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US Army Corps
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Construction Engineering
Research Laboratories

CERL Technical Report 99/41
April 1999

Reliability Centered Maintenance (RCM) Guide

Operating a More Effective Maintenance Program

Alan Chalifoux and Joyce Baird

This manual outlines a comprehensive method of organizing an efficient maintenance program by applying the concepts of Reliability Centered Maintenance (RCM). RCM combines professional intuition and a rigorous statistical approach, and recognizes that different maintenance strategies apply to different facility equipment: run-to-failure, preventive, predictive, and proactive maintenance. The RCM approach applies these differing maintenance strategies in an optimal mix, to ensure that facility equipment is maintained sufficient to accomplish the facility mission without wasting maintenance labor. This guide is meant to help maintenance supervisors, managers, and technicians organize and operate an efficient and effective maintenance program in an environment of maintenance budget cutbacks.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of Information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave Blank)

2. REPORT DATE
April 1999

3. REPORT TYPE AND DATES COVERED
Final

4. TITLE AND SUBTITLE
Reliability Centered Maintenance (RCM) Guide: Operating a More Effective Maintenance Program

5. FUNDING NUMBERS
4A162720
D048
Y67

6. AUTHOR(S)
Alan Chalifoux and Joyce Baird

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Construction Engineering Research Laboratory (CERL)
P.O. Box 9005
Champaign, IL 61826-9005

8. PEFORMING ORGANIZATION REPORT NUMBER
TR 99/41

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Madigan Army Medical Center
ATTN: MAMC-FMD
Tacoma, WA 98431

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

9. SUPPLEMENTARY NOTES
Copies are available from the National Technical Information Service, 5385 Port Royal Road, Springfield, VA 22161

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This manual outlines a comprehensive method of organizing an efficient maintenance program by applying the concepts of Reliability Centered Maintenance (RCM). RCM combines professional intuition and a rigorous statistical approach, and recognizes that different maintenance strategies apply to different facility equipment: run-to-failure, preventive, predictive, and proactive maintenance. The RCM approach applies these differing maintenance strategies in an optimal mix, to ensure that facility equipment is maintained sufficient to accomplish the facility mission without wasting maintenance labor. This guide is meant to help maintenance supervisors, managers, and technicians organize and operate an efficient and effective maintenance program in an environment of maintenance budget cutbacks.

14. SUBJECT TERMS
Madigan Army Medical Center (MAMC)
equipment managment
maintenance and repair

15. NUMBER OF PAGES
104

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. SECURITY CLASSIFICATION OF ASTRACT
Unclassified

20. LIMITATION OF ABSTRACT
SAR

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std 239-18
298-102

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Executive Summary

Maintenance management is a complicated business. Facility maintenance budgets are continually scrutinized by fiscal managers in a constant effort to trim dollars. Maintenance managers are under constant pressure to squeeze every last bit of productivity out of every maintenance dollar.

This manual outlines a comprehensive method of organizing an efficient maintenance program through applying the concepts of Reliability Centered Maintenance (RCM). Combining professional intuition and a rigorous statistical approach, RCM recognizes that there are different maintenance strategies followed for different facility equipment: run-to-failure, preventive maintenance, predictive maintenance, and proactive maintenance. The RCM approach applies these differing maintenance strategies in an *optimal mix*, to ensure that facility equipment is being maintained sufficiently to accomplish the facility mission without wasting inordinate amounts of maintenance labor "baby sitting" facility equipment.

This manual presents the RCM approach for maintenance supervisors, managers, and technicians to use as a guide in organizing and operating a tight, cost-effective, "lean and mean" maintenance program in light of and in spite of the continual cutbacks in maintenance budgets.

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Foreword

This study was conducted for the Facilities Management Division (EMD) at Madigan Army Medical Center (MAMC) under Project 4A162720D048, "Industrial Operations Pollution Control Technology."; Work Unit Y67, "Reliability Centered Maintenance." The technical monitor was Michael Carico, MAMC-FMD.

The work was performed by the Environmental Processes Branch (CN-E), of the Installations Division (CN), U.S. Army Construction Engineering Research Laboratory (CERL). The CERL principal investigators were Alan Chalifaux and Jearldine I. Northrup. Special credit is given to the National Aeronautics and Space Administration (NASA) for the use of its document *Reliability Centered Maintenance Guide for Facilities and Collateral Equipment, December 1996* in the preparation of this report. Mark W. Slaughter is Chief, CECER-CN-E and Dr. John T. Bandy is Chief, CECER-CN. The CERL technical editor was William J. Wolfe, Information Technology Laboratory.

Dr. Michael J. O'Connor is Director of CERL.

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1 Introduction

Background

Maintenance often takes a low priority in the overall operating strategy of a facility. Maintenance programs are managed and funded by people, and human nature seems to abide by the old tenet, "If it ain't broke, don't fix it." In facilities management, the definition of "broke" is extreme. "Broke" typically means that a piece of equipment has catastrophically failed (e.g., resulting in a pollution fine), or (at the very least) that it has failed to the point that it has become an annoying disturbance in the normal daily operation of a facility.

While few people will argue against the need for performing regular maintenance, few fiscal managers will make the financial commitment to funding maintenance programs at a level that will keep a facility well maintained. Fiscal managers usually assign maintenance programs a very low priority. Compared to other facility departments, maintenance departments have no real "product" and - as such - produce no real income. Many fiscal managers view money spent on maintenance as money thrown down a black hole. In spite of any life-cycle "proofs" to the contrary, fiscal managers look to cut maintenance budgets first when any other fiscal need arises. Not until they see the bathroom floor flooded with sewage or swelter in an office working at 85 °F for hours do they realize that something is "broken" and may need repair.

Fiscal managers continually put maintenance budgets under the closest scrutiny in an effort to reduce dollars spent on maintenance, while expecting facility performance to remain on a constant par. This forces maintenance supervisor/managers to trim essential (but less obvious) work from their daily agendas. The most common area trimmed is preventive maintenance, i.e., those maintenance activities performed on facility equipment *before* equipment failure. The importance of preventive maintenance is less obvious to those people not intimately familiar with facility equipment and operation. The consequences and cost of not performing preventive maintenance (PM) only become obvious when it is too late.

Preventive maintenance requires that maintenance personnel pay regular visits to observe the condition of facility equipment. The most basic tasks on these PM

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visits is to take a look at the equipment to see if there are any telltale signs of failure or imminent failure. Also, depending on the type of equipment, the maintenance mechanic may have a checklist of tasks he has to perform (e.g., draining a little oil and visually checking for foreign matter or discoloration). In large facilities such as Madigan Army Medical Center (MAMC), the basic PM task of walking out to a piece of equipment and giving it a quick look over requires a great deal of time. It also requires that this time be invested by a trained mechanic; untrained personnel are likely to miss telltale signs of failure. MAMC-FMD wanted to determine if there was any means of automating this basic PM inspection activity. By doing so, it (or any other facility) could free up skilled labor for other tasks, thereby "squeezing more" out of every maintenance dollar.

Preventive maintenance is typically performed based on the calendar. Maintenance personnel schedule visits to a particular piece of equipment based on certain time intervals having elapsed. While certainly better than no PM at all, calendar-based PM may result in *too much time* being spent on a piece of equipment. Each visit to a properly functioning piece of equipment takes time away from other maintenance activities. Many visits to a piece of equipment with "no news to report" can be regarded as wasted maintenance dollars. Calendar-based PM (much preferable to no PM), is not the optimal way to run a PM program.

Typically, the next step up (from calendar-based PM) is performing PM based on equipment run time. This method is thought to provide a better means of getting a maintenance mechanic out to a piece of equipment just as it is beginning to show signs of wear. Intuitively, performing PM based on equipment run time makes sense. Equipment does not have to be checked repeatedly if it has not been used. Generally speaking, it is the actual operation of the equipment that wears it down, so it makes sense to check the equipment after it has run a sufficient amount of time to incur some wear. (However, run time is not a proper criterion for performing PM on all equipment. There are certain pieces of equipment that require visual inspection when they have *not* been run).

Calendar-based PM assumes that failure probabilities can be determined statistically for individual machines, components, and parts can be replaced or adjustments performed in time to preclude failure. This is not always true. A common practice has been to replace bearings after a certain number of operating hours, the assumption being that bearing failure rate increases with time in service. Figure 1 shows that this assumption is not always true. This figure shows the failure distribution of a group of 30 identical 6309 deep groove ball bearings installed in bearing test machines that run the bearings to failure. The wide variation in bearing life is evident; there is no strong correlation between bearing operating hours and bearing life.

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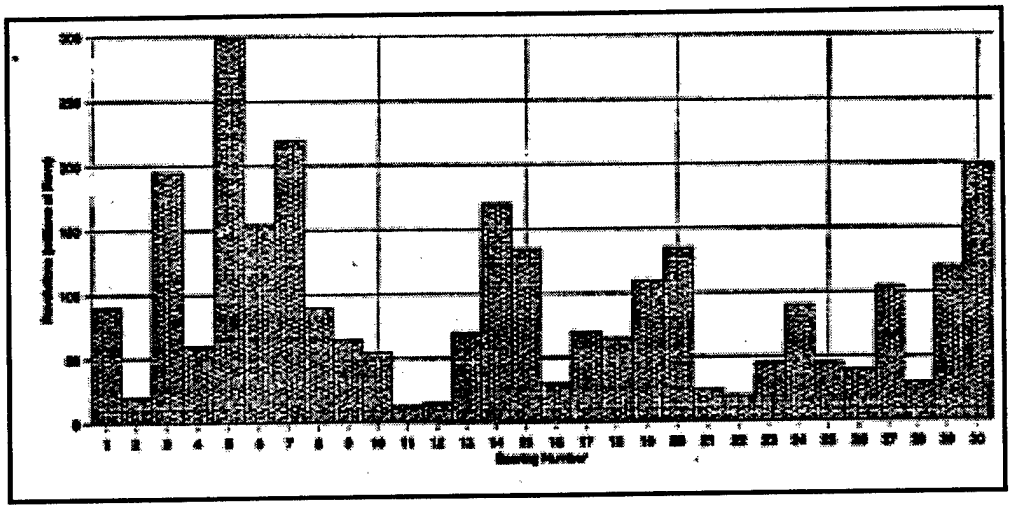

Figure 1. Bearing life scatter.

An improvement on calendar-based PM (and the traditional next step up) is condition monitoring (CM). Here the maintenance supervisor/manager defines some critical parameters that reflect the condition of a piece of machinery (e.g., amperage draw, bearing temperature, shaft vibration). Acceptable limits are defined for each of these parameters. Some sort of data acquisition devices are attached to measure the critical parameters and the stream of real-time data are compared to the limits. Once the limits are exceeded, an alarm is issued so that a PM visit can be scheduled.

The original focus of the CERL research project was to integrate condition monitoring equipment with the computerized maintenance management system (CMMS) at MAMC. The intent was to collect real-time data and feed it into the MAMC CMMS. However, once MAMC and CERL personnel took a hard look at what data could/should be collected and transferred to the MAMC CMMC, issues arose that were broader than the technical issues of data acquisition:

1. Hardware and software technology exists to collect, store, and analyze gigabytes of data. But does it make sense to replace all other maintenance activities with data collection? (No, not necessarily.)

2. Is the path of data intensive maintenance management always the best? (No, data collection, storage, and analysis systems cost money to install, operate, and maintain. They are not always the most effective maintenance techniques.)

3. Is there a downside to taking "the man away from the machine," replacing the regular human visits with electronic CM? (Yes, the human technician may see something wrong that is not monitored by the CM in place.)

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Given questions (and answers) such as the above, the process of replacing PM with CM is a complicated one. Any decision to replace calendar-based PM with CM generates several organizational/policy-related questions regarding a facility's maintenance program. Technical analysis of CM techniques quickly becomes overshadowed; workable solutions to the larger issues seem out of reach.

MAMC and CERL found a workable solution in the concept of Reliability Centered Maintenance (RCM) as developed by the National Aeronautics and Space Administration (NASA). The RCM approach is a dynamic, ongoing effort, requiring constant review today of the maintenance practices and policies put in place yesterday. Its basic aim is to increase the reliability of machinery/systems using a combination of four maintenance techniques: reactive maintenance, preventive maintenance, predictive maintenance, and proactive maintenance. This manual is meant to serve as a guide to MEDCOM maintenance personnel implementing an RCM program.

Objectives

The Facilities Management Division (FMD) at Madigan Army Medical Center (MAMC) realizes the importance of constant and regular maintenance, and has pursued and practiced an aggressive maintenance program since its inception. Its maintenance program was planned and implemented as the facility was being built, and the maintenance program has been managed and documented from the beginning using commercial computerized maintenance management system (CMMS) software. Preventive maintenance is a keystone of the program and accounts for about 60 percent of the maintenance dollars expended at MAMC. The objective of this project was to help FMD determine if certain essential, but rote, preventive maintenance efforts could be automated to free up maintenance workers' time.

Approach

A literature search was done to uncover recent, relevant information in the area of Reliability Centered Maintenance. A manual was prepared to serve as a guide to MEDCOM maintenance personnel implementing an RCM program.

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Scope

Although this work was done specifically at the request of MAMC, it is important to note that RCM is a generally approach to equipment maintenance applicable at many military, industrial, or commercial facilities. However, RCM is not a formulaic "cookbook" methodology that can be followed mindlessly. A good RCM program requires that maintenance supervisor/managers and staff be engaged in and constantly thinking about the value of their procedures. This manual is meant to provide some basic direction to maintenance supervisors in bringing their experience to bear on the specific facilities entrusted to their care.

Units of Weight and Measure

U.S. standard units of measure are used throughout this report. A table of conversion factors for Standard International (SI) units is provided below.

SI conversion factors		
1 in.	=	2.54 cm
1 ft	=	0.305 m
1 yd	=	0.9144 m
1 sq in.	=	6.452 cm^2
1 sq ft	=	0.093 m^2
1 sq yd	=	0.836 m^2
1 gal	=	3.78 L
1 lb	=	0.453 kg
1 oz	=	28.35 kg
1 psi	=	6.89 kPa
°F	=	(°C x 1.8) + 32

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2 RCM Definition and Philosophy

Definition

Reliability Centered Maintenance can be defined as "an approach to maintenance that combines reactive, preventive, predictive, and proactive maintenance practices and strategies to maximize the life that a piece of equipment functions in the required manner." RCM does this at minimal cost. *In effect, RCM strives to create the optimal mix of an intuitive approach and a rigorous statistical approach to deciding how to maintain facility equipment.*

The key to developing an effective RCM program lies in effectively combining the intuitive and statistical approaches. Intuition and statistics each have strong and weak points. Intuition is an effective tool when applied judiciously; however, if applied without serious reflection and review, it results in arbitrary, "shoot-from-the-hip" solutions to problems. A rigorous statistical approach has its limits, too. The first limit of the statistical approach is cost. Developing and/or analyzing an amount of data sufficient to provide a statistical basis is an expensive task. One may also fall into the "analysis paralysis" pitfall; the more one delves into a problem, the more data it seems are required to solve it. The second limit of the statistical approach is applicability. Statistics often do not tell the whole story. Data do not always produce definite trends, since there may be none.

RCM Analysis

RCM analysis carefully considers the following questions:

- What does the system or equipment do?
- What functional failures are likely to occur?
- What are the likely consequences of these functional failures?
- What can be done to prevent these functional failures?

To implement RCM, it is imperative that maintenance supervisors/managers and maintenance technicians think about their facilities in terms of *function*. That

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means thinking about facility equipment in terms of systems, subsystems, components, and subcomponents. This terminology is used throughout this manual.

