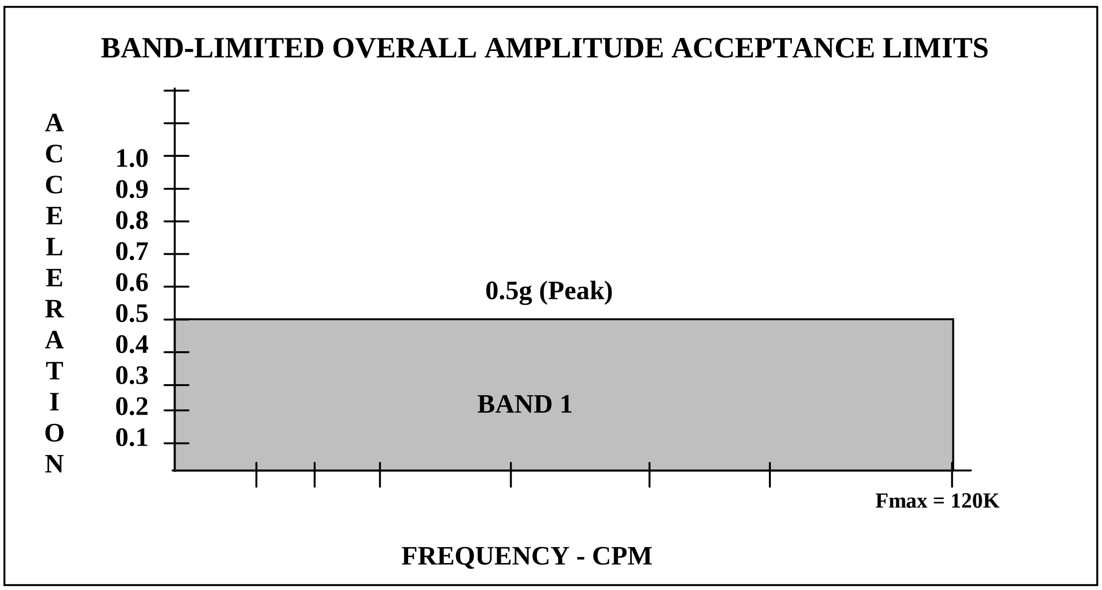


Figure E-11. Band Limited Overall Amplitude Acceptance Limits for Fans



9.2.6 Other Requirements

a. Variable speed or adjustable sheaves shall not be used in the final installation.

b. Drive sheave and driven sheave should differ in size by 20 percent or more to avoid "beat" vibration.

9.3 VIBRATION STANDARDS FOR PUMPS

9.3.1 Pumps shall be defined in two (2) categories:

- Positive Displacement including, but not limited to Piston, Gear, and Vane
- Centrifugal

9.3.2 Operating Conditions

- Non-cavitating, non-separating condition
- No piping strain
- Shaft coupling aligned
- Straight suction pipe to pump (Reference Hydraulic Institute Standard.)
- Certification shall be performed while pumps are operating within design specifications

9.3.3 Limits for Positive Displacement and Centrifugal Pumps

For purposes of Line Amplitude evaluations a Pumping Frequency (PF) band will be established. The PF Band will be centered on the Pumping Frequency (Number of pumping elements X Pump RPM). The band will extend + 2 lines of resolution on either side of the line of resolution containing the Pumping Frequency (i.e. Bandwidth = 5 lines of resolution).

Excluding the lines of resolution contained in the Pumping Frequency (PF) Band, the Velocity Amplitude (Inch/sec-Peak) of any line of resolution, measured at bearing locations (ref. Section 5) in any direction (as defined in Section 4) shall not exceed the Line-Amplitude Band Limit values specified in Table 9.3. and graphed in Figure 9.3.1, when determined in accordance with Section 7.2.1 using the frequency range from 0.3 X Running Speed (pump RPM) to F_{max} = 120,000 CPM (2,000 Hertz)

The Velocity Band-Limited Overall Amplitude (Inch/sec - Peak) at bearing locations (ref. Section 5) in any direction (as defined in Section 4) shall not exceed the Pumping Frequency Band Limited Overall Amplitude Acceptance Limit value specified in Table 9.3. and graphed in Figure 9.3.1 when determined in accordance with Section 7.22 using the frequency range from 0.8 X PF to 1.2 X PF.

The Acceleration Band-Limited Overall Amplitude (g's Peak) at bearing locations (ref. Section 5) in any direction (as defined in Section 4) shall not exceed the Band-Limited Overall Amplitude Acceptance Limit values specified in Table 9.3. and graphed in Figure 9.3.2 when determined in accordance with Section 7.2.2 using the frequency range from 0.3 X Running Speed to 300,000 CPM.

Table E-9.3. Maximum Allowable Vibration Levels for Positive Displacement And Centrifugal Pumps

LINE-AMPLITUDE BAND LIMITS		
BAND	FREQUENCY RANGE (CPM)	VELOCITY (INCH/SEC - PEAK)
1	0.3 x RPM 0.8 x RPM	0.04
2	0.8 x RPM 1.2 x RPM	0.075
3	1.2 x RPM 3.5 x RPM	0.04
4	3.5 x RPM 120,000 CPM	0.03
BAND-LIMITED OVERALL AMPLITUDE LIMITS		
BAND	FREQUENCY RANGE (CPM)	ACCELERATION (g's PEAK)
1	0.3 x RPM - 300K CPM	1.5g - POSITIVE DISPLACEMENT 1.0g - NON-POSITIVE DISPLACEMENT

Figure E-12. Line Amplitude Acceptance Limits for Positive Displacement & Centrifugal Pumps

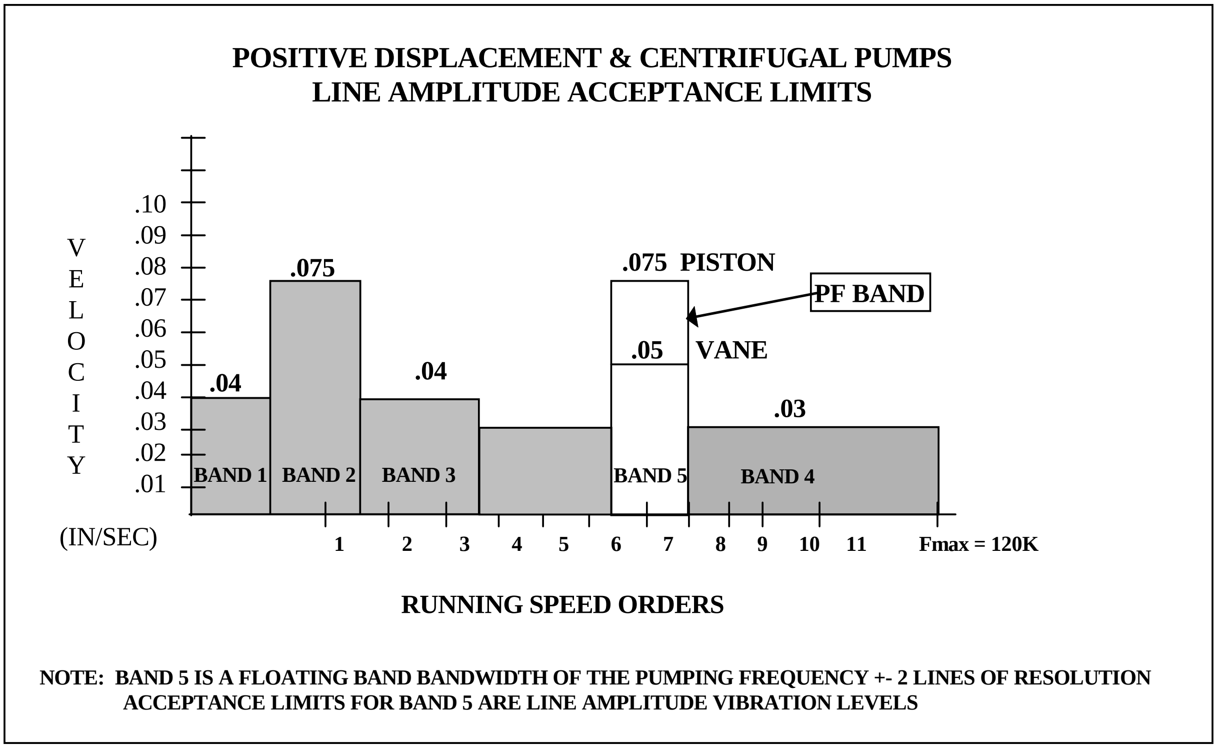
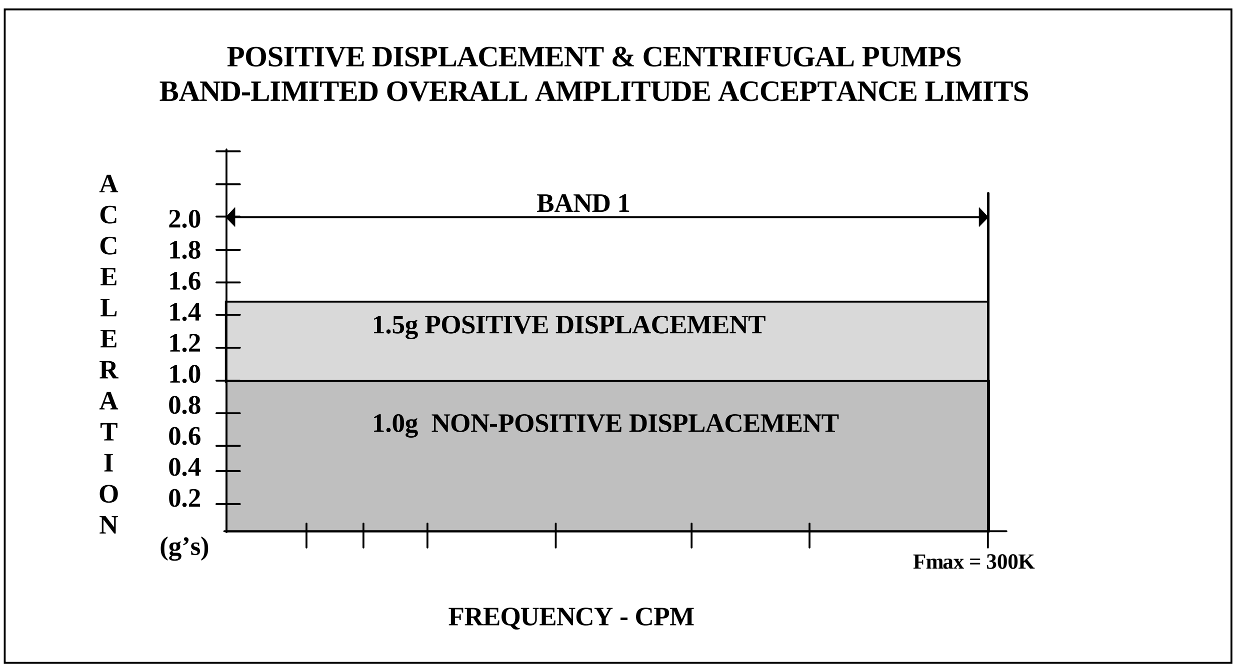


Figure E-13. Band-Limited Overall Amplitude Acceptance Limits for Positive Displacement & Centrifugal Pumps



9.3.4 Vertical Mounted Pumps

Vertically mounted pump systems with a "Vertical Mount Height" greater than 5 feet will have an allowable increase in Velocity Amplitude Acceptance Limits in Bands 1, 2, and 3 of 5 percent per foot of "Vertical Mount Height" greater than 5 feet. (e.g. A 7 foot Vertical Mount Height would yield a 10 percent increase (7 ft - 5 ft) x 5%/ft] in the Table 9.3. A Velocity Amplitude Acceptance Limits specified for Bands 1, 2, and 3. Therefore the limit for Band 1 would be [0.4 Inch/sec + (0.4 Inch/sec x 0.1)] = 0.44 Inch/sec-Peak.

Vertical Mount Height is defined as the furthest measurable distance from the machine mounting to the end of the driver or the end of the pump, which ever is greater.

9.4 VIBRATION STANDARDS FOR GEARBOXES

Figure E-14. Line Amplitude Acceptance Limits for Gearboxes

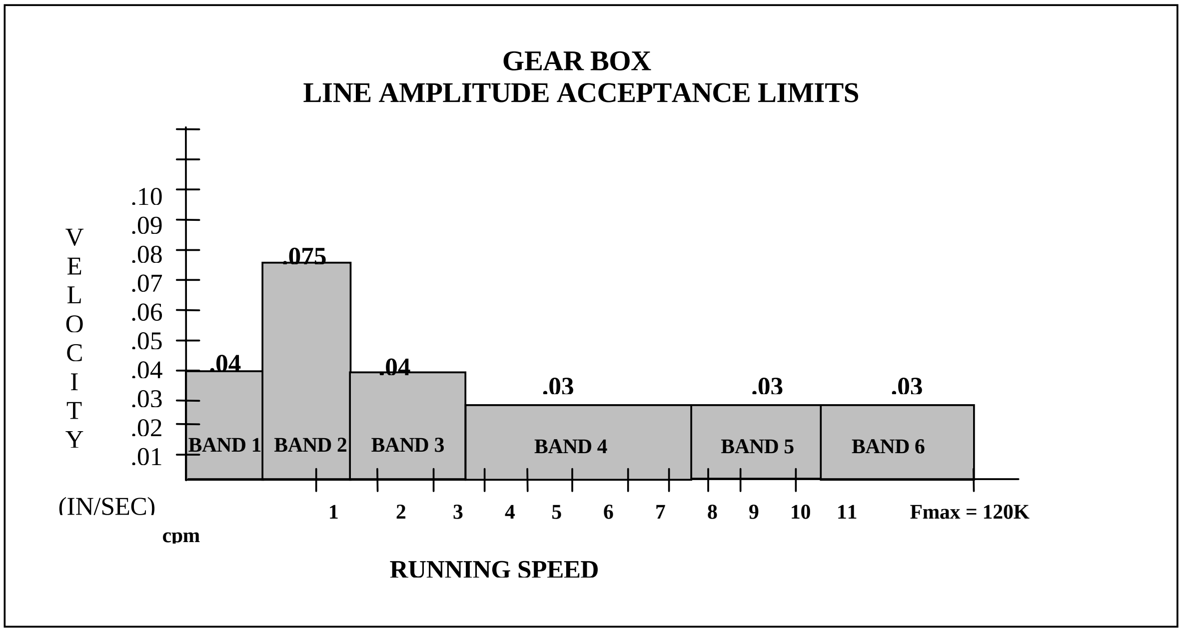
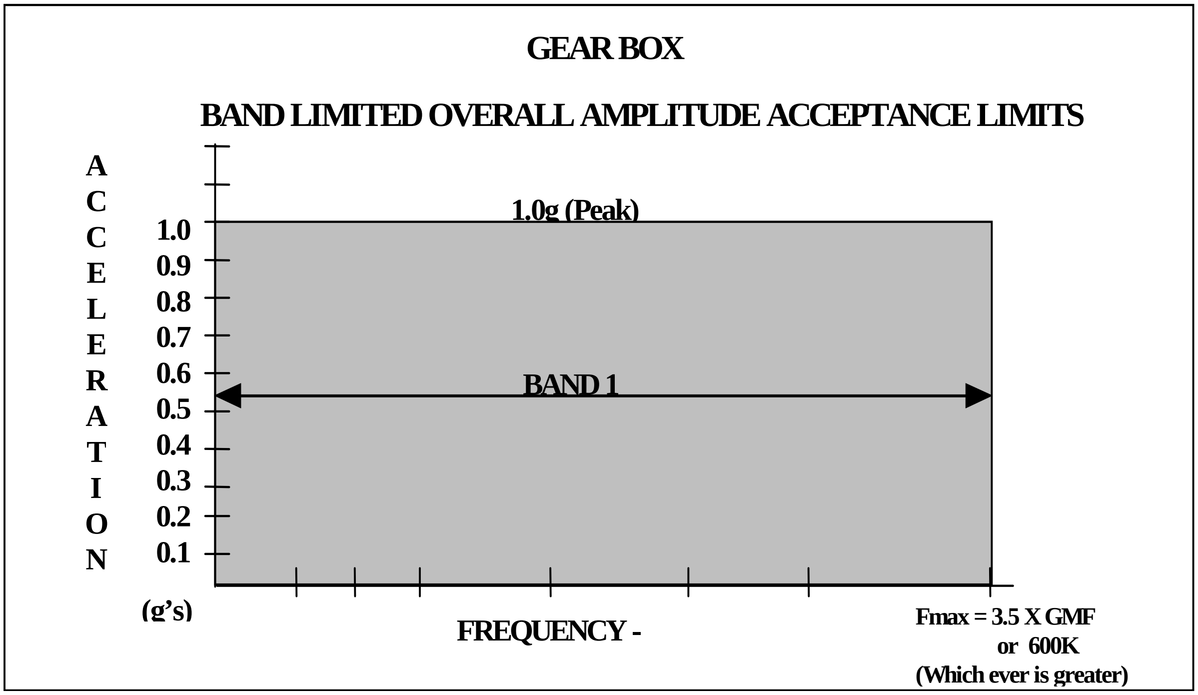


Figure E-15. Band-Limited Overall Amplitude Acceptance Limits for Gearboxes



9.5 VIBRATION STANDARDS FOR DEFAULT LIMITS

If Vibration Limit values are not available for the machine being considered, the Specification Limit shall (unless specified otherwise by the purchaser) default to the following:

9.5.1 Non-Machine Tools

Non-machine Tools shall not exceed the Vibration Limits specified in Table 9.5 and graphically illustrated in figures 9.5.1 and 9.5.2.

Table E-9.5. Maximum Allowable Vibration Levels for Non-Machine Tools

VELOCITY LINE-AMPLITUDE BAND LIMITS		
BAND	FREQUENCY RANGE (CPM)	VELOCITY (INCH/SEC - PEAK)
1	0.3 x RPM 0.8 x RPM	0.04
2	0.8 x RPM 1.2 x RPM	0.075
3	1.2 x RPM 3.5 x RPM	0.04
4	3.5 x RPM 8.5 x RPM	0.03
5	8.5 x RPM 60,000 CPM	0.03
6	60,000 CPM 120,000 CPM	0.03
ACCELERATION BAND-LIMITED OVERALL AMPLITUDE LIMITS		
BAND	FREQUENCY RANGE (CPM)	ACCELERATION (g's PEAK)
1	0.3 x RPM - 120K	0.5

Figure E-16. Default Line Amplitude Acceptance Limits for Non-Machine Tools

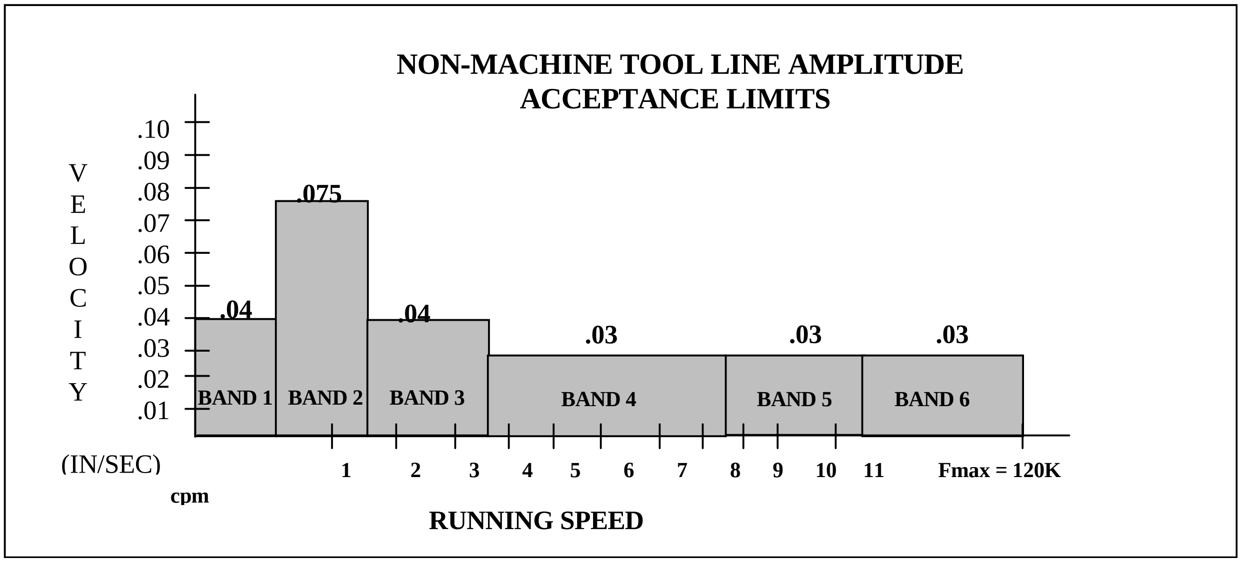
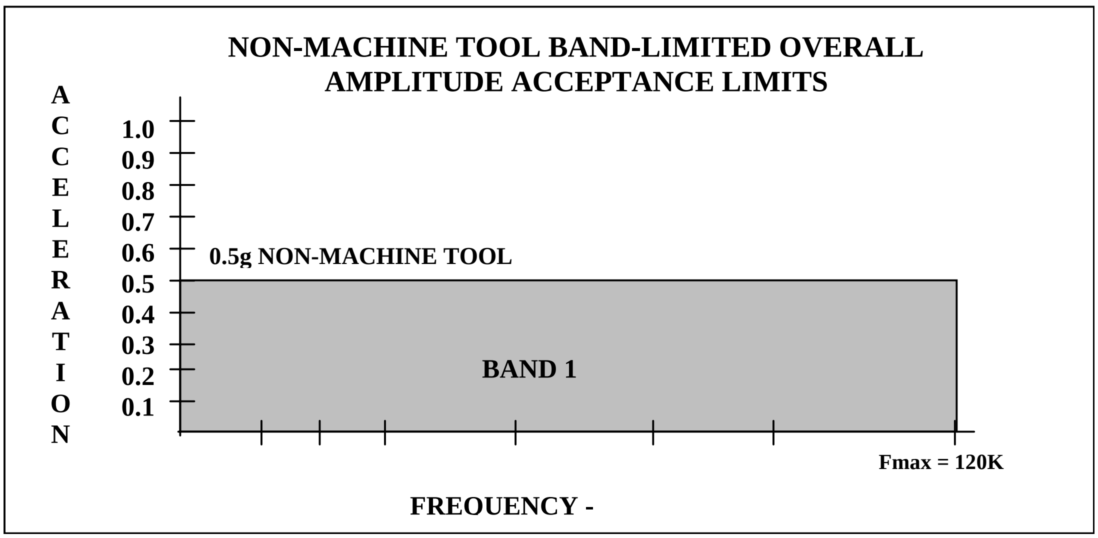


Figure E-17. Default Band-Limited Overall Amplitude Acceptance Limits for Non-Machine Tools



10.0 GLOSSARY

Acceleration: The time rate of change of velocity. Typical units are ft/sec^2 and g's (1 g = 32.17 ft/sec^2 = 386 in/sec^2 = 9.81 meter/sec^2). Acceleration measurements are made with accelerometers. (Note: By international agreement, the value 9.80665 m/s^2 = 980,665 cm/s^2 = 386.089 in/s^2 = 32.174 ft/s^2 has been chosen as the standard acceleration due to gravity (g). ISO 2041 (1990))

Accelerometer: Transducer whose output is directly proportional to acceleration. Most commonly used are mass loaded piezoelectric crystals to produce an output proportional to acceleration.

Amplitude: A measure of the severity of vibration. Amplitude is expressed in terms of peak-to-peak, zero-to-peak (peak), or rms. For pure sine waves only:

- Peak (P) = 1.414 x RMS
- Peak-to-Peak = 2 x Zero-to-Peak (Peak)

Amplitude Limits: The total vibration level "A" in a band, as defined by the following equation, shall not exceed the Overall Amplitude Acceptance Limit specified for the Band

$$A = \sqrt{\frac{\sum_{i=1}^{N} A_i^2}{W}}$$

- A = Overall vibration level in the Band
- Ai = Amplitude in the ith line of resolution in the Band
- (i = 1) = The first line of resolution in the Band
- (i=N) = The last line of resolution in the Band
- N = The number of lines of resolution in the Band
- W = Window Factor (W = 1.5 for a Hanning Window)

Anti-Aliasing Filter: A low-pass filter designed to filter out frequencies higher than 1/2 the sample rate in order to prevent aliasing.

Anti-Friction Bearing: See ROLLING ELEMENT BEARING.

Average: The sum of the values of the measurements taken divided by the number of measurements taken.

Balance: When the mass center line and rotational center line of a rotor are coincident.

Balancing: A procedure for adjusting the radial mass distribution of a rotor by adding or removing weight, so that the mass centerline approaches the rotor geometric centerline achieving less vibration amplitude at rotational speed.

Band-Limited Overall Amplitude: For vibration level limits specified in terms of "BAND-LIMITED OVERALL

Beats: Periodic variations in the amplitude of an oscillation resulting from the combination of two oscillations of slightly different frequencies. The beats occur at the difference frequency. ISO 2041 (1990).

Beat Frequency: The absolute value of the difference in frequency of two oscillations of slightly different frequencies. ISO 2041 (1990)

Blade Pass Frequency (Pumping Frequency): A potential vibration frequency on any bladed machine (turbine, axial compressor, fan, pump, etc.). It is represented by the number of fan blades or pump vanes times shaft rotating frequency.

Calibration: A test to verify the accuracy of measurement instruments. For vibration, a transducer is subjected to a known motion, usually on a shaker table, and the output readings are verified or adjusted.

Complete Machine: A complete machine is defined as the entire assembly of components, sub-components, and structure, which is purchased to perform a specific task(s). On a Complete Machine Assembly with all individual components operating in their normal operating condition, mode, and sequence, the Component Vibration Level Limits for the complete machine acceptance are the same as when the component is tested individually.

Critical Speed: The speed of a rotating system corresponding to a system resonance frequency.

Decibel (Db): A logarithmic representation of amplitude ratio, defined as 20 times the base ten logarithm of the ratio of the measured amplitude to a reference. DbV readings, for example, are referenced to 1 volt rms. dB amplitude scales are required to display the full dynamic range of an FFT Analyzer.

Displacement: The distance traveled by a vibrating object. For purposes of this document, displacement represents the total distance traveled by a vibrating part or surface from the maximum position of travel in one direction to the maximum position of travel in the opposite direction (Peak-to-Peak) and is measured in the unit mil (1 mil = 0.001 inch).

Dynamic Range: The difference between the highest measurable signal level and the lowest measurable signal level that is detectable for a given Amplitude Range setting. Dynamic Range is usually expressed in decibels, typically 60 to 90 dB for modern instruments.

Dynamic Mass: To determine if the mass of the transducer is effecting the measurement, perform the following steps:

- Make the desired measurement with the accelerometer.

- Place a mass equivalent to the mass of the accelerometer adjacent to the measuring accelerometer.
- Repeat the measurement.
- Compare data from a. and c.

If any differences (i.e. shift in frequencies) between a. and c. exist, then a less massive transducer should be used in a.

FFT Analyzer: Vibration analyzer that uses the Fast Fourier Transform to display vibration frequency components.

FFT (Fast Fourier Transform): A calculation procedure which converts a time domain signal into a frequency domain display; A calculation procedure which produces a mathematical relationship between the time domain and the frequency domain resulting in discrete frequency components from the sampled time data.

Field Balancing: The process of balancing a rotor in its own bearings and supporting structure rather than in a balancing machine.

Flexible Rotor: A rotor that deforms significantly at running speed. This term is used for rotors that operate close to or above their first critical speed. A rotor is considered flexible when its speed is more than 75 percent of its lowest natural frequency in bending.

Forced Vibration: The oscillation of a system under the action of a forcing function. Typically forced vibration occurs at the frequency of the exciting force.

Free Vibration: Vibration of a mechanical system following an initial force -- typically at one or more natural frequencies.

Frequency: The repetition rate of a periodic event, usually expressed in cycles per second (Hertz -abr. HZ), cycles per minute (CPM), or multiples of rotational speed (Orders). Orders are commonly referred to as IX for rotational speed, 2X for twice rotational speed, etc. Frequency is the reciprocal of the Period. (Note**:** Vibration frequencies are expressed in Hertz (cycle per sec) or CPM (cycle per minute). Rotational speed (Running Speed) is expressed in RPM (Revolutions per minute).)

Frequency Domain: Presentation of a signal whose amplitude is measured on the Y axis, and the frequency is measured on the X-axis.

Frequency Resolution (ΔF): Δ f = (FMAX - FMIN)/# Lines of resolution. Δf represents the minimum spacing between data points in the spectrum.

F_{MAX}: Maximum Frequency Limit of the spectrum being evaluated.

F_{MIN}: Minimum Frequency Limit of the spectrum being evaluated.

Frequency Response: Portion of the frequency spectrum which can be covered within specified frequency limits.

G: The value of acceleration produced by the force of gravity. (32.17 ft/sec^2, 386 in/sec^2, 9.81 m/sec^2).

Gear Mesh Frequency: A potential vibration frequency on any machine that contains gears: equal to the number of teeth multiplied by the rotational frequency of the gear.

Hanning Window: A Digital Signal Analysis (DSA) window function that provides better frequency resolution than the flat top window, but with reduced amplitude

Harmonic: Frequency component at a frequency that is an integer (whole number e.g. 2X. 3X. 4X, etc.) multiple of the fundamental (reference) frequency.

Hi Bandpass Filter: A device that separates the components of a signal and allows only those components above a selected frequency to be amplified.

Hertz (Hz): The unit of frequency represented by cycles per second.

Imbalance: Unequal radial weight distribution of a rotor system; a shaft condition such that the mass and shaft geometric centerlines do not coincide.

Integration: A process producing a result that when differentiated, yields the original quantity. Integration of acceleration, for example, yields velocity. Integration is performed in an FFT Analyzer by dividing by $2\pi f$ where f is the frequency of vibration. Integration is also used to convert velocity to displacement.

Large Apparatus Ac/Dc Motors: Reference NEMA Publication No. MG 1, Motors and Generators, Section III

Large Machines: Part 20. Induction Machines, Part 21. Synchronous Motors, and Part 23. DC Motors.

Linear Non-Overlapping Average: An averaging process where each Time block sample used in the averaging process contains data not contained in other Time blocks (i.e. Non-overlapping) used in the averaging. Linear averaging is performed in the Frequency Domain, and each sample is weighted equally.

