NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

RELIABILITY CENTERED MAINTENANCE GUIDE FOR FACILITIES AND COLLATERAL EQUIPMENT

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Chapter 1 - Background

1.1 Introduction

Reliability Centered Maintenance (RCM) is the process that is 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 a Run-to-Failure approach, as shown in Figure 1-1. The principal features of each strategy are shown below their block in Figure 1-1. RCM is an ongoing process that gathers data from operating systems performance and uses this data to improve design and future maintenance. These maintenance strategies, rather than being applied independently, are integrated to take advantage of their respective strengths in order to optimize facility and equipment operability and efficiency while minimizing life-cycle costs. The elements of RCM are developed in Chapter 2 and the maintenance strategies are defined and discussed in Chapter 3.

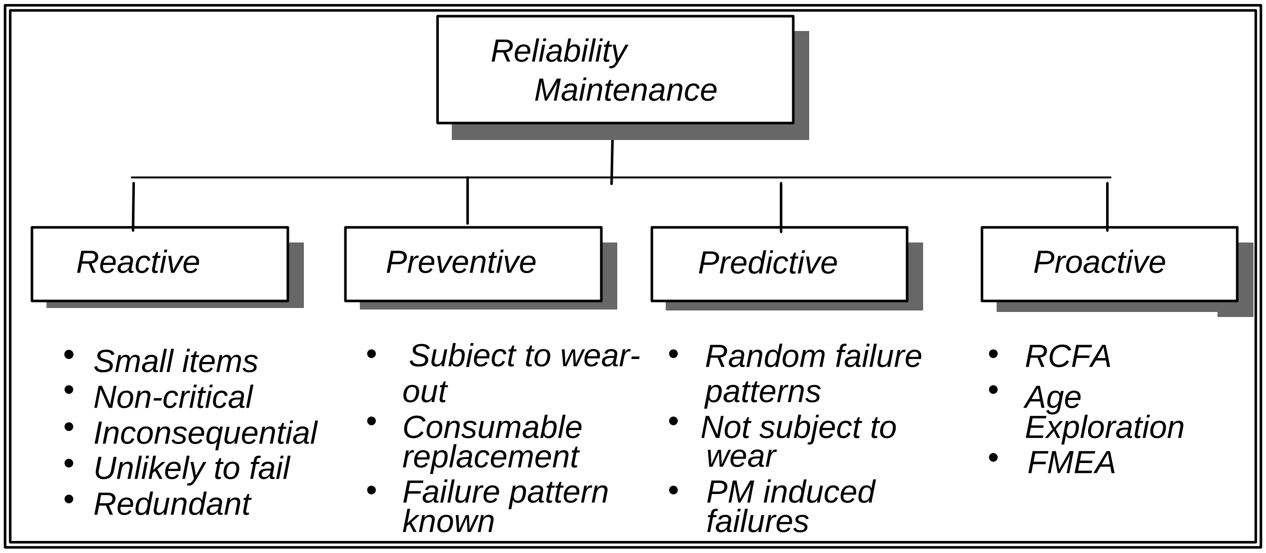

Figure 1–1. Components of an RCM Program

1.2 Historical Evolution of RCM

Analysis of maintenance policy in the airline industry in the late 1960's and early 1970's led to the development of Reliability Centered Maintenance (RCM) concepts. The principles and applications of RCM were documented in Nowlan and Heap's publication, *Reliability-Centered Maintenance*.[1] The work demonstrated that a strong correlation between age and failure rate did not exist and the basic premise of time based maintenance was false for the majority of equipment. Additional studies performed by the Department of Defense (DOD) and several nuclear utilities confirmed Nowlan and Heap's work.

[1] F. Stanley Nowlan and Howard F. Heap. Reliability-Centered Maintenance. United Airlines and Dolby Press, sponsored and published by the Office of Assistant Secretary of Defense, 1978.

From approximately 1960 until the late 1980s, Preventive Maintenance (PM) was the most advanced technique used by progressive facilities maintenance organizations. PM is based on two principles - 1) a strong correlation exists between equipment age and failure rate, and 2) individual component and equipment probability of failure can be determined statistically, and therefore, parts can be replaced or rebuilt prior to failure.

PM assumes that failure probabilities can be determined statistically for individual machines and components and parts or adjustments can be replaced or performed in time to preclude failure. For example, a common practice in the past was to replace or renew bearings after some number of operating hours based on the assumption that bearing failure rate increases with time in service. This has proven to be ineffective.

Figure 1–2 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. The wide variation in bearing life is obvious and precludes the use of any effective time-based maintenance strategy[2]. The X-axis is the individual bearing being tested while the Y-axis is the number of revolutions achieved prior to fatigue failure of the individual bearing. It should be noted that the bearings are tested at above-design loads to accelerate the failure rate. This is the standard procedure used to test bearings in order to determine the expected life of a bearing.

In all the studies, it was noted that a difference existed between the perceived and the intrinsic design life for the majority of equipment and components. In fact, it was discovered that in many cases equipment bearing life greatly exceeded the perceived or stated design life. For example, SKF Industries proposed changes in the method for evaluating bearing life - from the original method (empirical) proposed by Lundberg and Palmgren[3] to one where "bearings exhibit a minimum fatigue life; that is, 'crib deaths' due to rolling contact fatigue are non-existent when the aforementioned operating conditions (properly lubricated, mounted, operated and protected from dirt and moisture) are achieved."[4] This lack of a predefined fatigue life for bearings greatly impacts the concept of a predetermined design life for rotating equipment where rolling element bearings are used and provides the basis for extending the time between overhauls and equipment replacement.

This process, known as Age Exploration (AE), was used by the U.S. Submarine Force in the early 1970's to extend the time between periodic overhauls and to replace time based tasks with condition based tasks. While the initial program was limited to Fleet Ballistic Missile (FBM) submarines, it was continuously expanded until it included all submarines, aircraft carriers, other major combatants, and ships of the Military Sealift Command (MSC). Furthermore, the Navy has invoked the requirements of RCM and condition monitoring as part of new ship design specifications.

It should not be inferred from the above that all interval based maintenance should be replaced by condition based maintenance. In fact, interval based maintenance is often appropriate for

[2] Eschmann, et al, Ball and Roller Bearings: Theory, Design, & Application, John Wiley & Sons, 1985
[3] G. Lundberg and A. Palmgren, Dynamic Capacity of Roller Bearings, Acra Polytech, Mechanical Engineering Series 1, R.S.A.E.E., No. 3, 7, 1947.
[4] Tedric A. Harris, Roller Bearing Analysis, Second Edition, John Wiley and Sons, New York, 1984

those instances where an abrasive, erosive, or corrosive wear takes place, material properties change due to fatigue, embrittlement, etc. and/or a clear correlation between age and functional reliability exists.

Development of new technologies during the 1990's, including affordable microprocessors and increased computer literacy in the work force, has made it possible to determine the actual condition of equipment and not have to rely upon estimates of when the equipment might fail based on age. These new cost effective technologies and the lack of correlation between age and failure in many equipment items have increased the emphasis on condition monitoring. Condition monitoring, commonly called Predictive Testing and Inspection (PT&I) within the NASA facilities maintenance environment, has resulted in a need to review existing Preventive (PM) and Programmed (PGM) Maintenance efforts and ensure that the most effective approach is being used. RCM provides the structure for developing that approach.

Closely aligned with determining what maintenance approach to use are the subjects of who should do the work and what parts and material will be needed to ensure that the work is done in the most cost efficient manner.

Most recently, RCM has taken on a prominent role in NASA's facility and equipment maintenance and operations program. RCM principles have been integrated into the SPECSINTACT (See Appendix K, Clauses with RCM Applications) wherein designs now have requirements for designing to maintainability. PT&I is used within the construction contractor's quality control program before and during commissioning to ensure that there are no latent manufacturing and installation defects at the time of equipment acceptance. PT&I and proactive

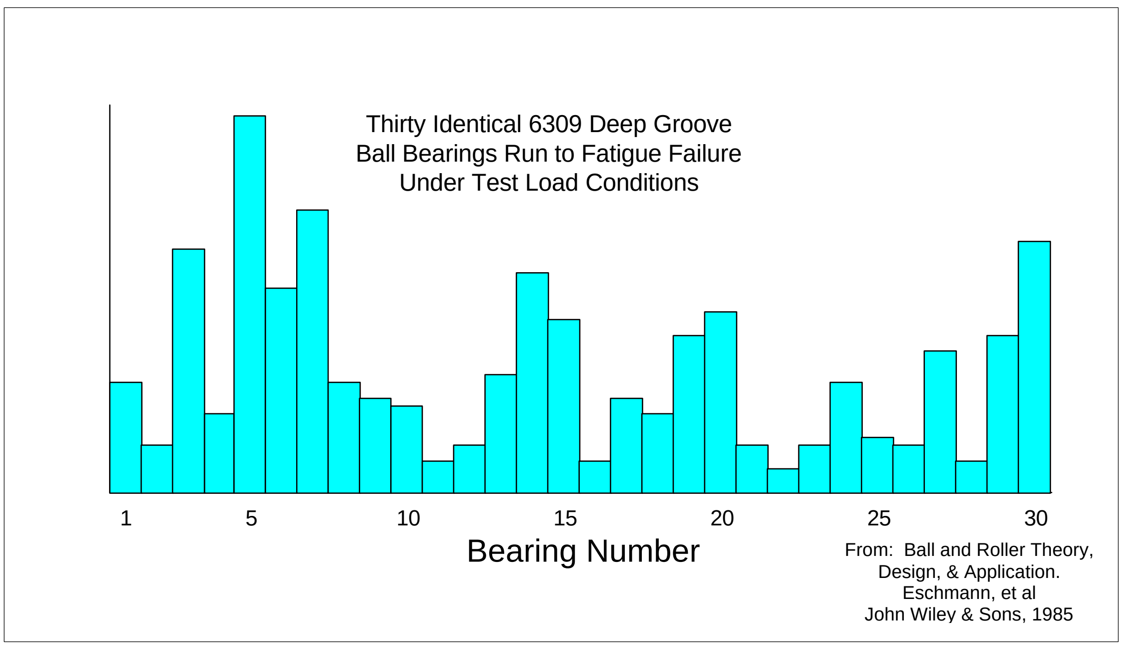

Figure 1-2: Bearing Life Scatter

analyses are used as tools by NASA Quality Assurance Evaluators (QAEs) to monitor the contractor's compliance with the specific requirements of performance based contracts. RCM is used in developing Condition Assessments and in determining the Backlog of Maintenance and Repair (BMAR). RCM principles and procedures are used every day in the maintenance of NASA's facilities where methods, frequencies, periodicities and other criteria are identified in the Annual, 5-Year, and more frequent Work Plans.

This guide is intended to provide detailed information for aiding in the implementation of RCM concepts and supporting programs within the NASA facilities community. Intended users include facility planners, designers, equipment procurement specialists, construction managers, systems engineers, and maintenance and operations (M&O) contract planners and managers. Figure 1-3 provides a visual representation of the RCM strategy and process relationship.

1.3 Purpose of This Guide

The purpose of this guide is to provide NASA Headquarters and Center (including Component Facilities) personnel, Maintenance and Operations (M&O) contractor personnel, and others involved in NASA facilities maintenance and/or construction a single reference document to be used to identify the RCM requirements during the facilities life cycle. This guide is intended to provide the following:

- An Overview of RCM
- An Introduction to Root Cause Failure Analysis
- An Overview of PT&I Technologies
- Guidelines for Establishing Monitoring Intervals
- Requirements for the Certification of PT&I Personnel
- In-service Criteria for Facilities Equipment and Systems
- Guidelines for Developing Procurement Specifications and Criteria
- Contract Clauses for Planning, Design, Construction, and Maintenance
- Guidelines for Performing Facilities Condition Assessment in an RCM environment

1.4 Applicability and Use of This Guide

This guide, particularly its sample contract clauses, should be used for facilities planning, design, new construction, modification, equipment procurement, and M&O contracts. It can also be used in preparing any Requests for Proposals (RFPs) or Requests for Quotations (RFQs) for facilities contracts and contract modifications. Its sister publication, the *NASA Building and Equipment Commissioning Guide*, provides criteria based on RCM principles for equipment acceptance. Other uses of this guide are recommended in the *NASA Facility Maintenance*

Management Handbook[5]. Proactive techniques such as machinery alignment and balance criteria, Age Exploration, and Facility Condition Assessment (FCA) are also addressed.

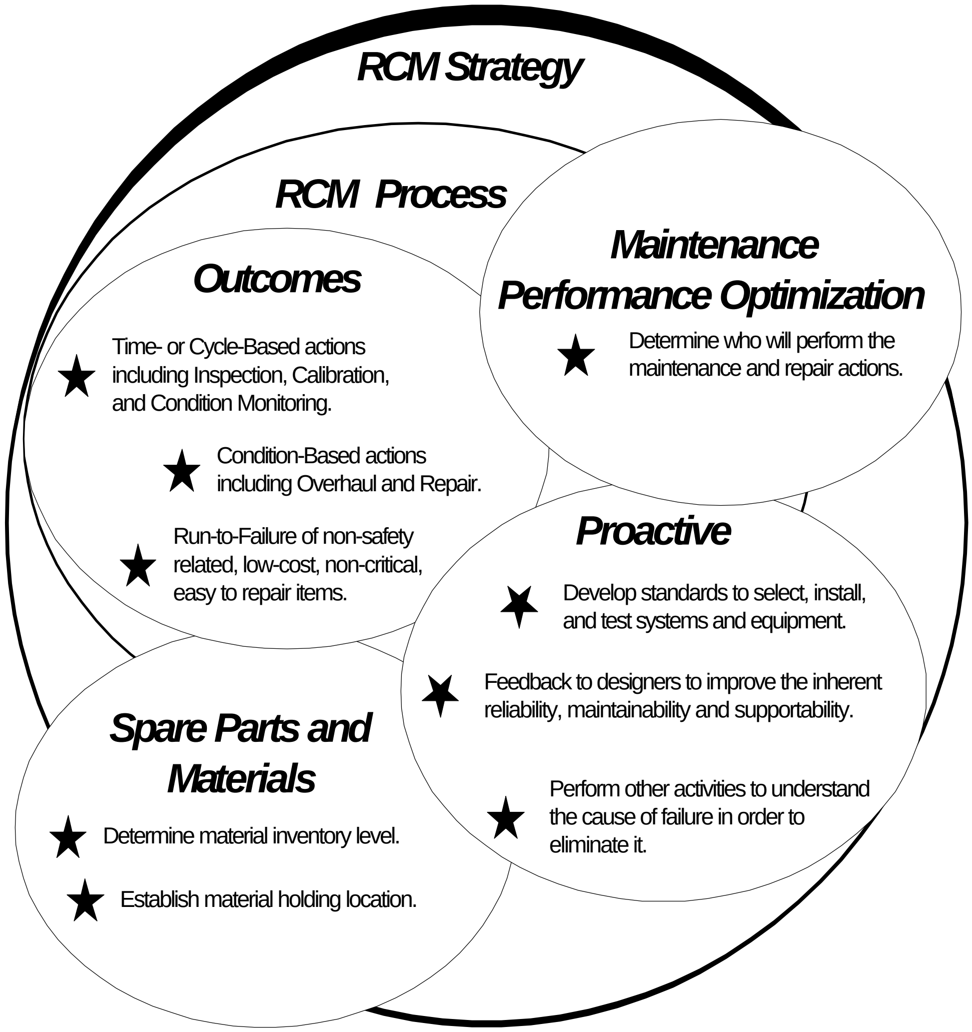

Figure 1-3. RCM Strategy and Process

[5] NASA NPG 8831.2, Facilities Maintenance Management Handbook

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Chapter 2 - Reliability Centered Maintenance (RCM) Approach

2.1 Philosophy

The RCM philosophy employs Preventive Maintenance (PM), Predictive Testing and Inspection (PT&I), Repair (also called reactive maintenance) and Proactive Maintenance techniques in an integrated manner to increase the probability that a machine or component will function in the required manner over its design life cycle with a minimum of maintenance. The goal of the philosophy is to provide the stated function of the facility, with the required reliability and availability at the lowest cost. RCM requires that maintenance decisions be based on maintenance requirements supported by sound technical and economic justification. As with any philosophy, there are many paths, or processes, that lead to a final goal. This is especially true for RCM where the consequences of failure can vary dramatically.

Rigorous RCM analysis has been used extensively by the aircraft, space, defense, and nuclear industries where functional failures have the potential to result in large losses of life, national security implications, and/or extreme environmental impact. A rigorous RCM analysis is based on a detailed Failure Modes and Effects Analysis (FMEA) and includes probabilities of failure and system reliability calculations. The analysis is used to determine appropriate maintenance tasks to address each of the identified failure modes and their consequences.

While this process is appropriate for these industries, it is not necessarily the most practical or best approach to use for facilities systems maintenance. For these systems a streamlined or intuitive RCM analysis process may be more appropriate. This is 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 streamlined approach uses the same principles as the rigorous, but recognizes that not all failure modes will be analyzed. NASA has reviewed the various processes in use and has determined that the most economical and efficient approach is to use a combination of rigorous (formal) and intuitive analysis depending on system criticality and failure impact. Candidates for rigorous 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 more rigorous analysis may be needed for those systems and components where the streamlined or intuitive RCM process has been utilized and the resultant reliability is still unacceptable in terms of safety, cost, or mission impact.

2.2 RCM Analysis

The RCM analysis carefully considers the following questions:

- What does the system or equipment do; what is its function?
- 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?

Figures 2-1 and 2-2 illustrate the RCM approach and the interactive streamlined process.

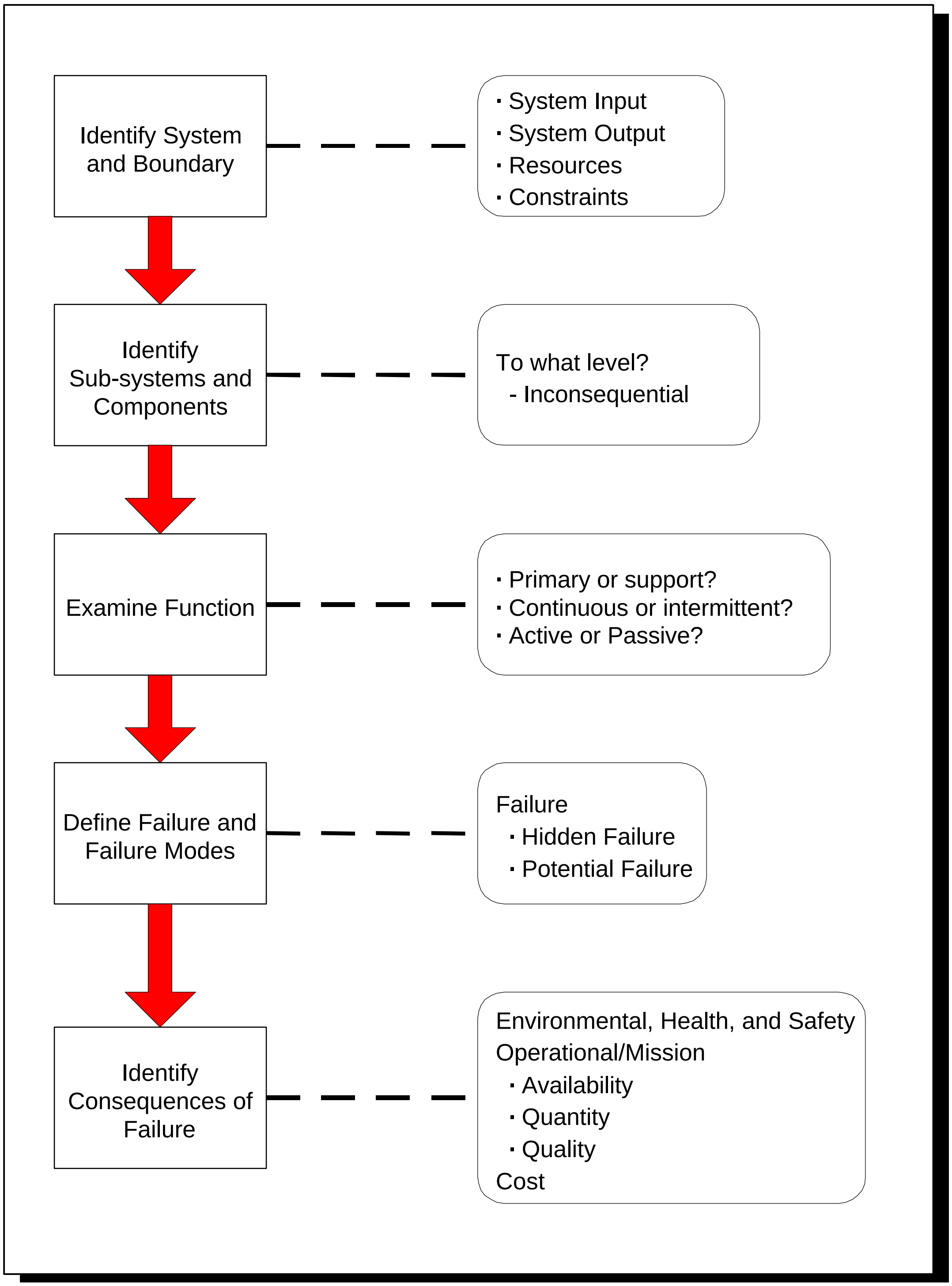

Figure 2-1. RCM Analysis Considerations

2.3 RCM Principles

The primary RCM principles are:

a. **RCM is Function Oriented—**It seeks to preserve system or equipment function, not just operability for operability's sake. Redundancy of function, through multiple equipment, improves functional reliability, but increases life cycle cost in terms of procurement and operating costs.

b. **RCM is System Focused—**It is more concerned with maintaining system function than individual component function.

c. **RCM is Reliability Centered—**It 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).

d. **RCM Acknowledges Design Limitations—**Its objective 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, at best, only achieve and maintain the level of reliability for equipment, which is provided for by design. However, RCM recognizes that maintenance feedback can improve on the original design. In addition, 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.

e. **RCM is Driven by Safety and Economics—**Safety must be ensured at any cost; thereafter, cost-effectiveness becomes the criterion.

f. **RCM Defines Failure as Any Unsatisfactory Condition—**Therefore, failure may be either a loss of function (operation ceases) or a loss of acceptable quality (operation continues).

g. **RCM Uses a Logic Tree to Screen Maintenance Tasks—**This provides a consistent approach to the maintenance of all kinds of equipment.

h. **RCM Tasks Must Be Applicable—**The tasks must address the failure mode and consider the failure mode characteristics.

i. **RCM Tasks Must Be Effective—**The tasks must reduce the probability of failure and be cost effective.

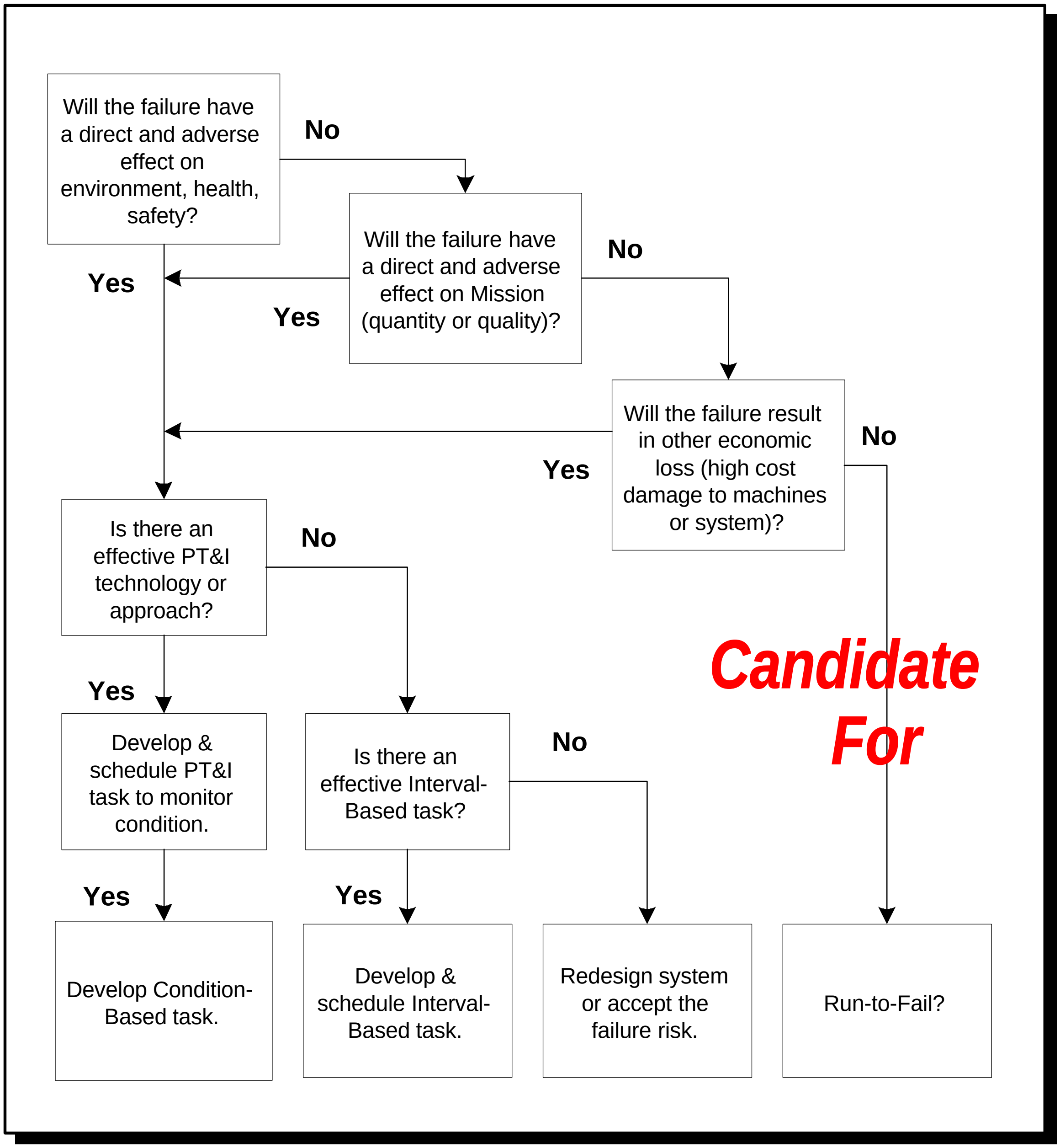

Figure 2-2. Maintenance Analysis Process

j. **RCM Acknowledges Three Types of Maintenance Tasks -** These tasks are time-directed (PM), condition-directed (PdM), 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 pending failure. Run-to-Failure is a conscious decision and is acceptable for some equipment.

k. **RCM is a Living System**—It 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 2-2, has only four possible outcomes:

- Perform Interval (Time- or Cycle-)-Based actions
- Perform Condition-Based actions
- Perform no action and choose to repair following failure
- Or determine that no maintenance action will reduce the probability of failure AND that failure is not the chosen outcome (Redesign or Redundancy).

These approaches will be discussed further in Chapter 3.

A formal 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. Regardless of the technique used to determine the maintenance approach, the approach must be reassessed and validated. Figure 2-3 depicts an iterative RCM process that can be used for a majority of NASA facilities and collateral equipment.

2.4 Failure

Failure is the cessation of proper function or performance. RCM examines failure at several levels: the system level, sub-system level, component level, and sometimes even the parts level. 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 (A simple example is the failed headlamp on an automobile. That failed component has little effect on the overall system performance). Conversely, several degraded components may combine to cause the system to have failed even though no individual component has itself failed.

2.4.1 System and System Boundary

A system is any user-defined group of components, equipment, or facilities that support an operational requirement. These operational requirements are defined by mission criticality or by environmental, health, safety, regulatory, quality, or other NASA-defined requirements. Most systems can be divided into unique sub-systems 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.

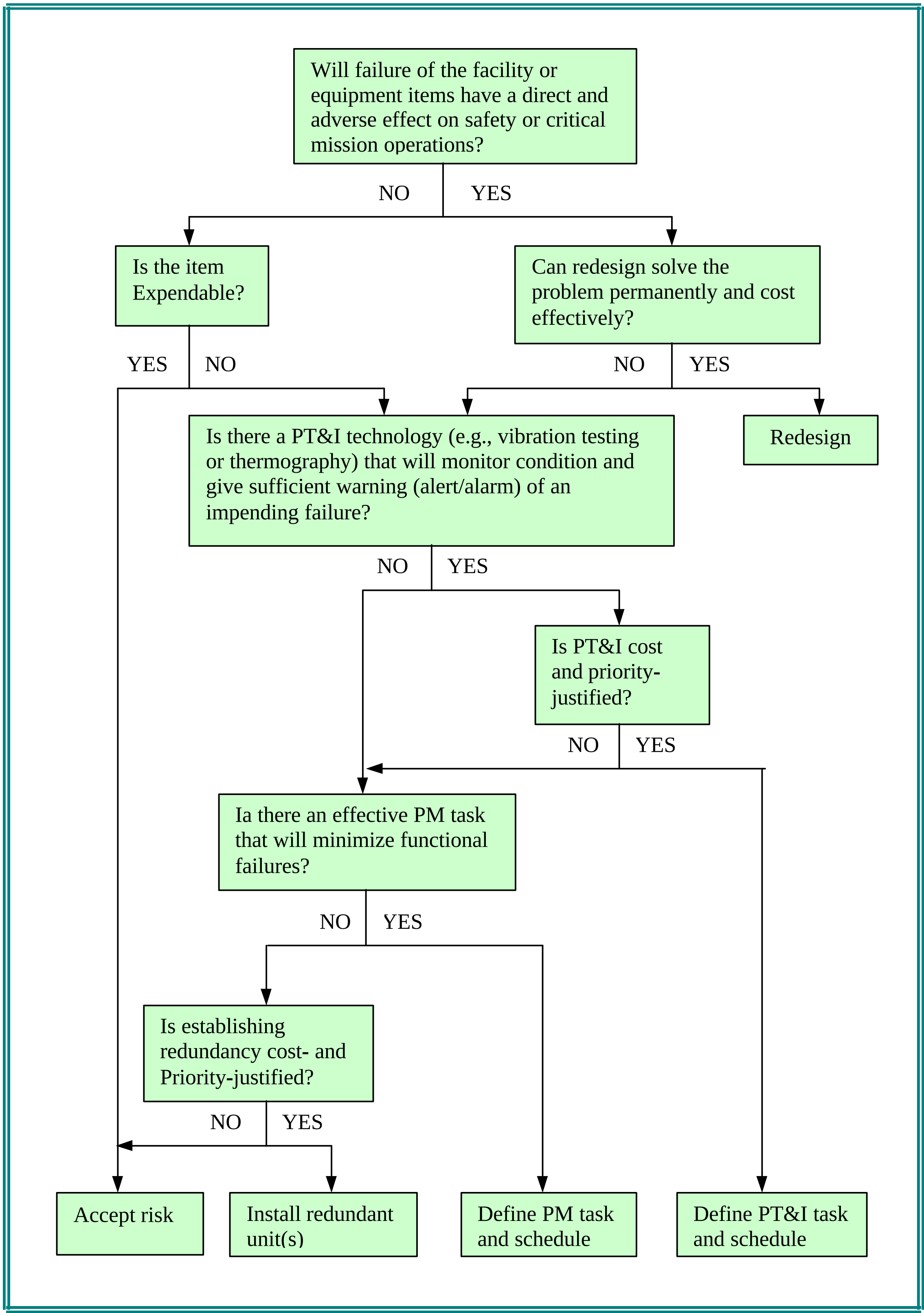

Figure 2-3. Reliability Centered Maintenance (RCM) Decision Logic Tree

- A system boundary or interface definition contains a description of the inputs and outputs that cross each boundary.

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

2.4.2 Function and Functional Failure

The function defines the performance expectation and can have many elements. Elements include physical properties, operation performance including output tolerances, and time requirements such as continuous operation or limited required availability.

Functional failures are descriptions of 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 in paragraph 2.4.1 (Systems and System Boundary) 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 how much water, at what pressure, at what efficiency, etc.

2.4.3 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. In addition, 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 their occurring is remote or their effect is inconsequential.

2.4.4 Reliability

Reliability is the probability that an item will survive a given operating period, under specified operating conditions, without failure. The *conditional probability of failure* measures the probability that an item entering a given age interval will fail during that interval. If the conditional probability of failure increases with age, the item shows wear-out characteristics. 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 rate or frequency plays a relatively minor role in maintenance programs because it is too simple a measure. Failure frequency is useful in making cost decisions and determining maintenance intervals, but it tells nothing about which maintenance tasks are appropriate or about 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.

2.4.5 Failure Characteristics

Conditional probability of failure (P_{cond}) curves fall into six basic types, as graphed (P_{cond} vs. Time) in Figure 2-4. The percentage of equipment conforming to each of the six wear patterns as determined in three separate studies is also shown in Figure 2-4.

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 of 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.

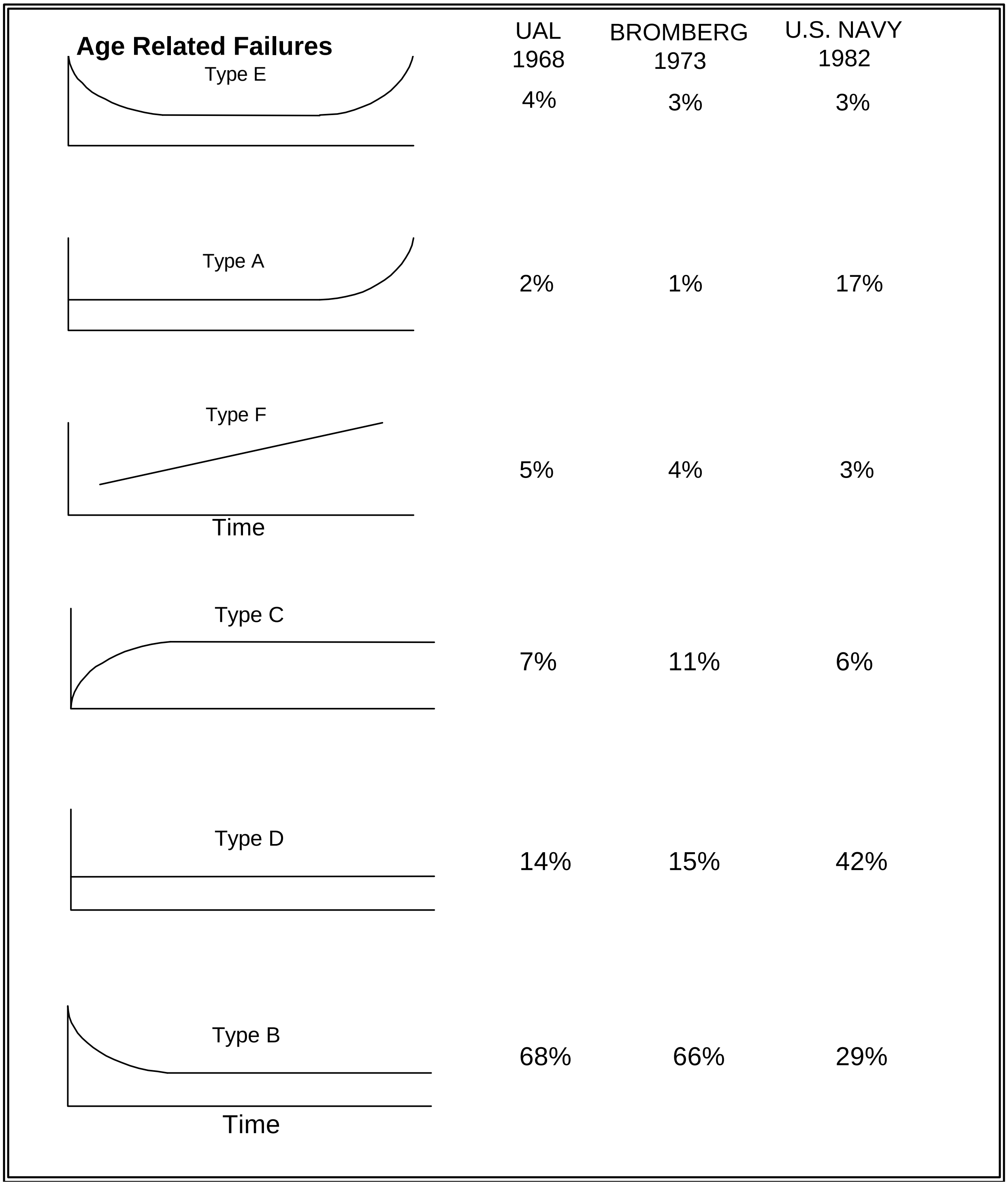

Figure 2-4. Conditional Probability of Failure Curves.

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 shown in Figure 2-4 were first noted in the previously cited book, *Reliability-Centered Maintenance*[6]. Follow-on studies in Sweden in 1973, and by the U.S. Navy in 1983, produced similar results. In these three studies, random failures accounted for 77-92% of the total failures and age related failure characteristics for the remaining 8-23%.

2.4.6 Preventing Failure

Every equipment item has a characteristic that can be called *resistance to* or *margin to failure*. Using equipment subjects it to stress that can result in failure when the stress exceeds the resistance to failure. Figure 2-5 depicts this concept graphically. The figure shows that failures may be prevented or item life extended by:

a. 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.

b. 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.

c. 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. It may increase, decrease, or remain constant with use or time. 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 one is considering preventive maintenance for some simple item and can find a way to measure its resistance to failure, one can use that information 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 so that 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 a few dominant or critical failure modes.

[6] F. Stanley Nowlan and Howard F. Heap, Reliability Centered Maintenance, United Airlines and Dolby Press, sponsored and published by the Office of Assistant Secretary of Defense, 1978

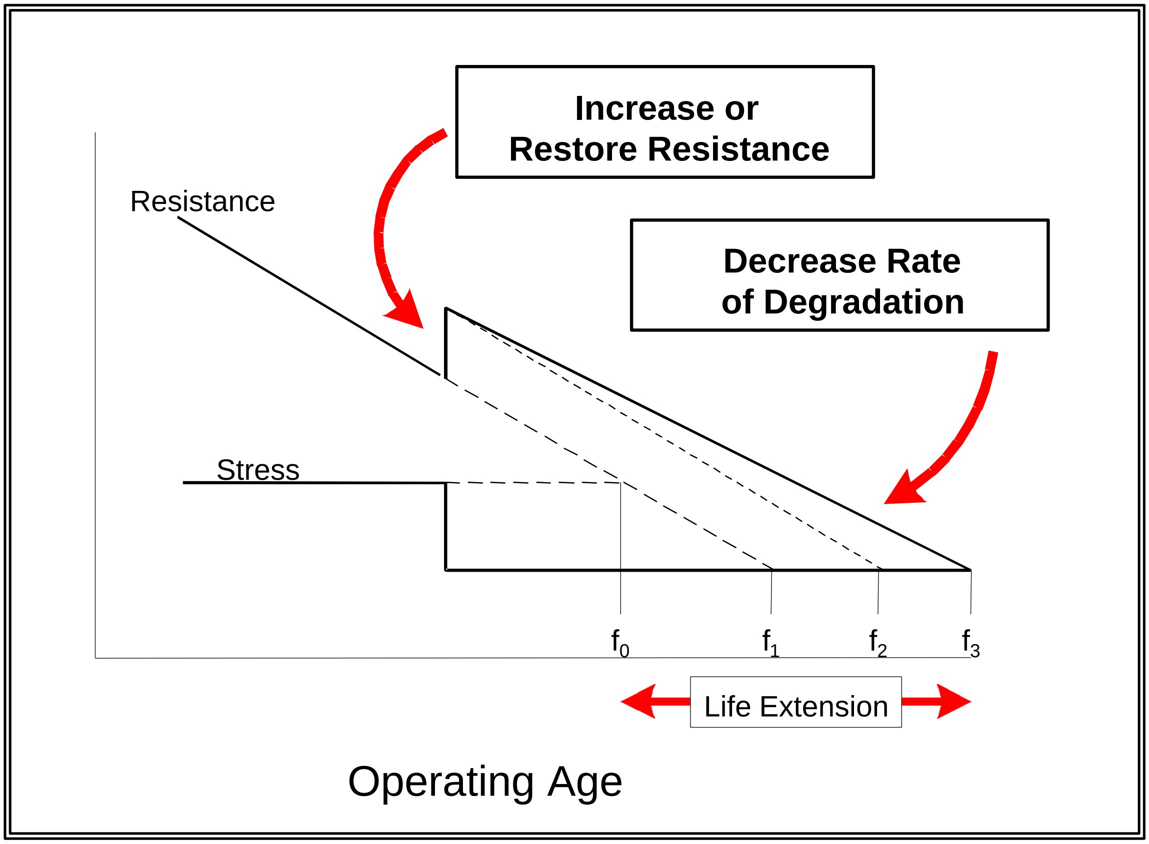

Figure 2-5. Preventing Failure

2.5 Failure Modes and Effects Analysis

Failure Modes and Effects Analysis (FMEA) is applied to each system, sub-system, and component identified in the boundary definition. For every function identified, there can be multiple failure modes. The FMEA addresses each system function (and, since failure is the loss of function, all possible failures), and the dominant failure modes associated with each failure, and then examines the consequences of the failure. What effect did the failure have on the Mission or operation, the system and on the machine?

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

Likewise, similar systems and machines will often have the same failure modes. However, 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. However, the dominate failure mode will often change from machine to machine, the cause of the failure may change, and the effects of the failure will differ.

Figure 2-6 provides an example of a FMEA worksheet. The key elements identified on the worksheet reflect the items identified in the RCM analysis (see Figure 2-1). There are two new terms identified in Figure 2-6: Criticality and Probability of Failure Occurrence.

2.5.1 Criticality and Probability of Occurrence

Criticality assessment provides the means for quantifying how important a system function is relative to the identified Mission. Table 2-1 provides a method for ranking system criticality. This system, adapted from the automotive industry[7], 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.

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.

Table 2-1. Criticality/Severity Categories

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

Identify Center, Building, System Name : If Used : Who prepared this FMEA

Page 1 of ____
Printed: Date and

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

Figure 2-6. FMEA Worksheet

The Probability of Occurrence (of Failure) is also based on work in the automotive industry. Table 2-2 provides one possible method of quantifying the probability of failure. If there is historical data available, it will provide a powerful tool in establishing the ranking. If the historical data is not available, a ranking may be estimated based on experience with similar systems in the facilities area. The statistical column in Table 2-2 can be based on operating hours, day, cycles, or other unit that provides a consistent measurement approach. Likewise, the statistical bases may be adjusted to account for local conditions. For example, one organization changed the statistical approach for ranking 1 through 5 to better reflect the number of cycles of the system being analyzed.

Ranking	Effect	Comment
1	1/10,000	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 similar 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.

Table 2-2. Probability of Occurrence Categories

2.5.2 Cause of Failure

Once the function and failure modes are understood, 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 Table 2-3.

Each of the individual components that makes up the chilled water system would then have a similar analysis performed, as illustrated in Table 2-4:

Function	Functional Failure	Failure Mode	Source of Failure
Provide chilled water at specified: Flow Rate 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 be to maintain the room temperature?	Total loss of flow.	Electric Motor Failed	See next table.
		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 2-3. Chilled Water System 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, mechanical imbalance.
	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 2-4. Electric Motor Component Analysis

Table 2-5 focuses on one failure mode, the seized bearing. Similar information will be needed for each failure mode. This information can become extensive for even the simplest of systems and can require a significant amount of effort and expense to compile. Table 2-5 is an abbreviated and simplistic compilation.

Notice that through the iterative, albeit 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. Medical doctors follow similar reasoning in their determination of patients' health problems - they eliminate the non-symptoms, then through an iterative process, deduct each possible cause of the problem, starting with the most likely first.

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

Table 2-5. Cause of Motor Bearing Failure

2.6 Reliability Centered Maintenance Goals

The RCM goals are to identify for each system and equipment the failure modes and their consequences and to determine the most cost-effective and applicable maintenance technique to minimize the risk and impact of failure. This allows system and equipment functionality to be maintained in the most economical manner. Specific RCM objectives as stated by Nowlan and Heap[8] are:

- To ensure realization of the inherent safety and reliability levels of the equipment.

[8] F. Stanley Nowlan and Howard F. Heap, Reliability Centered Maintenance, United Airlines and Dolby Press, sponsored and published by the Office of Assistant Secretary of Defense, 1978

- 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.

2.7 Program Benefits

2.7.1 Safety

Per NPD 8700.1, *NASA Policy for Safety and Mission Success*, NASA policy is to "Avoid loss of life, personal injury or illness, property loss or damage, or environmental harm from any of its activities and ensure safe and healthful conditions for persons working at or visiting NASA facilities." By its very features, including analysis, monitoring, taking decisive action on systems before they become problematic, and thorough documentation, RCM is highly supportive of and an integral part of the NASA Safety policy.