RCM Principles

The primary RCM principles are:

1. *RCM is Concerned with Maintaining System Functionality*. RCM seeks to preserve system or equipment function, not just to maintain a piece of machinery's operability for operability's sake. It should be noted that a common strategy is to maintain system function through equipment redundancy. Equipment redundancy improves functional reliability but increases system life cycle cost (due to the increased first cost of installing the redundant equipment). The increased life cycle cost of installing redundant equipment often eliminates redundancy as the RCM method of providing system reliability.

2. *RCM is System Focused*. It is more concerned with maintaining system function than individual component function. The question asked continually is: "Can this system still provide its primary function if a component fails? (In this example, if the answer is "yes," then the component is allowed to run to failure.)

3. *RCM is Reliability Centered*. RCM treats failure statistics in an actuarial manner. The relationship between operating age and 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 piece of equipment).

4. *RCM Recognizes Design Limitations*. The objective of RCM is to maintain the *inherent* reliability of system function. A maintenance program can only maintain the level of reliability inherent in the system design; no amount of maintenance can overcome poor design. This makes it imperative that maintenance knowledge be fed back to designers to improve the next design. RCM recognizes that there is a difference between perceived design life (what the designer thinks the life of the system is) and actual design life. RCM explores this through the Age Exploration (AE) process (p 42).

5. *RCM is Driven by Safety First, then Economics*. Safety must be maintained at any cost; it always comes first in any maintenance task. Hence, the cost of maintaining safe working conditions is not calculated as a cost of RCM. Once safety on the job is ensured, RCM assigns costs to all other activities.

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6. *RCM Defines Failure as an Unsatisfactory Condition.* ("Failure is not an option.") Here failure is defined as a loss of acceptable product/service quality level, or failure is defined as a function not being maintained.

7. *RCM Tasks Must Produce a Tangible Result.* The tasks performed must be shown to reduce the number of failures, or at least to reduce the damage due to failure.

8. *RCM Recognizes Four Maintenance Categories and Uses a Logic Tree to Screen Maintenance Tasks.* This ensures consistency in determining how to perform maintenance on all types of facility equipment. Each piece of equipment is assigned to one of four categories:

   a. Run-to-Failure - Under an RCM program, run-to-failure is a conscious decision reached after analysis of what facility function(s) would be affected by system failure versus the (life cycle) cost of preventing failure.

   b. Calendar-Based Maintenance (PM) - This is the most basic approach. It schedules tasks based on the time since that task was last performed. It is the type of maintenance most often performed in Preventive Maintenance programs.

   c. Condition Monitoring (CM) - This maintenance is performed based on predictive testing and inspection. Real-time data are gathered and analyzed as a way to determine when a piece of equipment requires maintenance.

   d. Proactive Maintenance - Efforts in this area of a maintenance program are aimed at applying the lessons learned from past maintenance experience to future situations. This includes writing better specifications, precision rebuild, failed part analysis, and root-cause failure analysis. Figure 2 shows the logic tree used to determine what kind of maintenance should be applied to each piece of facility equipment.

9. RCM is an Ongoing Process. This is one of the most important characteristics of RCM. No maintenance procedures escape review. Maintenance personnel gather data from the successes/failures achieved and feed these data back to improve future maintenance procedures and design of new systems. This feedback loop is an essential part of the RCM process. This includes: changing old equipment specifications that have been proven inadequate or incorrect, rebuilding worn/failed equipment to better resist failure, performing failed-part analysis, and performing root-cause failure analysis.

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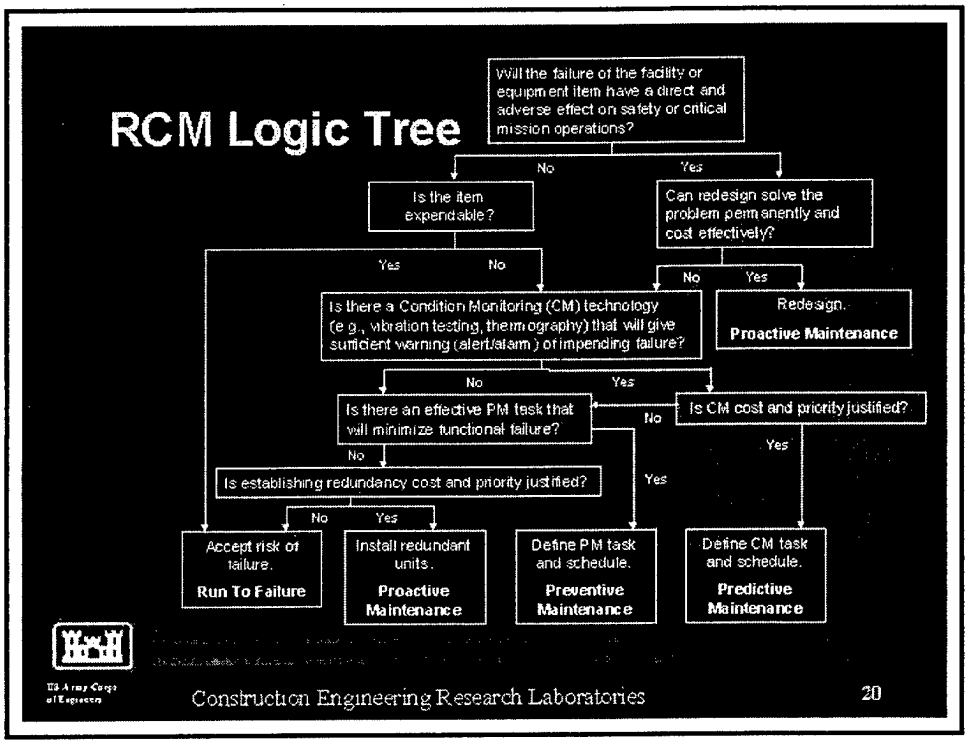

Figure 2. RCM logic tree.

The RCM Process

RCM grew out of the aircraft industry in the late 1960s and 1970s. Since many aircraft equipment failures have disastrous consequences, the basic RCM process developed was very formal and rigorous. The basic steps in developing a formal RCM analysis are:

1. *Define the major systems and components.* The user defines the systems. Where systems are extremely complex and this complexity makes analysis difficult, the user may opt to define subsystems as a means of organizing the problem into manageable pieces.

2. *For each system, define all "functions" of that system.*

3. *For each of those functions, define the possible "functional failures"* that could occur (i.e., what could go wrong that would prevent the system function from occurring).

4. *For each functional failure, define all possible "failure modes"* (i.e., each equipment failure could be the cause of the functional failure).

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5. *For each failure mode, state whether it would be due to improper operation, improper maintenance, or both.*

Figure 3 presents a sample RCM analysis sheet ("RCM System Data Sheet") that would be generated in applying a rigorous RCM analysis to a chilled water system supplying computer equipment. Figure 3 analyzes the system and the *functions* it performs. It also lists the functional failures that could occur. Figure 4 presents one of the sample Failure Mode Sheets that would be produced describing how one of the components of the chilled water system could fail; it lists the "failure modes" of the component. Note that Figure 4 is a breakout of motor failure one of the 12 distinct failure modes listed in Figure 3. In a formal and complete RCM analysis, 11 other Failure Mode Sheets such as Figure 4 would be produced. Figures 5 and 6 present the root cause failure analyses of two sub-components of the component analyzed in Figure 4 (motor = "component," while stator = "sub-component" of motor, and rotor = "sub-component" of motor in this example). Figures 5 and 6 represent two of nine sheets detailing how/why sub-components of the motor would fail.

Review of the sample RCM Information Sheet, the sample component failure mode sheet, and the two sample Root Cause Failure sheets illustrate how extensive, time-consuming, and expensive a formal RCM process can become. Due to the extensive up-front effort involved in producing a formal RCM analysis, it is recommended that MEDCOM facilities only pursue this level of detail for those systems where the consequences of failure are catastrophic.

Building Chilled Water System			
Function	**Functional Failures**	**Failure Modes**	**Maintenance (M) or Operation (O)**
Provide chilled water at specified flow rate and temperature	Total loss of flow	Motor Failure	Both
		Pump Failure	Both
		Catastrophic Leak	M
		Blocked Line	M
		Valve out of position	Both
	Insufficient flow	Pump cavitation	O
		Drive problem	M
		Blocked line	M
		Valve out of position	Both
		Instrumentation	M
	Chilled water temperature too high	Chiller fatigue	Both
		Low refrigerant	M
		Fouled heat exchanger	M
		Instrumentation problem	M
		Cooling tower problem	M
		Valve out of position	Both

Figure 3. Sample RCM system data sheet.

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RCM Program Benefits

1. *Reliability*. The primary goal of RCM is to improve equipment reliability. This improvement comes through constant reappraisal of the existing maintenance program and improved communication between maintenance supervisors/managers, maintenance mechanics, facility planners, building designers, and equipment manufacturers. This improved communication creates a feedback loop from the maintenance mechanic in the field all the way to the equipment manufacturers.

2. *Cost*. Due to the initial investment required to obtain the technological tools, training, equipment condition baselines, a new RCM program typically results in a short-term increase in maintenance costs (see Figure 7). The increase is relatively short-lived. The cost of reactive maintenance decreases as failures are prevented and preventive maintenance tasks are replaced by condition monitoring. The net effect is a reduction of reactive maintenance and a reduction in total maintenance costs. As a by-product, energy savings are often realized from the use of the CM techniques that are part of any RCM program.

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Electric Motor # 123456			
Function: To provide sufficient power to pump 300 gpm chilled water			
Component	**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	Burnt rotor	Insulation contamination Excessive current Excessive temperature Imbalance
	Wrong speed	Excessive vibration	
Bearings	Motor will not turn	Bearing seized	Fatigue Improper lubrication Misalignment Imbalance Electrical pitting Contamination Excessive Thrust Excessive temperature
Motor Controller	Motor will not turn	Bearing seized	Mainline contact failure Control circuit failure Loss of electrical power Cabling failure
	Wrong speed	VFD malfunction	
Overloads/fuse	Motor will not turn	Device burned out	Excessive current Excessive torque Poor connection
Shaft/coupling	Pump will not turn	Shaft/coupling sheared	Fatigue Misalignment Excessive torque

Figure 4. Sample failure mode sheet.

3. *Scheduling*. The ability of a condition monitoring program to forecast certain maintenance activities provides time for planning, obtaining replacement parts, making the necessary logistical arrangements (i.e., notifying occupants of equipment downtime) before the maintenance is executed. CM reduces the unnecessary maintenance performed by a calendar-based preventive maintenance program, which tends to err consistently on the "safe" side in determining time intervals between maintenance tasks.

4. *Equipment / Parts Replacement*. A principal advantage of RCM is that it obtains the maximum use from the equipment. With RCM, equipment replacement is based on equipment condition, not on the calendar. This condition based approach to maintenance extends the life of the facility and its equipment.

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Root Cause of Failure Mode for Electric Motor Bearings			
Failure Mode	**Mechanism**	**Reason**	**Root Cause**
Bearing Seized (This includes seals, shields, lubrication system, and lock nut	Lubrication	Contamination	Seal Failure
			Cleanliness
		Insufficient	Oil Leak
			Procedural
		Excessive	Procedural
		Wrong Type	Procedural
	Fatigue	Metallurgical	Inherent
			Excessive Temp.
		Excessive Load	Imbalance
			Misalignment
			Fit-up
			Application
	Surface Distress	Installation	Procedural
		Contamination	See lubrication
		Storage	Procedural
		Electrical	Insulation
			Welding

Figure 5. Failure mode sheet for bearings.

Root Cause Failure Mode for Electric Motors (Electrical)			
Stator Insulation resistance reading zero ohms	Oxidation	Age	Inherent
		Environment	Chemical attack
	Overheating	Excessive current	Power quality
			Phase imbalance
			Short on/off cycle
			Low voltage
			Overloaded
	Contamination	Environment	Moisture
			Improper lube Process related
	Fatigue	Excessive vibration	Lack of winding support
			Phase imbalance Imbalance Misalignment
			Resonance

Figure 6. Failure mode sheet for stator.

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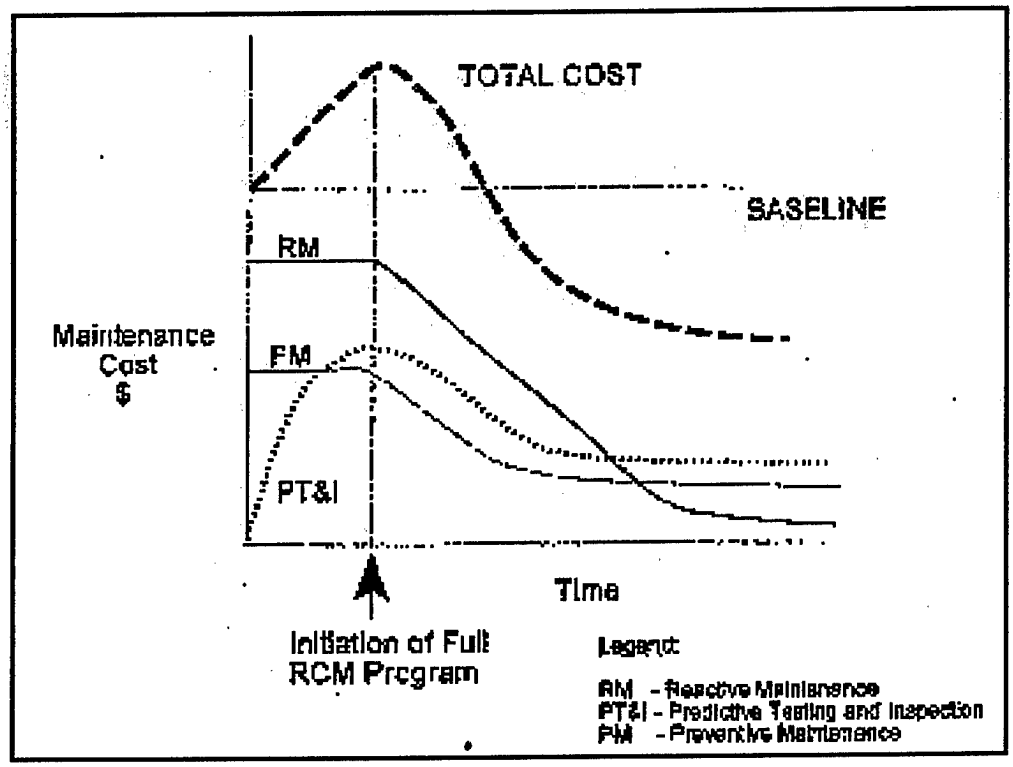

Figure 7. Maintenance cost trends under an RCM program.

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 when it is needed. Maintenance that is not cost-effective is identified and not performed.

In summary, the multi-faceted RCM approach promotes the most efficient use of resources. The equipment is maintained as required by its characteristics and the consequences of its failures.

Impact of RCM on a Facility's Life Cycle

RCM must be a consideration throughout the life cycle of a facility if it is to achieve maximum effectiveness. The four recognized major phases of a facility's life cycle are:

- Planning
- Design
- Construction
- Operations and Maintenance.

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Figure 8 shows that planning (including conceptual design) fixes 2/3 (66.7 percent) of a facility's life cycle cost. The subsequent design phases fix about another 30 percent of the life-cycle cost, leaving only about 4 percent fixable in the later phases. Thus, the decision to institute RCM at a facility, including condition monitoring, will have a major impact on the life-cycle cost of that RCM program. This decision 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.