Lines: The total number of data points in a spectrum (e.g. 400, 800, 1600, etc.).

Line Amplitude Limit: The maximum amplitude of any line of resolution contained within a band shall not exceed the Line Amplitude Acceptance Limit for the Band.

Line of Resolution: A single data point from a spectrum which contains vibration amplitude information. The Line of Resolution amplitude is the Band Overall Amplitude of the frequencies contained in the Δf Frequency Resolution.

Measurement Point: A location on a machine or component at which vibration measurements are made.

Micrometer (Micron): One millionth (0.000001) of a meter. (1 micron = 1 x 10^{-6} meters = 0.04 mils.)

Mil: One thousandth (0.001) of an inch. (1 mil = 25.4 microns.)

Natural Frequency: The frequency of free vibration of a system when excited with an impact force. (Bump Test.)

Order: A unit of frequency unique to rotating machinery where the first order is equal to rotational speed. See FREQUENCY

Band Limited Overall Reading: The vibration severity amplitude measured over a frequency range defined by a FMIN and a FMAX

Peak: Refers to the maximum of the units being measured, i.e., peak velocity, peak acceleration, peak displacement.

Peak-To-Peak: Refers to the displacement from one travel extreme to the other travel extreme. In English units, this is measured in mils (.001 inch) and in metric units it is expressed in micro-meter μM (.000001 meters).

Period: The amount of time, usually expressed in seconds or minutes, required to complete one cycle of motion of a vibrating machine or machine part. The reciprocal of the period is the frequency of vibration.

Phase (Phase Angle): The relative position, measured in degrees, of a vibrating part at any instant in time to a fixed point or another vibrating part. The Phase Angle (usually in degrees) is the angle between the instantaneous position of a vibrating part and the reference position. It represents the portion of the vibration cycle through which the part has moved relative to the reference position.

Precision Spindle: Spindles used in machining processes which require high accuracy, high speed, or both.

Radial Measurement: Measurements taken perpendicular to the axis of rotation.

Radial Vibration: Shaft dynamic motion or casing vibration which is in a direction perpendicular to the shaft centerline.

Resonance: The condition of vibration amplitude and phase change response caused by corresponding system sensitivity to a particular forcing frequency. A resonance is typically identified by a substantial amplitude increase and related phase shift.

Rigid Rotor: A rotor that does not deform significantly at running speed. A rotor whose parts do not take up motion relative to each other, i.e., all points move in the same direction at the same instant of time. A rotor is considered rigid when its speed is less than 75 percent of its lowest natural frequency in bending.

RMS (Root mean square): Equal to 0.707 times the peak of a sinusoidal signal.

Rolling Element Bearing: Bearing whose low friction qualities derive from rolling elements (balls or rollers), with little lubrication.

Rotational Speed: The number of times an object completes one complete revolution per unit of time, e.g., 1800 RPM.

Side Band: Equals the frequency of interest plus or minus one times the frequency of the exciting force.

Signature (Spectrum): Term usually applied to the vibration frequency spectrum which is distinctive and special to a machine or component, system or subsystem at a specific point in time, under specific machine operating conditions, etc. Usually presented as a plot of vibration amplitude (displacement, velocity or acceleration) versus time or versus frequency. When the amplitude is plotted against time it is usually referred to as the TIME WAVE FORM.

Small (Fractional) and Medium (Integral) Horsepower Ac/Dc Motors: Reference NEMA Publication No. MG 1, Section II SMALL (FRACTIONAL) AND MEDIUM (INTEGRAL) MACHINES. Part 12. Tests and Performance - AC and DC Motors.

Time Domain: Presentation of a signal whose amplitude is measured on the Y axis and the time period is measured on the X axis.

Transducer (Pickup)-Vibration: A device that converts shock or vibratory motion into an electrical signal that is proportional to a parameter of the vibration measured. Transducer selection is related to the frequencies of vibration which are important to the analysis of the specific machine(s) being evaluated/analyzed.

Unbalance: See IMBALANCE.

Velocity: The time rate of change of displacement with respect to some reference position. For purposes of this document, velocity is measured in the units Inch per second-Peak.

(Note: The reference for many of the definitions in this glossary is the glossary from the Hewlett Packard publication “Effective Machinery Measurements Using Dynamic Signal Analyzers,” Application Note 243-1.)

APPENDIX F: PT&I TECHNOLOGIES CORRELATION RELATIONSHIPS

This appendix contains the correlation relationships between the various PT&I technologies.

Table F-1. Vibration Monitoring Correlation

Technology	Correlation	Indication	When Used
Ultrasonic Analysis (36-44 kHz)	Trending & Absolute Limit	These techniques are indicators of minor bearing damage and/or lubrication starvation and/or contamination. All rely on detection of micro-impacting between the rollers and raceway which excites the natural frequency of the bearing rings.	Not recommended for use on critical equipment.
Spike Energy (25-35 kHz)	Trending & Absolute Limit		
Shock Pulse (32 kHz Ctr. freq.)	Trending & Absolute Limit		
Vibration Narrowband Signature Analysis (0-20 kHz)	Trending & Absolute Limit	Provides adequate detection of most mechanical and electrical faults. Effectiveness related to sensor mounting and analysis techniques.	Periodic monitoring, establish interval-based on absolute level and rate of change, criticality and equipment application.
Displacement	Trending & Absolute Limit	Shaft position relative to bearing journal.	Primarily used for supervisory systems, limited machinery diagnostic capability.
Overall Measurements	Limited Trending	Limited applicability. Should be used as a pass/fail criteria. Does not support fault analysis.	Not recommended except for low cost/low risk equipment.
Time Domain Analysis	Trending Time Coincident	Troubleshooting	Transient monitoring, impact detection, and in response to alarms.
Phase Analysis	Time Coincident	Troubleshooting	Phase is unstable for electrical faults, looseness, oil whirl/whip, and resonance. Phase is stable for imbalance and misalignment. Note: Misalignment typically shows 180 degree phase shift.

Table F-2. Correlation of Vibration Monitoring with Other CdM Technologies

Technology	Correlation	Indication	When Used
Wear Particle Analysis	Trending Time coincident	Spectrometric and ferrographic indications of bearing, gear, or seal wear.	Initial interval of six months. When discrete frequency associated with gears or bearings is present. See oil analysis section for more details.
Thermal Analysis	Time coincident	High temperature & high vibration level are indicative of imminent failure.	When vibration levels are above alarm limits.
Advanced Filtration/Debris Analysis	Trending	For all lubricated bearings indication that damage to bearing surfaces has occurred.	Confirm bearing damage.
Motor Current Signature Analysis	Time coincident	Detects Electro-mechanical faults such as broken rotor bars, defective shorting rings, air gap eccentricity, and non-symmetrical magnetic field.	Supplement vibration monitoring on critical motors.
Motor Circuit Analysis/Evaluation	Time coincident	Measures complex phase impedance (resistance and inductance), resistance and capacitance to g-round, and rotor influence on magnetic field (indirectly).	Supplement vibration monitoring on critical motors. Acceptance testing.
Performance Testing	Time coincident	Degradation of thermodynamic and operating performance.	Pressure, temperature, flow, power consumption, cycle time, and operating hours.

Table F-3. Correlation of Lubricant & Wear Particle Analysis with Other Technologies

Technology	Correlation	Indication	When Used
Vibration	Trending	Wear particle buildup precedes significant vibration in most cases.	Routinely, when equipment is being operated.
Thermal Analysis	Time coincident	High temperature often comes with major wear particle production just before bearing failure.	Confirm bearing degradation.
Advanced Filtration/Debris Analysis	Trending Time coincident	Major bearing damage has occurred when material appears in lubricating system filters.	Routinely, with every filter cleaning or change.

Table F-4. Correlation of Thermal Analysis with Other Technologies

Technology	Correlation	Indication	When Used
Vibration	Time coincident	Significant vibration accompanies rising temperatures.	On condition of suspected bearing or coupling problem.
Lubrication Wear Particle Analysis	Trending	High temperature often comes with major wear particle production just before bearing failure.	On condition of suspected bearing problem.
Advanced Filtration/Debris Analysis	Trending	Damage creates material residue.	After high temperature alerts personnel to damage potential.
Leak Detection	Time coincident	Abnormal temperatures coincident with acoustic signals indicating internal leak.	On condition of suspected leak.
Electrical Circuit Testing	Time coincident	High resistance generating heat.	On condition of suspected circuit problem.
Visual inspection	Trending	Discoloration from overheating due to corrosion/oxidation at connectors.	On condition of indicated problem.

Table F-5. Correlation of Advanced Filtration & Debris Analysis with Other Technologies

Technology	Correlation	Indication	When Used
Vibration analysis	Trending	Filter debris buildup confirms damage causing increased vibration.	Routinely, when equipment is being operated.
Lubricant Analysis	Trending	Debris analyzed and source identified by spectrographic or other means.	Routine oil samples show marked increase in level of foreign material.

Table F-6. Correlation of Flow Measurement with Other Technologies

Technology	Correlation	Indication	When Used
Passive Ultrasonics	Time coincident	Acoustic signals corroborate flow indications of valve leakage by the seat. Indicator of tube/tubesheet leakage.	To confirm leakage by isolation valves.
Thermal Analysis	Time coincident	High or low temperatures corroborate indications of valve leakage by the seat.	Confirm bearing degradation.
Thermal Analysis (Differential temperatures)	Time coincident	Increasing)T as flow decreases due to blockage or pump degradation.	On condition of flow decrease/change)T across heat exchanger.
Vibration analysis	Time coincident	Cavitations caused by pump, impeller, or wear ring deterioration. Line blockage indicated by increased vane frequency.	On condition of reduced system flow rate.
Visual inspection	Trending	Heat exchanger inspection shows internal fouling.	To confirm reduced flow.

Table F-7. Correlation of Valve Operator Testing with Other Technologies

Technology	Correlation	Indication	When Used
Dew Point Monitoring	Trending	Moisture induced corrosion and clogging of orifices and binding of operators.	Periodically, frequency depending on dew point readings.
Hydraulic oil testing	Trending	Dirt and contaminants clog orifices, restrictors and bind valve operators.	Periodically, frequency depending on contamination buildup.

Table F-8. Correlation of Electrical Testing with Other Technologies

Technology	Correlation	Indication	When Used
Vibration analysis	Time coincident (MCSA)	Distinguish between unbalance, rotor bar or end ring breakage, or high resistance.	On condition - when routine vibration analysis indicates possible rotor bar or end ring problems.
Motor Current Analysis	Trending (Surge Comparison)	Rotor winding defects in slip ring induction motors.	On condition - when motor current analysis indicates potential rotor problem.
Thermal analysis (IRT imaging)	Time coincident (TDR)	High temperatures/high resistance in motor control and electrical cabling/circuits.	On condition. Either technology can confirm a finding of the other.
Visual inspection	Time coincident	Insulation and connector discoloration, corrosion, pitting and other signs of deterioration caused by heat.	Periodically, when access is available to the busses, cabling and terminal boards.
RF Monitoring	Time coincident	Arcing in the windings of large generators.	Continuous monitoring where RF system installed.

Table F-9. Correlation of Ultrasonic/Acoustic Leak Detection with Other Technologies

Technology	Correlation	Indication	When Used
Thermal analysis	Time coincident	Abnormal temperatures coincident with acoustic signals indicating leak.	On condition of suspected leak.
Visual inspection	Trending	Visual evidence of damage to valve discs and seats sufficient to cause leakage.	When valve internals are open and available for inspection.
Nonintrusive flow	Time coincident	Flow downstream of shut valve provides acoustic indication of leakage by the seat.	On condition of suspected leak.

Table F-10. Correlation of Breakaway or Coast-down Testing with Other Technologies

Technology	Correlation	Indication	When Used
Vibration analysis	Trending	Nature of specific problem implied by abnormal breakaway or coastdown testing.	Start up after major repair or extended shutdown.
Vibration analysis	Time coincident	Abnormal vibration during startup. Abnormal vibration during operation.	Start up after major repair or extended shutdown. Before shutdown to conduct investigation of suspected problem.
Thermal analysis	Trending	Abnormal temperature during operation.	Before shutdown to conduct investigation of a suspected problem.
Lubricant Wear Particle Analysis	Trending	Abnormal wear indicating increased internal friction within machine.	Before shutdown to conduct investigation of a suspected problem.
Advance Filtration/Debris Analysis	Trending	Abnormal condition indicating increased friction.	Before shutdown to conduct investigation of a suspected problem.

Table F-11. Correlation of Dew Point Measurement with Other Technologies

Technology	Correlation	Indication	When Used
Visual inspection (including fiber optics)	Time coincident Trending	Physical condition of flask/pressure vessel. Wall thickness reduced.	On condition of long periods (>10%) of "wet" gas in system.
Ultrasonic imaging	Time coincident Trending	Physical condition of flask/pressure vessel. Wall thickness reduced.	On condition of long periods (>10%) of "wet" gas in system.

Table F-12. Correlation of Visual Inspections with Other Technologies

Technology	Correlation	Indication	When Used
Vibration Analysis	Trending (Post replacement analysis)	Physical condition of parts are deteriorated or worn.	For each condition where damaged parts are found after detection by vibration analysis.
Thermal Analysis	Time coincident	Visual and infrared images of suspected faults.	Visual image taken to accompany each IRT image.
Thermal Analysis	Trending	Increasing)T across heat exchanger with operating time.	On condition where heat exchanger fouling, not pump condition, is suspected cause.
Lubricant Physical Analysis	Trending	Conditions created by lengthy operation with lubricant OOS.	When system inspection reveals buildup of contaminants.
Lubricant Wear Particle Analysis	Trending	Examination of wear particles.	For suspected cases of abnormal wear.
Dew Point Measurement	Trending	Internal corrosion of system components (particularly HP air).	When system internals are open and available for inspection.
Nonintrusive Flow Measurement	Trending	Reduced flow through heat exchanger due to fouling.	On condition where heat exchanger fouling, not pump condition, is suspected cause.

Table F-13. Correlation of Trace Element Sensing with Other Technologies

Technology	Correlation	Indication	When Used
Acoustic Leak Detection	Time coincident	Identifies location of leak requiring repair. Characteristic sonic or ultrasonic signature.	On condition to confirm and locate leak.
Thermal imaging	Time coincident	Identifies location of leak requiring repair. "Cool" spots indicate condenser leaks.	On condition to confirm and locate leak.
Lubricant Wear Particle Analysis	Time coincident Trending	Trace elements exposed by wear.	Continuously monitor and confirm particle presence.

Table F-14. Correlation of Ultrasonic Imaging with Other Technologies

Technology	Correlation	Indication	When Used
Acoustic emission	Trending	Metal fatigue/intergranular stress corrosion cracking detectable in large metal vessels using ultrasonic imaging.	Confirms whether or not acoustic emission indications of metal lattice breakdown are valid.
Trace Element Sensing	Time coincident	Presence and concentration of trace element nuclides indicates erosion/corrosion induced wall thinning.	To confirm and measure wall thinning.
In Service Stress/Strain, Torque Measurement	Trending	Monitored stress exceeds yield point of monitored component.	To confirm whether actual damage in the form of cracking or thinning has occurred.
Radiography	Trending	Condition of objects being inspected for erosion, corrosion, cracking or exfoliation.	When the item being inspected has a surface subject to wall thinning or an internal volume subject to cracking.

Table F-15. Correlation of Radiography with Other Technologies

Technology	Correlation	Indication	When Used
Acoustic Emission	Trending	Metal fatigue/intergranular stress corrosion cracking detectable in large metal vessels using ultrasonic imaging.	Confirms whether or not acoustic emission indications of metal lattice breakdown are valid.
Trace Element Sensing	Time coincident	Presence and concentration of trace element nuclides indicates erosion/corrosion induced wall thinning.	To confirm and measure wall thinning.
In Service Stress/Strain, Torque Measurement	Trending	Abnormal strain coincident with indication of a strain-related defect.	To confirm whether actual damage in the form of cracking or thinning has occurred.
Ultrasonic imaging	Trending	Condition of objects whose near-surface volume can be scanned.	Where confirmation of a defect is required before opening for repair.

Table F-16. Correlation of Stress-Strain Measurement with Other Technologies

Technology	Correlation	Indication	When Used
Thermal Analysis	Time coincident	Relationship between temperature, temperature cycles and strain.	When needed to understand the relationships to devise better control measures.
Acoustic Emission (Fatigue Monitoring)	Time coincident	Ultrasonic noise produced as a result of existing crack cleaving. Determining crack location possible.	Pressure flasks and tanks.

Table F-17. Correlation of Acoustic Emission with Other Technologies

Technology	Correlation	Indication	When Used
Dynamic Radiography	Trending	Cracking in heavy metal weld joints.	In conjunction with code requirements for periodic (10 year) inspection or after a rise in acoustic emission events in a specific region which may indicate developing cracks.
In Service Stress/Strain, Torque Measurement	Time coincident	High levels of strain coincident or distortion evident from other methods.	To monitor pressure vessel or heavy section weld deterioration during hydro test or other high stress event.
Ultrasonic Imaging	Trending	Flaw detection and mapping.	In conjunction with code requirements for periodic (10 year) inspection or after a rise in acoustic emission events in a specific region.

Table F-18. Correlation of Ultrasonic, Eddy Current, and Photonic Position Sensors with Other Technologies

Technology	Correlation	Indication	When Used
Lubricant Wear Particle Analysis	Trending Time coincident	Confirmation of bearing wear.	On condition when position indicator shows bearing wear.
Thermal analysis	Time coincident	Confirmation of bearing wear.	On condition when position indicator shows wear.
Vibration analysis	Time coincident	Confirmation of shaft misalignment.	On condition when position indicator shows movement or wear.
Advanced Filtration/Debris Analysis	Trending	Confirmation of bearing wear.	On condition when position indicator shows movement or wear.

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APPENDIX G: ALIGNMENT STANDARD[3]

G.1 FOREWORD

The Laser Alignment Specification for New and Rebuilt Machinery and Equipment provides engineering performance guidelines for use by engineering, maintenance and design personnel as well as machinery and equipment builders during the design and building of new equipment and the rebuild of existing equipment. This standard helps to accomplish the following:

- Allow verification of machine productivity and machine life.
- Allow identification of unique errors in machine motions and structure.

[3] Acknowledgments: We wish to thank General Motors for the free use of their alignment and vibration specifications, which are included in this document. This document may be copied in whole or in part for the use of providing standards for maintainability of equipment.

G.2 TABLE OF CONTENTS

G.3 LIST OF FIGURES AND TABLES

1.0 PURPOSE

The purpose of this specification is to ensure that provisions for laser alignment are designed into all new and rebuilt machine.

2.0 SCOPE

This document addresses the use of laser alignment systems for Shaft Alignment.

3.0 COUPLED SHAFTS LASER ALIGNMENT

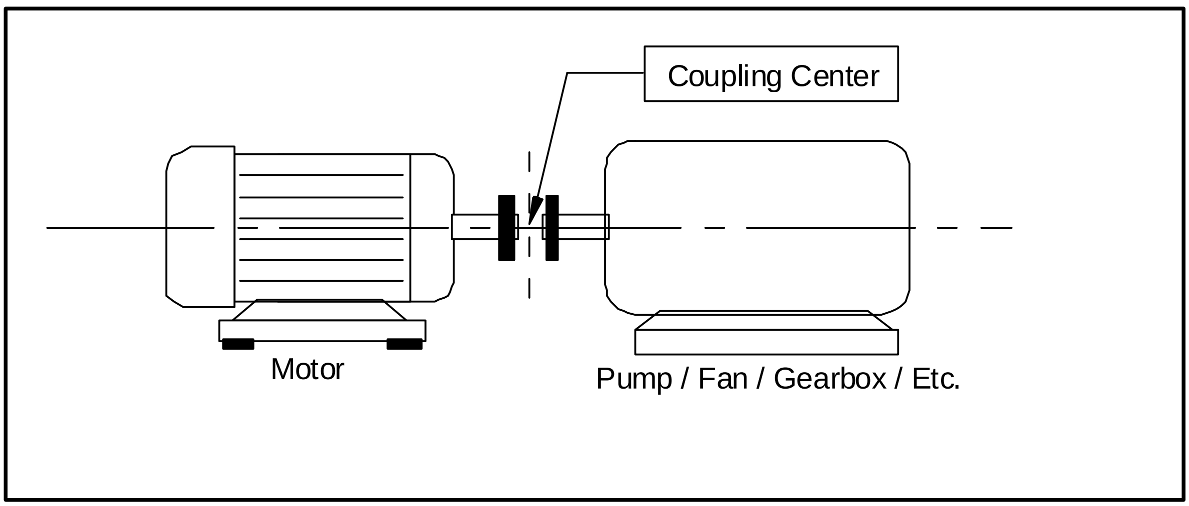
3.1 COUPLED SHAFT ALIGNMENT REQUIREMENT

NASA should require laser alignment on all shaft coupled machines to maximize part quality and productivity, and to eliminate premature machine failure due to misalignment.

3.2 COUPLED SHAFTS ALIGNMENT

Coupled shaft alignment is the positioning of two or more machines so that the rotational centerlines of their shafts are collinear at the coupling center under operating conditions.

Figure G-1. Coupled Shafts Alignment



3.3 LASER SHAFT ALIGNMENT SYSTEM REQUIREMENTS

The Laser Alignment System used for Coupled Shafts Alignment shall use either a combined laser emitter and laser target detector unit or separate units for its laser emitter and laser target detector.

3.4 SHAFT ALIGNMENT

All shaft-to-shaft centerline alignments shall be within the tolerances specified in Table 1 unless more precise tolerances are specified by the machine manufacturer or by the purchasing engineer for special applications.

Table G-1. Coupled Shaft Alignment Tolerance Values

	RPM	TOLERANCE SPECIFICATION
Soft Foot	ALL	<0.002 inch (0.0508 mm) at each foot

	RPM	HORIZONTAL & VERTICAL PARALLEL OFFSET	ANGULARITY/GAP Inch/10 inch (mm/254 mm) Coupling Diameter
Short Couplings			
	<1000	0.005 in (1.2700 mm)	0.015 in (0.3810 mm)
	1200	0.004 in (1.0160 mm)	0.010 in (0.2540 mm)
	1800	0.003 in (0.7620 mm)	0.005 in (0.1270 mm)
	3600	0.002 in (0.5080 mm)	0.003 in (0.0762 mm)
	7200	0.001 in (0.2540 mm)	0.0025 in (0.0635 mm)

		HORIZONTAL & VERTICAL PARALLEL OFFSET PER INCH (25.4 mm) OF SPACER LENGTH
Couplings		
With	<1000	0.0020 in (0.0508 mm)
Spacers	1200	0.0015 in (0.0381 mm)
	1800	0.0010 in (0.0254 mm)
	3600	0.0005 in (0.0127 mm)
	7200	0.0003 in (0.0076 mm)

3.4.1 Jackshifts

- Below "critical speed" of Jackshaft
- Short coupling tolerances apply to each coupling of the jackshaft.
- Above "critical speed" of Jackshaft
- Short coupling tolerances apply relative to the centerlines of the two machines.

3.4.2. The Tolerances specified in Table 1 are the maximum allowable deviations from Zero-Zero Specifications or ALIGNMENT TARGET SPECIFICATIONS (i.e. an intention targeted offset and/or angularity).

3.4.3 Acknowledging that machines often move after start-up due to Thermal Growth, dynamic load shifts, etc., the alignment parameters shall be measured and adjusted for operating conditions.

3.5 COUPLED SHAFTS ALIGNMENT VERIFICATION

3.5.1 Laser alignment will be performed at the purchaser's facility on all shaft coupled machines during installation of the equipment.

3.5.2 When verifying the alignment of coupled shafts the contractor must document and provide the following data for each set of coupled shafts:

- Alignment tolerances used.
- Soft Foot
- Vertical Angularity (Pitch) at the Coupling Point. (Refer to Figure 2.)
- Vertical Offset at the coupling point.
- Horizontal angularity (Yaw) at the coupling point.
- Horizontal offset at the coupling point.

3.5.3 This information shall be provided to the purchaser at the time of functional check out.

3.6 MACHINE BASES

3.6.1 Machine Base Construction

a. A solid and rigid machine base is required to achieve and maintain shaft alignment.

b. Where bases are constructed using concrete or grouts final shaft alignment shall not be conducted until ample curing time has taken place. (A minimum of Thirty days is recommended)

c. Where the machine foundation installation specification does not require a concrete or grout base or the installation schedule does not permit the proper cure time for the concrete/grout, refer to Figures 3a and 3b for suggested alternate machine base constructions.

d. Where corrosion is or may be a problem the base must be fabricated of corrosive resistant materials.

e. Where the machine base is constructed from commercially available steel or castings:

f. Use H, M, I, square, tube, and bar shapes with a minimum 0.5 inch (1.27 cm) thickness.

g. For machine bases consisting of a single steel plate, plate thickness must equal or exceed the thickness of the machine foot, but be no less than 1.0 inch (2.54 cm). The plate surface that the driver and driven machines will be bolted to must be machine ground and of sufficient size to accommodate the machine components, push/pull blocks and/or jack screws. Jackscrews must not rest on any rounded edges.

h. Use of channel or angle stock is not recommended. Where use is necessary, the channel or angle stock must be reinforced using square bar or plate meeting the preceding thickness requirements.

i. After all welding and machining is completed, stress relieves the entire base.

3.6.2. Foot Center Lines

The stiffness of the machine base shall be sufficient that no foot centerline shall deform or deflect more that .001” (.0254 mm) over the operating range from alignment conditions to full load conditions.

3.6.3 Joining Shapes Together

When joining shapes together they shall conform to the appropriate applicable A.S.M.E. standard(s) for welding.

3.6.4 Requirements for Machine Pads or Flats

After all welding and machining has been completed and the base has been stress relieved, the surface of all pads or flats for each machine to be installed on the base must be co-planar, within .001 inch (0.0254 mm). (Refer to figures 3a and 3b.)

3.6.5 Machine Base Support

The feet of the driver and driven machines must not overhang the machine base.

3.7 JACKBOLTS

Jackbolts shall be located at the front and rear feet of the movable machine for horizontal alignment positioning. (This requirement also applies to vertically mounted units and vertically mounted flanged units). Jackbolts shall be parallel to the flat/pad surface and align on the center line formed by the hold down bolts in the cross machine direction. Ample room shall be left for removal and insertion of shims used in the vertical alignment of the coupled machines.

3.8 HOLD-DOWN BOLTS

The use of hold down bolts is the preferred method of fastening components to the base. Hold-down bolts shall meet the following specifications:

- Hold-down bolts for both the driver and the driven machine(s) (in pairs or in trains) shall be positioned (spotted) after the machine's shafts have been aligned.
- Hold-down bolts shall be centered in the hole of the machine foot.
- Hold-down bolts shall be the preferred method of fastening machines to the base.
- Hold-down bolts shall not be undercut ("Chicagoed") to achieve HORIZONTAL adjustment.

3.9 PIPING

Piping must be fitted, supported, and sufficiently flexible such that soft foot due to movement caused by tightening pipe flanges doesn't exceed .002" (.051 mm). Piping must not restrict the minimum 180 degree rotation requirement of the laser alignment system.

3.10 SHIMS

Shims shall meet the following specifications:

- Commercially die-cut.
- Made of corrosion and crush resistant stainless steel, which is dimensionally stable when subjected to high compression over long periods of time.
- Consistent over the whole shim area, without seams or folds from bending.
- Clean, free from burrs, bumps, nicks and dents of any kind.
- Size numbers or trademarks etched into the shim, not printed or stamped.
- The smallest commercial shim that will fit around the hold down bolts without binding shall be used.
- The overall shim pack shall not exceed a total of three (3) shims.
- Lie on bare metal, not paint or other coatings.

3.11 MACHINE VERTICAL MOBILITY

All machines shall be installed with a minimum of .125 inch (3.0 mm) dimensionally stable shims under each surface mounting point for vertical mobility.

3.12 COUPLING PLAY/BACKLASH

OEM's must use only the couplings specified by the Government unless otherwise agreed upon by the purchaser. During the alignment process coupling play or backlash must be eliminated to accomplish a precision shaft alignment.

3.13 AXIAL SHAFT PLAY

Axial shaft play or end-play must be no greater than .125 inch (3.175 mm). Accommodation of end movement must be done without inducing abnormal loads in the connecting equipment.