2.7.2 Cost

Due to the initial investment required for obtaining the technological tools, training, and equipment condition baselines, a new RCM Program typically results in a short-term increase in maintenance costs. This increase is relatively short-lived. 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 a reduction in total maintenance cost. Often energy savings are also realized from the use of PT&I techniques.

2.7.3 Reliability

RCM places great emphasis on improving equipment reliability, principally 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 and, therefore, greater availability for mission support and lower maintenance costs.

2.7.4 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 tends to be 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 equipment condition, not on the calendar. This condition-based approach to maintenance thereby extends the operating life of the facility and its equipment.

2.7.5 Efficiency/Productivity

Safety is the primary concern of RCM. The second most important concern 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. Maintenance that is not cost effective is identified and not performed.

2.8 Impact of RCM on the Facilities Life Cycle

The facilities life cycle 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 Table 2-6.

Decisions made early in the acquisition cycle profoundly 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 conceptually in Figure 2-7, planning (including conceptual design) fixes two-thirds of the facility's overall life-cycle costs. The subsequent design phases determine an additional 29% of the life-cycle cost, leaving only about 5% of the life-cycle cost that can be impacted by the later phases.

Thus, the decision to include a facility in an RCM program, including PT&I and condition monitoring, which will have a major impact on its life-cycle cost, is best made during the planning phase. As RCM decisions are made later in the life cycle, it becomes more difficult to achieve the maximum possible benefit from the RCM program.

Even though maintenance is a relatively small portion of the overall life-cycle cost, typically 3% to 5% of a facility's operating cost, RCM is still capable of introducing significant savings during the M&O phase of the facility's life. Savings of 30% to 50% in the annual maintenance budget are often obtained through the introduction of a balanced RCM program.

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 Operation (M&O)	Not Applicable	RCM Operations Training/Certification

Table 2-6. RCM Facility Life-Cycle Implications

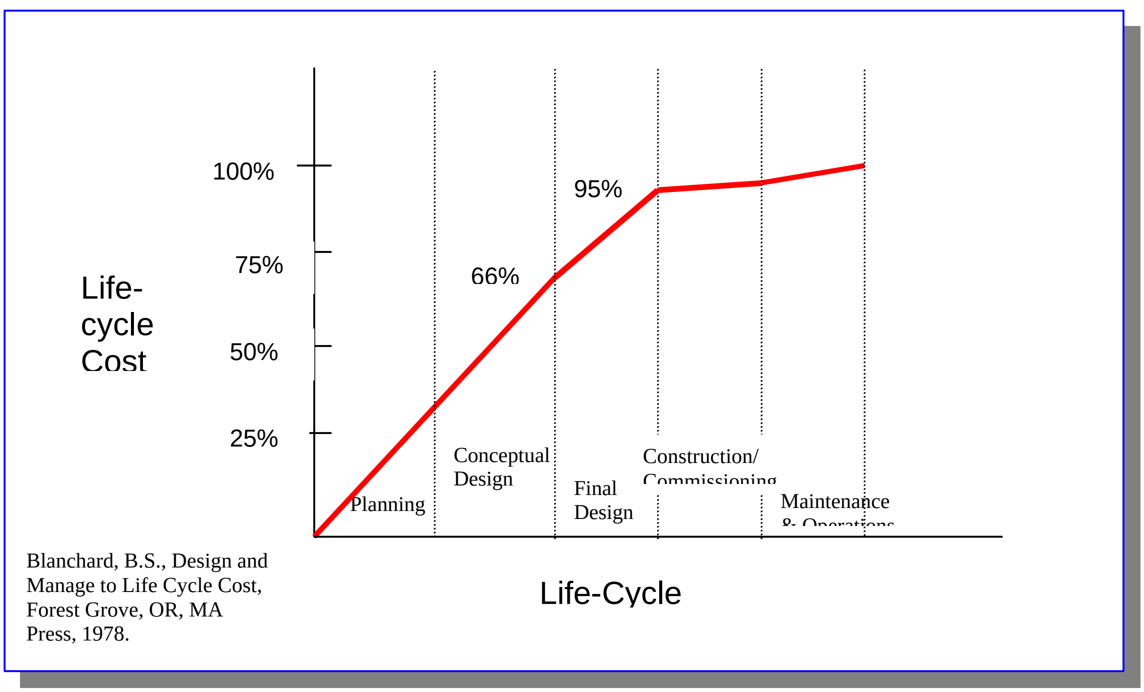

Figure 2-7. Stages of Life-Cycle Cost Commitment

Chapter 3—RCM Program Components

An RCM program includes reactive, preventive, predictive, and proactive maintenance. In addition, 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 paragraphs describe these key RCM components.

Table 3–1 suggests the criteria to be used in determining RCM priorities.

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.

Table 3–1. Maintenance Priority Levels

3.1 Reactive Maintenance

Reactive maintenance also is referred to as breakdown, repair, fix-when-fail, or run-to-failure (RTF) maintenance. When applying this maintenance technique, maintenance, equipment repair, or replacement occurs only when the deterioration in the equipment's condition causes a functional failure. This type of maintenance assumes that failure is equally likely to occur in any part, component, or system. Thus, this assumption precludes identifying 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 while parts are obtained. If certain parts are urgently needed to restore a critical machine or system to operation, a premium for expedited delivery must be paid. Also, there is no ability to influence when the failures occur because no (or minimal) action is taken to control or prevent them. *When this is the sole type of maintenance practiced*, a high percentage of unplanned maintenance activities, high replacement part inventories, and inefficient use of maintenance effort typify this strategy. 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 RTF is applicable are non-critical electric motors less than 7.5 HP, comfort cooling, restroom exhaust fans, water heaters, and items where the consequences of failure are negligible.

3.1.1 Reactive Maintenance Criteria

Table 3–2 suggest criteria to be used in determining the priority for repairing or replacing the failed equipment in the reactive maintenance program.

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.

Table 3–2. Reactive Maintenance Priorities

3.2 Preventive Maintenance (PM)

PM consists of regularly scheduled inspection, adjustments, cleaning, lubrication, parts replacement, calibration, and repair of components and equipment. PM is also referred to as time-driven or interval-based maintenance. It is performed without regard to equipment condition.

PM schedules periodic inspection and maintenance at pre-defined intervals (time, operating hours, or cycles) in an attempt to reduce equipment failures for susceptible equipment. Depending on the intervals set, PM can result in a significant increase in inspections and routine maintenance; however, it should also reduce 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 therefore one can replace a part due for failure before it fails. The availability of statistical failure information tends to lead 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. In addition, this renewal task is based on the perception new components are less likely to fail than old components of the same design. See Figures 1–2 and 2–3.

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* failure rate. The reality is failures are equally likely to occur at random times and with a frequency unrelated to the average failure rate. Thus, selecting a specific time to conduct periodic maintenance for a component with a random failure pattern is difficult at best.

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

3.2.1 Preventive Maintenance Criteria

Preventive maintenance criteria reflect the age-reliability characteristics of the equipment based upon the equipment history. They are not necessarily related to mission criticality. The selection of maintenance tasks is made using the process shown in Figure 2–1. 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.

3.2.2 Determining PM Task and Monitoring Periodicity

This section offers suggestions for selecting monitoring periodicities.

3.2.2.1 PM Tasks

Although numerous ways have been proposed for determining the correct periodicity of preventive maintenance tasks, none are 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 equipment condition vs. age.

Careful analysis of similar kinds of hardware in industry has shown that, overall, more than 90% of the hardware analyzed showed no adverse age-reliability relationship. This does not mean that individual parts do not wear; they do. It means that the ages at failure are distributed in such a way that there is no value in imposing a preventive maintenance task. In fact, in a large number of cases, imposing an arbitrary preventive task increases the average failure rate through "infant mortality."

The Mean Time Between Failures (MTBF) is often used as the initial basis for determining PM interval. This approach is incorrect in that it 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. In many cases a Weibull distribution, as used by the bearing industry to specify bearing life, will provide more accurate information on the distribution of failures.

The best thing that can be done if good information on the effect of age on reliability is not available, is to monitor the equipment condition.

3.2.2.2 Equipment Monitoring

The factors above still apply, but with several important modifications. The aim in monitoring equipment condition is to (1) determine equipment condition and (2) develop a trend with which to forecast future equipment condition. For trending purposes, a minimum of three monitoring points before failure may reasonably be expected are recommended. Using three data points provides two to establish the trend and the third to provide confirmation. The following techniques are recommended for setting initial periodicity:

a. Anticipating Failure from Experience.

For some equipment, failure history and personal experience provide an intuitive feel as to when equipment failure may be expected. In these cases, failure is time related. The monitoring periodicity should be selected such that there are at least three monitoring intervals before the anticipated onset of failures. It is prudent in most cases to shorten the monitoring interval as the wear-out age is approached.

b. 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 an equipment exceeding some life. For example, bearings are normally specified by their B10 life; i.e., the number of revolutions that will be exceeded by 90% of the bearings.

Depending on the criticality of the equipment, an initial periodicity is recommended which allows a *minimum* of three monitoring samples prior to the B10 life or, in less severe cases, prior to the MTBF point. In more severe cases a B2 life; i.e., the number of revolutions that will be exceeded by 98% of the bearings should be specified and the monitoring interval adjusted accordingly.

c. 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 predictive analysis methods, the monitoring interval should be reduced and additional analysis should be performed in order to gain more detailed information on the condition of the equipment.

3.3 Predictive Testing & Inspection (PT&I)

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. It 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 following ways to determine the condition of the equipment and identify the precursors of failure. The methods of analysis include:

- 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 4 for information on PT&I technologies.

3.3.1 Data Correlation

Data acquired from the various PT&I techniques can and 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 3–1 depicts a simplified Chilled Water 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 to be used for the entire system to be evaluated:

a. **Flow Rates—**Flow would be measured using precision, non-intrusive flow detectors.

b. **Temperature—**Differential temperature would be measured to determine heat transfer coefficients and to indicate possible fouling of tubes.

c. **Pressure—**Differential pump and chiller pressures would be measured to determine pressure drops and pump efficiency.

d. **Electrical—**Motor power consumption and motor circuit testing would be used to assess the condition of the motor circuits and to correlate with pump efficiencies.

e. **Ultrasonic Thickness—**Pipe wall thickness would be measured to determine erosion and corrosion degradation.

f. **Vibration—**Vibration monitoring would be used to assess the condition of the rotating components such as pumps and motors. Additionally, structural problems would be identified through resonance and model testing.

g. **Lubricant Analysis—**Oil condition and wear particle analysis would be used to identify problems with the lubricant and correlated with vibration when wear particle concentrations exceed pre-established limits.

h. **Fiber Optics—**Fiber optic inspections would be used in response to indications of component wear, tube fouling, etc.

i. **Thermography—**Thermography scans would be used to check motor control centers and distribution junction boxes for high temperature conditions. Piping insulation should be checked for porosities.

j. **Eddy Current—**Eddy current would be used to determine and locate leaking tubes.

k. **Airborne Ultrasonics—**Airborne Ultrasonics would be used to detect leaking air from control system and compressor leaks.

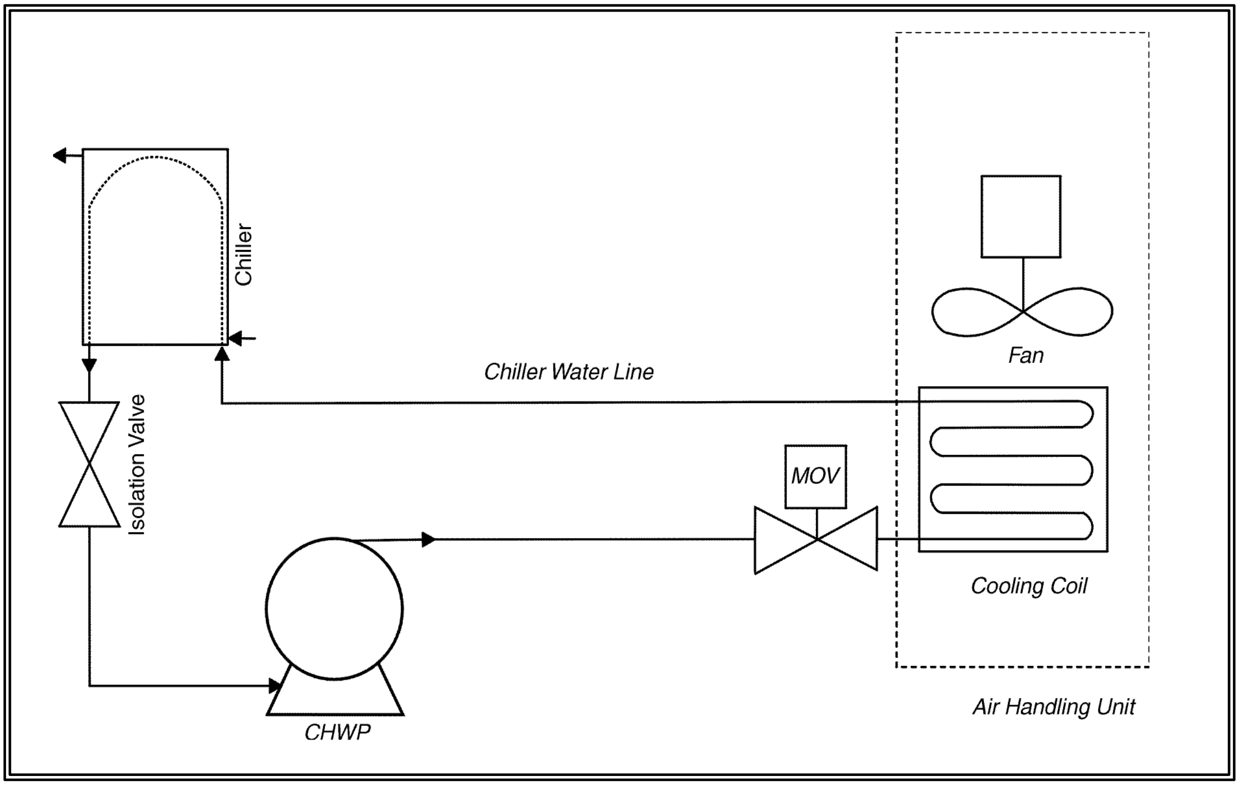

Figure 3 – 1. Sample System

3.4 Proactive Maintenance

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

- Specifications for new/rebuilt equipment
- Precision rebuild and installation
- Failed-part analysis
- Root-cause failure analysis
- Reliability engineering
- Rebuild certification/verification
- Age Exploration
- Recurrence Control

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 forever.
- Periodic evaluation of the technical content and performance interval of maintenance tasks (PM and PT&I).

A proactive maintenance program is the capstone of the RCM philosophy. The seven most commonly recognized proactive techniques listed above are described in the following.

3.4.1 Specifications for New/Rebuilt Equipment

The design and fabrication of many new types of equipment too often fail to provide the capability to obtain reliable equipment condition data easily while the equipment is operating. It has been alleged that this oversight might result from design using CAD/CAM systems that require little practical experience on the part of the designers. Existing standards, often 25 to 30 years old and not reflective of changes in technology, are usually inadequate, typically addressing only general or minimal performance criteria. Additionally, 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 solve this problem, reliability engineers must write proper specifications, test the equipment of different vendors, and document problems. These specifications should include, as a minimum, vibration, alignment, and balancing criteria. Documenting historical data, so engineers can write verifiable purchasing and installation specifications for new and rebuilt equipment, is the basis of this proactive technique. Performance testing is then conducted (1) in the factory prior to shipment, (2) as the equipment is installed prior to acceptance, and (3) to establish a performance baseline as the equipment begins operation.

In addition, the use of PT&I for measuring equipment condition are not normally contained in the procurement specifications. It is rare to see a banded-vibration criteria, a quantifiable alignment/ balance specification, or a complex phase impedance for an electric motor.

3.4.2 Precision Rebuild and Installation

Equipment requires proper installation to control life-cycle costs and maximize reliability. Poor installation often results in problems routinely faced by both maintenance personnel and operators. 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 leveling equipment being installed should include a maximum acceptable slope of the base and the frame; e.g., a maximum slope of 0.001 inch per foot. The specification also should include the type and accuracy of the instrument used for measuring the slope; e.g., a 12-inch machinist's level graduated to 0.0002 inch per foot. 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.

3.4.2.1 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% 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:

a. Ball Bearings

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

b. Roller Bearings

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

Where, L_{10} is the number of hours 90% 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; and P is the actual bearing load, static and dynamic. C is obtained from a bearing manufacturer's catalogue and P is calculated during equipment design.

As shown, 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.

3.4.2.2 Balance Calculations[9]

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 usually sufficient to simply perform a single plane balance of a rotor to a level of 0.10 in/sec or 1.0 nor, is it sufficient to balance a rotor until it achieves low vibration levels. Precision balance methods should also include the calculation of residual imbalance. The following equation can be used to calculate residual imbalance:

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

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:

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

Permissible imbalance is related to equipment type and rotor mass. In general, 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}):

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

The relationship between speed and imbalance can be expressed by the following equation:

$$e_{per}\ x\ w = a\ constant$$

where, ω is the rotor angular velocity at *maximum* operating speed.

Table 3–3 below contains the ISO1940/1-1986 balance quality grades for various groups of representative rigid rotors.

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

Balance Quality Grade	Product of The Relationship (e_{per} x) [1,2] mm/s	Rotor Types—General Examples
G4,000	4,000	Crankshaft/drives[3] of rigidly mounted slow marine diesel engines with uneven number of cylinders[4]
G1,600	1,600	Crankshaft/drives of rigidly mounted large two-cycle engines
G630	630	Crankshaft/drives of rigidly mounted large four-cycle engines Crankshaft/drives of elastically mounted marine diesel engines
G250	250	Crankshaft/drives of rigidly mounted fast four cylinder diesel engines[4]
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 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
G6.3	6.3	Parts of process plant machines Marine main turbine gears (merchant service) Centrifuge drums Paper machinery rolls: print rolls Fans Assembled aircraft gas turbine rotors

Balance Quality Grade	Product of The Relationship (e_{per} x) [1,2] mm/s	Rotor Types—General Examples
		Flywheels Pump impellers Machine-tool and 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	Gas and steam turbines, including marine turbines (merchant service) Rigid turbo-generator rotors Computer memory drums and discs Turbo-compressors Machine-tool drives 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	Tape recorder and phonograph (gramophone) drives Grinding-machines drives Small electric armatures with special requirements
G0.4	0.4	Spindles, disc, and armatures of precision grinders Gyroscopes

Table 3–3. Balance Quality Grades for Various Groups of Representative Rigid Rotors (ISO 1940/1-1986)

Notes:

1. $\omega=2\pi n/60\approx n/10$, if n is measured in revolutions per minute and ω is in radians per second
2. For allocating the permissible residual unbalance to correction planes.
3. A crankshaft/drive is an assembly which, includes a crankshaft, flywheel, clutch, pulley, vibration damper, rotating portion of connecting rod, etc.

4. For the purposes of this part of ISO 1940, slow diesel engines are those with a piston velocity of less than 9 m/s; fast diesel engines are those with a piston velocity of greater than 9 m/s.
5. n complete engines, the rotor mass comprises the sum of all masses belonging to the crankshaft/drive described in note 3 above.

3.4.2.3 Effect of Imbalance

As discussed earlier, 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:

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

F	=	Force
m	=	imbalance (lbs)
r	=	radius of imbalance (in)
f	=	rotational speed (Hz)
g	=	386.4 in/sec^2

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

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

Thus, 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% of the design life as shown below.

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

3.4.2.4 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. Contrary to popular belief, both laser alignment and reverse dial indicator equipment offer equal levels of precision; however, laser alignment is considerably easier and quicker to learn and use. Recommended specifications for precision alignment are provided in Table 3–4.

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 (Meåsurement 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

Table 3–4. Recommended Coupled Alignment Tolerances (General Motors, 1993)

In addition to the alignment specifications, Table 3–5 contains the following additional tolerance recommendations.

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

Table 3–5. Alignment Related Tolerances (General Motors, 1993)

3.4.2.5 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 decrease by 7%.
- Machinery availability increases by 12%.

Table 3–6 and Figure 3–2 provide limitations and effect of misalignment on rolling element bearings, respectively. The maximum acceptable misalignment is based on experience data in bearing manufacturers' catalogs.

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

Table 3–6. Limitations on Rolling Bearing Misalignment (Harris,1984)

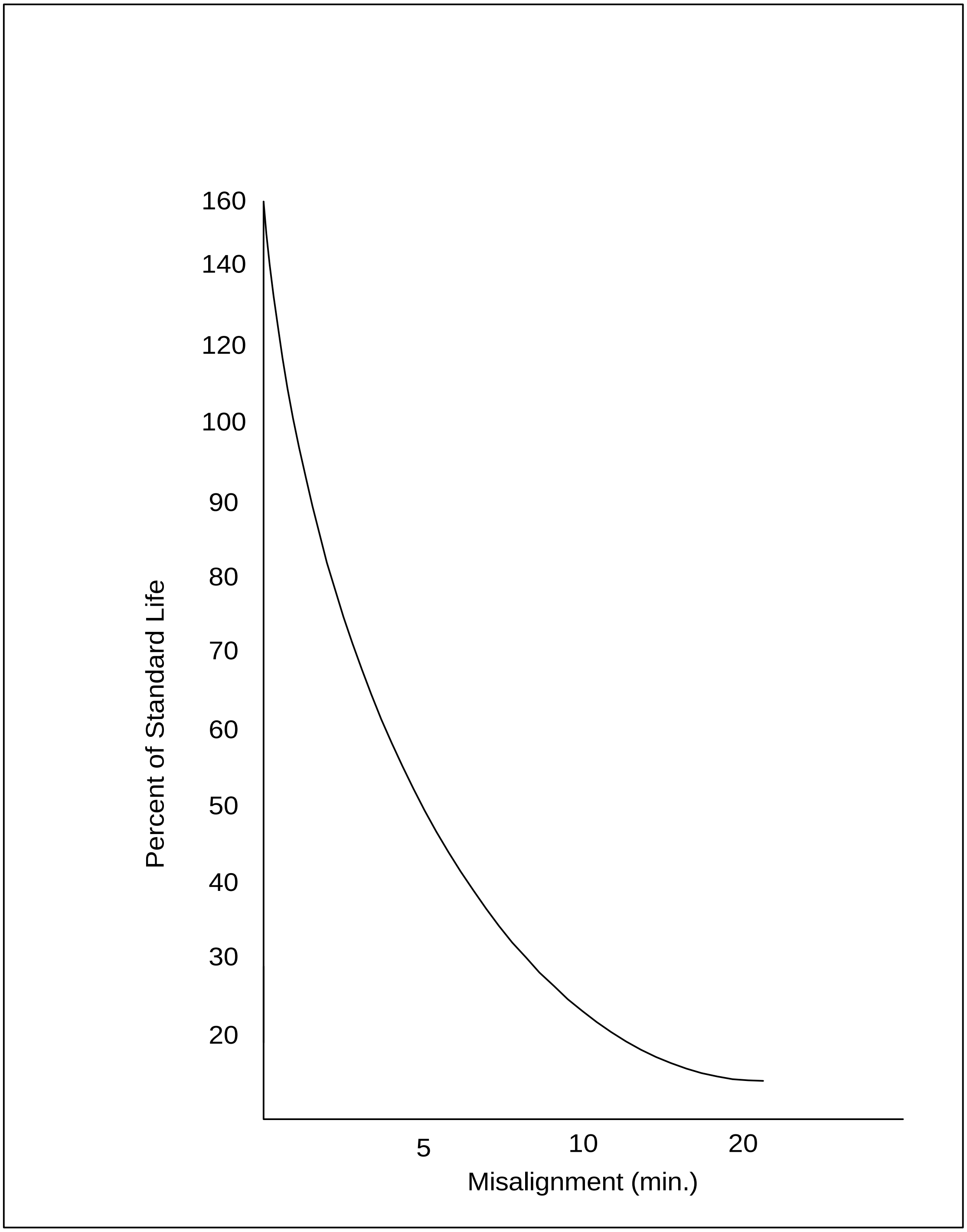

Figure 3 – 2. Effects of Misalignment on Roller Bearings

3.4.3 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 to 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.

Over half of all bearing problems result from contamination or improper installation. While indicators of contamination normally appear on the internal surfaces of bearings, indicators of installation problems generally are evident on both internal and external surfaces.

3.4.4 Root-Cause Failure Analysis (RCFA

In some cases, plant equipment fails repeatedly, and the failures are 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. However, 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. Further, 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.

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.”

3.4.5 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.

3.4.6 Reliability Calculations

a. Mean Time Between Failure (MTBF)

MTBF should be calculated from data collected from machinery history information stored in the Computerized Maintenance Management Software. Other sources of MTBF data are operator logs, parts usage, and contractor records. Reliability can be expressed by the following reliability function:

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

where 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:

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

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

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

where L is the mean life, t is the time period of interest and e is the natural logarithm base (2.7183...). The reliability at time t is:

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

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).

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

Where, 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% probability that a system will survive its mean life without failure. Mean life and failure rates are related by

$$Fr = 1/L$$

b. 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 = No. of failures/Total operating hours

Example:

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 a total operating hours of:

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.

Fr= 5/3805= .001314 failures/hr.

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

MTBF = 1/Fr = 1/.001314 = 761 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. That is, the system is operating beyond the infant mortality period of decreasing failure rate and either before the wear out region of increasing failure rate, or as in the majority of cases a period of increasing failure rate does not exist.

c. Reliability Component Relationships

1. 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.

$$\text{Reliability } (R) = (R_A)(R_B)(R_C)$$

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

$$R_S = e^{-(l\ +l\ +\ldots+l\ )t}$$

2. Parallel networks

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

$$\text{Reliability } (R) = R_A + R_B - (R_A)(R_B)$$ 2 component network

$$(R) = 1 - (1-R_A)(1-R_B)(1-R_C)$$ 3 component network

$$(R) = 1 - (1-R)^n$$ n identical components

3. Series-parallel networks

Figure 3–3 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.

d. Related Reliability Factors

1. Availability (A)

   (a) Inherent Availability (A_i)

   (1) 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.

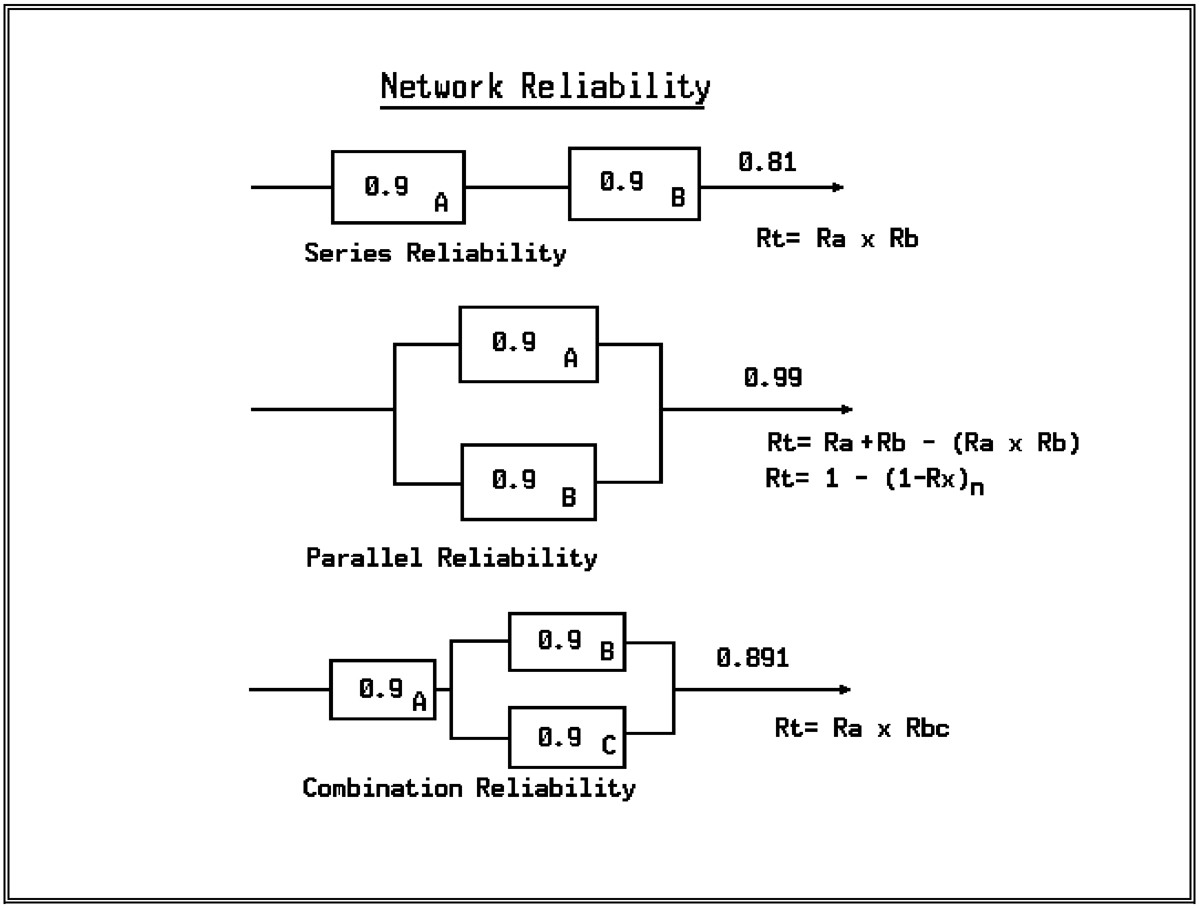

Figure 3 – 3. Determining Network Reliability

(2) Excludes preventive or scheduled maintenance actions, logistics delay time and administrative delay time.

(b) Achieved Availability (A_a)

(1) 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.
(2) Preventive (scheduled) maintenance is included.
(3) Excludes logistics delay time and administrative delay time.

c. Operational Availability (A_o)

(1) The probability that a system or equipment, when used under stated conditions in an actual operational environment, will operate satisfactorily when called upon.
(2) Includes active maintenance time, logistics delay time and administrative delay time.

e. `Weibull Distributions

The Weibull distribution is generally used to determine probability of the failure due to fatigue. The original work was conducted in 1933 and titled, *A Statistical Theory of the Strength of Materials*. While the original work was not directly related to bearings, it was 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 used to identify the introduction of new sources of failure, i.e., changes in operating condition, lubrication/installation practices, etc.

The Weibull distribution is:

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

where, F(t) is the failure probability, T is the point in time at which 63.2% 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 (10) identical bearings operating under as close to identical conditions as possible.

3.4.7 Rebuild Certification/Verification

When new or rebuilt equipment is installed, it is essential to verify that it is operating properly. To avoid unsatisfactory operation and early failure, the equipment should be tested against formal certification and verification standards.

3.4.8 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:

a. 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.

b. **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.

c. **Task Grouping—**Tasks with similar periodicity are grouped together to improve the amount of time spent on the job site and minimize outages.

3.4.9 Recurrence Control

This section provides a systematic approach using technical analysis of hardware and/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, i.e.:

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

The following items should be considered 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/component failures using a form similar to Figure 3 – 4
- Establish priorities for solution and allocation of resources
- Assign problems for analysis

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

In addition to developing a process for evaluating repetitive failures, a systematic approach similar to the following should be established:

a. Monitor performance and identify failures by reviewing Trouble Calls and machinery history contained in the CMMS and PT&I databases.

   1. Extend PT&I monitoring activities as widely as possible across the Facility consistent with the concepts of RCM.

   2. Encompass the Facility's critical components as identified by RCM. Include safety-related systems and components and include systems and components that support safety systems.

b. Monitor the performance of both systems and components because;

   1. System monitoring will identify potential loss of equipment due to aging, corrosion, wear, design or operational problems.

   2. Component monitoring will identify possible generic failure problems that may affect multiple plant systems.

c. Sources of repetitive failure data are:

   1. Number of maintenance man-hours by system or component

   2. Number of maintenance work orders by system or component

   3. Maintenance backlog (by system)

   4. Control instruments out of service

   5. Achievement of maintenance performance goals. i.e,

      - Safety system unavailability

- Number of inadvertent safety system actuations
- Number of unplanned facility shutdowns
- Lost mission or production time
- Forced outage rate
- Number of Incident Reports

d. Establish priorities by performing the following:

1. Ranking identified problems using Pareto Analysis.
2. Providing a framework for the allocation of resources.
3. Focusing attention on problems identified as the most important to the achievement of the Facility's operational and safety goals.
4. Considering the following in the ranking process:
   - Overall plant performance goals
   - Reliability Centered Maintenance (RCM) studies
   - Plant Safety Analyses/Technical Specifications
   - Costs in hours, dollars, exposure or lost production due to recurring failures

e. Assign problems for analysis based on the following:

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

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

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

g. Select corrective actions for implementation

1. Evaluate and prioritize the possible corrective actions.
2. Factors to consider are:

- 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
- Design bases and regulatory requirements

h. Implement selected corrective actions by performing the following:

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

i. Monitor impact of implemented corrective actions by performing the following:

1. Monitor system performance (PT&I and process data should be used).
2. Determine whether the improvement goals have been met.

Failure Analysis Form

Reliability Centered Maintenance

Equipment Identification: **Unit #:** ____________ **Equip. Type:** ____________

Ser.#: ____________ **Location:** ____________

Name of Person(s) Responding: ____________________________

Time the Equipment Failure: **Date:** __________ **Time:** __________

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 was Performed: ______________ **Associated WO #:** __________

Direct Cost Data:	**In-house**	**Contract**	**Subtotal**
Labor:	**$** ______	**$** ______	**$** ______
Material:	**$** ______	**$** ______	**$** ______
		Total Cost:	**$** ______

Failure Analysis Report completed by: ______________ **Date:** __________

Figure 3 – 4. Failure Analysis Form

3.4.10 Facilities Condition Assessment

The Facilities Condition Assessment (FCA) process should be considered as a continuous process and not as a series of discrete independent events. This can be accomplished by using the existing CMMS and PT&I databases, customer inputs, and Facility or Building Manager periodic inspections.

Individual system reliability and M&O costs, number of Trouble Calls normalized to operating hours and plotted over service life can be tracked by the CMMS. Equipment condition relative to other similar equipment can be tracked by reviewing the PT&I data and statistically determining the selected component relationships with respect to the mean and standard deviation. For example, a facility has X number of centrifugal water pumps of similar but not identical design in the range of 15–25 Hp. All of the pumps receive quarterly vibration monitoring, which includes a visual inspection, and annual insulation resistance check or motor circuit test. The insulation resistance checks are temperature corrected so they may be trended. In addition, where possible, flow and/or discharge pressure are noted during the vibration surveys and trended.

Each pump/motor combination is assigned a value of 1, 4, or 9 based on its relationship with the mean. For example, as illustrated in Figure 3-5, 50% of the equipment would be in better condition than the mean, 68.3% better than the mean plus 1 σ (sigma), 95.4% better than the mean plus two σ (sigma), and 99.7% better than the mean plus three σ (sigma).

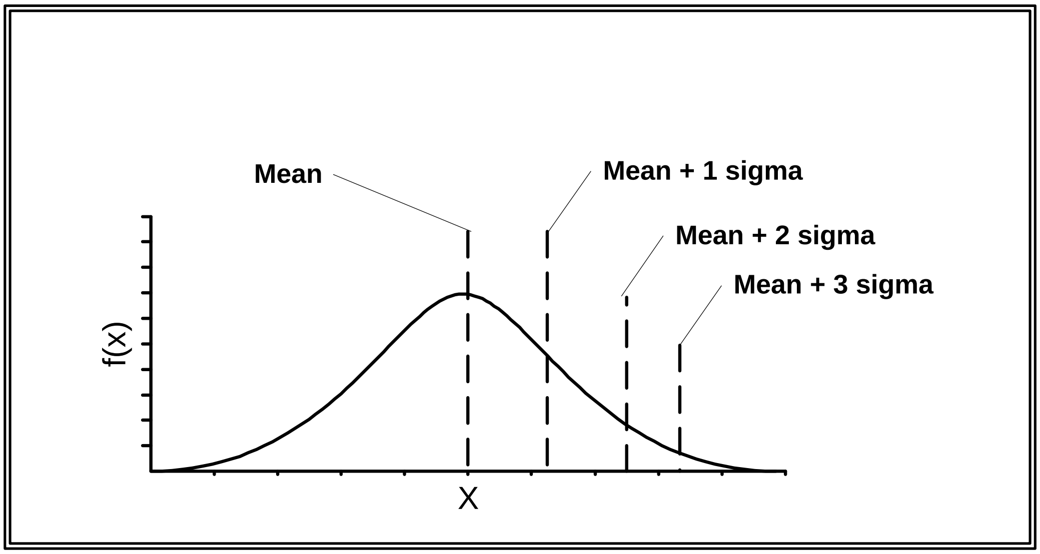

Figure 3 – 5. Mean and Standard Deviation

For example, if the vibration amplitude is below mean + 1σ (sigma) the unit would be scored as 1, below mean + 2σ it would be scored as 4, and above mean + 2σ it would be scored as a 9. Table 3–7 provides an example.

For more complex equipment and/or for equipment where more PT&I technologies are used, the table would be expanded. In addition, similar Tables should be prepared for Trouble Calls/Repairs normalized to operating hours, M&O costs, PT&I alarms normalized to operating hours, Availability, etc. The sum of all the Tables will result in a rank ordering of the equipment in terms of condition. This approach will address the functional condition in terms of availability and cost to maintain function.

Pump/Motor	Vibration Value	Resistance Value	Total
1	1	1	2
2	1	1	2
3	4	4	8
4	4	1	5
5	9	1	10

Table 3–7. Equipment Condition Classification Based on PT&I Data

Structures can be treated in a similar manner. In these cases, a periodic inspection by the Facility Manager of the common spaces, hallways, equipment rooms, roofs, and grounds combined with PT&I data from thermography, airborne ultrasonics, etc.

While the preceding technique is appropriate for equipment and structures, private spaces, such as offices, should be handled by the user. A form similar to Figure 3-6 can be used to obtain user input and address more subjective issues related to morale and appearance.

The office user should fill out a form similar to Figure 3 – 6 on an annual or semiannual basis to identify problems with the space. This information is then used to generate a work order which, can be prioritized and tracked.

OFFICE CONDITION FORM

LOCATION: Facility No. ________________ Room No. _________ DATE: ___________

NO CHANGE SINCE LAST INSPECTION ☐

Inspected By: ____________________ Phone No. _____________

SKETCH OFFICE HERE

DESK

Please indicate the following on the above office outline:

Ceiling Tiles: No. Missing _____ No. Broken _____ No. Stained _____

Windows: Mark Locations
Cracked or Broken ______
Leaks ______

Electrical Outlets and Switches: Mark Location
Missing _____
Cracked _____

Doors: Mark Locations
Handle, Hinges or Lock

Walls: Paint ____ Cracks _____

Lighting: Good ____ Poor ____

Ventilation: Airflow _____ Air Quality _____ Temperature Control _____

Carpet: Stains _____ Rips _____ Frayed _____

Resilient Titles: No. Cracked _____ No. Stained: _____

Overall Appearance: Good ______ Fair _____ Poor _____

Comments:____

Work Control No. ______________________
Date Received ______________________
Date Cleared ______________________

Signature ______________________

Figure 3-6. Office Assessment Form

Chapter 4— Predictive Testing & Inspection (PT&I) Technologies

4.1 Introduction

This chapter describes each of the primary PT&I technologies in terms of its purpose, techniques, application, effect, equipment required, operators, training available, and cost.

A variety of methods are used to assess the condition of systems/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 as well as the use of process parameters to determine overall equipment condition. The data acquired permits an assessment of system/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 approaches covered include:

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

Figure 4–1 provides information on the applicability of the technologies to various facility and production components. Data should be correlated as described in Section 3 and Appendix F.

4.1.1 Alerts and Alarms

Alerts and alarms are set to meet specific user requirements. Common methods used to determine alert and alarm values are:

a. **Arbitrary Value—**Set an arbitrary value for change from a baseline value. In this situation 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 middle 1980s at which time it was abandoned in favor of a more statistical approach as described below.

b. **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.

TECHNOLOGIES / APPLICATIONS	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									●	●	

Figure 4-1. PT&I Applications

c. **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. This is why it is important to document trends, the values at which failures occur, and the operating environment for future reference. 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.

4.2 Vibration Monitoring & Analysis

Analysis of system and equipment vibration levels is one of the most commonly used PT&I techniques. Vibration monitoring helps determine the condition of rotating equipment and structural stability in a system. In addition, vibration monitoring aids in the identification and localization of airborne noise sources.

Machinery and system vibration is 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 at some point it destroys the suspension, wheel, or tire. This analogy depicts what occurs as bearing and gear defects begin and then increase in size with each additional impact.

4.2.1 Applications and Techniques

Applicable to all rotating equipment; e.g., motors, pumps, turbines, compressors, engines, bearings, gearboxes, agitators, fans, blowers, shafts, etc. In addition, modern data loggers support resonance testing, equipment balancing, and airborne noise measurements.

4.2.1.1 Conditions Monitored

Wear, imbalance, misalignment, mechanical looseness, bearing damage, belt flaws, sheave and pulley flaws, gear damage, flow turbulence, cavitation, structural resonance, fatigue, etc.

4.2.1.2 Detection Interval

Narrowband vibration analysis can provide several weeks or months of warning of impending failure. Base the time interval on the experience of the analyst and the type, quantity, and quality of data collected.

4.2.1.3 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 probability of detection and false alarm rates.

4.2.1.4 Overall Vibration

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 but does not provide a complete picture of a systems condition. A modern maintenance program will not depend solely on an overall measurement approach to vibration analysis.

4.2.1.5 Spectrum Analysis and Waveform Analysis

Spectrum analysis of the frequency domain is the most commonly employed analysis method for machinery diagnostics. The spectrum analysis is used to identify the majority of all rotating equipment failures (due to mechanical degradation) prior to failure. Waveform analysis, or time domain analysis, is another extremely valuable analytical tool. While not employed as regularly as spectrum analysis, the waveform often aids the analyst in a more correct diagnosis of the machine problem.

4.2.1.6 Torsional Vibration

Often utilized to detect the vibration associated with gear vibration and shaft torque. It proves most helpful in situations where, due to transmission path attenuation, the casing vibration signal has a signal-to-noise ratio insufficient to detect the problem. Torsional vibration measurement is especially effective in situations where unsteady forces excite the resonance of the structure or housing. Torque is measured by using pairs of matched sensors spaced at an interval. This is done to take advantage of the phase difference in the signals due to shaft twisting, which is a function of shaft stiffness and load.

4.2.1.7 Multi-Channel Vibration Analysis

Offers several extremely powerful methods for machinery analysis such as force-response analysis, cross-coupling phase analysis, analysis of resonance mode characteristics, and multi-plane balancing. Additionally, coherence functions offered by multi-channel analyzers allow for checking the quality and linearity of data collected with typical data loggers.

4.2.1.8 Shock Pulse Analysis

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

4.2.1.9 Vibration Sensor Mounting

The use of a low mass accelerometer (100mV/g) and a rare earth super magnet attached to an accelerometer is the recommended approach to monitor most facilities machinery. In some cases, the use of a permanently mounted accelerometer is required. The permanently mounted accelerometer will provide the best signal transfer but it is not usually the most cost effective method. The use of a magnet mounted accelerometer, and a smooth mounting surface has been proven by the U.S. Navy to provide a usable upper frequency limit of 5 kHz. By utilizing special purpose accelerometers and a couplant between the accelerometer, magnet, and mounting disc, accurate measurements to 20 kHz are possible. Figure 7–1 provides a recommended frequency response curve for a properly mounted accelerometer.