Murphy's Law being what it is, it is rare that a complete and well-planned RCM program is instituted at the planning stage of a project. However, maintenance personnel need not despair. Even though maintenance is a relatively small portion of the overall life-cycle cost, a balanced RCM program is still capable of achieving savings of 30 to 50 percent in a facility's annual maintenance budget. While these operations and maintenance (O&M) savings may not be the majority of the facility's life cycle cost, they are still a significant portion of the yearly operating costs of a facility, and would be well appreciated by any fiscal manager looking to cut operating costs.

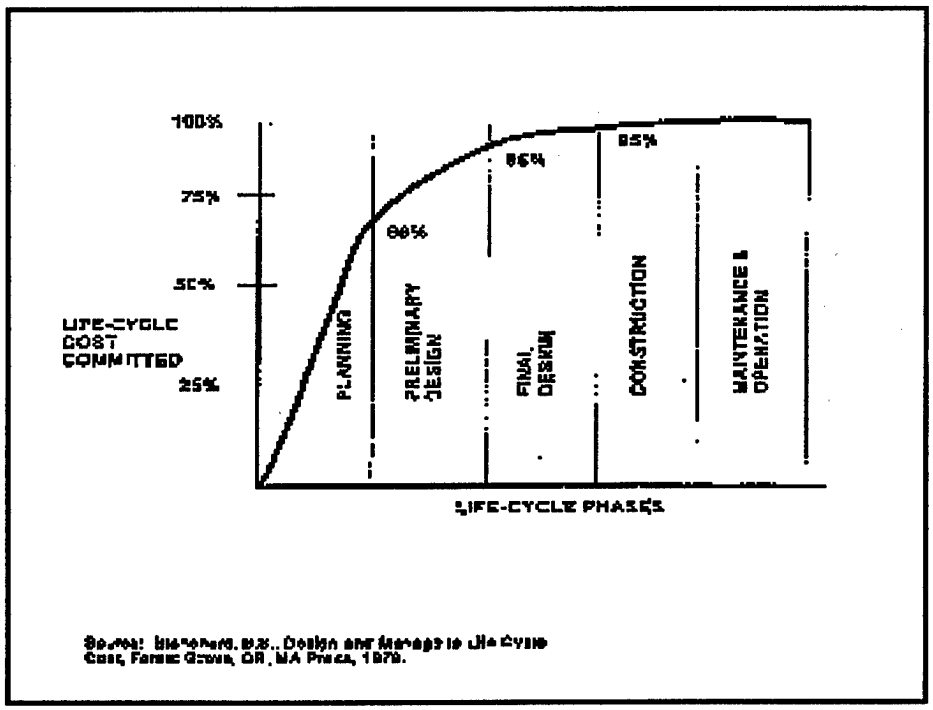

Figure 8. Stages of life cycle cost commitment.

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3 RCM Program Components

An RCM program implements reactive maintenance, preventive maintenance, condition monitoring, and proactive maintenance in an optimal mix. It also combines the intuitive approach with the statistical approach in determining equipment condition.

Reactive Maintenance

Reactive maintenance is referred to by many different names: breakdown maintenance, repair, fix-when-fail, and run-to-failure (RTF) maintenance. When applying this maintenance strategy, a piece of equipment receives maintenance (e.g., repair or replacement) only when the deterioration of the equipment's condition causes a functional failure. The strategy of reactive 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.

The major downside of reactive maintenance is unexpected and unscheduled equipment downtime. If a piece of equipment fails and repair parts are not available, delays ensue while the parts are ordered and delivered. If these parts are urgently required, a premium for expedited delivery must be paid. If the failed part is no longer manufactured or stocked, more drastic and expensive actions are required to restore equipment function. Cannibalization of like equipment or rapid prototyping technology may satisfy a temporary need, but at substantial cost. Also, there is no ability to influence when failures occur because no (or minimal) action is taken to control or prevent them. When this is the sole type of maintenance practiced, both labor and materials are used inefficiently. Labor resources are thrown at whatever breakdown is most pressing. In the event that several breakdowns occur simultaneously, it is necessary to practice a kind of maintenance triage in an attempt to bring all the breakdowns under control. Maintenance labor is used to "stabilize" (but not necessarily fix) the most urgent repair situation, then it is moved on to the next most urgent situation, etc. Replacement parts must be constantly stocked at high levels, since their use cannot be anticipated. This incurs high carrying charges and is not an efficient way to run a storeroom.

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A purely reactive maintenance program ignores the many opportunities to influence equipment survivability. However, it can be effective if used selectively and performed as a conscious decision based on the results of an RCM analysis. This RCM analysis compares the risk of failure with the cost of the maintenance required to mitigate that risk and cost of failure (again, refer to Figure 2, RCM Logic Tree).

Examples of equipment that may be reactively maintained (run-to-failure) are: non-critical electrical motors less than 7.5 HP, restroom exhaust fans, water heaters serving bathrooms, lamps in areas where a few burned out lamps will not pose any safety hazard or affect the use of the area (e.g., halls, cafeterias, lounges).

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 calendar-based maintenance. It is performed without regard to equipment condition or (possibly) degree of use.

PM schedules periodic inspection and maintenance at pre-defined intervals (intervals based on 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 seriousness and frequency of unplanned machine failures for components with defined, age-related wear patterns.

Traditional PM is keyed to failure rates and times between failures. It assumes that these variables can be determined statistically, and that one can therefore replace a part that is "due for failure" shortly 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 parts restores the machine to a like-new condition with no harmful side effects. In addition, this renewal task is based on the perception that new components are less likely to fail than old components of the same design.

Failure rate or its reciprocal, Mean-Time-Between-Failure (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 periodicities is that failure rate data determine only the average failure rate.

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The reality is that 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.

As stated earlier (p 17), RCM grew out of the aircraft industry in the late 1960s and early1970s. This early RCM approach is documented in *Reliability Centered Maintenance* (Nowlan and Heap 1978), which demonstrated that a strong correlation between age and failure did *not* exist and that the basic premise of time-based maintenance was false for the majority of equipment. In summary, PM can be costly and ineffective when it is the sole type of maintenance practiced.

Preventive Maintenance Criteria

Preventive maintenance criteria should reflect the age-reliability characteristics of the equipment based on the equipment history. Equipment that has undergone PM should show a strong failure rate versus age correlation. There should be definite data (or at least definite conclusive in-house experience) to bear out that a piece of equipment will fail at a certain age.

However, whether a piece of equipment should receive PM is not necessarily a function of that equipment's mission criticality. In selecting equipment that should receive PM, the maintenance supervisor/manager should use the process shown in Figure 2. The selection process guides maintenance supervisor/manager in selecting the maintenance strategy appropriate to each piece of equipment.

Determining PM Task and Monitoring Periodicity

This section offers suggestions for selecting equipment monitoring periodicities, i.e., determining the time intervals between PM visits.

Although many ways have been proposed for determining the correct frequency of preventive maintenance tasks, none are valid unless the in-service age-reliability (i.e., failure rate versus age) characteristics of the system or are known. This information is not normally available and must always be collected for new systems and equipment. Condition monitoring techniques (e.g., taking real-time data to determine the "health" of a piece of machinery) can be used to help determine equipment condition vs. age.

Careful analysis of similar kinds of hardware in industry has shown that, overall, more than 90 percent of the hardware analyzed showed no adverse age-

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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 some cases, imposing an arbitrary preventive task increases the average failure rate because some PM tasks are actually detrimental to machines (e.g., machine disassembly, overgreasing). Of course, one would hope that detrimental tasks are never intentionally assigned, but overzealous PM technicians have sometimes done this.

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 (for a group of components) at which failure occurs, not the most likely age (for a specific component). 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.

If good information on the effect of age on reliability is lacking, the best thing that can be done is to monitor the equipment condition ("condition monitoring"). This is explained in the next section.

The goals of a PM visit to a piece of equipment are: (1) to determine equipment condition, and (2) to develop a trend to forecast future equipment condition. The following techniques are recommended for setting initial periodicity:

1. *Anticipating Failure from Experience*. For some equipment, failure history and personal experience provides an intuitive feel for when to expect equipment failure. In these cases, failure is time related. Set monitoring so that there are at least three monitoring PM visits before the anticipated onset of failures. These three visits will give the maintenance technician enough of a "look" at the piece of equipment to become familiar with it. In most cases it is prudent to shorten the monitoring interval as the wear-out age is approached:

2. *Failure Distribution Statistics*. In using statistics to determine the basis for selecting periodicities, the distribution and probability of failure should be known. Weibull distributions can provide information on the probability that equipment may exceed its design life. For example, bearings are normally specified by their B 10 life; i.e., the number of revolutions that will be exceeded by 90 percent of the bearings. Depending on the criticality of the equipment, an initial periodicity is recommended that allows a minimum of three monitoring samples prior to the B10 life or, in less severe cases, prior to the MTBF point. In more critical cases, a B2 life can be calculated and the monitoring interval can be adjusted accordingly.

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3. *Lack of Information or "Conservative Approach."* The most common practice in the industry is to monitor the equipment biweekly or monthly due to 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 adversely impacting 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 done to gain more detailed information on the condition of the equipment.

Condition Monitoring (CM)

Condition monitoring, also known as predictive maintenance, uses primarily nonintrusive testing techniques, visual inspection, and performance data to assess machinery condition. It replaces arbitrarily timed maintenance tasks with maintenance 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 CM data collected are used in one of the following ways to determine the condition of the equipment and to identify the precursors of failure:

- *Trend Analysis*. Reviewing data to see if a machine is on an obvious and immediate "downward slide" toward failure.
- *Pattern Recognition*. Looking at the data and realizing the causal relationship between certain events and machine failure. For example, noticing that after machine x is used in a certain production run, component a_x fails due to stresses unique to that run.
- *Tests against Limits and Ranges*. Setting alarm limits (based on professional intuition) and seeing if they are exceeded.
- *Statistical Process Analysis*. If published failure data on a certain machine/component exist, comparing failure data collected on site with the published data to verify/disprove that you can use that published data.

For trending purposes, it is recommended that data be taken from a minimum of three monitoring points at a point in the machine's life-cycle before failure may reasonably be expected to occur. Three data points allow one to determine whether equipment condition depreciates linearly.

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CM does not lend itself to all types of equipment or possible failure modes and therefore *should not be the sole type of maintenance practiced.* Chapters 5-10 give information on specific CM technologies and instrumentation. For example, to obtain the total picture of a chilled watered system, a CM effort would have to collect the following data (one can see how extensive - and costly - this approach could become):

1. *Flow Rates.* Chiller water flow would be measured using precision, nonintrusive flow detectors.

2. *Temperature.* Differential temperature would be measured to determine heat transfer coefficients and to indicate possible tube fouling.

3. *Pressure.* Differential pressures across the pump would be measured to determine pump performance, and differential pressures across the chiller evaporator and condenser sections should be measured to determine the condition of the chiller tubes (i.e., whether they were fouling).

4. *Electrical.* Motor power consumption would be used to assess the condition of the motor windings.

5. *Ultrasonic Testing.* Pipe wall thickness would be measured to determine erosion and corrosion degradation.

6. *Vibration.* Vibration monitoring would be used to assess the condition of rotating equipment (such as pumps and motors). Additionally, structural problems can be identified through resonance and model testing.

7. *Lubricant Analysis.* Oil condition and wear particle analysis would be used to identify problems with the lubricant, and to correlate those problems with vibration when wear particle concentrations exceed pre-established limits.

8. *Fiber Optics.* Fiber optic inspections would be used to determine component wear, tube fouling, etc.

9. *Thermography.* Thermography scans check motor control centers and electrical distribution junction boxes for high temperature conditions. High temperature is indicative of loose connections, shorts, or failing conductor insulation. Piping insulation should be checked for porosities. Here, high temperatures are indicative of failed/failing areas in the pipe insulation.

10. *Eddy Current.* Eddy current testing is used to determine and locate leaking tubes.

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11. *Airborne Ultrasonics*. Airborne ultrasonics indicate air leaking from control system piping and compressors.

Proactive Maintenance

A proactive maintenance program is the capstone of RCM philosophy. It provides a logical culmination to the other types of maintenance described above (reactive, preventive, and predictive). Proactive maintenance improves maintenance through better design, installation, maintenance procedures, workmanship, and scheduling.

Proactive maintenance is characterized by the following attitudes:

- Maintaining a feedback loop from maintenance technicians to building architects, engineers, and designers, in an attempt to ensure that design mistakes made in the past are not repeated in future designs.
- Viewing maintenance and supporting functions from a life-cycle perspective. This perspective will often show that cutting maintenance activities to save money in the short term often costs more money in the long term.
- Constantly re-evaluating established maintenance procedures in an effort to improve them and ensure that they are being applied in the proper mix.

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

- proper installation and precision rebuild
- failed-parts analysis
- root-cause failure analysis
- reliability engineering
- rebuild certification/verification
- age exploration
- recurrence control.

These proactive maintenance strategies are explained in the following sections.

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Specifications for New/Rebuilt Equipment

Equipment requires proper installation to control life cycle costs and manmade 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. Adopting and enforcing 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 in./ft. The specification also should include the type and accuracy of the instrument used for measuring the slope; e.g., a 12-in. machinist's level graduated to 0.0002 in./ft. 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.

Equipment is often procured using inadequate specifications. Existing standards, often 25 to 30 years old, do not reflect current changes in building technology, but usually address 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 (by regulation) must procure conforming products solely based on initial least cost.

To solve this problem, design engineers must write proper specifications, research (and test if possible) the equipment of different vendors, and document problems. These specifications should include, as a minimum, *vibration, alignment, and balancing criteria*. If these criteria are included in the plans and specifications for new construction or major building renovations, they become part of the contractual documents that the contractor must fulfill. This gives the building owner some solid recourse to make the contractor prove that the equipment in the building is *operating properly* and not just that it is operating. At the turnover of the facility to the owner/tenant, if the contractor does not fulfill the requirements listed in these vibration, alignment, and balancing criteria listed in the specifications, then the owner can refuse acceptance of the building until the contractor does so. For example, rotating equipment has some sort of shaft(s) and bearings. Vibration analysis can determine if the shafts are aligned and if the bearings have been damaged in shipment or installation. Finding alignment and bearing problems before turnover is preferable to the more usual scenario, in which a certain number of bearings fail after turnover — well before any normal wear or operation would have caused them to fail.

Local companies that specialize in vibration measurement (and work with vibration daily) and shaft alignment should be consulted to assist in writing the sec-

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tions of the contract specifications that deal with vibration/alignment. That way, the designer can be sure that all pertinent vibration/alignment criteria are included.

Performance testing is another proactive maintenance strategy that must be conducted. Performance testing can occur in several places: (1) in the factory prior to shipment, (2) after the equipment is installed and immediately prior to acceptance, and (3) at the beginning of the daily operation of the equipment, to establish a performance baseline as the equipment begins operation.

Balance

Bearings are the machine components that support and transfer the forces from the rotating element to the machine frame. The fact that only 10 to 20 percent of rolling element bearings achieve their design life results in the perception that bearings inherently pose a reliability problem. One of the leading causes of premature rolling element/bearing failure is parasitic load due to excessive forces imposed by imbalance and misalignment. 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. for ball Bearings:

$$L_{10} \text{ Life Hours} = (16{,}667/\text{RPM}) \times (C/P)^3$$

b. for roller Bearings:

$$L_{10} \text{ Life Hours} = (16{,}667/\text{RPM}) \times (C/P)^{10/9}$$

Where:

L_{10} = the number of hours 90 percent of a group of bearings should attain or exceeded under a constant load (P) prior to fatigue failure

C = the bearing load that will result in a life of 1 million revolutions

P = the actual bearing load, static and dynamic.

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.