Figure G-2. Offset and Angular

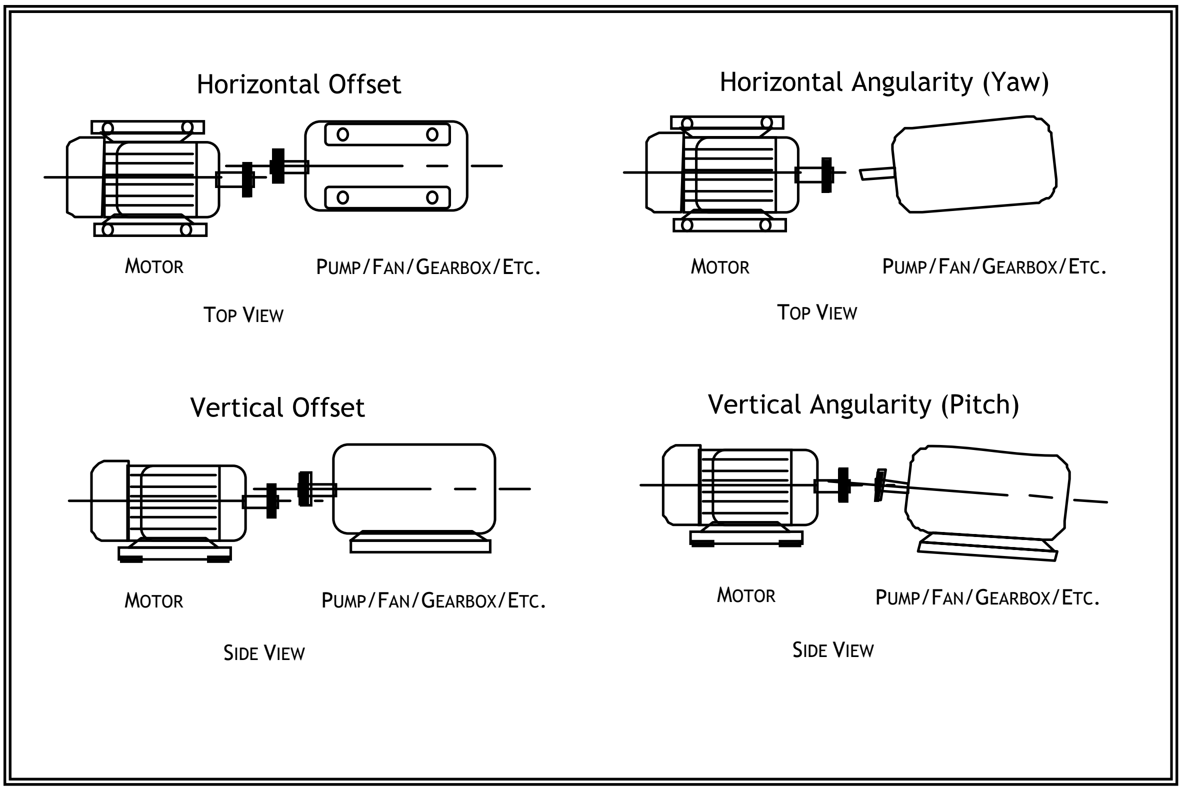
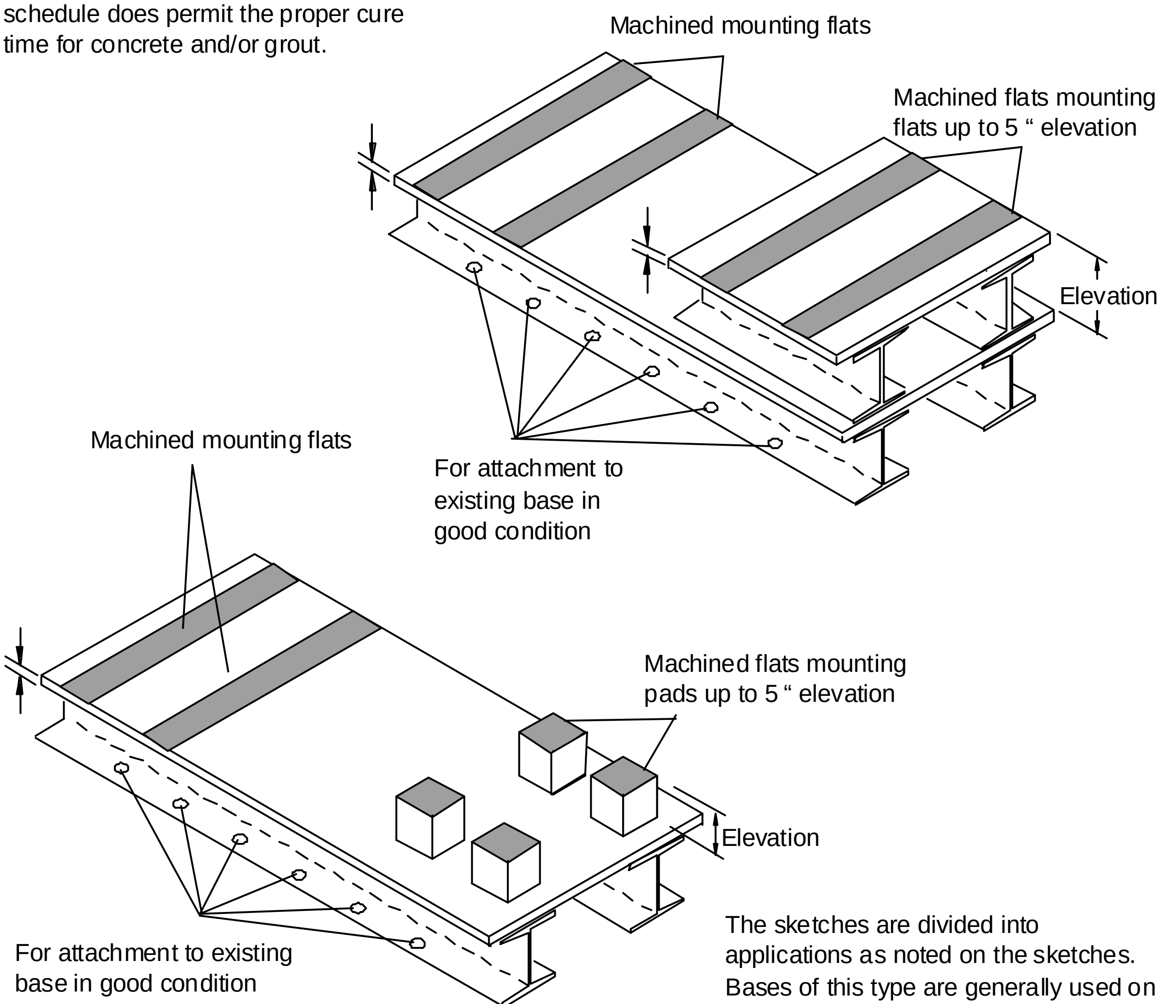


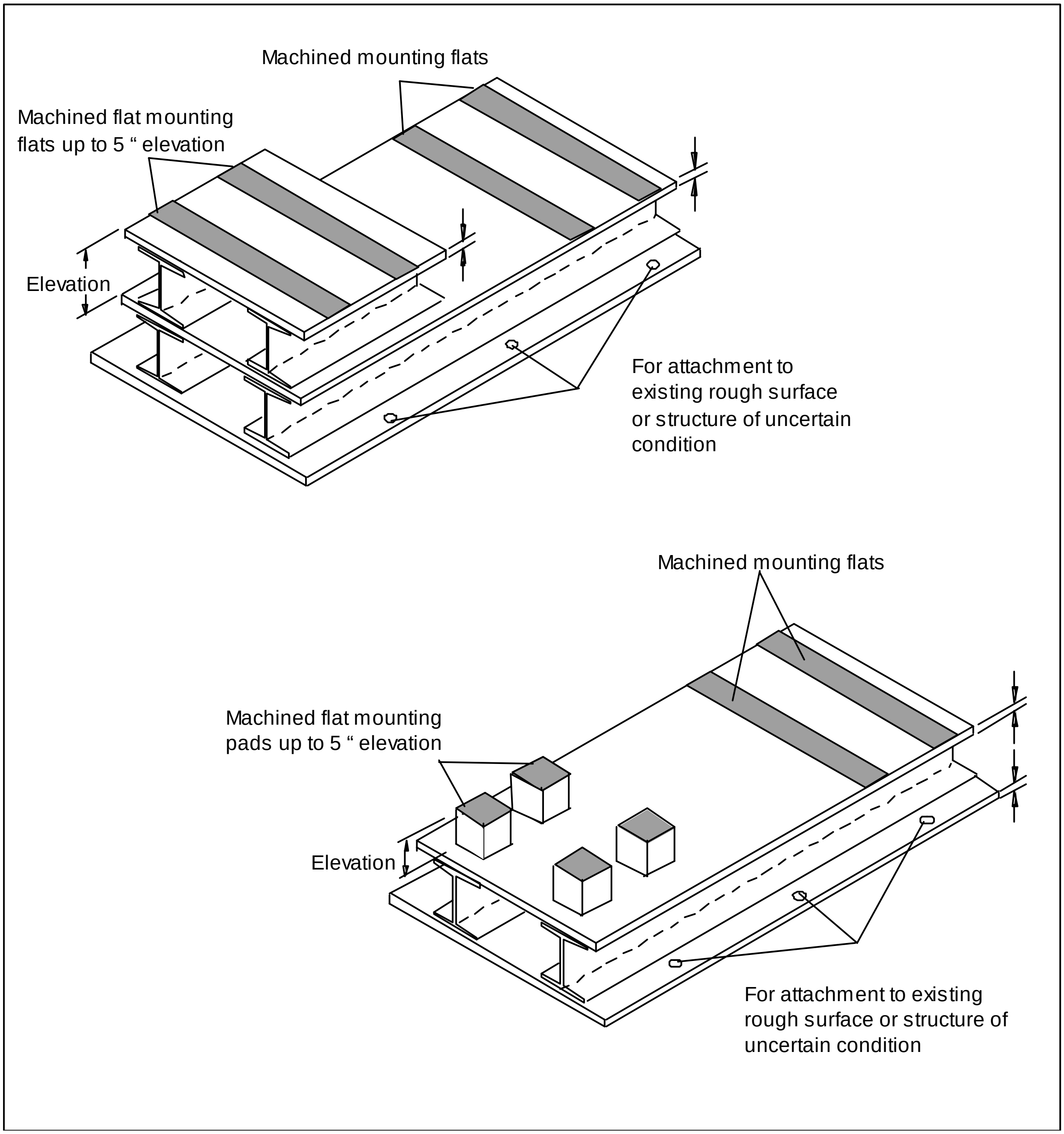
Figure G-3a. Suggested Baseplate Assemblies

The following sketches are provided for a general guideline and are not construction drawings. These bases are intended for situations where the schedule does permit the proper cure time for concrete and/or grout.



The sketches are divided into applications as noted on the sketches. Bases of this type are generally used on equipment in the range of 10 hp to 500 hp. Depending upon the speed and size, between 500 hp and 1000hp it becomes more cost effective to use the flanges of I-beams mounted cross-frame to support the machine instead of using plate.

Figure G-3b. Suggested Baseplate Assemblies



4.0 ALIGNMENT OF BELT DRIVEN MACHINES

4.1 MOTOR BASES

4.1.1 Motors will be provided with adjustable motor bases unless otherwise specified.

4.1.2 Motors over 5600 watts of power will be provided with adjustable, pivoted motor bases.

4.1.3 Base will have enough adjustment to allow belt replacement without stretching the new belts.

4.1.4 Adjustment method will be by use of two adjusting bolts.

4.2 RUNOUT

4.2.1 After sheaves are installed on the motor and driven shafts, the sheaves will be checked to ensure that they are true on the shaft.

4.2.2. Runout on the sheaves will be checked with a dial indicator

4.2.3. Sheave runout shall not exceed 0.0580 mm (0.002 in.)

4.3 SHEAVE ALIGNMENT

4.3.1 Unless otherwise specified, drive and driven sheaves will be aligned by the four-point method.

4.3.2 If the sheave web thickness is not the same on the drive and driven sheave, shims of the appropriate thickness will be used on the narrower sheave for the alignment. The thickness of the shims will be recorded and supplied with the machine information

5.0 GLOSSARY

Accessible: The ability to reach and adjust the aligning feature. Consideration should be given to confined space restrictions, removing guards, bushing plates, hydraulic lines, lubrication lines, electric lines, etc.

Alignment Target Specifications: Desired intentional offset and angularity at coupling center to compensate for thermal growth and/or dynamic loads. Most properly specified as an *Offset*, and an angle in two perpendicular planes, horizontal and vertical.

Angular Error: A misalignment condition characterized by the angular error between the desired centerline and the actual centerline. This misalignment condition may exist in planes both horizontal and vertical to the axis of rotation. (Reference Figure 2)

Angularity: The angle between the rotational centerlines of two shafts. Angularity is a "slope" expressed in terms of a rise (millimeters or thousandths of an inch) over a run (meter or inches). (Reference Figure 2.)

A.S.M.E.: American Society of Mechanical Engineers, 345 East 47th Street, New York, NY 1017, 212-705-7722.

Axial Play, Axial Float, End Float: Shaft axial movement along its centerline caused by axial forces, thermal expansion or contraction, and permitted by journal bearings, sleeve bearings and/or looseness.

Base Plate: The surface, often made of steel plate or cast iron, to which the feet of a machine are attached. (Reference Figure 3a and 3b.)

Co-Linear: Co-linear means two lines that are positioned as if they were one line. Co-linear as used in alignment means two or more centerlines of rotation with no offset or angularity between them. Two or more lines are co-linear when there is no offset or angularity between them (i.e. they follow the same path).

Coplanar: The condition of two or more surfaces having all elements in one plane. (per ANSI Y14.5)

Coupling Point: The phrase "Coupling Point" in the definition of "Shaft Alignment" is an acknowledgment that vibration due to misalignment originates at the point of power transmission, the coupling. The shafts are being aligned and the coupling center is just the measuring point.

Full Bearing Fitting Spacer Block: A single spacer block used for aligning the machine tool in the vertical plane.

Flatness: The condition of a surface having all elements in one plane. (Per ANSI Y 14.5.) (Note: As used in this specification, a flat is a small surface flush with or cut into a *Base Plate,* machined flat, and co-planar with the other flats in the base plate. The flats support the Shims and/or feet of the machine to be installed. A pad is a small block of metal that serves to elevate the feet of the machine above the surface of the base plate. Pads are commonly used compensate for differences in machine center line heights, and for increased corrosion resistance by raising the machine feet out of any possible standing fluids. Pads and flats have holes drilled and tapped in their centers to accept hold down bolts.)

Horizontal: Parallel to the mounting surface.

Jackbolts, Jackscrews: Positioning bolts on the machine base which are located at, each foot of the machine and are used to adjust the position of the machines.

Level: Parallel to a reference plane or a reference line established by a laser.

Machine: The total entity made up of individual machine components such as motors, pumps, spindles, fixtures, etc. Also reference *Machine Component.*

Machine Base: The structure that supports the machine or machine components under consideration.

Machine Component: An individual unit such as a motor, pump, spindle, fixture, etc. often referred to as a machine in its own context.

Machine Dependent: A condition that is dependent on the machining operation and the design requirement of the part being machined.

N.I.S.T.: National Institute of Standards and Technology, Building 304 Room 139, Gaithersburg, MD 20899, 301-975-3503.

Offset: The distance (in thousands of an inch or in millimeters) between the rotational centerlines of two parallel shafts. (Reference Figure 1).

Pitch: An angular misalignment in the vertical plane. (ANSI/ASME b5.54-1991)

Position Error (Centerline/Offset Misalignment): A misalignment condition that exist when the shaft centerline is parallel but not in line with (not coincidental) with the desired alignment centerline. (Reference Figure 1.)

Qualifying Level Points: Qualified leveling points are locations that have their heights defined and must be in same plane. That plane must be parallel to the mounting surfaces of the slide assembly.

Repeatability: The consistency of readings and results between consecutive sets of measurements.

Shaft Alignment: Positioning two or more machines (e.g. a motor driving a hydraulic pump(s), etc.) so that the rotational centerlines of their shafts are collinear at the coupling center under operating conditions. (Reference Figure 2.)

Soft Foot: A condition that exists when the bottom of all of the feet of the machinery components are not on the same plane (can be compared to a chair with one short leg). Soft foot is present if the machine frame distorts when a foot bolt is loosened or tightened. It must be corrected before the machine is actually aligned.

Parallel Soft Foot: A parallel gap between the machine foot and its support surface.

Angular Soft Foot: An angled gap between the machine foot and its support surface.

Induced Soft Foot: A type of soft foot that is caused by external forces, (pipe strain, coupling strain, etc.,) acting on a machine independent of the foot to base plate connection.

"Squishy" Soft Foot: A type of soft foot characterized by material (such as Shims, paint, rust, grease, oil, dirt, etc.) acting like a spring between the underside of the machine foot and the base plate contact area.

Spacer Blocks: See Full Bearing Fitting Spacer Block.

Stress Free Condition: The condition that exists when there are no forces acting on the structure of a machine, machine component, or machine base that would cause distortion in the structure such as bending, twist, etc.

Thermal Effects (Growth or Shrinkage): This term is used to describe displacement of shaft axes due to machinery temperature changes (or dynamic loading effects) during start-up.

Tolerance, Deadband, Window, or Envelope: An area where all misalignment forces sum to a negligible amount and no further improvement in alignment will reduce significantly the vibration of the machine or improve efficiency.

Tolerance Values: Maximum allowable deviation from the desired values, whether such values are zero or non-zero.

Vertical: Perpendicular to the horizontal plane.

Yaw Misalignment: An angular misalignment in the horizontal plane.

APPENDIX H: BALANCE STANDARD[4]

H.1 FOREWORD

It is recommended that Balance Certification of all new and rebuilt machinery and equipment be a part of implementation of Reliability Centered Maintenance. Precision balance and certification, as a part of machine performance evaluation will:

- Maximize part quality, machine productivity and machine life;
- Minimize machine installation and set-up time; and
- Allow verification of machine performance and "health" throughout the machine's life.

The BALANCE STANDARD FOR NEW AND REBUILT MACHINERY AND EQUIPMENT provides engineering performance guidelines for use by Facilities Maintenance and Operations as well as machinery and equipment builders during the design, development, and building of new equipment and the rebuild of existing equipment. The balance quality, specified by the user and acknowledged by the contractor, establishes a common goal of acceptability by both parties. Such quality also enables contractors to provide evidence of the superiority and build integrity of their product.

[4] Acknowledgments: We wish to thank General Motors for the free use of their balance, alignment and vibration specifications, which are included in this document. This document may be copied in whole or in part for the use of providing standards for maintainability of equipment.

H.2 TABLE OF CONTENTS

H.3 TABLES AND FIGURES

1.0 PURPOSE

The purpose of this standard is to:

- Reduce operating costs by establishing acceptable balance grades for new and rebuilt rotating machinery and equipment.
- Improve the life and performance of rotating machines and equipment purchased.
- Provide a uniform procedure for evaluating the balance characteristics of a machine for certification and acceptance.

2.0 SCOPE

This standard establishes acceptable quality for balance of new and rebuilt rotating machinery and equipment purchased.

3.0 BALANCE REQUIREMENTS

3.1 DEFAULT BALANCE SPECIFICATION

If no other limit is specified, the vibration criteria listed in Table 1 will be used for acceptability of the machine in question. The vibration criteria are for the vibration amplitude at the fundamental rotational frequency or one times running speed (1X). This is a narrowband limit. An overall value is not acceptable.

Table H-1. Default Balance Specifications

Nominal Shaft Speed (RPM)	Maximum Vibration (in/sec, Peak)	Maximum Displacement (mils, Peak-to-Peak)
900	0.02	0.425
1200	0.026	0.425
1800	0.04	0.425
3600	0.04	0.212

3.2 BALANCE CALCULATION

Table 2 provides the ISO1940/1-1986 balance quality grades for various groups of representative rigid rotors. The RCM Manual contains more detailed information and the complete ISO 1940/1 –1986 table.

Table H-2. Balance Quality Grades for Various Groups of Representative Rigid Rotors (ISO 1940/1-1986)

Balance Quality Grade	Product of the Relationship $(e_{per} \times \omega)^{1,2}$ mm/s	Rotor Types–General Examples
G100	100	Crankshaft/drives of rigidly mounted fast diesel engines with six or more cylinders[4] Complete engines (gas or diesel) for cars, trucks, and locomotives[5]
G40	40	Car wheels, wheel rims, wheel sets, drive shafts Crankshaft/drives of elastically mounted fast four-cycle engines (gas or diesel) with six or more cylinders Crankshaft/drives of engines of cars, trucks, and locomotives
G16	16	Drive shafts (propeller shafts, cardan shafts) with special requirements Parts of crushing machines and parts of agricultural machinery Individual components of engines (gas or diesel) for cars, trucks and locomotives Crankshaft/drives of engines with six or more cylinders under special requirements

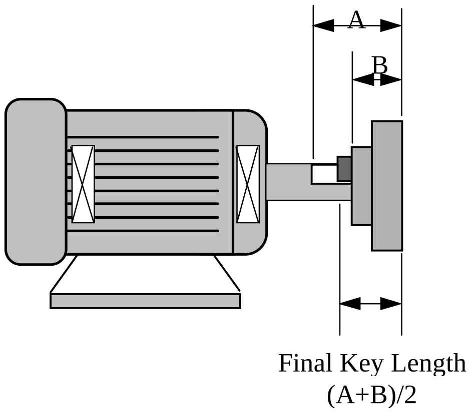
Table H-2. Balance Quality Grades for Various Groups of Representative Rigid Rotors (ISO 1940/1-1986) (Continued)

Balance Quality Grade	Product of the Relationship $(e_{per} \times \omega)^{1,2}$ mm/s	Rotor Types–General Examples
G6.3	6.3	Parts of process plant machines Centrifuge drums, fans, flywheels, pump impellers, general machinery parts Medium and large electric armatures (of electric motors having at least 80 mm shaft height) without special requirements Small electric armatures, often mass produced, in vibration insensitive applications and/or with vibration isolating mountings Individual components of engines under special requirements
G2.5	2.5	Rigid turbo-generator rotors, turbo-compressors Medium and large electric armatures with special requirements Small electric armatures not qualifying for one or both of the conditions specified for small electric armatures of balance quality grade G6.3 Turbine-driven pumps
G1	1	Grinding-machines drives Small electric armatures with special requirements
G0.4	0.4	Spindles, disc, and armatures of precision grinders; gyroscopes

3.3 STANDARD KEY

For rotating machines and machine components with a keyed shaft, balancing will achieved using a standard one-half key in the key seat in accordance with ISO 8821-1989. If a "full key", corresponding to the half key used for balancing, is not provided with the rotating machine, a tag, as shown in Figure 1, will be attached to the machine indicating the dimension of the key used to perform the balance test.

Figure 1. Balance Test Key Dimension



A = Key length as used for balancing this rotor (usually in the form of a "half depth"

B = Key length as used for balancing the attached rotor (such as coupling half, pulley, fan, etc.) This is determined by measuring the attached. rotors keyway length at its hub.

3.4 BALANCE WEIGHTS

Permanently attached balancing weighs must be secured by welding, bolting, pop-riveted, or of a "clip-on" design.

- If bolted, a hardened bolt must be used in conjunction with a mechanical locking device (e.g. lock washer or lock nut).
- "Clip-on" balancing weights can only be used on centrifugal type fans and must be located and attached on the ID pitch of the blades such that the rotational motion of the fan creates a positive seating of the "clip-on" weight against the fan blade.
- Balancing weights and method of attachment must be stable at equipment operating temperature, and of a material compatible with the parent material of the fan to which the balancing weight is attached. Note: the use of stick on lead weights is not acceptable.
- Any parent metal removed to achieve dynamic or static balance shall be drilled out in a manner which will maintain the structural integrity of the rotor or sheave.
- Access to any fan rotor for field balancing shall be designed in to the system. Note: It is recommended that components (rotor, shafts, sheaves, etc.) be balanced individually and then trim balanced as a totally assembly.

4.0 MACHINE QUOTATION, CERTIFICATION, AND ACCEPTANCE

4.1 QUOTATION

The Quotation shall specify that the equipment will meet the applicable balance quality of this Specification - or the balance quality (if different from Specification B1.0 Latest Version) specified by the purchaser in the "Request for Quote."

The Quotation shall state the applicable specification balance quality being quoted.

Any additional costs required to meet the specification quality shall be grouped in a separate section of the Quotation and titled "BALANCE QUALITY". Costs must be itemized and sufficiently detailed to permit a complete evaluation by the Purchaser.

4.2 MEASUREMENT REQUIREMENTS FOR MACHINE CERTIFICATION

Balance measurements shall:

- Be the responsibility of the supplier unless specified otherwise by the purchaser.
- Be performed by technically qualified person who is trained and experienced in machinery balancing. The technical qualifications of the person doing the balance certification shall be submitted as a part of the machine balance certification data.
- Be submitted to the maintenance organization or other authorized representative before acceptance of the machinery or equipment being purchased will be authorized.
- Balance quality for machine certification shall be measured prior to "run-off' at the vendor's facility. Where it is impractical to set-up and test a complete machine at the vendor's facility, arrangements shall be made to perform the test at the purchaser's facility. Under this circumstance, shipment of the equipment does not relieve the vendor of the responsibility for meeting the specified balance quality.
- The purchaser shall have the option to verify balance quality of equipment during machine "run-off' at the vendor's test site prior to shipment - or at the plant site per Section 4.2.3 - prior to final acceptance authorization.

4.3 ACCEPTANCE

Authorization for machine/equipment acceptance based on the balance quality of this specification requires signature by the purchaser's authorized representative. A copy of the acceptance must be sent to the Purchasing department before final acceptance is authorized.

5.0 GLOSSARY

Acceleration: The time rate of change of velocity. Typical units are ft/sec^2 and g's (1 g = 32.17 ft/sec^2 = 386 in/sec^2 = 9.81 $meter/sec^2$). Acceleration measurements are made with accelerometers. (Note: By international agreement, the value 9.80665 m/s^2 = 980,665 cm/s^2 = 386.089 in/s^2 = 32.174 ft/s^2 has been chosen as the standard acceleration due to gravity (g). ISO 2041 (1990))

Accessible: The ability to reach and adjust the aligning feature. Consideration should be given to confined space restrictions, removing guards, bushing plates, hydraulic lines, lubrication lines, electric lines etc.

Amplitude: A measure of the severity of vibration. Amplitude is expressed in terms of peak-to-peak, zero-to-peak (peak), or rms. For pure sine waves only:

- Peak (P) = 1.414 x RMS
- Peak-to-Peak = 2 x Zero-to-Peak (Peak)

Balance: When the mass centerline and rotational centerline of a rotor are coincident.

Balancing: A procedure for adjusting the radial mass distribution of a rotor by adding or removing weight, so that the mass centerline approaches the rotor geometric centerline achieving less vibration amplitude at rotational speed.

Calibration: A test to verify the accuracy of measurement instruments.

Complete Machine: A complete machine is defined as the entire assembly of components, sub-components, and structure, which is purchased to perform a specific task(s). On a Complete Machine Assembly with all individual components operating in their normal operating condition, mode, and sequence, the Component Balance Quality for the complete machine acceptance are the same as when the component is tested individually.

Displacement: The distance traveled by a vibrating object. For purposes of this document, displacement represents the total distance traveled by a vibrating part or surface from the maximum position of travel in one direction to the maximum position of travel in the opposite direction (Peak-to-Peak) and is measured in the unit mil (1 mil = 0.001 inch).

Field Balancing: The process of balancing a rotor in its own bearings and supporting structure rather than in a balancing machine.

Flexible Rotor: A rotor that deforms significantly at running speed. This term is used for rotors that operate close to or above their first critical speed. A rotor is considered flexible when its speed is more than 75 percent of its lowest natural frequency in bending.

Frequency: The repetition rate of a periodic event, usually expressed in cycles per second (Hertz -abr. HZ), cycles per minute (CPM), or multiples of rotational speed (Orders). Orders are commonly referred to as IX for rotational speed, 2X for twice rotational speed, etc. *Frequency* is the reciprocal of the *Period*. (Note: Vibration frequencies are expressed in Hertz (cycle per sec) or CPM (cycle per minute). Rotational speed (Running Speed) is expressed in RPM (Revolutions per minute).)

Hertz (Hz): The unit of frequency represented by cycles per second.

Imbalance: Unequal radial weight distribution of a rotor system; a shaft condition such that the mass and shaft geometric centerlines do not coincide.

Large Apparatus Ac/Dc Motors: Reference NEMA Publication No. MG 1, *Motors and Generators*, Section III.

Large Machines: Part 20. *Induction Machines*, Part 21. *Synchronous Motors*, and Part 23. *DC Motors*.

Level: Parallel to a reference plane or a reference line established by a laser.

Machine: The total entity made up of individual machine components such as motors, pumps, spindles, fixtures, etc. Also reference *Machine Component*.

Machine Component: An individual unit such as a motor, pump, spindle, fixture, etc. often referred to as a machine in its own context.

Micrometer (Micron): One millionth (0.000001) of a meter. (1 micron = 1 x 10^{-6} meters = 0.04 mils.)

Mil: One thousandth (0.001) of an inch. (1 mil = 25.4 microns.)

N.I.S.T.: National Institute of Standards and Technology, Gaithersburg, MD 20899, 301-975-3503.

Order: A unit of frequency unique to rotating machinery where the first order is equal to rotational speed. See *Frequency*

Peak: Refers to the maximum of the units being measured, i.e., peak velocity, peak acceleration, peak displacement.

Peak-To-Peak: Refers to the displacement from one travel extreme to the other travel extreme. In English units, this is measured in mils (.001 inch) and in metric units it is expressed in micro-meter μM (.000001 meters).

Rigid Rotor: A rotor that does not deform significantly at running speed. A rotor whose parts do not take up motion relative to each other, i.e., all points move in the same direction at the same instant of time. A rotor is considered rigid when its speed is less than 75 percent of its lowest natural frequency in bending.

RMS (Root mean square): Equal to 0.707 times the peak of a sinusoidal signal.

Rotational Speed: The number of times an object completes one complete revolution per unit of time, e.g., 1800 RPM.

Small (Fractional) and Medium (Integral) Horsepower Ac/Dc Motors: Reference NEMA Publication No. MG 1, Section II *Small (Fractional) And Medium (Integral) Machi*nes. Part 12. *Tests and Performance - AC and DC Motors*.

Tolerance Values: Maximum allowable deviation from the desired values, whether such values are zero or non-zero.

Unbalance: See IMBALANCE.

Velocity: The time rate of change of displacement with respect to some reference position. For purposes of this document, velocity is measured in the units Inch per second-Peak.

APPENDIX I: MAINTENANCE PROCEDURES

This Appendix provides Maintenance Procedure Templates (MPT). The MPTs have been developed to provide a sample source of time/cycle based maintenance actions, test procedures and information. A section at the end of the MPT, identified as *Engineers Notes*, provides technical information that may be useful when developing site-specific procedures.

The MPTs are based on sample procedures provided by Government and private industry. The objective of the MPT is to provide instructions without becoming overly detailed. Simple steps, that provide little value for the typical work force, have not been included. In some high-risk industry, like nuclear power, maintenance procedures are extremely detailed and often do not allow even minor deviations. That is not the basis for the NASA MPTs.

I.1 THE MAINTENANCE PROCEDURE TEMPLATE

The procedure layout is such that all actions are taken in sequence. A technician performing the procedure should arrive at the work site with all necessary tools and materials (including reference material).

The MPT headings are as follows:

- Procedure Number: The number is assigned for use in indexing the procedure. It is expected that NASA sites will change this number if the procedure is incorporated into the site-specific CMMS.

- System Description: This section is text that describes the machine/equipment application.

- Procedure Description: Text that describes the procedure purpose. The body of the procedure is often divided into sub-sections. Each sub-section has a heading and that heading is duplicated in the Procedure Description. This ensures that the entire scope of work is well understood.

- Related Tasks: Identifies other tasks that should be performed. Usually tasks with a shorter periodicity. For example, an annual procedure will identify any semi-annual, quarterly, or monthly procedures to ensure that all work is done during a single visit to the work site.

- Periodicity: Describes how often the procedure is scheduled. NASA sites will want to modify the periodicity code to fit the site. Codes used in the MPTs are:

    - D = Daily
    - W = Weekly
    - M = Monthly
    - Q = Quarterly
    - S = Semi-Annually

- A = Annually

- (Note: Multiples of the above are sometimes used and are identified by a number followed by a letter. For example, 2W indicates that the procedure is scheduled every 2 weeks and 5A indicates that the procedure is scheduled every 5 years.)