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

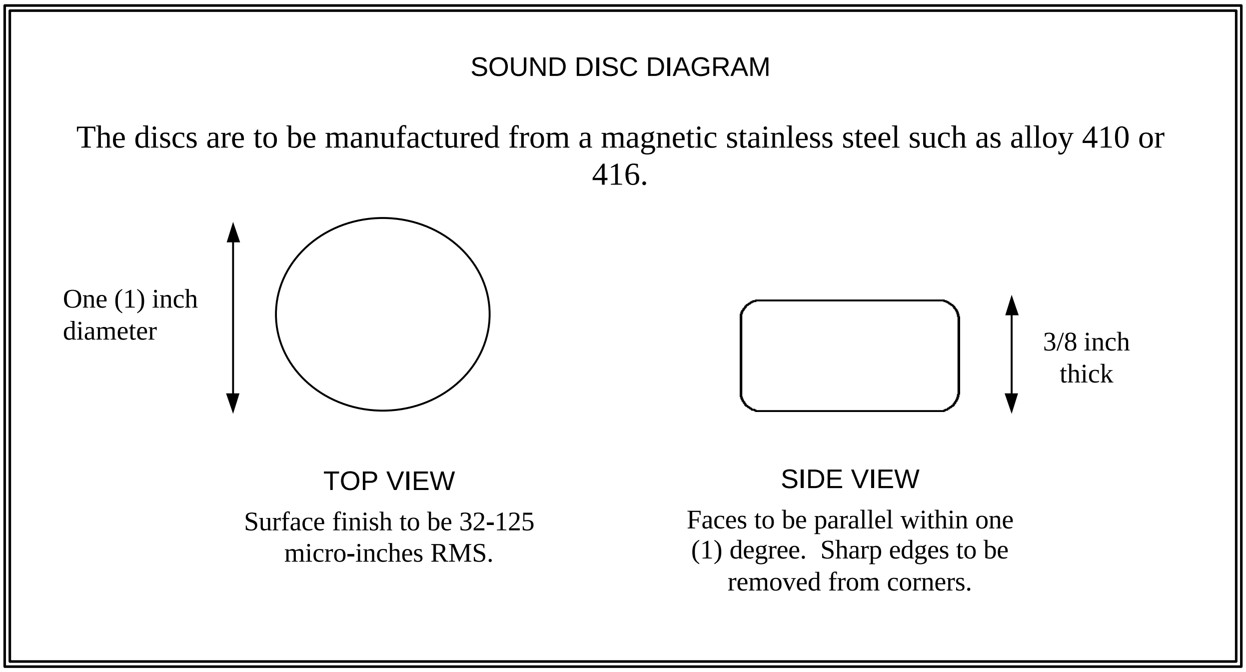

Figure 4-2. Sound Disc Diagram

Identify each monitoring point and epoxy magnetic corrosion resistant steel discs (sound discs) at every location. Sound discs should be a minimum of one inch in diameter and 3/16 to 3/8 inch thick. The discs can be purchased[10] 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. Figure 4–2 provides a dimensional drawing of a sound disc. The surface finish should be a minimum 63 micro-inch. Good frequency response is more related to placing the magnet on a clean surface with a lubricant between the magnet and the disk than a highly polished surface. 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. Surface must be level within 1 degree or .001 inch.

Use a tested epoxy such as Hysol Gray Epoxy Patch (available from Structural Adhesives) or Loctite Depend 330 to adhere the sound disc to the equipment. Prepare the surface for the epoxy by grinding or spot facing with a portable milling machine and wiping down with a solvent. If the portable milling machine is used to spot face the surface, ensure that the face diameter is ¼ inch in diameter larger than the disc diameter. The use of superglue type adhesives is not recommended, the sound discs do not adhere well when this type adhesive is used. Wielding the discs to the machine is also an option, but it is not recommended because of possible damage to the machine and distorting of the disc surface.

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

[10] 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."

The sound disc or machined surface should be marked (using a label or plate) "Vibration data collection point - Do Not Paint"

4.2.2 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.

Additionally, single channel analysis cannot always accurately determine the source of the vibration on complex machines.

4.2.3 Logistics

4.2.3.1 Equipment Required

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

4.2.3.2 Operators

- Requires personnel who have the ability to understand the basics of vibration theory and who have a basic knowledge of machinery and failure modes.
- Staffing requirements are site specific

4.2.3.3 Training Available

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

4.2.3.4 Cost (1998)

$20,000 to $120,000 for narrowband systems, software, and introductory training. The high-priced systems are for a basic multi-channel, installed system which can be expanded at a cost of $500-$1,000 per additional sensor. Portable analyzers appropriate for use are approximately $25 – $32,000, which includes all hardware, software, and training.

4.3 Infrared Thermography

Infrared Thermography (IRT) is the application of infrared detection instruments to identify pictures of temperature differences (thermogram). The test 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 (than long wave) to solar reflections and the inspector will need to be aware of this when performing outdoor inspections such as in substations and switchyards. 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 $+300^{o}C$, and accurate within ±3%. In addition, the instrument must be capable of storing an image of the thermogram for later use.

IRT inspections are identified as either qualitative or quantitative. 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 in a methodical fashion to properly 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. The knowledge and understanding discussed above is needed in order to perform a meaningful inspection. However, qualitative inspections are significantly less time consuming because the thermographer is not concerned with highly accurate temperature measurement. What the thermographer does obtain is highly accurate temperature differences (Δ T) between like components. For example, a typical motor control center will supply three-phase power, through a circuit breaker and controller, to a motor. Current flow through the three-phase circuit should be uniform which means that the components within the circuit should have similar temperatures, one to the other. Any uneven heating, perhaps due to dirty or loose connections, 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 so important to a highly accurate temperature measurement have very little influence on the temperature differences between like components.

4.3.1 Applications

IRT can be utilized to identify degrading conditions in facilities electrical systems such as transformers, motor control centers, switchgear, substations, switchyards, or power lines. In mechanical systems, IRT can identify blocked flow conditions in heat exchanges, condensers, transformer cooling radiators, and pipes. It can also be used to verify fluid level in large containers such as fuel storage tanks and identify insulation system condition in building walls and roof or refractory in boilers and furnaces. Temperature monitoring, infrared thermography in particular, is a reliable technique for finding the 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 can be used to quantify energy losses and their cost. IRT can also be used as a damage control tool to locate mishaps such as fires and leaks. Unless requested otherwise, the thermographer will normally only provide an exception report consisting of finds/faults.

In-service condition for electrical and mechanical systems can be assessed and work prioritized based upon the temperature difference criteria (ΔT) guideline. IRT criteria are provided in Section 8.2.3.

4.3.2 Limitations

Thermography is limited to line of sight. The infrared camera has limited ability to see through material. Most items that are usually considered transparent to the human eye, such as glass and plastic, are opaque to the infrared camera. Errors can be introduced due to type of material, material geometry, and by environmental factors such as solar loading and wind effects.

4.3.3 Logistics

4.3.3.1 Equipment Required

- Equipment ranges from simple, contact devices such as thermometers and crayons to full color imaging, 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.

4.3.3.2 Operators

- Operators and mechanics can perform temperature measurements and analysis using contact-type devices with minimal training on how and where to take the 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. With adequate training (Level I and Level II) and certification, electrical/mechanical technicians and/or engineers can perform this technique.

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

4.3.3.3 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 (NDT) (Level I, II, or III) thermographer certification (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. The thermographer's employer normally pays for any training and for making the decision to certify the thermographer. The trainer provides course completion certificates and recommends certification criteria, but the ultimate certification decision is the employer's.

4.3.3.4 Cost (1998)

- Noncontact infrared thermometers/scanners start at approximately $1,000. Full color microprocessor imaging systems with data storage and print capability range from approximately $15,000 to $60,000.
- Digital IR 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 provide 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.

4.4 Ultrasonic Noise Detection

Ultrasonic noise detection devices operate in the frequency range of 20kHz–100kHz 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.

4.4.1 Applications and Procedures

The following applications are applicable to all airborne ultrasonic devices.

4.4.1.1 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.

4.4.1.2 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:

a. **Tone Generator—**An ultrasonic source is placed inside the area to be tested (one tone generator required for each 4,000 cubic feet of volume), the instrument is set 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. A scan is then performed on the pipe or tubes.

b. **Differential Pressure Method—** Gas pressure difference 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.

4.4.1.3 Boilers

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

4.4.1.4 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[11] surveys in the petrochemical industry revealed that 34% of the steam traps inspected had failed, mostly in the open position. Assuming a nominal steam pressure of 100 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 were discovered during each survey:

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

[11] Yarway Technical Note STA-9

The numbers above can be used to estimate the number of leaks for a facility and combined with the data in Table 4 – 1 then used to approximate the total steam loss due to the steam leaks.

Leak Diameter (inches)	Steam Loss per Month (lbm)
1/64	3,300
1/32	6,650
1/16	13,300
1/8	52,200
1/4	209,000
1/2	833,000

Table 4 – 1. Estimated Steam Loss

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 25kHz 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.

a. **Intermittent Traps—**The operator will hear an opening and closing sound. The trap normally fails in the open position, producing a continuous, rushing sound.

b. **Inverted Bucket—**A normal trap sounds as if it is floating; a failed trap sinks, producing a continuous flow noise.

c. **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.

d. **Float and Thermostatic (Continuous Load)—** Flow and noise associated with these traps are usually modulated. Failed traps are normally cold and silent.

e. **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.

4.4.1.5 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 (which is not normally detectable using 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.

4.4.1.5 Bearings

Airborne ultrasonics can be used to detect bearing problems but it is not the preferred method. Vibration analysis is recommended.

4.4.2 Limitations

Airborne ultrasonics are subjective and dependent on perceived differences in noises. To maximize the usefulness of this technology, care should be taken when setting test equipment controls for frequency ranges, sensitivity, and scale. Additionally, the operator should be cognizant of the fact that piping bends and the presence of moisture and solids may dissipate and/or block the ultrasonic signal.

4.4.3 Logistics

4.4.3.1 Equipment Required

Ultrasonic monitoring scanner for airborne sound or ultrasonic detector for contact mode through metal rod.

4.4.3.2 Operators

Maintenance technicians and engineers.

4.4.3.3 Training Available

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

4.4.3.4 Cost (1998)

Scanners and accessories range from $1,000 to approximately $8,000. Complex acoustic valve leak detection systems are approximately $100,000.

4.5 Lubricant and Wear Particle Analysis

4.5.1 Purpose

Lubricating oil analysis is performed for three reasons: to determine the machine mechanical wear condition, to determine the lubricant condition, and to determine if 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.

4.5.1.1 Machine Mechanical Wear Condition

The criteria for analyzing the lubricating oil to determine the machine’s condition is similar as analyzing the vibration signature. That is, all machines with motors of a selected size (for example, 7.5 HP or larger), critical machines, or high cost machines. Generally the routine sampling and analysis periodicity will be the same as 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.

4.5.1.2 Lubricant Condition

Lubricating oil is either discarded or reconditioned through filtering and/or replacing additives. Analyzing the oil to determine the lubricant condition is therefore driven by costs. 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. In this example, the costs to replace the automobile oil (the replacement oil, labor to change the oil, and disposal costs) are lower, through economies of scale and competition, than the cost to analyze the oil (sample materials, labor to collect the sample and the analysis). Generally speaking, 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.

4.5.1.3 Lubricant Contamination

Lubricating oil can become 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. In addition, a periodic analysis following "topping off" or reconditioning the oil is performed. The root cause of any oil contamination needs to be determined and eliminated in order 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 to troubleshoot known problems. As previously discussed, lubricating oil analysis is performed for three reasons: to determine the machine mechanical wear condition, to determine the lubricant condition, and to determine if the lubricant has become contaminated. Tests have been developed to address indicators of these conditions and vary in cost dependent upon time and materials needed to accomplish the testing. The tests selected for use in the PT&I program must balance the need for understanding the lubrication condition and the cost of the testing.

4.5.2 Standard Analytical Tests

Lubricating oil and hydraulic fluid analysis should proceed from simple, subjective techniques such as visual and odor examination through more sophisticated techniques. The more sophisticated (and expensive) techniques should be used when conditions indicate the need for additional information and the equipment cost or criticality justifies the cost.

4.5.2.1 Visual and Odor

Simple inspections can be performed weekly by the equipment operator to look at and smell the lubricating oil. A visual inspection looks for changes in color, haziness or cloudiness, and particles. This test is very subjective but can be an indicator of recent water or dirt contamination and advancing oxidation. A small sample of fresh lubricating oil, in a sealed, clear bottle, can be kept on-hand for visual comparison. A burned smell may indicate oxidation of the oil and other odors could indicate contamination. Odor is more subjective than the visual inspection because sensitivity to smell is different between people and there is not an effective way to compare the odor between samples. The operator must be careful not to introduce dirt into the system when taking a sample.

4.5.2.2 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 procedure. Viscosity is measured in Centistoke (cSt) and minimum and maximum values are identified by ISO grade. Testing is usually part of a commercial laboratory standard test package.

4.5.2.3 Water

Water in lubricating oil and hydraulic fluid contributes to corrosion and formation of acids. Small amounts of water (less than 0.1%) can be dissolved in oil and can be detected using the crackle test or infrared spectroscopy (minimum detectable is .05% or approximately 500 PPM; 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% water, if suspended or emulsified in the oil, will appear cloudy or hazy. Free water in oil collects in the bottom of reservoirs and can be found by draining from the bottom.

4.5.2.4 Percent Solids/Water

A simple, inexpensive test is used to provide a gross estimate of solids and/or 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% to 20% of volume and is usually part of a commercial laboratory standard test package.

4.5.2.5 Total Acid Number (TAN)

Total acid is an indicator of the lubricating oil condition and is monitored relative to the TAN of new oil. In some systems the TAN will also be used to 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) or electrical conductivity change (ASTM D664).

4.5.2.6 Total Base Number (TBN)

Similar to TAN in test method, this 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 or ASTM D2896). When comparing test results (for example, against baseline data from the oil supplier), ensure that the same test method is used as results can vary between test methods.

4.5.2.7 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 μm). 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.

4.5.2.8 Infrared Spectroscopy

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 Water, discussed earlier) and lubricant conditions (such as oxidation and anti-oxidant and other additive depletion). Ongoing work is coupling 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.

4.5.2.9 Particle Counting

Particle counting is used to identify metal and non-metal particles over 5 microns and up to 40 to 50 microns. Two methods are used and each has advantages and drawbacks. Both methods 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 depends on the analyst skill. The benefit of the visual method is that the analyst is able to identify the types of particles such as dirt, seal material, and metal. The electronic counting method is much faster and does not depend on the analyst's ability but it does not distinguish or identify the particle make up. A commercial laboratory will quote electronic particle count; visual particle counting is only done on request and costs more.

4.5.2.10 Direct-Reading (DR) Ferrography

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

4.5.2.11 Analytical Ferrography

More detailed than DR ferrography, analytical ferrography is often initiated based on changes in DR, spectrometric metal increases, or increased particle count. The analysis is sometimes performed on a regular basis on high cost or critical machines. Process is labor intensive and involves the preparation of sample and then examination under magnification. Results depend on analysts capability but the procedure can provide detailed information 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 be critical in finding the root cause of wear problems. Costs are moderately high; test is performed on a fixed price basis (per sample) from a commercial laboratory.

4.5.3 Special Tests

Special tests are sometimes needed to monitor lubricant conditions on some high cost or critical systems. Usually the special test is monitoring a lubricant contaminate, a characteristic or additive depletion. This section identifies some of the special tests available. Special tests are rarely needed for routine monitoring of lubricants and the tests listed here are provided as samples. Test procedures are constantly being developed and refined. The annual ASTM Standards[12] provide a description of current test methods.

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

4.5.3.1 Glycol Antifreeze

Glycol contamination can be detected using infrared spectroscopy (see Infrared Spectroscopy, discussed earlier) at levels greater than 0.1% (1,000 PPM) which is usually adequate for condition monitoring. However, additional tests can be specified to identify if small amounts of glycol are present. ASTM test D2982 will indicate if trace amounts are present. ASTM D4291 uses gas chromatography to quantify small amounts of glycol.

4.5.3.2 Karl Fischer Water

Water contamination can be detected using infrared spectroscopy (see Infrared Spectroscopy, discussed earlier) at levels greater than 0.05% (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, is useful when accepting new oil or evaluating clean up efforts. Cost of the test is moderate.

4.5.3.3 Foaming

Some oil may have anti-foam agents added to improve the lubrication capability in specific applications such as gearboxes or mixers. ASTM test D892 can be used to test the oils foam characteristics. The test blows air through a sample of the oil and then the foam volume is measured. Cost of the test is moderately high.

4.5.3.4 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 (or ASTM D3603). Results are pass/fail and the cost of the test is high.

4.5.3.5 Rotating Bomb Oxidation Test (RBOT)

Also known as Rotary Bomb Oxidation Test, ASTM D2272, is used to estimate oxidation stability and, therefore, identify the remaining useful life of oil. The test simulates aging to identify when rapid oxidation takes place indicating that anti-oxidants have been depleted. Test is not a one-time test; it must be performed over time, including a baseline test with new oil, in order to develop a trend line. Because of the high cost, and the multiple tests required, this test is usually only performed on large volume reservoirs or expensive oil.

4.5.4 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 in the same way that the vibration analysis schedule is adjusted. 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 are indicating emerging problems; less frequently for machines that have stable conditions and are not run on a continuous basis. A new baseline analysis will be needed 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. Generally speaking, it is 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 usually not analyzed on a regular basis. Although most of the testing that is done on oil can also be done on grease, there is a problem getting a representative sample. In order to get a representative sample- one that is a homogeneous mixture of the grease, contaminants, and wear- the machine must usually be disassembled. Analysis of grease to diagnose a failure can sometimes be useful.

A concern common to all machines with lubricating oil systems is keeping dirt and moisture out of the system. Common components of dirt, such as silica, are abrasive and naturally 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. Ideally, there would be no dirt or moisture in the lubricant; this, of course, is not possible. The lubricant analysis program must therefore monitor and control contaminants. Large systems, with filters, will 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.

4.5.4.1 Motors, Generators, Pumps, Blowers, Fans

For those machines that have been selected for monitoring (as discussed in Section 2) and have less than 5 gallons in the lubrication system, the analyst is mostly concerned with machine condition. Lubricant condition and contamination are of interest in that they contribute to machine condition i.e. viscosity, percent solids/water, and spectrometric metals. Monitor trends and discard or refresh the oil when viscosity changes 10% from the baseline. Viscosity normally increases above the baseline with the oil service time. If the viscosity decreases below the baseline, it usually means that 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%). If there is water, the source of the water needs to be identified and corrected.

For machines with more than 5 gallons of oil in the system, add infrared spectroscopy (minimum amount of water detectable is .05%) and particle counting. Changes in particle count can 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 can be used to identify the source of the contamination. In addition, perform DR ferrography for high cost or critical machines. In all machines, changes in spectrometric metals or DR should be investigated further using analytical ferrography and correlated with vibration analysis.

4.5.4.2 Gearboxes

Same as above, with the following additions. For all gearboxes, including those with less than 5 gallons of oil, add particle counting. Include DR ferrography for high cost or critical gearboxes. Monitor trends and correlate with vibration readings.

4.5.4.3 Chillers

In addition to the items identified above, add TAN and Direct Read ferrography.

4.5.4.4 Diesel Engines

Same as chillers except substitute TBN for TAN when oil has high detergent additives. A decrease in viscosity below the baseline may indicate fuel contamination. Coolant leakage (glycol and other characteristics) is identified from the infrared spectroscopy analysis.

4.5.4.5 Compressors

Centrifugal compressors; same as chillers. Reciprocating compressors; same as diesel engines.

4.5.4.6 Hydraulic Systems

Same as gearboxes. 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 7 – 9.

4.5.4.7 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 and then 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.

4.5.4.8 Lubrication Analysis

Figure 4–3, Lubrication Analysis Chart, summarizes the various lubricant tests, monitoring interval, and application.

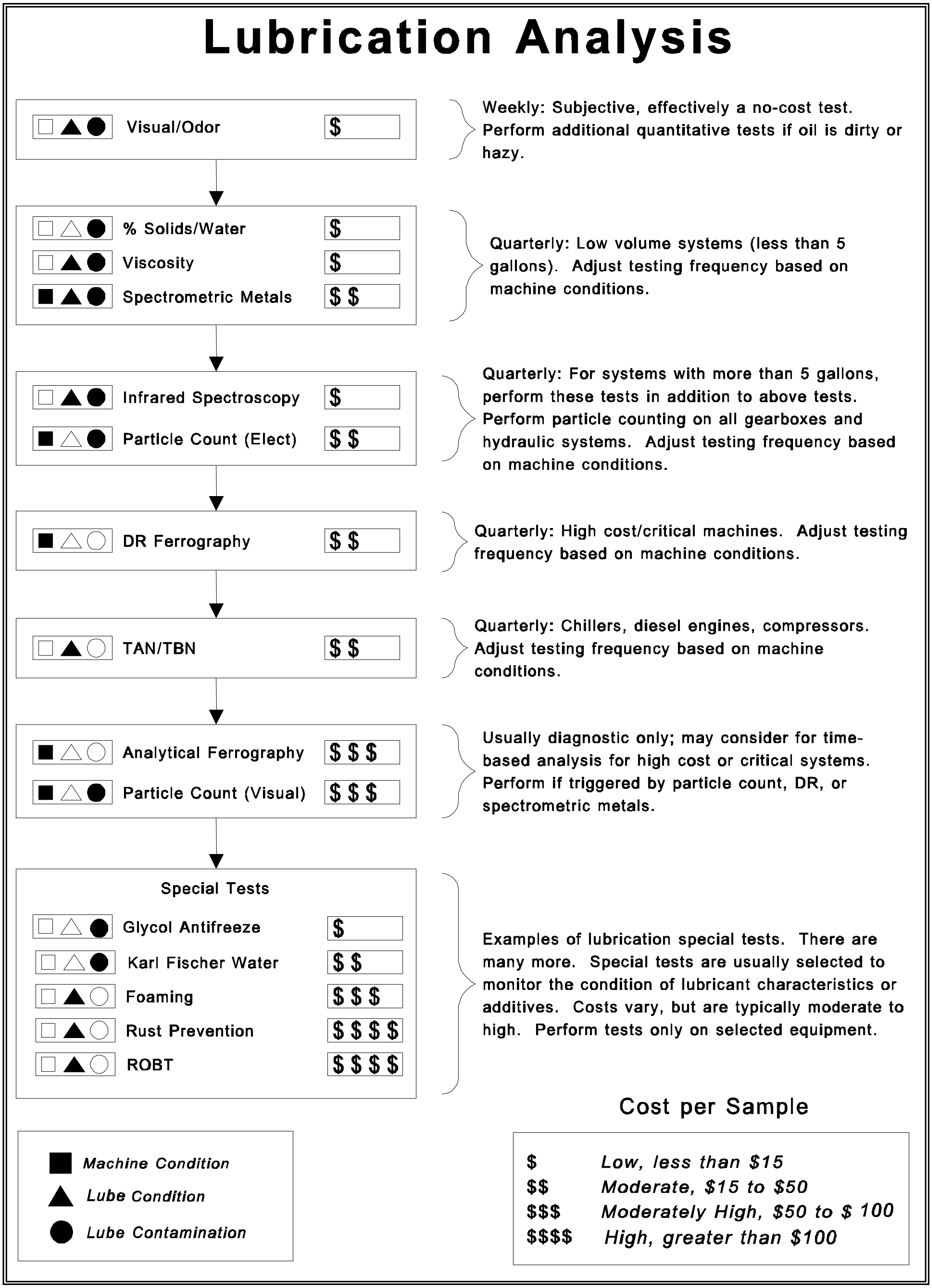

Figure 4 – 3. Lubrication Analysis Chart

4.5.5 Sampling

Oil samples must be collected safely and in a manner that will not introduce dirt and other contaminates into the machine/system or into the sample. It may be necessary to install permanent sample valves in some lubricating systems to do this. The oil sample should be representative of the oil seen in the machine. The sample should, therefore, be collected from a mid-point in reservoirs and prior to filtering in circulating systems. Sample collection bottles and tubing can be procured through testing laboratories. The testing laboratory will also be able to provide guidance as regards to the cleanliness level needed. Oil sample pumps for extracting oil from reservoirs must be used properly to avoid contamination. Samples must be collected from the same point in the system in order to assure consistency in the test analysis; therefore, the maintenance procedure must provide detailed direction on where and how to collect samples.

The equipment operators can 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.

Additional information on sampling points and techniques is contained in Section 7.1.9.

4.6 Electrical Condition Monitoring

A major portion of a facility’s capital investment is represented by electrical equipment. From the power distribution system to electric motors, the electrical systems 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), present safety concerns (fires) and life cycle cost issues (premature replacement of equipment). According to the Electric Power Research Institute[13], voltage imbalances of as little as 5% in motor power circuits result in a 50% reduction in motor life expectancy and efficiency in 3 phase AC motors. A 25% increase in motor temperatures can be generated by the same 5% voltage imbalance accelerating insulation degradation.

4.6.1 Techniques

- Infrared Thermography
- Insulation Power Factor Testing
- Insulation Oil Analysis

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

- Gas-in-Oil Analysis
- Megohmmeter Testing
- High Potential Testing (HiPot)
- Airborne Ultrasonics
- Battery Impedance Testing
- Surge Testing
- Motor Circuit Analysis (MCA)
- Motor Current Signature (Spectrum) Analysis
- Very Low Frequency Testing (VLF)
- Circuit Breaker Timing Tests
- Circuit Breaker Contact Resistance

(*Note*: HiPot and surge testing should be performed with caution. The high voltage applied during these tests may induce premature failure of the units being tested. For that reason these tests are normally performed only for acceptance testing, not for condition monitoring.)

4.6.1.1 Infrared Thermography

Infrared thermography has widespread application in electrical systems, because of its ability to be used safely on energized equipment, to detect temperature differences and overheating of circuits. See the discussion earlier in this section for more information.

4.6.1.2 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, which is expressed in percent of the resistive current flowing through an insulation to the total current flowing. To measure this value a known voltage is applied to the insulation and the resulting current and current/voltage phase angle is measured. Figure 4-4 shows the phase relationships of the resulting currents. I_R is the resistive current, I_C is the capacitive current, I_T is the resultant, or total current, and V is the applied voltage.

Usually, I_R is very small compared to I_T because most insulation is capacitive in nature. As a comparison, look at the similarities between a capacitor and a piece of electrical insulation. A capacitor is two current carrying plates separated by a dielectric material. An electrical coil, such as would be found in a transformer or motor, 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 through" until such a time that the voltage level of the two plates exceeds the voltage capacity of the dielectric. The coil insulation prevents the current from flowing to ground, also until such a time that the voltage level exceeds the voltage capacity of the insulation.

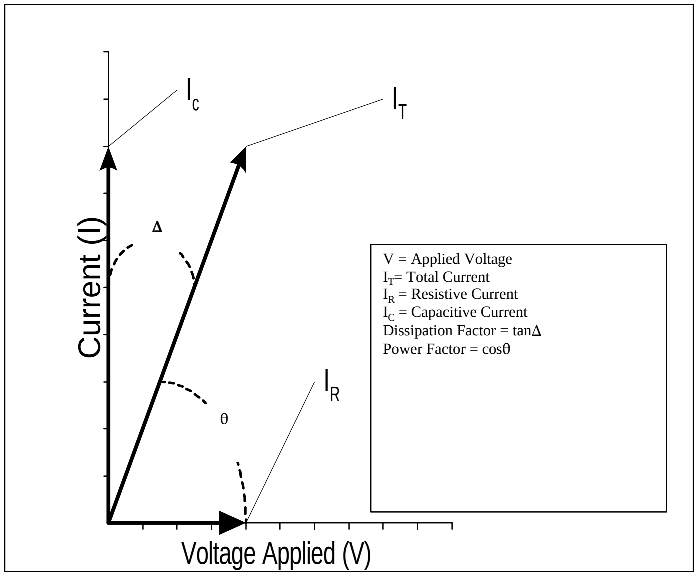

Figure 4 – 4. Power Factor Current/Voltage Relationship

Referring back to Figure 4 - 4, it can be seen 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 then becomes less, 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. It is one of the best electrical PT&I tests.

4.6.1.3 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 a wealth of information as to the operational history and current condition of the equipment. Below are listed available tests, the ASTM standard number[14] (note that several of these standards were discussed in the lubricating oil section), and a brief description of what each test reveals.

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

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

b. **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.

c. **Neutralization Number, ASTM D-974—**Commonly called the acid number, this measurement indicates 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.

d. **Interfacial Tension(IFT), ASTM D-971—**Measures the tension at the interface between two immiscible liquids, oil and water. It is expressed in dynes/centimeter. This test is extremely sensitive to oil decay products and contamination from solid insulating materials. 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, contaminates such as oxygen and free water are released into the oil. The properties that allow the oil to “float” on top of the oil then begin to break down and the result is a lower IFT. Along with the neutralization number, the IFT can reveal the presence of sludge in insulating oils.

e. **Color, ASTM D-1524—**as insulating oils in electrical equipment age, the color of the oil tends to gradually darken. A marked color change from one year to the next could indicate a deteriorating oil.

f. **Sediment, ASTM D-1698—**indicates deterioration and/or contamination of the oil.

g. **Power Factor, ASTM D-924—**taken at 25 ^{o} C, this test can reveal 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%.

h**.** **Visual Examination, ASTM D-1524—**insulating oil is clear and sparkling, not cloudy and dull. Cloudiness indicates the presence of moisture or other contaminates. This is a good “quick look” field test and can be used to trigger a Karl Fischer or Dielectric Breakdown test.

4.6.1.4 Gas-in-Oil Analysis

Gas-in-oil analysis, also called dissolved gas analysis, is probably the best 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. In most cases these stresses can be detected early on; 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[15]. 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)

Different combinations of these gasses reveal different conditions. Large amounts of CO and CO_2 indicates 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, and C_2H_2 is a sign of internal arcing. Various industry publications exist to help determine potential problems.

4.6.1.5 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 referred to as the polarization index.

[15] 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.

4.6.1.6 High Potential Testing (HiPot)

HiPot testing applies a voltage equal to twice the operating voltage plus 1000 volts to cables and motor windings testing the insulation system. This is typically a go/no-go test. Industry practice calls for HiPot test 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 routinely repeated condition monitoring technique, but as an acceptance test. An alternative use of the equipment 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.

4.6.1.7 Airborne Ultrasonic Noise

Electrical arcing and discharges create noise in the upper, or ultrasonic frequency ranges, sometimes long before a failure occurs. Things like corona discharges in switchyards, loose switch connections, and internal arcing in deadfront electrical connections can all sometimes be heard with an ultrasonic noise detector. Also see the additional information in Section 4.4.

4.6.1.8 Battery Impedance Testing

Batteries are DC energy storage devices with many shapes, sizes, capacities, and types. 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. The resulting voltage is measured and the impedance then calculated. This measurement can be accomplished without removing the battery from service since the AC signal is low level and "rides" 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, second, the reading is compared with other batteries in the same bank. Each battery should be within 10% of the others and 5% of its last reading. A reading outside of these values indicates a cell problem or capacity loss. Additionally, if the battery has an internal short the impedance tends to go to zero. If there is an open the impedance will try to go to infinity, and premature aging due to excessive heat or 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. It should take less than an hour to perform this test on a battery bank of 60 cells.

4.6.1.9 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. Like HiPot testing, the applied voltage equals two times operating voltage plus 1000 volts. This test also is primarily an acceptance, go/no-go test. 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 (short circuits). Because of the repeated stress of the insulation system, Surge testing is not recommended for routine condition monitoring.

4.6.1.10 Motor Circuit Analysis

The motor circuit analysis technology packages several motor tests into a single unit. The test device will check the following test parameters in a motor circuit: resistance to ground, capacitance to ground, resistive imbalance, inductive imbalance, rotor influence, and will perform a polarization index. The tests are performed with the motor de-energized and use low voltage that does not over stress 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.

4.6.1.11 Motor Current Signature (Spectrum) Analysis (MCSA)

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. It can be compared to vibration analysis in the methods both use to analyze data. 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 FFT process to identify the presence of electrical fault frequencies.

4.6.1.12 Very Low Frequency 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.

4.6.1.13 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 coming 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. The numbers are normally printed out from the test set, and the chart is stored in memory for downloading into a computer.

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.

4.6.1.14 Circuit Breaker Contact Resistance

This test is used to determine the contact condition on a breaker or switch without visual inspection. The results of this test can be trended over time to help in scheduling 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 two things, 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. It should be noted that for oil filled breakers, using a 100 amp test set is recommended because oil tends to glaze on contact surfaces and, in some cases, 10 amps is not enough current to overcome the glaze.

4.6.2 Additional Techniques and Troubleshooting

There are numerous electrical tests that, while not forecast orientated, provide indications of the system condition.

4.6.2.1 Time Domain Reflectometry

A voltage spike is sent through a conductor. Each discontinuity in the conductor path generates a reflected pulse. The time difference between initial pulse and reception of the reflected pulse indicate the location of the discontinuity. This technology is used for power cables to help locate faults within a cable run. The test is performed with the cable de-energized.

4.6.2.2 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, 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, which reduce service life and cause spurious tripping of circuit breakers, which can be a major inconvenience. A harmonic analyzer is used to measure the harmonic current and identify the source. Filters can then be placed on the circuit to minimize the impact. This test is performed with the system energized.

4.6.2.3 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.

4.6.2.4 Transformer Turns Ratio (TTR)

This test measures the turns-ratio of a transformer and is mainly used as an acceptance test. It can also be used as a trouble shooting 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.

The test is performed by applying a voltage across the primary windings and measuring the resulting voltage across the secondary winding. The ratio of active windings can be calculated. This measurement can be used to determine the condition of the transformers inductive capability. The turns 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.

4.6.3 Applications

4.6.3.1 Equipment to be Monitored

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

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

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

c. **Electrical Distribution Transformers—**Oil Analysis, Turns Ratio, Power Factor and Harmonic Distortion.

d. **Electrical Motors—**Motor Current Signature Analysis, Motor Circuit Analysis, Megohmmeter, HiPot, Surge Test, , Starting Current and Coast Down Time, Infrared Thermography, Airborne Ultrasonics.

e. **Generators—**Megohmmeter, VLF Testing, and Coast Down Time.

f. **Distribution System—**Infrared Thermography, HiPot, Airborne Ultrasonics, Power Factor and Harmonic Distortion.

4.6.3.2 Conditions Monitored

Temperature, voltage, current, resistance, complex impedance, capacitance, insulation integrity, phase imbalance, mechanical binding, and presence of arcing.

4.6.3.3 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. Additionally, 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.

.4.6.3.4 Accuracy

Accuracy is dependent on the testing technique applied and rating of the instrument.

4.6.3.5 Limitations

The technologies presented can be divided into two categories:

a. **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, Insulation Oil Analysis (Including Gas-in-Oil).

b. **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.

Each technology will require 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.

4.6.4 Logistics

4.6.4.1 Equipment Required

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

4.6.4.2 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.

4.6.4.3 Training Available

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

4.6.3.4 Cost

a. **Equipment—**Equipment costs vary from $20 for a simple multi-meter to approximately $40,000 for integrated motor-current analysis (MCA) testers. A full inventory of electrical testing equipment can cost in excess of $100,000.

b. **Training—**Training averages between $750 and $1,000 per week per person trained for each technology.

4.7 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. Instead of statistical sampling techniques that use only surface measurements or require the destructive testing of selected components from a production lot, NDT is used when these testing techniques are cost prohibitive or ineffective (see Figure 4–5). Typically, NDT has been

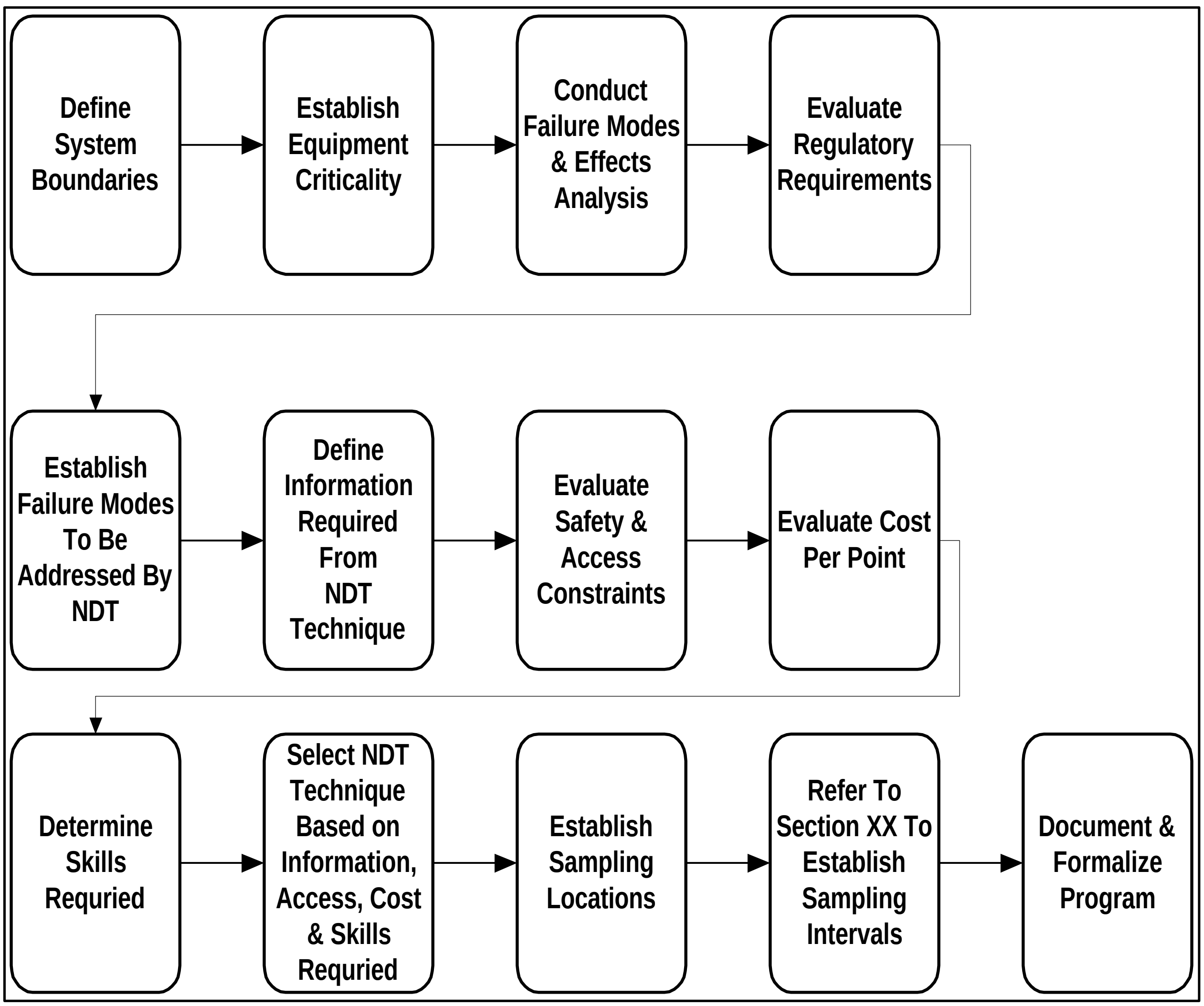

Figure 4 – 5. NDT Technique Selection Process

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.

4.7.1 Techniques

a. **Radiography—**Detection of deep sub-surface defects. Radiography or x-ray is one of the most powerful NDT techniques available in industry. Depending on the strength of the radiation source, radiography can provide a clear representation (radiograph) of discontinuities or inclusions in material several inches thick. X-ray or gamma ray sensitive film is placed on one surface of the material to be examined. The radiation "source" is positioned on the opposite side of the piece. The source may be either a natural gamma emitter or a powered X-ray emitter. The source is accurately aligned to assure the proper exposure angle through the material (Figure 4–6). When all preparations and safety precautions are complete, radiation source energized or unshielded. The gamma or x-rays passing through the material to the film expose the film.

   By developing the film in a similar manner to photographic film, an image of defects or inclusions in the material is produced. More advanced radioluminescent film does not require photographic processing. Multiple "shots" from varying angles provide 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, these can be classified into either acceptable inclusions or unacceptable defects.

   Defects in the material must be accurately located to facilitate minimal material removal, yet assure the defect has been completely eliminated. 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, though a versatile tool, is limited by the potential health risks. Use of radiography usually requires the piece be moved to a special shielded area (Figure 4–6) or personnel evacuated from the vicinity to avoid exposure to the powerful radiation source required to penetrate several inches of dense material. Temporary shielding may also be installed, but the installation and removal of thousands of pounds of lead is labor intensive. Radiography technicians are trained in radiation health physics and material properties. These technicians can visually distinguish between welding slag inclusions, porosity, cracking and fatigue when analyzing radiographic images.

b. **Ultrasonic Testing (Imaging)—**Detection of deep sub-surface defects. Ultrasonic (UT) inspection of welds and base material is often an alternative or complementary NDT technique to radiography. Though more dependant on the skill of the operator, 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

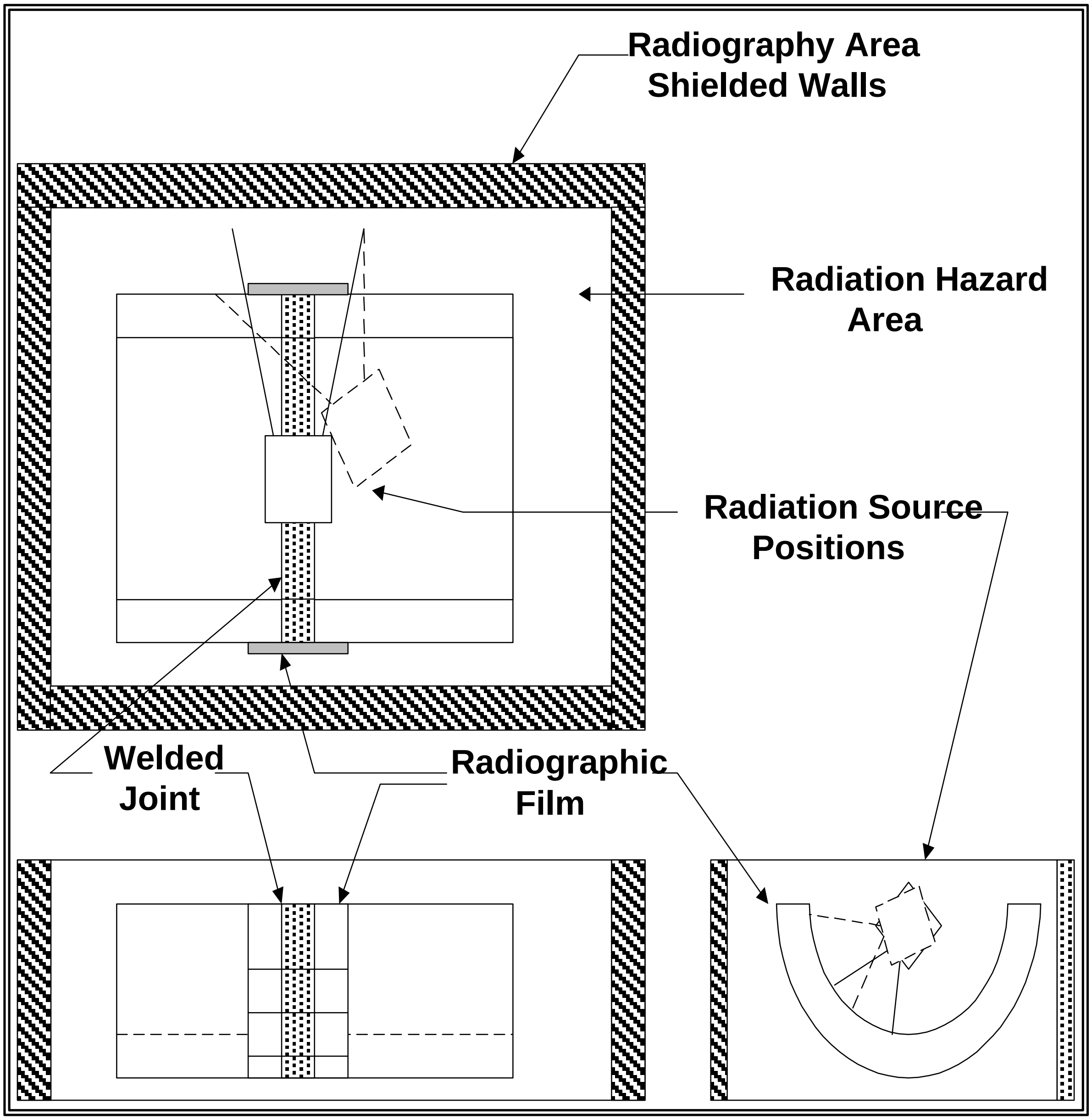

Figure 4 – 6. Shielded Radiography Enclosure

surrounding material. An ultrasonic signal is applied through a transducer into the material being inspected. 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 of interest. 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.

Three scan types are most commonly used; A Scan, B Scan and C Scan. 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 the reliable test results. Surface preparation is also critical to reliable UT results. Any surface defects such as cracks, corrosion, or gouges will adversely affect the reliability of UT results.

Due to the time and effort involved in surface preparation and testing, 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 of the condition of the material can be accomplished. 100% UT inspection is typically reserved for original construction of high stress components such as nuclear reactor vessels or chemical process vessels.

c. **Magnetic Particle—**Detection of shallow sub-surface defects. Magnetic Particle Testing (MT) techniques are useful during localized inspections of weld areas and specific areas of high stress or fatigue loading. MT provides the opportunity to locate shallow sub-surface defects. Two electrodes are placed several inches apart on the surface of the material to be inspected. 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, see Figure 4–7. 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. Also, good electrode contact and placement is important to assure 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.