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Balance Calculations

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 perform a single plane balance of a rotor to a level of 0.10 in/sec, nor is it sufficient to balance a rotor until it achieves seemingly low vibration levels. When analyzing a piece of rotating equipment, the vibration technician should take readings in the vertical and horizontal planes, and at all bearing points. The technician should also take axial readings. Precision balance methods should also include the calculation of residual imbalance.* Residual imbalance calculates the imbalance "left in" the piece of equipment once the balancing procedure has been executed. Nothing is perfect. A piece of rotating equipment will never be balanced so that all of the mass is distributed evenly around the axis of rotation. As the piece of equipment rotates the additional force imposed by this "extra" piece of mass will be "slung" around the axis.

The following equation can be used to calculate residual imbalance:

$$U \equiv \frac{Vr}{Ve} \times M \qquad \textbf{Eq. 1}$$

Where:

U = amount of residual imbalance

Vr = actual imbalance

Ve = trial mass imbalance

M = trial mass.

This equation can be expressed as:

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

* Note: The following equations and discussion of permissible imbalance is based on ISO 1940/1, *Mechanical Vibration-Balance Quality Required of Rigid Motors* (1986).

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Permissible imbalance is related to equipment type and rotor mass. In general, the greater the rotor mass, the greater the permissible imbalance.

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 imbalance on a 12-in. radius.

Calculating the amount of centrifugal force due to imbalance:

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

Where:

F = Force

m = imbalance (lb)

A = acceleration (in.^{2}/sec)

r = radius of imbalance (in.)

ω = rotational velocity (radians/sec)

f = rotational frequency (Hz)

g = 386.4 in./sec.

Substituting 1 oz. (1/16 lb.), 12 in., 3600 RPM (60 Hz) yields:

$$\mathrm{F} = 0.102 \times (1/16) \times (12) \times (60)^2 = 275 \text{ lb}$$

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

$$\begin{aligned} Actual\ L_{10}\ Life &= (Design\ Life) \times [(1000/1000 + 275)]^3 \\ &= 0.48\ Design\ L_{10}\ Life \end{aligned}$$

Alignment

The forces of vibration from misalignment also cause gradual deterioration of seals, couplings, drive windings, and other rotating elements with close tolerances. Maintenance technicians should use precision equipment and alignment

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methods, (e.g., reverse dial or laser alignment system) to bring alignment tolerances within precision standards. Contrary to popular belief, both laser alignment and reverse dial indicator equipment offer equal levels of precision; however, laser alignment is considerably easier to learn and much easier to execute in the field.

In addition to the alignment specifications, Table 1 contains the additional tolerance recommendations.

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 percent
- machinery availability increases by 12 percent.

Table 1. Recommended coupled alignment tolerances (General Motors, 1993).

Coupling Type	Maximum Speed (RPM)	Tolerance	
		Horizontal & Vertical Parallel Offset (IN).	Angularity (Inch/10 inch of Coupling Dia.)
Short Coupling	600	0.005	0.010
	900	0.0053	0.007
	1200	0.0025	0.005
	1800	0.002	0.003
	3600	0.001	0.002
	7200	0.0005	0.001
Coupling with Spacer (Measurement is per inch of spacer length)	600	0.005	N/A
	900	0.0018	N/A
	1200	0.0012	N/A
	1800	0.0009	N/A
	3600	0.0006	N/A
	7200	0.00015	N/A
Source: NASA RCM Guide, page 3-14.			

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Figure 9 presents the effect of misalignment on bearing life of a cylindrical roller bearing and shows the drastic decrease in component life caused by a few minutes (i.e., micro-degrees) misalignment.

Misalignment can also cause a significant increase in the cost of energy consumption. Consider the case below. After re-alignment, the current draw of a 460V motor decreased from 25 to 23 Amp. Assume the motor has a power factor of 0.90, given in the relation:

$$\Delta kW = \frac{(3)^{1/2}(\Delta AV \times PF)}{1000}$$

Where:

ΔkW = Change in power consumption, kilowatts

ΔA = Change in Amperage draw

V = Rated Voltage

PF = Power Factor.

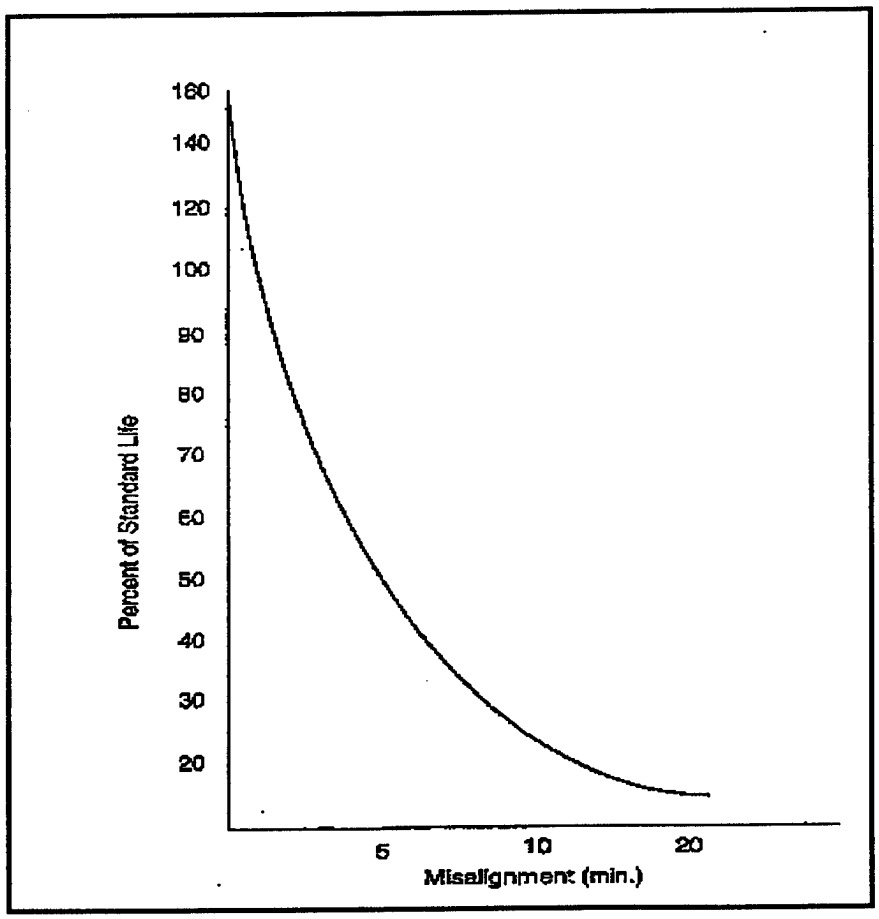

Figure 9. Decrease in life of cylindrical roller bearings as a function of misalignment.

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Substituting the values given above:

$$\Delta kW = \frac{1.732 \times (2\,Amps)(460\,V)(0.90)}{1000}$$
$$= 1.43kW$$

Assuming the motor runs an average of 7,000 hours per year, and the average cost of power during the year is $0.07/kW-hour:

$$\$ \text{ saved per machine train} = 1.43(0.07)(7000) = \$700.00/\text{year}$$

Failed-Part Analysis

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

Bearings are generally the weakest equipment components since they are subjected to constant wear. 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 race surfaces of bearings, indicators of installation problems generally are evident on both internal and external race surfaces.

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. Without performing RCFA, maintenance personnel only see the symptomatic problems; they can do nothing other than 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 personnel safety hazard.

CM methods can identify most equipment faults at an early enough stage to prevent equipment failure. However, CM methods are not directed at discovering

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the underlying *reason* for the failures. For example, a bearing may fail repeatedly because of excessive bearing loads caused by an underlying misalignment problem. CM would most likely predict a bearing failure and thus allow the bearing to be replaced before it fails; however, if no one recognizes the misalignment and corrects it, then conditions causing the failure will remain. The failures will recur and continue to require unnecessary corrective work and cause undue 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."

Reliability Engineering and Reliability Calculations

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 component metal or adding a sealant is all that is required.

Mean Time Between Failure

Reliability can be expressed by the following reliability function:

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

where:

F(t) = the probability the system will fail by time t, and

$0 < F(t) < 1$

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

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

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

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

L = the mean life

t = the time period of interest

e = the natural logarithm base (2.7183),

the reliability at time t is:

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

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). Thus,

where:

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

F = the instantaneous failure rate

M = the MTBF.

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:

$$\text{Fr} = \frac{(\text{No. of Failures})}{\text{Total Operating Hours}}$$

In the following example, as a system component fails, it is replaced and data are taken to record when the replacements occurred.

Component #	Failed at Time (Operating Hours)
1	75
2	125
3	130
4	325
5	525
Total Operating Hours	1180

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$$Fr = 5/1180 = 0.0042$$

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

$$MTBF = 1/Fr = 1/0.0042 = 236 \text{ hours}$$

Reliability Component Relationships

1. Series networks

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

If a series configuration is expected to operate for a specified time period, its overall reliability can be derived by the following expression:

$$RS = e^{-nt}$$

Where n = the number of components in the series.

2. Parallel networks

Reliability $R = R_A + R_B - (R_A \times R_B)$	2-component network
Reliability $R = 1 - (1-R_A)(1-R_B)(1-R_C)$	3-component network
Reliability $R = 1 - (1-R)^n$	n identical components

3. Series-parallel networks

Network reliability for systems that contain both series and parallel components is calculated similarly to calculating overall electrical resistance for a network that has resistors in parallel and series arrangements. As with electrical circuits, analyze the parallel portions to create an equivalent resistance (reliability), and then complete the analysis by combining all components and equivalents serially.

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Related Reliability Factors

1. Inherent Availability (A_i)

a. The probability that a system (or piece of equipment) when used under stated conditions in an ideal support environment, will operate satisfactorily at any point in time as required.

b. Excludes preventive or scheduled maintenance time and administrative delay time.

2. Achieved Availability (A_a)

a. The probability that a system or equipment, when used under stated conditions in an ideal support environment, will operate satisfactorily at any point in time.

b. Preventive (scheduled) maintenance is included.

c. Excludes logistics delay time and administrative delay time.

3. Operational Availability (A_o)

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

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

Weibull Distributions

The Weibull distribution is generally used to determine probability of a failure due to fatigue. The original work was conducted in 1933 and was entitled *A Statistical Theory of the Strength of Materials.* The original work was not directly related to bearings; however, it was modified in 1947 by Lundberg and Palingren to account for the effect of the lubricant and the fact that not all cracks propagate to the bearing surface (Lundberg 1947).

The importance of the Weibull distribution is that the fatigue behavior of a group of bearings can be assessed, and that changes in the failure distribution could be used to identify the introduction of new sources of failure, i.e., changes in operating condition, lubrication/installation practices, etc.

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The Weibull distribution is:

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

where:

F(t) = the failure probability

T = the point in time at which 63.2 percent of the bearings have failed

k = corresponds to the gradient.

The value of k for bearings is 10/9 for ball bearings and 27/20 for roller bearings. Given these values, F(t) should fall in the range from 0.07 to 0.60.

To use the Weibull distribution to determine failure probability for bearings, it is necessary to have a minimum of 10 identical bearings operating under conditions as nearly identical as possible.

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.

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 an attempt to optimize the maintenance process. For example, suppose a vendor recommends that maintenance technicians open and inspect a chiller at certain intervals. During the "open and inspect," the technician notes the condition of various components of the chiller. Ideally, the condition evaluation sheet completed by the technician is then correlated with performance data from the facility energy management control system (EMCS), vibration data, and oil analysis data. As a result of this analysis, the decision may be made to change the interval of the open and inspect until monitored conditions indicate a degradation has occurred.

However, if there are no data available from the EMCS, the maintenance crews may perform a simpler form of AE. Using their best professional judgment, they increase the time period until the next "open and inspect." If the chiller shows no adverse signs of wear at the next opening, the time period until the next "open and inspect" is increased some more. Plainly, this type of AE relies solely on the

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experience of the attending maintenance technician(s) to increase the time intervals between regular heavy maintenance. This simpler form of AE uses "gut feeling" to "push the envelope" of the machine and must be practiced judiciously. (It probably also warrants assigning the same technician to the device consistently.)

No matter which AE method is used — correlation of machinery condition with performance data or "gut feeling" — it is essential that data be available to gauge the success of the AE effort. These data may be as simple as a listing of the dates the PM inspections were performed and a verbal record of what each inspection found. To proceed with AE and to take *no* data is a contradiction; by definition, the process of AE lengthens the time intervals between regular PM inspections, and subsequently records the effects of lengthening those time intervals.

Recurrence Control

This section provides a systematic means for dealing with repetitive failures. 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 equipment,
- repeated failures of various equipment within a system or subsystem, or
- failures of the same or similar components in several different systems.

Repetitive failures may become evident when reviewing data from these sources:

- number of maintenance man-hours by system or component
- number of maintenance work orders by system or component
- maintenance backlog (by system)
- control instruments out of service
- number of inadvertent safety system actuations
- number of unplanned facility shutdowns
- lost mission or production time
- forced outage reports
- number of accident reports.

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

- Monitor plant or equipment performance
- Identify repetitive system failures
- 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.

Facility Condition Assessment

A well-rounded and proactive maintenance program incorporates a constant process of Facilities Condition Assessment (FCA). FCA is characterized as follows:

- FCA is a continuous process wherein the in-house staff analyzes the effectiveness of the maintenance program; it is not a series of discrete independent events, "studies" done by outside consultants, or "flavor of the month" buzzwords.
- FCA is data intensive. In addition to making qualitative judgments based on experience, the maintenance supervisor/manager must have maintenance data and the computer tools (hardware and software) available to analyze these data.

The first characteristic (goal, really) can only be achieved if the facility commander realizes that a good maintenance program is a crucial element to the successful operation of the facility, and if the maintenance supervisors/managers instills in their technicians the attitude that their job is important and worth doing right. The second characteristic requires that the maintenance supervisors/managers have sufficient data available to track maintenance labor and material costs, and the database tools to "slice and dice" that data as they find necessary. The maintenance supervisors/managers must have a software tool that is easy to use, yet powerful enough to generate the graphs and charts required, a tool simple enough to use that the maintenance technician can enter data on a *daily* basis.

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4 Use of Condition Monitoring (CM) Technologies

Introduction

A variety of methods are available to assess the condition of systems/equipment, to determine the most effective time to schedule maintenance:

- vibration monitoring and analysis
- thermography
- passive ultrasonics
- lubricant and particle wear analysis (oil analysis)
- electrical condition monitoring
- nondestructive testing.

Chapters 5 to 10 describe each of the CM technologies, covering the basic theory of how the technology operates, the purpose of applying the technology, acceptable applications, the equipment and operators required, available training, and cost. Note that no attempt is made to provide a current, up-to-date listing of commercial CM products available; product models and prices change too quickly. The intent is to provide readers with a basic understanding of the available CM technologies so that they can make informed decisions about which to employ at their facilities. In reviewing the various technologies, the maintenance manager/supervisor should keep in mind that a well-rounded preventive maintenance program is not built on any one technology.

Spot Readings versus Continual Real-Time Data Collection

Condition monitoring can be performed in two basic ways:

1. One can take spot readings with hand-held instruments.
2. One can install permanent data acquisition equipment and take repeated readings that are stored for future analysis.

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Generally, taking spot readings provides sufficient information for making informed decisions regarding maintenance of facilities. The degradation of facility equipment is usually not so rapid as to require the "up to the minute" reporting that a permanent data acquisition system produces. Usually, the maintenance technician can keep a log of these spot readings and develop trends from these logs.

Permanent condition monitoring equipment is expensive to install, and the data bases created cost money to analyze and maintain. Typically, permanent data-logging equipment is installed only on super critical equipment used in production processes, equipment that - if it goes down - costs the facility "money by the minute" when it is not operating. MEDCOM facilities do not usually have equipment that warrants this expense.