- Labor (Hours): This information will usually be two numbers. First is number of people, second is estimated time for each craftsperson. For example: 2-people/2 hrs each. The time estimate is to perform the task. Because each site is different, no time was estimated to get to the job site.

- Special Tools: Identifies tools and test equipment that the technician will need at the job site. Common tools are not usually identified.

- Materials: All materials that will be needed at the job site are listed in this section.

- Reference Data: Identifies information, such as a test procedure, that the craftsperson will need in order to perform the task. This section does not identify reference data that may have been used to develop the procedure. Only that reference data needed to perform the task is listed in this section.

- Warning Summary: A warning is identified in the procedure anytime there is the potential for injury (including toxic release to the environment). This section lists every warning that is part of the procedure. If a warning is used many times in the procedure, it is only listed once in this section.

- Caution Summary: Similar to warning summary. A caution is identified in the procedure anytime there is the potential for damage to the equipment or damage to other installed equipment. (Note: Although not listed in a summary block, the procedure may also contain a note. A note provides relevant information to the person performing the procedure.)

- Preliminary: The first part of the procedure is identified as the preliminary section. This section includes all steps taken before going to the job site, or if at the job site, before starting work on the specified machine. Although there is not a maximum number of preliminary steps, this section is usually less than 10 steps.

- Procedure: The start of the procedure is clearly identified by the title "Procedure." The first step in the procedure is labeled "A" and is a phrase that identifies the work to be accomplished. The next step is labeled "A1" and is an action item. Each subsequent action step is numbered in ascending order, "A2, A3 ..." If the procedure can be broken into discrete sections, there maybe a "B", "C", etc.

- Inspection Data: If data is to be collected, there will usually be an Inspection Data section. The procedure will identify the data and direct where it is to recorded in the Inspection Data section or other location. The Inspection Data section is always located at the end of the Procedure section. A section at the end of the MPT is identified as Engineers Notes. The Engineers Notes provides background information that may be useful when developing site-specific procedures. It is not part of the procedure in that it is not intended to be provided (printed out) for use in the field or entered into the site CMMS. The Engineers Notes are a tool for use in developing site-specific procedures.

Procedure numbers listed below refer to sample procedures in this appendix.

Table I-1: Sample Procedures

Procedure Number	Page #I-	Machine/System	Procedure Summary
PT&I-0001	276	Rotating Machinery	Vibration Data Collection
PT&I-0002	277	Various	Qualitative Infrared Thermography Inspection
PT&I-0003	279	Motor	Test Insulation
PT&I-0004	281	Transformer	Test Insulation
PT&I-0005	284	Circuit Breaker	Test Insulation
PT&I-0006	286	Oil Filled Transformer	Sample and Test Transformer Oil
PT&I-0007	288	Transformer	Power Factor Test
PT&I-0008	292	Electrical Distribution	Power Factor Test
PT&I-0009	295	Bushing	Power Factor Test
E-0001	298	Transformer	Inspect and Clean Transformer
E-0002	300	Battery Bank	Battery Impedance Test
E-0003	302	Uninterruptable Power Supply	Inspect and Test UPS
E-0004	304	Electrical Distribution	Inspect and Clean Electrical Panels
E-0005	306	High/Med Volt Circuit Breaker	Inspect and Test Circuit Breaker
M-0001	309	Air Handler	Inspect and Clean
M-0002	311	Chiller	Inspect and Clean
M-0003	313	Post Indicator Valve	Inspect and Clean
M-0004	314	Hot Water Boiler, Oil/Gas/Comb., 120-500 MBH	Inspect and Clean
M-0005	315	Fan Coil Unit	Inspect and Clean

Table I-1: Sample Procedures (Continued)

Procedure Number	Page #I-	Machine/System	Procedure Summary
M-0006	316	Condensate Return Pump	Inspect and Clean
M-0007	317	Centrifugal Pump w/reduction gear, over 1 HP	Inspect and Clean
M-0008	318	Air Conditioning Split System, DX, air-cooled, over 10 tons	Inspect and Clean
M-0009	319	Air Compressor Reciprocating, over 40 H.P.	Inspect and Clean
M-00010	320	Air ,Cooled Condenser, 26 to 100 tons	Inspect and Clean
M-00011	321	Cooling Tower, Water, 51 to 500 tons	Inspect and Clean
M-00012	322	Heat Pump, Air Cooled, over 5 tons	Inspect and Clean
M-00013	323	Package Unit, Computer Room	Inspect and Clean
M-00014	324	Pump, Air Lift, Well	Inspect and Clean
M-00015	325	Forced Air Heater, Oil/Gas fired, up to 120 MBH	Inspect and Clean
M-00016	326	Valve, Automatic, above 4 inches	Inspect and Clean
M-00017	327	Valve, Butterfly, auto, above 4 inches	Inspect and Clean

Table I-2 is a sample procedure lay out with a combination of description and sample text.

Table I-2: Sample Procedures Layout

Block Title	Text
Procedure Number	PT&I-0003 - This procedure number is assigned by the NASA sites for use in a CMMS and for indexing purposes. The objective of the procedure is to provide instructions without becoming overly detailed.
System Description	Motor - Text that describes the machine/equipment application.
Procedure Description	1. Test Insulation - Text to describe what the procedure does. The body of the procedure is often divided into sub-sections.
	2. Next Procedure - Each sub-section has a heading and that heading is duplicated in the Procedure Description. This ensures that the entire scope of work is well understood.
Related Tasks	E-0009 - Identifies other tasks that should be performed concurrent with this task. Usually tasks with a shorter periodicity. This is an aid to ensuring effective use of time.
Periodicity	A - Code that describes how often the procedure is scheduled. Codes are assigned by site work control and are used by the CMMS. Sample codes are: D = Daily, W = Weekly, M = Monthly, Q = Quarterly, S = Semi-Annually, A = Annually, 2W = every 2 weeks, 5A = every 5 years.
Labor (Hrs)	0.5 - Estimate of number of people, and time for each person, to perform task. If number of people is not specified, assume one person.
Special Tools	Direct Current Insulation Resistance Tester (Megohmmeter, Megger), Thermometer - Identifies special tools and test equipment that will be needed at the job site. Common tools, that the technician normally would carry, are not usually identified.
Materials	Oil Filter, Air Filter, Belt - All replacement parts and materials that will be needed at the job site are listed in this section. The CMMS usually contains detailed part numbers for these items.
Reference Data	OEM Manual, Other Standards, NASA Procedure - Identifies information, such as a test procedure, that the field technician will need in order to perform the task.

Table I-2: Sample Procedures Layout (Continued)

Block Title	Text
Warning Summary	1. Test to ensure all circuits are de-energized. - A warning is identified in the procedure anytime there is the potential for injury (including toxic release to the environment). This section lists every warning that is part of the procedure. 2. Circuit may have dangerous voltage potential following testing. - If the same warning is used many times in the procedure, it is only listed once in this section. If there is more than one warning, they are numbered in this section.
Caution Summary	Protect semi-conductor control devices from potential high voltage. - Similar to warning summary. A caution is identified in the procedure anytime there is the potential for damage to the equipment or damage to other installed equipment.
Reserved	This section is reserved for future use by the Sites.
Preliminary	This section includes all steps taken before going to the job site, or if at the job site, before starting work on the specified machine.
1	Charge batteries and backup batteries. - This section is usually less than 10 steps.
2	Ensure equipment/component identification (name and/or number) is legible and securely affixed to equipment. Repair as required.
Procedure	The start of the procedure is clearly identified by the title “Procedure.”
A	Test Insulation - The first step in the procedure is labeled “A” and is a phrase that identifies the work to be accomplished.
A1	De-energize equipment and tag out in accordance with site safety practices. - The next step is labeled “A1” and is an action item.
A2	Open motor control panels or doors to gain access to circuit to be tested. - Each subsequent action step is numbered in ascending order, “A2, A3, ...”
A3	Perform next step. - Each step begins with an action verb such as Open, Inspect, Test, Perform, etc. This keeps the procedure focused.
WARNING	Test to ensure all circuits are de-energized. - A warning, if needed, comes just before the step where potential for injury exists.

Table I-2: Sample Procedures Layout (Continued)

Block Title	Text
A4	Place thermometer in close ...
CAUTION	Protect semi-conductor control devices from potential high voltage. - A caution, if needed, comes just before the step where potential for equipment damage exists.
A5	Attach ground cable (black cable) from tester to ground.
Note 1	A note can be inserted anywhere in the procedure. If there is more than one Note, they are numbered. The note is information or direction for the technician in the field.
Note 2	The note is not an action step. The note is used to clarify an action step or to offer a decision. Avoid using the note to state why the action is being taken.
A6	Test to ensure a ground established. - Keep the step as short and clear as possible. Modifiers (such as "the") are not needed. Simple directions, that provide little value for the typical work force, need not be included.
Note 3	In some high-risk industry, like nuclear power, maintenance procedures are extremely detailed and often do not allow even minor deviation.. That is not the basis for the typical industry procedure.
A7	Attach test cable (usually red cable) to circuit to be tested.
A8	Energize tester.
A9	Record test results at one minute intervals for 10 minutes. - Anytime data is needed, the procedure states "Record...". A section for Inspection Data needs to be part of the procedure OR other data collection means identified.
A9	De-energize tester.
WARNING	Circuit may have dangerous voltage potential following testing.
A10	Discharge circuit.
B	Next Procedure - New procedure sub-section. This heading is duplicated in the Procedure Description.
B1	Remove test cables.

Table I-2: Sample Procedures Layout (Continued)

Block Title	Text
B2	Remove thermometer, record temperature.
B3	Close access doors and panels.
B4	Return motor to service.
B5	Repeat steps A1 through A10 for next motor. - Repeat steps or reference to other procedures can be used. Figures can also be used.
Note 4	The procedure layout is such that all actions are taken in sequence. A technician performing the procedure should arrive at the work site with all necessary tools and materials (including reference material).
Inspection Data	If data is to be collected, there will usually be an Inspection Data section. The Inspection Data section is always located at the end of the Procedure section.
ID-1	Insulation Resistance at 1 min (Megohm) - Identify the units for data collection.
ID-2	Insulation Resistance at 2 min (Megohm)
ID-3	Insulation Resistance at 3 min (Megohm)
ID-4	Insulation Resistance at 4 min (Megohm)
ID-5	Insulation Resistance at 5 min (Megohm)
ID-6	Insulation Resistance at 6 min (Megohm)
ID-7	Insulation Resistance at 7 min (Megohm)
ID-8	Insulation Resistance at 8 min (Megohm)
ID-9	Insulation Resistance at 9 min (Megohm)
ID-10	Insulation Resistance at 10 min (Megohm)
ID-11	Temperature (degree C or F)
Engineer's Notes	The Engineers Notes provides background information that may be useful when developing site-specific procedures. This section is not part of the procedure. It is not intended to be provided (printed out) for use in the field or entered into the site CMMS.

Table I-3: Sample Procedure PT&I-0001, Vibration Data Collection

Block Title	Text
Procedure Number	PT&I-0001
System Description	
Procedure Description	Vibration Data Collection
Related Tasks	
Periodicity	Q
Labor (Hrs)	
Special Tools	Vibration Data Collector with accelerometer.
Materials	
Reference Data	
Warning Summary	Exercise caution when working around rotating machinery.
Caution Summary	
Reserved	
Preliminary	
1	Charge batteries and backup batteries.
2	Download vibration collection route data from host computer.
3	Test operation of vibration data collector and accelerometer.
Procedure	
A	Vibration Data Collection
WARNING	Exercise caution when working around rotating machinery.
A1	Notify operators or other local occupant before collecting vibration data.

Table I-3: Sample Procedure PT&I-0001, Vibration Data Collection (Continued)

Block Title	Text
WARNING	Exercise caution when working around rotating machinery.
A1	Notify operators or other local occupant before collecting vibration data.
A2	Record machine operating condition (usually directly into the data collector).
A3	Place accelerometer on installed machine sound disk. Ensure sound disk is clean and dry. Roll magnet onto the sound disk to avoid damage and overload to the accelerometer
Note	If sound disk is missing, take data directly on machine surface. Ensure surface is clean and dry. Scrape any paint or glue off surface. Replace sound disk at next opportunity.
A4	Collect vibration data. If needed, adjust data collector and take additional data.
A5	Note any unsatisfactory conditions (machine or area) and report them to supervisor.
A6	Repeat procedure for remaining positions on machine.
A7	Repeat procedure for remaining machines on schedule (route).
A8	Upload vibration data to host computer.
Engineer's Notes	
EN1	For time estimating purposes, allow one minute per data point. Approximately 10 to 12 minutes for a typical 4 bearing machine. Triaxial accelerometers will require less time to collect data.
EN2	Periodicity can be adjusted after a baseline is established.

Table I-4: Sample Procedure PT&I-0002, Qualitative Infrared Thermography Inspection

Block Title	Text
Procedure Number	PT&I-0002
System Description	
Procedure Description	Qualitative Infrared Thermography Inspection
Related Tasks	
Periodicity	A
Labor (Hrs)	2 People
Special Tools	Infrared Camera, Spare Batteries, Notepad
Materials	
Reference Data	
Warning Summary	1. Exercise caution when working around rotating machinery.
	2. Maintain minimum safe distance from energized electrical circuits.
	3. Observe standard safety precautions when working on elevated structures or roofs.
Caution Summary	
Reserved	
Preliminary	
1	Charge batteries and backup batteries for infrared camera.
2	Prepare image storage devices such as computer disks or PCMICA cards.
3	Inspect imaging system cables and test camera operation. Verify correct date/time (if available) has been set in camera.
4	Notify operators or other local occupant before starting inspection.

Table I-4: Sample Procedure PT&I-0002, Qualitative Infrared Thermography Inspection (Continued)

Block Title	Text
5	Ensure electrical circuits to be inspected are opened and energized to minimum 40% of full load current.
Procedure	
A	Qualitative Infrared Thermography Inspection
WARNING	Exercise caution when working around rotating machinery.
WARNING	Maintain minimum safe distance from energized electrical circuits.
WARNING	Observe standard safety precautions when working on elevated structures or roofs.
A1	Adjust camera settings such as distance to object and emissivity.
A2	Perform thermographic inspection looking for hot and cold spots, relative differences in temperature, and temperature deviations from the normal or expected range.
A3	Save image of items of interest. Ensure camera is adjusted to show entire temperature range (no "white" or "black" areas in the image).
A4	Note machine, location, and operating or environmental conditions for each image saved and (if any) immediate actions taken to correct fault.
A5	Repeat procedure for remaining machines/areas on schedule.
A6	Notify operators or other local occupant when inspection is complete.
Note	Immediately notify supervisor of any temperature difference (delta-T) greater than 40C (70F).
A7	Upload infrared images to host computer for analysis and reporting (if required). Provide notes for analyst use.
Engineer's Notes	
EN1	Detailed information regarding safety guidelines is contained in OSHA Regulations Part 1910. This regulation should be used in developing site specific procedures.
EN1a	See standard 1910.333 for electrical safety including closest approach distances for energized circuits.

Table I-5: Sample Procedure PT&I-0003, Insulation Test, Motor

Block Title	Text
Procedure Number	PT&I-0003
System Description	Motor
Procedure Description	Test Insulation
Related Tasks	
Periodicity	A
Labor (Hrs)	0.5
Special Tools	Direct Current Insulation Resistance Tester (Megohmmeter, Megger), Thermometer
Materials	
Reference Data	
Warning Summary	1. Test to ensure all circuits are de-energized. 2. Circuit may have dangerous voltage potential following testing.
Caution Summary	Protect semi-conductor control devices from potential high voltage.
Reserved	
Preliminary	
1	Ensure equipment/component identification (name and/or number) is legible and securely affixed to equipment. Repair as required.
Procedure	
A	Test Insulation
A1	De-energize equipment and tag out in accordance with site safety practices.
A2	Open motor control panels or doors to gain access to circuit to be tested.

Table I-5: Sample Procedure PT&I-0003, Insulation Test, Motor (Continued)

Block Title	Text
WARNING	Test to ensure all circuits are de-energized.
A3	Place thermometer in close proximity to circuit to be tested.
CAUTION	Protect semi-conductor control devices from potential high voltage.
A4	Attach ground cable (black cable) from tester to ground.
A5	Test to ensure a ground established.
A6	Attach test cable (usually red cable) to circuit to be tested.
A7	Energize tester.
A8	Record test results at one minute intervals for 10 minutes.
A9	De-energize tester.
WARNING	Circuit may have dangerous voltage potential following testing.
A10	Discharge circuit.
A11	Remove test cables.
A12	Remove thermometer, record temperature.
A13	Close access doors and panels.
A14	Return motor to service.
Inspection Data	
ID-1	Insulation Resistance at 1 min (Megohm)
ID-2	Insulation Resistance at 2 min (Megohm)
ID-3	Insulation Resistance at 3 min (Megohm)
ID-4	Insulation Resistance at 4 min (Megohm)
ID-5	Insulation Resistance at 5 min (Megohm)

Table I-5: Sample Procedure PT&I-0003, Insulation Test, Motor (Continued)

Block Title	Text
ID-6	Insulation Resistance at 6 min (Megohm)
ID-7	Insulation Resistance at 7 min (Megohm)
ID-8	Insulation Resistance at 8 min (Megohm)
ID-9	Insulation Resistance at 9 min (Megohm)
ID-10	Insulation Resistance at 10 min (Megohm)
ID-11	Temperature (degree C or F)
Engineer's Notes	
EN1	Specify the Insulation Resistance test voltage as follows:
EN1a	Circuit 480V or less, test voltage 500V
EN1b	Circuit 600V, test voltage 1000V
EN1c	Circuit 2400V, test voltage 2500V
EN1d	Circuit 4160V and above, test voltage 5000v
EN2	Technical standards are updated by the sponsoring organization (such as ASTM and IEEE). Often the update year is part of the standard number. Check with the sponsoring organization for the current version of the standard.
EN2a	See IEEE Standard 43-1974, IEEE Recommended Practice for Testing Insulation Resistance of Rotating Machinery, for guidance on insulation condition and interpretation of polarization index test results.

Table I-6: Sample Procedure PT&I-0004, Insulation Test, Transformer

Block Title	Text
Procedure Number	PT&I-0004
System Description	Transformer
Procedure Description	Test Insulation
Related Tasks	
Periodicity	1 to 3 yr
Labor (Hrs)	2 people/1hr ea
Special Tools	Direct Current Insulation Resistance Tester (Megohmmeter, Megger), Thermometer, 2-Shorting Cables (copper wire or braid)
Materials	
Reference Data	
Warning Summary	1. Test to ensure all circuits are de-energized. 2. Circuit may have dangerous voltage potential following testing.
Caution Summary	
Reserved	
Preliminary	
1	Ensure equipment/component identification (name and/or number) is legible and securely affixed to equipment. Repair as required.
Procedure	
A	Test Insulation
A1	De-energize equipment and tag out in accordance with site safety practices.
A2	Open transformer panels or doors to gain access to primary and secondary winding bushings.
WARNING	Test to ensure all circuits are de-energized.

Table I-6: Sample Procedure PT&I-0004, Insulation Test, Transformer (Continued)

Block Title	Text
A3	Place thermometer in close proximity to transformer bushings.
A4	Perform three point ground test. Record test results.
Note	Three point ground test is performed to verify transformer ground. Do not continue with this procedure if ground test is unsatisfactory.
A5	Disconnect all lighting arresters, current transformers, and bus or cable connections. Disconnect primary switch.
A6	Attach ground cable (black cable) from tester to ground.
A7	Test to ensure a ground established.
A8	Tie (short circuit) the primary bushings together using copper wire or braid.
A9	Tie (short circuit) the secondary bushings together using copper wire or braid.
A10	Attach test cable (usually red cable) to primary bushing.
A11	Energize tester.
A12	Record test results at one minute intervals for 10 minutes.
A13	De-energize tester.
WARNING	Circuit may have dangerous voltage potential following testing.
A14	Discharge circuit.
A15	Move test cable to secondary bushing.
A16	Repeat steps A11 through A14.
WARNING	Circuit may have dangerous voltage potential following testing.
A17	Move test cable back to primary bushing.
A18	Move ground cable to secondary bushing.
A19	Repeat steps A11 through A14.

Table I-6: Sample Procedure PT&I-0004, Insulation Test, Transformer (Continued)

Block Title	Text
WARNING	Circuit may have dangerous voltage potential following testing.
A20	Attach ground cable (black cable) from tester to primary switch ground.
A21	Test to ensure a ground established.
A22	Move test cable to primary switch, load side, A-phase.
A23	Energize tester.
A24	Record test results at one minute.
A25	De-energize tester.
WARNING	Circuit may have dangerous voltage potential following testing.
A26	Discharge circuit.
A27	Repeat steps A21 through A25 for B- and C-phase.
A28	Remove test and shorting cables.
A29	Remove thermometer, record temperature.
A30	Perform related tasks, if any.
A31	Reconnect all lighting arresters, current transformers, and bus or cable connections. Reconnect primary switch.
A32	Close access doors and panels.
A33	Return transformer to service.
Inspection Data	
ID-1	Ground Test (ohms)
ID-2	Primary to Ground Insulation Resistance at 1 min (Megohm)
ID-3	Primary to Ground Insulation Resistance at 2 min (Megohm)

Table I-6: Sample Procedure PT&I-0004, Insulation Test, Transformer (Continued)

Block Title	Text
ID-4	Primary to Ground Insulation Resistance at 3 min (Megohm)
ID-5	Primary to Ground Insulation Resistance at 4 min (Megohm)
ID-6	Primary to Ground Insulation Resistance at 5 min (Megohm)
ID-7	Primary to Ground Insulation Resistance at 6 min (Megohm)
ID-8	Primary to Ground Insulation Resistance at 7 min (Megohm)
ID-9	Primary to Ground Insulation Resistance at 8 min (Megohm)
ID-10	Primary to Ground Insulation Resistance at 9 min (Megohm)
ID-11	Primary to Ground Insulation Resistance at 10 min (Megohm)
ID-12	Secondary to Ground Insulation Resistance at 1 min (Megohm)
ID-13	Secondary to Ground Insulation Resistance at 2 min (Megohm)
ID-14	Secondary to Ground Insulation Resistance at 3 min (Megohm)
ID-15	Secondary to Ground Insulation Resistance at 4 min (Megohm)
ID-16	Secondary to Ground Insulation Resistance at 5 min (Megohm)
ID-17	Secondary to Ground Insulation Resistance at 6 min (Megohm)
ID-18	Secondary to Ground Insulation Resistance at 7 min (Megohm)
ID-19	Secondary to Ground Insulation Resistance at 8 min (Megohm)
ID-20	Secondary to Ground Insulation Resistance at 9 min (Megohm)
ID-21	Secondary to Ground Insulation Resistance at 10 min (Megohm)
ID-22	Primary to Secondary Insulation Resistance at 1 min (Megohm)
ID-23	Primary to Secondary Insulation Resistance at 2 min (Megohm)
ID-24	Primary to Secondary Insulation Resistance at 3 min (Megohm)
ID-25	Primary to Secondary Insulation Resistance at 4 min (Megohm)

Table I-6: Sample Procedure PT&I-0004, Insulation Test, Transformer (Continued)

Block Title	Text
ID-26	Primary to Secondary Insulation Resistance at 5 min (Megohm)
ID-27	Primary to Secondary Insulation Resistance at 6 min (Megohm)
ID-28	Primary to Secondary Insulation Resistance at 7 min (Megohm)
ID-29	Primary to Secondary Insulation Resistance at 8 min (Megohm)
ID-30	Primary to Secondary Insulation Resistance at 9 min (Megohm)
ID-31	Primary to Secondary Insulation Resistance at 10 min (Megohm)
ID-32	Primary Switch, Phase-A to Ground Insulation Resistance at 1 min (Megohm)
ID-33	Primary Switch, Phase-B to Ground Insulation Resistance at 1 min (Megohm)
ID-34	Primary Switch, Phase-C to Ground Insulation Resistance at 1 min (Megohm)
ID-35	Temperature (degree C or F)
Engineer's Notes	
EN1	Technical standards are updated by the sponsoring organization (such as ASTM and IEEE). Often the update year is part of the standard number. Check with the sponsoring organization for the current standard.
EN1a	ANSI/IEEE Standard C57.12.90-1993; IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers.
EN1b	ANSI/IEEE Standard C57.12.91-1979 (updated 1995); IEEE Test Code for Dry-Type Distribution and Power Transformers .
EN2	Specify the Insulation Resistance test voltage as follows:
EN2a	Circuit 480V or less, test voltage 500V
EN2b	Circuit 600V, test voltage 1000V

Table I-6: Sample Procedure PT&I-0004, Insulation Test, Transformer (Continued)

Block Title	Text
EN2c	Circuit 2400V, test voltage 2500V
EN2d	Circuit 4160V and above, test voltage 5000v
EN3	The Polarization Index (PI) is the 10 minute insulation resistance reading divided by the 1 minute insulation resistance reading. This value should be monitored and trended to help determine the condition of the windings.
EN3a	For liquid filled transformers: PI greater than 2.0 is good, 1.25 to 2.0 is fair, 1.1 to 1.25 is poor, and less than 1.1 is bad.
EN3b	For dry transformers the PI will normally be between 1.0 and 1.25. Insulation resistance value should be greater than 10,000 megohms.
EN4	Procedure is written for a step-down transformer and assumes the high voltage side is the line side. For step-up transformer, reverse the test procedure to test the load side first.
EN4a	If the line side of the primary switch is also de-energized, you can modify this procedure to test the line and load sides of the primary switch. Prior to step A22 close the primary switch and then take insulation data. Add Warning to test the circuit.
EN5	Time estimate is based upon transformer already de-energized. Add additional 2 to 3 hours to de-energize and tag out.

Table I-7: Sample Procedure PT&I-0005, Insulation Test, Circuit Breaker

Block Title	Text
Procedure Number	PT&I-0005
System Description	Circuit Breaker
Procedure Description	Test Insulation
Related Tasks	
Periodicity	1 to 3 yr
Labor (Hrs)	2 people/1hr ea
Special Tools	Direct Current Insulation Resistance Tester (Megohmmeter, Megger), Thermometer, Shorting Cable (copper wire or braid)
Materials	
Reference Data	
Warning Summary	1. Test to ensure all circuits are de-energized. 2. Circuit may have dangerous voltage potential following testing.
Caution Summary	
Reserved	
Preliminary	
1	Ensure equipment/component identification (name and/or number) is legible and securely affixed to equipment. Repair as required.
Procedure	
A	Test Insulation
A1	De-energize equipment and tag out in accordance with site safety practices.
A2	Open circuit breaker panels or doors to gain access to line side and load side bushings.
WARNING	Test to ensure all circuits are de-energized.

Table I-7: Sample Procedure PT&I-0005, Insulation Test, Circuit Breaker (Continued)

Block Title	Text
A3	Place thermometer in close proximity to circuit breaker mechanism.
A4	Attach ground cable (black cable) from tester to ground.
A5	Test to ensure a ground established.
A6	Tie (short circuit) the A-phase line and load bushings together using copper wire or braid.
A7	Attach test cable (usually red cable) to A-phase bushing.
A8	Energize tester.
A9	Record test results at one minute.
A10	De-energize tester.
A11	Discharge circuit.
WARNING	Circuit may have dangerous voltage potential following testing.
A12	Repeat steps A6 through A11 for the B-phase.
WARNING	Circuit may have dangerous voltage potential following testing.
A13	Repeat steps A6 through A11 for the C-phase.
WARNING	Circuit may have dangerous voltage potential following testing.
A14	Remove test and shorting cables.
A15	Remove thermometer, record temperature.
A16	Perform related tasks, if any.
A17	Close access doors and panels.
A18	Return circuit breaker to service.
Inspection Data	

Table I-7: Sample Procedure PT&I-0005, Insulation Test, Circuit Breaker (Continued)

Block Title	Text
ID-1	Phase-A to Ground Insulation Resistance at 1 min (Megohm)
ID-2	Phase-B to Ground Insulation Resistance at 1 min (Megohm)
ID-3	Phase-C to Ground Insulation Resistance at 1 min (Megohm)
ID-4	Temperature (degree C or F)
Engineer's Notes	
EN1	Specify the Insulation Resistance test voltage as follows:
EN1a	Circuit 480V or less, test voltage 500V
EN1b	Circuit 600V, test voltage 1000V
EN1c	Circuit 2400V, test voltage 2500V
EN1d	Circuit 4160V and above, test voltage 5000v
EN2	Technical standards are updated by the sponsoring organization (such as ASTM and IEEE). Often the update year is part of the standard number. Check with the sponsoring organization for the current version of the standard.
EN2a	ANSI/IEEE Standard C37.50-1989; American National Standard for Switchgear-Low Voltage AC Power Circuit Breakers Used in Enclosures - Test Procedures .
EN2b	ANSI/IEEE Standard C37.09-1979; IEEE Standard Test Procedures for AC High-Voltage Breakers Rated on a Symmetrical Current Basis.