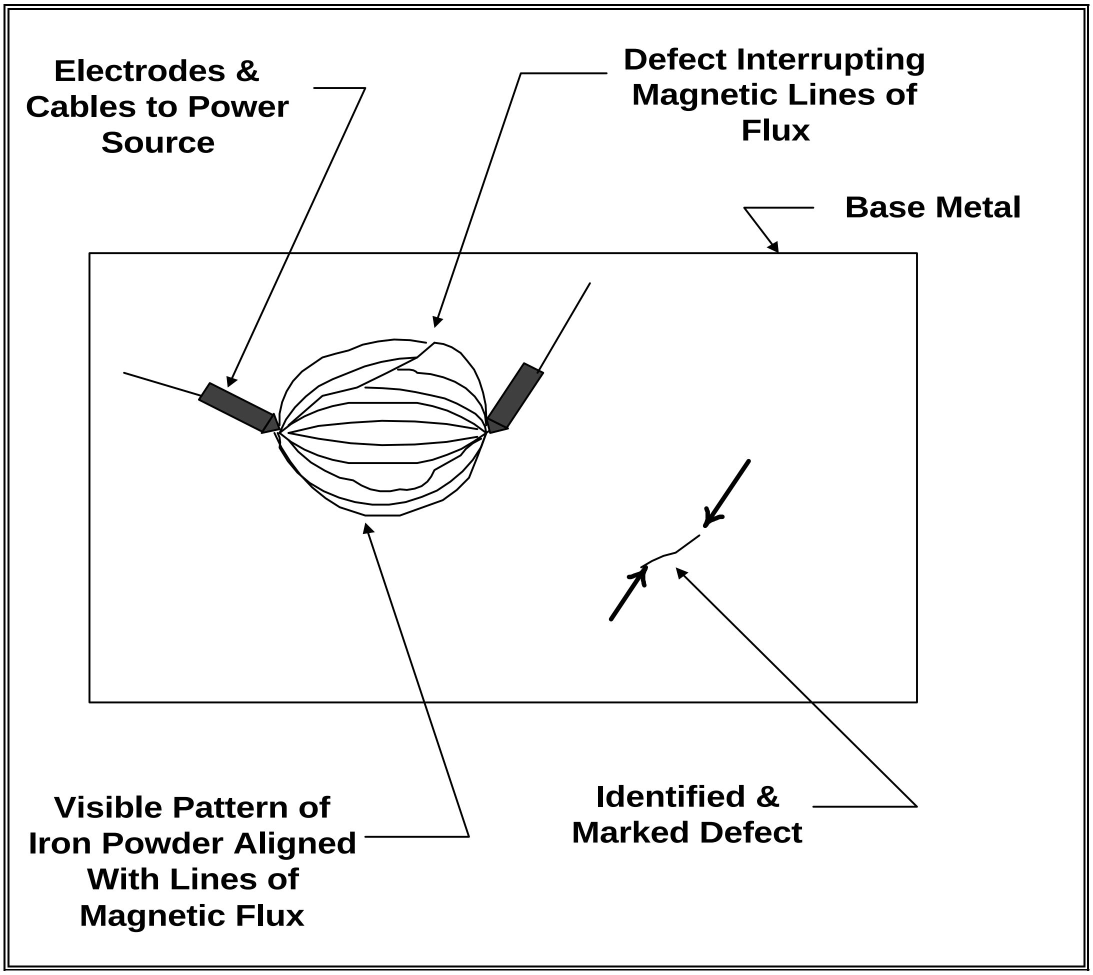

Figure 4 – 7. Magnetic Particle Testing

d. **Dye Penetrant—**Detection of surface defects. Dye Penetrant (DP) inspections provide a simple method for detecting 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. The dye is allowed to penetrate for several minutes. The excess dye is then wiped from the surface leaving only the dye that has been drawn into surface defects. A developer (usually white) is sprayed on the entire surface (same area as the dye application). 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.

e. **Hydrostatic Testing—**Detection of breeches in a system's pressure boundaries. Hydrostatic Testing (Hydro) is an NDT method for detecting defects that completely penetrate pressure boundaries. Hydros are typically conducted prior to the delivery or operation of completed systems or sub-systems 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 as well as monitoring pressure drop and make-up 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 also be used with compressed gases. This type of test is typically called an air drop test and is often used to test the integrity of high-pressure air or gas systems.

f. **Eddy Current Testing—**Detection of surface and shallow sub-surface defects. Also known as electromagnetic induction testing. Eddy Current testing provides a portable and consistent method for detecting surface and shallow sub-surface defects. This technique provides the capability to quickly inspect 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 materials 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 are used to induce electrical currents (eddy currents) into the component being tested. The induced currents produce magnetic fields, which are then detected by a set of sensing coils. Typically 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 signal 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.

4.7.2 Location & Intervals

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

4.7.2.1 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 NDT techniques applicable to the situation will affect the inspection interval (Table 4–2). Other factors may enter into consideration, if warranted.

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

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**

Table 4–2. Recommended Maximum Inspection Intervals (API 570)

In-place corrosion rates in conjunction with 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 service 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.

Relevant regulatory requirements must be taken into account when determining NDT inspection intervals. With the multitude of professional codes and government regulations this section will not attempt to cover specific regulations. Many government regulations provide sufficient leeway for the experts within an organization to set intervals in accordance with technically sound methods. Some regulations simply require a technically sound plan that the organization follows.

Before accepting what seems like an unreasonable interval simply in the name of 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 Weibul 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 4–8). As thermodynamic properties change, they can provide an indication of 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.

4.7.2.2 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.
- Presence of "Dead-Heads" that can create turbulence or stagnant areas where material may accumulate and set up corrosion cells.
- Junctions of dissimilar metals. Galvanic corrosion is prevalent in these areas unless specific steps are taken to prevent it.
- 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 4 – 8. Inspection Program Development

4.7.3 Applications

a. **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.

b. **Ultrasonics—**UT techniques are readily applicable to metal components including weld deposits. Specialized applications for plastics or composite materials are common. Whenever possible, UT is a preferred method over radiography for in-place applications, due to expense and safety precautions required by radiography. 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.

c. **Magnetic Particle—**MT techniques are applicable only to materials that conduct electric current and magnetic lines of flux. Only shallow defects are detectable with MT inspection. Typically 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.

d. **Dye Penetrant—**DP inspections are applicable for any non-porous material that is chemically compatible with the dye and developer. This is the simplest NDT technique in which to gain proficiency.

e. **Hydrostatic Testing—**Hydros test 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.

f. **Eddy Current—**Eddy current techniques are used to detect internal defects such as cracks, seams, holes or laminations separation on both flat sheets and more complex cross-sections as well as monitoring 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.

4.7.4 Limitations

a. **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 piece being examined or installation of extensive shielding.

Even with these limitations, 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% penetration.

b. **Ultrasonics—**UT 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, since 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.

c. **Magnetic Particle—**MT 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.

d. **Dye Penetrant—**Minute surface discontinuities such as machining marks will become readily apparent. The inspector must be trained to distinguish between normal surface discontinuities and defects that must be repaired. 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 DP inspection.

e. **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 hydros 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.

Hydros 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.

f. **Eddy Current—**Eddy Currents tend to flow parallel to the surface to which the exciting field is applied. Some orientations of laminar discontinuities parallel to this surfaces 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.

4.8 Photography

Videotaping is often used to record complex machines during operation. The tape is played back at a slow speed in order to what is happening. This is especially good tool for analyzing and troubleshooting packaging machines.

a. **Monitor -** Broadcast industry quality is recommended.

b. **VCR -** A unit with 4 heads and shutter control to allow tape movement one frame at a time. This is critical to viewing slow motion. It also is capable of recording and playing back in Super VHS that allows for clearer recordings.

c. **Camera** - Minimum 10 - 1 zoom lens, low light capability, Super VHS capability and a shutter speed of at least 1000.

d. **Lights -**The stand alone Tungsten work lights are recommended.

e. **Digital Camera** – Sufficient memory to store twenty pictures. The highest resolution available is recommended.

f. **Approximate Cost** - $2,500

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Chapter 5—RCM Requirements during Facilities Acquisition

This chapter discusses RCM requirements during the acquisition stage of the facilities life cycle; i.e., during facilities planning, design, and construction.

5.1 Planning

Early in the planning of a new facility, consideration must be given to the extent RCM analysis and PT&I techniques will be used to maintain the facility and its equipment. This is likely an issue that crosses organizational lines (i.e. between operations, maintenance and engineering) which should be addressed in the SOP with prior commitment from managers in those organizations. The fundamental determination is the amount of built-in condition monitoring, data transfer, and sensor connections to be used. 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 that it will be available for the units to be monitored. Continuously monitored equipment tied into performance analyzers permits controlling functions and monitoring degradation. In the future, on-line monitors will become increasingly capable and important. Installed systems also reduce manpower requirements as compared with collecting sensor data with a portable data collector. However, for many uses, portable condition monitoring equipment does provide the advantages of lower cost and flexibility of application as compared with post-acquisition installed systems.

5.2 Design

The following should be considered during the design phase:

5.2.1 Maintainability and Ease of Monitoring

In recent years great strides have been made in designing new equipment to ensure a high level of reliability. By extending this approach to the maintainability and ease of monitoring of equipment during design, one further enhances reliability and ensures improved maintainability for the life of the equipment.

a. Maintainability factors that are within the control of the designer are:

   1. **Access -** Equipment, its components, and facilities should be accessible for maintenance.

   2. **Material -** Choose materials for durability, ease of maintenance, availability, and value (optimal cost vs. special requirements trade-offs).

   3. **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.

4. **Quantitative Maintenance Goals -** Use quantitative measures of maintenance (i.e., mean-time-between-maintenance (MTBM), maintenance downtime (MDT), etc.) to set goals for maintainability which will influence design.

b. Ease of Monitoring factors within the control of the designer are:

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

2. **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.

3. **Metrics -** Management, or performance indicators (Metrics) are discussed in Chapter 10. For an RCM program, the Metrics 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.

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

5.2.2 Technology Review

As mentioned earlier, the technology review should be a part of the SOP for new facilities and/or equipment design and acquisition and should address the following six areas:

a. **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.

b. **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.

c. **Feedback -** Update or improve the design based on feedback, prior experience, and lessons learned.

d. **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.

e. **Qualification -** Contractor qualifications should provide for a demonstration of familiarity and/or understanding of the PT&I technologies planned for the RCM program.

f. **Specifications and Drawings -**

1. The designer has a major impact on the life-cycle cost of the equipment by incorporating the RCM lessons learned from the history of similar or identical equipment.

2. The design specifications should address the use of condition-based maintenance in lieu of interval-based maintenance and its effect on manufacturer's warranties.

3. 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. The attainment of these requirements is an important aspect of equipment performance.

4. 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 also should specify the PT&I technologies to be used and the related acceptance criteria as part of the post-installation acceptance testing for all collateral equipment and structures and for determining if a building is ready for occupancy.

5.3 Construction

During the construction phase, a major concern is to monitor the progress and quality of construction 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:

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

b. **RCM Analyses—**It is during this phase that RCM analyses are done, the maintenance program tasks should be chosen, and maintenance procedures and instructions should be written.

c. **O&M—**Operations and maintenance personnel should take advantage of the construction phase to become familiar with the details of construction which will no longer be easily accessible after the facility is completed.

d. **Inspectors—**The construction inspectors should assure that the construction contractor properly installs, aligns, and checks the equipment in accordance with the contract specifications and the equipment manufacturer's recommendations. Incorrect installation can void the manufacturer's warranty and cause early equipment failure.

e. **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 equipment he intends to provide for approval by the Government. The equipment should be approved by the Government (including the RCM technologists) to ensure that it satisfies the requirements of the contract specifications. If the contract specifications require that the contractor establish a vibration and thermographic baseline for the equipment, the Governmant should ensure that this is done and that the baseline information is properly documented and turned over to the Government with the equipment technical manuals and other information required from the contractor.

5.4 Maintenance and Operations (M&O)

How the facility and its equipment will be operated and maintained 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. Although the performance of M & O tasks occur during the operations stage of the life cycle of the equipment or facility, some preparatory activities may be carried out during the latter part of the acquisition stage. These activities include personnel selection, PT&I training, procedure preparation, review of specifications, and the collection of nameplate data.

Chapter 6 - RCM Considerations during Facilities Operation

This chapter discusses RCM requirements during the operational stage of the facilities life cycle (maintenance and operations).

6.1 RCM Program Data

The need to maintain an adequate level of funding is a continuing requirement during the life cycle of a facility. As a result, there is a recurring need to input RCM program data into an Annual Work Plan (AWP) and/or other budgetary planning documents. To support these periodic requirements, the collection of data for justification purposesshould not be left to chance or to the last minute.

It is important for RCM maintenance costs, cost avoidance, and program savings to be documented as they occur. A good Computerized Maintenance Management System (CMMS) has the capability to track this information. Direct maintenance program savings are usually apparent, but maintenance personnel must become attuned to recognizing and documenting the less obvious “costs avoided.” This data also becomes a key part of the Continuous Improvement (CI) process in that it is the feedback that reinforces the behavior created by the RCM organization.

One use of maintenance data is in tracking the maintenance burden; i.e., the man-hours and/or labor costs expended for all types of maintenance on a particular equipment. By identifying the equipment on which maintenance effort is spent and categorizing the type of maintenance (i.e., RM, PM or PT&I), the maintenance burden may be allocated to end use. 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 use of Pareto analysis, or some other method of prioritization of maintenance resource assignment, will permit the easy identification of areas that demand attention from the standpoint of maintenance effectiveness or the need for modification to improve reliability. As the intensive PT&I efforts take hold, the effects on themaintenance burden can be analyzed to determine their costs and relative values, especially as increased availability and improved quality impacts each activity.

The task of maintaining and updating drawings and specifications to keep facility documentation abreast of the modifications and alterations should not be neglected. If not already part of the Standard Operating Procedures (SOP), it should be added. The effectiveness of the facility and the RCM program will reflect the degree to which this updating is accomplished.

6.2 Maintenance Feedback

During the life of the facility and its equipment, a continual effort is required for modifications and alterations to the design as operators and maintenance personnel gain experience with the facility. Sometimes these changes result from an expanded or modified facility mission. As the facility matures, new methods and tools become available to accomplish the mission and tasks in a more efficient or cost-effective manner. This need for changes and modifications must be documented and returned to the designers as feedback. Again, this needs to be a part of the operating culture and should be added to the SOP.

An important function of feedback during the life cycle of any facility is to improve and optimize the performance of the equipment. The RCM organization can be tasked with this function and, if done properly, will become a crucial asset to future designs. As shown in Figure 6–1, design improvements from one generation of equipment to the next can have a significant effect on reliability. 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 as well, thus contributing to a lower life-cycle-cost, which is one of the goals of the RCM and Continuous Improvement process.

6.3 Maintenance and Operations (M&O) Considerations

The following are RCM considerations during the M&O activity:

a. **Labor Force**—The RCM program requires a labor force with the special 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, infant mortality rate. The quality of maintenance is influenced by: 1) the skill of the maintenance technicians, 2) their workmanship, 3) the quality of supporting documentation and procedures, and 4) the technologies in use.

b. **System Experts—**The responsibility for condition monitoring, predictive analysis, and maintenance planning should be assigned to someone not subject to random or frequent reassignment. To maintain continuity of effort, to gain experience for a single individual or group, and to ensure a consistent technical approach, a single person should be assigned maintenance oversight responsibility for a given equipment or group of similar equipment.

   The involvement of a single person in all maintenance actions for the equipment or system(s) for which they are responsible is the heart of the *system expert* concept and is an excellent way to provide continuity of experience and expertise with regard to the equipment and systems. The system expert is the person responsible for monitoring and analyzing the maintenance data for an assigned equipment or system. The system expert should receive all the related data, work requests, and test documents for review, analysis, and filing. The system experts designated to maintain expertise and provide continuing oversight, analysis, and continuity for designated facility systems or equipment. The *system expert* concept results in a significant contribution to better overall management of facility maintenance and provides the critical elements of the organization’s memory and its analysis.

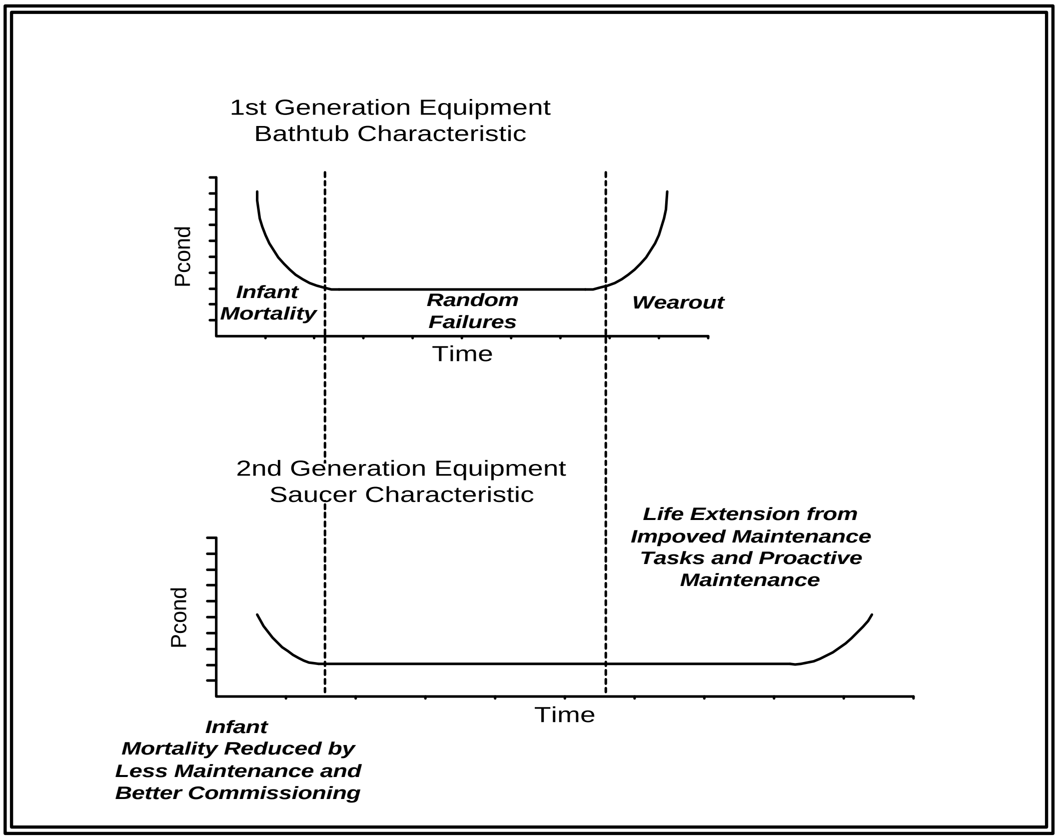

Figure 6 – 1. Design Improvements through Maintenance Feedback

The system expert is not intended to replace or supplant the technical expertise normally found within the design organization of the original equipment manufacturer (OEM), the facility, or at the Center or NASA headquarters. 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.

c. **Training—**Training plays a major role in reaching and maintaining the required RCM workforce skill level. The training is both technology/equipment specific and of a more general nature. Management and supervisory personnel benefit from training which presents 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.

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			

Table 6–1. Maintenance Training

d. **Equipment—**During the operation of the facility and its equipment, a Continuous Improvement program should be in place. The need for equipment modifications and alterations is documented by feedback from the operators and maintenance personnel.

An important function of feedback during the life of the facility is to improve the performance of the facility and its equipment. The M&O-to-designer linkage is crucial in this improvement process. As shown in Figure 6–1, design improvements from one generation of equipment to the next have a significant effect on operability, maintainability and reliability.

e. **Maintenance History—**An important function of the CMMS is to collect, organize, display, and disseminate maintenance data. The CMMS provides the facility's maintenance history, which is critical to the success of the RCM program because:

1. It contains information to establish whether an age-reliability relationship (wear-out) exists for equipment, and if so, what is the critical failure-onset age.

2. It contains the data that is analyzed to trend and forecast equipment failure.

3. It forms the basis for analysis of long-term equipment and system performance trends.

4. It provides the statistics used to determine the failure rates, which influence spare part stock levels.

5. It contains test results, performance data, and feedback information used to improve equipment performance and document equipment condition.

f. **Procedural Documentation—**For a maintenance organization to be truly world class, it must perform reactive maintenance expeditiously and correctly. Complex repair tasks should be planned in advance. The use of maintenance planners to generate maintenance work orders, which include detailed procedures, repair parts, tools, maintenance personnel training, and specific test procedures, is part of a good work order system for a complicated or critical repair. This detailed work planning has been proven to be vital by quality maintenance organizations. Work preparations ensure smooth repair with few surprises and greatly reduce the incidence of "infant mortality" which often accompanies the difficult repairs. The lessons learned from each repair are included in the equipment history for future reference. As a maintenance organization gains experience, it builds a file of work orders that may be reused repeatedly.

The use of standard procedures in PT&I ensures that data is collected in a consistent and comparable manner without being dependent on the experience of the collecting technician. Improvements in data collection techniques can be applied to all similar collection efforts by modifying the standard procedures.

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Chapter 7 - RCM Contract Clauses

There are several basic contract purposes involved in the facility and equipment life cycle. They are as follows:

- Architect/Engineering (A&E) Contracts
- Construction Contracts
- Equipment Procurement Contracts
- Maintenance and Operation Contracts

There is a need for RCM-related clauses in each of these types of contracts. Standard clauses have been developed for this purpose.

These contracts occur during the following life cycle phases:

Life Cycle Phase	Contract Type
Planning	None
Design	A&E
Construction	Construction
Maintenance and Operations	Equipment Procurement
	Maintenance and Operations

This chapter contains recommended standard RCM contract clauses. Clauses are grouped by equipment and the applicable technology. Tables 7–11 through 7–14 identify and cross-reference the applicability of each RCM contract clause, component, and type of contract for each phase of the contract.

The following describes the applicability of each table:

A&E Contracts	Table 7–11
Construction Contracts	Table 7–12
Equipment Procurement Contracts	Table 7–13
Maintenance and Operations Contracts	Table 7–14

The applicable RCM contract clause and criteria should be included in all Requests for Proposals (RFPs), Requests for Quotations (RFQs), and in the contracts themselves.

The clauses may be used without modification; however, they will have to be renumbered to fit the organization of the specification in which they are used.

7.1 General Contract Clauses

This section contains the standard contract clauses for all of the phases in the facility life cycle. The specific clauses to be used in each phase are suggested in paragraphs 7.2 through 7.5.

For example, the vibration data listed in paragraphs 7.1.7 through 7.1.8 should be included in contract specifications if vibration analysis is to be performed as part of the RCM program.

7.1.1 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:

a. **Test Equipment—**List of all test equipment used, including manufacturer, model number, serial number, calibration date, certificate of calibration, and special personnel qualifications required.

b. **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.

7.1.2 Bearing Information

a. **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.

b. **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.

c. **Operating Data—**The required equipment data the contractor shall provide the procuring organization under this contract shall include the operating speed for constant speed units and the normal operating speed range for variable speed equipment.

7.1.3 Gearbox Information

The contractor shall provide to the procuring organization the type and number of teeth on each gear used in the gearbox and 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.

7.1.4 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

7.1.5 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

7.1.6 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/vanes
- Number of stationary fan blades/vanes
- Rotating speed(s)

The contractor shall provide to the procuring organization the following additional information if the fans/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 is present to allow for cleaning and in-place balancing of the fan.

7.1.7 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.

7.1.7.1 Instrumentation and Sensors

The contractor shall use the type of instrumentation and sensors specified. For example, for a 3,600 RPM machine an accelerometer with a sensitivity of 100 mV/g and a resonant frequency of at least 15,000 Hz is required. A rare earth super magnet and a sound disc shall be used in conjunction with any vibration data collector which has the following characteristics:

- A minimum of 400 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 window.
- Autoranging.
- Sensor frequency response shall conform to Figure 7–1.

The contractor shall provide to the procuring organization narrowband spectral vibration data for all machines as follows:

a. For machines operating at or below 1,800 RPM, the frequency spectrum provided shall be in the range of 5 to 2,500 Hz.

b. For machines operating greater than 1,800 RPM, the frequency spectrum provided shall be in the range of 5 to 5,000 Hz.

c. Two narrowband spectra for each point shall be obtained in the following manner:

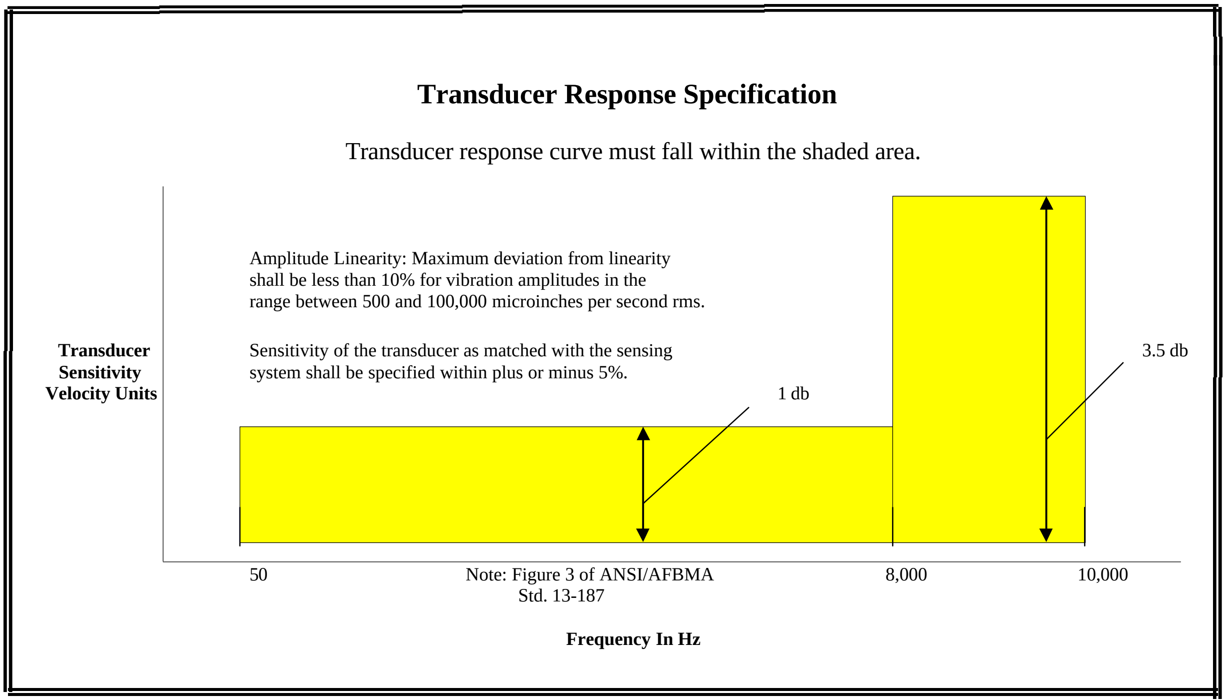

Figure 7-1. Transducer Response

1. 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.

2. An additional spectrum of 5 to 2,500 or 5 to 5,000 Hz shall be acquired for machines operating at or below 1800 RPM or greater than 1,800 RPM, respectively. This higher frequency range allows early detection of rolling element bearing, gear rotor and stator problems.

3. The contractor shall report vibration data in velocity (inches/second). If proximity probes are installed, the contractor shall acquire and analyze vibration and phase data.

4. The contractor shall ensure that the equipment provided meets the following acceptable vibration amplitudes for each machine:

   (a) **Developing Vibration Criteria—**Specific vibration criteria are provided in this guide where possible. Where specific criteria are not provided the following procedure is recommended for the guide user for use in developing the vibration criteria:

      (1) Obtain nameplate data.

(2) Obtain vibration spectra on similar machines. Differences in baseplate stiffness and mass will affect the vibration signature.

(3) Calculate all forcing frequencies, i.e., imbalance, misalignment, bearing defect, impeller and/or vane, electrical, gear, belt, etc.

(4) Construct a mean vibration signature for the similar machines.

(5) Compare this mean vibration signature to the specifications and guidelines provided in this guide.

(6) Note any deviations from the guidelines and determine if the unknown frequencies are system related; e.g., a resonance frequency from piping supports.

(7) Collect vibration data on the new component at the recommended positions.

(8) Compare the vibration spectrum with the mean spectrum determined in step (5) above as well as with the criteria and guidelines provided in this guide.

(9) Any new piece of equipment should have a vibration spectrum which is no worse than a similar unit of equipment which is operating satisfactorily.

(b) **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 7.1.8 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 procuring organization prior to shipment.

Vibration tests are recommended under the following situations if the equipment fails the initial test and/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.

A significant change in the vibration signature could indicate a problem with thermal distortion and/or bearing overloading due to failure of one of the bearings to float.

(c) **Vibration Criteria for Electric Motors**

(1) **General—**All motor vibration spectra should be analyzed 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.

The following is a list of rolling element bearing frequencies:

- Outer race defect frequency
- Inner race defect frequency
- Ball defect (ball spin frequency)
- Fundamental train frequency

Plain or journal bearings indicate faults at harmonics of running speed and at the frequency corresponding to 0.4-0.5 of running speed.

Other sources of vibration in motors 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 SCR firing frequencies for variable speed motors.

Broken rotor bars will often produce sidebands spaced at two times the slip frequency. The presence of broken rotor bars can be confirmed through the use of electrical testing.

(2) **Balance—**The vibration criteria listed in Table 7–1 are for 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.

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 7–1. Motor Balance Specifications

(3) **Additional Vibration Criteria—**All testing should be conducted at normal operating speed under full load conditions. Suggested motor vibration criteria are provided in Table 7–2. In addition, Appendix E contains criteria for common machines and an example of how to calculate 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

Table 7–2. Motor Vibration Criteria

(4) **Rewound Electric Motors—**Due to the potential of both rotor and/or stator damage incurred during the motor rewinding process (usually resulting from the bake-out of the old insulation and subsequent distortion of the pole pieces) a rewound electrical motor should be checked both electrically and

mechanically. The mechanical check consists of 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%. 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 a motor will not correct problems associated with thermal distortion of the iron.

(5) **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 should be deemed unacceptable.

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

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

(6) **Specific Equipment—**Use the criteria shown in Table 7–3 on boiler feedwater, split case, and progressive cavity pumps:

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

Table 7–3. Pump Vibration Limits

(7) **Belt Driven Fans—**Use the criteria in Table 7–4 for belt-driven fans:

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

Table 7–4. Belt-Driven Fan Vibration Limits

(8) **Vibration Guidelines (ISO)—**Table 7–5 is based on International Standards ISO 3945 and should be used as a guideline (not as an absolute limit) for determining the acceptability of a machine for service. The vibration acceptance classes and ISO 3945 machine classes are shown in Tables 7–6 and 7–7, respectively. Note that 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.

5. The contractor shall collect vibration data at normal operating load, temperature, and speed.

6. The contractor shall supply all critical speed calculations. In addition, the contractor shall perform a check for machine resonance following installation and correlated with all known forcing frequencies; i.e., running speed, bearing, gear, impeller frequencies, etc.

Ranges of Radial Vibration Severity			Quality Judgement for Separate Machine Classes			
Range	RMS Velocity in 10-1000 Hz at the Range Limits mm/sec	in/sec	Class I	Class II	Class III	Class IV
0.28	0.28	0.011	A	A	A	A
0.45	0.45	0.018	A	A	A	A
0.71	0.71	0.028	A	A	A	A
1.12	1.12	0.044	B	A	A	A
1.80	1.80	0.071	B	B	A	A
2.80	2.80	0.110	C	B	B	A
4.50	4.50	0.180	C	C	B	B
7.10	7.10	0.280	D	C	C	B
11.20	11.20	0.440	D	D	C	C
18	18	0.710	D	D	D	C
28	28	1.10	D	D	D	D
71	71	2.80	D	D	D	D

Table 7–5. ISO 3945 Vibration Severity Table.

Class	Condition
A	Good
B	Satisfactory
C	Unsatisfactory
D	Unacceptable

Table 7–6. Vibration Acceptance Classes

Machine Classes for ISO 3945	
Class I	Small size machines to 20 HP
Class II	Medium size machines (20-100 HP)
Class III	Large machines (600-12,000 RPM) 400 HP and Greater Rigid mounting
Class IV	Large machines (600-12,000 RPM) 400 HP and Greater Flexible mounting

Table 7–7. Machine Classifications

7. The contractor shall analyze all motor vibration spectra at the following forcing frequencies and provide the results to the procuring organization:

- One times running speed (1X) for imbalance.
- Two times running speed (2X) for misalignment.
- Multiples of running speed (NX) for looseness, resonance, and plain bearing defects.
- Electric line frequency and harmonics (60 or 120 Hz for AC motors) for stator and rotor problems.
- Roller element bearing frequencies, when present.

7.1.8 Vibration Monitoring Locations

a. **Monitoring Discs—**For all rotating equipment provided under the contract, the contractor shall install vibration monitoring discs using the following guidelines:

1. 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 be attached by welding or stud mounting. The contractor has the option of machining the equipment case in order to achieve a flat and smooth spot which meets the same tolerances as the sound disc if the equipment case is manufactured from a magnetic material.

2. The contractor shall ensure monitoring locations are positioned on structural members. Installation of sound discs on bolted cover plates or other non-rigid members are not acceptable.

b. **Centrifugal Pumps, Vertically Mounted—**Sound discs shall be mounted in the radial direction 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, at the coupled end of the motor and pump, and in the axial direction on the pump and motor, if possible.

c. **Centrifugal Pumps, Horizontally Mounted—**Sound discs shall be mounted 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 and coupled end of the motor and pump, and in the axial direction on the motor and pump, if possible.

d. **Positive Displacement Pumps—**Sound discs shall be mounted 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.

e. **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 shall be monitored in the axial direction.

f. **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 as close to the input and output shafts as possible.

g. **Compressors—**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 as close to the input and output shafts as possible.

h. Centrifugal compressors may be monitored effectively in this manner. However, reciprocating air compressors shall only be monitored for balance and alignment problems.

i. **Blowers & Fans—**Motors on blowers and fans shall have sound discs installed in the radial and axial directions as previously described. Fan bearings shall be monitored radially in the vertical direction.

j. **Chillers**

1. **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 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 compressor discharge, and located at the free end, at the coupled end of the motor and compressor, and in the axial direction on compressor and motor.

2. **Reciprocating—**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 as close to the input and output shafts as possible.

7.1.9 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 this contract:

a. **Liquid Lubricants**

Viscosity grade in ISO units

AGMA and/or SAE classification as applicable

Viscosity in Saybolt Universal Seconds (SUS) or centipoise at the standard temperature and at designed normal operating temperature. The following formula should be used to calculate SUS and absolute viscosity:

$$\mathbf{Z = p_t(0.22s-180/s)}$$

where: Z = absolute viscosity in centipoise at test temperature
s = Saybolt Universal Seconds
p_t = specific gravity at test temperature
t = temperature (°F)

Changes in density can be calculated by the formula:

$$\mathbf{p_t = p_r-0.00035(t-60)}$$

where: p_r = specific gravity at the reference temperature (normally 60° F)
t = temperature (°F)

b. **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 following formula shall be used to calculate SUS and absolute viscosity:

$$\mathbf{Z = p_t(0.22s - 180/s)}$$

where: Z = absolute viscosity in centipoise at test temperature
s = Saybolt Universal Seconds
p_t = specific gravity at test temperature
t = temperature (°F)

Changes in density can be calculated by the formula:

$$p_t = p_r - 0.00035(t-60)$$

where: p_r = specific gravity at the reference temperature (normally 60° F)
t = temperature (°F)

c. **Lubricant Tests—**The contractor shall draw lubricants and perform the lubricant tests listed in Table 7–8 on all lubricants supplied by him and shall submit the results of the tests to the procuring organization.

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 & 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

Table 7–8. Lubricant Tests

d. **Hydraulic Fluids—**All bulk and equipment-installed hydraulic fluids supplied under this contract shall meet the cleanliness guidelines in Table 7–9. The procuring organization will specify System Sensitivity. In Table 7–9, the numbers in the 5 micron and 15 micron columns are the number of particles greater than 5 microns and 15 microns in a 100-milliliter sample.

The particle counting technique utilized shall be quantitative. Patch test results are not acceptable.

The ISO numbers in the right-hand column of Table 7–9 are based on the concentration of particles greater than 5 microns and greater than 15 microns per 100-milliliter sample.

The concentration can then be converted to the ISO number using an ISO Range Number Table that should be available from a hydraulic fluid vendor or lubrication laboratory.

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. Med. 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

Table 7–9. Sperry Vickers Table of Suggested Acceptable Contamination Levels for Various Hydraulic Systems

e. **Insulating Fluids**—The contractor shall identify the type of oil used as an insulating fluid for all oil-filled transformers supplied under the contract. In addition, the contractor shall test the insulating oil using the American Society for Testing Materials (ASTM) test listed in Table 7–10 and provide the results to the Government. Any deviation from the typical properties listed below shall be corrected by the contractor before the Government will accept the transformer.

Test (Units)	Silicone	Mineral	Asakrel
Dielectric Breakdown ASTM D877 (KV)	30+	30+	30+
Power Factor ASTM D924 (%)	0.01	0.05 max	0.05
Neutralization Number ASTM D974 (mg KOH/g)	<0.03	<0.03	<0.03
Interfacial Tension ASTM D2285 (dynes/cm)	N/A	35 min	N/A
Specific Gravity ASTM 1298	0.96	0.88	1.55
Flash Point ASTM D92 ©	>305	160	N/A
Fire Point ASTM D92 ©	360	177	None to Boiling
Pour Point ASTM D97 ©	-55	-51 max	-30 max
Water Content ASTM D1533 (ppm)	30 max	30 max	30 max
Viscosity at 40C ASTM D445 (SUS)	232	57.9	55.8-61.0
Color & Appearance	clear/water like	pale yellow clear	pale yellow clear

Table 7–10. Typical Properties of Transformer Oils

f. **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). Method No. 1 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:

1. **For Pressurized Systems—**A ball valve is placed 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 shall be located in a turbulent flow region and upstream of any filters.

2. **For Reservoirs and Non-Pressurized Systems—**A 1/8" stainless steel line and ball valve is placed in the side of the oil sump or tank. The line shall be located as close to the midpoint of the structure as feasible. In addition, the sample line shall extend internally to and as close to the center of the tank as possible.

7.1.10 Thermography

a. **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.

   Any defects noted by an observable difference in temperature of surveyed components or unexplained temperature rise above ambient shall be corrected by the contractor at no additional expense to the procuring organization. The contractor shall resurvey repaired areas to assure proper corrective action has been taken.

b. **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.

   Any voids in the piping insulation shall be corrected by the contractor at no additional cost to the procuring organization. The contractor shall resurvey repaired areas to assure proper corrective action has been taken.

c. **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 and/or the presence of wetted insulation. In addition, the presence of air gaps in building joints such as seams, door frames, window frames, etc., shall be checked via thermographic survey using an appropriate procedure and specifications described in the following:

ASTM C1060-90	*Thermographic Inspection of Insulation in Envelope Cavities In Wood Frame Buildings*.
ASTM C1153-90	*Standard Practice for the 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 E1186-87	*Standard Practices for Air Leakage Site Detection in Buildings*.

   The contractor shall clearly identify by photographs, scale drawings, and/or by description all voids or gaps noted during the thermographic scan.

For areas where the moisture content of the insulation or building envelope is questionable, the contractor shall use either destructive or non-destructive testing techniques that confirm the amount of moisture. Specific testing procedures to be used shall be proposed by the contractor and approved by the procuring organization.

d. **Boilers, Furnaces, and Ovens—**The contractor shall perform a thermographic survey during the start-up phase of installation of all furnaces, boilers, and ovens as a means of determining voids in insulation or refractory materials. Any voids detected during the survey shall be corrected by the contractor 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.

e. **Temperature Criteria—**Thermography inspections are identified as either qualitative or quantitative. The quantitative inspection is interested in the accurate measurement of the temperature of the item of interest. 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.

f. **Relative Readings—**In general, to locate abnormalities, compare similar components with similar loads are compared. Taking relative readings on the same equipment and trending over time is also effective in detecting problems.

g. **Motors and Bearings—** Large machines should be scanned closely. Abnormal hot spots on the body may indicate flaws in the stator windings. The surface temperature of a motor is normally 7.5% lower than the winding temperature. Bearing temperatures are normally 5–20 degrees F higher than the housing temperature.

h. **Power Transformers—**Abnormal heat at connections may indicate looseness, corrosion, or other flaws. Other localized heating may be indicative of flaws in windings or of insufficient ventilation of the surrounding area. Temperature variations in cooling fins or tubes may indicate internal cooling problems, such as a loss of coolant or plugging. A bank of same-type transformers with significantly different temperature readings may indicate unbalanced loading or a defective transformer.

7.1.11 Airborne Ultrasonics

The contractor shall perform an airborne ultrasonic survey during the start-up phase of the installation unless the airborne ultrasonic survey is waived by the procuring organization. The contractor shall survey electrical equipment for indications of arcing or electrical discharge, including corona. Piping systems shall be surveyed for indications of leakage.

Any defects or exceptions noted by the use of airborne ultrasonics shall be corrected by the contractor at no additional expense to the procuring organization. The contractor shall re-survey repaired areas to assure proper corrective action has been taken.

7.1.12 Pulse Echo Ultrasonics

The contractor shall perform material thickness measurements on a representative sample of all material where a thickness is specified in the contract. Thickness measurements shall be performed at the fabricator's place of business prior to shipment of any material to the project site. Material which does not meet the specified requirements of the contract shall not be shipped without the prior approval of the procuring organization.

7.1.13 Motor Circuit Analysis (Complex Phase Impedance)

Upon motor installation, the contractor shall take and provide to the procuring organization the following acceptance/baseline readings and measurements, first for the motor alone, and then, for motor and circuit together:

- Conductor path resistance
- Inductive imbalance
- Capacitance to ground

7.1.14 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% or greater load when specified by the procuring organization.

7.1.15 Insulation Resistance

Upon installation, the contractor shall take and provide to the procuring organization the following acceptance/baseline readings and measurements; first, for the circuit or for the motor alone, and 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

7.1.16 Surge Testing

The contractor shall perform surge testing and high potential (high-pot) resistance testing of the motor(s) prior to their installation and procuring organization acceptance. The contractor shall provide to the procuring organization documentation of test results, including test voltage, waveforms, and high potential leakage current.

7.1.17 Start-up Tests

With the motor installed and operational, the contractor shall collect and provide to the procuring organization the following baseline data:

- Coast-down time
- Peak starting current

7.1.18 Maintainability and Ease of Monitoring

The contractor shall provide for facility and equipment maintainability and ease of monitoring through design. The contractor shall provide documentation to illustrate and support the maintainability and ease of monitoring incorporated by the design.

For example, mobile industrial equipment shall be equipped with fluid sampling ports on the engine and hydraulic systems. Accessibility to these ports shall facilitate periodic fluid sampling and system monitoring.

7.1.19 Leveling of Equipment Upon Installation

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.

7.2 Architectural/Engineering (A&E) Contracts

Table 7–11 identifies the clauses that are appropriate for use in A&E contracts.

Contract Clause	Element	PT&I Technology
7.1.18	Facility	Maintainability and ease of monitoring
7.1.18	Equipment	Maintainability and ease of monitoring

Table 7–11. RCM Clauses for A&E Contracts

7.3 Construction Contracts

Table 7–12 identifies the clauses that are appropriate for use in construction contracts.

Contract Clause	Equipment Type	PT&I Technology
7.1.1	Measurements/surveys	N/A
7.1.2; 7.1.4; 7.1.7; 7.1.8	Pump	Vibration
7.1.9	Pump	Lubricant & wear particle analysis
7.1.2; 7.1.5; 7.1.7; 7.1.8	Compressor	Vibration
7.1.9	Compressor	Lubricant & wear particle analysis
7.1.2; 7.1.6; 7.1.7; 7.1.8	Blower/fan	Vibration
7.1.9	Blower/fan	Lubricant & wear particle analysis
7.1.2; 7.1.3; 7.1.7; 7.1.8	Gearbox	Vibration
7.1.9	Gearbox	Lubricant & wear particle analysis
7.1.10	Boiler, furnace	Infrared thermography
7.1.11	Piping	Passive ultrasound
7.1.12	Piping/pressure vessel	Pulse echo ultrasound
7.1.10	Piping insulation	Infrared thermography
7.1.10	Chiller/refrigeration	Infrared thermography
7.1.9	Chiller/refrigeration	Lubricant & wear particle analysis
7.1.2; 7.1.7; 7.1.8	Chiller/refrigeration	Vibration
7.1.11	Electrical switchgear/ circuit breakers	Passive ultrasound
7.1.10	Electrical switchgear/ circuit breakers	Infrared thermography
7.1.15	Electrical switchgear/ circuit breakers	Insulation resistance
7.1.15	Motor & Motor Circuit	Insulation resistance
7.1.13	Motor & Motor Circuit	Motor circuit analysis
7.1.14	Motor & Motor Circuit	Motor current spectrum analysis
7.1.17	Motor & Motor Circuit	Start up tests

7.1.10	Building envelope	Infrared thermography
7.1.10	Heat exchanger/condenser	Infrared thermography
7.1.11	Heat exchanger/condenser	Passive ultrasound
7.1.2; 7.1.7; 7.1.8	Electric motor	Vibration
7.1.16	Electric motor	Surge testing
7.1.2; 7.1.7; 7.1.8	Electrical generator	Vibration
7.1.13	Electrical generator	Motor circuit analysis
7.1.15	Electrical generator	Insulation resistance
7.1.10	Transformer	Infrared thermography
7.1.9	Transformer	Oil analysis
7.1.19	Rotating Equipment Electrical Mechanical	Equipment leveling upon installation

Table 7–12. RCM Clauses for Construction Contracts

7.4 Equipment Procurement Contracts

Table 7–13 identifies the clauses that are appropriate for use in equipment procurement contracts.