A simple and inexpensive means of acquiring real-time data is to use the existing direct digital control (DDC) energy management and control system (EMCS) if the building has one. The major expense of installing a permanent data-logging system is running the hardware (e.g., cabling throughout the building and data collection devices). If a building has a DDC EMCS, this major expense has already been absorbed. However, a building's DDC system is designed for comfort control and does not contain the diagnostic data points that would be required by the maintenance department for equipment monitoring. If a DDC system does exist, the maintenance department will most likely have to add a few points to the control system to acquire the diagnostic data required for CM. This will entail some additional software programming.

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5 Vibration Monitoring and Analysis

Theory, Applications, and Techniques

Analysis of system and equipment vibration levels is one of the most commonly used CM techniques. Vibration monitoring helps determine the condition of rotating equipment and structural stability in a system. It also helps identify noise sources. (Severely vibrating equipment is noisy.)

Basic Vibration Theory

Vibration is simply the movement of a machine or machine part back and forth from its position of rest. A weight hanging on a spring is the simplest example of how vibration works. Until a force is applied to the weight to cause it to move, we have no vibration. By applying an upward force, the weight moves upward, compressing the spring. If we released the weight, it would drop below its neutral position to some bottom limit of travel, where the spring would stop the weight. The weight would then travel upward through the neutral position to the top limit of motion, and back again through the neutral position. The motion will continue in exactly the same manner as the force is reapplied. Thus, vibration is the response of a system to some internal or external force applied to the system.

With a few exceptions, mechanical troubles in a machine cause vibration. The most common problems that produce vibration are:

- unbalance of rotating parts
- misalignment of couplings and bearings
- bent shafts
- worn, eccentric, or damaged parts
- bad drive belts and drive chains
- bad bearings
- torque variations
- electromagnetic forces

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- aerodynamic forces
- hydraulic forces
- looseness
- rubbing
- resonance.

The amount of time required to complete one full cycle of a vibration pattern is called the period of vibration. If a machine completes one full cycle in 1/60th of a second, the period of vibration is said to be 1/60th of a second. The period of vibration is a simple and meaningful characteristic often used in vibration detection and analysis. Another simple characteristic is the frequency. Frequency is related to period by the following formula:

$$\text{frequency} = 1/\text{period}$$

Frequency is the inverse of period. In reality, frequency is a measure of the number of complete vibration cycles that occur in a specified amount of time.

The frequency of vibration is usually expressed in cycles per minute (CPM). Specifying vibration frequency in CPM makes it easy to relate this characteristic to another important specification of rotating machinery: revolutions per minute (RPM). So, if you have a piece of machinery that operates at 3600 RPM, you can expect certain problems to create vibration at a frequency of 3600 RPM. Frequency is sometimes expressed in cycles per second, or Hertz (Hz). The relationship between Hz and CPM is expressed by the following equation:

$$CPM = Hz \times 60$$

Vibration displacement is defined as the total distance traveled from one extreme limit to the other (the "peak-to-peak displacement"). "Peak-to-peak vibration displacement" is usually expressed in mils, where 1 mil equals 1/1000th of an inch (0.001 in.).

Since a vibrating piece of machinery is moving, it has a velocity. The vibration velocity constantly changes. At the top limit of the motion the speed is zero since the weight must come to a stop before it can go in the opposite direction. The speed of velocity is greatest as the weight passes through the neutral position. Since the velocity of the part is constantly changing throughout the cycle, the highest "peak" is selected for measurement. Vibration velocity is expressed in inches per second.

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Since vibration velocity is directly related to vibration severity, for the most general purpose vibration measurements, it is the preferred parameter for measurement. As a rule of thumb, vibrations occurring in the 600 to 60,000 CPM frequency range are generally best measured using vibration velocity.

Under conditions of dynamic stress, displacement alone may be a better indication of severity, especially when the machine part exhibits the property of brittleness, the tendency to break or snap when stressed beyond a given limit. For example, consider a slowly rotating machine that operates at 60 RPM, and that exhibits vibration of 20 mils peak-to-peak displacement caused by rotor unbalance. In terms of vibration velocity, 20 mils at 60 CPM is only 0.0585 in./sec, which would be considered "good" for general machinery and little cause for immediate concern. However, keep in mind that the bearing of this machine is being deflected 20 mils. Under these conditions, fatigue may occur due to stress (resulting from the displacement) rather than due to fatigue (caused by the velocity of displacement).

Generally, the most useful presentation of vibration data is a graph showing vibration velocity (expressed in inches/second) on the vertical axis and frequency on the horizontal axis. By analyzing these data, a trained vibration technician can ascertain what kinds of problems exist. The trained technician has, in effect, learned to "read" vibration signatures; he has learned to interpret what the different peaks in the different frequency ranges indicate. For example, when analyzing a 3600 RPM pump motor, a peak at 3600 RPM indicates some kind of mass imbalance. A peak at 7200 RPM (two times the rotational frequency) generally indicates a bent shaft.

Figure 10 illustrates what vibration data are typically taken. The top part of the figure shows a schematic diagram of a fan/motor assembly, the points where vibration data are taken (points A,B,C,D), and manual recording of the readings obtained at those points. The bottom part of the figure shows a graph of the data. Notice the spikes in the graph. These are what the vibration analyst learns to interpret.

Figure 11 shows two plots of vibration data juxtaposed in the same graph. The bottom plot is the vibration data for an engine running properly. The top plot shows the vibration data for the same engine with a misfiring cylinder. Observe the notes written by the analyst who has interpreted the peaks. Specific vibration frequencies indicate how different parts of the motor are operating. When reviewed by a trained vibration analyst, vibration data are extremely helpful in determining the "health" of the machine.

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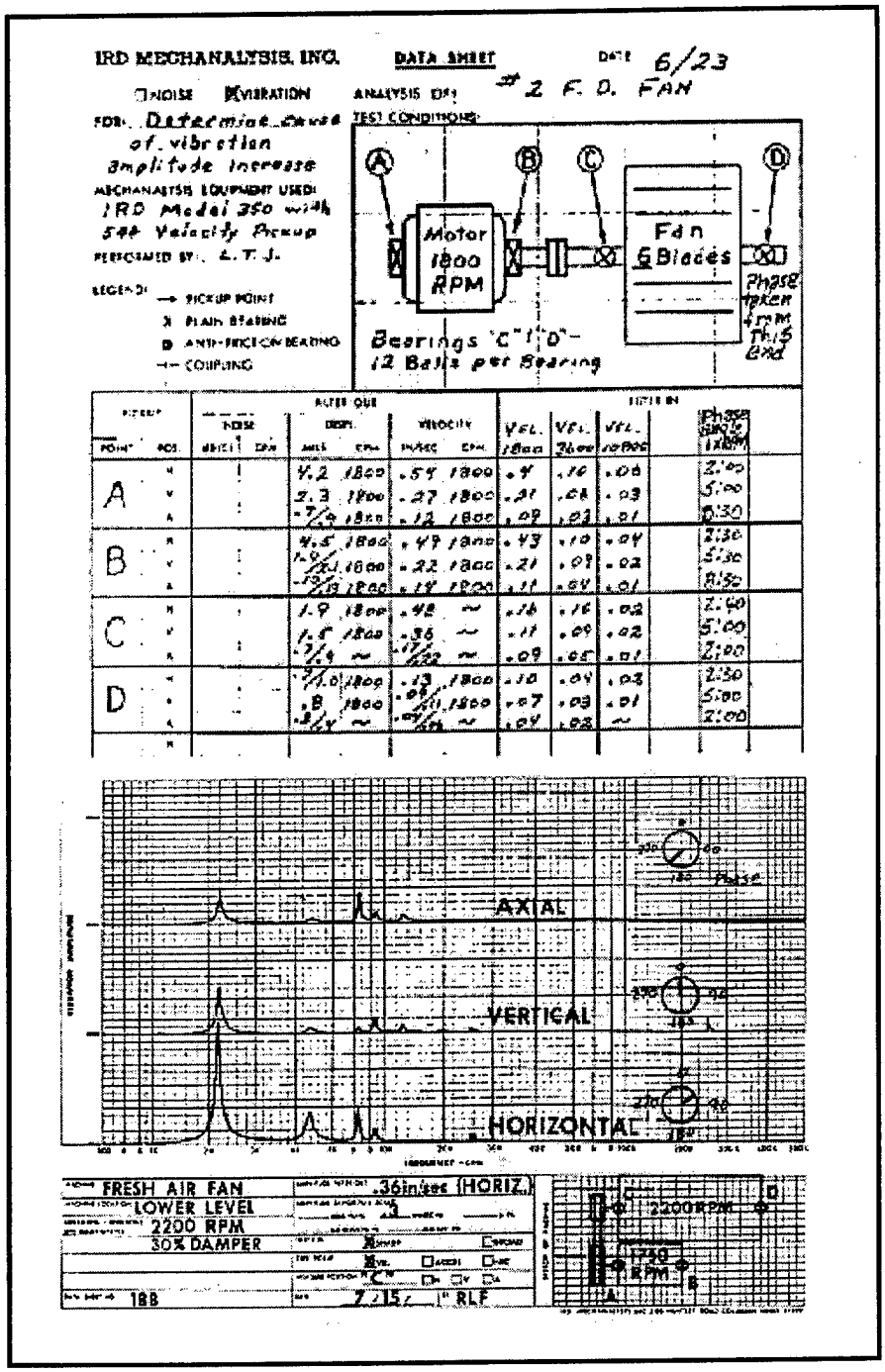

Figure 10. Sample vibration data.

All rotating machinery will exhibit a certain degree of vibration. The question then becomes "How much is too much?" There are no realistic figures for selecting a vibration limit, which, if exceeded, will result in immediate machinery failure. The events surrounding the development of a mechanical failure are too complex to set reliable limits. However, there are some general guidelines that have been developed over the years that can serve as general indication of the condition of a piece of machinery.

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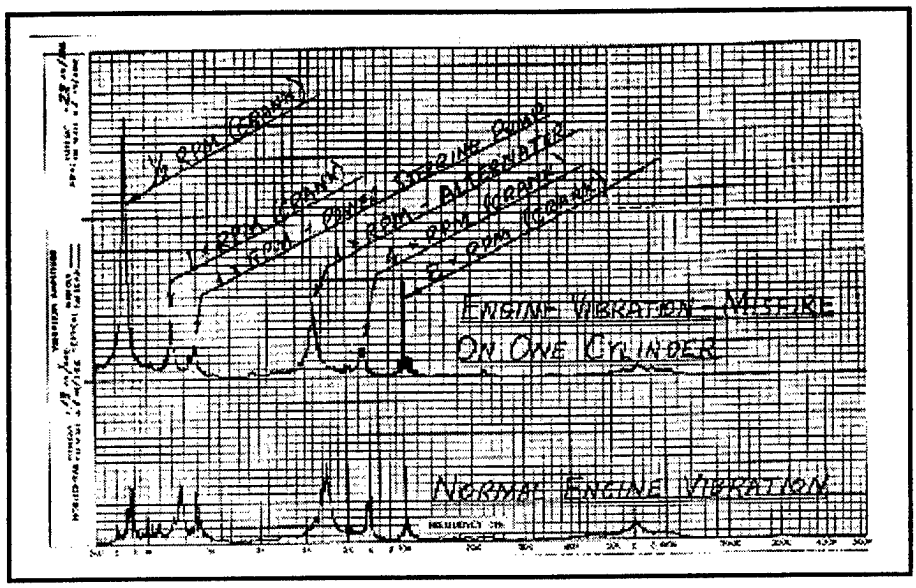

Figure 11. Two plots of vibration data juxtaposed in the same graph.

When setting up a vibration monitoring program that uses hand-held vibration instrumentation, it is necessary to ensure that the measurements are taken consistently. A slight variation in the location where a measurement is taken on a piece of machinery can significantly alter its accuracy. This issue becomes especially difficult to police when several technicians take measurements at different times on the same piece of machinery.

Information Obtained through Vibration Monitoring

If applied by a trained professional, vibration monitoring can yield information regarding: wear, imbalance, misalignment, mechanical looseness, bearing damage, belt flaws, sheave and pulley flaws, gear damage, flow turbulence, cavitation, structural resonance, and material fatigue.

The maintenance supervisor/manager must make the decision whether it makes economic sense to perform this function with in-house labor forces or whether it should be outsourced to a contractor specializing in vibration monitoring and analysis. In making this decision, maintenance supervisors/managers should consider whether they have sufficient in-house labor to dedicate to vibration monitoring. Vibration monitoring theory is complicated, the equipment is expensive, and the analysis of the data collected is a skill that must be practiced regularly. Once they have completed the basic vibration training (costing several thousands of dollars), maintenance technicians must be committed and allowed to work at least 3 days per month in vibration analysis to stay competent with the technology and analysis techniques.

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Detection Interval/Amount of Data Collected

Narrow band vibration analysis can provide several weeks or months of warning of impending failure. In establishing a vibration monitoring program, one must first determine how often to take sampling data. Different vibration frequencies forebode different upcoming failures. The frequency of data collection depends on machine type and failure category. Typically, it is not cost effective to take real-time vibration data; spot checking facility equipment once per month (or once per quarter) with hand-held vibration monitoring equipment usually provides sufficient warning of impending problems. Facility rotating equipment (e.g., fans, pumps) does not deteriorate fast enough to warrant continual real time data collection.

Maintenance technicians should realize that accumulating more data is not necessarily indicative of a better vibration monitoring program. Even after the first costs of the vibration monitoring and data acquisition system have been absorbed, there is an "overhead" associated with data collection. The data must be analyzed and interpreted. Even with the sophisticated software available to help maintenance technician with these tasks, it is an ongoing time investment.

Overall Vibration

Overall vibration is defined as the sum of a vibration energy produced across a filtered band-width. Overall measurements are rarely used in today's modern maintenance programs. It is typically better to concentrate on specific frequencies.

Spectrum Analysis and Waveform Analysis

Spectrum analysis is the most commonly employed analysis method for machinery diagnostics. In this type of analysis, the vibration technician focuses on analyzing specific "slices" of the vibration data taken over a certain range of CPM. (Figures 10 and 11 above show how vibration data are presented in graphical form.) Spectrum analysis can used to identify the majority of all rotating equipment failures (due to mechanical degradation) before failure.

Waveform analysis, or time domain analysis, is another extremely valuable analytical tool. While not used as regularly as spectrum analysis, the waveform often helps the analyst more correctly diagnose the problem.

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Torsional Vibration

Torsional vibration is often used to detect the vibration associated with the measurement of gear vibration and 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 (i.e., the noise obscures the signal). Torsional vibration is especially effective in situations where unsteady forces excite the resonance of the structure or housing. Measure torque by using pairs of matched sensors spaced at a sonic interval to take advantage of the phase difference in the signals.

Multi-Channel Vibration Analysis

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 dataloggers.

Shock Pulse Analysis

This type of analysis is used to detect impacts caused by contact between the surfaces of the ball or roller and the raceway during rotation of anti-friction 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.

Vibration Sensor Mounting (Permanent Installations)

Identify each monitoring point and epoxy magnetic corrosion resistant steel discs (sound discs) at every location. Sound discs can be purchased for approximately $26.00 each or the maintenance machinist can cut them from 1-in. alloy 410 or 416 magnetic stainless steel bar stock using a fly cutter. Use a tested epoxy such as Hysol Gray Epoxy Patch available from Structural Adhesives to adhere the sound disc to the equipment. Prepare the surface for the epoxy by grinding and wiping down with a solvent. The use of super-glue type adhesives is not recommended as the mounting pads tend to fall off.