Table I-8: Sample Procedure PT&I-0006, Oil Filled Transformer Oil Tests

Block Title	Text
Procedure Number	PT&I-0006
System Description	Oil Filled Transformer
Procedure Description	1. Sample Transformer Oil
	2. Perform Field Oil Tests
Related Tasks	PT&I-0007
Periodicity	A
Labor (Hrs)	2 people/2hrs ea
Special Tools	50cc Glass Syringe, two 16 ounce glass oil sample bottles, Power Factor Test Set, Acidity Test Kit, Oil Dielectric Test Set, Oil Color Chart
Materials	
Reference Data	ASTM Standard Test Methods (STM)
	D-3613-92 - Sampling Electrical Insulating Oils for Gas Analysis and Determination of Water Content
	D-877-87 - Dielectric Breakdown Voltage of Insulating Liquids Using Disk Electrodes (Dielectric Withstand Test)
	D-1534-90 - Approximate Acidity in Electrical Insulating Liquids by Color-Indicator Titration
	D-1524-84 - Visual Examination of Used Electrical Insulating Oil of Petroleum Origin In the Field
	Power Factor Test Set Operating Instructions
Warning Summary	Prior to obtaining oil sample verify transformer is not PCB filled or PCB contaminated. PCB oil goes by many trade names including Inerteen, Pyranol, and Askarel. Contact maintenance engineer if oil type is not known.
Caution Summary	

Table I-8: Sample Procedure PT&I-0006, Oil Filled Transformer Oil Tests (Continued)

Block Title	Text
Reserved	
Preliminary	
1	Ensure equipment/component identification (name and/or number) is legible and securely affixed to equipment. Repair as required.
2	Record unsatisfactory conditions observed on work order and report them to supervisor.
Procedure	
A	Sample Transformer Oil
WARNING	Prior to obtaining oil sample verify transformer is not PCB filled or PCB contaminated. PCB oil goes by many trade names including Inerteen, Pyranol, and Askarel. Contact maintenance engineer if oil type is not known.
A1	Collect dissolved gas oil sample from transformer. Use 50cc glass syringe and follow procedure in ASTM standard D3613-98.
A2	Collect two additional oil samples in sample bottles. Record equipment number, date, and oil temperature on one bottle.
B	Perform Field Oil Tests
B1	Use oil in un-labeled bottle for steps B2 through B5.
B2	Perform Dielectric Withstand Test (ASTM D877-87).
B3	Perform Field Acidity Test (ASTM D1534-95).
B4	Perform Visual Examination (ASTM D1524-94).
Note	See Power Factor Test Set operating instructions for Oil Power Factor test procedure.
B5	Perform Oil Power Factor.
B6	Record test results in the Inspection Data Section, item ID-1 to ID-4.
B7	Deliver oil sample in labeled bottle to supervisor for analysis.

Table I-8: Sample Procedure PT&I-0006, Oil Filled Transformer Oil Tests (Continued)

Block Title	Text
Inspection Data	
ID-1	Dielectric Withstand Test (kV)
ID-2	Field Acidity Test (mg KOH/ml)
ID-3	Visual Examination (color scale)
ID-4	Oil Power Factor (percent)
Engineer's Notes	
EN1	Technical standards are updated by the sponsoring organization (such as ASTM and IEEE). Often the update year is part of the standard number. Check with the sponsoring organization for the current version of the standard.
EN1a	ANSI/IEEE Standard C57.12.90-1993; IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers.
EN2	Send oil sample in the labeled bottle to test lab for a Karl Fischer (ASTM D1533-00), Acid Number (ASTM D974-97), and Interfacial Tension (ASTM D971-99a) test.
EN3	Send 50cc syringe to test lab for gas-in-oil analysis (ASTM D3613-98)
EN4	Field oil test results shall be as follows:
EN4a	Dielectric Test: >30kV
EN4b	Acidity Test: <.05 mg KOH/ml
EN4c	Visual Examination: <4.0
EN4d	Power Factor: <2.0%
EN5	Generate work order if tests fall outside minimum parameters

Table I-9: Sample Procedure PT&I-0007, Transformer Power Factor Test

Block Title	Text
Procedure Number	PT&I-0007
System Description	Transformer
Procedure Description	Power Factor Test
Related Tasks	PT&I-0004, PT&I-0006, E-0003
Periodicity	3 to 5 yr.
Labor (Hrs)	2 people/1hr ea
Special Tools	Direct Current Insulation Resistance Tester (Megohmmeter, Megger), Power Factor Test Set, psychrometer (or temperature/humidity meter), 2-Shorting Cables (copper wire or braid)
Materials	
Reference Data	Power Factor Test Set Operating Instructions
Warning Summary	1. Test to ensure all circuits are de-energized. 2. Energized electrical circuits. Observe test device safety precautions. 3. Circuit may have dangerous voltage potential following testing.
Caution Summary	Ensure shorting cables are removed from primary and secondary bushings.
Reserved	
Preliminary	
1	Review prior maintenance test data including thermal image and ultrasonic noise test results (if available).
2	Ensure equipment/component identification (name and/or number) is legible and securely affixed to equipment. Repair as required.
3	Record as-found conditions in Inspection Data section; Item ID-1 to ID-10.
4	For any step in procedure, record unsatisfactory conditions on work order and report them to supervisor.

Table I-9: Sample Procedure PT&I-0007, Transformer Power Factor Test (Continued)

Block Title	Text
Procedure	
A	Power Factor Test
A1	De-energize equipment and tag out in accordance with site safety practices.
A2	Open transformer panels or doors to gain access to primary and secondary winding bushings.
WARNING	Test to ensure all circuits are de-energized.
A3	Perform three point ground test. Record test results.
Note 1	Three point ground test is performed to verify transformer ground. Do not continue with this procedure if ground test is unsatisfactory.
A4	Disconnect all lighting arresters, current transformers, and bus or cable connections.
A5	Tie (short circuit) the primary bushings together using copper wire or braid.
A6	Tie (short circuit) the secondary bushings, including neutral, together using copper wire or braid.
Note 2	If transformer has on-load tap changer, mark the as found position. Test can not be performed with the on-load tap changer in the neutral position. Leave no-load tap changer, if installed, in normal operating position.
A7	Move on-load tap changer (if installed) to minus 1 from neutral position.
A8	Connect test set high voltage lead to primary bushing.
A9	Connect test set return lead to secondary bushing.
A10	Connect test ground to transformer ground.
Note 2	For each test performed, record results in Inspection Data section.
WARNING	Energized electrical circuits. Observe test device safety precautions.

Table I-9: Sample Procedure PT&I-0007, Transformer Power Factor Test (Continued)

Block Title	Text
A11	Perform primary-to-secondary test with ground circuit guarded.
A12	Perform primary-to-secondary test with secondary circuit guarded.
A13	Perform primary-to-secondary test with secondary and ground circuit included.
WARNING	Circuit may have dangerous voltage potential following testing.
A14	Discharge circuit.
A15	Connect test set high voltage lead to secondary bushing.
A16	Connect test set return lead to primary bushing.
WARNING	Energized electrical circuits. Observe test device safety precautions.
A17	Perform secondary-to-primary test with ground circuit guarded.
A18	Perform secondary-to-primary test with ground circuit included.
WARNING	Circuit may have dangerous voltage potential following testing.
A19	Discharge circuit.
A20	Remove shorting cables from primary and secondary bushings.
A21	Move on-load tap changer (if installed) to neutral.
Note 3	If transformer has no-load tap changer, leave in normal operating position.
A22	Connect test set high voltage lead to primary bushing 1 (usually identified as H1).
A23	Connect test set return lead to primary bushing 2 (usually identified as H2).
WARNING	Energized electrical circuits. Observe test device safety precautions.
A24	Perform excitation test H1 to H2.

Table I-9: Sample Procedure PT&I-0007, Transformer Power Factor Test (Continued)

Block Title	Text
WARNING	Circuit may have dangerous voltage potential following testing.
A25	Discharge circuit.
A26	Connect test set high voltage lead to primary bushing 2 (usually identified as H2).
A27	Connect test set return lead to primary bushing 3 (usually identified as H3).
WARNING	Energized electrical circuits. Observe test device safety precautions.
A28	Perform excitation test H2 to H3.
WARNING	Circuit may have dangerous voltage potential following testing.
A29	Discharge circuit.
A30	Connect test set high voltage lead to primary bushing 3 (usually identified as H3).
A31	Connect test set return lead to primary bushing 1 (usually identified as H1).
WARNING	Energized electrical circuits. Observe test device safety precautions.
A32	Perform excitation test H3 to H1.
WARNING	Circuit may have dangerous voltage potential following testing.
A33	Discharge circuit.
A34	Remove all test cables.
A35	Reconnect all lighting arresters, current transformers, and bus or cable connections.
A36	Return tap changer to original position.
CAUTION	Ensure shorting cables are removed from primary and secondary bushings.
A37	Perform related tasks, if any.

Table I-9: Sample Procedure PT&I-0007, Transformer Power Factor Test (Continued)

Block Title	Text
A38	Close access doors and panels.
A39	Return transformer to service.
Inspection Data	Fill in all applicable.
ID-1	Wet Bulb Temperature (C)
ID-2	Dry Bulb Temperature (C)
ID-3	Relative Humidity (%)
ID-4	Weather Conditions (Cloudy, etc.)
ID-5	Oil Level
ID-6	Oil Temperature (C)
ID-7	Maximum Oil Temperature (C)
ID-8	Winding Temperature (C)
ID-9	Maximum Winding Temperature (C)
ID-10	Tank Pressure (psi)
ID-11	Ground Test (ohms)
ID-12	Power Factor, primary-to-secondary, ground circuit guarded.
ID-13	Power Factor, primary-to-secondary, secondary circuit guarded.
ID-14	Power Factor, primary-to-secondary, secondary and ground circuit included.
ID-15	Power Factor, secondary-to-primary, ground circuit guarded.
ID-16	Power Factor, secondary-to-primary, ground circuit included.
ID-17	Power Factor Excitation, H1-H2

Table I-9: Sample Procedure PT&I-0007, Transformer Power Factor Test (Continued)

Block Title	Text
ID-18	Power Factor Excitation, H2-H3
ID-19	Power Factor Excitation, H3-H1
Engineer's Notes	
EN1	Specify the Power Factor test voltage as follows:
EN1a	Circuit less than 2400V, test voltage 500V
EN1b	Circuit 2400V to 4160V, test voltage 2500V
EN1c	Circuit 4160V to 10,000V, test voltage 5000V
EN1d	Circuit 10,000V and above, test voltage 10,000V
EN2	Time estimate is based upon transformer already de-energized. Add additional 2 to 3 hours to de-energize and tag out.
EN3	A Power Factor test measures the watts loss and the phase angle between the current and voltage in the equipment under test. From this information a determination can be made as to the integrity of the insulation.
EN3a	The Power Factor test is NOT a go-no/go test. Comparisons of past readings are necessary to determine the insulation condition
EN3b	All test values must be temperature corrected to 20C.
EN3c	Liquid filled (Oil, Silicone): less than 2% change indicates good condition; 2% to 4% change, investigate; over 4% change, bad condition.
EN3d	Dry windings: less than 5% change indicates good condition; 5% to 8% change, investigate; over 8% change, dry out transformer and retest.
EN4	The excitation test is the amount of current required to magnetize the iron and produce a voltage on the secondary.
EN4a	This current value is different for every transformer, dependent on the amount of iron in the winding core, purity of the iron/silicone laminations, and amount of copper/aluminum in the windings.

Table I-9: Sample Procedure PT&I-0007, Transformer Power Factor Test (Continued)

Block Title	Text
EN4b	Consequently there is not an absolute value/limit that is applicable; the % change from the transformer baseline is the monitored condition.
EN4c	Excitation: Any two phases approximately the same, third phase 20% less than the other two. A change of 10% from previous test needs to be investigated.

Table I-10: Sample Procedure PT&I-0008, Electrical Distribution Test

Block Title	Text
Procedure Number	PT&I-0008
System Description	Electrical Distribution
Procedure Description	1. Switchgear and Phase Bus Power Factor Test
	2. Circuit Breaker Power Factor Test
	3. Restore to Service
Related Tasks	PT&I-0005
Periodicity	3 to 5 year
Labor (Hrs)	
Special Tools	Power Factor Test Set, psychrometer (or temperature/humidity meter), Shorting Cable (copper wire or braid), Thermometer
Materials	
Reference Data	Power Factor Test Set Operating Instructions
Warning Summary	1. Test to ensure all circuits are de-energized. 2. Energized electrical circuits. Observe test device safety precautions. 3. Circuit may have dangerous voltage potential following testing.
	4. Closed circuit breaker has high spring pressure. Keep clear of all moving parts.
Caution Summary	Ensure shorting cables are removed from circuit breaker bushings.
Reserved	

Table I-10: Sample Procedure PT&I-0008, Electrical Distribution Test (Continued)

Block Title	Text
Preliminary	
1	Review prior maintenance test data including thermal image and ultrasonic noise test results (if available).
2	Ensure equipment/component identification (name and/or number) is legible and securely affixed to equipment. Repair as required.
3	Record as-found conditions in Inspection Data section; Item ID-1 to ID-4.
4	For any step in procedure, record unsatisfactory conditions on work order and report them to supervisor.
Procedure	
A	Switchgear and Phase Bus Power Factor Test
A1	De-energize equipment and tag out in accordance with site safety practices.
A2	Open switchgear panels or doors.
WARNING	Test to ensure all circuits are de-energized.
A3	Disconnect all lighting arresters, current transformers, and bus or cable connections.
A4	Place thermometer in close proximity to switchgear or phase bus.
A5	Rack out all circuit breakers and open all switches.
A6	Remove or disconnect all potential transformers.
A7	Connect test set ground to switchgear or phase bus ground.
A8	Connect test set high voltage lead to A-phase bus.
WARNING	Energized electrical circuits. Observe test device safety precautions.
A9	Perform A-phase test and record results.
WARNING	Circuit may have dangerous voltage potential following testing.

Table I-10: Sample Procedure PT&I-0008, Electrical Distribution Test (Continued)

Block Title	Text
A10	Discharge circuit.
A11	Repeat steps A7 through A9 for B-phase.
A12	Repeat steps A7 through A9 for C-phase.
A13	Remove thermometer, record temperature.
A14	Remove all test cables.
B	Circuit Breaker Power Factor Test
B1	Open circuit breaker.
WARNING	Test to ensure all circuits are de-energized.
B2	Rack out circuit breaker or otherwise disconnect from phase leads or phase bus.
B3	Place thermometer in close proximity to circuit breaker mechanism.
B4	Connect test set ground to circuit breaker ground.
Note	Circuit breaker bushings number 1 through 3 are line side A-phase through C-phase respectively. Bushings 4 through 6 are load side A-phase through C-phase respectively.
B5	Connect test set high voltage lead to circuit breaker bushing 1.
WARNING	Energized electrical circuits. Observe test device safety precautions.
B6	Perform circuit breaker power factor test and record results.
WARNING	Circuit may have dangerous voltage potential following testing.
B7	Discharge circuit.
B8	Repeat steps B4 through B6 for circuit breaker bushing 2.
B9	Repeat steps B4 through B6 for circuit breaker bushing 3.
B10	Repeat steps B4 through B6 for circuit breaker bushing 4.

Table I-10: Sample Procedure PT&I-0008, Electrical Distribution Test (Continued)

Block Title	Text
B11	Repeat steps B4 through B6 for circuit breaker bushing 5.
B12	Repeat steps B4 through B6 for circuit breaker bushing 6.
WARNING	Closed circuit breaker has high spring pressure. Keep clear of all moving parts.
B13	Close circuit breaker.
B14	Tie (short circuit) the A-phase line and load bushings together using copper wire or braid.
B15	Connect test set high voltage lead to circuit breaker bushing 1.
WARNING	Energized electrical circuits. Observe test device safety precautions.
B16	Perform circuit breaker power factor test and record results.
WARNING	Circuit may have dangerous voltage potential following testing.
B17	Discharge circuit.
B18	Remove shorting cable from A-phase bushings.
B19	Repeat steps B13 through B17 for B-phase bushings.
B20	Repeat steps B13 through B17 for C-phase bushings.
B21	Remove thermometer, record temperature.
B22	Open the circuit breaker.
B23	Rack in circuit breaker or reconnect phase leads or phase bus.
B24	Repeat procedure for remaining circuit breakers.
C	Restore to Service
C1	Remove all test cables.
C2	Reconnect all lighting arresters, current transformers, and bus or cable connections.

Table I-10: Sample Procedure PT&I-0008, Electrical Distribution Test (Continued)

Block Title	Text
C3	Perform related tasks, if any.
C4	Close circuit breakers and switches as required.
CAUTION	Ensure shorting cables are removed from circuit breaker bushings.
C5	Return distribution system to service.
Inspection Data	Fill in all applicable.
ID-1	Wet Bulb Temperature (C)
ID-2	Dry Bulb Temperature (C)
ID-3	Relative Humidity (%)
ID-4	Weather Conditions (Cloudy, etc.)
ID-5	Power Factor Switchgear or Phase Bus, A-phase, ground specimen test.
ID-6	Power Factor Switchgear or Phase Bus, B-phase, ground specimen test.
ID-7	Power Factor Switchgear or Phase Bus, C-phase, ground specimen test.
ID-8	Temperature (degree C or F)
ID-9	Power Factor Circuit Breaker, Bushing 1, ground specimen test.
ID-10	Power Factor Circuit Breaker, Bushing 2, ground specimen test.
ID-11	Power Factor Circuit Breaker, Bushing 3, ground specimen test.
ID-12	Power Factor Circuit Breaker, Bushing 4, ground specimen test.
ID-13	Power Factor Circuit Breaker, Bushing 5, ground specimen test.
ID-14	Power Factor Circuit Breaker, Bushing 4, ground specimen test.
ID-15	Power Factor Circuit Breaker, A-phase, ground specimen test.

Table I-10: Sample Procedure PT&I-0008, Electrical Distribution Test (Continued)

Block Title	Text
ID-16	Power Factor Circuit Breaker, B-phase, ground specimen test.
ID-17	Power Factor Circuit Breaker, C-phase, ground specimen test.
ID-18	Temperature (degree C or F)
Engineer's Notes	
EN1	Specify the Power Factor test voltage as follows:
EN1a	Circuit less than 2400V, test voltage 500V
EN1b	Circuit 2400V to 4160V, test voltage 2500V
EN1c	Circuit 4160V to 10,000V, test voltage 5000V
EN1d	Circuit 10,000V and above, test voltage 10,000V
EN2	A Power Factor test measures the watts loss and the phase angle between the current and voltage in the equipment under test. From this information a determination can be made as to the integrity of the insulation.
EN2a	The Power Factor test is NOT a go-no/go test. Comparisons of past readings are necessary to determine the insulation condition
EN2b	Attention systems engineer. All test values must be temperature corrected to 20C.
EN2c	For the switchgear and phase bus, power factor should be less than 2%. High readings indicate excess moisture or loose connections. Loose connections can be verified using infrared thermograph on an energized circuit.
EN2d	For the circuit breakers, bushings test is for the individual bushing while the phase test is for the bushing and the lift rods and contacts. Each phase and bushing should be within 5% of each other.
EN2e	Individual bushings should be less than 5% after cleaning. Large 115kV and 230kV breakers with oil filled bushings will have the Power Factor baselines etched on the bushing base.

Table I-11: Sample Procedure PT&I-0009, Oil Filled Bushing Power Factor Test

Block Title	Text
Procedure Number	PT&I-0009
System Description	Oil Filled Bushing
Procedure Description	1. Power Factor Test Hot Collar Method
	2. Power Factor Test Capacitance Tap Method
Related Tasks	PT&I-0005, PT&I-0008
Periodicity	3 to 5 yr.
Labor (Hrs)	2 people/1hr ea
Special Tools	Power Factor Test Set, psychrometer (or temperature/humidity meter), Thermometer, Culenite Bushing Cleaner
Materials	
Reference Data	Power Factor Test Set Operating Instructions
Warning Summary	1. Test to ensure all circuits are de-energized. 2. Energized electrical circuits. Observe test device safety precautions. 3. Circuit may have dangerous voltage potential following testing.
Caution Summary	
Reserved	
Preliminary	
1	Review prior maintenance test data including thermal image and ultrasonic noise test results (if available).
2	Ensure equipment/component identification (name and/or number) is legible and securely affixed to equipment. Repair as required.

Table I-11: Sample Procedure PT&I-0009, Oil Filled Bushing Power Factor Test (Continued)

Block Title	Text
3	Record as-found conditions in Inspection Data section; Item ID-1 to ID-4.
4	For any step in procedure, record unsatisfactory conditions on work order and report them to supervisor.
Procedure	
A	Power Factor Test Hot Collar Method
A1	De-energize equipment and tag out in accordance with site safety practices.
A2	Gain access to bushing.
WARNING	Test to ensure all circuits are de-energized.
A3	Disconnect all lighting arresters, current transformers, and bus or cable connections.
A4	Clean bushing.
Note	Do not use any alcohol based cleaning product.
A5	Place thermometer on bushing.
A6	Place power factor test hot collar strap under uppermost bushing petticoat or rainshield.
A7	Connect test set high voltage lead to hot collar strap.
A8	Ground bushing terminal.
WARNING	Energized electrical circuits. Observe test device safety precautions.
A9	Perform grounded specimen power factor test and record results.
WARNING	Circuit may have dangerous voltage potential following testing.
A10	Discharge circuit.
A11	Remove thermometer, record temperature.
A12	Remove all test cables.

Table I-11: Sample Procedure PT&I-0009, Oil Filled Bushing Power Factor Test (Continued)

Block Title	Text
A13	Repeat steps A2 through A12 for other bushings.
A14	Reconnect all lighting arresters, current transformers, and bus or cable connections.
A15	Perform related tasks, if any.
A16	Return system to service.
B	Power Factor Test Capacitance Tap Method
B1	De-energize equipment and tag out in accordance with site safety practices.
B2	Gain access to bushing.
WARNING	Test to ensure all circuits are de-energized.
B3	Disconnect all lighting arresters, current transformers, and bus or cable connections.
B4	Clean bushing.
Note	Do not use any alcohol based cleaning product.
B5	Place thermometer on bushing.
B6	Remove capacitance tap cover (at base of bushing).
B7	Connect test set return lead to capacitance tap.
B8	Connect test set high voltage lead to bushing terminal.
WARNING	Energized electrical circuits. Observe test device safety precautions.
B9	Perform grounded specimen power factor test and record results.
WARNING	Circuit may have dangerous voltage potential following testing.
B10	Discharge circuit.
B11	Remove thermometer, record temperature.

Table I-11: Sample Procedure PT&I-0009, Oil Filled Bushing Power Factor Test (Continued)

Block Title	Text
B12	Remove all test cables.
B13	Repeat steps A2 through A12 for other bushings.
B14	Reconnect all lighting arresters, current transformers, and bus or cable connections.
B15	Perform related tasks, if any.
B16	Return system to service.
Inspection Data	Fill in all applicable.
ID-1	Wet Bulb Temperature (C)
ID-2	Dry Bulb Temperature (C)
ID-3	Relative Humidity (%)
ID-4	Weather Conditions (Cloudy, etc.)
ID-5	Power Factor Bushing, ground circuit guarded.
ID-6	Temperature (degree C or F)
Engineer's Notes	
EN1	Specify the Power Factor test voltage as follows:
EN1a	Circuit less than 2400V, test voltage 500V
EN1b	Circuit 2400V to 4160V, test voltage 2500V
EN1c	Circuit 4160V to 10,000V, test voltage 5000V

Table I-11: Sample Procedure PT&I-0009, Oil Filled Bushing Power Factor Test (Continued)

Block Title	Text
EN1d	Circuit 10,000V and above, test voltage 10,000V
EN2	A Power Factor test measures the watts loss and the phase angle between the current and voltage in the equipment under test. From this information a determination can be made as to the integrity of the insulation.
EN2a	The Power Factor test is NOT a go-no/go test. Comparisons of past readings are necessary to determine the insulation condition
EN2b	All test values must be temperature corrected to 20C.
EN2c	Individual bushings should be less than 5% after cleaning. Large 115kV and 230kV oil filled bushings will have the Power Factor baselines etched on the bushing base.
EN3	Time estimate is based upon testing only. Allow an additional hour (each person) to clean bushings.

Table I-12: Sample Procedure E-0001, Transformer Inspection and Cleaning

Block Title	Text
Procedure Number	E-0001
System Description	Transformer
Procedure Description	Inspect and Clean Transformer
Related Tasks	PT&I-0004, PT&I-0006, PT&I-0007, PT&I-0008
Periodicity	3 to 5 yr
Labor (Hrs)	2 people/2hr ea
Special Tools	Vacuum Cleaner
Materials	Corrosion Inhibitor, Culenite Bushing Cleaner
Reference Data	
Warning Summary	1. Test to ensure all circuits are de-energized. 2. If PCB or PCB contaminated oil has leaked from the transformer, stop work, and notify maintenance engineer.
Caution Summary	
Reserved	
Preliminary	
1	Review prior maintenance test data including thermal image and ultrasonic noise test results (if available).
2	Ensure equipment/component identification (name and/or number) is legible and securely affixed to equipment. Repair as required.
3	For any step in procedure, record unsatisfactory conditions on work order and report them to supervisor.
Procedure	
A	Inspect and Clean Transformer

Table I-12: Sample Procedure E-0001, Transformer Inspection and Cleaning (Continued)

Block Title	Text
A1	De-energize equipment and tag out in accordance with site safety practices.
WARNING	Test to ensure all circuits are de-energized.
A2	Open transformer panels or doors to gain access to components and install safety grounds.
Note1	Procedure is for both liquid filled and dry type transformers. Components identified for inspection in this procedure are not necessarily on all transformers.
Note 2	Some older oil filled transformers may be PCB filled or PCB contaminated. PCB oil goes by many trade names including Inerteen, Pyranol, and Askarel. Contact maintenance engineer if oil type is not known.
WARNING	If PCB or PCB contaminated oil has leaked from the transformer, stop work, and notify maintenance engineer.
A3	Inspect transformer and disconnect device (where applicable) for signs of excessive heating and/or insulation damage.
A4	Inspect all exposed conduit and potheads for secure mounting, corrosion, damaged fittings, and signs of moisture contamination.
A5	Inspect tank, cooling accessories, seals, valves, gauges, fittings, fans, fuses, and other external parts and accessories for corrosion, leaks, looseness, and damage.
A6	Inspect desiccant and desiccant lines (on conservator units) for looseness and corrosion. Replace desiccant if more than 50% has changed color from blue to clear.
A7	Inspect nitrogen system (on blanketed units) for corrosion, looseness, and leaks.
A8	Inspect all exposed ground connections. Ensure connections are clean and tight. Treat with corrosion inhibitor.
A9	Clean transformer primary and secondary bushings (if accessible). Clean disconnect switch bushings and insulators (where applicable). Examine bushings for cracks, chips, or corona flashover.

Table I-12: Sample Procedure E-0001, Transformer Inspection and Cleaning (Continued)

Block Title	Text
A10	Clean transformer windings (if possible), enclosure, and panels with vacuum cleaner.
A11	Ensure heaters (if installed) are working correctly.
A12	Make minor repair. Contact supervisor if repairs are not possible. Note on work order.
A13	Perform spot cleaning and touchup painting as required.
A14	Perform related tasks, if any.
A15	Remove safety grounds.
A16	Close access doors.
A17	Re-energize transformer and return to service.
A18	Remove debris from work-site.
Engineer's Notes	
EN1	In order make effective use of time, this procedure for cleaning and inspecting a transformer should be used in conjunction with other procedures (identified in Related Task section) for testing transformers.
EN2	Technical standards are updated by the sponsoring organization (such as ASTM and IEEE). Often the update year is part of the standard number. Check with the sponsoring organization for the current standard.
EN2a	ANSI/IEEE Standard C57.12.90-1993; IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers.
EN2b	ANSI/IEEE Standard C57.12.91-1979 (updated 1995); IEEE Test Code for Dry-Type Distribution and Power Transformers .

Table I-13: Procedure Number E-0002, Battery Bank Impedance Test

Block Title	Text
Procedure Number	E-0002
System Description	Battery Bank
Procedure Description	Battery Impedance Test
Related Tasks	PT&I-0002
Periodicity	S
Labor (Hrs)	2 people/1hr ea
Special Tools	Battery Impedance Test Set
Materials	Scotchbrite or very fine emery cloth.
Reference Data	Manufacture's/equipment output specification.
Warning Summary	Observe standard safety precautions when working on energized electrical circuits.
Caution Summary	
Reserved	
Preliminary	
1	Review prior maintenance test data including thermal image and ultrasonic noise test results (if available).
2	Ensure equipment/component identification (name and/or number) is legible and securely affixed to equipment. Repair as required.
3	For any step in procedure, record unsatisfactory conditions on work order and report them to supervisor.
Procedure	
A	Battery Impedance Test
WARNING	Observe standard safety precautions when working on energized electrical circuits.

Table I-13: Procedure Number E-0002, Battery Bank Impedance Test (Continued)

Block Title	Text
A1	Connect battery impedance test set AC signal leads to positive (+) and negative (-) terminals of battery bank.
A2	Clamp impedance receiver unit around positive AC signal lead.
A3	Measure impedance of first cell. Record impedance reading on note paper or in battery book.
A4	Measure impedance of first strap. Record impedance reading on note paper or in battery book.
A5	Repeat steps A3 and A4 for each cell/strap combination in battery bank.
A6	Inspect batteries and battery connections for leaks, overheating, or corrosion.
A7	Make minor repair. Contact supervisor if repairs are not possible. Note on work order.
A8	Perform spot cleaning and touchup painting as required.
A9	Record battery voltage and trickle charge rate.
A10	Remove debris from work-site.
Inspection Data	Fill in all applicable.
ID-1	Battery impedance test results (use separate sheet or record in battery book).
ID-2	Record battery voltage and trickle charge in standby mode.
Engineer's Notes	
EN1	Technical standards are updated by the sponsoring organization (such as ASTM and IEEE). Often the update year is part of the standard number. Check with the sponsoring organization for the current standard.

Table I-13: Procedure Number E-0002, Battery Bank Impedance Test (Continued)

Block Title	Text
EN1a	IEEE Standard 446-1995, "IEEE Recommended Practice for Emergency and Standby Power Systems for Industrial and Commercial Applications", IEEE Orange Book.
EN2	Battery impedance tests.
EN2a	Battery cell impedance shall be within 10% of each other and within 10% from last test.
EN2b	Battery strap impedance shall be less than 0.1 ohm. Readings above 0.1 ohm require cleaning and retorque.
EN-3	Battery voltage and trickle charge in standby to be within 5% of manufacturer's specifications.