ContractClause	Equipment Type	PT&I Technology
7.1.2; 7.1.4; 7.1.7; 7.1.8	Pump	Vibration
7.1.9	Pump	Lubricant & wear particle analysis
7.1.2;7.1.5; 7.1.7; 7.1.8	Compressor	Vibration
7.1.9	Compressor	Lubricant & wear particle analysis
7.1.2; 7.1.6; 7.1.7; 7.1.8	Blower/fan	Vibration
7.1.9	Blower/fan	Lubricant & wear particle analysis
7.1.2; 7.1.3; 7.1.7; 7.1.8	Gearbox	Vibration
7.1.9	Gearbox	Lubricant & wear particle analysis
7.1.10	Boiler, furnace	Infrared thermography
7.1.11	Piping	Passive ultrasound
7.1.12	Piping/pressure vessel	Pulse echo ultrasound
7.1.10	Piping insulation	Infrared thermography

7.1.10	Chiller/refrigeration	Infrared thermography
7.1.9	Chiller/refrigeration	Lubricant & wear particle analysis
7.1.2; 7.1.7; 7.1.8	Chiller/refrigeration	Vibration
7.1.11	Electrical switchgear/ circuit breakers	Passive ultrasound
7.1.10	Electrical switchgear/ circuit breakers	Infrared thermography
7.1.15	Electrical switchgear/ circuit breakers	Insulation resistance
7.1.15	Motor & motor circuit	Insulation resistance
7.1.13	Motor & motor circuit	Motor circuit analysis
7.1.14	Motor & motor circuit	Motor current spectrum analysis
7.1.17	Motor & motor circuit	Start-up tests
7.1.10	Heat exchanger/condenser	Infrared thermography
7.1.11	Heat exchanger/condenser	Passive ultrasound
7.1.2; 7.1.7; 7.1.8	Electric motor	Vibration
7.1.16	Electric motor	Surge testing
7.1.2; 7.1.7; 7.1.8	Electrical generator	Vibration
7.1.13	Electrical generator	Motor circuit analysis
7.1.15	Electrical generator	Insulation resistance
7.1.10	Transformer	Infrared thermography
7.1.9	Transformer	Oil analysis
7.1.1	Measurements/surveys	N/A

Table 7–13. RCM Clauses for Equipment Procurement Contracts

7.5 Maintenance and Operations (M&O) Contracts

Table 7–14 identifies clauses that are appropriate for use in M&O contracts involving RCM features.

ContractClause	Equipment Type	PT&I Technology
7.1.2; 7.1.4; 7.1.7; 7.1.8	Pump	Vibration
7.1.9	Pump	Lubricant & wear particle analysis
7.1.2; 7.1.5; 7.1.7; 7.1.8	Compressor	Vibration
7.1.9	Compressor	Lubricant & wear particle analysis
7.1.2; 7.1.6; 7.1.7;	Blower/fan	Vibration

7.1.8		
7.1.9	Blower/fan	Lubricant & wear particle analysis
7.1.2; 7.1.3; 7.1.8	Gearbox	Vibration
7.1.9	Gearbox	Lubricant & wear particle analysis
7.1.10	Boiler, furnace	Infrared thermography
7.1.11	Piping	Passive ultrasound
7.1.12	Piping/pressure vessel	Pulse echo ultrasound
7.1.10	Piping insulation	Infrared thermography
7.1.10	Chiller/refrigeration	Infrared thermography
7.1.9	Chiller/refrigeration	Lubricant & wear particle analysis
7.1.2; 7.1.7; 7.1.8	Chiller/refrigeration	Vibration
7.1.11	Electrical switchgear /circuit breakers	Passive ultrasound
7.1.10	Electrical switchgear /circuit breakers	Infrared thermography
7.1.15	Electrical switchgear /circuit breakers	Insulation resistance
7.1.15	Motor & motor circuit	Insulation resistance
7.1.13	Motor & motor circuit	Motor circuit analysis
7.1.14	Motor & motor circuit	Motor current spectrum analysis
7.1.17	Motor & motor circuit	Start-up tests
7.1.10	Building envelope	Infrared thermography
7.1.10	Heat exchanger/condenser	Infrared thermography
7.1.11	Heat exchanger/condenser	Passive ultrasound
7.1.2; 7.1.7; 7.1.8	Electric motor (new and rewound)	Vibration
7.1.16	Electric motor (new and rewound)	Surge testing
7.1.2; 7.1.7; 7.1.8	Electrical generator	Vibration
7.1.13	Electrical generator	Motor circuit analysis
7.1.15	Electrical generator	Insulation resistance
7.1.10	Transformer	Infrared thermography
7.1.9	Transformer	Oil analysis
7.1.1	Measurements/surveys	N/A
7.1.19	Rotating Equipment- Electrical & Mechanical	Equipment leveling upon installation

Table 7–14. RCM Clauses for M&O Contracts

Chapter 8—PT&I Criteria

8.1 Baselines

Baseline data is that condition monitoring data representative of an equipment in a new and/or properly operating condition. The baseline data is the foundation of the predictive trending analysis required to forecast equipment condition. It is important that this baseline data is established as early as possible in the life of the equipment. The baseline readings and periodic monitoring data should be taken under the same conditions (or as close as can be achieved). These conditions should be recorded. It is only under identical conditions that the relative comparison of data is valid. Significant changes in conditions often affect the data in unquantifiable ways because of unknown or complex relationships. Baseline readings should be re-established each time equipment undergoes major maintenance.

8.2 Criteria by PT&I Technology

8.2.1 Vibration Monitoring

The development of specific vibration criteria for every machine at all possible operating speeds in all applications and in every mounting arrangement is not possible. Vibration amplitude varies with operating speed, load, and mounting arrangement, so developing criteria based solely on amplitude can be misleading. The frequency content of the spectrum is often as important as the amplitude. For example, the presence of a tone associated with an inner race defect on a new bearing is unacceptable regardless of the amplitude. Furthermore, one must consider the difference between the vibration amplitude and frequency content of a reciprocating machine as compared to a centrifugal machine.

The vibration specifications provided in this guide are based on International Standards Organization (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.

a. **Developing Vibration Criteria—**Specific vibration criteria are provided in this guide where possible. Where specific criteria are not provided, the procedure provided in paragraph 7.1.7.1.c.(4).(a) is recommended to the guide user for use in developing the vibration criteria.

b. **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 7.1.8 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.

Vibration tests are recommended under the situations listed in paragraph 7.1.7.1.c.(4)(b) if the equipment fails the initial test and/or if problems are encountered following installation.

c. Vibration Criteria for Electric Motors

1. **General—**All motor vibration spectra should be analyzed at the following forcing frequencies described in paragraph 7.1.7.1.c.(4)(c).

2. **Balance** - The vibration criteria listed in Table 7–1 are for 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.

3. **Additional Vibration Criteria—**All testing should be conducted at normal operating speed under full load conditions. Suggested motor vibration criteria are provided in Table 7–2. In addition, Appendix E contains criteria for common machines and an example of how to calculate criteria.

d. **Rewound Electric Motors—**Due to the potential of both rotor and/or stator damage incurred during the motor rewinding process (usually resulting from the bake-out of the old insulation and subsequent distortion of the pole pieces) a rewound electrical motor should be checked both electrically and mechanically. The mechanical check consists of 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%. 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 a motor will not correct problems associated with thermal distortion of the iron.

e. General Equipment Vibration Standards

1. 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 should be deemed unacceptable.

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

3. 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.

f. **Specific Equipment—**Use the criteria shown in Table 7–3 on boiler feedwater, split case, and progressive cavity pumps.

g. **Belt Driven Fans—**Use the criteria in Table 7–4 for belt-driven fans:

h. **Vibration Guidelines (ISO)—**Table 7–5 is based on International Standards ISO 3945 (Appendix C) and should be used as a guideline (not as an absolute limit) for determining the acceptability of a machine for service. The vibration acceptance classes and ISO 3945 machine classes are shown in Tables 7–6 and 7–7, respectively. Note that 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.

8.2.2 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), and the presence of contaminants such as fuel, solids, and water. In addition, the levels of additives in lubricants can be determined. Tracking the acid/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 (resistance to flow) provides a key to the lubricating qualities of the lubricant. These qualities may be adversely affected by contamination with water, fuel, or solvents and 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. In performing a spectrometric analysis, one burns a small amount of the fluid sample and analyzes the resulting light frequencies and intensities to determine the type and amount of compounds present based on their absorption of characteristic light frequencies. Sample results are compared 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 is another key indicator of 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. With experience and historical information, one can project degradation rates and estimate the time until machine failure. Wear particle analysis includes ferrography, which is a technique used to analyze 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. Analyzing and trending the amount, size, and type of wear particles in a machine’s lubrication system can pinpoint how much and where degradation is occurring. Figure 8–1 illustrates the relationship between wear particle size, concentration and equipment condition.

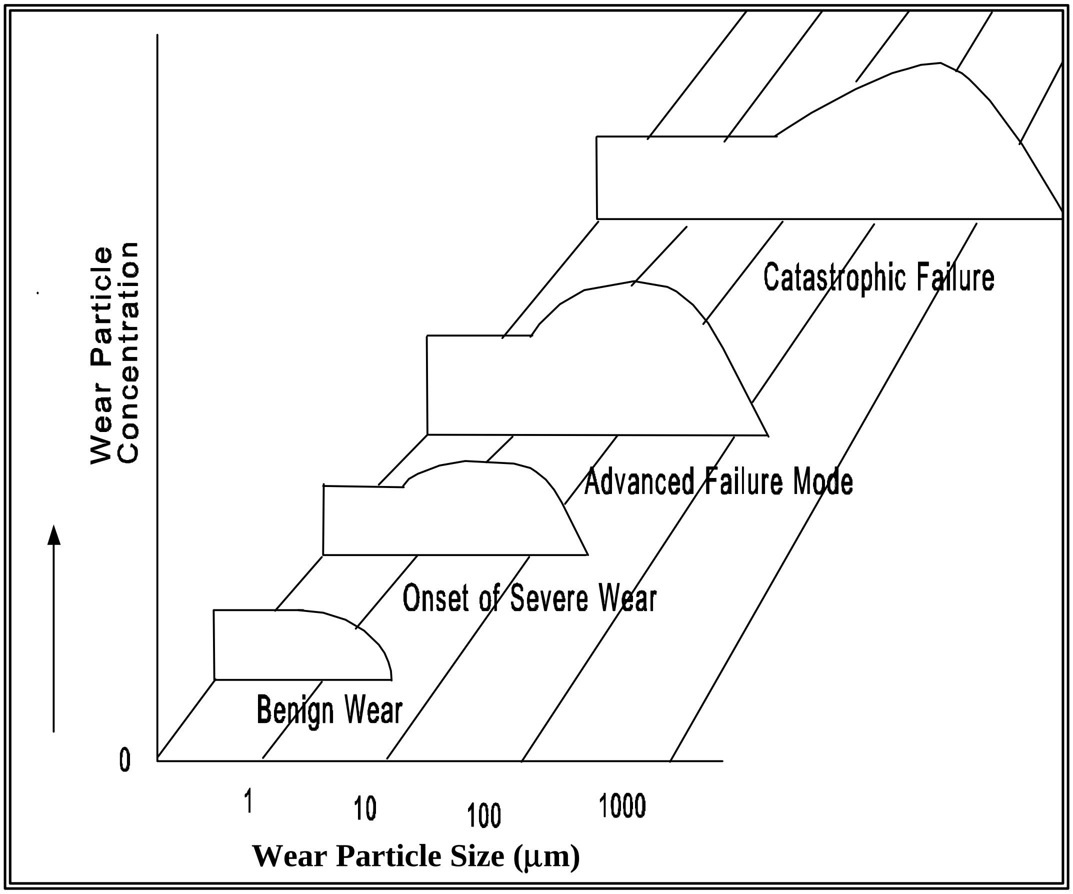

Figure 8 – 1. Wear Particle Size and Equipment Condition

8.2.3 Thermography

There are two basic criteria for evaluating temperature conditions. They are differential temperature (ΔT) and absolute temperature. Each is described below.

a. **Differential Temperature (ΔT)** - Temperature difference criteria are simple, easy to apply in the field, and provide an adequate qualitative screening system to identify thermal exceptions and problems. The ΔT criteria compares component temperature to the ambient temperature and may be used for electrical equipment. ΔT may also be used for mechanical components.

   The typical ΔT criteria, which may be modified easily based on experience, are as shown in Table 8–1:

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

Table 8–1. Actions Required Based on Temperature Rise Under Load

b. **Absolute Temperature**—Absolute temperature criteria are generally specific to an equipment model, type of equipment, class of insulation, service use, or any of many other salient characteristics. As a result, absolute temperatures are more 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 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).

A very useful summary of temperature criteria is found in the Guideline for Infrared Inspection of Electrical and Mechanical Systems, published by the Infraspection Institute of Shelburne, Vermont (Appendix C).

Table 8–2 provides absolute temperature limits for materials commonly found in the Government Plants:

8.2.4 Airborne Ultrasonics

The use of a passive ultrasonic instrument as a leak detector, i.e., 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, rather than a calibrated, absolute scale. However, by using relative changes in intensity from baseline readings, the degradation process may be trended and tracked.

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

Table 8–2. Temperature Limits for Selected Components

8.2.5 Motor Circuit Analysis

Motor circuit analysis 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 procedure is recommended for use when performing motor current analysis (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 can provide indications of circuit problems directly in electrical terms that can be used by maintenance personnel to pinpoint and correct faults. The test set may then be used to perform post-repair tests.

The following are MCA resistance imbalance guidelines:

Conductor Path Resistance Imbalance Guidelines

Less than 2%—Expected and acceptable when new

Greater than 5%—Plan troubleshooting to locate cause of increased resistance when convenient

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

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

Greater than 10%—Schedule effort to locate and eliminate problem in order to preserve motor life

Inductive Imbalance Guidelines

Less than 10%—Acceptable from OEM or rewind shop

10-15%—Acceptable in service

Greater than 15%—Isolate cause(s), increase monitoring frequency

Greater than 25%—Begin planning for motor repair or replacement

Greater than 40%—Be prepared for failure, within weeks

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

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

The following are MCA capacitance imbalance guidelines:

Capacitance Imbalance Guidelines

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

8.2.6 Motor Current Signature Analysis (MCSA)

Mechanical/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). Through analysis and interpretation of the relationship between 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 decrease in magnitude, the greater the concern should be 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

8.2.7 Insulation Resistance

There are several forms of insulation resistance measurement:

a. **Megohmmeter Testing—**Used to measure phase-to-phase and phase-to-ground resistance. It gives an overall indication of insulation condition, however, reliable trending requires temperature correction. Even the best insulation will show unacceptably low insulation resistance readings just following an oven bake or dry-out.

b. **Dielectric Absorption Ratio and Polarization Index—**Insulation resistance ratios are frequently used to evaluate insulation-to-ground conditions in order to avoid having to compensate 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:

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

greater than1.5—OK
less than 1.25—Danger

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

greater than 2 up to ~4—OK
less than 2 insulation—weak
greater than 5 insulation—possibly too dry and brittle

c. **Leakage current**—An overall indicator of insulation condition and cleanliness of the equipment. The accumulation of dirt and moisture provides a path for leakage current. There are no absolute values by which to gauge the deterioration of insulation using leakage current. The comparison of successive values permits the comparison and trending of leakage current.

8.2.8 Surge Testing

A surge test uses high voltage, high energy discharge pulses that are inserted into two windings of a polyphase motor simultaneously. These pulses cycle between motor windings and the test set. Current waveform analysis may indicate problems to an experienced and trained analyst. The test also indicates the voltage level at which the insulation breaks down.

Surge Testing, in the view of the Electric Power Research Institute, accomplishes 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.

- This is a go/no-go proof test and, as such, does not provide information that will allow making an assessment of remaining life.

- Experience is required to perform the test and to interpret the results, especially if complete windings rather than individual coils are tested.

8.2.9 Start-Up Tests

There are two types of start-up tests as described below:

a. **Coast-down time—**A simple and often overlooked test. In this test the time for the motor to coast to a stop after the removal of power is recorded and trended. This data tracks the mechanical condition of the motor bearings over the life of the machine.

b. **Peak starting current—**Another simple test which involves periodically recording the peak starting current of a motor. This test also provides an indication of the mechanical condition of the motor.

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Chapter 9 - Checklists for RCM Quality Assurance

9.1 Planning

Table 9–1 contains some factors to be considered in the planning phases of facilities acquisition.

Planning QA Checklist	
Are the RCM requirements for the facility determined?	
Is built-in monitoring planned where cost-effective?	
Has the use of performance data for condition monitoring been considered and planned?	
Is the collection of cost, cost avoidance, and cost savings incorporated?	
Does the CMMS require a PT&I module?	
Is there a mechanism provided for maintenance feedback?	
Have PT&I technologies that are appropriate for the equipment been selected?	

Table 9–1. RCM Quality Assurance Planning Considerations

9.2 Design

Table 9–2 contains some factors to be considered for quality assurance during the design phase of facilities acquisition.

Design QA Checklist	
Are maintainability factors considered?	
Access	
Material	
Standardization	
Quantitative goals set	
Are ease of monitoring factors considered?	
Access	
On-line data collection	
Performance indicators	
Are predictive technologies specified and incorporated?	
Do the contractor qualifications match the RCM requirements?	
Has a predictive analysis capability been provided?	
Has the distribution of raw data to those who could use it been incorporated?	
Are test and maintenance results distributed to users?	
Have design modifications based on maintenance feedback been incorporated?	

Table 9–2. RCM Quality Assurance Design Considerations

9.3 Construction

Table 9–3 lists some factors to consider during the construction phase of facilities acquisition.

Construction QA 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 the training of maintenance personnel been initiated?	
Is the selection of maintenance tasks in progress?	
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?	
Does the contractor need specialized subcontractors?	
Have the contractor equipment submittals been approved?	

Table 9–3. RCM Quality Assurance Construction Considerations

9.4 Equipment Procurement

Table 9–4 lists some factors to consider during the equipment procurement phase of facilities acquisition.

Equipment Procurement QA Checklist	
Are specifications determined to meet RCM requirements?	
Are acceptance testing requirements 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 equipment condition monitoring, if applicable?	
Are baseline data required?	
Are equipment life cycle costs required/provided?	
Are embedded (on-line) sensors required/provided?	

Table 9–4. RCM Quality Assurance Equipment Procurement Considerations

9.5 Maintenance and Operations

Table 9–5 contains some factors to be considered during the maintenance and operations phase of a facility life cycle.

Maintenance and Operations QA Checklist	
Is the inventory of skills to support the RCM program available?	
Is training planned to fill 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 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 use and effective?	
Are failed components subject to post-failure examination and results recorded?	
Are predictive forecasts tracked and methods modified based on experience?	
Are PM task 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 following major repair or replacement of equipment?	
Are appropriate measures of maintenance performance (metrics) in use?	

Table 9–5. RCM Quality Assurance Maintenance and Operations Considerations

Chapter 10 – Key Performance Indicators (Metrics)[16]

10.1 General

There are a number of management indicators used to measure the effectiveness of an RCM program. The most useful indicators are numerical. The numerical, or quantified indicators, often referred to as "metrics," can be expressed as goals and objectives, measured and displayed in several ways for the purpose of analysis and management decision making. This chapter addresses the description, benefits and methods for using metrics as an integral part of the Reliability Centered Maintenance (RCM) implementation process. These quantifiable indicators 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. Since 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, Metrics must be in place to measure how well the following are achieved:

- Maintenance integration
- Maintenance optimization
- Maximized operability and efficiency
- Life-cycle cost control

These are all areas that require a method to manage and to describe the effectiveness of implementing RCM. Metrics are the key to measuring, managing and benchmarking all phases of the RCM implementation process.

10.2 Purpose of Metrics

Metrics provide a yardstick to measure performance and effectiveness. There is an old saying, "If you don't measure it, you can't manage it". In this time when many changes to maintenance processes and technologies are being implemented, a system is needed to help achieve goals, measure implementation progress, and benchmark with others. Vital to the success of any program for facilities maintenance management is a hierarchy of distinct metrics, all linked to management goals.

[16] Metrics and Benchmarks developed by Mr. Alan Pride, Mr. Robin Rubrecht and Ms. Nancy Bray and presented presentation to the Association for Facilities Engineering's Facilities America '99 conference October 16-20, 1999.

To management, Metrics are used in the strategic planning process for the development, optimization and **direction** of management objectives. Metrics should reveal the effectiveness of the management program, and measure costs (to support the budget process). Management is responsible for the translation of technical level metrics into overall facilities maintenance management metrics, which support NASA goals and objectives. Metrics can be used to support the functions of staffing, budget formulation, training, contracting, and to ensure compliance with certain regulatory requirements.

Metrics are needed to monitor and control the performance of specific equipment, systems, and processes. Supervisors, Engineers, Technicians, and Crafts use these metrics to support optimization and continuous improvement of the maintenance program.

10.2.1 Metrics Ownership

An important aspect of any performance measurement system is ownership. Managers and workers at all levels of the organization need to participate in the development and refinement of metrics in their functional areas, thereby generating a sense of ownership. Metrics must reflect results which managers and workers can effectively change through job performance. It is this sense of ownership that supports the continuous improvement process.

10.2.2 Definition of Metrics

Metrics are relationships used for indicating the effectiveness of an operation and for comparing performance with goals and objectives. There are two types of performance indicators: intangible and tangible (words and numbers). Metrics are tangible, and thus preferred, as they are quantitative, objective, precise, and more easily trended than intangible benefits. Metrics should consist of a descriptor and a benchmark. In addition, Metrics can be global or event based.

10.2.2.1 Descriptor

A descriptor is a word or group of words describing the units, the function, or the process to be measured. Examples are the number of corrective actions developed by the PT&I program, the number of hours of equipment run-time, and the equipment availability expressed as a ratio of equipment hours available to equipment hours required.

10.2.2.2 Benchmark

A benchmark is a numerical expression of a goal or objective to be achieved. It is that against which one measures one's performance. It can be an absolute number or a range. For example, the benchmark for equipment availability might be 90%. The metric (descriptor and benchmark) would therefore be:

$$\frac{\text{Equipment available (hours)}}{\text{Equipment required (hours)}} = 90\%$$

10.3 Sample Metrics

The following are sample metrics one might choose to measure the effectiveness of an RCM program. The benchmarks suggested are averages taken from approximately 50 major corporations world-wide surveyed in the early 1990s:

Metric	Benchmark
a. Equipment Availability	96%

$$\% = \frac{\text{Hours Each Unit of Equipment is Available to Run at Capacity}}{\text{Total Hours During the Reporting Time Period}}$$

b. Maintenance Overtime Percentage	5% or less

$$\% = \frac{\text{Total Maintenance Overtime Hours During Period}}{\text{Total Regular Maintenance Hours During Period}}$$

c. Emergency Percentage	10% or less

$$\% = \frac{\text{Total Hours Worked on Emengency Jobs}}{\text{Total Hours Worked}}$$

d. Percent of Candidate Equipment Covered by PT&I	100%

$$\% = \frac{\text{Number of Equipment Items in PT \& I Program}}{\text{Total Equipment Candidates for PT \& I}}$$

e. Percent of Emergency Work to PT&I and PM Work	20% or less

$$\% = \frac{\text{Total Emergency Hours}}{\text{Total PT \& I \& Preventive Maintenance Hours}}$$

f. Percent of Faults Found in Thermographic Survey	3% or less

$$\% = \frac{\text{Number of Faults Found}}{\text{Number of Devices Surveyed}}$$

Metric	Benchmark
g. Percent of Faults Found in Steam Trap Survey	10% or less

$$\% = \frac{\text{Number of Defective Steam Traps Found}}{\text{Number of Steam Traps Surveyed}}$$

h. Ratio of PM/PT&I Work to Reactive Maintenance Work

A = 70% PM/PT&I
B = 30% Reactive Maintenance

$$A\% = \frac{\text{Manhours of PM/PT \& I Work}}{\text{Manhours of Reactive} + \text{PM/PT \& I Work}}$$

$$B\% = \frac{\text{Manhours of Reactive Work}}{\text{Manhours of Reactive} + \text{PM/PT \& I Work}}$$

A% + B% = 100%

10.4 Trending Indicators

The following indicators also are recommended for consideration 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 3 months old.
- Number of problems found by other PT&I techniques (i.e., infrared thermography, ultrasonics, lube oil analysis, etc.) and corrected per month, work orders open at the end of the month, and work orders over 3 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).

10.5 Recommended Agencywide Facilities Metrics

A NASA Inter-center working group lead by KSC and LaRC, with input from the other Centers, has recommended to NASA Headquarters[17], Code JX, that the following four metrics be used to track Facilities Maintenance:

a. **Requirements vs. Funding vs. 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 (i.e., Mission Critical, Mission Support, and Center Support).

   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, PGM, Repair, TC, and ROI as defined by latest edition of NHB 8831.2 Appendix A.

b. **Backlog of Maintenance and Repair (BMAR)—**The purpose of this metric is to track the change in BMAR by fiscal year.

   This metric includes 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.

   The metric should be broken down by Facility Classification.

c. **Facility Reliability—**The purpose of this metric is to identify the reliability of facilities and systems based on the level of unplanned work that must be applied to the facility or system. The metric is the ratio of planned actual maintenance (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, supervision, etc.

   The metric should be broken down by Facility Classification.

[17] KSC letter IM-FEO-A from Nancy Bray dated June 7, 1996, Final Recommendation of Agency wide Facilities Maintenance Metrics.

d. **Log of Unplanned Failures and Avoided Failures—**The purpose of this metric is to demonstrate the impact of the overall maintenance program effectiveness by tracking failures and failures avoided by detection of the failure precursor through either PM or PT&I.

   The metric should be broken down by Facility Classification.

10.6 Metric Selection

Significant thought must go into the process of selecting Metrics to support the maintenance program. The value of meaningful Metrics cannot be overstated, however the value of Metrics that are inaccurate or inapplicable cannot be understated. One must first identify the goals and objectives of the organization because they will have an impact on the selection of Metrics at all levels of maintenance activity. Do not pick Metrics that you cannot possibly obtain, shoot for things you can control. Issues of concern should also be identified so that they will be considered in the selection of Metrics. All processes owners who are key to the implementation of the overall effort should have a metric to indicate goals and progress. In each case the process owners and implementers, as previously stated, should have a stake in selecting the Metrics to be used. This will foster the acceptance of collecting data to support the Metrics and will also promote the use of the Metrics for continuous improvement. One must certainly consider the capabilities of the organization to collect the data for Metrics, i.e. the process used for collecting and storing the data and the ease of extracting and reporting the Metrics. In doing this, we must calculate the cost of obtaining data for Metrics and the relative value they add to the overall program. As we are advocating doing the right things within the maintenance program with life-cycle cost as a driver, we must also pay close attention to the cost of the capturing supporting Metrics.

10.7 Benchmark Selection

After selection of the appropriate metrics is complete, benchmarks should be established to characterize the organizations' goals and/or progress points for using these metrics as a tool for maintenance optimization and continuous improvement. Benchmarks may be derived from the organizational goals and objectives or they may be selected from a survey performed with similar organizations. These benchmarks will be used as a target for growth and to evaluate risk associated with non-achievement of progress.

10.8 Utilization of Metrics

After benchmarks are established and data is being collected, we must act on the information in a timely manner in order to maintain continuity within all of the processes which are counting on Metrics as a performance enhancement tool. In order to take full advantage of the benefits of Metrics they should be displayed in public areas.

The tracking and publication of Metrics informs the people of what is important, what are the goals, and where do they stand with respect to performance expectations. The impact of displaying Metrics often has an immediate effect on the workers in the functional area being measured. In addition, Metrics are an integral part of any Team Charter as they allow the Team and Management to determine Team productivity.

10.9 Examples of Benchmarks

The following tables provide examples of Benchmarks. All data is for the upper quartile of chemical and process industrial plants.

When using Benchmarks it is important to focus on patterns and not individual data points. For example, if the maintenance budget as a percent of Current Replacement Value (CRV) is below 1% it could be either 1) due to an effective maintenance program or 2) an indicator that the facility is being consumed.

DATA SOURCE		MAINT. COST AS % OF CRV	MAINT COST AS (%) OF CONTROL-LABLE COST	TRAINING COST/ MAINT. HRLY. ($US)	MAINT. COST AS PERCENT OF TOTAL SALES	CONTRACTOR COST AS PERCENT 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) or Low (L)		L[1]	L	H	L	L or H[2]

Table 10 – 1. Financial Benchmarks

Notes:

1. If a maintenance budget is below 2% of Current Replacement Value (CRV) the overall condition of the facility should be evaluated to determine if the infrastructure is under-going slow degradation or if an excessive number of projects are required to maintain the facilities.

2. 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.

DATA SOURCE		REPORTING LEVELS	MAINT. HRLY/MAINT SUPPORT STAFF	MAINT. HRLY/FIRST LINE SUPERVISOR	MAINT. HRLY/ MAINT. PLANNER	MAINT. HRLY/STOR E-ROOM EMPLOYEE	MAINT. HRLY/ MAINT. ENGINEER	MAINT. HRLY 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) or Low (L)		L	H	H	H	H	L	L

Table 10 – 2. Organizational Benchmarks

DATA SOURCE		EMERGENCY WORK ORDERS (%)	PM/PT&I WORK ORDERS (%)	WORK ORDER COVERAGE (%)	PLANNED REPAIR COMPLIANCE (%)	PM SCHEDULE COMPLIANCE (%)	AVERAGE WORK WEEK (Hrs.)
PRIVATE INDUSTRY	High	22.2	27.3	100	89	100	50.5
	Mean	7.8	13.4	88	65	91	
	Low	2.1	5.4	78	50	77	41.3
BEST High (H) or Low (L)		L	H	H	H	H	L

Table 10 – 3. Work Practices Benchmarks

DATA SOURCE		BACKLOG LEVELS ($000,000US)	CRV/ MAINT. HOURLY ($000,000US)	NUMBER OF CRAFT LINES	HOURLY TURNOVER (%)	OSHA Injuries Per 200K Hours	HOURLY ABSENTEE (%)
PRIVATE INDUSTRY	High	N/A	7.2	13.0	7.4	18	4.1
	Mean	N/A	4.8	5.5	3.8	4	2.1
	Low	N/A	2.1	1.2	1.1	0	0.2
BEST High (H) or Low (L)		L	H[1]	L	L	L	L

Table 10 – 3. Work Practices Data (Cont.)

10.10 Planning & Scheduling Metrics

1. BACKLOG OF READY TO WORK JOBS (Target = 3 to 5 Crew Weeks)

$$\text{Crew Weeks} = \frac{\text{Total Estimated Labor Hrs. for All Ready to Work Jobs}}{\text{Actual Hours Avaliable to Schedule Each Week}}$$

2. BACKLOG OF ALL OPEN WORK ORDERS (Target = 4 to 6 Crew Weeks)

$$\text{Crew Weeks} = \frac{\text{Total Estimated Labor Hrs. for All Open Work Orders}}{\text{Actual Hours Available to Schedule Each Week}}$$

3. SCHEDULE COMPLIANCE (Target = 90% or better)

$$\% = \frac{\text{Total Labor Hrs. Worked on Scheduled Jobs}}{\text{Total Labor Hrs. Scheduled}}$$

4. ESTIMATED MANHOURS VERSUS ACTUAL MANHOURS IN COMPLETED JOBS (Target = $\pm$ 15%)

$$\% = \frac{\text{Total Estimated Labor Hrs. for Completed Work Orders for Week}}{\text{Total Actual Labor Hrs. for Completed Work Orders for Week}}$$

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.

6. AVERAGE LABOR HRS. SPENT ON LOGBOOK JOBS (Target = 2 Labor Hours or less)

$$\text{Labor Hrs./Logbook Job} = \frac{\text{Total Labor Hrs. spent on Logbook Jobs}}{\text{Total Logbook Jobs completed for the Week}}$$

7. INDIRECT MANHOURS PERCENTAGE (Target = 2% or less)

$$\% = \frac{\text{Total Indirect Hours}}{\text{Total Hours Worked}}$$

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.

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)

10.11 RCM Metrics

1. PERCENT OF PRODUCTION LINE AVAILABILITY (Target = 96%)

$$\% = \frac{\text{Hours each critical Facility is Available to Run at Capacity}}{\text{Total Hours During the Reporting Time Period}}$$

2. MAINTENANCE COST PER UNIT OF PRODUCTION (Target = Declining Annually)

$$\text{Cost/Unit} = \frac{\text{Total Maintenance Cost per Time Period}}{\text{Total Finished Units Produced per Time Period}}$$

3. MAINTENANCE OVERTIME PERCENTAGE (Target = 5% or less)

$$\% = \frac{\text{Total Maintenance Overtime Hours During Period}}{\text{Total Regular Maintenance Hours During Period}}$$

4. EMERGENCY PERCENTAGE (Target = 10% or less)

$$\text{Labor Hrs.}\,\% = \frac{\text{Total Hours Worked on Emergency Jobs}}{\text{Total Hours Worked}}$$

$$\text{Jobs}\,\% = \frac{\text{Total Emergency Jobs Worked}}{\text{Total Jobs Worked}}$$

5. PERCENT OF EQUIPMENT COVERED BY CONDITION MONITORING (Target = 100%)

$$\% = \frac{\text{Number of Equipment Items in Predictive Maintenance Program}}{\text{Total Equipment Candidates for Predictive Maintenance}}$$

6. PERCENT OF EMERGENCY WORK TO PT&I AND PM WORK (Target <20%)

$$\% = \frac{\text{Total Emergency Hours}}{\text{Total Predictive \& Preventive Maintenance Hours}}$$

7. PERCENT OF FAULTS FOUND IN THERMOGRAPHIC SURVEY (Target <3%)

$$\% = \frac{\text{Number of Faults Found}}{\text{Number of Devices Surveyed}}$$

8. PERCENT OF FAULTS FOUND IN STEAM TRAP SURVEY (Target = 10% or less)

$$\% = \frac{\text{Number of Defective Steam Traps Found}}{\text{Number of Steam Traps Surveyed}}$$

9. RATIO OF PM/PT&I WORK TO CORRECTIVE MAINTENANCE WORK

Target = 70% PM/PT&I work.
Target = 30% Corrective Maintenance work.

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Appendix A—Glossary

Age Exploration— The process of determining the most effective intervals for maintenance tasks. Its 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.

Availability— (1) Informally, the time a machine or system is available for use. (2) From the Overall Equipment Effectiveness 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, or administrative delays.

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.

B-Life— The time at which a set percentage of failures are expected. For example, the B1 life is when 1% of the units being examined will have failed; B10 is when 10% of the units will have failed.

Building Commissioning— The systematic process for achieving, verifying, and documenting that the performance of NASA Faculties and Collateral Equipment meets 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-collateral Equipment):

> <u>Building-Type Equipment</u>. A term used in connection with facility projects to connote 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.
>
> <u>Built-In or Large, Substantial Affixed Equipment.</u> A term used in connection with facility projects of any type other than building-type equipment that is to be built in,

affixed to, or installed in real property 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 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.

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 –

a. Facility/Equipment Inventory
b. Facility/Equipment History
c. Work Input Control
d. Job Estimating
e. Work Scheduling and Tracking
f. Preventive and Predictive Maintenance
g. Facility Inspection and Assessment
h. Material Management
i. 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 Monitoring (also know as Predictive Maintenance)— The continuous or periodic monitoring and diagnosis of systems and equipment in order to forecast failure. OR Condition Monitoring: 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. Condition Monitoring is also known as Predictive Maintenance.

Condition-Based Maintenance— 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

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.

Current Replacement Value (CRV)— Approximate cost to replace an existing facility in its present form. NASA calculates CRV by escalating facility and collateral equipment acquisition cost, and any incremental book value changes of $1,000 or more to present-year dollars using the Engineering News Record (ENR) Building Cost Index (BCI). The NASA Real Property Data System program or NASA Headquarters-approved equivalent is used in performing the required calculations.

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.

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 the loss of the facilities and collateral equipment function.

Facilities Maintenance— The recurring day-to-day work required to preserve facilities (buildings, structures, grounds, utility systems, and collateral 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, Predicative Testing & Inspection, 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-collateral 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 Modes 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. An element of Reliability Centered Maintenance (RCM).

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 Oct. 1 of one calendar year through Sept. 30 of the following year.

Function— Defined performance standard. Usually quantitative in nature (flow rate, cooling capacity, etc.).

Inspection— A time- or cycle-based action performed to identify hidden failure or potential failure.

Infrared Thermography— A predictive 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— See System Life Cycle.

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 capability of local work force

Maintenance— Action taken to retain function (i.e., prevent failure). Actions include Preventive Maintenance, Predictive Testing & Inspection, lubrication and minor repair (such as replacing belts and filters), and inspection for failure. Also see Preventive Maintenance and Predictive Testing & Inspection.

Maintenance Approach— The plan to prevent failure and, when failure occurs, perform repair.

Mean Time Between Failure (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.

Mission Critical— A building, area, or system that is critical to the Center/Facility mission or essential for Center of Excellence performance. Also see Mission Support and Center/Facility Support.

Mission Support— A building, area, or system that provides support to the Center/Facility primary mission or Center of Excellence assignment. Also see Mission Critical and Center/Facility Support.

Motor Circuit Analysis (MCA)— A predictive 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 predictive 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 collateral 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. Noncollateral 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 stand, 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 Collateral 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% of a population will cause 80% of the problems associated with the population.

Performance Standards— Those standards which 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.

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.

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 Center 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.

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.

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 that is 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 collateral 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 collateral equipment necessitated by incipient or actual breakdown. Also, restoration of function, usually after failure. Also see Planned Repair.

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 is taken (Time- or Cycle-Based actions), following installation, to prevent failure. Candidate systems or machines for Run-to-Failure are usually low-cost, easily-repaired, and non-critical.

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 Predictive Testing and Inspection.

Vibration Analysis— The dominant technique used in predictive maintenance. 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.

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Appendix B—Abbreviations/Acronyms

AC	Alternating Current
AE	Age Exploration
AGMA	American Gear Manufacturer's Association
AMA	Annual Maintenance Actual
AMF	Annual Maintenance Funding
AMR	Annual Maintenance Requirements
ANSI	American National Standards Institute
API	American Petroleum Institute
ASNT	American Society for Non-Destructive Testing
ASTM	American Society for Testing and Materials
AWP	Annual Work Plan
BMAR	Backlog of Maintenance and Repair
CAD/CAM	Computer-Aided Design/Computer-Aided Manufacturing
CI	Continuous Improvement
CMMS	Computerized Maintenance Management System
CPM	Cycles per Minute
CRV	Current Replacement Value
DC	Direct Current
DP	Dye Penetrant
DR	Direct Reading (Ferrography)
DSA	Digital Signal Analysis
EPRI	Electric Power Research Institute

FCA	Facility Condition Assessment
FFT	Fast Fourier Transform
FMEA	Failure Modes and Effects Analysis
FTIR	Fourier Transform Infrared
HP	Horsepower
Hz	Hertz; Cycles per Second
IEEE	Institute of Electrical and Electronic Engineers
IRT	Infrared Thermography
ISO	International Organization for Standardization
KPI	Key Performance Indicator
M&O	Maintenance and Operations
MCA	Motor Circuit Analysis
MCSA	Motor Current Signature Analysis
MDT	Mean Down Time
MT	Magnetic particle Testing
MTBF	Mean Time Between Failure
MTBM	Mean Time Between Maintenance
NDT	Non-Destructive Testing
NEMA	National Electrical Manufacturers Association
NFPA	National Fluid Power Association
NLGI	National Lubrication and Grease Institute
OEM	Original Equipment Manufacturer
PdM	Predictive Maintenance

PF	Pumping Frequency
PGM	Programmed Maintenance
PI	Polarization Index
PM	Preventive Maintenance
ppm	Parts Per Million
PT&I	Predictive Testing and Inspection
RBOT	Rotating Bomb Oxidation Test
RCFA	Root-Cause Failure Analysis
RCM	Reliability Centered Maintenance
RF	Radio Frequency
RMS	Root Mean Square
RPM	Revolutions Per Minute
RTF	Run to Failure
SAE	Society of Automotive Engineers
SUS	Saybolt Universal Seconds
TAN	Total Acid Number
TBN	Total Base Number
TDR	Time Domain Reflectometry
TTR	Transformer Turns Ratio
UT	Ultrasonic
VLF	Very Low Frequency

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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.

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 6781	*Thermal Insulation-Qualitative Detection of Thermal Irregularities in Building Envelopes-Infrared Method*, 1983.
ISO 3945	*Mechanical Vibration of Large Rotating Machines with Speed Range from 10-200 rev/s-Measurement and Evaluation of Vibration Severity in Situ*, 1985.
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.

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-1989, *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

WWW Sites as of January 1999:

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

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
Reliability Magazine	http://www.reliability-magazine.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.

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Appendix D—Sources of PT&I Equipment, Services, and Training

The vendors listed here are representative of those producing PT&I equipment, services, and/or training.