As an alternative, the monitoring locations may be machined on the machine's surface at the locations listed in the next section. The machined surface should be between 32 and 125 micro-inches (1 micro-inch [mic] = 0.001 in.) and within one degree of perpendicularly with respect to the shaft center line.

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The use of a low mass accelerometer (100 mV/g) and a rare earth super magnet to attach the accelerometer to the sound disc is recommended. This technique has been proven by the U.S. Navy to provide a usable upper frequency limit of 5 kHz. By using special purpose accelerometers and a couplant between the accelerometer, magnet, and mounting disc, accurate measurements to 20 kHz are possible.

Laser Shaft Alignment

Laser shaft alignment is a natural complement to vibration analysis. Properly aligning shafts eliminates one of the major causes of vibration in rotating machines and also drastically extends bearing life. For the minimal amount of work involved, the payback is great. Figure 9 illustrates how drastically cylindrical roller bearing life is shortened by minimal misalignments of a few minutes (i.e., a fraction of a one-degree misalignment).

Limitations

The effectiveness of vibration monitoring depends on sensor mounting, resolution, machine complexity, data collection techniques, and the ability of the analyst. This last factor, the ability of the analyst, is probably the most important aspect of establishing an effective vibration monitoring program. The analyst must be someone who possesses a thorough understanding of vibration theory and the extensive field experience necessary to make the correct diagnosis of the vibration spikes that may appear in the data acquired.

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.

Logistics

Equipment Required

For permanent data collection, vibration analysis systems include microprocessor-based 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. Portable hand-held

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data collectors consist of a hand-held data collection device (about the size of a palm-top computer) and a magnetized sensing device.

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.

Available Training

- Training is provided by equipment vendors, as well as by the Vibration Institute, 6262 South Kingery Highway, Willowbrook, IL 60514 (708) 654-2254.
- The Vibration Institute has published certification guidelines for vibration analysts. Passing a written examination is required for certification.

Cost

Vibration analysis systems cost $20,000 to $120,000 for narrow band systems, software, and primary training. The $20,000 will buy an adequate hand-held system (about $13,000) and the training (about $7000) required for the technician to use that device and interpret the data acquired with it. The high end of this price range is for a basic multi-channel, permanently installed system that can be expanded for an additional cost of $500 to $1,000 per additional sensor. In integrating vibration-monitoring into a CM program, it is often advisable to contract out-of-house for a year or two to companies specializing in vibration analysis. During that time, MEDCOM facility maintenance personnel can become familiar with the technology and analysis process, make sure the correct equipment is being analyzed, and make sure vibration analysis has an acceptable payback for the facility. If only a few pieces are being analyzed at a facility, it may make sense to contract the service out on a regular basis.

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6 Thermography

Infrared Thermography (IRT) is the application of infrared detection instruments to identify temperature differences. The test instruments used are noncontact, line-of-sight, thermal measurement and imaging systems. Because IRT is a noncontact 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 electromagnetic 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. The maintenance technician will need to be aware of this when performing outdoor inspections in areas such as transformers, motor control centers, switchgear, substations, switchyards, or power lines. In such cases, sunlight reflected from shiny surfaces may make those surfaces appear to be "hotter" than the adjacent surfaces when they really are not. To be effective in facilities applications, IRT instruments must be portable, sensitive to within 0.20 °C over a range of temperatures from -100 to +3000 °C, and accurate within +/-3 percent. In addition, the instrument must be capable of storing an image of the thermogram for later analysis.

IRT inspections are identified as either qualitative or quantitative. The *quantitative* inspection attempts to accurately measure 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, and environmental factors, as well as the limitations of the detection instrument. This knowledge and understanding must be applied in a methodical fashion to control the imaging system properly and to obtain accurate temperature measurements. Quantitative measurements of temperature are extremely time-consuming, and 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 to perform a meaningful qualitative

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inspection. However, qualitative inspections are significantly less time-consuming because the thermographer is not concerned with highly accurate temperature measurement. In qualitative inspections the thermographer obtains accurate temperature *differences* (ΔT) between like components. For example, a typical motor control center will supply three-phase power, through a circuit breaker and controller to a motor. Ideally, current flow through the three-phase circuit should be uniform so the components within the circuit should have similar temperatures. 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 quantitative temperature measurement have very little influence on the temperature differences between like components.

Theory and Applications

IRT can be used 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. IRT can also be used to verify fluid level in large containers such as fuel storage tanks. IRT can identify insulation system degradation in building walls and roof, as well as 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 ground energy losses of pipes. IRT can also be used as a damage control tool to locate mishaps such as fires and leaks. In soliciting consultants to perform thermography, one should remember that (unless requested otherwise) the thermographer will normally provide only an exception report that identifies finds/faults (i.e., his analysis will be of qualitative temperature differences).

In summary, IRT can assess the in-service condition of electrical and mechanical systems. Once this is done, the maintenance supervisor/manager can prioritize work based on the temperature difference criteria. The greater the ΔT, the more urgent the problem.

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Limitations

Thermography is limited to line of sight. Errors can be introduced due to color of material, material geometry, and by environmental factors such as solar heating and wind effects.

Logistics

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 the thermal images.
- The "deep-probe" temperature technique requires temperature probes, analysis software and equipment to determine the location of piping systems.

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 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.

Training Available

- Training is available through infrared imaging system manufacturers and vendors.
- The American Society of Non-destructive Testing (ASNT) has established guidelines for nondestructive testing (NDT) thermographer certification. These guidelines, intended for use in non-destructive testing, may be used as guidelines for thermography in CM if appropriately applied. Certification is not easily obtained. When deciding which maintenance technician should be certified as a thermographer, the maintenance manager should consider general background, work experience, and any previous thermographic experience or thermographic training.

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Cost

- Prices of noncontact infrared thermometers/scanners start at approximately $1,000. Full color microprocessor imaging systems with data storage and print capability range from approximately $25,000 to $70,000.
- Average thermographic system rental is approximately $1,500 per week. Operator training costs approximately $1,250 per week of training.
- Thermographic contractor services cost approximately $3,000 per day. Contract services for deep-probe temperature analysis cost $5,000 to $6,000 for the first day of service, and $1,500 to $2,000 for each additional day.

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7 Passive (Airborne) Ultrasonics

Airborne ultrasonic devices are highly sensitive listening "guns" (similar in size to the radar speed guns used by police at speed traps). The maintenance technician should use a piece of equipment to obtain a translation of the noise (into the range audible to human ears) produced by that piece of equipment. It provides a convenient, nonintrusive means of testing equipment. It is especially easy and useful in testing remote (i.e., pole-mounted) electrical equipment, as well as shielded electrical equipment (i.e., connections inside switchgear and panels.) In the case of high voltage insulator failures, airborne ultrasonic devices can often detect faults earlier than can infrared thermography. Except for severe cases where a current path to ground was established, infrared thermography would not detect high-voltage insulation failures because the corona or tracking typically produces little or no heat. Airborne ultrasonic devices can also detect the noise caused by loose connections as they vibrate inside of panels.

Airborne ultrasonic devices operate in the frequency range from 20 to 100kHz and translate the high frequency signal to a signal within the audible human range. This allows the operator to hear changes in noise levels associated with leaks, corona discharges, and other high frequency events. For example, a maintenance technician could use ultrasonic equipment to "hear" a bearing ring and surrounding housing resonating at the resonant frequency. Once detected, a maintenance technician could then proceed to find the cause of the problem. (Insufficient lubrication and minor bearing material defects would be the likely cause of this malfunction.)

Theory, Applications, and Techniques

Some of the most common plant applications of ultrasound detection are: leak detection in pressure and vacuum systems (i.e., boiler, heat exchanger, condensers, chillers, distillation columns, vacuum furnaces, specialty gas systems), bearing inspection, steam trap inspection, valve blow-by, pump cavitation, detection of corona in switch gear, compressor valve analysis, and the integrity of seals and gaskets in tanks, pipe systems, and large walk-in boxes. The information in the following sections is applicable to all airborne ultrasonic devices. Any specific procedures listed are those followed when using an UltraProbe 2000 (manufactured by UE Systems). While specific to a particular ultrasonic probe,

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these procedures illustrate the effort involved when using any ultrasonic sensing equipment.

Basic Theory of Ultrasonic Detection

All operating equipment and most leakage problems produce a broad range of sound. The high frequency ultrasonic components of these sounds are extremely short wave in nature, and a short wave signal tends to be fairly directional. It is therefore easy to isolate these signals from background noises and detect their exact location. In addition, as subtle changes begin to occur in mechanical equipment, the nature of ultrasound allows these potential warning signals to be detected early — before actual failure.

Airborne ultrasound instruments, often referred to as "ultrasonic translators," provide information two ways: qualitatively, due to the ability to "hear" ultrasounds through a noise isolating headphone, and quantitatively, via incremental readings on a meter. This is accomplished in most ultrasonic translators by an electronic process called "heterodyning," which accurately converts the ultrasounds sensed by the instrument into the audible range where users can hear and recognize them through headphones.

Although the ability to gauge intensity and view sonic patterns is important, it is equally important to be able to "hear" the ultrasounds produced by various equipment. That is precisely what makes these instruments so useful; they allow inspectors to confirm a diagnosis on the spot by being able to discriminate among various equipment sounds.

The reason users can accurately pinpoint the location of a particular ultrasonic signal in a machine or from a leak is due to its high frequency short wave. Most of the sounds sensed by the human ear range between 20 Hz and 20 kHz (20 cycles per second to 20,000 cycles per second). They tend to be relatively gross when compared with the sound waves sensed by ultrasonic translators. Low frequency sound in the audible range are approximately 1.9 cm to 17 m in length, whereas ultrasounds sensed by ultrasonic translators are only 0.3 to 1.6 cm long. Since ultrasound wave lengths are magnitudes smaller, the ultrasonic environment is much more conducive to locating and isolating the source of problems in loud plant environments.

Airborne ultrasound translators are relatively simple to use. They consist of a basic handheld unit with headphones, a meter, a sensitivity adjustment, and (most often) interchangeable modules that are used in either a scanning or a contact mode. Some instruments have the ability to adjust the frequency re-

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sponse from between 20 to 100 kHz. An ultrasonic transmitter called a tone generator is often included.

Many of these features are useful in helping a user adapt to a specific test situation. For example, if an ultrasound source is too difficult to locate due to an intense signal, a user can focus on the exact site by adjusting the sensitivity downward. In another instance, if a low level leak occurs in a water valve, the frequency tuning can be adjusted to help a user hear the trickle of the water leak.

Interchangeable modules allow users to adjust for different types of inspection problems. The scanning mode is used to detect ultrasounds that travel in the atmosphere such as a pressure leak or a corona discharge, while the contact mode is used to detect ultrasounds generated within a casing such as in a bearing, pump, valve, or steam trap housing.

Leak Detection

This category covers a wide area of plant operations. It can be viewed as a way of keeping a system running more efficiently. Some plants include it as part of an energy conservation program, while others refer to it as fugitive emissions. Regardless, leaks cost money, affect product quality, and can wreak havoc with the environment. Ultrasonic detection can often locate the problem, whether the leakage occurred in a liquid or a gas system.

The reason ultrasound is so versatile is that it detects the sound of a leak. When a fluid (liquid or gas) leaks, it moves from the high pressure side through the leak site to the low pressure side, where it expands rapidly and produces a turbulent flow. This turbulence has strong ultrasonic components. The intensity of the ultrasonic signal falls off rapidly from the source, allowing the exact spot of a leak to be located.

Generalized gas leak detection is also very easy. An area should be scanned while listening for a distinct rushing sound. With continued sensitivity adjustments, the leak area is scanned until the loudest point is heard.

Some instruments include a rubber focusing probe that narrows the area of reception so that a small emission can be pinpointed. The rubber focusing probe is also an excellent tool for confirming the location of a leak. This is done by pressing it against the surface of the suspected area to determine if the sound of the leak remains consistent. If it decreases in volume, the leak is elsewhere.

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Vacuum leaks may be located in the same manner; the only difference being that the turbulence will occur within the vacuum chamber. For this reason, the intensity of the sound will be less than that of a pressurized leak. Though it is most effective with low-mid to gross leaks, the ease of ultrasound detection makes it useful for most vacuum leak problems.

Liquid leaks are usually determined through valves and steam traps, although some successes have been reported in locating water leaks from pressurized pipes buried underground. A product can be checked for leakage if it produces some turbulence as it leaks.

Valves are usually checked for leakage with the contact probe on the downstream side. This is accomplished by first touching the upstream side and adjusting the sensitivity to read about 50 percent of scale. The downstream side is then touched and the sound intensity is compared. If the signal is lower than upstream, the valve is considered closed; if it is louder than upstream and is accompanied by a typical rushing sound, it is considered to be leaking.

Steam traps are also inspected easily with ultrasonic translators. During the steam trap operation and while observing the meter, trap condition can be interpreted. The speed and simplicity of this type of test allow every trap in a plant to be routinely inspected. Each type of steam trap produces a distinct sound as briefly described below.

1. *Intermittent Traps* - When the trap is operating properly, the operator will hear an open and closing sound. The trap normally fails in the open position, producing a continuous, rushing sound.

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

3. *Thermostatic* - Ultrasonic testing results of thermostatic traps vary. The noise produced by these traps can be continuous or intermittent and will produce different sounds accordingly.

4. *Float and Thermostatic (Continuous Load)* - Flow in these traps is usually modulated. Failed traps are normally cold and silent.

5. *Continuous Flow* - This type of trap, when operating normally, produces the intermittent sound of condensate flow only. If it has failed in the open position, a continuous flow sound should be heard.

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Leaking tubes in heat exchangers and condensers as well as boiler casing leaks are detectable with ultrasonic translators. In most power plants, the problem of condenser in-leakage is a major concern. Condenser fittings are often routinely inspected using the leak detection method previously described. If a leak is suspected in a condenser tube bundle, it is possible to locate the leak by putting a condenser at partial load and opening up a water box of a suspected tube bundle. After the tube sheet is cleared of debris, the tube sheet is scanned.

How To Locate Leaks

Select the Log setting on the meter selection dial. Use "fixed band" position on the Frequency selection dial. If too much background noise is present, try some of the shielding methods. Start off with the sensitivity selection a 10 (maximum). Begin to scan by pointing the module towards the test area. The procedure is to go from the "gross" to the "fine" with more subtle adjustments made as the leak is approached.

If there is too much ultrasound in the area, reduce the sensitivity setting and continue to scan. If it is difficult to isolate the leak due to competing ultrasound, place the rubber focusing probe over the scanning module and scan the test area. Listen for a rushing sound while observing the meter. Follow the sound to the loudest point. The meter will show a higher reading as the leak is approached. To focus in on the leak, keep reducing the sensitivity setting and move the instrument closer to the suspected leak site until you can confirm a leak.

To confirm a leak, position the rubber focusing probe (if it is on the scanning module) close to the suspect leak site and move it slightly back and forth in all directions. If the leak is at this location, the sound will increase and decrease in intensity as you sweep over it. In some instances, it is useful to position the rubber focusing probe directly over the suspect leak site and push down to seal it from surrounding sounds. If the probe is over the leak, the rushing sound will continue. If it is not the leak site, the sound will drop off.

Overcoming Competing Ultrasounds

If competing ultrasounds make it difficult to isolate a leak, there are two options: manipulate the environment, i.e., when possible, turn off the equipment that is producing the competing ultrasound or isolate the area by closing a door or window. Manipulate the instrument and use shielding techniques.