Table I-14: Procedure Number E-0003, Uninterruptible Power Supply Test/Repair/Service

Block Title	Text
Procedure Number	E-0003
System Description	Uninterruptible Power Supply
Procedure Description	1. Battery Impedance Test 2. Inspect and Repair 3. Restore to Service
Related Tasks	E-0002
Periodicity	S
Labor (Hrs)	2 people/1hr ea
Special Tools	Relay Timing Test Set.
Materials	Scotchbrite or very fine emery cloth.
Reference Data	Manufacture's/equipment output specification.
Warning Summary	Test to ensure all circuits are de-energized.
Caution Summary	
Reserved	
Preliminary	
1	Review prior maintenance test data including thermal image and ultrasonic noise test results (if available).
2	Ensure equipment/component identification (name and/or number) is legible and securely affixed to equipment. Repair as required.
3	For any step in procedure, record unsatisfactory conditions on work order and report them to supervisor.
4	Perform Battery Impedance Test (E-0002)
Procedure	

Table I-14: Procedure Number E-0003, Uninterruptible Power Supply Test/Repair/Service (Continued)

Block Title	Text
A	Inspect and Repair
A1	Disconnect UPS from load.
A2	De-energize equipment and tag out in accordance with site safety practices.
WARNING	Test to ensure all circuits are de-energized.
A3	Open cabinet.
A4	Inspect casing for overheating, corrosion, or damage.
A5	Inspect printed circuit boards for overheating, cracks, or looseness.
A6	Inspect contactor/transfer switch contacts. Clean with scotchbrite or very fine emery cloth as required.
A7	Inspect batteries and battery connections for leaks, overheating, or corrosion.
A8	Make minor repair. Contact supervisor if repairs are not possible. Note on work order.
A9	Clean air intakes. Clean or replace air filters.
A10	Test undervoltage relay. Relay should operate at 90% (+ or - 2.5%) of rated voltage. Calibrate if needed.
A11	Test meters. Meters should operate within + or - 2.5% of scale. Calibrate if needed.
Note	Reference the UPS manufacturer technical manual for step A10.
A12	Test all circuit breakers. Recalibrate trip and close settings as required.
B	Restore to Service
B1	Perform spot cleaning and touchup painting as required.
B2	Reconnect unit to load.

Table I-14: Procedure Number E-0003, Uninterruptible Power Supply Test/Repair/Service (Continued)

Block Title	Text
B3	Re-energize unit.
B4	Perform operational test of unit. Simulate power failure and check for proper switching, verify proper voltage and frequency under load.
B5	Return unit to standby mode.
B6	Record battery voltage and trickle charge rate.
B7	Remove debris from work-site.
Inspection Data	Fill in all applicable.
ID-1	Record undervoltage relay as left pick-up.
ID-2	Record as found and as left meter readings.
ID-3	Record load test parameters.
ID-4	Record battery voltage and trickle charge in standby mode.
Engineer's Notes	
EN1	Technical standards are updated by the sponsoring organization (such as ASTM and IEEE). Often the update year is part of the standard number. Check with the sponsoring organization for the current standard.
EN1a	IEEE Standard 446-1995, "IEEE Recommended Practice for Emergency and Standby Power Systems for Industrial and Commercial Applications", IEEE Orange Book.
EN2	UPS should engage at less than 90% system voltage, + or - 2.5%.
EN3	Operational Parameters (for yearly reference)
EN-3a	Voltage shall be within -5% to +5%
EN-3b	Frequency shall be within -0.5% to +0.5%

Table I-14: Procedure Number E-0003, Uninterruptible Power Supply Test/Repair/Service (Continued)

Block Title	Text
EN-3c	Output current shall be within -5% to +5% of rated current
EN-4	Battery voltage and trickle charge in standby to be within 5% of manufacturer's specifications.

Table I-15: Procedure Number E-0004, Electrical Distribution Panel Inspection & Cleaning

Block Title	Text
Procedure Number	E-0004
System Description	Electrical Distribution Panel
Procedure Description	Inspect and Clean Electrical Panels
Related Tasks	PT&I-0002, PT&I-0008
Periodicity	1 to 3 yr
Labor (Hrs)	2 people/1hr ea
Special Tools	Vacuum Cleaner
Materials	
Reference Data	
Warning Summary	1. Test to ensure all circuits are de-energized. 2. Closed circuit breaker has high spring pressure. Keep clear of all moving parts.
Caution Summary	
Reserved	
Preliminary	
1	Review prior maintenance test data including thermal image and ultrasonic noise test results (if available).
2	Ensure equipment/component identification (name and/or number) is legible and securely affixed to equipment. Repair as required.
3	For any step in procedure, record unsatisfactory conditions on work order and report them to supervisor.
Procedure	
A	Inspect and Clean Electrical Panels
A1	De-energize equipment and tag out in accordance with site safety practices.

Table I-15: Procedure Number E-0004, Electrical Distribution Panel Inspection & Cleaning (Continued)

Block Title	Text
A2	Open electrical panels or doors.
WARNING	Test to ensure all circuits are de-energized.
A3	Rack out circuit breakers and open switches as required.
WARNING	Closed circuit breaker has high spring pressure. Keep clear of all moving parts.
A4	Inspect cables, connectors, terminal boards, and bus work for signs of excessive heating and/or insulation damage.
A5	Inspect all exposed connections for secure mounting, corrosion, damaged insulators, and signs of moisture contamination.
Note	Loose connectors are identified through infrared thermography inspection. Torque connectors to specified value or, if unknown, maximum 25 in-lb.
CAUTION	Do not over tighten connectors.
A6	Tighten loose connectors.
A7	Inspect all exposed ground connections. Ensure connections are clean and tight. Treat with corrosion inhibitor.
A8	Clean bus insulators.
A9	Clean conductors, terminal boards, enclosures, and panels with vacuum cleaner.
A10	Ensure heaters (if installed) are working correctly.
A11	Make minor repair. Contact supervisor if repairs are not possible. Note on work order.
A12	Perform touchup painting as required.
A13	Perform related tasks, if any.
A14	Close switches and rack in circuit breakers as required.
A15	Close panels and doors and return panel to service.

Table I-15: Procedure Number E-0004, Electrical Distribution Panel Inspection & Cleaning (Continued)

Block Title	Text
A16	Remove debris from work-site.
Engineer's Notes	
EN1	Connector torque value, see specification SAE AIR1471. All values are + or - 12.5%.
EN1a	5/32-32: 25 in-lb.
EN1b	5/32-36: 26 in-lb.
EN1c	3/16-32: 42 in-lb.
EN1d	1/4-28: 95 in-lb.
EN1e	5/16-24: 185 in-lb.
EN1f	1/2-20: 800 in-lb.

Table I-16: Procedure Number E-0005, High/Med Volt Circuit Breaker Test

Block Title	Text
Procedure Number	E-0005
System Description	High/Medium Voltage Circuit Breaker
Procedure Description	Inspect and Test Circuit Breaker
Related Tasks	PT&I-0002, PT&I-0005, PT&I-0008, E-0004
Periodicity	3 to 5 yr
Labor (Hrs)	2 people/8 hr ea
Special Tools	Breaker Timing Test Set, Contact Resistance Test Set, psychrometer (or temperature/humidity meter), Thermometer
Materials	
Reference Data	ASTM Standard Test Methods (STM)
	D-877-87 - Dielectric Breakdown Voltage of Insulating Liquids Using Disk Electrodes (Dielectric Withstand Test)
	D-1534-90 - Approximate Acidity in Electrical Insulating Liquids by Color-Indicator Titration
	Breaker Timing Test Set Operating Instructions
	Contact Resistance Test Set Operating Instructions
Warning Summary	1. Test to ensure all circuits are de-energized. 2. Closed circuit breaker has high spring pressure. Keep clear of all moving parts.
Caution Summary	Do not over tighten connectors.
Reserved	
Preliminary	
1	Review prior maintenance test data including thermal image and ultrasonic noise test results (if available).

Table I-16: Procedure Number E-0005, High/Med Volt Circuit Breaker Test (Continued)

Block Title	Text
2	Ensure equipment/component identification (name and/or number) is legible and securely affixed to equipment. Repair as required.
3	Record as-found conditions in Inspection Data section; Item ID-1 to ID-6.
4	For any step in procedure, record unsatisfactory conditions on work order and report them to supervisor.
Procedure	
A	Inspect and Test Circuit Breaker
A1	Open breaker, de-energize and tag out in accordance with site safety practices.
A2	Open electrical panels or cubicle doors.
WARNING	Test to ensure all circuits are de-energized.
A3	Install safety grounds if applicable.
A4	Disconnect line and load cables/bus from circuit breaker bushings or rack breaker out and remove from cubicle.
A5	Inspect breaker bushings and connectors for cracks, chips, looseness, burning, and arcing/tracking.
A6	Inspect operating mechanism, for loose nuts, bolts, and pins.
A7	Inspect control wiring for burnt or frayed insulation.
Note 1	Loose connections are identified through infrared thermography inspection. Torque connectors to specified value or, if unknown, maximum 25 in-lb.
CAUTION	Do not over tighten connectors.
A8	Tighten loose connectors.
A9	Make minor repair. Contact supervisor if repairs are not possible. Note on work order.

Table I-16: Procedure Number E-0005, High/Med Volt Circuit Breaker Test (Continued)

Block Title	Text
A10	Perform three point ground test. Record test results in Inspection Data section.
WARNING	Closed circuit breaker has high spring pressure. Keep clear of all moving parts.
A11	Perform breaker-timing test. Record test results in Inspection Data section.
Note 2	See Breaker Timing Test Set Operating Instructions for procedure.
A12	Perform related task PT&I-0005, Circuit Breaker Insulation Resistance.
A13	Perform related task PT&I-0008, Circuit Breaker Power Factor Test.
A14	Perform contact resistance test. Record test results in Inspection Data section.
Note 3	See Contact Resistance Test Set Operating Instructions for procedure.
Note 4	Perform step A15 for vacuum type breakers. Perform step A16 through A18 for oil filled type breakers.
A15	Perform vacuum bottle integrity test and/or a DC high-potential test at 2.5 times the rated AC voltage level.
Note 5	There is currently no standard for bottle integrity test. See manufacturer instructions for guidance.
A16	Perform Dielectric Withstand Test (ASTM D877-87).
A17	Perform Field Acidity Test (ASTM D1534-95).
A18	Filter oil if needed.
Note 6	Oil will need to be filtered if dielectric breakdown is less than 24kV or acidity is more than .3 gram KOH/ml
A19	Perform touchup painting as required.
A21	Remove safety grounds.
A22	Reassemble circuit breaker and return to service.

Table I-16: Procedure Number E-0005, High/Med Volt Circuit Breaker Test (Continued)

Block Title	Text
A23	Remove debris from work-site.
Inspection Data	Fill in all applicable.
ID-1	Wet Bulb Temperature (C)
ID-2	Dry Bulb Temperature (C)
ID-3	Relative Humidity (%)
ID-4	Weather Conditions (Cloudy, etc.)
ID-5	Oil Filled Breaker Oil Level
ID-6	Oil Filled Breaker Oil Temperature (C)
ID-7	Three Point Ground, ohms
ID-8	Contact Resistance, Phase A
ID-9	Contact Resistance, Phase B
ID-10	Contact Resistance, Phase C
ID-11	Vacuum Bottle, Phase A
ID-12	Vacuum Bottle, Phase B
ID-13	Vacuum Bottle, Phase C
ID-14	Oil dielectric, kV
ID-15	Acidity, gram KOH/ml
Engineer's Notes	
EN1	Technical standards are updated by the sponsoring organization (such as ASTM and IEEE). Often the update year is part of the standard number. Check with the sponsoring organization for the current version of the standard.

Table I-16: Procedure Number E-0005, High/Med Volt Circuit Breaker Test (Continued)

Block Title	Text
EN1a	IEEE C37.11-1997 IEEE Standard Requirements for Electrical Control for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis
EN1b	ANSI/IEEE C37.09-1979, Standard Test Procedure for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis.
EN2	Breaker timing test results should verify the integrity of the operating mechanism. Compare current test with last test to confirm velocity, travel, time, and contact wipe. Deviations from the manufacturers' specs indicate adjustment is required.
EN2a	Contact resistance measurements normally range from 50 microhms to 1200 microhms. Consult manufacturers' specifications for specific values. Contact resistance of each phase should be within 10% of the other phases.
EN2b	Deviations indicate burnt or misaligned contacts, or misadjusted operating mechanism.
EN3	A Vacuum Bottle Integrity Test and/or a DC High-Pot at 2.5 the rated AC voltage level are go/no-go tests that verify the bottle is still in a vacuum condition.
EN4	Oil tests for Oil Circuit Breakers can reveal the operating history and condition of the contact assemblies. High acidity and low dielectric are indicative of burning or arcing contacts, and/or high numbers of full load operations
EN4a	Levels outside the values identified in the procedure, Note 5, require the oil to be filtered and the contact assemblies to be inspected.
EN5	Connector torque value, see specification SAE AIR1471. All values are + or - 12.5%.
EN5a	5/32-32: 25 in-lb.
EN5b	5/32-36: 26 in-lb.
EN5c	3/16-32: 42 in-lb.
EN5d	1/4-28: 95 in-lb.
EN5e	5/16-24: 185 in-lb.
EN5f	1/2-20: 800 in-lb.

Table I-17: Procedure Number M-0001, Air Handler, Inspection & Cleaning

Block Title	Text
Procedure Number	M-0001
System Description	Air Handler
Procedure Description	Inspect and Clean
Related Tasks	PT&I -0001, PT&I -0003
Periodicity	A
Labor (Hrs)	2
Special Tools	Vacuum Cleaner, Belt Tensiomometer
Materials	Biological Control Tablets, Drive Belt(s), Air Filters
Reference Data	
Warning Summary	
Caution Summary	
Reserved	
Preliminary	
1	Review prior maintenance data including vibration data test results (if available).
	Notify operators or other local occupant before starting inspection.
2	Ensure equipment/component identification (name and/or number) is legible and securely affixed to equipment. Repair as required.
3	For any step in procedure, record unsatisfactory conditions on work order and report them to supervisor.
Procedure	
A	Inspect and Clean
A1	Record air filter differential pressure (if installed).

Table I-17: Procedure Number M-0001, Air Handler, Inspection & Cleaning (Continued)

Block Title	Text
A2	Record air temperature differential across cooling coils.
A3	Record air temperature differential across reheat coil.
A4	De-energize equipment and tag out in accordance with site safety practices.
A5	Open access covers and doors. Remove pulley and belt guards.
A4	Inspect pulley and belts. Replace belts if needed. Align belt sheave and adjust belt tension using tensiomometer.
Note	When replacing belts, replace all belts on multi-belt pulley. Note on work order.
A5	Clean cooler drains and condensate pans.
A6	Renew biological control tablet (if used).
A7	Clean fan or blower blades.
A8	Clean coils (cooling, heating, preheat, reheat).
A9	Clean motor air inlet and exit.
A10	Inspect motor mounts, seals, valves, gauges, fittings, ducts and other parts and accessories for corrosion, leaks, looseness, and damage.
A11	Inspect gages, thermometers, and indicators for proper calibration. Note any overdue items on work order.
A12	Make minor repair. Contact supervisor if repairs are not possible. Note on work order.
A13	Replace air filters
A14	Perform touchup painting as required.
A15	Perform related tasks, if any.
A16	Replace pulley and belt guards.
A17	Close access covers and doors and return air handler to service.

Table I-17: Procedure Number M-0001, Air Handler, Inspection & Cleaning (Continued)

Block Title	Text
A18	Remove debris from work-site.
Inspection Data	Fill in all applicable.
ID-1	Air filter differential pressure.
ID-2	Air temperature differential across cooling coils. (F or C)
ID-3	Air temperature differential across reheat coil. (F or C)
Engineer's Notes	
EN1	Biological control tablets are used to control fungus and bacterial growth in the condensate pan. Contact environmental control personnel for the proper agents/tablets.
EN2	PT&I group needs to know if belts are changed or aligned.

Table I-18: Procedure Number M-0002, Chiller Inspection

Block Title	Text
Procedure Number	M-0002
System Description	Chiller
Procedure Description	1. Open and Inspect
	2. Clean
Related Tasks	PT&I-0001, PT&I-0003
Periodicity	A
Labor (Hrs)	2 people/4 hr ea
Special Tools	Halide Leak Detector, Electronic Leak Detector, Ultrasonic Noise Detector
Materials	Tube Plugging Kit, Oil Filter
Reference Data	OEM Drawings and Procedures
Warning Summary	1. Liquid or gas may be environmental hazard.
	2. Extreme pressure or vacuum may be present.
Caution Summary	
Reserved	
Preliminary	
1	Review prior maintenance data including vibration data test results (if available).
	Notify operators or other local occupant before starting inspection.
2	Ensure equipment/component identification (name and/or number) is legible and securely affixed to equipment. Repair as required.
3	For any step in procedure, record unsatisfactory conditions on work order and report them to supervisor.

Table I-18: Procedure Number M-0002, Chiller Inspection (Continued)

Block Title	Text
Procedure	
A	Tube Leak Test
A1	De-energize equipment and tag out in accordance with site safety practices.
A2	Isolate fluid systems and tag out in accordance with site safety practices.
Note	Check with site environmental control personnel before venting or draining any gas or liquid from unit.
WARNING	Liquid or gas may be environmental hazard.
WARNING	Extreme pressure or vacuum may be present.
A3	Open condenser/cooler vent and equalize pressure.
A4	Drain condenser/cooler.
A5	Open condenser/cooler access covers or remove shell head. See OEM for procedure.
A4	Perform tube leak test.
A5	Repair leaking tube. Plug tubes that can not be repaired.
A6	Record on work order tubes repaired or plugged.
Note	See OEM manual for tube location diagram.
B	Clean and Inspect
B1	Replace oil filter, clean oil line strainer.
B2	Clean compressor oil cooler and gear box oil cooler.
B3	Calibrate chiller control system, load limiting system, and safety controls.
WARNING	Extreme pressure or vacuum may be present.

Table I-18: Procedure Number M-0002, Chiller Inspection (Continued)

Block Title	Text
WARNING	Liquid or gas may be environmental hazard.
B4	Drain purge unit.
B5	Clean purge condensing unit tubes, shell, water compartment, float and chamber.
B6	Inspect mounts, seals, valves, gauges, fittings, and other parts and accessories for corrosion, leaks, looseness, and damage.
B7	Inspect gages, thermometers, and indicators for proper calibration. Note any overdue items on work order.
B8	Make minor repair. Contact supervisor if repairs are not possible. Note on work order.
B9	Perform touchup painting as required.
B10	Perform related tasks, if any.
B11	Replace parts and covers removed for cleaning or testing.
B12	Fill and leak test unit.
B13	Return chiller to service.
B14	Remove debris from work-site.
Engineer's Notes	
EN1	See manufacturers have specification for limit regarding maximum number of plugged tubes.
EN2	Notify PT&I group following this procedure to schedule condition monitoring retest.

Table I-19: Procedure Number M-0003, Post Indicator Valve, Inspection & Cleaning

Block Title	Text
Procedure Number	M-0003
System Description	Post Indicator Valve
Procedure Description	Inspect and Clean
Related Tasks	PT&I-0002
Periodicity	S
Labor (Hrs)	1
Special Tools	
Materials	Lubricants
Reference Data	
Warning Summary	High pressure may be present
Caution Summary	
Reserved	
Preliminary	
1	Notify operators or other local occupant before starting inspection.
2	Ensure equipment/component identification (name and/or number) is legible and securely affixed to equipment. Repair as required.
3	For any step in procedure, record unsatisfactory conditions on work order and report them to supervisor.
Procedure	
A	Inspect and clean.
A1	Remove set screw, cap and seal.
A2	Apply lubricant to threads, open and close valve.

Table I-19: Procedure Number M-0003, Post Indicator Valve, Inspection & Cleaning (Continued)

Block Title	Text
A3	Check operation of, and sign and clean glass indicator windows.
A4	Install cap and tighten screw, install handle and wire seal with handle open.
A5	Clean valve exterior and area around valve.
A6	Fill out maintenance checklist and report deficiencies
Engineer's Notes	

Table I-20: Hot Water Procedure Number M-0004, Boiler, Inspection & Cleaning

Block Title	Text
Procedure Number	M-0004
System Description	Hot Water Boiler, Oil/Gas/Comb, 120 to 500 MBH
Procedure Description	Inspect and Clean
Related Tasks	PT&I-0002
Periodicity	A
Labor (Hrs)	4
Special Tools	Vacuum cleaner
Materials	
Reference Data	
Warning Summary	Extreme temperatures and pressures may be present
Caution Summary	Notify operators or other local occupant before starting inspection.
Reserved	
Preliminary	
1	Review prior maintenance data including infrared data test results (if available).
2	Ensure equipment/component identification (name and/or number) is legible and securely affixed to equipment. Repair as required.
3	For any step in procedure, record unsatisfactory conditions on work order and report them to supervisor.
Procedure	
A	Inspect and Clean
A1	Check combustion chamber for air or gas leaks.

Table I-20: Hot Water Procedure Number M-0004, Boiler, Inspection & Cleaning (Continued)

Block Title	Text
A2	Inspect and clean oil burner gun and ignition assembly where applicable.
A3	Inspect fuel system for leaks and change fuel filter element, where applicable.
A4	Check fuel lines and connections for damage.
A5	Check for proper operational response of burner to thermostat controls.
A6	Check and lubricate burner and blower motors
A7	Check main flame failure protection and main flame detection scanner on boiler equipped with spark ignition (oil burner).
A8	Check electrical wiring to burner controls and blower.
A9	Clean firebox (sweep and vacuum).
A10	Check operation of mercury control switches (i.e., steam pressure, hot water temperature limit, atomizing or combustion air proving, etc.)
A11	Check operation and condition of safety pressure relief valve.
A12	Check operation of boiler low water cutoff devices.
A13	Check hot water pressure gages.
A14	Inspect and clean water column sight glass (or replace).
A15	Check condition of flue pipe, damper and exhaust stack.
A16	Check boiler operation through complete cycle, up to 30 minutes.
A17	Check fuel level with gauge pole, add as required.
A18	Clean area around boiler.
A19	Fill out maintenance checklist and report deficiencies.
Engineer's Notes	

Table I-21: Procedure Number M-0005, Fan Coil Unit, Inspection and Cleaning

Block Title	Text
Procedure Number	M-0005
System Description	Fan Coil Unit
Procedure Description	Inspect and Clean
Related Tasks	PT&I-0003
Periodicity	S
Labor (Hrs)	2
Special Tools	Vacuum Cleaner
Materials	Filters, Lubricants
Reference Data	
Warning Summary	
Caution Summary	
Reserved	
Preliminary	
1	Notify operators or other local occupant before starting inspection.
2	Ensure equipment/component identification (name and/or number) is legible and securely affixed to equipment. Repair as required.
3	For any step in procedure, record unsatisfactory conditions on work order and report them to supervisor.
Procedure	
A	Inspect and Clean
A1	Check with operating or area personnel for deficiencies.
A2	Check coil unit while operating.

Table I-21: Procedure Number M-0005, Fan Coil Unit, Inspection and Cleaning (Continued)

Block Title	Text
A3	Remove access panel and vacuum inside of unit and coils.
A4	Check coils and piping for leaks, damage and corrosion; repair as necessary.
A5	Lubricate blower shaft and fan motor bearings.
A6	Clean coil, drip pan, and drain line with solvent.
A7	Replace filters as required.
A8	Replace access panel.
A9	Check operation after repairs.
A10	Clean area.
A11	Fill out maintenance checklist and report deficiencies.
Engineer's Notes	

Table I-22: Procedure Number M-0006, Condensate Return Pump, Inspection and Cleaning

Block Title	Text
Procedure Number	M-0006
System Description	Condensate Return Pump, over 1 H.P.
Procedure Description	Inspect and Clean
Related Tasks	PT&I-0001, PT&I-0002, PT&I-0003
Periodicity	S
Labor (Hrs)	1
Special Tools	
Materials	Lubricants
Reference Data	
Warning Summary	
Caution Summary	
Reserved	
Preliminary	
1	Review prior maintenance data including vibration data test results (if available).
2	Ensure equipment/component identification (name and/or number) is legible and securely affixed to equipment. Repair as required.
3	For any step in procedure, record unsatisfactory conditions on work order and report them to supervisor.
Procedure	
A	Inspect and Clean
A1	Check for proper operation of pump.

Table I-22: Procedure Number M-0006, Condensate Return Pump, Inspection and Cleaning (Continued)

Block Title	Text
A2	Check for leaks on suction and discharge piping, seals, packing glands, etc.; make minor adjustments as necessary.
A3	Check pump and motor operation for vibration, noise, overheating, etc.
A4	Check alignment of pump and motor; adjust as necessary.
A5	Lubricate as necessary.
A6	Clean exterior of pump, motor and surrounding area.
A7	Fill out maintenance checklist and report deficiencies.
Inspection Data	
Engineer's Notes	

Table I-23: Procedure Number M-0007, Centrifugal Pump, Inspection and Cleaning

Block Title	Text
Procedure Number	M-0007
System Description	Centrifugal Pump w/reduction gear, over 1 H.P.
Procedure Description	Inspect and Clean
Related Tasks	PT&I-0001, PT&I-0002, PT&I-0003
Periodicity	S
Labor (Hrs)	1
Special Tools	
Materials	Lubricants
Reference Data	
Warning Summary	
Caution Summary	
Reserved	
Preliminary	
1	Review prior maintenance data including vibration data test results (if available).
2	Ensure equipment/component identification (name and/or number) is legible and securely affixed to equipment. Repair as required.
3	For any step in procedure, record unsatisfactory conditions on work order and report them to supervisor.
Procedure	
A	Inspect and Clean
A1	Check with operating or area personnel for deficiencies.

Table I-23: Procedure Number M-0007, Centrifugal Pump, Inspection and Cleaning (Continued)

Block Title	Text
A2	Clean pump exterior and check for corrosion on pump exterior and base plate.
A3	Check for leaks on suction and discharge piping, seals, packing glands, etc.
A4	Check pump, gear and motor operation for vibration, noise, overheating, etc.
A5	Check alignment and clearances of shaft reduction gear and coupler.
A6	Tighten or replace loose, missing, or damaged nuts, bolts and screws.
A7	Lubricate pump and motor as required.
A8	When available, check suction or discharge, pressure gauge readings and flow rate.
A9	Clean area around pump.
A10	Fill out maintenance checklist and report deficiencies.
Inspection Data	Fill in all applicable.
ID-1	Suction or discharge pressure.
ID-2	Flow rate.
Engineer's Notes	

Table I-24: Procedure Number M-0008, Air Conditioning, Split System, Inspection and Cleaning

Block Title	Text
Procedure Number	M-0008
System Description	Air Conditioning Split System, DX, air-cooled, over 10 tons
Procedure Description	Inspect and Clean
Related Tasks	PT&I-0001, PT&I-0003
Periodicity	A
Labor (Hrs)	2
Special Tools	Steam Cleaner, Belt Tensiomometer
Materials	Filters, Refrigerant, Lubricant, Belts
Warning Summary	
Caution Summary	
Preliminary	
1	Review prior maintenance data including vibration data test results (if available).
	Notify operators or other local occupant before starting inspection.
2	Ensure equipment/component identification (name and/or number) is legible and securely affixed to equipment. Repair as required.
3	For any step in procedure, record unsatisfactory conditions on work order and report them to supervisor.
Procedure	
A	Inspect and Clean
A1	Check with operating or area personnel for deficiencies.
A2	Check tension, condition, and alignment of belts; adjust/replace as necessary.

Table I-24: Procedure Number M-0008, Air Conditioning, Split System, Inspection and Cleaning (Continued)

Block Title	Text
A3	Lubricate shaft and motor bearings, as necessary.
A4	Pressure wash condenser coils with coil clean solution, as required.
A5	Replace air filters.
A6	Clean electrical wiring and connections and tighten loose connections.
A7	Clean evaporator coils, drain pan, blowers, fans, motors and drain piping as required.
A8	Perform operational check of unit; make adjustments on controls and other components as required.
A9	During operation of unit, check refrigerant pressure; add refrigerant as necessary.
A10	Check compressor oil levels; add oil as required.
A11	Clean area around equipment.
A12	Fill out maintenance checklist and report deficiencies.
Engineers Notes	
EN1	PT&I group needs to know if belts are changed or aligned.

Table I-25: Procedure Number M-0009, Air Compressor, Reciprocating, Inspection and Cleaning

Block Title	Text
Procedure Number	M-0009
System Description	Air Compressor Reciprocating, over 40 H.P.
Procedure Description	Inspect and Clean
Related Tasks	PT&I-0001, PT&I-0002, PT&I-0003
Periodicity	Q
Labor (Hrs)	2
Special Tools	Belt Tensiomometer
Materials	Air filter, Oil, Belts, Lubricants
Warning Summary	High pressures may be present.
Caution Summary	
Preliminary	
1	Review prior maintenance data including vibration data test results (if available).
2	Ensure equipment/component identification (name and/or number) is legible and securely affixed to equipment. Repair as required.
3	For any step in procedure, record unsatisfactory conditions on work order and report them to supervisor.
Procedure	
A	Inspect and Clean
A1	Check with operating or area personnel for deficiencies.
A2	Perform operational check of compressor system and adjust as required.
A3	Replace compressor oil.

Table I-25: Procedure Number M-0009, Air Compressor, Reciprocating, Inspection and Cleaning (Continued)

Block Title	Text
A4	Check motor(s) operation for excessive vibration, noise and overheating; lubricate motors, as necessary.
A5	Clean cylinder cooling fins and air cooler on compressor.
A6	Check tension, condition and alignment of V-belts; adjust/replace as necessary.
A7	Check operation of pressure relief valve.
A8	Check low-pressure cut-in and high-pressure cut-out switches.
A9	Drain moisture from air storage tank and check low pressure cut-in; while draining, check discharge for indication of interior corrosion.
A10	Clean air intake filter on air compressor(s); replace if necessary.
A11	Clean oil and water trap.
A12	Check indicating lamps or gages for proper operation if appropriate; replace burned out lamps or repair/replace gages.
A13	Clean area around equipment.
A14	Fill out maintenance checklist and report deficiencies.
Engineer's Notes	
EN1	PT&I group needs to know if belts are changed or aligned.

Table I-26: Procedure Number M-00010, Air Cooled Condenser, Inspection and Cleaning

Block Title	Text
Procedure Number	M-0010
System Description	Air Cooled Condenser, 26 tons to 100 tons
Procedure Description	Inspect and Clean
Related Tasks	PT&I-0001, PT&I-0002, PT&I-0003
Periodicity	A
Labor (Hrs)	1
Special Tools	Belt Tensiomometer
Materials	Lubricant, Belts
Reference Data	
Warning Summary	
Caution Summary	Notify operators or other local occupant before starting inspection.
Reserved	
Preliminary	
	1. Review prior maintenance data including vibration data test results (if available). 2. Ensure equipment/component identification (name and/or number) is legible and securely affixed to equipment. Repair as required. 3.For any step in procedure, record unsatisfactory conditions on work order and report them to supervisor.
Procedure	
A	Inspect and Clean
A1	Check with operating or area personnel for deficiencies.
A2	Check unit for proper operation, excessive noise or vibration.
A3	Pressure wash coils and fans with coil cleaning solution.