VIBRATION MONITORING

Bently Nevada Corp.
1617 Water St.
Minden, NV 89423
(702) 782-3611

Predict/DLI Corp.
253 Winslow Way West
Bainbridge Island, WA 98110
(206) 842-7656

Entek/IRD, Inc.
6150 Huntley Rd.
Columbus, OH 43229
(614) 885-5376

Structural Adhesives
1 Dexter Drive
Seabrook, NH 03874
(603) 474-5541

Wilcoxon Research
21 Firstfield Road (Suite 200)
Gaithersburg, MD 20878
(301) 330-8811

Vibration Institute
6262 South Kingery Highway
Willowbrook, IL 60514
(708) 654-2254

Computational Systems, Inc. (CSI)
835 Innovation Dr.
Knoxville, TN 37932
(615) 675-2110

Hewlett Packard
4 Choke Cherry Road
Rockville, MD 20850
(301) 670-4300

SKF Condition Monitoring
4141 Ruffin Road
San Diego, CA 92123-1841
(619) 496-3400

Bruel & Kajer
2364 Park Central Blvd.
Decatur, GA 30035
(404) 987-9311

Endevco Corporation
30700 Rancho Viejo Road
San Juan Capistrano, CA 92675
(714) 493-8181

Technical Associates
347 North Caswell Road
Charlotte, NC 28204
(704) 333-9011

Update International
2103 South Wadsworth Boulevard
Denver, CO 80227
(303) 986-6761

Vitec, Inc.
23600 Mercantile Road
Cleveland, OH 44122
(216) 464-4670

Massachusetts Institute of Technology
Department of Materials Science and Engineering
77 Massachusetts Avenue (Bldg.8, Room 309)
Cambridge, MA 02139
(617) 253-3300

OIL ANALYSIS & WEAR PARTICLE ANALYSIS

Analyst, Inc.
P.O. Box 955
Torrance, CA 90509
(310) 212-7001

Cleveland Technical Center
18419 Euclid Ave.
Cleveland, OH 44112
(216) 383-8200

Maintenance Technologies
58 Harvest Lane
Milford, CT 06460
(203) 877-3217

Predict/DLI
9555 Rockside Rd., Suite 350
Cleveland, OH 44125
(216) 642-3223

Southwest Spectro-Chem Labs
1009 Louisiana Ave.
So. Houston, TX 77587
(713) 944-3694

Computational Systems, Inc. (CSI)
835 Innovation Dr.
Knoxville, TN 37932
(615) 675-2110

Herguth Laboratories, Inc.
101 Corporate Place
Vallejo, CA 94590
(800) 645-5227

National Tribology Services, Inc.
245D Lynnfield St.
Peabody, MA 01960
(508) 531-6123

PdMA Corp.
5909-C Hampton Oaks Pkwy.
Tampa, FL 33610
(813) 621-6463

INFRARED THERMOGRAPHY

AGEMA\Flir Infrared Systems, Inc.
550 County Avenue
Secaucus, NJ 07094
Phone: (201) 867-5390
Fax: (201) 867-2191

Cincinnati Electronics
7500 Innovation Way
Mason, OH 45040-9699
Phone: (513) 573-6100
Fax: (513) 573-6290

Electro Physics Corp.
373 Route 46 West, Bldg E
Fairfield, NJ 07004
Phone: (201) 882-0211
Fax: (201) 882-0997

Agema\Flir Systems, Inc.
16505 S.W. 72nd Avenue
Portland, OR 97224
Phone: (503) 684-3731
Fax: (503) 684-7046

Inframetrics, Inc.
16 Esquire Road
N. Billerica, MA 01862
Phone: (508) 670-5555
Fax: (508) 667-2702

Insight Vision Systems, Inc.
9836 Campbell Drive
P.O. Box 13
Kensington, MD 20895
Phone: (301) 495-0211
Fax: (301) 495-2619

Ircon (formerly Square D Company)
Infrared Measurement Division
7301 North Caldwell Avenue
Niles, IL 60648
Phone: (708) 967-5151
Fax: (708) 647-0948

I.S.I. Group, Inc.
211 Conchas SE
Albuquerque, NM 87123
Phone: (505) 298-7646
Fax: (505) 299-4926

Land Infrared
2525 Pearl Buck Road,
Bristol, PA 19007
Phone: (215) 781-0700
Fax: (215) 781-0723

Raytek
1201 Shaffer Road, Box 1820
Santa Cruz, CA 95061-1820
Phone: (408) 458-1110
Fax: (408) 458-1239

ULTRASONICS—Airborne Passive

C.J. Analytical Engineering
R. R. 1, Box 355
Francisco, IN 47649
(812) 782-3416

EPD Technology Corp.
12 W. Main St.
Elmsford, NY 10523
(914) 592-1234

ITI Industrial
109 Terrace Hall Ave.
Burlington, MA 01803
(617) 272-7233

Leak Detection Services, Inc.
1009 Beach St.
Annapolis, MD 21401
(800) 345-7157

SDT USA
2985 Dutton Ave. #6
Santa Rosa, CA 95407
(707) 577-8053

Superior Signal Corp.
P.O. Box 96
Spotswood, NJ 08884
(908) 251-0800

UE Systems
12 W. Main St.
Elmsford, NY 10523
(914) 592-1220

Ultrasound of Florida
31 Scott Dr.
Marietta, GA 30067
(404) 977-2453

ULTRASONICS—Active Pulse

EPD Technology Corp.
12 W. Main St.
Elmsford, NY 10523
(914) 592-1234

Kraut Kramer Branson
P.O. Box 350
Lewistown, PA 17044
(717) 273-8805

Mgr., NDE Services
Babcock & Wilcox
Nuclear Power Division
3110 Odd Fellows Rd.
Lynchburg, VA 24501
(804) 847-3737

Ultraimage International
Two Shaws Cove
New London, CT 06320
(203) 442-0100

CABLE TESTING

AVO International
4651 S. Westmoreland Rd.
Dallas, TX 75237
(214) 333-3201

Char Services, Inc.
P.O. Box 119
Lebanon, PA 17042
(717) 273-8805

ECAD Div. of CM Technologies Corp.
1026 Fourth Ave.
Corapolis, PA 15108
(412) 262-0734

NGI
1711 Elmhurst Rd.
Elkgrove Village, IL 60007
(708) 437-6444

Project Services International
Robinson Plaza 3, Suite 300
Pittsburgh, PA 15205
(800) 860-0111

MOTOR CIRCUIT ANALYSIS

PdMA Corporation
5909-C Hampton Oaks Parkway
Tampa, FL 33610
(813) 621-6463

Savo Electronics Division
IdL, Inc.
P.O. Box 1373
Corvallis, OR 97339
(503) 758-7235

MOTOR CURRENT SIGNATURE ANALYSIS

Computational Systems, Inc. (CSI)
835 Innovation Dr.
Knoxville, TN 37932
(615) 675-2110

ENTEK\IRD Scientific Corp.
4480 Lake Forest Drive
Suite 316
Cincinnati, OH 45242
(513) 563-7500

ENTEK\IRD Mechanalysis, Inc.
6150 Huntley Rd.
Columbus, OH 43229
(614) 885-5376

Performance Technologies, Inc.
510 Little Creek Road
Lynchburg, VA 24502
(804) 237-2583

Predictive Maintenance Inspections

Wyk Laboratories Scientific

P.O. Box 432
Madison, AL 35758
(205) 464-9679

Services & Systems, Inc.
7800 Govenors Drive
P.O. Box 1008
Huntsville, AL 35807
(205) 837-4411

INSULATION TESTING/RESISTANCE TO GROUND

AVO International
4651 S. Westmoreland Rd.
Dallas, TX 75237
(214) 333-3201

Amprobe Instrument Division of Core Ind.
630 Merrick Rd.
P.O. Box 329
Lynbrook, NY 11583
(516) 593-5600

Baker Instrument Co.
2310 E. Prospect Rd.
Fort Collins, CO 80525
(303) 221-3150

Esterline Angus
1201 Main St.
Indianapolis, IN 46224
(317) 244-7611

Hipotronics
P.O. Drawer A, Route 22
Brewster, NY 10509
(914) 279-8091

John Fluke Mfg. Co.
P.O. Box C9090
Everett, WA 98206
(206) 347-6100

Moore Industries
16650 Schoenborn St.
Sepulveda, CA 91343
(818) 894-7111

PdMA Corporation
5909-C Hampton Oaks Parkway
Tampa, FL 33610
(813) 621-6463

VALVE AND BLADE TESTING

Liberty Technologies, Inc.
(215) 834-0330
POC: Tony Moffa, Sr.

Appendix E—Vibration Criteria[18]

FORWARD

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 Operations and Maintenance 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.

[18] 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.

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VIBRATION STANDARD
FOR NEW AND REBUILT MACHINERY AND EQUIPMENT

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 $\Delta f = 300$ 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 as follows:

- For displacement and velocity measurements ±l0% or ±1 dB.
- For acceleration measurements ±20% or ±1.5 dB.

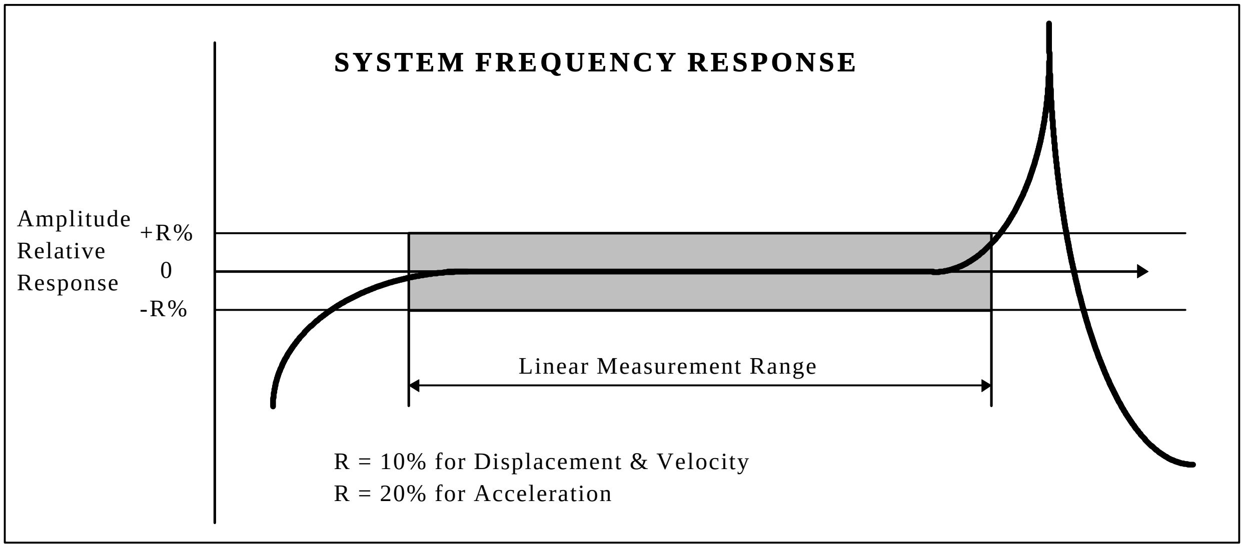


Figure 1. Measurement System Frequency Response

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

3.4.l 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 (F_{min}) and maximum frequency (F_{max}) 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).

3.4.2 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 % 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

3.4.3 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

4.1 **AXIAL DIRECTION** (A) shall be parallel to the rotational axis of the machine (reference Figures 2 and 3.

4.2 **RADIAL DIRECTIONS** (R) shall be:

- at 90° (perpendicular) relative to the shaft (rotor) centerline.

4.3 **VERTICAL** 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).

4.4 **HORIZONTAL** shall be in a radial direction:

- at a right angle (90°) from the vertical readings:
- In the direction of the shaft (rotor) rotation (Reference Figure 2 and 3).

4.5 OTHER:

- Any radial direction other than Horizontal or Vertical as defined in Sections 4.3 and 4.4.

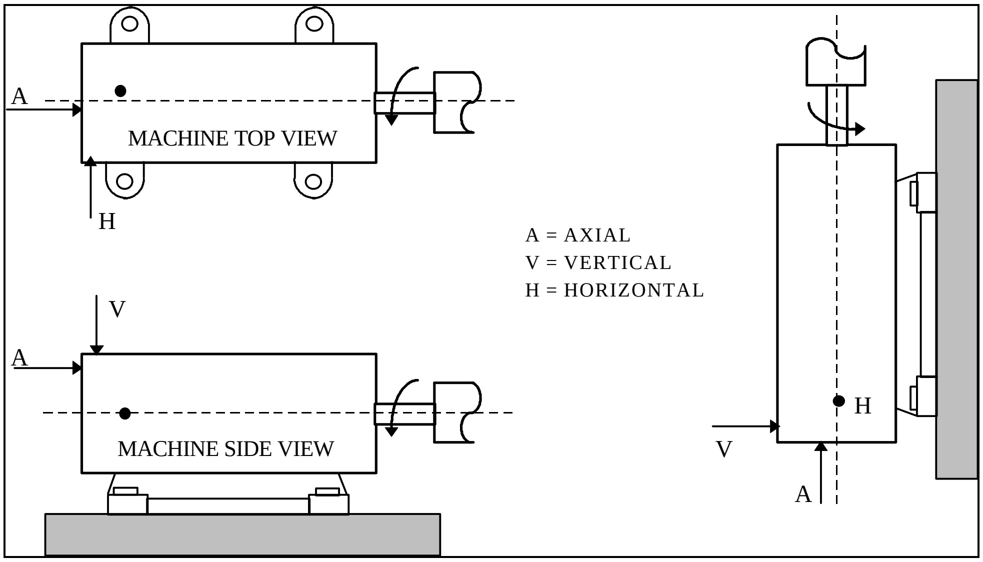


Figure 2 Vibration Measurement Axes Directions - Foot Mounted

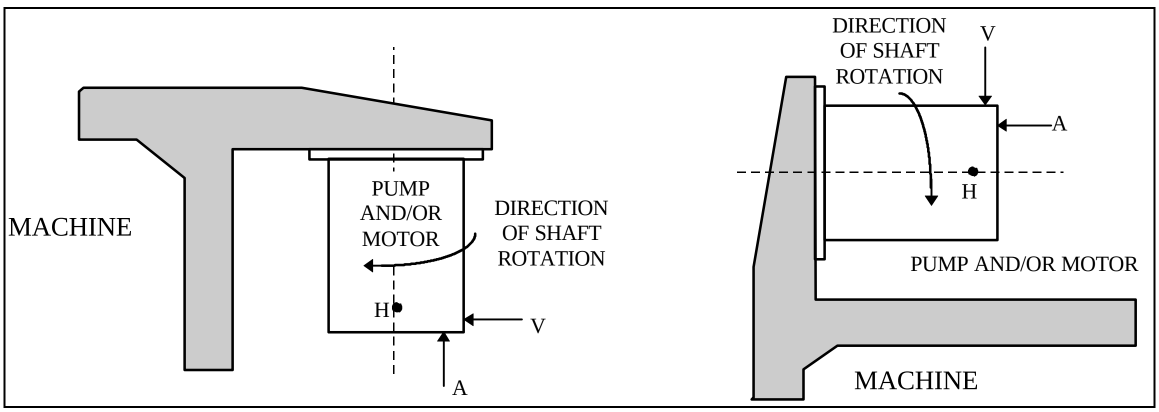


Figure 3 - Vibration Measurement Axes Directions - End-Mounted

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 the contractor, and shall meet the following requirements:

5.1 CONVENTIONS

Follow the convention specified in Sections 4.0 and 5.0, unless specified otherwise by the purchaser.

5.1.1 If an obstruction or safety prevents locating a transducer as specified, locate as close as possible to the standardized position.

5.1.2 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.

5.1.3 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.

5.1.4 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

5.2.1 Guarding must be designed to allow accessibility to all measurement locations (Reference Section 5.7).

5.2.2 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)

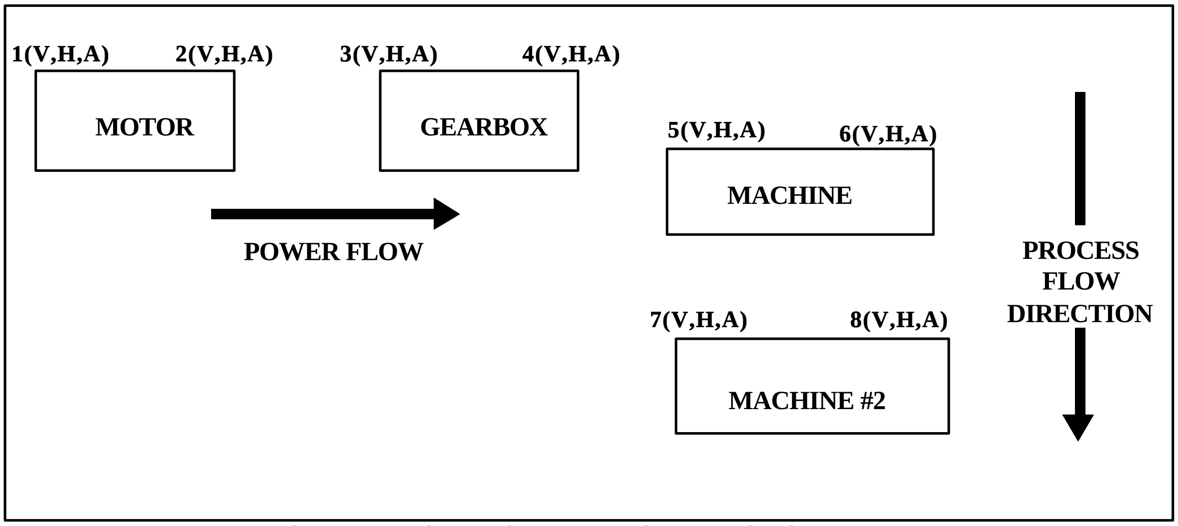


Figure 4 Order and Consecutive Numbering Sequence

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

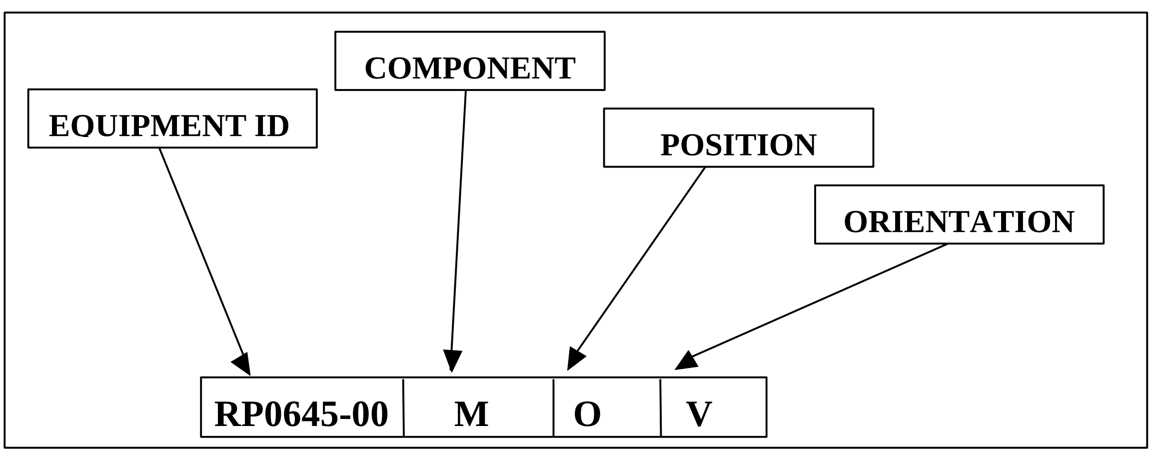


Figure 5 Measurement Location Documentation Convention

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		

Table 1 Recommended Component Identification Symbols

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.

6.1.1 Hand-held pickups are not acceptable for measurement by this specification.

6.1.2 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."

6.1.3 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.

6.1.4 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% of the manufacturer's stated resonance for "hard" adhesives and by 50% of the manufacturer's stated resonance for "soft" adhesives. Transducer manufacturer's specifications should be consulted.

6.1.5 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

6.2.1 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.

6.2.2 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.

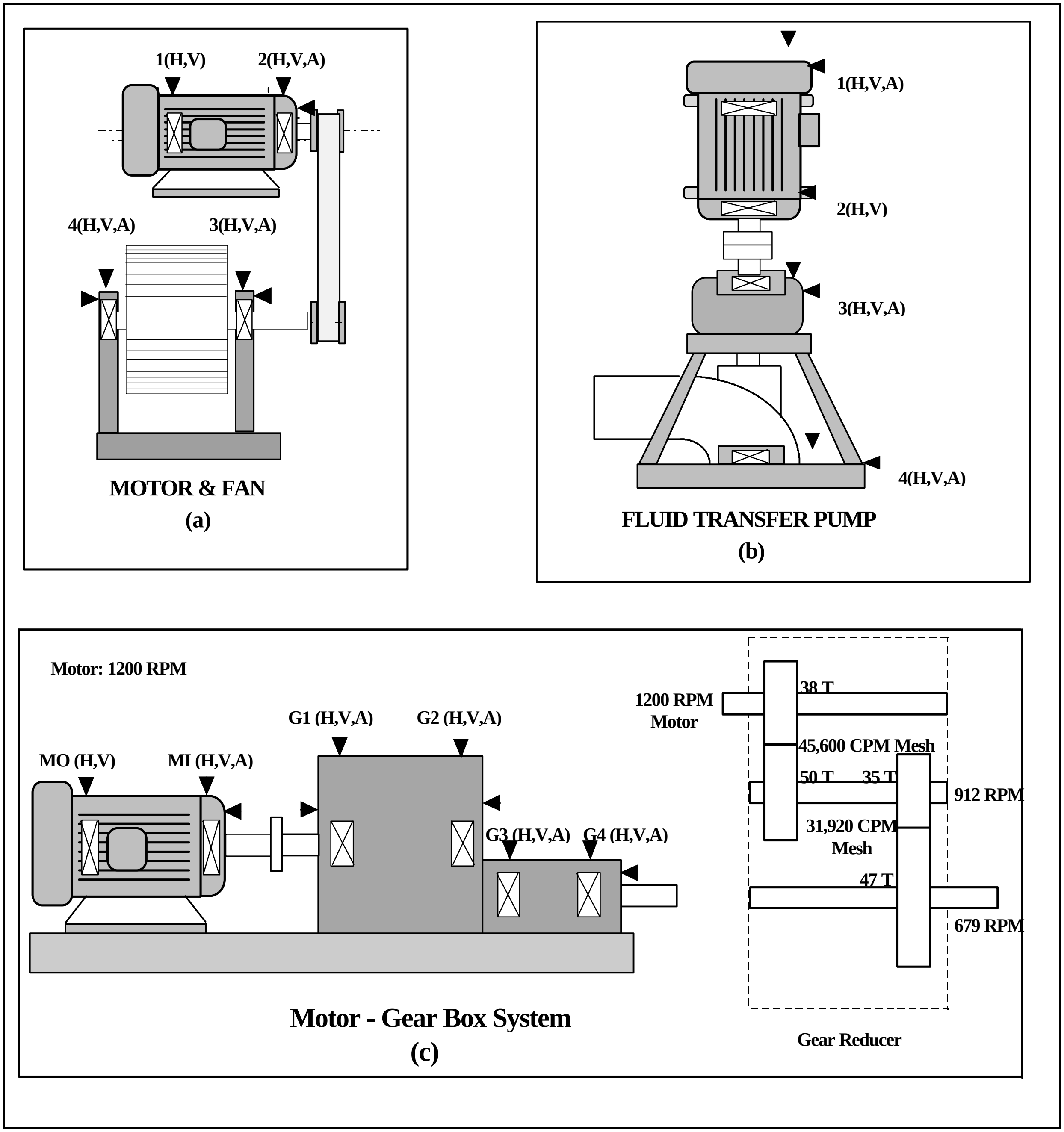


Figure 6 Vibration Measurement Locations

7.0 TECHNICAL REQUIREMENTS

7.1 VIBRATION MEASUREMENT UNITS

Vibration data for machine certification and acceptance shall be expressed in the following measurement units:

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

Table 2 Vibration Measurement Units

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.(Ref. Figure 7)

7.2.1 **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

7.2.2 **Other Bands**

Bands 4 through N shall be defined by the specific machine application.

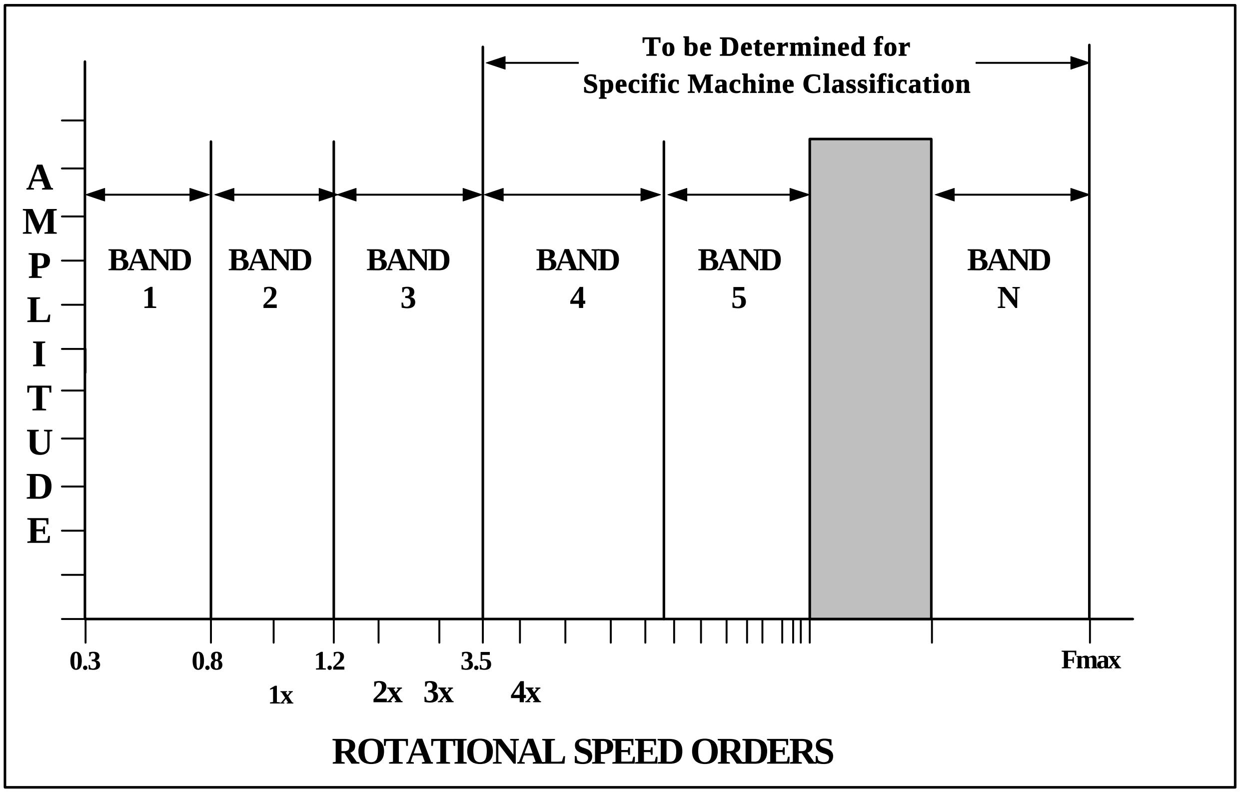


Figure 7 Frequency Bands

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 LIMITS

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.

7.4.1 If a line of resolution is coincidental with the Fmin/Fmax Of two adjacent bands, that line of resolution will be included in the band having the lowest acceptance level limit.

7.4.2 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.

7.4.3 Certification will be based on:

- Hanning Window.

- Four (4) averages (Linear non-overlapping).

7.4.4 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."

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

7.6.1 **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 8, will be attached to the machine indicating the dimension of the key used to perform the balance test.

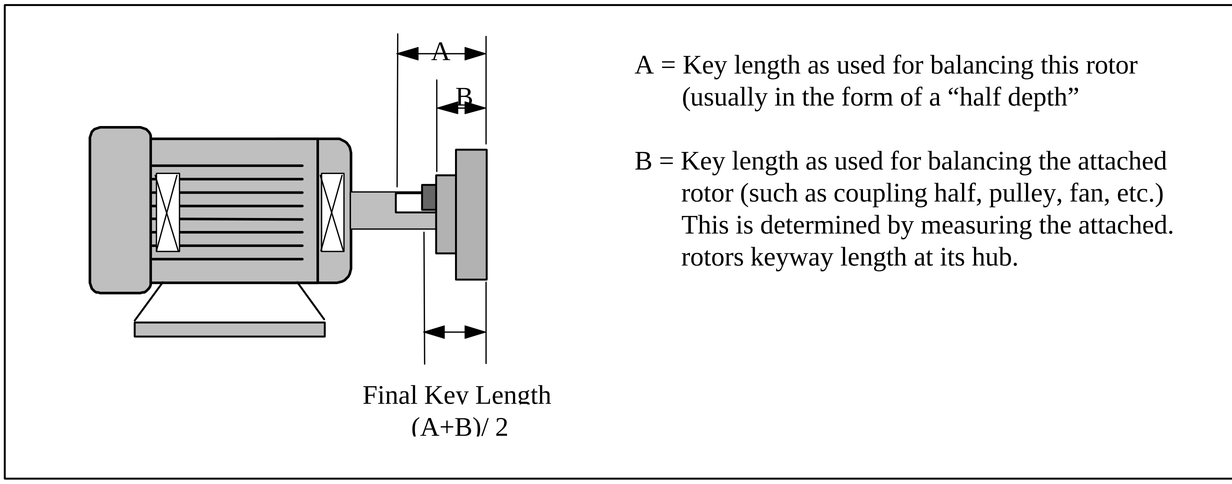


Figure 8 Balance Test Key Dimension

7.6.2 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

8.1.1 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."

8.1.2 The Quotation shall state the applicable specification vibration level limits being quoted.

8.1.3 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

8.2.1 Vibration measurements shall:

8.2.1.1 Be the responsibility of the supplier unless specified otherwise by the purchaser.

8.2.1.2 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.

8.2.1.3 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--either actual or simulated--will be applied during collection of machine vibration data.

8.2.1.4 Prior to taking vibration measurements, the machine will be "run-in" until it reaches operating speed and thermal stability

8.2.2 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.

8.2.3 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.

8.2. 4 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.

8.2.5 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

9.1 ELECTRIC MOTORS -- Refer to Section 9.1 Vibration Standards for Electric Motors."

9.2 FANS -- Refer to Section 9.2 Vibration Standards for Fans."

9.3 PUMPS -- Refer to Section 9.3 Vibration Standards for Pumps."

9.4 GEARBOXES -- Refer to Section 9.4 Vibration Standards for Gearboxes."

9.5 DEFAULT VIBRATION LEVEL LIMITS -- Refer to Section 9.5 Vibration Standard Default Limits."

9.6 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.

SECTION 9.1

VIBRATION STANDARDS FOR ELECTRIC MOTORS

9.1.1. ELECTRICAL MOTOR REQUIREMENTS

9.1.1.1 Motors will be defined by four (4) categories:
Standard motor.......Utility Operations
Special motor..........Semi-Finish Operations
Precision motor.......Finish Operations
Other motor............Per agreement by vendor and the Government

9.1.1.2 The frequency range for motor certification will be from Fmin = 0.3 X Running Speed (synchronous speed) to Fmax = 120,000 CPM (2,000 Hertz)

9.1.1.3 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.

9.1.1.4 MOTOR ISOLATION

9.1.1.4.1 Method of Motor Isolation for Measuring Vibration
Place the motor on an 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.

MOTOR SYNCHRONOUS SPEED (RPM)	ISOLATION PAD COMPRESSION (INCHES)
900	1
1200	9/16
1800	1/4
3600	1/16
7200	1/64
Note: The required deflection is inversely proportional to the speed squared.	

Table 9.1.1 Motor Isolation Requirements

9.1.1.4.2 All new and rebuilt motors shall conform to the vibration limits specified in Table 9.1 when tested in accordance with this specification.

9.1.1.5 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:

ROTOR DESIGN	FIRST ACTUAL CRITICAL SPEED LOCATION
Rigid Shaft	At least 25% Above Rated Motor Speed
Flexible Shaft	Maximum of 85% of Motor Speed

Table 9.1.2 Critical Speed Offset Requirement

9.1.1.6 LIMITS

9.1.1.6.1 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:

9.1.1.6.1.1 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.

9.1.1.6.1.2 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.

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

TABLE 9.1.3 Maximum Allowable Vibration Levels For Electric Motors

9.1.2. ELECTRICAL MOTOR CERTIFICATION

9.1.2.1 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.

9.1.2.2 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.

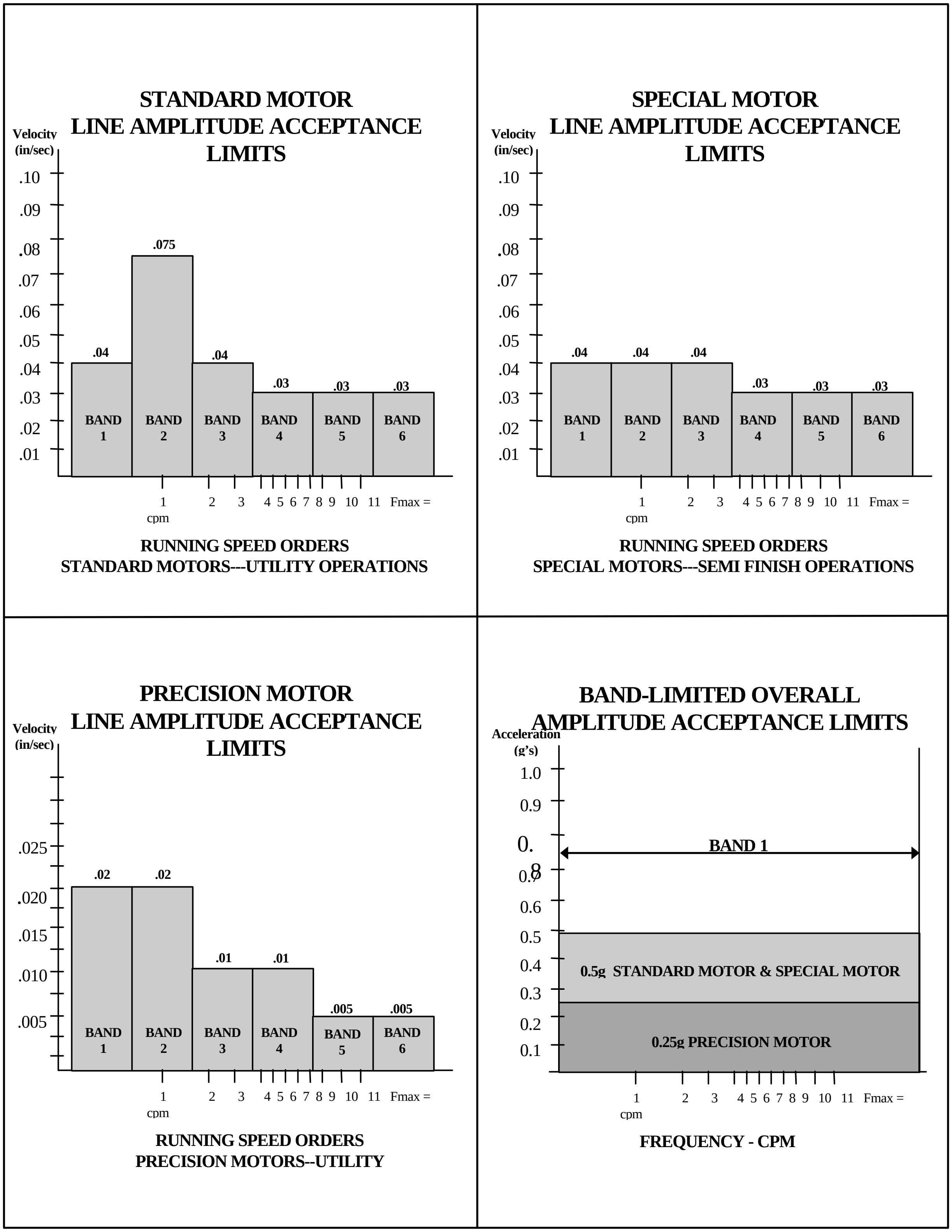


Figure 9.1 Maximum Allowable Vibration Limits for Electric Motors

9.1.2.3 The motor nameplate shall carry the following designation:

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 NASA

Table 9.1.4 Motor Nameplate Vibration Data Requirements

9. 1.2.4 Vibration data and signatures must be submitted with the motor to the NASA Maintenance organization or other authorized representative before acceptance of the motor will be authorized.

9. 1.2.5 Motors not meeting the certification shall be rejected.

SECTION 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

9.2.2.1 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 ON LEAD WEIGHTS IS NOT ACCEPTABLE**

9.2.2.2 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.

9.2.2.3 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% removed from a natural frequency of the system.)

9.2.5 LIMITS

9.2.5.1 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.

9.2.5.2 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.

9.2.5.3 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.

9.2.5.4 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.

9.2.5.5 Acceptance limits for fans running over 3600 RPM shall be specified by the purchaser.

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)		

Table 9.2 Maximum Allowable Vibration Levels For Fans

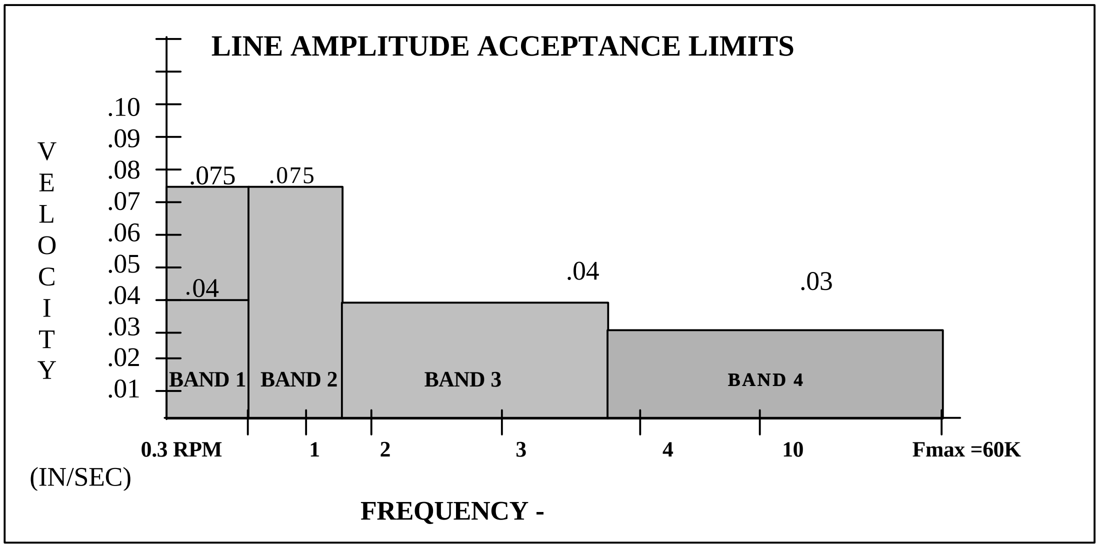


Figure 9.2.1 Line Amplitude Acceptance Limits for Fans

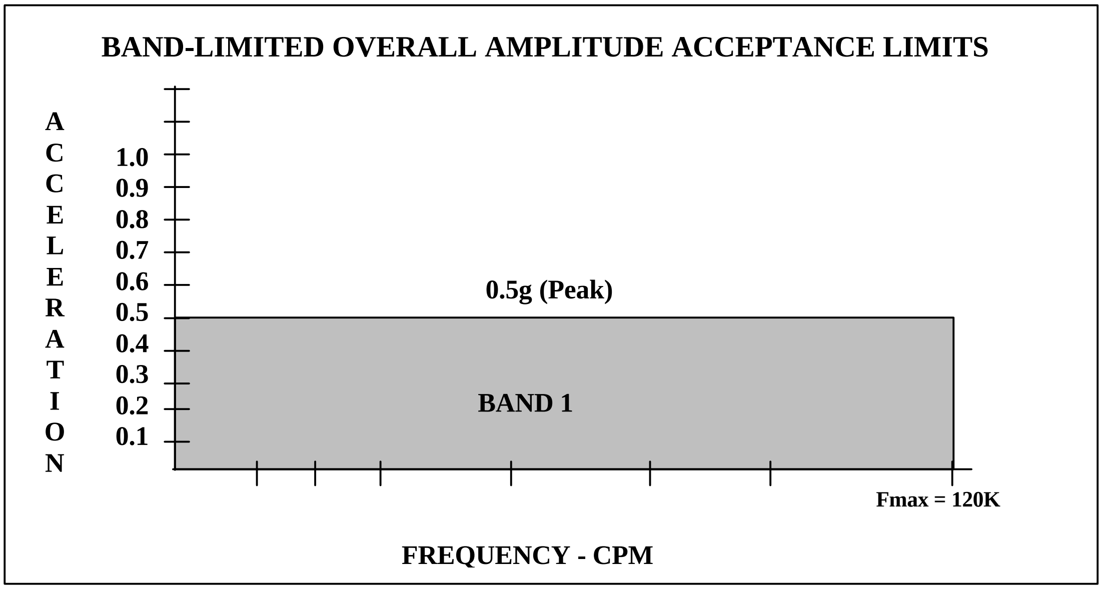


Figure 9.2.2 Band Limited Overall Amplitude Acceptance Limits for Fans

9.2.6 OTHER REQUIREMENTS

9.2.6.1 Variable speed or adjustable sheaves shall not be used in the final installation.

9.2.6.2 Drive sheave and driven sheave should differ in size by 20 % or more to avoid "beat" vibration.

SECTION 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

9.3.2.1 Non-cavitating, non-separating condition

9.3.2.2 No piping strain

9.3.2.3 Shaft coupling aligned

9.3.2.4 Straight suction pipe to pump. (Reference Hydraulic Institute Standard)

9.3.2.5 Certification shall be performed while pumps are operating within design specifications

9.3.3 LIMITS FOR POSITIVE DISPLACEMENT & CENTRIFUGAL PUMPS

9.3.3.1 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)

9.3.3.2 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)

9.3.3.3 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.

9.3.3.4 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.

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
PUMPING FREQ. BAND (PF)	FREQUENCY RANGE (CPM)	VELOCITY (INCH/SEC - PEAK)
BAND 5	5 Lines of resolution centered on PF.	0.075 PISTON 0.05 VANE

Table 9.3 Maximum Allowable Vibration Levels For Positive Displacement And Centrifugal Pumps

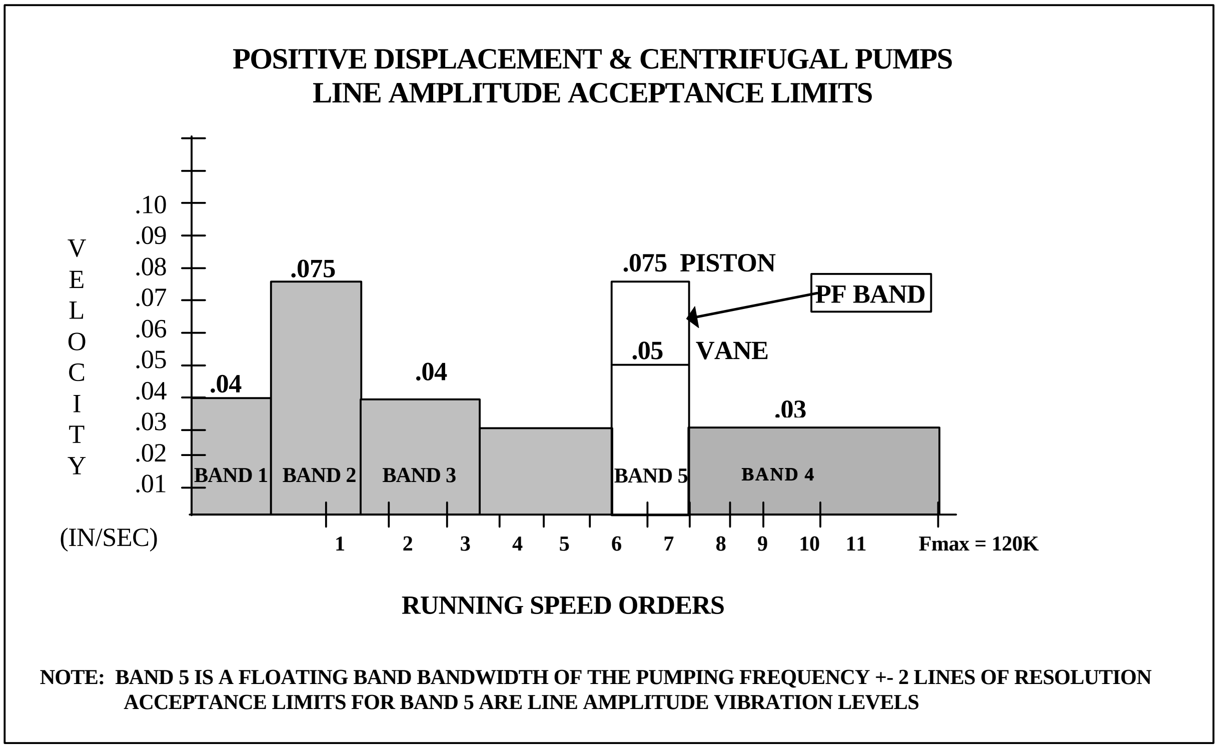


Figure 9.3.1 Line Amplitude Acceptance Limits for Positive Displacement & Centrifugal Pumps

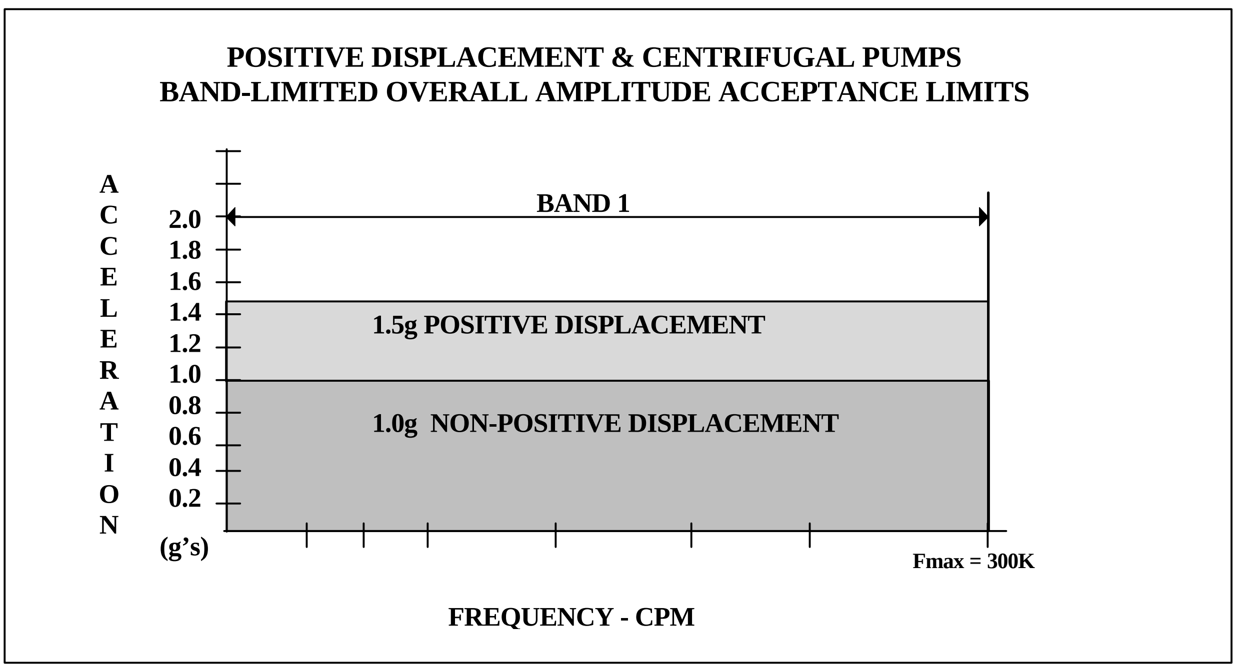


Figure 9.3.2 Band-Limited Overall Amplitude Acceptance Limits for Positive Displacement & Centrifugal Pumps

9.3.4 VERTICAL MOUNTED PUMPS

9.3.4.1 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% per foot of "Vertical Mount Height" greater than 5 feet. (e.g. A 7 foot Vertical Mount Height would yield a 10% 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.