If environmental manipulation is not possible, try to get as close as possible to the test site and manipulate the instrument so that it is pointing away from the

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competing ultrasound. Isolate the leak area by reducing the sensitivity of the unit and by pushing the tip of the focusing probe up to the test area, checking a small section at a time.

In some extreme instances, when the leak check is difficult in the fixed band mode of the frequency selection dial, try to tune in to the leak sound by tuning out the problem sound. In this instance, adjust the frequency selection dial until the background sound is minimized and then proceed to listen for the leak.

Since ultrasound is a high frequency, short wave signal, it can usually be blocked or shielded.

Note: when using any method, be sure to follow your plant or company safety guidelines.

Electrical Problems

Three types of high voltage electrical problems detectable with ultrasound are:

1. *Arcing*: An arc occurs when electricity flows through space. Lightning is a good example.

2. *Corona*: When voltage on an electrical conductor, such as an antenna or high voltage transmission line, exceeds threshold value, the air around it begins to ionize to form a blue or purple glow.

3. *Tracking*: Often referred to as "baby arcing," electricity follows the path of damaged insulation, using surrounding dirt, debris, and moisture as the conductive medium.

Although theoretically, ultrasonic detection can be used in low, medium, and high voltage systems, applications normally use medium and high voltage systems. When electricity escapes in high voltage lines or when it jumps across a gap in an electrical connection, it disturbs the air molecules around it and generates ultrasound. Often this sound will be perceived as a crackling or frying sound; in other situations, it will be heard as a buzzing sound. Applications include: insulators, cable, switchgear, bus bars, relays, contractors, and junction boxes. In substations, components such as insulators, transformers, and bushings may be tested. Ultrasonic testing is often used for evaluation at voltages exceeding 2,000 volts, especially in enclosed switchgear. This is especially useful in identifying corona problems. In enclosed switchgear, the frequency of detection of corona greatly exceeds the frequency of serious faults identified by infrared. It is

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recommended that both tests be used with enclosed switchgear. When testing electric equipment, follow plant or company safety procedures. When in doubt, ask your supervisor. Never touch live electrical apparatus with the system.

The method for detecting electric arc and corona leakage is similar to the procedure outlined in leak detection. Instead of listening for a rushing sound, a user will listen for a crackling or buzzing sound. In some instances, as in trying to locate the source of radio/TV interference or in substations, the general area of disturbance may be located with a gross detector such as a transistor radio or a wide-band interference locator. Once the general area has been located, the scanning module is used with a general scan of the area. The sensitivity is reduced if the signal is too strong to follow on the meter until the loudest point is located. Determining whether a problem exists is relatively simple. By comparing sound quality and sound levels among similar equipment, the problem will become easy to identify, even though the sound itself will differ somewhat as it resonates through various types and sizes of equipment.

On lower voltage systems, a quick scan of bus bars will often pick up a loose connection. Checking junction boxes can reveal arcing. As with leak detection, the closer one gets to the leak site, the louder the signal. If power lines are to be inspected and the signal does not appear to be intense enough to be detectable from the ground, you can use an ultrasonic waveform concentrator (a parabolic reflector), which will double the detection distance of the system and provide pinpoint detection.

Ultrasonic Inspection

Ultrasonic inspection and monitoring of bearings is a reliable Method for detecting incipient bearing failure. The ultrasonic warning appears prior to a rise in temperature or an increase in driving torque. Ultrasonic inspection of bearings is useful in recognizing the beginning of fatigue failure, brinnelling of bearing surfaces, flooding (or lack) of lubricant.

In ball bearings, as the metal in the raceway, roller, or bearing balls begins to fatigue, a subtle deformation begins to occur. This deforming of the metal will produce an increase in the emission of ultrasonic sound waves. When testing, changes in amplitude of from 12 to 50 times the original reading is indication of incipient bearing failure. When a reading exceeds any previous reading by 12 dB, it can be assumed that the bearing has entered the beginning of the failure mode. This information was originally discovered through experimentation performed by NASA on ball bearings. In tests performed while monitoring bearings at frequencies ranging from 24 through 50 kHz, the changes in amplitude indi-

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cated the onset of, or incipient, bearing failure before other indicators, including heat and vibration changes. (An ultrasonic system based on detection and analysis of modulations of bearing resonance frequencies can provide subtle detection capability, whereas conventional methods have difficulty detecting very slight faults.) As a ball passes over a pit or fault in the race surface, it produces an impact. A structural resonance of one of the bearing components vibrates or rings by this repetitive impact. The sound produced is observed as an increase in amplitude in the monitored ultrasonic frequencies of the bearing.

Brinelling of bearing surfaces will produce a similar increase in amplitude due to the flattening process as the balls get out of round. These flat spots also produce a repetitive ringing that is detected as an increase in amplitude of monitored frequencies. The ultrasonic frequencies detected by the system are reproduced as audible sound. This signal can greatly assist a user in determining bearing problems. When listening, it is recommended that a user become familiar with the sounds of a good bearing; often heard as a rushing or hissing noise. Crackling or rough sounds indicate a bearing in the failure stage. In certain cases a damaged ball can be heard as a clicking sound, whereas a high intensity may indicate uniform ball damage. Loud rushing sound of a good bearing only slightly rougher can indicate lack of lubrication. There are two basic procedures of testing for bearing problems: comparative and historical. The comparative method involves testing two or more similar bearings and comparing potential differences. Historical testing requires monitoring a specific bearing over a period of time to establish its history. By analyzing bearing history, wear patterns at particular ultrasonic frequencies become obvious, allowing for early detection and correction of bearing problems.

Comparative Test

Use the contact (stethoscope) module. Select LIN on the meter selection dial. Select the desired frequency on the frequency selection dial. Select a test spot on the bearing housing and mark it for future reference. Touch that spot with the contact module. In ultrasonic sensing, the more media or materials ultrasound has to travel through, the less accurate the reading will be. Therefore, be sure the contact probe is actually touching the bearing housing. If this is difficult, touch a grease fitting or touch as close to the bearing as possible. For consistency, always approach the test spot at the same angle. Reduce sensitivity until the meter reads 20. Listen to the bearing sound through headphones to hear the quality of the signal for proper interpretation. Select same type bearings under similar load conditions and same rotational speed. Approach the bearings at the same angle, touching approximately the same area on the bearing housing. Compare differences of meter reading and sound quality.

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Historical Bearing Test

There are two methods to historically trend a bearing. The first is a very common, field proven method called the "simple" method. The other provides greater flexibility in terms of decibel selection and trending analysis, and is referred to as the "attenuator transfer curve" method. The "attenuator transfer curve" method is used in the Bearing Trac software, which provides trending, graphs, and historical analysis. Before starting with either of the two historical methods for monitoring bearings, the comparative method must be used to determine a baseline.

Simple Method

Use the basic procedure as outlined above in the comparative test. Note frequency, meter reading, and sensitivity selection on your bearing history chart. Compare this reading with previous or future readings. On all future readings, adjust frequency and sensitivity level to the original level recorded in the bearing history chart. If the meter reading has moved from the original "20" mark up to or past 100, there has been a 12 dB increase. (Increments of 20 on the meter in the linear mode is about 3 decibels; e.g., 20 – 40 = 3 dB, etc.) Note: Increase of 12 dB or greater indicates the bearing has entered a failure mode. Lack of lubrication is usually indicated by an 8 dB increase over baseline. It is usually heard as a loud rushing sound. If lack of lubrication is suspected, after lubricating, retest. If readings do not go back to original levels and remain high, consider that the bearing may fail soon and recheck frequently.

Lack of Lubrication

To avoid lack of lubrication, note the following: as the lubricant film reduces, the sound level will increase. A rise of about 8 dB over baseline accompanied by a uniform rushing sound will indicate lack of lubrication. When lubricating, add just enough to return the reading to baseline. Use caution. Some lubricants will need time to run to uniformly cover the bearing surfaces. Lubricate a little at a time. Do not over lubricate.

Overlubrication

One of the most frequent causes for bearing failure is overlubrication. The excess stress of lubricant often breaks bearing seals or causes a buildup of heat, which can create stress and deformity. To avoid overlubrication do not lubricate if the baseline reading and baseline sound quality is maintained. When lubricating, use just enough lubricant to bring the ultrasonic reading to baseline. As

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mentioned above, use caution. Some lubricants will need time to uniformly cover the bearing surfaces.

Ultrasonic Translators

It is advisable to have instruments that are sensitive enough to detect the type of problems you will encounter in the plant. A wide dynamic range in an instrument enables you to look for small leaks on one end and locate gross mechanical problems on the other. Since sound quality is an important consideration, make sure the instrument heterodynes the ultrasonic signal. This will assure users that they are getting an accurate reproduction of the ultrasonic signal, for signal clarity and interpretation of the headphone sound. It is essential to have noise-attenuating headphones with good sound quality. If the sound quality is not clear, it will be difficult to understand what is being sensed. It is advisable to get over-the-ear headphones that will block out ambient plant sounds during inspections. Without proper radio frequency RF shielding, stray electronic signals will interfere with test results. In some instances, radio programs have been heard, a phenomenon that totally confused operators.

Since every plant is different, special accessories may be needed to assist in some situations. For example, compressor valve analysis might be easier with a magnetically mounted probe and an oscilloscope interface. If you are going to inspect a variety of equipment or have fluids of different viscosities, it would be useful to have the ability to change frequencies. For leak detection of potentially explosive or flammable gases, it is advisable to use equipment that is rated intrinsically safe.

Limitations

Airborne ultrasonics are subjective and depend 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 realize that piping bends and the presence of moisture and solids may dissipate and/or block the ultrasonic signal.

Logistics

If a vibration program already exists for bearing analysis, an ultrasonic bearing monitoring program can help. Ultrasound translators can be used to aid a diagnosis. The high frequency, short wave characteristic of ultrasound allows the

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signal to be isolated so that a user can determine if a bearing has been correctly diagnosed as failing.

At times equipment connected to a particular bearing can generate false signals. By adjusting the sensitivity and frequency, and by listening to the sound, one can determine whether it is the bearing, a rotor, or something else that is the root of the problem. The ability to hear what is going on can prove very important. Ultrasound detectors work well on slow speed bearings. In some extreme cases, just being able to hear some movement of a bearing through a well greased casing could provide information about potential failure. The sound might not have enough energy to stimulate classic vibration accelerometers, but will be heard via ultrasonic translators, especially those with frequency tuning. Sometimes there are so many bearings in a plant that not every piece of equipment can be checked routinely by a limited staff of trained technicians. Since ultrasound technicians require little training, a technician or the machine operator can determine potential bearing problems and notify the vibration technician for follow-up.

Equipment Required

The equipment required for performing ultrasonic detection of faulty equipment is an ultrasonic monitoring scanner for airborne sound or ultrasonic detector for contact mode. (With the contact mode detector, contact to the equipment in question is made with a metal rod. This is the high-tech version of the maintenance technician putting a screwdriver on a piece of equipment and putting his ear to the other end.)

Operators

Maintenance technicians and maintenance engineers are easily taught ultrasonic detection.

Training Available/Required

Minimal training is required with the exception of that required for use of multichannel Acoustic Valve Leak Detectors (AVLDs).

Cost

The price of scanners and accessories ranges from $1,000 to approximately $8,000. Complex acoustic valve leak detection systems are approximately $100,000.

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8 Lubricant and Wear Particle Analysis

Purpose

Lubricating oil analysis is performed for three reasons:

1. To determine the machine mechanical wear condition
2. To determine the lubricant condition
3. To determine if the lubricant has become contaminated.

A wide variety of tests can 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. The three areas are not unrelated; 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 test packages that provide information about all three areas.

Machine Mechanical Wear Condition

The criteria for analyzing the lubricating oil to determine the machine's condition are generally the same as for performing vibration analysis. This analysis is applicable to all machines with motors 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 with a condition history (a year or more of data), this is typically performed quarterly.

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 machines, those with oil reservoirs 1 gal 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,

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the costs to replace the automobile oil (the replacement oil, labor to change the oil, and disposal costs) are lower than the cost to analyze the oil (i.e., the cost of sample materials, labor to collect the sample, and the analysis). In the case of automobile oil, time-based replacement is cheaper than analysis due to competition and the economies of scale that have been created to meet the consumer need for replacing automobile oil.

In the case of lubricating oil used in facility equipment, simply replace and discard the machine lubricating oil if it is cheaper than analyzing it. When making this decision, the maintenance manager must have firm prices for materials used to take samples and the labor hours it will take to collect, package, and send the samples out for analysis. Remember, though, that one oil sample is sufficient for many tests.

Lubricant Contamination

Lubricating oil can become contaminated due to the machine's operating environment, improper filling procedures, or through the mixing of different lubricants in the same machine. If a machine is "topped off" with oil frequently, the maintenance technician should send the oil out for analysis periodically to check the machine for any serious problems.

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.

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. Other odors could indicate contamination. Odor is more subjective than the visual inspection because people's sensitivity to smell varies, and there is no effective way

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to compare the odor between samples. The operator must be careful not to introduce dirt into the system when taking a sample.

Viscosity

Viscosity is a measure of oil flow rate at a specified temperature. A change (increase or decrease) in viscosity over time indicates changes in the lubricant condition, or it may indicate lubricant contamination. Viscosity can be tested using portable equipment, or it can be tested more accurately in a laboratory using the ASTM D445 procedure. Viscosity is measured in centistoke (cSt), and minimum and maximum values are identified by the ISO grade. Testing oil viscosity is usually part of a commercial laboratory standard test package.

Water

Water in lubricating oil and hydraulic fluid contributes to corrosion and formation of acids. Small amounts of water (less than 0.1 percent) can be dissolved in oil and can be detected using the crackle test or infrared spectroscopy (minimum detectable is 0.05 percent or approximately 500 ppm by both methods), the ASTM D95 distillation method (minimum detectable is 0.01 percent/100 ppm), the ASTM D1744 Karl Fischer method (minimum detectable is 0.002 percent/100 ppm). If greater than 0.1 percent water is suspended or emulsified in the oil, the oil will appear cloudy or hazy. Free water in oil collects in the bottom of oil reservoirs and can be found by draining them from the bottom.

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 percent of volume and is usually part of a commercial laboratory standard test package.

Total Acid Number

Total Acid Number (TAN) 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 (mg KOH/g). KOH is used in a titration process and the end point is indicated by color change (ASTM D974) or electrical conductivity change (ASTM D664).

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Total Base Number (TBN)

Similar to the TAN test method, the TBN test measures alkalinity (ability to neutralize acid) of oil sample. This 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 (per ASTM D664 or ASTM D2896). When comparing test results from your oil against baseline data from the oil supplier, make sure that the same test method was used for your oil as was used in generating the baseline data. Results can vary significantly between test methods.

Spectrometric Metals

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

Infrared Spectroscopy

This technique is also known as infrared analysis, infrared absorption spectroscopy or spectrophotometry, and Fourier Transform Infrared (FTIR) spectroscopy. The technique examines the infrared wavelength that is absorbed by the oil sample. The test is used to identify nonmetallic contamination (see Water, discussed above in this chapter) and lubricant conditions (e.g., oxidation, antioxidant, other additive depletion). In the future, it may become possible to couple computer expert system analysis with known oil spectra, in an effort to produce highly accurate diagnoses 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.

Analytical Ferrography

More detailed than Direct Reading (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 expensive or critical machines. The test process is labor intensive and involves the preparation of sample and examination under magnification. Results vary with the analyst's capability, but the procedure can provide detailed infor-

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mation regarding wear: e.g., wear type (rubbing, sliding, cutting), color, particle types (oxide, corrosive, crystalline), and other nonferrous particles. This detailed information can be critical in finding the root cause of wear problems. Costs are moderately high; the test is performed on a fixed price basis (per sample) from a commercial laboratory.