Table I-26: Procedure Number M-00010, Air Cooled Condenser, Inspection and Cleaning (Continued)

Block Title	Text
A4	Check electrical wiring and connections; tighten loose connections.
A5	Lubricate shaft bearings and motor bearings, as necessary.
A6	Inspect fan(s) or blower(s) for bent blades or imbalance; adjust as necessary.
A7	Check belts for proper tension, condition and misalignment; adjust for proper tension and/or alignment, if applicable, replace as required.
A8	Inspect valves and piping for leaks; tighten connections as necessary.
A9	Clean area around equipment.
A10	Fill out maintenance checklist and report deficiencies.
Engineer's Notes	
EN1	PT&I group needs to know if belts are changed or aligned.

Table I-27: Procedure Number M-00011, Cooling Tower, Inspection and Cleaning

Block Title	Text
Procedure Number	M-0011
System Description	Cooling Tower, Water, 51 tons to 500 tons
Procedure Description	Inspect and Clean
Related Tasks	PT&I-0001, PT&I-0003
Periodicity	S
Labor (Hrs)	5
Special Tools	Belt Tensiomometer
Materials	Belts, Lubricants
Warning Summary	
Caution Summary	
Preliminary	
1	Review prior maintenance data including vibration data test results (if available).
2	Ensure equipment/component identification (name and/or number) is legible and securely affixed to equipment. Repair as required.
3	For any step in procedure, record unsatisfactory conditions on work order and report them to supervisor.
Procedure	
A	Inspect and Clean
A1	Check with operating or area personnel for deficiencies.
A2	Check operation of unit for water leaks, noise or vibration.
A3	Clean and inspect hot water basin.
A4	Remove access panel.

Table I-27: Procedure Number M-00011, Cooling Tower, Inspection and Cleaning (Continued)

Block Title	Text
A5	Check electrical wiring and connections; make appropriate adjustments.
A6	Lubricate all motor and fan bearings, as required.
A7	Check fan blades or blowers for imbalance and tip clearance.
A8	Check belts for wear, tension and alignment; adjust/replace as required.
A9	Drain and flush cold water sump and clean strainer.
A10	Clean inside of water tower using water hose; scrape, brush and wipe as required; heavy deposits of scale should be removed with scale removing compound.
A11	Refill with water, check make-up water assembly for leakage, and adjust float if necessary.
A12	Replace access panel.
A13	Remove, clean and reinstall conductivity and pH electrodes in chemical water treatment system.
A14	Inspect and clean around cooling tower.
A15	Fill out maintenance checklist and report deficiencies.
Engineer's Notes	
EN1	PT&I group needs to know if belts are changed or aligned.

Table I-28: Procedure Number M-00012, Heat Pump, Air Cooled, Inspection and Cleaning

Block Title	Text
Procedure Number	M-0012
System Description	Heat Pump, Air Cooled, over 5 tons
Procedure Description	Inspect and Clean
Related Tasks	PT&I-0001, PT&I-0003
Periodicity	A
Labor (Hrs)	2
Special Tools	Belt Tensiomometer
Materials	Drive Belt(s), Lubricants, Filters, Refrigerant
Reference Data	
Warning Summary	
Caution Summary	Notify operators or other local occupant before starting inspection.
Reserved	
Preliminary	
1	Review prior maintenance data including vibration data test results (if available).
2	Ensure equipment/component identification (name and/or number) is legible and securely affixed to equipment. Repair as required.
3	For any step in procedure, record unsatisfactory conditions on work order and report them to supervisor.
Procedure	
A	Inspect and Clean
A1	Check with operating or area personnel for deficiencies.
A2	Check unit for proper operation, excessive noise or vibration.

Table I-28: Procedure Number M-00012, Heat Pump, Air Cooled, Inspection and Cleaning (Continued)

Block Title	Text
A3	Clean intake side of condenser coils, fans and intake screens.
A4	Check electrical wiring and connections; tighten loose connections.
A5	Inspect fan(s) for bent blades or unbalance; adjust and clean as necessary.
A6	Check belts for condition, proper tension and misalignment; adjust/replace as required.
A7	Lubricate shaft bearings and motor bearings, as necessary.
A8	Inspect piping and valves for leaks; tighten connections as necessary.
A9	Replace air filters.
A10	Check refrigerant pressure, add refrigerant as necessary.
A11	Lubricate and check operation of dampers, if applicable.
A12	Check compressor oil levels and add oil, if required.
A13	Cycle the reverse cycle valve to insure proper operation.
A14	Clean evaporative drain pan, and drain piping as required.
A15	Clean area around equipment.
A16	Fill out maintenance checklist and report deficiencies.
Inspection Data	
Engineer's Notes	
EN1	PT&I group needs to know if belts are changed or aligned.

Table I-29: Procedure Number M-00013, Package Unit, Computer Room, Inspection and Cleaning

Block Title	Text
Procedure Number	M-0013
System Description	Package Unit, Computer Room
Procedure Description	Inspect and Clean
Related Tasks	PT&I-0001, PT&I-0003
Periodicity	A
Labor (Hrs)	2
Special Tools	Belt Tensiomometer
Materials	Filters, Refrigerant, Lubricant, Belts
Warning Summary	
Caution Summary	
Preliminary	
1	Review prior maintenance data including vibration data test results (if available).
	Notify operators or other local occupant before starting inspection.
2	Ensure equipment/component identification (name and/or number) is legible and securely affixed to equipment. Repair as required.
3	For any step in procedure, record unsatisfactory conditions on work order and report them to supervisor.
Procedure	
A	Inspect and Clean
A1	Check with operating or area personnel for deficiencies.
A2	Run microprocessor check, if available, or check controls and unit for proper operation.

Table I-29: Procedure Number M-00013, Package Unit, Computer Room, Inspection and Cleaning (Continued)

Block Title	Text
A3	Check for unusual noise or vibration.
A4	Clean coils, evaporator drain pan, humidifier pan, blower, motor and drain piping, as required.
A5	Replace air filters.
A6	Lubricate shaft and motor bearings, as necessary.
A7	Check tension, condition, and alignment of belts; adjust as necessary.
A8	Check humidity lamp, replace if necessary.
A9	During operation of unit, check refrigerant pressure; add refrigerant as necessary.
A10	Inspect exterior piping and valves for leaks; tighten connections as required.
A11	Clean area around equipment.
A12	Fill out maintenance checklist and report deficiencies.
Engineers Notes	
EN1	PT&I group needs to know if belts are changed or aligned.

Table I-30: Procedure Number M-00014, Pump, Air Lift, Well, Inspection and Cleaning

Block Title	Text
Procedure Number	M-0014
System Description	Pump, Air Lift, Well
Procedure Description	Inspect and Clean
Related Tasks	PT&I-0001, PT&I-0002
Periodicity	S
Labor (Hrs)	1
Special Tools	
Materials	Lubricants, Oil
Reference Data	
Warning Summary	
Caution Summary	Notify operators or other local occupant before starting inspection.
Reserved	
Preliminary	
1	Review prior maintenance data including vibration data test results (if available).
2	Ensure equipment/component identification (name and/or number) is legible and securely affixed to equipment. Repair as required.
3	For any step in procedure, record unsatisfactory conditions on work order and report them to supervisor.

Table I-30: Procedure Number M-00014, Pump, Air Lift, Well, Inspection and Cleaning (Continued)

Block Title	Text
Procedure	
A	Inspect and Clean
A1	Check with pump operating personnel for deficiencies.
A2	Check for proper operation of compressor and pump.
A3	Check water sample for air or water contamination.
A4	Check compressor oil level, add oil as necessary and lubricate pump and compressor shaft bearings as applicable.
A5	Inspect electrical system for frayed wires or loose connections; repair as required.
A6	Check and cycle high and low shut off valves.
A7	Inspect and clean air intake filter.
A8	Clean pump body and tighten or replace loose hardware.
A9	Calibrate and adjust pressure gauge.
A10	Clean surrounding area.
A11	Fill out maintenance checklist and report deficiencies.
Inspection Data	
Engineer's Notes	

Table I-31: Procedure Number M-00015, Forced Air Heater, Inspection and Cleaning

Block Title	Text
Procedure Number	M-0015
System Description	Forced Air Heater, Oil/Gas fired, up to 120 MBH
Procedure Description	Inspect and Clean
Related Tasks	PT&I-0001, PT&I-0002, PT&I-0003
Periodicity	A
Labor (Hrs)	3
Special Tools	Belt Tensiomometer
Materials	Filters (air and fuel), Lubricant, Belts
Reference Data	
Warning Summary	
Caution Summary	
Reserved	
Preliminary	
1	Review prior maintenance data including vibration data test results (if available).
	Notify operators or other local occupant before starting inspection.
2	Ensure equipment/component identification (name and/or number) is legible and securely affixed to equipment. Repair as required.
3	For any step in procedure, record unsatisfactory conditions on work order and report them to supervisor.

Table I-31: Procedure Number M-00015, Forced Air Heater, Inspection and Cleaning (Continued)

Block Title	Text
Procedure	
A	Inspect and Clean
A1	Check with operating or area personnel for deficiencies.
A2	Inspect, clean and adjust electrodes and nozzles on oil burners or controls valves and thermo-sensing bulbs on gas burners; lubricate oil burner motor bearings as applicable.
A3	Inspect fuel system for leaks.
A4	Change fuel filter element on oil burner, where applicable.
A5	Check for proper operation of primary controls, and check and adjust thermostat.
A6	Replace air filters in air handler.
A7	Check blower and motor for noise and vibration and lubricate bearings, as applicable.
A8	Check belts for wear and proper tension, tighten if required.
A9	Check electrical wiring to burners, controls and blower.
A10	Inspect and clean firebox.
A11	Clean blower and air plenum.
A12	Check condition of flue pipe, damper and stack.
A13	Check furnace operation through complete cycle or up to 10 minutes.
A14	Clean area around furnace.
A15	Fill out maintenance checklist and report deficiencies.
Engineers Notes	
EN1	PT&I group needs to know if belts are changed or aligned.

Table I-32: Procedure Number M-00016, Valve, Automatic, Inspection and Cleaning

Block Title	Text
Procedure Number	M-0016
System Description	Valve, Automatic, above 4 inches
Procedure Description	Inspect and Clean
Related Tasks	PT&I-0002
Periodicity	A
Labor (Hrs)	1
Special Tools	
Materials	Lubricants
Reference Data	
Warning Summary	High pressure may be present
Caution Summary	
Reserved	
Preliminary	
1	Notify operators or other local occupant before starting inspection.
2	Ensure equipment/component identification (name and/or number) is legible and securely affixed to equipment. Repair as required.
3	For any step in procedure, record unsatisfactory conditions on work order and report them to supervisor.
Procedure	
A	Inspect and clean.
A1	Lubricate valve actuator stem and valve stem, where possible.
A2	Check automatic valve for proper operation.

Table I-32: Procedure Number M-00016, Valve, Automatic, Inspection and Cleaning (Continued)

Block Title	Text
A3	Check packing gland for leaks; adjust as required.
A4	Check pneumatic operator and tubing for air leaks.
A5	Clean valve exterior and area around valve.
A6	Fill out maintenance checklist and report deficiencies
Engineer's Notes	

Table I-33: Procedure Number M-00017, Valve, Butterfly Inspection and Cleaning

Block Title	Text
Procedure Number	M-0017
System Description	Valve, Butterfly, auto, above 4 inches
Procedure Description	Inspect and Clean
Related Tasks	PT&I-0002
Periodicity	A
Labor (Hrs)	1
Special Tools	
Materials	Lubricants
Reference Data	
Warning Summary	High pressure may be present
Caution Summary	
Reserved	
Preliminary	
1	Notify operators or other local occupant before starting inspection.
2	Ensure equipment/component identification (name and/or number) is legible and securely affixed to equipment. Repair as required.
3	For any step in procedure, record unsatisfactory conditions on work order and report them to supervisor.
Procedure	
A	Inspect and clean.
A1	Lubricate valve actuator stem and valve stem where possible.
A2	Check automatic valve for proper operation.

Table I-33: Procedure Number M-00017, Valve, Butterfly Inspection and Cleaning (Continued)

Block Title	Text
A3	Check packing gland for leaks; adjust as required.
A4	Check pneumatic operator and tubing for air leaks.
A5	Clean valve exterior and area around valve.
A6	Fill out maintenance checklist and report deficiencies
Engineer's Notes	

APPENDIX J: GENERIC FMEA WORKSHEETS

Table J-1. Air Cooled HVAC

Control Number	Name	Function/ Performance Requirement	Potential Failure Modes	Potential Failure Effects	Crit	Prob	PROD	MA Code	Maintenance Approach	Remarks/Continue
1	HVAC System	Provide sufficient air flow at required pressure and temperature to meet design requirements.	See Below	Loss of atmosphere control.	7	3	21	PM, CdM	Combination of visual inspection, vibration analysis, oil analysis, electrical and thermodynamic testing. In addition, PM routines and water quality and non-destructive testing	Water treatment for chilled and condenser water.
1.1	Chiller	Chill water in sufficient quantity to provide designed cooling.	See Below	Loss of chilled water	5	3	15	PM, CdM	Combination of visual inspection, vibration analysis, oil analysis, electrical and thermodynamic testing. In addition, PM routines and water quality and non-destructive testing	Redundant Chillers
1.1.2	Condenser	Transfer heat from the refrigerant to the condenser	Erosion, corrosion, fouling/scaling	Reduced water flow/thermal efficiency, increased electrical consumption	5	3	15	PM, CdM	BAS trending	Trend logs should be established in the BAS to measure and trend thermal performance and energy usage

Table J-1. Air Cooled HVAC (Continued)

Control Number	Name	Function/ Performance Requirement	Potential Failure Modes	Potential Failure Effects	Crit	Prob	PROD	MA Code	Maintenance Approach	Remarks/Continue
1.1.2.1.	Condenser Barrel	Contain the refrigerant	Corrosion, cracking, seal failure of end bells	Environmental impact, reduced thermal efficiency, compressor shutdown.	5	2	10	PM, CdM	Visual inspection, halogen detection, airborne ultrasonics, differential temperature	Includes end caps.
1.1.2.2	Tubes	Separate the water from the refrigerant and transfer heat.	Tube fouling, pitting, corrosion	Reduced heat transfer, leaks	5	2	10	PM, CdM	Differential temperature, visual inspection, eddy current testing, hydrostatic testing	Note: Tubes should be rodded out based on thermodynamic test results.
1.1.2.3	Evaporator	Transfer heat from the refrigerant to the condenser	Erosion, corrosion, fouling/scaling	Reduced water flow/thermal efficiency, increased electrical consumption	5	2	10	PM, CdM	Differential temperature, visual inspection	
1.1.3	Scroll Compressor	Compress the refrigerant into a high pressure liquid using a stationary and orbiting scroll.	Galling, scoring, corrosion, erosion, bearing failure	Loss of or reduced environmental control	5	2	10	PM, CdM	Vibration monitoring, oil analysis, leak detection, thermal perfromance	Redundant compressor capability exists

Table J-1. Air Cooled HVAC (Continued)

Control Number	Name	Function/ Performance Requirement	Potential Failure Modes	Potential Failure Effects	Crit	Prob	PROD	MA Code	Maintenance Approach	Remarks/Continue
1.1.3.1	Motor	Convert electrical energy to mechanical energy. Provide sufficient torque and speed to meet design specifications.	Listed in line items 1.1.3.1.1 - 1.1.3.1.4	Loss of cooling Specific equipment failure effects listed in line items 1.1.3.1.1 - 1.1.3.1.4	5	3	15	PM, CdM	Combination of visual inspection, resistance testing, measurement of running current, and motor current signature analysis.	
1.1.3.1.1	Frame	Maintain correct geometry for rotating assembly. Minimize environmental impact.	Corrosion, structural failure	Interference between stator and rotor. Nonsymmetrical air gap.	5	1	5	PM, CdM	Visual inspection	
1.1.3.1.2	Stator	Provide rotating magnetic field for induction.	Breakdown of insulation, high impedance connections, turn-to-turn shorts, open conductor path.	Low or zero resistance to ground. Increased vibration. Nonsymmetrical magnetic field.	5	2	10	PM, CdM	Insulation resistance testing, measurement of running current	

Table J-1. Air Cooled HVAC (Continued)

Control Number	Name	Function/ Performance Requirement	Potential Failure Modes	Potential Failure Effects	Crit	Prob	PROD	MA Code	Maintenance Approach	Remarks/Continue
1.1.3.1.3	Rotors	Transfer energy to fan impeller via sheaves and drive belts.	Broken rotor bars. Shaft failure.	Reduced torque, increased vibration levels, change in current signature.	5	2	10	PM, CdM	Motor current signature analysis	
1.1.3.1.4	Bearings	Reduce friction and maintain geometry of rotor to stator.	Fatigue, contamination, under/over lubrication, overload, misalignment, imbalance	Increased temperature, increased vibration/noise levels, seized motor	5	3	15	PM, CdM	Oil analysis, open and inspect	Vibration analysis/temperature measurement is not effective on reciprocating chillers of this type
1.1.3.2.7	Valves	Control discharge for loading	Fatigue cracks, work hardening (loss of tension)	Low discharge/suction pressure, reduced cooling	5	3	15	PM, CdM	Measure suction & discharge pressure and compare, open & inspect, oil analysis	
1.1.3.2.9	Case	Contain refrigerant under pressure and provide structural integrity	Cracking, thermal stress	Loss of lubricant and refrigerant. Unit failure	5	1	5	PM, CdM	Visual inspection	

Table J-1. Air Cooled HVAC (Continued)

Control Number	Name	Function/ Performance Requirement	Potential Failure Modes	Potential Failure Effects	Crit	Prob	PROD	MA Code	Maintenance Approach	Remarks/Continue
1.1.3.2.10	Oil Pump	Provide sufficient oil pressure and flow to lubricate and cool bearings, reduce ring and cylinder wear	Catastrophic failure	Unit shutdown, total loss of cooling	5	2	10	PM, CdM	Automatic shutdown on low pressure, open and inspect, oil analysis	
1.1.3.2.11	Heater	Reduce oil viscosity and minimize refrigerant contamination	Increases starting current	Reduces motor life	5	3	15	PM, CdM	Check oil temperature	
1.2	Piping	Contain and direct the flow of water to specified location	Corrosion, erosion, fatigue	Flooding, no water at point of use	5	1	5	PM, CdM	Visual inspection, thickness measurement	Single point of failure for majority of piping.
1.3	Valves	Isolate sections/components for maintenance and/or repair. Throttle flow. Prevent backflow.	Dominant failure modes for valves are leaking around stem and bonnet, debris and erosion on sealing surfaces, corrosion, insufficient energy for actuation (voltage or pressure), broken return spring, improper calibration (automatic valves) and over-pressure discharge (pressure relief valves). Valves in continuous service are rarely operated and are the most susceptible to failure when needed during shutdown.	Reduced thermal efficiency, refrigerant leaks	5	2	10	PM, CdM	Leak detection, visual inspection, trend thermal performance, refrugerant usage.	Reduced thermal perfromance could be the result of valave seat leakage or valva operator degradation

Table J-1. Air Cooled HVAC (Continued)

Control Number	Name	Function/ Performance Requirement	Potential Failure Modes	Potential Failure Effects	Crit	Prob	PROD	MA Code	Maintenance Approach	Remarks/Continue
1.3.1	Isolation Valves	Isolate sections/components for maintenance and/or repair	Galling, scoring, corrosion, erosion	Flooding	5	1	5		Visual inspection/operational checks	
1.3.2	Throttle Valves	Control flow	Galling, scoring, corrosion, erosion	Excessive flow or pressure	5	2	10	PM, CdM	Visual inspection/operational checks, leak detection, refrigerant usage	
1.3.3	Check Valves	Prevent back flow		Back flow, loss of pressure /flow at point of use						
1.3.4	Pressure Relief	Prevent over-pressurization and structural failure.		System/component ruputre. Flooding.						
1.3.5	Vacuum Breakers	Prevent under-pressurization and structural failure.		System/component collapse. Flooding.						
1.4	Pump	Provide sufficient flow and pressure to meet heat transfer requirements.	Fatigue, contamination, under/over lubrication, overload, misalignment, imbalance	Loss of redundancy	5	3	15	PM, CdM	Vibration analysis, temperature measurement, lubrication, visual inspection, operational test	Redundant Pumps

Table J-1. Air Cooled HVAC (Continued)

Control Number	Name	Function/ Performance Requirement	Potential Failure Modes	Potential Failure Effects	Crit	Prob	PROD	MA Code	Maintenance Approach	Remarks/Continue
1.4.1	Casing	Maintain proper geometry between stationary and rotating elements. Contain water	Erosion, corrosion, fatigue	Loss or reduced pumping capacity	5	1	5	PM	Visual inspection	
1.4.2	Impeller	Provide required pressure and flow	Erosion, corrosion, fatigue	Reduced pressure and flow	5	1	5	CdM	Vibration analysis	
1.4.3	Seals	Provide a seal between the shaft and the casing to contain the water	Imbalance, misalignment, friction, erosion, corrosion	Loss of pumping capacity, flooding	5	3	15	PM, CdM	Visual inspection	Misalignment has historically reduced seal life.
1.4.4	Bearings	Reduce friction and maintain geometry of rotor to stator.	Fatigue, contamination, under/over lubrication, overload, misalignment, imbalance	Increased temperature, increased vibration/noise levels, seized motor	5	3	15	CdM	Vibration analysis, temperature measurement, lubrication	

Table J-1. Air Cooled HVAC (Continued)

Control Number	Name	Function/ Performance Requirement	Potential Failure Modes	Potential Failure Effects	Crit	Prob	PROD	MA Code	Maintenance Approach	Remarks/Continue
1.5	Coupling	Provide flexible connection between pump and motor to reduce effect of misalignment	Misalignment, overload	Loss of pump	5	3	15	CdM	Visual inspection, vibration analysis, temperature measurement	Sensitive to misalignment
1.6	AHU	Circulates air at designed flow and pressure.	See Below	Loss or reduced air flow	7	3	21	PM, CdM	Combination of visual inspection, vibration monitoring, condition based lubrication, insulation resistance testing, measurement of running current. Thermodynamic process monitoring.	
1.6.1	Supply/Return Fan	Circulates air at designed flow and pressure.	See Below	Loss or reduced air flow	7	3	21	CdM	Combination of visual inspection, vibration monitoring, condition based lubrication, insulation resistance testing, measurement of running current. Thermodynamic process monitoring.	

Table J-1. Air Cooled HVAC (Continued)

Control Number	Name	Function/ Performance Requirement	Potential Failure Modes	Potential Failure Effects	Crit	Prob	PROD	MA Code	Maintenance Approach	Remarks/Continue
1.6.2	Fan Motors	Convert electrical energy to mechanical energy. Provide sufficient torque and speed to meet design specifications.	Listed in line items 1.2.1.1.1 - 1.2.1.3.1	Loss of air flow. Specific equipment failure effects listed in line items 1.2.1.1.1 - 1.2.1.3.1	7	3	21	PM, CdM	Combination of visual inspection, vibration monitoring, condition based lubrication, insulation resistance testing, measurement of running current. Thermodynamic process monitoring.	For high efficiency motors the power quality should be measured to ensure that negative sequencing currents do not occur.
1.6.2.1	Frame	Maintain correct geometry for rotating assembly. Minimize environmental impact.	Corrosion, structural failure	Interference between stator and rotor. Nonsymmetrical air gap.	7	1	7	CdM	Visual inspection	
1.6.2.2	Stator	Provide rotating magnetic field for induction.	Breakdown of insulation, high impedance connections, turn-to-turn shorts, open conductor path.	Low or zero resistance to ground. Increased vibration. Nonsymmetrical magnetic field.	7	2	14	CdM	Insulation resistance testing, measurement of running current	

Table J-1. Air Cooled HVAC (Continued)

Control Number	Name	Function/ Performance Requirement	Potential Failure Modes	Potential Failure Effects	Crit	Prob	PROD	MA Code	Maintenance Approach	Remarks/Continue
1.6.2.3.	Rotor	Transfer energy to fan impeller via sheaves and drive belts.	Broken rotor bars. Shaft failure.	Reduced torque, increased vibration levels, change in current signature.	7	2	14	CdM	Vibration analysis	
1.6.2.4	Bearings	Reduce friction and maintain geometry of rotor to stator.	Fatigue, contamination, under/over lubrication, overload, misalignment, imbalance	Increased temperature, increased vibration/noise levels, seized motor	7	3	21	CdM	Vibration analysis, temperature measurement	Motor bearings are to be lubricated only when there is excessive noise/vibration or increased end cap temperature.
1.6.3	Sheaves	Transfer energy from motor to belts and to fan sheave.	Friction wear, misalignment, mechanical failure	Increased vibration/noise levels, reduced airflow, loss of airflow	7	4	28	CdM	Visual inspection, measurement of sheaves, vibration analysis, temperature measurement	
1.6.4	Belts	Transfer energy to fan impeller via sheaves.	Glazing, cracking	Increased vibration/noise levels, reduced airflow, loss of airflow	7	4	28	CdM	Visual inspection, vibration analysis, temperature measurement	

Table J-1. Air Cooled HVAC (Continued)

Control Number	Name	Function/ Performance Requirement	Potential Failure Modes	Potential Failure Effects	Crit	Prob	PROD	MA Code	Maintenance Approach	Remarks/Continue
1.7	Fan Impeller	Provide required air flow and discharge pressure.	Corrosion, imbalance, fatigue	Increased vibration/noise levels, reduced airflow, loss of airflow	7	2	14	CdM	Visual inspection, vibration analysis	
1.7.1	Fan bearings	Reduce friction and maintain geometry of rotor to stator.	Fatigue, contamination, under/over lubrication, overload, misalignment, imbalance	Increased temperature, increased vibration/noise levels, seized fan	7	3	21	CdM, PM	Vibration, temperature measurement, visual inspection and periodic lubrication	Fan (pillow block bearings) should be relubricated semiannually if operating speed is over 1500 RPM and annually if operating speed is les than 1500 RPM when high noise/vibration levels exist or high bearing temperature.
1.7.2	Housing/ Frame	Provide structural support to fan assembly and connection point to ducting.	Fatigue, corrosion, looseness	Increased vibration/noise levels, reduced airflow, loss of airflow	7	1	7	CdM	Visual inspection, vibration analysis	
1.8	Duct work	Contain and direct airflow	Fatigue, corrosion	Reduced/loss of airflow	7	1	7	PM	Visual inspection	
			Contamination	Sick building	8	3	24	CdM, PM	Visual inspection, air sampling	

Table J-1. Air Cooled HVAC (Continued)

Control Number	Name	Function/ Performance Requirement	Potential Failure Modes	Potential Failure Effects	Crit	Prob	PROD	MA Code	Maintenance Approach	Remarks/Continue
1.8.1	Dampers	Throttle and direct airflow	Fatigue, operator failure, galling	Reduced/loss of airflow	9	2	18	CdM, PM	Visual inspection, BAS operation	Potential pressurization and/or purge impact
1.9	Water Treatment	Filter and treat water to remove corrosive agents, minimize biologicals, and control pH.	Failed media, loss of chemical additive capability	Increased corrosion rate of components, loss of system integrity, flooding, loss of cooling	7	2	14	CdM, PM	Measure pH and hardness, visual inspection for biological growth, and ensure chemical addition system is properly filled and operating.	The majority of the piping system is a single point of failure.
1.9.1	Filtration	Remove particulate matter from water	Tunneling	Particulate contamination, reduced water flow	7	2	14	CdM, PM	Monitor flow rate and differenial pressure	
			Clogged	Reduced water flow						
1.9.2	Ion Exchange	Remove unwarranted ions from water	Resin failure	Increased corrosion rate of components, loss of system integrity, flooding, loss of cooling	7	2	14	CdM, PM	Sample ion exchanger discharge. Measure pH, chloride concentration, check for resin beads.	
			Clogged	Reduced water flow						

Table J-1. Air Cooled HVAC (Continued)

Control Number	Name	Function/ Performance Requirement	Potential Failure Modes	Potential Failure Effects	Crit	Prob	PROD	MA Code	Maintenance Approach	Remarks/Continue
			Tunneling	Increased corrosion rate of components, loss of system integrity, flooding, loss of cooling						
1.9.3	Chemical Treatment	Control pH	Loss of chemical addition capability	Increased corrosion rate of components, loss of system integrity, flooding, loss of cooling	7	3	21	CdM, PM	Measure pH and ensure chemical addition system is properly filled and operating.	
		Control biologicals	Biological growth	Fouling of heat transfer surfaces and piping	8	1	8	CdM, PM	Sampling, visual inspection, ensure chemical addition system is functioning properly	
				Sickness, death	8	1	8	CdM, PM		
1.10	Variable Frequency Drive (VFD)	Vary speed of motor to control water/air flow based on demand. Improved energy efficiency.	Short or open circuits. Capacitor failure.	Loss of speed control. Increased energy consumption. Air flow imbalance.	4	2	8	CdM, PM	Operational test, thermography	Note: Narrowband vibration analysis of the associated motor will often show SCR firing degradations.

Table J-1. Air Cooled HVAC (Continued)

Control Number	Name	Function/ Performance Requirement	Potential Failure Modes	Potential Failure Effects	Crit	Prob	PROD	MA Code	Maintenance Approach	Remarks/Continue
1.11	Make-up AHU	Provide filtered, and scrubbed make-up air to ensure positive pressure in building.			9	2	18	CdM, PM		Note: Building has three pressurization zones.
1.11.1	Fan Motors	Convert electrical energy to mechanical energy. Provide sufficient torque and speed to meet design specifications.	Listed in line items 1.2.1.1.1 - 1.2.1.3.1	Loss of air flow. Specific equipment failure effects listed in line items 1.2.1.1.1 - 1.2.1.3.1	9	4	36	PM, CdM	Combination of visual inspection, vibration monitoring, condition based lubrication, insulation resistance testing, measurement of running current. Thermodynamic process monitoring.	For high efficiency motors the power quality should be measured to ensure that negative sequencing currents do not occur.
1.11.1.1	Frame	Maintain correct geometry for rotating assembly. Minimize environmental impact.	Corrosion, structural failure	Interference between stator and rotor. Nonsymmetrical air gap.	9	1	9	CdM	Visual inspection	

Table J-1. Air Cooled HVAC (Continued)

Control Number	Name	Function/ Performance Requirement	Potential Failure Modes	Potential Failure Effects	Crit	Prob	PROD	MA Code	Maintenance Approach	Remarks/Continue
1.11.1.2	Stator	Provide rotating magnetic field for induction.	Breakdown of insulation, high impedance connections, turn-to-turn shorts, open conductor path.	Low or zero resistance to ground. Increased vibration. Nonsymmetrical magnetic field.	9	2	18	CdM	Insulation resistance testing, measurement of running current	
1.11.1.3	Rotor	Transfer energy to fan impeller via sheaves and drive belts.	Broken rotor bars. Shaft failure.	Reduced torque, increased vibration levels, change in current signature.	9	2	18	CdM	Vibration analysis	
1.11.1.4	Bearings	Reduce friction and maintain geometry of rotor to stator.	Fatigue, contamination, under/over lubrication, overload, misalignment, imbalance	Increased temperature, increased vibration/noise levels, seized motor	9	3	27	CdM	Vibration analysis, temperature measurement	Motor bearings are to be lubricated only when there is excessive noise/vibration or increased end cap temperature.
1.12	Sheaves	Transfer energy from motor to belts and to fan sheave.	Friction wear, misalignment, mechanical failure	Increased vibration/noise levels, reduced airflow, loss of airflow	9	4	36	CdM	Visual inspection, measurement of sheaves, vibration analysis, temperature measurement	May be direct drive fan.