9.3.4.2 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.

SECTION 9.4

VIBRATION STANDARDS

FOR GEARBOXES

9.4.1 Gearboxes shall not exceed the Vibration Limits specified in Figures 9.4.1 and 9.4.2

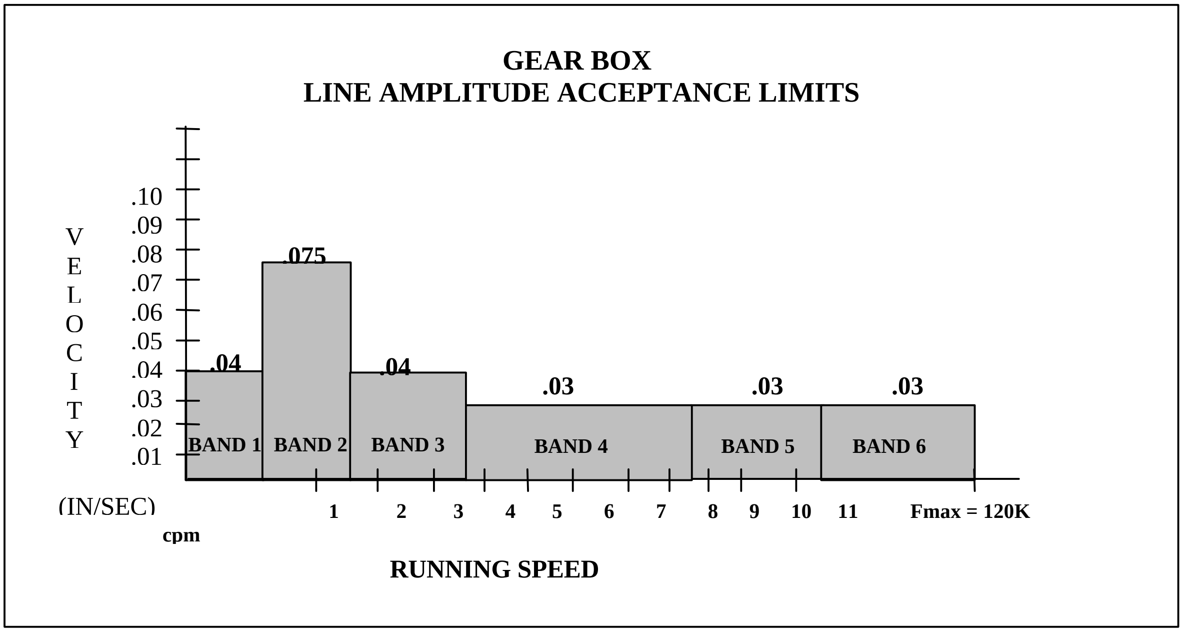


Figure 9.4.1 Line Amplitude Acceptance Limits for Gearboxes

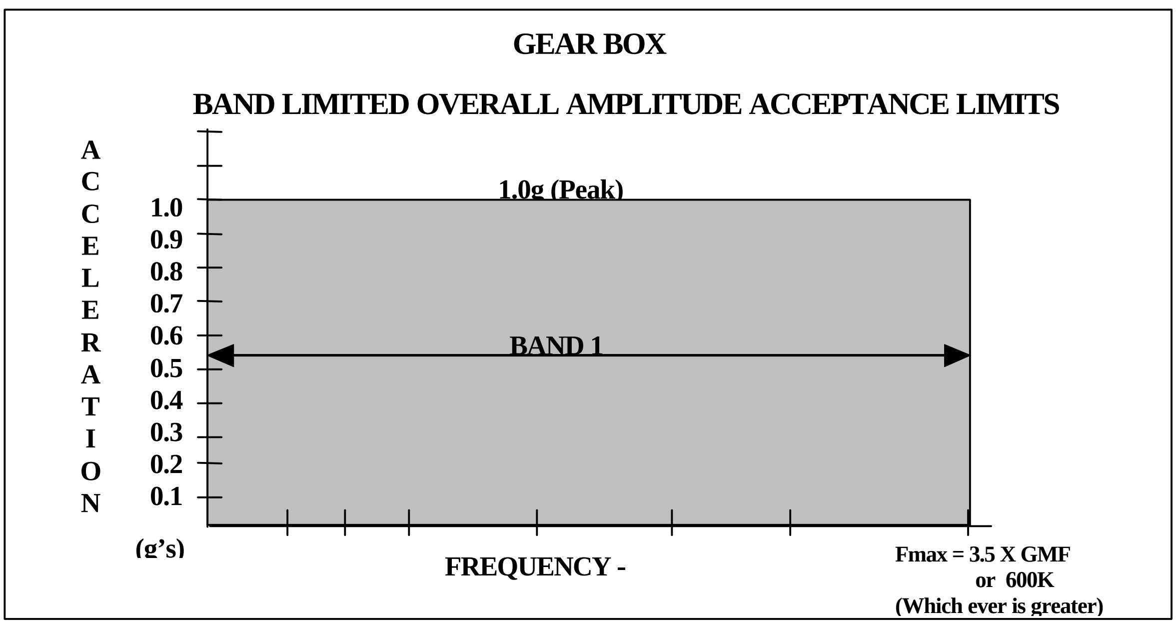


Figure 9.4.2 Band-Limited Overall Amplitude Acceptance Limits for Gearboxes

SECTION 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.

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

Table 9.5 Maximum Allowable Vibration Levels for Non-Machine Tools

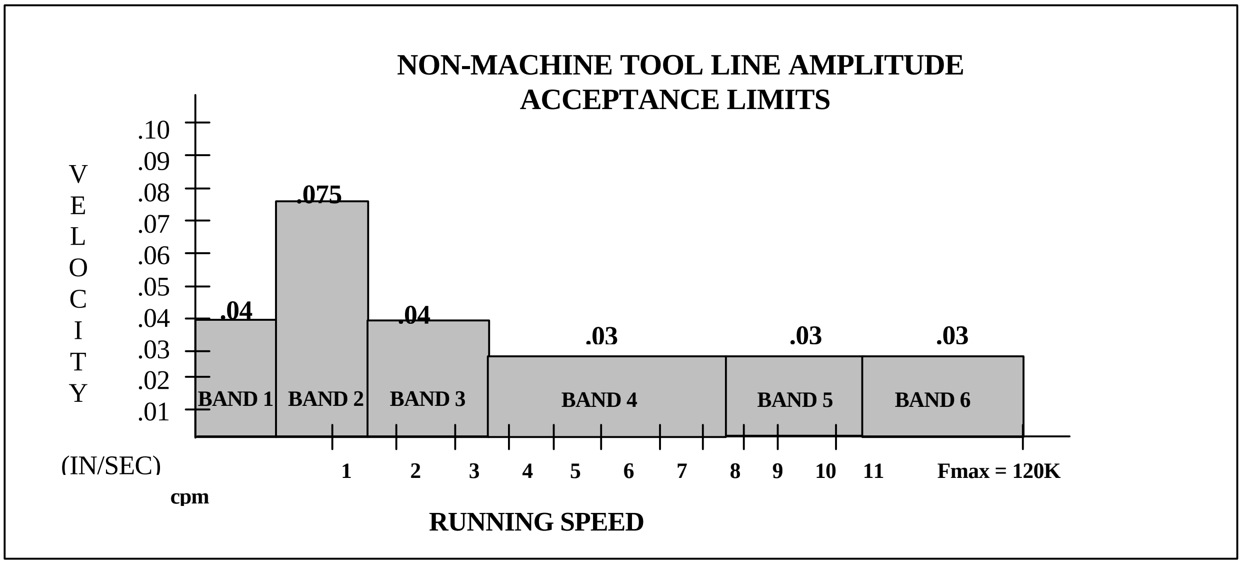


Figure 9.5.1 DEFAULT Line Amplitude Acceptance Limits for Non-Machine Tools

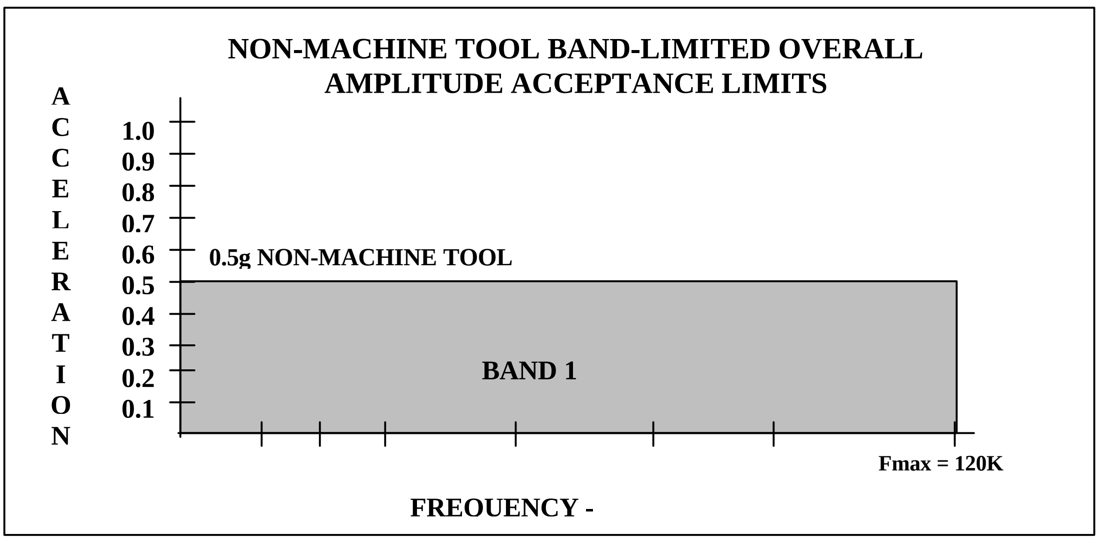


Figure 9.5.2 DEFAULT Band-Limited Overall Amplitude Acceptance Limits for Non-Machine Tools

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)

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

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)

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 F 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:

a. Make the desired measurement with the accelerometer.
b. Place a mass equivalent to the mass of the accelerometer adjacent to the measuring accelerometer.
c. Repeat the measurement.
d. Compare data from a. and c.
e. 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.

FIELD BALANCING: The process of balancing a rotor in its own bearings and supporting structure rather than in a balancing machine.

FFT (FAST FOURIER TRANSFORM): 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.

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% 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 2πf 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 = 1×10^{-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 a 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% 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 (see paragraph 3.3.1).

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 as effective	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–1. Vibration Monitoring Correlation

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 are presents. 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, 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–2. Correlation of Vibration Monitoring with Other PT&I 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–3. Correlation of Lubricant & Wear Particle 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 or corrosion/oxidation at connectors.	On condition of indicated problem.

Table F–4. Correlation of Thermal 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–5. Correlation of Advanced Filtration & Debris Analysis 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 ΔT as flow decreases due to blockage or pump degradation.	On condition of flow decrease/ ΔT change across heat exchanger.
Vibration analysis	Time coincident	Cavitation 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–6. Correlation of Flow Measurement 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–7. Correlation of Valve Operator 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–8. Correlation of Electrical Testing 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–9. Correlation of Ultrasonic/Acoustic Leak Detection 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–10. Correlation of Breakaway or Coastdown Testing 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–11. Correlation of Dew Point Measurement 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–12. Correlation of Visual Inspections 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–13. Correlation of Trace Element Sensing 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–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	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–15. Correlation of Radiography 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–16. Correlation of Stress-Strain Measurement 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–17. Correlation of Acoustic Emission 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.

Table F–18. Correlation of Ultrasonic, Eddy Current, and Photonic Position Sensors with Other Technologies

Figure F–1 depicts a simplified Chilled Water System and the various components that can be monitored using the aforementioned correlated PT&I technologies.

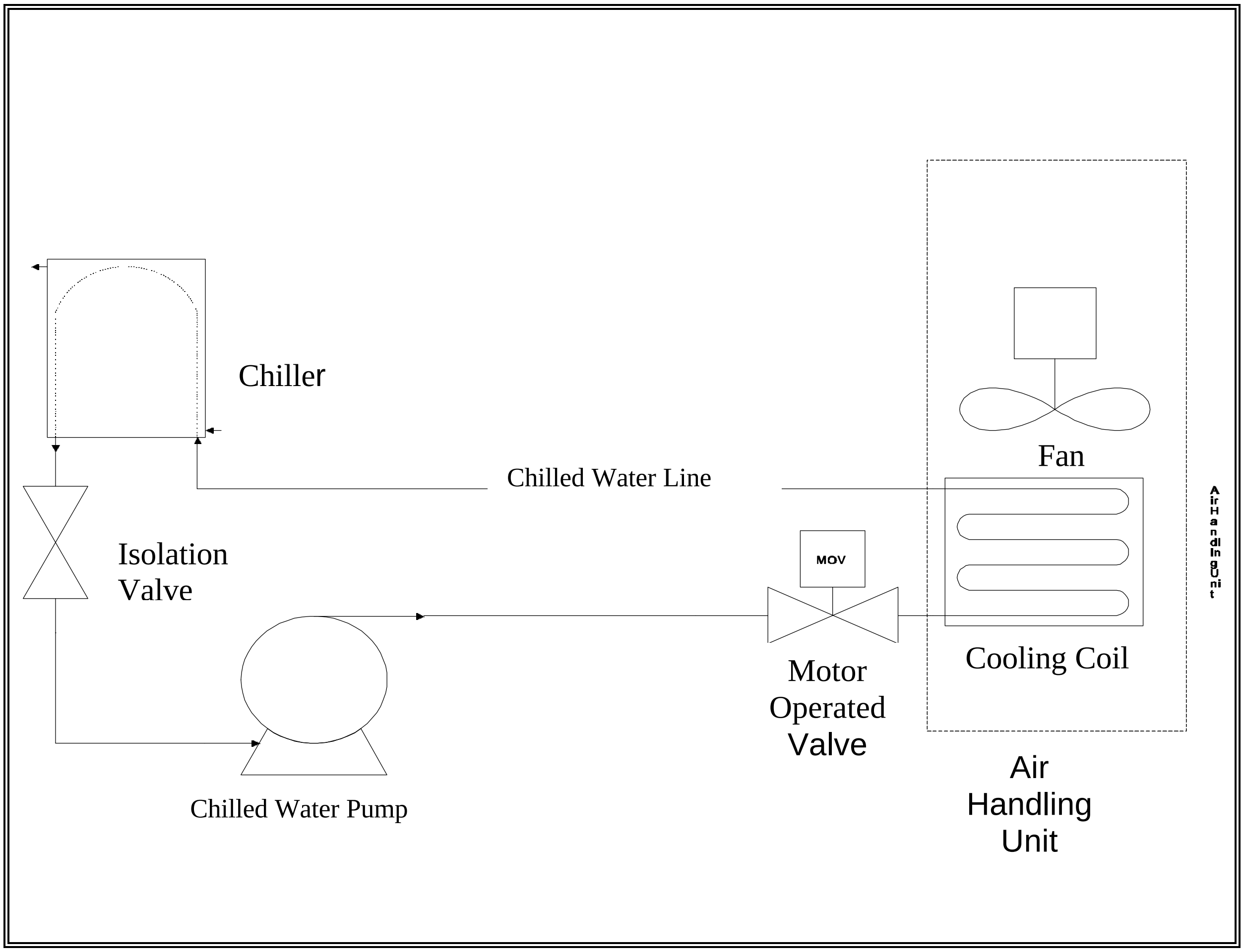


Figure F-1. Chilled Water System

For example, a chilled water system would require the following PT&I techniques to be used in order for the entire system to be evaluated:

a. **Flow Rates**—Chiller water flow would be measured using precision, non-intrusive flow detectors.

b. **Temperature**—Differential temperature would be measured to determine heat transfer coefficients and to indicate possible fouling of tubes.

c. **Pressure**—Differential pump and chiller pressures would be measured to determine pressure drops and pump efficiency.

d. **Electrical**—Motor power consumption and motor circuit testing would be used to assess the condition of the motor circuits and to correlate with pump efficiencies.

e. **Ultrasonic Thickness**—Pipe wall thickness would be measured to determine erosion and corrosion degradation.

f. **Vibration**—Vibration monitoring would be used to assess the condition of the rotating components such as pumps and motors. Additionally, structural problems would be identified through resonance and model testing.

g. **Lubricant Analysis**—Oil condition and wear particle analysis would be used to identify problems with the lubricant and correlated with vibration when wear particle concentrations exceed pre-established limits.

h. **Fiber Optics**—Fiber optic inspections would be used in response to indications of component wear, tube fouling, etc.

i. **Thermography**—Thermography scans would be used to check motor control centers and distribution junction boxes for high temperature conditions. Piping insulation should be checked for porosities.

j. **Eddy Current**—Eddy current would be used to determine and locate leaking tubes.

k. **Airborne Ultrasonics**—Airborne ultrasonics would be used to detect leaking air from control system and compressor leaks.

Appendix G—Alignment Standard[19]

FORWARD

It is recommended that laser alignment be used on all shaft coupled machines be a part of implementation of Reliability Centered Maintenance. Laser alignment designed into the machine will:

- Minimize machine installation and set-up time.
- Allow verification of machine productivity and machine life.
- Allow identification of unique errors in machine motions and structure.

The LASER ALIGNMENT SPECIFICATION FOR NEW AND REBUILT MACHINERY AND EQUIPMENT provides engineering performance guidelines for use by Plant 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.

[19] **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.

TABLE OF CONTENTS

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 operations 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 colinear at the coupling center under operating conditions.

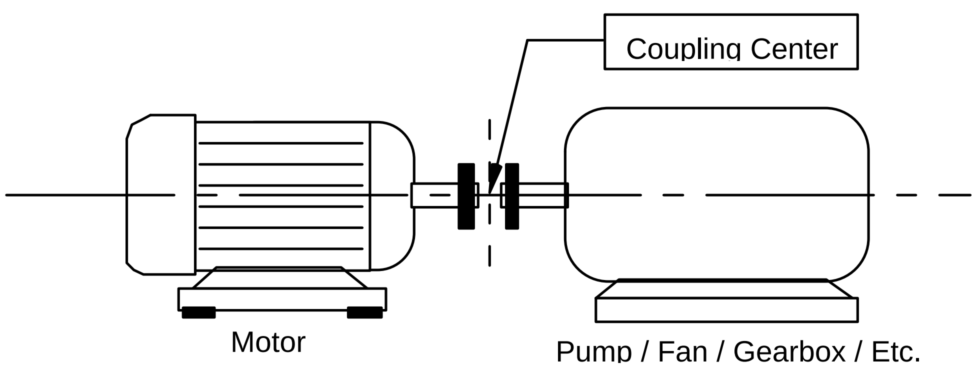


Figure 1 - Coupled Shafts Alignment

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 TOLERANCES

3.4.1 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.

	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)**
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)**	

TABLE 1 COUPLED SHAFT ALIGNMENT TOLERANCE VALUES

JACKSHAFTS: **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:

a. Alignment tolerances used.
b. **SOFT FOOT**
c. Vertical A**NGULARITY** (Pitch) at the **COUPLING POINT.** (Refer to **Figure-2)**
d. Vertical **OFFSET** at the coupling point.
e. Horizontal angularity (Yaw) at the coupling point.
f. 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

3.6.1.1 A solid and rigid machine base is required to achieve and maintain shaft alignment.

3.6.1.2 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)

3.6.1.3 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.

3.6.1.4 Where corrosion is or may be a problem the base must be fabricated of corrosive resistant materials.

3.6.1.5 Where the machine base is constructed from commercially available steel or castings:

3.6.1.5.1 Use H, M, I, square, tube, and bar shapes with a minimum 0.5 inch (1.27 cm) thickness.

3.6.1.5.2 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 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.

3.6.1.5.3 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.

3.6.1.6 After all welding and machining is completed, stress relieve 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

3.6.4.1 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:

a. 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.
b. Hold-down bolts shall be centered in the hole of the machine foot.
c. Hold-down bolts shall be the preferred method of fastening machines to the base.
d. 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:

a. Commercially die-cut.
b. Made of corrosion and crush resistant stainless steel, which is dimensionally stable when subjected to high compression over long periods of time.
c. Consistent over the whole shim area, without seams or folds from bending.
d. Clean, free from burrs, bumps, nicks and dents of any kind.
e. Size numbers or trademarks etched into the shim, not printed or stamped.

f. The smallest commercial shim that will fit around the hold down bolts without binding shall be used.
g. The overall shim pack shall not exceed a total of three (3) shims.
h. Shims must rest 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.

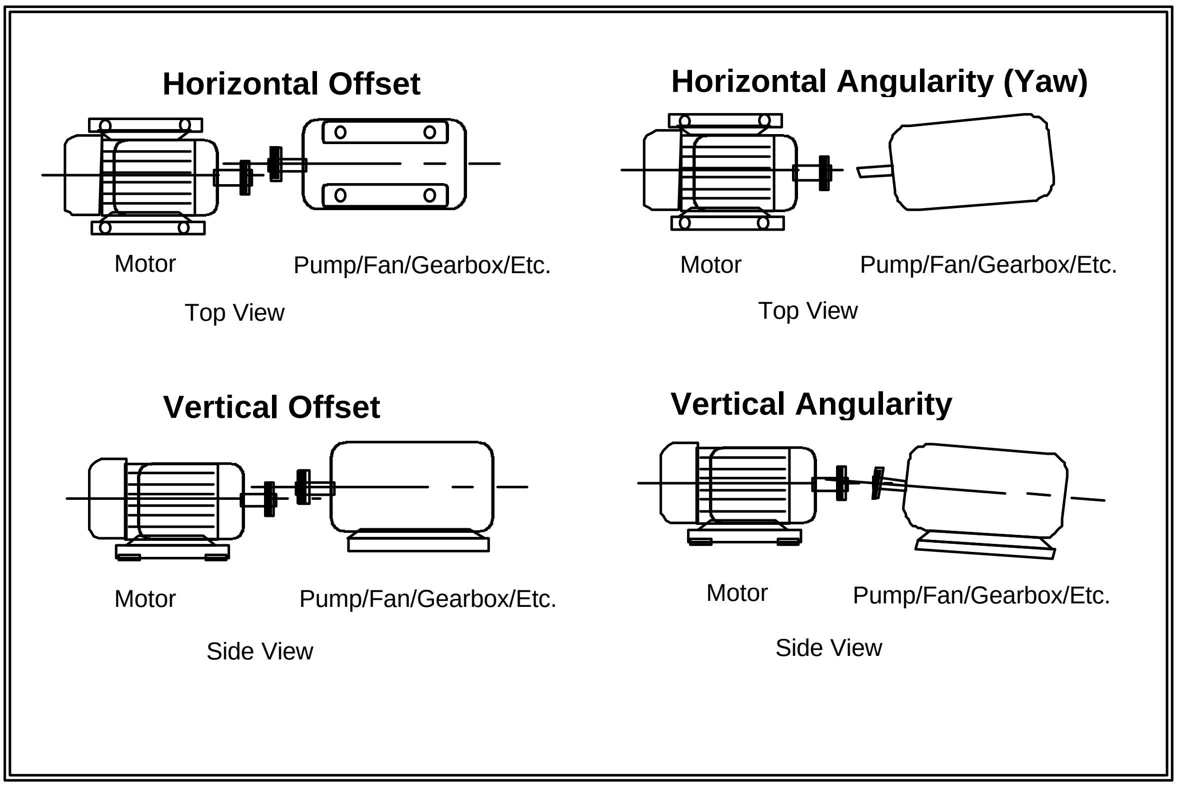
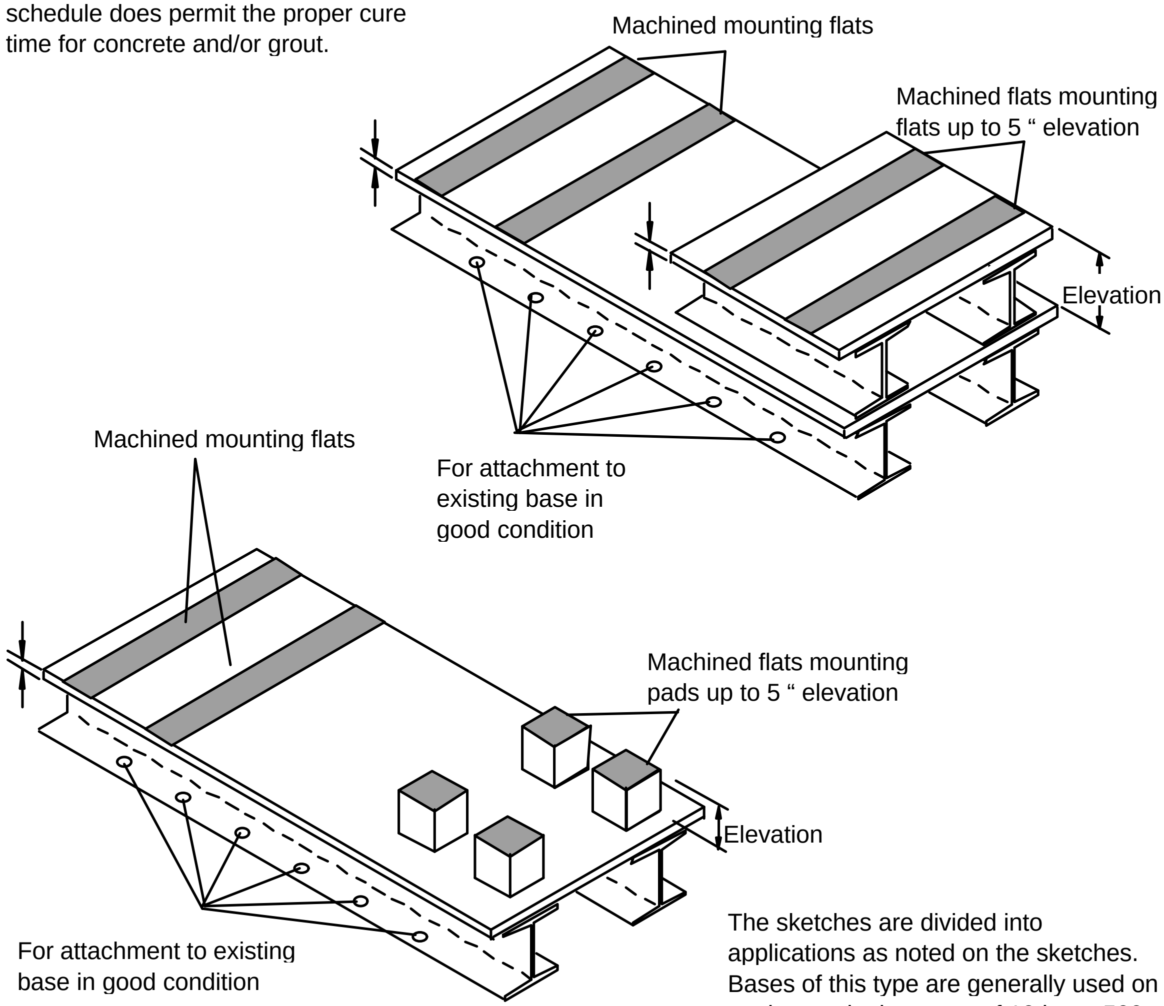


Figure 2 Offset and Angular

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 3a Suggested Baseplate Assemblies

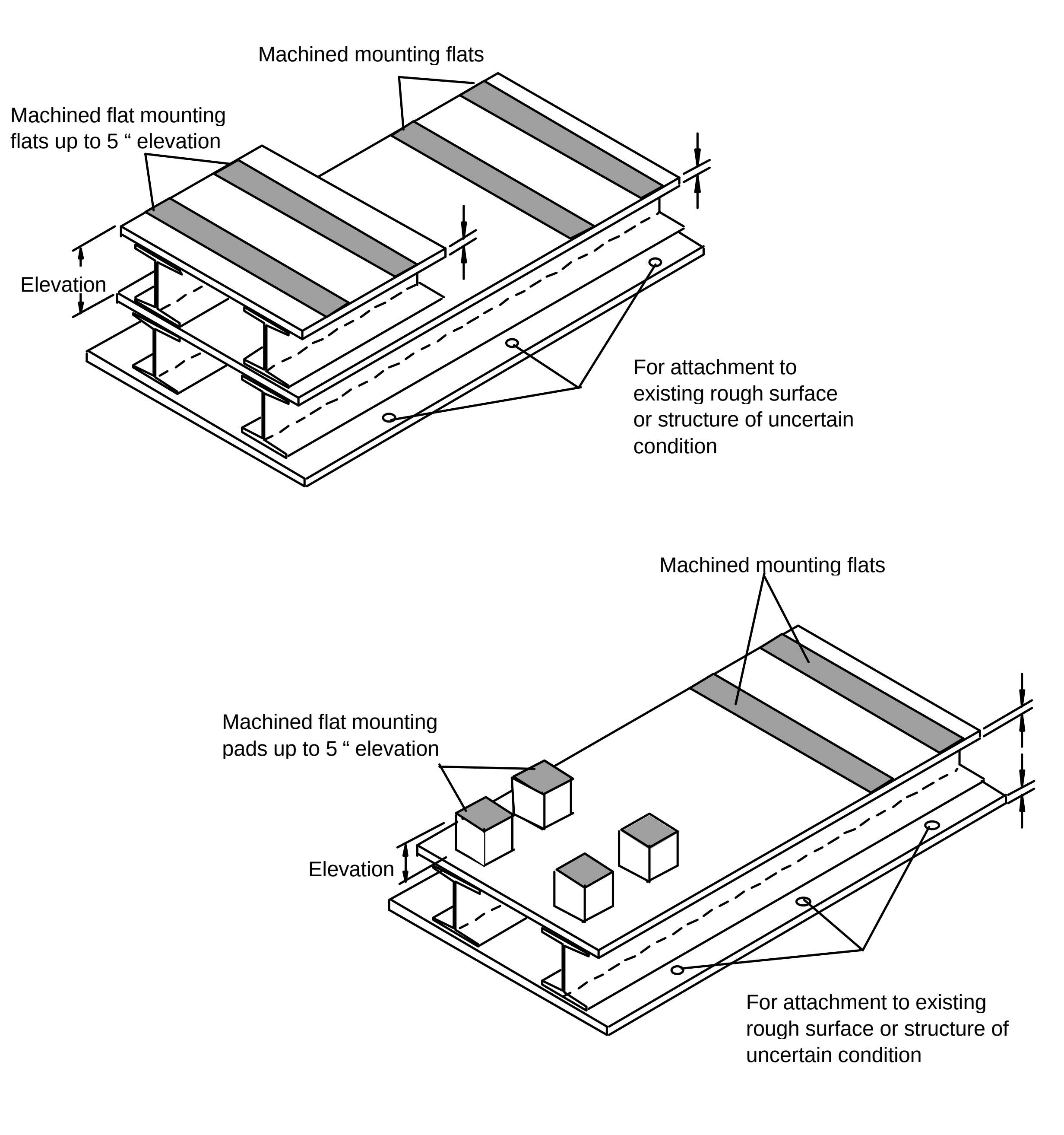


Figure 3b Suggested Baseplate Assemblies

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.

4.1.2.1 Base will have enough adjustment to allow belt replacement without stretching the new belts.

4.1.2.2 Adjustment method will be by use of two adjusting bolts.

4.2 RUNOUT

4.2.2 After sheaves are installed on the motor and driven shafts, the sheaves will be checked to ensure that they are true on the shaft.

4.2.3 Runout on the sheaves will be checked with a dial indicator

4.2.4 Sheave runout shall not exceed 0.0580 mm (0.002 in.)

4.3 SHEAVE ALIGNMENT

4.3.2 Unless otherwise specified, drive and driven sheaves will be aligned by the four-point method.

4.3.3 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.

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).**

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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 a 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 specifications, 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.

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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, (could be 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[20]

FORWARD

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.
- 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 Operations and Maintenance 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.

[20] **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.

TABLE OF CONTENTS

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.

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

Table 1. Default Balance Specifications

3.2 BALANCE CALCULATION

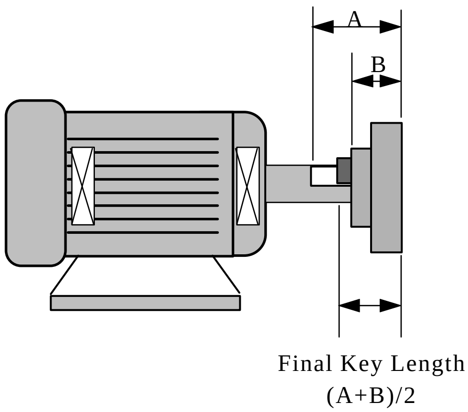
Table 2 provides the ISO1940/1-1986 balance quality grades for various groups of representative rigid rotors. The RCM Guide contains more detailed information and the complete ISO 1940/1 –1986 table.

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 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
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

Table 2. Balance Quality Grades for Various Groups of Representative Rigid Rotors (ISO 1940/1-1986)

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.



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.

Figure 1. Balance Test Key Dimension

3.4 BALANCE WEIGHTS:

Permanently attached balancing weighs must be secured by welding, bolting, pop-riveted, or of a "clip-on" design.

3.4.1 If bolted, a hardened bolt must be used in conjunction with a mechanical locking device (e.g. lock washer or lock nut).

3.4.2 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.

3.4.3 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.**

3.4.4 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.

3.4.5 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 TOTAL ASSEMBLY.

4.0 MACHINE QUOTATION, CERTIFICATION, AND ACCEPTANCE

4.1 QUOTATION

4.1.1 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."

4.1.2 The Quotation shall state the applicable specification balance quality being quoted.

4.1.3 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

4.2.1 Balance measurements shall:

4.2.1.1 Be the responsibility of the supplier unless specified otherwise by the purchaser.

4.2.1.2 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.

4.2.1 Be submitted to the maintenance orginization or other authorized representative before acceptance of the machinery or equipment being purchased will be authorized.

4.2.3 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.

4.2.4 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 plant's Purchasing department before final acceptance is authorized.

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% 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 = 1×10^{-6} meters = 0.04 mils.)

MIL: One thousandth (0.001) of an inch. (1 mil = 25.4 microns.)

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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% 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) MACHINES. 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 — AC Motor Repair and Reconditioning

1.0 SCOPE

This specification together with the Data Sheets covers the Repair and Reconditioning of AC Induction Motors. The purpose of this specification is to establish the minimum standards and documentation recommended for the repair and refurbishment of 3-phase AC Motors.

2.0 STANDARDS AND CODES

These specifications are in addition to the industry accepted practices as stated in the following Standards and Codes:

IEEE 1068-1990	*Recommended Practice for the Repair and Rewinding of Motors for the Petroleum and Chemical Industry*
IEEE 43-1974	*Recommended Practice for Testing Insulation Resistance of Rotating Machinery*
IEEE 95-1977	*Recommended Practice for Insulation Testing of Large AC Rotating Machinery with High Direct Voltage*
NEMA MG 1-1987	*Motors and Generators*
ISO 1940	*Unbalance Tolerance Guide for Rigid Rotors*
ISO 3945-1977	*Mechanical Vibration of Large Rotating Machines with Speed range from 10-200 rev/s-Measurement and Evaluation of Vibration Severity in Situ*

EASA Standards for the Repair of Electrical Apparatus, February 1992
SKF Engineering Data Handbook dated December 1980

2.1 All repairs to Explosion-Proof, Dust Ignition-Proof, or other severe duty motors will not compromise their original UL Certification.

3.0 GENERAL- ALL ELECTRICAL APPARATUS

3.1 **Incoming Inspection:** Each machine shall have all nameplate information, all hardware (i.e., coupling, hub, lifting eyes, etc.), and general condition noted. In addition, note any damaged or broken parts and, if possible, the primary cause of failure. The endbells shall be matchmarked.

Visually inspect the stator windings for damage, tightness, cracked insulation, and the general condition of the motor leads. Report all damage.

3.2 **Cleaning:** All windings and parts must be cleaned free from dirt, grit, grease, and oil. Cleaning agents shall be completely removed by steam cleaning then, dried by baking at a maximum temperature of 300^0F. Winding temperature shall not exceed 176^0F during the drying process.

3.3 **Stripping:** Defective windings will be removed in such a manner that no mechanical damage is done to the laminations or frame. Winding burnout shall be done in a temperature controlled environment to ensure the stator iron temperature does not exceed 650^0F.

3.4 **Insulation System:** All insulation and components which make up the insulation system shall be rated NEMA Class F. All varnishes and coatings shall be compatible with the insulation. Vacuum pressure impregnation (VPI) is the preferred method of varnish application.

3.5 **Motor Leads:** The motor leads shall have a temperature and insulation rating equal to or greater than the temperature and insulation rating of the insulation system. Leads on totally enclosed fan cooled (TEFC) and explosion-proof apparatus shall be properly sealed to meet the original classification of the motor.

3.6 **Exterior Finish:** The apparatus shall be externally cleaned, sandblasted, and refinished with primer and a good quality enamel paint. Each repaired motor shall be labeled with a metal tag which states the name of the repair company and the date of repair.

3.7 **Shipment:** Block the shaft to prevent axial travel. Cover the motor with plastic to protect from weather during shipment. For motors shipped without sufficient lubricant for industrial operation, attach a red tag labelled "Lubrication Required" to each fill point.

Return completed "Motor Data Sheet" with the motor.

4.0 SHAFTS

4.1 **Inspection:** Shafts shall be checked for unusual wear, scoring, and straightness. On motors greater than 100 HP, a dye penetrant inspection of the shaft is required.

4.2 **Bearing Journals and Shaft Extensions:** The bearing journals and shaft extension shall be concentric with the shaft center, smooth polished, and of proper size and fit. A minimum of two readings using a dial indicator per shaft are required. The tolerance for total indicated runout (TIR) regardless of shaft size or motor horsepower are:

4.3 **Axial End Play:** Total end play in sleeve bearing motors shall be approximately 1/16" per inch diameter of the shaft journal. For rolling element bearings, if minimum end play tolerances are not provided on motor drawings a value of 0.003 inch should be used.

Maximum Motor Speed (RPM)	Maximum TIR (inches)
900	0.002
1200	0.002
1800	0.0015
3600	0.001

Table I – 1.Maximum Total Indicated Runout

4.4 **Balancing:** All motors greater than 5 HP shall be balanced as close to operating speed as possible to ISO 1940 G-2.5 using one of the following:

a) All keyways completely filled with half keys; or,
b) With sheaves, coupling hubs, etc. filled with keys.

The balance report shall be included with the motor and include the following: Initial and final imbalance, location and weight used, length of key stock used, and rotor weight.

5.0 BEARINGS

All bearings are to be replaced unless otherwise specified. Replacement of the bearings with a brand or model other than originally installed must be approved by the Government.

The shaft bearings shall be grease lubricated, anti-friction bearings with minimum L-10 life rating of 40,000 hours in accordance with the Anti-Friction Bearing Manufactures' Association (AFBMA) method in determining expected bearing life. Bearings must be able to withstand the loads due to dead weight, unbalance and thrust of rotor assembly. Bearings shall be rated for 24 hour per day continuous duty service.

5.1 **Ball and Roller Bearings:** Ball and roller bearings shall be free from defects or contamination. As a minimum, Annular Bearing Engineers' Committee (ABEC) and Roller Bearing Engineers' Committee (RBEC) Tolerance 1 bearings shall be used unless otherwise specified.

For high speed motors (>1800 RPM) , a bearing with an internal clearance of C3 shall be used.

5.1.1 **Removal and Installation:** Antifriction bearings shall be removed using hydraulic or screw-driven bearing pulling equipment. Removal by hammering is not acceptable.

Bearing condition and fretting patterns shall be noted.

Antifriction bearings shall be installed using an oil bath or induction heater. Bearings shall not be heated to greater than 230^0F.

5.2 **Sleeve Bearings:** Sleeve bearings are to be checked for cracks or babbitt disbonding by performing a dye penetrant test.

5.2.1 **Installation:** Sleeve bearings shall be fitted to the journals using a nondrying bluing compound. A minimum of 80% contact between the babbitt and the shaft journal is required. Vendor to specify the method for determining clearance.

5.3 **Lubricants:** Lubricant will be specified by the Government. Where sealed or shielded bearings are used, the grease fittings shall be removed and noted on the motor data sheet. For motors shipped without sufficient lubricant for industrial operation, attach a red tag labeled "Lubrication Required" to each fill point.

6.0 ELECTRICAL TEST AND INSPECTION

6.1 **Inspection:** Visual inspect the rotor for iron damage, rub marks, and overheating of the rotor bars. Magnetically inspect or Growler test the bars for cracks.

6.2 **Electrical Testing:** Perform the following electrical tests:

6.2.1 **Insulation Resistance:** Apply the following test voltage for one (1) minute:

Rated Motor Voltage	Test Voltage
200-600	1000
2400-4800	2500

Table I – 2. Insulation Resistance Test Voltages

The minimum acceptable insulation resistance, corrected to 40^0C, between the connected leads and the stator is:

Minimum Acceptable = 1M + (Motor Rated Voltage in kV X 1M)

6.2.2 **Polarization Index (PI):** Perform a ten (10) minute polarization index test on the motor by applying a DC voltage equal to the motor nameplate voltage and recording the readings at one(1) and ten (10) minutes. A minimum PI value of 2.0 must be obtained before performing any overvoltage test.

6.2.3 **Overvoltage Testing: DO NOT PERFORM ANY OVERVOLTAGE TEST OF THE MOTOR IF UNSATISFACTORY RESULTS ARE OBTAINED FROM THE INSULATION RESISTANCE OR POLARIZATION INDEX TESTS.** If PI<2.0 contact the Government for additional instructions.

6.2.4 **High DC Potential and Comparative Surge Test:** Perform the tests at the following voltages (2X Rated Voltage +1000V):

Rated Motor Voltage (nominal)	Highpot VDC (10%)	Surge VDC (10%)
460	2000	2000
2300	5600	5600
4000	9000	9000

Table I – 3. Surge and High Potential Voltages

Record leakage current and any indications of turn-to-turn insulation breakdown.

6.2.5 **Phase Imbalance Tests:** The three phases of the motor shall be checked for proper impedance balance by conducting a no-load test and recording the voltage and current of all three phases. A maximum current imbalance of 4% is allowed and shall be calculated as follows:

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

$$Where: \quad I_{avg} = \frac{(I_1 + I_2 + I_3)}{3}$$

6.2.6 Electrically insulated bearings shall be tested using a megohmmeter with an output of <50V. The minimum resistance reading is 50 M .

6.3 Vibration Tests: Vibration data shall be acquired at each bearing location radial to the shaft in the vertical and horizontal planes. In addition, readings shall be taken axial to the shaft at both ends of the motor. The following guidelines and criteria apply to all vibration readings:

6.3.1 Vibration Analyzer: The contractor shall use the type of instrumentation and sensors specified. For example, for a 3,600 RPM machine an accelerometer with a sensitivity of 100 mV/g and a resonant frequency of at least 15,000 Hz is required.

A rare earth super magnet and a sound disc shall be used in conjunction with any vibration data collector which has the following characteristics:

(1) A minimum of 400 lines of resolution.
(2) A dynamic range greater than 70 dB.
(3) A frequency response range of 5Hz-10kHz (300-600,000 cpm).
(4) The capability to perform ensemble averaging.
(5) The use of a hanning window.
(6) Autoranging.

6.3.2 Vibration Data: The vendor shall provide the Government narrowband (400-line) spectral vibration data for all motors as follows:

(1) For machines operating at or below 1,800 RPM, the frequency spectrum provided shall be in the range of 5 to 2,500 Hz.
(2) For machines operating greater than 1,800 RPM, the frequency spectrum provided shall be in the range of 5 to 5,000 Hz.
(3) Two narrowband spectra for each point shall be obtained in the following manner:

(a) 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.
(b) An additional spectrum of 5 to 2,500 or 5 to 5,000 Hz shall be acquired for machines operating at or below 1800 RPM or greater than 1,800 RPM, respectively. This higher frequency range allows early detection of rolling element bearing, gear rotor and stator problems.

(c) Vibration data shall be reported in velocity (inches/second or mm/sec).

(d) The motor shall meet the following applicable vibration criteria:

Motor Speed (RPM)	Special Application		Standard Application	
	(in/sec, Peak)	(mm/sec, Peak)	(in/sec, Peak)	(mm/sec, Peak)
900	0.02	0.5	0.08	2.0
1200	0.026	0.66	0.08	2.0
1800	0.04	1.0	0.08	2.0
3600	0.04	1.0	0.08	2.0

Table I – 4. Motor Balance Specifications

(4) Additional Vibration Criteria. All final testing shall be conducted at normal operating speed under full load conditions.

Frequency (X RPM) Motor Component	Maximum Amplitude (in/sec Peak)	Maximum Amplitude (mm/sec Peak)
Overall	0.10	2.5
0.4 - 0.5	Not detectable	
1X	See Motor Balance Specifications	
2X	0.02	0.5
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	0.5

Table I – 5. Motor Vibration Criteria

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Appendix J—Maintenance Procedures

This appendix provides NASA Maintenance Procedure Templates (called MPTs for short). 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 upon sample procedures provided by several NASA Centers, private industry, and others. 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 deviation when accomplishing. That is not the basis for the NASA MPTs. The procedures were originally developed in a spreadsheet format and were provided to the NASA Centers for use in developing site specific procedures.

The Maintenance Procedure Template

The procedure layout is such that all actions are taken in sequence. A person 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 Centers 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 Centers 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

Multiples of the above are sometimes used and are identified by a number followed by a letter. For example, 5A indicates that the procedure is scheduled every 5 years.

Labor (Hrs) - This information will usually be two numbers. First is number of people, second is estimated time for each person. 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 technician 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 collateral 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.

Table J-1: Sample Procedures

Procedure numbers, listed below, refer to sample procedures in this appendix.

Procedure Number	Machine/System	Procedure Summary
PT&I-0001	Rotating Machinery	Vibration Data Collection
PT&I-0002	Various	Qualitative Infrared Thermography Inspection
PT&I-0003	Motor	Test Insulation
PT&I-0004	Transformer	Test Insulation
PT&I-0005	Circuit Breaker	Test Insulation
PT&I-0006	Oil Filled Transformer	Sample and Test Transformer Oil
PT&I-0007	Transformer	Power Factor Test
PT&I-0008	Electrical Distribution	Power Factor Test
PT&I-0009	Bushing	Power Factor Test
E-0001	Transformer	Inspect and Clean Transformer
E-0002	Battery Bank	Battery Impedance Test
E-0003	Uninterruptible Power Supply	Inspect and Test UPS
E-0004	Electrical Distribution	Inspect and Clean Electrical Panels
E-0005	High/Med Volt Circuit Breaker	Inspect and Test Circuit Breaker
M-0001	Air Handler	Inspect and Clean
M-0002	Chiller	Inspect and Clean

Table J-2 is a sample procedure lay out with a combination of description and sample text.

Table J-2

Block Title	Text
Procedure Number	PT&I-0003 - This procedure number is assigned by the centers 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 Center work control and are used by the CMMS. Sample codes are: D = Daily, W = Weekly, M = Monthly, Q = Quarterly, S = Semi-Annually, A = Annually, 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 Standard, NASA Procedure - Identifies information, such as a test procedure, that the field technician will need in order to perform the task.
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 collateral equipment.
Reserved	This section was reserved for future use by the Centers.
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.
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 when accomplishing. 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

Sample Layout

Sample Layout

	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.
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 person 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 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 J-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 magnet mounted 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.
A2	Record machine operating condition (usually directly into the data collector).
A3	Place magnet mounted 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.

Inspection Data	
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 J-4: Sample Procedure PT&I-0002, Vibration Data Collection

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.
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.

Procedure PT&I-0002

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.
EN1a	See standard 1910.333 for electrical safety including closest approach distances for energized circuits.

Table J-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.
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.

Procedure PT&I-0003

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)
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 J-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.
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.

Procedure PT&I-0004

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.
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)
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)
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
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. Guidelines are from S.D.Myers.
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 J-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.
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	
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 J-8: Sample Procedure PT&I-0006, Oil Filled Transformer 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	
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.

Procedure PT&I-0006

Procedure PT&I-0006

A1	Collect dissolved gas oil sample from transformer. Use 50cc glass syringe and follow procedure in ASTM standard D-3613-92.
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 D-877-87).
B3	Perform Field Acidity Test (ASTM D-1534-90).
B4	Perform Visual Examination (ASTM D-1524-84).
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 or PT&I for analysis.
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 D-1533-88), Acid Number (ASTM D-974-87), and Interfacial Tension (ASTM D- 971-82) test.
EN3	Send 50cc syringe to test lab for gas-in-oil analysis (ASTM D-3613-92)
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 J-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.
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.
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.
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.
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
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.
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 J-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 yr.
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	
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.
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.
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.
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.
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 J-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.
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.
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.
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
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.

Procedure E-0001

Table J-12: Transformer

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
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.
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 .

Procedure E-0002

Table J-13: Battery Bank

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.
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.
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.

Procedure E-0003

Table J-14: Uninterruptible Power Supply

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	
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.
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%
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.

Procedure E-0004

Table J-15: Electrical Distribution

Block Title	Text
Procedure Number	E-0004
System Description	Electrical Distribution
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.
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.
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 J-16: High/Med Volt Circuit Breaker

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).
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.
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 D-877-87).
A17	Perform Field Acidity Test (ASTM D-1534-90).
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.
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.
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.

Procedure M-0001

Table J-17: Air Handler

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)
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).
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 sheeve 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	Perform touchup painting as required.
A14	Perform related tasks, if any.
A15	Replace pulley and belt guards.
A16	Close access covers and doors and return air handler to service.
A17	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 for the proper agents/tablets.
EN2	PT&I group needs to know if belts are changed or aligned.

Procedure M-0002

Table J-18: Chiller

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.
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 group 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.
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.

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Appendix K—SPECSINTACT Clauses with RCM Applications

The following table includes reference numbers, titles, and general RCM application descriptions for clauses where RCM principles have been integrated into the SPECSINTACT. They can be used as a ready reference to access SPECSINTACT for more detail

Clause	Title	General RCM Application
Division I	**General Requirements**	
01450	Quality Control	
1.4.4.2	Inspection and Test Records	Final test reports shall be provided to the Contracting Officer for forwarding to the Systems Engineer/Condition Monitoring Office/Predictive Testing Group for inclusion in the Maintenance Database.
01600	Product Requirements	
2.1	Mechanical Materials and Equipment	Material “cut sheets” and final test data to be forwarded to CM Office/PT&I Group for inclusion in Maintenance database
01750	Starting and Adjusting	
1.3.1	Tests Required	Tests are to be performed on systems including electrical switchgear, protective relaying, fluid and gas systems, pump/motor combinations, boiler systems, hydraulic and pneumatic control, condition/performance monitoring systems, energy control and monitoring systems and other assemblies and components that need to be tested as an interrelated whole.
1.3.2	Factory Tests	Tests shall be performed by the factory to verify proper build. These test results will be used in the "Final Acceptance Test" section to verify no shipping damage and proper installation.
1.3.4	Final Acceptance Test	Final test reports shall be provided to the Contracting Officer for forwarding to the Systems Engineer/Condition Monitoring Office/Predictive Testing Group for inclusion in the Maintenance Database.
01780	Closeout Submittals	

Clause	Title	General RCM Application
1.3	Submittals	Preventative Maintenance and Condition Monitoring (Predictive Testing) and Inspection schedules shall be submitted by the Contractor with instructions that state when systems should be retested.
Division II	Site Work	
02535	Packaged Lift Stations	
1.2	Submittals	Bearings shall be included in manufacturer's catalog data. Preventative Maintenance, Predictive Testing and Inspection procedures for Package Lift Stations shall be submitted. Procedures should include frequency of preventative maintenance, frequency of predictive testing and inspection, adjustment, lubrication, and cleaning necessary to minimize corrective maintenance and repair.
2.11	Balance	Allowable vibration limits shall be in accordance with ISO 1940/1, Table 1.
2.12	Shafts	NOTE: When possible, specify sealed bearings on motors. When properly installed sealed bearings have as long a life as conventional bearings, with almost no maintenance requirements.
2.14	Lubrication	Bearings on vertical-shaft pumps shall be self lubricating, permanently sealed.
Division VII	Thermal & Moisture Protection	
07210	Building Insulation	
3.10.1	Finished-Building Insulation	Following a minimum of 90 days operation (or installation), but no later than one year, the Systems Engineer/Condition Monitoring Office/Predictive Testing Group should inspect the installation using advanced monitoring technologies such as Infrared Imaging or Ultrasonic mapping.
07220	Roof and Deck Insulation	

Clause	Title	General RCM Application
3.3.5	Acceptance	Following a minimum of 90 days operation (or installation), but no later than one year (but prior to the warranty expiration date), the Systems Engineer/Condition Monitoring Office/Predictive Testing Group should inspect the installation using advanced monitoring technologies such as Infrared Imaging or Ultrasonic mapping. Final acceptance will also depend upon providing construction (as built) details to the Contracting Officer Systems Engineer/ Condition Monitoring Office/Predictive Testing Group for inclusion in the Maintenance Database.
07510	Built-up Bituminous Roofing	
3.4.3	Acceptance	Following a minimum of 90 days operation (or installation), but no later than one year (but prior to the warranty expiration date), the Systems Engineer/Condition Monitoring Office/Predictive Testing Group should inspect the installation using advanced monitoring technologies such as Infrared Imaging or Ultrasonic mapping. Final acceptance will also depend upon providing construction (as built) details to the Contracting Officer Systems Engineer/ Condition Monitoring Office/Predictive Testing Group for inclusion in the Maintenance Database.
07511	Built-up Asphalt Roofing	

Clause	Title	General RCM Application
3.4.11	Acceptance	Following a minimum of 90 days operation (or installation), but no later than one year (but prior to the warranty expiration date), the Systems Engineer/Condition Monitoring Office/Predictive Testing Group should inspect the installation using advanced monitoring technologies such as Infrared Imaging or Ultrasonic mapping. Final acceptance will also depend upon providing construction (as built) details to the Contracting Officer Systems Engineer/ Condition Monitoring Office/Predictive Testing Group for inclusion in the Maintenance Database.
07530	Single Ply Membrane Roofing	
3.9	Acceptance	Following a minimum of 90 days operation (or installation), but no later than one year (but prior to the warranty expiration date), the Systems Engineer/Condition Monitoring Office/Predictive Testing Group should inspect the installation using advanced monitoring technologies such as Infrared Imaging or Ultrasonic mapping. Final acceptance will also depend upon providing construction (as built) details to the Contracting Officer.
Division IX	Finishes	
09915	Painting	
---	Intro Note	For harsh indoor environments (any area subjected to chemical and/or abrasive action), and all outdoor installations, reference Section 09960, "High Performance Coatings.”
09960	High Performance Coatings	
---	Intro Note	This section covers special coatings as required for harsh indoor locations or operations (any area subjected to chemical and/or abrasive action), and all outdoor installations.
2.2	Epoxy Coatings	Epoxy resin coatings must be used where surfaces to be coated require high corrosion resistance, chemical resistance, bond strength, UV resistance, and toughness.

Clause	Title	General RCM Application
2.3	Polyurethane Coatings	Polyurethane-based coatings must be used where surfaces to be coated require high abrasion resistance, good flexibility and chemical resistance, UV resistance, and must be a two-part, prepolymer, catalytic-cured resin material
Division XIII	Special Construction	
13960	Carbon Dioxide Extinguishing Systems	
3.2.1	Preliminary Tests	Storage batteries shall be given an impedance test of each cell and the results recorded to be used as baselines. Final Test Reports shall be forwarded to the Systems Engineer/Condition Monitoring Office/Predictive Testing Group for inclusion in the Maintenance Database.
Division IXV	Conveying Systems	
14210	Electric Traction Elevators	
2.3.2	Gears and Bearings	When possible the use of sealed bearings is encouraged. One of the major causes of bearing failures is over lubrication and lubrication contamination. Using sealed bearings helps to eliminate this failure mode.
2.3.5	Hoist Motor	When possible the use of sealed bearings is encouraged. One of the major causes of bearing failures is over lubrication and lubrication contamination. Using sealed bearings helps to eliminate this failure mode.
2.4	Motor-Generator Set	When possible the use of sealed bearings is encouraged. One of the major causes of bearing failures is over lubrication and lubrication contamination. Using sealed bearings helps to eliminate this failure mode.
14240	Hydraulic Elevators	
1.2	Submittals	Submitted test results shall include Hydraulic oil purity tests results.
2.2	Pump	When possible the use of sealed bearings is encouraged. One of the major causes of bearing failures is over lubrication and lubrication contamination. Using sealed bearings helps to eliminate this failure mode.

Clause	Title	General RCM Application
2.3	Motor	When possible the use of sealed bearings is encouraged. One of the major causes of bearing failures is over lubrication and lubrication contamination. Using sealed bearings helps to eliminate this failure mode.
3.2.2	Tests	Hydraulic oil purity test should include measurement of viscosity and ferrographic analysis to insure the oil is free from contaminates.
14600	Hoists and Cranes	
1.9.5	Bearings and Bearing Life	When possible the use of sealed bearings is encouraged. One of the major causes of bearing failures is over lubrication and lubrication contamination. Using sealed bearings helps to eliminate this failure mode.
2.5.8	Motor Bearings	When possible the use of sealed bearings is encouraged. One of the major causes of bearing failures is over lubrication and lubrication contamination. Using sealed bearings helps to eliminate this failure mode.
2.5.12	Motor Controller	Ability to open and/or remove access covers is required for maintenance activities. In addition, access may be required to inspect this device while circuits are energized (for example, using infrared imaging). Minimum distances to energized circuits is specified in OSHA Standards Part 1910.333 (Electrical - Safety-Related work practices).
3.8	Crane Electrification System Factory Tests	Certification test reports shall be provided to the Contracting Officer for forwarding to the Systems Engineer/Condition Monitoring Office/Predictive Testing Group for inclusion in the Maintenance Database.
3.9	On-Site Complex Electrification System Tests	Final test reports shall be provided to the Contracting Officer for forwarding to the Systems Engineer/Condition Monitoring Office/Predictive Testing Group for inclusion in the Maintenance Database.
14920	Monorail System	

Clause	Title	General RCM Application
2.16.4	Hoist Motors	When possible the use of sealed bearings is encouraged. One of the major causes of bearing failures is over lubrication and lubrication contamination. Using sealed bearings helps to eliminate this failure mode.
2.16.6	Motor Bearings	When possible the use of sealed bearings is encouraged. One of the major causes of bearing failures is over lubrication and lubrication contamination. Using sealed bearings helps to eliminate this failure mode.
2.16.7	Motor Controller	NOTE: Ability to open and/or remove access covers is required for maintenance activities. In addition, access may be required to inspect this device while circuits are energized (for example, using infrared imaging). Minimum distances to energized circuits is specified in OSHA Standards Part 1910.333 (Electrical - Safety-Related work practices).
Division XV	Mechanical	
15003	General Mechanical Provisions	
1.7	Prevention Of Corrosion	For all outdoor applications and all indoor applications in a harsh environment refer to Section 09960, "High Performance Coatings."
2.4	Painting	For all outdoor applications and all indoor applications in a harsh environment refer to Section 09960, "High Performance Coatings."
3.1	Installation	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 visible by people in the area.
3.2	Equipment Pads	Equipment bases and foundations, when constructed of concrete or grout, shall cure a minimum of 28 or 14 days as specified before being loaded.
15083	Duct Insulation	
3.1	Installation of Insulation Systems	Insulation shall not impede access to duct covers/doors used for duct cleaning and/or maintenance.

Clause	Title	General RCM Application
3.3	Acceptance	Following a minimum of 90 days operation (or installation), but no later than one year (but prior to the warranty expiration date), the Systems Engineer/Condition Monitoring Office/Predictive Testing Group should inspect the installation using advanced monitoring technologies such as Infrared Imaging or Ultrasonic mapping. Final acceptance will also depend upon providing construction (as built) details to the Contracting Officer for forwarding to the Systems Engineer/Condition Monitoring Office/Predictive Testing Group for inclusion in the Maintenance Database..
15085	Piping Insulation	
3.3	Acceptance	Following a minimum of 90 days operation (or installation), but no later than one year (but prior to the warranty expiration date), the Systems Engineer/Condition Monitoring Office/Predictive Testing Group should inspect the installation using advanced monitoring technologies such as Infrared Imaging or Ultrasonic mapping. Final acceptance will also depend upon providing construction (as built) details to the Contracting Officer for forwarding to the Systems Engineer/Condition Monitoring Office/Predictive Testing Group for inclusion in the Maintenance Database..
15135	Centrifugal Pumps	
2.1.5	Balancing	Pump impeller assemblies shall be statically and dynamically balanced to ISO 1940/1-1986, G6.3, G2.5, or G1.0 as specified.
2.1.11	Bearings and Lubrication	Double-row ball or roller bearings for engineered-quality pumps shall shall have an L-10 rated life of not less than 30,000, 50,000, or 80,000 hours as specified. Bearings shall be permanently lubricated sealed bearings.
2.2.4	Balancing	Pump impeller assemblies shall be statically and dynamically balanced to ISO 1940/1-1986, G6.3, G2.5, or G1.0 as specified.

Clause	Title	General RCM Application
2.2.9	Bearings And Lubrication	Bearings shall be heavy-duty ball or roller type and shall have an L-10 rated life of not less than 30,000, 50,000, or 80,000 hours as specified. Bearings shall be permanently lubricated sealed bearings.
3.2	Grouting	Grout shall cure a minimum of 28 days or as specified before being loaded.
3.4	Alignment	Provides pump and driver minimum alignment specifications and doweling requirements.
3.6	Pump Acceptance	Prior to pump final acceptance vibration analysis shall verify pump conformance to specifications. Final test reports shall be provided to the Contracting Officer for forwarding to the Systems Engineer/Condition Monitoring Office/Predictive Testing Group for inclusion in the Maintenance Database.
15186	Condensate Pumps	
1.2	Submittals	Test Reports for condensate pumps shall consist of Pump Flow Capacity Tests in accordance with the paragraph entitled, "Testing," of this section, Efficiency Tests and Vibration Tests.
2.1.1	Pumps	When pump is operating at its worst hydraulic condition vibration readings shall conform to ISO 1940/1, G6.3, G2.5, or G1.0 as specified.
3.1	Installation	Pump and driver alignment specifications are given based on the motor nominal operating speed.
3.2.2	Acceptance Testing	Pump shall be operated and the demonstration shall verify that the pump is non-over loading at any operating point and that the flow capacity is as specified. Final test reports shall be provided to the Contracting Officer for forwarding to the Systems Engineer/ Condition Monitoring Office/Predictive Testing Group for inclusion in the Maintenance Database.
15445	Sump Pumps	

Clause	Title	General RCM Application
2	Products	Pump and Motor vibration levels shall conform to ISO Std. 1940/1 - (1986) Balance Quality Requirements of Rigid Rotors - Determination of Permissible Residual Unbalance unless otherwise noted. Motor vibration levels shall conform to NEMA Specification MG-1, Motors and Generators, Part 7 unless otherwise noted.
2.1.6	Bearings and Lubrication	Bearings shall be sealed and grease-lubricated and shall have an L-10 rating of not less than 80,000 hours in accordance with AFBMA 9 or AFBMA 11.
3.1.1	Alignment	
3.2.2	Pump Acceptance	Prior to final acceptance, pump conformance manufacturer's specifications shall be demonstrated by checking vibration with specified vibrometer while the pump is operating against shutoff head, i.e., with discharge valve closed. Final test reports shall be provided to the Contracting Officer for forwarding to the Systems Engineer/Condition Monitoring Office/Predictive Testing Group for inclusion in the Maintenance Database.
15510	Boilers	
3.4	Final Acceptance	Following a minimum of 90 days operation (or installation), but no later than one year (but prior to the warranty expiration date), the Systems Engineer/Condition Monitoring Office/Predictive Testing Group should inspect the installation using advanced monitoring technologies such as Infrared Imaging or Ultrasonic detection. Final test reports shall be provided to the Contracting Officer for forwarding to the Systems Engineer/Condition Monitoring Office/Predictive Testing Group for inclusion in the Maintenance Database.
15610	Refrigeration Compressors	

Clause	Title	General RCM Application
2	Products	Pump and Motor vibration levels shall conform to ISO Std. 1940/1 - (1986) Balance Quality Requirements of Rigid Rotors - Determination of Permissible Residual Unbalance unless otherwise noted. Motor vibration levels shall conform to NEMA Specification MG-1, Motors and Generators, Part 7 unless otherwise noted.
2.1.2	Compressor	Rotating parts shall be statically and dynamically balanced at the factory to ISO 1940/1 1986, G6.3, G2.5, or G1.0 as specified to eliminate vibration.
3.2.1	Vibration	Specifies the type and characteristics of the vibration analyzer the Contractor shall use. Final test reports shall be provided to the Contracting Officer for forwarding to the Systems Engineer/Condition Monitoring Office/Predictive Testing Group for inclusion in the Maintenance Database.
15625	Chilled Water Air Conditioning	
2.2.1	Centrifugal Fan	Fan and Motor balance shall conform to ISO Std. 1940/1 - (1986) Balance Quality Requirements of Rigid Rotors - Determination of Permissible Residual Unbalance unless otherwise noted. Motor vibration levels shall conform to NEMA Specification MG-1, Motors and Generators, Part 7 unless otherwise noted. When possible the use of sealed bearings is encouraged. Fans driven by motors rated over 7.5 HP [5.6 KW] shall be furnished with access doors and other provisions necessary to permit field balancing of the rotating elements, addition of corrective weights, and measurement of residual unbalance. Bearings shall have an L-10 rated life of not less than 30,000, 50,000 or 80,000 hours as specified in accordance with AFBMA 9 or AFBMA 11. Removable metal guard and adjustable rail specifications are provided.
2.2.5	Electrical Requirements	Ability to open and/or remove access covers is required for maintenance activities.

Clause	Title	General RCM Application
3.8	Acceptance Tests	Specifies the type and characteristics of the vibration analyzer the Contractor shall use. Final test reports shall be provided to the Contracting Officer and forwarded to the Systems Engineer/Condition Monitoring Office/Predictive Testing Group for inclusion in the Maintenance Database.
15626	Centrifugal Water Chillers	
2	Products	Provides pump and motor balance and vibration level specifications.
2.2	Compressor	Rotor assembly shall be statically and dynamically balanced to ISO 1941/1-1986, G6.3, G2.5, or G1.0 as specified.
2.7	Motors	Hermetically sealed motors shall conform to NEMA MG-1, ARI 520 and to requirements for motors as specified. Bearings shall be oil-lubricated, replaceable-sleeve, insertable type permanently lubricated, rolling element type.
3.4	Alignment	Provides pump and driver alignment specifications.
3.5	Field Testing	Prior to final acceptance, vibration analysis shall verify pump and motor conformance to specifications. Final test reports shall be provided to the Contracting Officer for forwarding to the Systems Engineer/Condition Monitoring Office/Predictive Testing Group for inclusion in the Maintenance Database.
15627	Reciprocating Water Chillers	
2	Products	Provides pump and motor balance and vibration level specifications.
2.3.1	Compressor	Rotating parts shall be statically and dynamically balanced to ISO 1940/1-1986, G16, or G6.3 as specified.
15675	Air-cooled Condensers	
2	Products	Provides pump and motor balance and vibration level specifications.
2.2	Fans and Drives	Fans shall be statically and dynamically balanced to ISO 1940/1-1986, G6.3 or G2.5 as specified. Bearings shall be permanently lubricated sealed bearings.
15700	HVAC Systems	
2	Products	Provides pump and motor balance and vibration level specifications.

Clause	Title	General RCM Application
2.7	Insulation	Insulation shall not impede access to duct covers/door used for duct cleaning and/or maintenance.
2.11.3.1	Fans and Drives	Fans shall be statically and dynamically balanced to ISO 1940/1 1986, G6.3, G2,5,or G1,0 as specified. Bearings shall be sealed against moisture and dirt, prelubricated, and suitable for not less than 10,000 operating hours without need of re-lubrication. Bearings shall be permanently lubricated sealed bearings.
2.13.7.5	Propellers and Motors	Propellers shall be dynamically balanced to ISO 1940/1-1986, G6.3, G2.5, or G1.0 as specified.
2.13.8.2	Fan and Drive Assembly	Fan and Rotating elements shall be statically and dynamically balanced to ISO 1940/1-1986, G6.3,.G2.5, or G1.0 as specified.
2.15	Air Handling Units (Factory Assembled)	Fan wheels shall be statically and dynamically balanced to ISO 1940/1-1986, G6.3, G2.5, or G1.0 as specified.
3.9	Air-Handling Systems Testing	The Systems Engineer/Condition Monitoring Office/Predictive Testing Group should inspect the installation during acceptance testing using advanced monitoring technologies such as Infrared Imaging or Ultrasonic Listening.
3.10	Refrigeration Systems Testing	The Systems Engineer/Condition Monitoring Office/Predictive Testing Group should inspect the installation during acceptance testing using advanced monitoring technologies such as Infrared Imaging or Ultrasonic Listening.
3.11	Air And Hydronic Systems Testing, And Adjustment	The Systems Engineer/Condition Monitoring Office/Predictive Testing Group should inspect the installation during acceptance testing using advanced monitoring technologies such as Infrared Imaging or Ultrasonic Listening.

Clause	Title	General RCM Application
3.12	Steam And Condensate Systems Testing	The Systems Engineer/Condition Monitoring Office/Predictive Testing Group should inspect the installation during acceptance testing using advanced monitoring technologies such as Infrared Imaging or Ultrasonic Listening.
3.13.1	Alignment	Added section to provide alignment directions and specifications.
3.13.2	Vibration Analyzer	Added section to provide vibration analyzer specifications.
3.13.3	Acceptance Tests	Added section to provide acceptance test requirements.
3.13.4	Test Records	Final test reports shall be provided to the Contracting Officer and forwarded to the Systems Engineer/Condition Monitoring Office/Predictive Testing Group for inclusion in the Maintenance Database.
15720	Air Handling Units	
1.2	General Requirements	Fan and motor balance shall conform to ISO Std. 1940/1 - (1986) Balance Quality Requirements of Rigid Rotors - Determination of Permissible Residual Unbalance unless otherwise noted. Motor vibration levels shall conform to NEMA Specification MG-1, Motors and Generators, Part 7 unless otherwise noted.
2.1	Air Handling Unit	AHU fan and motor shall be balanced to ISO 1940/1-1986, G6.3, G2.5, or G1.0 as specified.
3.2	Vibration Analyzer	Added section to provide vibration analyzer specifications.
3.3	Acceptance Tests	Added section to provide acceptance test requirements.
3.4	AHU TESTING	Final test reports shall be provided to the Contracting Officer for forwarding to the Systems Engineer/Condition Monitoring Office/Predictive Testing Group for inclusion in the Maintenance Database.
15725	Air Handling	

Clause	Title	General RCM Application
2.1	General Fan Requirements	Fan and motor balance shall conform to ISO Std. 1940/1 - (1986) Balance Quality Requirements of Rigid Rotors - Determination of Permissible Residual Unbalance unless otherwise noted. Motor vibration levels shall conform to NEMA Specification MG-1, Motors and Generators, Part 7 unless otherwise noted.
2.1.1	General	Dynamically balance at the factory to ISO 1940/1-1986, G6.3, G2.5 or G1.0 as specified.
2.1.2	Bearings	When possible the use of sealed bearings is encouraged. Bearings shall have a certified AFBMA 9 or AFBMA 11, L-10 minimum life expectancy rating of 30,000, 40,000, 50,000, 80,000 hours as specified under load conditions the service will impose.
2.3.3	Fan Wheel	Wheel shall be statically and dynamically balanced to ISO 1940/1-1986, G6,3, G2.5, or G1.0.
2.3.4		
2.3.5		
2.4.3	Fan Wheel	Wheel shall be statically and dynamically balanced to ISO 1940/1-1986, G6,3, G2.5, or G1.0 as specified.
2.5.3	Fan Wheel	Wheels shall be statically and dynamically balanced to ISO 1940/1-1986, G6,3, G2.5, or G1.0 as specified.
3.2	Vibration Analyzer	Added section to provide vibration analyzer specifications.
3.3	Acceptance	Added section to provide acceptance test requirements.
15736	Computer Room Air Conditioning Units	
2.1	General	Fan and motor balance shall conform to ISO Std. 1940/1 - (1986) Balance Quality Requirements of Rigid Rotors - Determination of Permissible Residual Unbalance unless otherwise noted. Motor vibration levels shall conform to NEMA Specification MG-1, Motors and Generators, Part 7 unless otherwise noted.
2.10	Compressors	Compressor[s] shall be balanced to ISO 1940/1-1986, G6,3, G2.5 or G1.0 as specified.

Clause	Title	General RCM Application
3.5.1	Vibration Analyzer	Added section to provide vibration analyzer specifications.
3.5.2	Acceptance	Added section to provide acceptance test requirements.
15740	Heat Pumps	
2.2.3	Electrical Requirements	All motors shall have copper windings, be equipped with heavy duty ball bearings sealed permanently lubricated bearings.
3.4	Insulation	Insulation shall not impede access to duct covers/doors used for duct cleaning and/or maintenance.
3.7	Tests	The Systems Engineer/Condition Monitoring Office/Predictive Testing Group should inspect the installation during acceptance testing using advanced monitoring technologies such as Infrared Imaging or Ultrasonic Listening. Final test reports shall be provided to the Contracting Officer for forwarding to the Systems Engineer/Condition Monitoring Office/Predictive Testing Group for inclusion in the Maintenance Database.
15762	Air Coils	
3.2	Tests	The Systems Engineer/Condition Monitoring Office/Predictive Testing Group should inspect the installation during acceptance testing using advanced monitoring technologies such as Infrared Imaging or Ultrasonic Listening. Final test reports shall be provided to the Contracting Officer for forwarding to the Systems Engineer/Condition Monitoring Office/Predictive Testing Group for inclusion in the Maintenance Database."
15764	Fan-coil Units	
2.1	General	Fan and motor balance shall conform to ISO Std. 1940/1 - (1986) Balance Quality Requirements of Rigid Rotors - Determination of Permissible Residual Unbalance unless otherwise noted. Motor vibration levels shall conform to NEMA Specification MG-1, Motors and Generators, Part 7 unless otherwise noted. NOTE: When possible the use of sealed bearings is encouraged.

Clause	Title	General RCM Application
2.4	Fan	Fan shall be balanced dynamically and statically to ISO Std. 1940/1 at the factory, after assembly in unit.
3.3		
3.4		
15766	Unit Heaters	
1.1		
1.3		
2	Products	When possible the use of sealed bearings is encouraged. Provides fan and motor balance and vibration level specifications.
15838	Power Ventilators	
2.3	Fan Type(s)	When possible the use of sealed bearings is encouraged.
2.5	Fan Motor	When possible the use of sealed bearings is encouraged.
3.3	Acceptance	Added section to provide acceptance test requirements.
3.3	Lubrication	Movable parts of dampers and related operating hardware shall be lubricated in accordance with manufacturer's printed instructions and shall operate smoothly and quietly without binding.
3.4	Final Test Reports	Final test reports shall be provided to the Contracting Officer for forwarding to the Systems Engineer/Condition Monitoring Office/Predictive Testing Group for inclusion in the Maintenance Database.
15902	Control systems	
2.8.2	Bearings	When possible the use of sealed bearings is encouraged.
2.11	Individual System Control Panels	Ability to open and/or remove access covers is required for maintenance activities. In addition, access may be required to inspect this device while circuits are energized (for example, using infrared imaging). Minimum distances to energized circuits is specified in OSHA Standards Part 1910.333 (Electrical - Safety-Related work practices).

Clause	Title	General RCM Application
3.5	Testing, Calibration, and Acceptance	The Systems Engineer/Condition Monitoring Office/Predictive Testing Group should inspect the installation during acceptance testing using advanced monitoring technologies such as Infrared Imaging or Ultrasonic Listening.
3.8		
15950	Testing and Balancing	
3	Execution	The Systems Engineer/Condition Monitoring Office/Predictive Testing Group should inspect the installation during acceptance testing using advanced monitoring technologies such as Infrared Imaging or Ultrasonic Listening.
3.3.7		
3.7	Test Reports	Final test reports shall be provided to the Contracting Officer for forwarding to the Systems Engineer/Condition Monitoring Office/Predictive Testing Group for inclusion in the Maintenance Database.
Division XVI	Electrical	
16003	General Electrical Provisions	
1.7	Prevention Of Corrosion	For all outdoor applications and all indoor applications in a harsh environment refer to Section 09960, "High Performance Coatings." Metallic materials shall be protected against corrosion. Equipment enclosures shall be given a rust-inhibiting treatment and the standard finish by the manufacturer when used for most indoor installations.
2.5	Painting	Refer to Section 09960, "High Performance Coatings," for requirements outdoors or in harsh environments.
16050	Basic Electrical Materials and Methods	
1.3	Prevention Of Corrosion	For all outdoor applications and all indoor applications in a harsh environment refer to Section 09960, "High Performance Coatings." Metallic materials shall be protected against corrosion. Equipment enclosures shall have the standard finish by the manufacturer when used for most indoor installations.

Clause	Title	General RCM Application
3.7	Panelboards	Ability to remove access covers is required for maintenance activities. No equipment shall be mounted within 36 inches of the front of the panel.
3.8	Dry-Type Distribution Transformers	Ability to remove access covers is required for maintenance activities. Minimum distances to energized circuits is specified.
3.10	Painting	Section 09960, "High Performance Coatings" was added to the specifications.
3.11	Field Testing	Adds final acceptance wire, cable and transformer inspection specifications. Final test data shall be provided to the Contracting Officer for forwarding to the Systems Engineer/Condition Monitoring Office/Predictive Testing Group for inclusion in the Maintenance Database.
16124	Medium Voltage Cables	
2.4	Multiple-Conductor Shielded Cables	Cross-linked polyethylene insulation has been shown to tree when installed in wet environments. Also added additional cables to recommended list.
3.2	Field Testing	Added testing specifications including radiographic tests of potheads at the discretion of the Contracting Officer. Final test reports shall be provided to the Contracting Officer for forwarding to the Systems Engineer/ Condition Monitoring Office/Predictive Testing Group for inclusion in the Maintenance Database.
16125	Motors	
1.3	Submittals	Data for electric motors rated over 20hp and those specified to meet a special vibration class in accordance with NEMA MG 1 indicate number of: Rotor Bars, Stator Slots, rotational Speed, Cooling Fan Blades Bearing Manufacturer, Bearing Style, Bearing Type, Balls/Elements, Commutator Bars, Communtator Brushes Firing Frequencies (for variable speed motors).

Clause	Title	General RCM Application
2.1	Equipment	Design, fabrication, testing, and performance of motors shall be in accordance with NEMA MG 1 and ISO 1940/1. Testing and performance of polyphase induction motors shall be in accordance with IEEE Std 112, Method B. Efficiency labeling shall be in accordance with NEMA MG 1. Allowable vibration limits shall be in accordance with ISO 1940/1, Table 1.
3.2	Site Testing	Added additional testing specifications and that final test data shall be forwarded to the responsible systems engineer for inclusion in the Predictive Maintenance Program/ Database.
16275	Transformers	
1.3	Submittals	Test Report submittals for the following test were added: Power Factor Tests, Insulation Resistance Tests, and Insulation Power Factor(Doble) Tests.
1.4	Qualification Testing	Transformer manufacturer's standard tests were expanded to include; insulation power factor (Doble) tests, insulation oil tests, and dielectric tests. For oil-filled units manufacturer shall certify that the oil contains no PCB's and shall affix a label to that effect on the transformer tank and on each oil drum containing the insulating oil.
2.2	Factory Finish	For all outdoor applications and all indoor applications in a harsh environment refer to Section 09960, "High Performance Coatings."
3.2	Field Testing	For transformers rated under 100KVA and less than 4160 Volts on both primary and secondaries power factor testing is an optional acceptance test. Transformers shall be tested in accordance with IEEE Std. 62.
3.2.1.1	Dielelectric Tests	Liquid filled transformers shall have the insulating liquid dielectrically tested after installation and before being energized. Insulating liquid shall be tested in accordance with ASTM D 877, and breakdown voltage shall be not less than 2, 5, or 8,000 volts as specified.

Clause	Title	General RCM Application
3.2.1.2	Power Factor Tests	Liquid filled transformers shall have the oil power factored at 20 degrees C, per ASTM D 924 prior to being energized. Results shall not be greater than 0.5 percent at 20 degrees C.
3.2.2	Insulation-Resistance Tests	Added additional test specifications
3.2.3	Insulation Power Factor (Doble) Tests	Transformer windings shall be given an insulation power factor test and winding excitation test in accordance with ANSI IEEE C57.12.90. Insulation power factor shall not exceed 0.5 percent for new liquid filled units. New dry type units can have power factors up to 5.0 percent and still be acceptable.
3.2.4	Acceptance	Final test reports shall be provided to the Contracting Officer for forwarding to the Systems Engineer/Condition Monitoring Office/Predictive Testing Group for inclusion in the Maintenance Database.
16276	Medium Voltage Transformers	
1.4	Qualification Testing	Added oil condition (acidity, water, power factor, dissolved gas, and dielectric), and the insulation power factor test (Doble Test). Maximum acceptable insulation power factor test value is 5 percent. Tests shall be conducted in accordance with IEEE C57.12.90, IEEE Std. 62, ASTM D 3612, and ASTM D 3487. Manufacturer shall certify that insulating oil contains no PCB's and shall affix a label to that effect on the transformer tank and on each oil drum containing the insulating oil.
2.8	Coils	For transformers to be installed in high fault current areas aluminum and sheet windings should be avoided.
2.11	Insulating Oil	Neutralization Number shall not be greater than .03 gm KOH/ml when measured in accordance with ASTM D 974. Emulsified water shall not exceed 25ppm at 20 degrees C. When measured in accordance with ASTM D 1533. Power factor shall not exceed .5 percent at 20 degrees C when measured in accordance with ASTM D 924.

Clause	Title	General RCM Application
2.13	Painting	For all outdoor applications and all indoor applications in a harsh environment refer to Section 09960, "High Performance Coatings." After fabrication, all exposed ferrous metal surfaces of the transformer and component equipment shall be cleaned and painted.
3.2	Field Testing	Upon satisfactory completion of the insulation resistance test the transformer windings shall be given an insulation power factor test and an excitation test. Added oil tests to be performed after electrical tests of the transformer. Transformer shall not be energized until recorded test data have been approved by the Contracting Officer. Final test reports shall be provided to the Contracting Officer for forwarding to the Systems Engineer/Condition Monitoring Office/Predictive Testing Group for inclusion in the Maintenance Database.
16285	Medium Voltage Power Factor Correction	
1.2	Submittals	Added report on Capacitance Value Tests.
2.4	Prevention of Corrosion	Section on corrosion prevention (painting) of capacitor equipment was added.
3.2	Field Testing	Additional high-voltage capacitor equipment test specifications were added. Final test reports shall be provided to the Contracting Officer for forwarding to the Systems Engineer/Condition Monitoring Office/Predictive Testing Group for inclusion in the Maintenance Database.
16286	Overcurrent Protective Devices	
1.2	Submittals	Factory Test Reports shall be submitted for Power, High Voltage, and Oil Circuit Breakers in accordance with ANSI C37.09 and shall include the following: Dielectric Tests, Bushing Tests, Insulating Oil Tests, Timing Tests, and Insulation Power Factor tests.

Clause	Title	General RCM Application
2.4.5	Oil Circuit Breakers	Oil for oil circuit breakers shall conform to ASTM D 3487. Oil circuit breakers shall be factory tested in accordance with ANSI C37.09.
2.12	Finish	For all outdoor applications and all indoor applications in a harsh environment refer to Section 09960, "High Performance Coatings."
3.2	Field Testing	Additional equipment test specifications were added. Final test reports shall be provided to the Contracting Officer for forwarding to the Systems Engineer/Condition Monitoring Office/Predictive Testing Group for inclusion in the Maintenance Database.
16325	Load Break Switches	
3.1	Installation	Final switch acceptance specifications were added.
16326	Air-Break Switches	
3.1	Installation	Final switch acceptance specifications were added.
16327	Oil Switches	
2.2	Accessories	For all outdoor applications and all indoor applications in a harsh environment refer to Section 09960, "High Performance Coatings."
3.3	Field Testing	Load break switch assembly insulation-resistance test was changed from 2500V to 5000V.
3.4	Inspection	Final test reports shall be provided to the Contracting Officer for forwarding to the Systems Engineer/Condition Monitoring Office/Predictive Testing Group for inclusion in the Maintenance Database.
16328	Load Break SF6 Gas Switches	
2.6	Factory Finish	For all outdoor applications and all indoor applications in a harsh environment refer to Section 09960, "High Performance Coatings."
3.3	Field Testing	Provides additional field test specifications. Final test reports shall be provided to the Contracting Officer for forwarding to the Systems Engineer/Condition Monitoring Office/Predictive Testing Group for inclusion in the Maintenance Database.
16345	Motor Control	

Clause	Title	General RCM Application
2.3	Construction	Access is required to inspect the motor control center while circuits are energized (for example, using infrared imaging). Minimum distances to energized circuits is specified in OSHA Standards Part 1910.333 (Electrical - Safety-Related work practices).
3.2	Field Testing	Provides additional field test specifications. Final test reports shall be provided to the Contracting Officer for forwarding to the Systems Engineer/Condition Monitoring Office/Predictive Testing Group for inclusion in the Maintenance Database.
16365	Primary Unit Substation	
1.3	Submittals	Power Transformers, Transformer Tanks, Bushings, Transformer Cores, and Transformer Coils were added to Manufacturer's Catalog Data requirements. Power Transformers, Transformer Tanks, Bushings, Transformer Cores, and Transformer Coils were added to fabrication drawings to be submitted. The following were added to test reports : Insulation Power Factor Tests, Oil Power Factor Tests, Oil Acidity Tests, Water-in-oil (Karl Fischer) Tests, Dissolved Gas Analysis, Sound Tests, Impulse Tests, Short Circuit Tests, and Bushing Tests.
2.1	Equipment Standards	ANSI C37.121 was added to standards.
2.4.1	Transformers	For transformers to be installed in high fault current areas aluminum and sheet windings should be avoided. Transformer oil neutralization Number shall not be greater than .03 gm KOH/ml when measured in accordance with ASTM D 974. Emulsified water shall not exceed 25 ppm at 20 degrees C, when measured in accordance with ASTM D 1533. Power factor shall not exceed 0.5 percent at 20 degrees C when measured in accordance with ASTM D 924. The manufacturer shall certify that the oil contains no PCB's and shall affix a label to that effect on the transformer tank and on each oil drum containing the insulating oil.

Clause	Title	General RCM Application
2.5.1	Switchgear And Auxiliary Equipment Compartments	Ability to remove access covers is required for maintenance activities. In addition, access may be required to inspect these devices while circuits are energized (for example, using infrared imaging). Minimum distances to energized circuits is specified in OSHA Standards Part 1910.333 (Electrical - Safety-Related work practices).
2.11		
2.11.2	Shop Finishing	For all outdoor applications and all indoor applications in a harsh environment refer to Section 09960, "High Performance Coatings."
3.2	Field Testing	The following transformer tests were added: Insulation Power Factor Tests Winding Excitation Tests Insulating Oil Tests Transformer windings and the main bus of primary-unit substations shall be subjected to insulation-resistance and insulation power factor test.
16366	Secondary Unit Substation	
2.3.1	Switchgear and Auxiliary Equipment Compartments	Ability to open access covers is required for maintenance activities. In addition, access may be required to inspect this device while circuits are energized (for example, using infrared imaging). Minimum distances to energized circuits is specified in OSHA Standards Part 1910.333 (Electrical - Safety-Related work practices).
2.4.1	Transformers, Outdoor	Added the following to transformer oil specifications: Neutralization Number shall not be greater than .03 gm KOH/ml when measured in accordance with ASTM D 974. Emulsified water shall not exceed 25 ppm at 20 degrees C, when measured in accordance with ASTM D 1533. Power factor shall not exceed 0.5 percent at 20 degrees C when measured in accordance with ASTM D 924.

Clause	Title	General RCM Application
2.5.1	Switchgear and Auxiliary Equipment Compartments	Ability to open access covers is required for maintenance activities. In addition, access may be required to inspect this device while circuits are energized (for example, using infrared imaging). Minimum distances to energized circuits is specified in OSHA Standards Part 1910.333 (Electrical - Safety-Related work practices).
2.6.3		
2.12	Painting	For all outdoor applications and all indoor applications in a harsh environment refer to Section 09960, "High Performance Coatings."
3.1		
3.2	Field Testing	A number of transformer tests were added Final test data shall be provided to the Contracting Officer for forwarding to the Systems Engineer/Condition Monitoring Office/Predictive Testing Group for inclusion in the Maintenance Database.
16445	Switchgear Assemblies	
1.6.1		
2.2.1	Switchgear and Auxiliary Compartments	Ability to remove access covers is required for maintenance activities. In addition, access may be required to inspect this device while circuits are energized (for example, using infrared imaging). Minimum distances to energized circuits is specified in OSHA Standards Part 1910.333 (Electrical - Safety-Related work practices).
2.5	Painting	For all outdoor applications and all indoor applications in a harsh environment refer to Section 09960, "High Performance Coatings."
3.2	Field Testing	Final test data shall be provided to the Contracting Officer for forwarding to the Systems Engineer/Condition Monitoring Office/Predictive Testing Group for inclusion in the Maintenance Database.
3.5	Energizing Switchgear Assemblies	Final test data shall be provided to the Contracting Officer for forwarding to the Systems Engineer/Condition Monitoring Office/Predictive Testing Group for inclusion in the Maintenance Database.