Table J-1. Air Cooled HVAC (Continued)

Control Number	Name	Function/ Performance Requirement	Potential Failure Modes	Potential Failure Effects	Crit	Prob	PROD	MA Code	Maintenance Approach	Remarks/Continue
1.13	Belts	Transfer energy to fan impeller via sheaves.	Glazing, cracking	Increased vibration/noise levels, reduced airflow, loss of airflow	9	4	36	CdM	Visual inspection, vibration analysis, temperature measurement	May be direct drive fan.
1.14	Fan Impeller	Provide required air flow and discharge pressure.	Corrosion, imbalance, fatigue	Increased vibration/noise levels, reduced airflow, loss of airflow	9	3	27	CdM	Visual inspection, vibration analysis	
1.14.1	Fan bearings	Reduce friction and maintain geometry of rotor to stator.	Fatigue, contamination, under/over lubrication, overload, misalignment, imbalance	Increased temperature, increased vibration/noise levels, seized fan	9	3	27	CdM, PM	Vibration, temperature measurement, visual inspection and periodic lubrication	Fan (pillow block bearings) should be relubricated semiannually if operating speed is over 1500 RPM and annually if operating speed is les than 1500 RPM when high noise/vibration levels exist or high bearing temperature.
1.14.2	Housing/Frame	Provide structural support to fan assembly and connection point to ducting.	Fatigue, corrosion, looseness	Increased vibration/noise levels, reduced airflow, loss of airflow	9	4	36	CdM	Visual inspection, vibration analysis	

Table J-1. Air Cooled HVAC (Continued)

Control Number	Name	Function/ Performance Requirement	Potential Failure Modes	Potential Failure Effects	Crit	Prob	PROD	MA Code	Maintenance Approach	Remarks/Continue
1.15	Duct work	Contain and direct airflow	Fatigue, corrosion, looseness, cracks	Reduced/loss of system integrity	9	4	36	CdM, PM	Visual inspection, pressurization combined with airborne ultrasonics.	Cracks, improperly sealed connections can result in system breach and contamination due to venturi effect.
			Non-biochem contamination	Sick building	9	1	9	CdM, PM	Visual inspection, air sampling	
1.15.1	Dampers	Throttle and direct airflow	Fatigue, operator failure, galling	Reduced/loss of airflow	9	4	36	CdM, PM	Visual inspection, BAS operation	
1.16	Filters	Filter, treat, and scrub airr to remove corrosive agents, organic and inorganic compounds, minimize biologicals	Clogged, tunneling, improperly seated	Sickness, death	9	4	36	CdM, PM	Visual inspection, performance testing	Filters and scrubbing agents must be tested IAW with DS procedures

Table J-2. Makeup Air

Control Number	Name	Function/ Performance Requirement	Potential Failure Modes	Potential Failure Effects	Crit	Prob	PROD	MA Code	Maintenance Approach	Remarks/Continue
2	AHU	Contain and direct airflow								
2.1	Supply/ Return Fan	Provide required air flow at design pressure								
2.1.1	Fan Motor	Convert electrical energy to mechanical energy. Provide sufficient torque and speed to meet design specifications.	Listed in line items 1.2.1.1.1 - 1.2.1.3.1	Loss of air flow. Specific equipment failure effects listed in line items 1.2.1.1.1 - 1.2.1.3.1	4	3	12	PM, CdM	Combination of visual inspection, vibration monitoring, condition based lubrication, insulation resistance testing, measurement of running current.	For high efficiency motors the power quality should be measured to ensure that negative sequencing currents do not occur.
2.1.1.1	Frame	Maintain correct geometry for rotating assembly. Minimize environmental impact.	Corrosion, structural failure	Interference between stator and rotor. Nonsymmetrical air gap.	4	1	4	CdM	Visual inspection	

Table J-2. Makeup Air (Continued)

Control Number	Name	Function/ Performance Requirement	Potential Failure Modes	Potential Failure Effects	Crit	Prob	PROD	MA Code	Maintenance Approach	Remarks/Continue
2.1.1.2	Stator	Provide rotating magnetic field for induction.	Breakdown of insulation, high impedance connections, turn-to-turn shorts, open conductor path.	Low or zero resistance to ground. Increased vibration. Nonsymmetrical magnetic field.	4	2	8	CdM	Insulation resistance testing, measurement of running current	
2.1.1.3	Rotor	Transfer energy to fan impeller via sheaves and drive belts.	Broken rotor bars. Shaft failure.	Reduced torque, increased vibration levels, change in current signature.	4	2	8	CdM	Vibration analysis	
2.1.1.4	Bearings	Reduce friction and maintain geometry of rotor to stator.	Fatigue, contamination, under/over lubrication, overload, misalignment, imbalance	Increased temperature, increased vibration/noise levels, seized motor	4	3	12	CdM	Vibration analysis, temperature measurement	Motor bearings are to be lubricated only when there is excessive noise/vibration or increased end cap temperature.
2.1.1.5	Sheaves	Transfer energy from motor to belts and to fan sheave.	Friction wear, misalignment, mechanical failure	Increased vibration/noise levels, reduced airflow, loss of airflow	4	4	16	CdM	Visual inspection, measurement of sheaves, vibration analysis, temperature measurement	

Table J-2. Makeup Air (Continued)

Control Number	Name	Function/ Performance Requirement	Potential Failure Modes	Potential Failure Effects	Crit	Prob	PROD	MA Code	Maintenance Approach	Remarks/Continue
2.2	Belts	Transfer energy to fan impeller via sheaves.	Glazing, cracking	Increased vibration/noise levels, reduced airflow, loss of airflow	4	4	16	CdM	Visual inspection, vibration analysis, temperature measurement	
2.3	Fan Impeller	Convert mechanical energy to flow energy.	Corrosion, imbalance, fatigue	Increased vibration/noise levels, reduced airflow, loss of airflow	4	2	8	CdM	Visual inspection, vibration analysis	
2.3.1	Fan bearings	Reduce friction and maintain geometry C5of rotor to stator.	Fatigue, contamination, under/over lubrication, overload, misalignment, imbalance	Increased temperature, increased vibration/noise levels, seized fan	4	3	12	CdM, PM		Fan (pillow block bearings) should be relubricated semiannually or when high noise/vibration levels exist or high bearing temperature.
2.3.2	Housing/ Frame	Provide structural support to fan assembly and connection point to ducting.	Fatigue, corrosion, looseness	Increased vibration/noise levels, reduced airflow, loss of airflow	4	1	4	CdM	Visual inspection, vibration analysis	

Table J-2. Makeup Air (Continued)

Control Number	Name	Function/ Performance Requirement	Potential Failure Modes	Potential Failure Effects	Crit	Prob	PROD	MA Code	Maintenance Approach	Remarks/Continue
2.4	Duct work	Contain and direct airflow	Fatigue, corrosion	Reduced/loss of airflow	4	1	4		Visual inspection	
			Contamination	Sick building	4	2	8		Visual inspection, air sampling	
2.4.1	Dampers	Throttle and direct airflow	Fatigue, operator failure, galling	Reduced/loss of airflow	4	2	8		Visual inspection, BAS operation	
2.50	Air Treatment	Filter and treat air to remove chemical agents, minimize biologicals	Failed media	Contaminated building, sick building syndrome	9	2	18		Measure differential pressure. Air quality monitoring	The majority of the ducting system is a single point of failure.
2.5.1	Filtration	Remove particulate and gaseous matter from make up air	Tunneling	Particulate contamination, reduced air flow	9	2	18		Measure differential pressure.	
			Clogged	Reduced air flow	9	2	18		Measure differential pressure.	

Table J-3. BAS

Control Number	Name	Function/Performance Requirement	Potential Failure Modes	Potential Failure Effects	Crit	Prob	PROD	MA Code	Maintenance Approach	Remarks/ Continue
3	Control System	Provide operation control of system	Loss of power, I&C failure, calibration	Loss of cooling, loss of automatic control	9	1	9	PM	Visual inspection, operational checks, annual calibration checks	Recommend differential temperature and pressure as well as tons per KW are trended on a weekly basis. In addition, chiller head pressure should be graphed.
3.1	Control Panel	Controls unit operation with electrical inputs and outputs, monitors temps, pressures, and current	Loss of power, I&C failure, calibration	Loss of cooling, loss of automatic control	9	1	9	PM		
3.1.1	Suction Pressure	Displays Suction pressure of compressors	Lack of refrigerant, loss of cooling	Loss of cooling, loss of automatic control	9	1	9	PM		
3.1.2	Discharge Pressure	Displays Discharge pressure of compressors	Excessive refrigerant, insufficient cooling	Loss of cooling, loss of automatic control	9	1	9	PM		

Table J-3. BAS (Continued)

Control Number	Name	Function/Performance Requirement	Potential Failure Modes	Potential Failure Effects	Crit	Prob	PROD	MA Code	Maintenance Approach	Remarks/ Continue
3.1.3	Evaporator Water Temperature (inlet & outlet)	Displays inlet and outlet evaporator temp.	Erosion, corrosion, fouling/scaling	Reduced water flow/thermal efficiency, increased electrical consumption	9	1	9	PM	Visual inspection, operational checks, annual calibration checks	Recommend differential temperature and pressure as well as tons per KW are trended on a weekly basis. In addition, chiller head pressure should be graphed.
3.1.4	Condenser Water Temperature (inlet & outlet)	Displays inlet and outlet condenser water temp.	Erosion, corrosion, fouling/scaling	Reduced water flow/thermal efficiency, increased electrical consumption	9	1	9	PM		
3.1.5	Ambient Temperature	Displays current ambient temperature	N/A	N/A	9	1	9	PM		
3.1.6	Motor Current	Monitor high and low current conditions	Compressor shutdown	Loss of cooling, loss of automatic control	9	1	9	PM		

Table J-3. BAS (Continued)

Control Number	Name	Function/Performance Requirement	Potential Failure Modes	Potential Failure Effects	Crit	Prob	PROD	MA Code	Maintenance Approach	Remarks/ Continue
3.1.7	Chill Water Set Point	Set to minimum chill water temp required	Compressor shutdown	Loss of cooling, loss of automatic control	9	1	9	PM	Visual inspection, operational checks, annual calibration checks	Recommend differential temperature and pressure as well as tons per KW are trended on a weekly basis. In addition, chiller head pressure should be graphed.
3.1.8	Low Pressure Cutout	Shuts down system upon detection of low pressure	Compressor shutdown	Loss of cooling, loss of automatic control	9	1	9	PM		
3.1.9	Lead/Lag Control	Changes assignment of compressor lead	Excessive wear on one system	Loss of cooling, loss of automatic control	9	1	9	PM		
3.1.10	Stages Of Loading	Loads/Unloads compressors for different cooling requirements		Loss of cooling, loss of automatic control	9	1	9	PM		

Table J-4: Domestic Water

Control Number	Name	Function/ Performance Requirement	Potential Failure Modes	Potential Failure Effects	Crit	Prob	PROD	MA Code	Maintenance Approach	Remarks/ Continue
4	Domestic Water System	Provide water to specified loads at deign pressure and flow Provide water source for fire protection	See Below	No or insufficient domestic water at point of use	5	1	5	PM, CdM	Combination of visual inspection, vibration monitoring, insulation resistance testing, measurement of running current, and inspection.	
4.1	Piping	Contain and direct the flow of water to specified location	Corrosion, erosion, fatigue	Flooding, no water at point of use	5	1	5	PM, CdM	Visual inspection, thickness measurement, vibration analysis	
4.1.1	Strainers	Remove particles larger than the specified size	Clogged	Loss of water flow	5	2	10	PM, CdM	Measure strainer differential pressure, open and clean.	
			Erosion, corrosion	Contamination of system, pump/valve failure	5	2	10	PM, CdM	Measure and record ΔP, open and inspect as required	
4.2	Storage Tanks	Provide source of back up domestic water	Cracks, spalling	Loss of back up water supply	5	1	5	PM	Trend water usage and tank level, visual inspection	A portable underwater light combined with a water proof boroscope should be used to minimize the number of confined space entries.

Table J-4: Domestic Water (Continued)

Control Number	Name	Function/ Performance Requirement	Potential Failure Modes	Potential Failure Effects	Crit	Prob	PROD	MA Code	Maintenance Approach	Remarks/ Continue
4.2	Storage Tanks	Provide source of back up water for fire suppression Provide source of back up water for chilled water	Fouling	Contaminated water supply. Loss of fire suppression back up water supply.	5	2	10	PM	Sampling, visual inspection, cleaning	A portable underwater light combined with a water proof boroscope should be used to minimize the number of confined space entries.
4.2.1	Level Control	Control water level	Failed sensors	Flooding/lack of water				PM	Visual inspection	
4.3	Domestic Water Pumps	Provide sufficient flow and pressure to meet load demand	See Below	Loss of potable water and potential loss of fire suppression support	5	3	15	PM, CdM	Vibration analysis, temperature measurement, lubrication, visual inspection, operational test	Redundant tanks and pumps

Table J-4: Domestic Water (Continued)

Control Number	Name	Function/ Performance Requirement	Potential Failure Modes	Potential Failure Effects	Crit	Prob	PROD	MA Code	Maintenance Approach	Remarks/ Continue
4.3.1	Motor	Convert electrical energy to mechanical energy. Provide sufficient torque and speed to meet design specifications.	Listed in line items	Loss of air flow. Specific equipment failure effects listed in line items	5	3	15	PM, CdM	Combination of visual inspection, vibration monitoring, condition based lubrication, insulation resistance testing, measurement of running current.	For high efficiency motors the power quality should be measured to ensure that negative sequencing currents do not occur.
4.3.1.1	Frame	Maintain correct geometry for rotating assembly. Minimize environmental impact.	Corrosion, structural failure	Interference between stator and rotor. Nonsymmetrical air gap.	5	1	5	CdM	Visual inspection	
4.3.1.2	Stator	Provide rotating magnetic field for induction.	Breakdown of insulation, high impedance connections, turn-to-turn shorts, open conductor path.	Low or zero resistance to ground. Increased vibration. Nonsymmetrical magnetic field.	5	2	10	CdM	Insulation resistance testing, measurement of running current	
4.3.1.3	Rotor	Transfer energy to fan impeller via sheaves and drive belts.	Broken rotor bars. Shaft failure.	Reduced torque, increased vibration levels, change in current signature.	5	2	10	CdM	Vibration analysis	

Table J-4: Domestic Water (Continued)

Control Number	Name	Function/ Performance Requirement	Potential Failure Modes	Potential Failure Effects	Crit	Prob	PROD	MA Code	Maintenance Approach	Remarks/ Continue
4.3.1.4	Bearings	Reduce friction and maintain geometry of rotor to stator.	Fatigue, contamination, under/over lubrication, overload, misalignment, imbalance	Increased temperature, increased vibration/noise levels, seized motor	5	3	15	CdM	Vibration analysis, temperature measurement	Motor bearings are to be lubricated only when there is excessive noise/vibration or increased end cap temperature.
4.3.2	Pump	Provide sufficient flow and pressure to meet load demand	See Below	Loss or reduced pumping capacity	5	3	15	PM, CdM		
4.3.2.1	Casing	Maintain proper geometry between stationary and rotating elements. Contain water	Erosion, corrosion, fatigue	Loss or reduced pumping capacity	5	1	5	PM	Visual inspection	
4.3.2.2	Impeller	Provide required pressure and flow	Erosion, corrosion, fatigue	Reduced pressure and flow	5	2	10	PM, CdM	Vibration analysis	
4.3.2.3	Seals	Provide a seal between the shaft and the casing to contain the water	Imbalance, misalignment, friction, erosion, corrosion	Loss of pumping capacity, flooding	5	3	15		Visual inspection	

Table J-4: DomesticWater (Continued)

Control Number	Name	Function/ Performance Requirement	Potential Failure Modes	Potential Failure Effects	Crit	Prob	PROD	MA Code	Maintenance Approach	Remarks/ Continue
4.3.2.4	Bearings	Reduce friction and maintain geometry of rotor to stator.	Fatigue, contamination, under/over lubrication, overload, misalignment, imbalance	Increased temperature, increased vibration/noise levels, seized motor	5	3	15	PM, CdM	Vibration analysis, temperature measurement, lubrication	
4.4	Coupling	Provide flexible connection between pump and motor to reduce effect of misalignment	Misalignment, overload	Loss of pump	5	3	15	PM, CdM	Visual inspection, vibration analysis, temperature measurement	
4.5	Valves	Isolate sections/components for maintenance and/or repair. Throttle flow. Prevent backflow.	Dominant failure modes for valves are leaking around stem and bonnet, debris and erosion on sealing surfaces, corrosion, insufficient energy for actuation (voltage or pressure), broken return spring, improper calibration (automatic valves) and over-pressure discharge (pressure relief valves). Valves in continuous service are rarely operated and are the most susceptible to failure when needed during shutdown.	Flooding, leakage	5	2	10	PM, CdM	Leak detection, visual inspection, trend thermal performance, refrugerant usage.	

Table J-4: Domestic Water (Continued)

Control Number	Name	Function/ Performance Requirement	Potential Failure Modes	Potential Failure Effects	Crit	Prob	PROD	MA Code	Maintenance Approach	Remarks/ Continue
4.5.1	Isolation Valves	Isolate sections/components for maintenance and/or repair	Galling, scoring, corrosion, erosion	Flooding	5	2	10	PM, CdM	Visual inspection/operational checks	
4.5.2	Throttle Valves	Control flow	Galling, scoring, corrosion, erosion	Excessive flow or pressure	5	2	10	PM, CdM	Visual inspection/operational checks	
4.5.3	Check Valves	Prevent back flow		Back flow, loss of pressure /flow at point of use						
4.5.4	Pressure Relief	Prevent over-pressurization and structural failure.		System/component ruputre. Flooding.						
4.5.5	Vacuum Breakers	Prevent under-pressurization and structural failure.		System/component collapse. Flooding.						
4.6	Water Treatment	Treat and filter water to remove contaminates (organic and inorganic) to acceptable levels.	Loss of filtration, ion exchange, sterilization, and/or chemical addition	Sickness, death	9	2	18	PM, CdM	Periodic sampling of water for inorganic and organic compounds.	

Table J-5. Fuel Distribution

Control Number	Name	Function/ Performance Requirement	Potential Failure Modes	Potential Failure Effects	Crit	Prob	PROD	MA Code	Maintenance Approach	Remarks/ Continue
6	Fill System	Transfer fuel from off site into storage tank	Corrosion, fatigue, mechanical failure	Loss of fill capability	7	2	14	PM	Visual Inspection	Portable hoses could be used as back-up.
6.1	Storage Tank	Store fuel for long term use	Dominant failure modes are cracking or deterioration due to settling, excessive water, or damage.	Loss of diesel power capability	7	2	14	PM	Monitor interstitial space.	
				Environmental Contamination	7	2	14	PM		Double walled tanks make this unlikely.
6.1.1	Vacuum Breakers	Prevent under-pressurization and structural failure.	Galling, scoring, corrosion, erosion	Tank collapse	7	1	7	PM	Annual calibration	
6.1.2	Pressure Relief	Prevent over-pressurization and structural failure.		Tank rupture	7	1	7	PM	Annual calibration	
6.1.3	Level Indication	Provide fuel storagre quantity	Failed sensors	Lack of sufficient fuel	7	1	7	PM	Annual calibration	
6.2	Transfer Pump	Transfer fuel from storage tank to day tank	Fatigue, contamination, under/over lubrication, overload, misalignment, imbalance	Manual fuel transfer required	7	1	7	PM		

Table J-5. Fuel Distribution (Continued)

Control Number	Name	Function/ Performance Requirement	Potential Failure Modes	Potential Failure Effects	Crit	Prob	PROD	MA Code	Maintenance Approach	Remarks/ Continue
6.3	Day Tank	Store fuel for immediate use	Corrosion, fatigue, mechanical failure	Bypass required	7	1	7	PM		
6.4	Fuel Filter	Filter particulate from fuel	Logged, ruptured	Loss of electrical power	7	4	28	PM	Measure differential pressure	Filter should include parallel water separators.
6.5	Fuel Pump	Pump fuel from day tank to diesel	See motor/pump	Loss of electrical power	7	2	14	PM		
6.6	Valves	Isolate sections/components for maintenance and/or repair. Throttle flow. Prevent backflow.	Dominant failure modes for valves are leaking around stem and bonnet, debris and erosion on sealing surfaces, corrosion, insufficient energy for actuation (voltage or pressure), broken return spring, improper calibration (automatic valves) and over-pressure discharge (pressure relief valves). Valves in continuous service are rarely operated and are the most susceptible to failure when needed during shutdown.	Various	7	1	7	PM	Exercise valves on an annual basis	

Table J-5. Fuel Distribution (Continued)

Control Number	Name	Function/ Performance Requirement	Potential Failure Modes	Potential Failure Effects	Crit	Prob	PROD	MA Code	Maintenance Approach	Remarks/ Continue
6.6.1	Isolation Valves	Isolate sections/components for maintenance and/or repair	Galling, scoring, corrosion, erosion	Fuel loss	7	1	7	PM	Visual inspection/ operational checks	
6.6.2	Throttle Valves	Control flow		Excessive flow or pressure						
6.6.3	Check Valves	Prevent back flow		Back flow, loss of pressure /flow at point of use						

Table J-6. Roofing

Control Number	Name	Function/ Performance Requirement	Potential Failure Modes	Potential Failure Effects	Crit	Prob	PROD	MA Code	Maintenance Approach	Remarks/ Continue
7	Roofing System	Prevent water from entering structure. Support miscellaneous equipment		Damage to roofing system and building components due to water infiltration	3	5	15	PM/ CdM	Visual inspection, thermography, capacitance testing, core testing	Minimizing roof traffic and limiting equipment installed on roof will prolong the life of the roofing system.
7.1	Ballast	Protect membrane form environment and abrasion	Erosion and abrasion	Premature failure of membrane	3	5	15	PM/ CdM	Visual inspection	
7.2	Membrane	Prevent water from entering structure, diverts water from roof	Ponding Blisters Cracks/Penetrations Abrasion	Damage to roofing system and building components due to water infiltration	3	5	15	PM/ CdM	Visual inspection, thermography, capacitance testing, core testing	
7.3	Insulation	Provide thermal insulation in order to minimize energy consumption.	Wetting from membrane leaks Environmental damage if membrane fails	Increased energy consumption	3	4	12	PM/ CdM	Thermography, capacitance testing, core testing	

Table J-6. Roofing (Continued)

Control Number	Name	Function/ Performance Requirement	Potential Failure Modes	Potential Failure Effects	Crit	Prob	PROD	MA Code	Maintenance Approach	Remarks/ Continue
7.4	Blocking	Support insulation and membrane.	Structural collapse	Membrane failure	3	4	12	PM/ CdM	Visual inspection for ponding	
7.5	Deck	Provide structural support and stability to roofing system	Structural collapse, cracking	Membrane failure	3	4	12	PM/ CdM	Visual inspection for ponding	
7.6	Expansion Joints	Allow for thermal expansion and contraction of roofing system to prevent cracking of membrane	Cracking	Membrane failure	3	5	15	PM/ CdM	Visual inspection	
7.7	Flashing	Direct water from penetrations and parapet connections onto membrane.	Mechanical damage, loss of seal, corrosion	Damage to roofing system and building components due to water infiltration	3	5	15	PM/ CdM		

Table J-6. Roofing (Continued)

Control Number	Name	Function/ Performance Requirement	Potential Failure Modes	Potential Failure Effects	Crit	Prob	PROD	MA Code	Maintenance Approach	Remarks/ Continue
7.8	Scuppers	Collect run off from membrane and direct to ground or dry sumps	Mechanical damage, blockage, corrosion	Damage to roofing system and building components due to water infiltration	3	3	9	PM/ CdM	Visual inspection	
7.9	Drains	Collect run off from membrane and direct to ground or dry sumps	Mechanical damage, blockage, corrosion	Damage to roofing system and building components due to water infiltration	3	4	12	PM/ CdM		

Table J-7. Elevator

Control Number	Name	Function/ Performance Requirement	Potential Failure Modes	Potential Failure Effects	Crit	Prob	PROD	MA Code	Maintenance Approach	Remarks/Continue
8	Elevator System	Provide vertical transportation of design loads at design speed.	Dominant modes of failure include wire rope wear, motor failure, travel way degradation, door opening mechanism failure, user interface failure and control calibration.	Reduced vertical access, loss of life	4	2	8	CM, PM	Maintenance methods include proper and frequent lubrication of all moving parts, travel ways and wire ropes, as well as frequent inspection of hooks, straps, wire ropes, beams and supports for signs of overloading and excess stress.	
8.1	Cab	Provide safe and attractive enclosure for load	Lighting Overload Safety Edge Operator chains/drive Debris Impact	Reduced vertical access	4	3	12	CM, PM	Inspection	
8.2	Guideways	Control geometric position of cab	Fastner failure	Reduced vertical access	4	2	8	CM, PM	Inspection	

Table J-7. Elevator (Continued)

Control Number	Name	Function/ Performance Requirement	Potential Failure Modes	Potential Failure Effects	Crit	Prob	PROD	MA Code	Maintenance Approach	Remarks/Continue
8.3	Sheaves	Transfer energy to cab	Frictional wear, looseness	Reduced vertical access	4	2	8	CM, PM	Inspection	
8.4	Wire Rope	Support of unit	Necking Rust (Rouge) Parting Broken Fastner	Reduced vertical access	4	2	8	PM	Inspection	
8.5	Motor	Control speed	See Motors	Reduced vertical access	4	2	8	CM, PM	Inspection, vibration monitoring	
8.6	Clutch	Control speed	Frictional wear	Reduced vertical access	4	2	8	PM	Inspection	
8.7	Winding Drum	Control speed and support unit	Frictional wear	Reduced vertical access	4	2	8	PM	Inspection	

Table J-7. Elevator (Continued)

Control Number	Name	Function/ Performance Requirement	Potential Failure Modes	Potential Failure Effects	Crit	Prob	PROD	MA Code	Maintenance Approach	Remarks/Continue
8.8	Brakes, Mechanical	Safety stop	Frictional wear	Reduced vertical access, loss of life	4	2	8	PM	Inspection	
	Brakes, Electrical	Controlled stop	Control circuit random failure	Reduced vertical access	4	2	8	PM	Inspection	
8.9	Indicators	Information	Totally random electrical failures	Reduced vertical access	4	2	8	CM, PM	Operational check, inspection	
8.10	Conrols	Floor call, leveling, acceleration, deceleration, overload	Overload, totally random	Reduced vertical access	4	2	8	CM, PM	Operational check, inspection	
8.11	Bearings	Reduce friction and provide geometric alignment	Lubrication Overload	Reduced vertical access	4	2	8	CM, PM	Inspection, vibration monitoring	

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APPENDIX K: ITEMS RECOMMENDED FOR FURTHER DISCUSSION

The following issues were raised during the RCM Guide review process but were not able to be addressed within either the timeframe or scope of the project. Several items remain unresolved due to lack of consensus or information. It is recommended that the NASA HQ FERP Division review and reconcile these issues so that there will be clear direction prior to the next revision of this guide.

OUT OF SCOPE				
Center	**Editor Initials**	**Chapter**	**Page**	**Comments**
GRC	HW	General		The value of a very disciplined CMMS should be show cased early on.
GRC	HW	General		Cradle to cradle (the Green sustainable approach) should be addressed, not just up to commissioning and O&M.
GRC	HW	General		This (8) should somehow be blendable into the NASA budget process, and should probably consider inclusion/mention of specific elements needed: BMAR, FCI, Critical Facilities, Mission Dependencies (demand) --- and yes, the annual and 5-yr. maintenance
GRC	HW	General		Types of maintenance referenced should reflect all the same varieties (yes, including roads and grounds ------ sustainability/green) specified in NPR 8831.

NEED FURTHER GUIDANCE				
Center	**Editor Initials**	**Chapter**	**Page**	**Comments**
GSFC	TW	General		The RCM Guide is recommending vibration levels that are not cost-effective or realistic for many systems. The criteria given are taken directly from the GM specifications, and in many instances are not appropriate or supportable.

NEED FURTHER GUIDANCE (Continued)				
Center	**Editor Initials**	**Chapter**	**Page**	**Comments**
GSFC	TW	General		Use of band limited criteria based on total vibration within a band is limited to proprietary methodologies. A better standard would directly reference the *highest peak within a band.* The proposed standards are cumbersome and not widely recognized.
GSFC	TW	General		Vibration, balance and alignment acceptance testing requiring reliance on vendor-collected data should be avoided. Vendors generally lack the expertise to perform or properly contract the testing.
GSFC	TW	General		There is excessive emphasis on the use of advanced technologies. There should be more attention given to assessing the appropriate level of technology required. The fact that a technology is available does not mean that it should be used.
GSFC	TW	General		Vibration test requirements do not always reflect many accepted or preferred practices. Signal processing requirements, (for instance, requiring use of Hanning window and or non-overlap processing) are open to challenge.
JPL	JAW	3	3-2	List all 7 questions specified by SAE J1011.
GRC	HW	5	5-10 +	Seems to be an overall compilation of terms (and RCM catch all, if you will), and not "…various methods for acceptance testing" as stated. Among the terms: RCFA (5.5.3), Reliability Calculations (5.5.5), a lecture on Reliability Component Relationships.