Special Tests

Special tests are sometimes needed to monitor lubricant conditions on some expensive or critical systems. Usually the special test is used to monitor a lubricant contaminant, a characteristic, or additive depletion. This section identifies some of the special tests available. Special tests are rarely needed for routine monitoring of lubricants. The list of special tests presented here is not meant to be all-inclusive — only a list of samples. Test procedures are constantly being developed and refined. The annual ASTM Standards provides a description of current test methods,

Glycol Antifreeze

Glycol contamination can be detected using infrared spectroscopy (see Infrared Spectroscopy, discussed earlier) at levels greater than 0.1 percent (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 D2982 will indicate if trace amounts are present. ASTM D4291 uses gas chromatography to quantify small amounts of glycol.

Karl Fischer Water

Water contamination can be detected using infrared spectroscopy (see Infrared Spectroscopy, p 74) at levels greater than 0.05 percent (500 ppm), which is usually adequate for condition monitoring. Using a titration process with a Karl Fischer reagent, low levels of water can be detected and quantified. The test, ASTM D1744, is useful when accepting new oil or evaluating clean up efforts. Cost of the test is moderate.

Foamlug

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

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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 an 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.

Rotating Bomb Oxidation Test (RBOT)

Also known as the Rotary Bomb Oxidation Test, ASTM D 2272 is used to estimate oxidation stability and the remaining useful life of oil. The test simulates aging, identifying when rapid oxidation takes place and indicating that antioxidants have been depleted. The test is not a one time test; it must be performed over time, starting with a baseline test of the new oil. Subsequent tests are necessary to develop the 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.

Application

Typically, lubricating oil analysis should be performed on a quarterly basis on all machines with motors 7.5 HP or larger, and on all critical or expensive machines. The analysis schedule should be adjusted in the same way that the vibration analysis schedule is adjusted. Analyze more frequently for machines that are indicating emerging problems; less frequently for machines that operate under the same 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 on the machine size and the cost effectiveness of performing the analysis. Generally, it is more cost effective in mobile equipment to maintain the hydraulic fluid based on 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. To get a representative sample that is a homogeneous mixture of the grease, contaminants, and wear, the machine must usually be disassembled. Once a machine has failed and must be disassembled, analysis of the grease to diagnose the failure can sometimes be useful.

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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 contaminants. Increases in contaminants indicate breakdown in the systems 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 of contamination. Some bearing lubricating systems have such a small amount of oil that a weekly check may be impractical.

Motors, Generators, Pumps, Blowers, Fan

For machines with less than 5 gal in the lubrication system, the analyst is mostly concerned with machine condition. Lubricant condition and contamination are of interest because they provide some indication of machine condition. Routinely monitor viscosity, percent solids/water, and spectrometric metals. Monitor trends and discard or refresh the oil when viscosity changes 10 percent from the baseline. Viscosity normally increases above the baseline with the oil service time. If the viscosity decreases below the baseline, it usually means that the oil is contaminated, probably from adding the wrong type of makeup oil. There should be no water present (minimum detectable water is 0.1 percent). If there is water, the source of the water needs to be identified and corrected. For machines with more than 5 gal of oil in the system, add infrared spectroscopy (minimum amount of water detectable is 0.05 percent) 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 expensive or critical machines. In all machines, changes in spectrometric metals or DR should be investigated further using analytical ferrography and correlated with vibration analysis.

Gearboxes

Same as above, except for gearboxes with less than 5 gal of oil, add particle counting. Implement DR ferrography for high cost or critical gearboxes. Monitor trends and correlate with vibration readings.

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Chillers

In addition to the items identified above, add Total Acid Number (TAN) and DR ferrography.

Diesel Engines

Use the same procedure as for chillers except substitute Total Base Number (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.

Compressors

Centrifugal compressors should be treated the same as chillers. Reciprocating compressors should be treated the same as diesel engines.

Hydraulic Systems

Perform the same oil analysis as that performed on 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). For these systems, oil analysis does not apply; however, perform particle control the same as for oil-filled hydraulic systems.

Large Reservoirs

For reservoirs over 500 gal, consider performing a Rotating Bomb Oxidation Test (RBOT) to assess the oxygen stability. Cost is usually the deciding factor. At least three tests are needed to develop a trend. Once the trend has been established, additional retesting should be performed at least once a year. Maintenance dollars are saved when replacing or refreshing a large volume of oil (or smaller volume of expensive oil).

Lubrication Analysis

As one can see from reading the above, there are numerous lubrication tests. Commercial laboratories performing the tests have charts available that summarize the various lubricant tests, monitoring interval, and application.

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Sampling

Oil samples must be collected safely and in a manner that will not introduce dirt and other contaminants into the machine/system, or into the sample. It may be necessary to install permanent sample valves in some lubricating systems. 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 upstream of the filter in circulating systems. Sample collection bottles and tubing can be procured through testing laboratories. The testing laboratory can also 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 to ensure 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 to make recommendations to correct abnormalities.

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9 Electrical Condition Monitoring

Electrical condition monitoring encompasses several technologies and techniques used to provide a comprehensive system evaluation. Electrical equipment represents a major portion of a facility's capital investment. From the power distribution system to electric motors, efficient operation of the electrical systems is crucial to maintaining operational capability of a facility.

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 involve life cycle cost issues (premature replacement of equipment). According to the Electric Power Research Institute, voltage imbalances of as little as 5 percent in motor power circuits result in a 50 percent reduction in motor life expectancy and efficiency in three phase AC motors. A 2.5 percent increase in motor temperatures can be generated by the same 5 percent voltage imbalance accelerating insulation degradation.

Techniques

- infrared thermography
- airborne ultrasonics
- transformer oil analysis
- megohmmeter testing
- high potential testing (HiPot)
- surge testing
- conductor complex impedance
- time domain reflectometry (TDR)
- motor current spectrum analysis
- RF monitoring
- power factor and harmonic distortion
- starting current and time

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- motor circuit analysis (MCA)
- motor current readings
- turns ratio

(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 normally are performed only for acceptance testing, not for condition monitoring.)

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 1 minute, and then again compare the readings after 10 minutes. This ratio is referred to as the polarization index.

High Potential Testing (HiPot)

HiPot testing applies a voltage equal to twice the operating voltage plus 1000 volts to cables and motor windings to test the insulation system. This is typically a "go/no-go" test. Industry practice calls for HiPot tests on new and rewound motors. This test stresses the insulation systems and can induce premature failures in marginal motors. 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 lower voltage and increase the applied voltage in steps and measure the change in insulation resistance readings.

Surge Testing

Surge Testing uses 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 are provided as a comparison of waveforms between two phases indicating the relative condition of the two phases with regard to short circuits. The readings for a particular motor can be trended, but the repeated stress of the insulation system is not recommended.

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Conductor Complex Impedance

The total resistance of a conductor is the sum of its resistance, capacitive impedance, and inductive impedance. Accurate measurement of the conductor impedance allows minor degradations in a motor to be detected and addressed prior to motor 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 contaminant forming the second plate. Maintaining proper phase balance is imperative to efficient operation and toward realizing the full lifetime of electrical equipment.

Time Domain Reflectometry

In this test, a voltage spike is sent through a conductor. Each discontinuity in the conductor path generates a reflected pulse. The reflected pulse and time difference between initial pulse and reception of the reflected pulse indicate the location of the discontinuity.

Motor Current Spectrum Analysis (MCSA)

MCSA is a method of detecting the presence of broken or cracked rotor bars or high resistance connections in end rings. Motor current spectra in both time and frequency domains are collected with a clamp-on ammeter and Fast Fourier Transform (FFT) analyzer. Rotor bar problems will appear as side-bands around the power supply line frequency. MCSA evaluates the amplitude of the side bands that occur about the line frequency.

Radio Frequency (RF) Monitoring

RF monitoring was developed to detect arcs caused by broken windings in generators. It consists of establishing RF background levels and the amplitude trend over a narrow frequency band.

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. If this detects a low power factor, subsequent engineering analysis will be required to devise a means of improving power system power factor.

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Motor Current Readings

Clamp-on ammeter attachments provide the capability to take actual current draw information while the equipment is operating. On three-phase equipment, comparison of current draws can reveal phase imbalance conditions.

Airborne (Passive) Ultrasonics

Refer to Chapter 7.

Transformer Oil Analysis

Refer to Chapter 8.

Applications

Equipment to be Monitored

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

1. *Electrical Distribution Cabling* - Megohmmeter, Time Domain Reflectometry, HiPot, IRT (if visible), and Airbourne Ultrasonics

2. *Electrical Distribution Switchgear and Controllers* - Timing, Visual Inspection, IRT, and Airborne Ultrasonics

3. *Electrical Distribution Transformer* - Oil Analysis, Turns Ratio, Power Factor, and Harmonic Distortion

4. *Electrical Motors* - Current Draw, Motor Current Spectrum Analysis, Motor Circuit Analysis, Megohmmeter. HiPot, Surge Test, Conductor Complex Impedance, Starting Current, and Coast-Down Time

5. *Generators* - Megohmmeter, RF, and Coast-Down Time

6. *Distribution System* - HiPot, Ultrasonics, Power Factor, and Harmonic Distortion.

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Conditions Monitored

Conditions to be monitored are: voltage, current, resistance, complex impedance, capacitance, insulation integrity, phase imbalance, mechanical binding and presence of arcing.

Detection Interval

Monitoring intervals of several weeks to several months 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. Several of the technologies outlined are also effective when used for acceptance testing and certification.

Accuracy

Accuracy depends on the technique applied and rating of instrument.

Limitations

The technologies presented can be divided into two categories:

- *Energized*. Those technologies that can safely provide information on energized systems and require the system be energized and operational. These technologies include IRT, Ultrasonics, Motor Current Readings, Starting Current, Motor Current Spectrum Analysis, RF, Power Factor, and Harmonic Distortion.
- *De-Energized*. Technologies that require the circuit to be de-energized for safe usage include Surge Testing, HiPot Testing, Time Domain Reflectometry (TDR), Megohmmeter, Motor Circuit Analysis, Transformer Oil Analysis, Turns Ratio, and Conductor Complex Impedance.

Each technology will require specific initial conditions to be set prior to conducting the test. For instance, prior to an IRT survey, typical equipment powered through the switch board 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.

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Logistics

Equipment Required

A comprehensive electrical testing program includes: multi-meters/volt-ohmmeters, current clamps, TDR, motor current spectrum analysis software, and integrated motor circuit analysis testers.

Operations

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

Training Available

Equipment manufacturers and consultants specializing in electrical testing techniques provide classroom training and seminars to teach these techniques.

Cost

- *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 should cost from about $30,000 to $75,000.
- *Training.* Training averages between $750 and $1,000 per week per person trained.

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10 Non-Destructive Testing

Non-Destructive Testing (NDT) evaluates material properties and quality of manufacture for expensive 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. Typically, NDT has been associated with the 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 ensure integrity of pressure boundaries for systems processing volatile substances.

Techniques

The following section discusses various NDT techniques.

Radiography

Radiography is performed to detect sub-surface defects. Radiography or X-ray is one of the most powerful NDT technique 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 ensure the proper exposure angle through the material. When all preparations and safety precautions are complete, the radiation source is energized or unshielded.

Gamma or X-rays pass through a material and expose film placed under the material. By developing the film in a manner similar 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.

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

Defects in the material must be accurately located to facilitate minimal material removal, yet ensure the defect has been completely eliminated. Minimizing material removal also minimizes repair cost and reduces the likelihood of additional defects created by the repair. The repair is then re-evaluated to ensure 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, or that personnel be 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 and rarely worth the expense. 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.

Ultrasonic Testing (Imaging)

Ultrasonic testing provides 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 dependent on the skill of the operator, UT does not produce the harmful radiation entailed with radiography. UT inspection is based on the difference in the wave reflecting properties of defects and the surrounding material. An ultrasonic signal is applied through a transducer into the 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 use a transmit 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 shifts. The signals travel between a specific surface and discontinuities. "B Scan" sys-

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tems 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 (4 to 8 sq in.) 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 samples of materials subjected to high stress levels, high corrosion areas and large welds. By evaluating the same sites at regular intervals, one can monitor the condition of the material. One hundred percent UT inspection is typically reserved for original construction of high stress components such as nuclear reactor vessels or chemical process vessels.

Magnetic Particle Testing

The NDT technique uses 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 ability 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. 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 are important to ensure consistent strength in the lines of magnetic flux.

A major advantage for MT is its portability and speed of testing. The hand-held electrodes allow 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 depends on the experience of the operator.

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Dye Penetrant

Dye Penetrant is used to detect surface defects. Dye penetrant (DP) inspections provide a simple method for detecting surface defects in nonporous 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.

Hydrostatic Testing

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 subsystems that act as pressure boundaries. As the name implies, hydrostatic tests fill the system to be tested with water or the operating fluid. The system is then sealed and the pressure is increased to approximately 1.5 times operating pressure.

This pressure is held for a defined period. During the test, inspections are conducted to find visible leaks to well as monitor pressure drop and make-up water additions. If the pressure drop is out of specification, the leak(s) 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.

Eddy Current Testing

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

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A set of magnetizing coils is used to induce electrical currents (eddy currents) into the component being tested. The induced currents produce magnetic fields, that 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 10 MHz) determines the depth of penetration through the material for the eddy currents. Lower excitation frequencies increase the penetration depth and improve effectiveness in detecting deeper defects. Higher frequencies are used 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 reliance on operator experience for consistent results.

Location and Intervals

Before 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 from each sample, and failure mode that each sample addresses. This plan will point out excessive testing as well as omissions from the NDT Program. Two of the more difficult variables to address are location and interval (time period) between inspections.

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, consequences of system breach, and type of NDT techniques applicable to the situation. All these will affect the inspection interval (Table 2).

Table 2. Recommended maximum inspection intervals (API 570).

Piping Circuit Classification	Thickness Measurements	External Visual Inspection
Class 1	5 years	5 years
Class 2	10 years	5 years
Class 3	10 years	10 years
Injection points	3 years	By class
Soil-to-air interfaces	N/A	By class

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American Petroleum Institute (API 570) recommends the following criteria for establishing intervals for NDT inspection: a piping service classification where Class 1 has the highest potential of resulting in an immediate emergency if a leak were to occur, any Class 3 has the lowest potential of resulting in an immediate emergency.

Relevant regulatory requirements must be taken into account when determining NDT inspection intervals. The multitude of professional codes and government regulations present this section from attempting 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." To ensure good reports from regulatory inspectors, inspection costs were significantly increased without a corresponding increase in plant safety or reliability. Investigate basic requirements and, if these are unclear, ask the originating agency for clarification of their expectations.

After the base inspection intervals have been established based on corrosion rate, class, and regulatory requirements, specific system intervals can be modified based on actual conditions, historical data, and operating parameters. Evaluate intervals based on operating conditions, previous history, current inspection results, or other indications of other than normal conditions. By conducting statistical analysis on historical NDT results and failure rates, intervals can be refined with a higher level of confidence. Pareto and Weibull analysis techniques can be applied to indicate systems where unusual failure rates are occurring. Corrosion coupons can be used to provide specific information on the corrosion rate of systems, allowing further refinement of inspection intervals. Process parameters can be used as "triggers" for specific NDT inspections. As thermodynamic properties change, they can provide indications of increased corrosion 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 overpressurization 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.

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Locations

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

- *Presence of "Dead-Heads"* that can create turbulence or stagnate 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.
- *Abrupt changes in direction of flow (elbows) and changes in pipe diameter* will cause turbulence that may accelerate many corrosion mechanics.
- *Stressed areas, welds, high stress fasteners and areas that undergo cyclic temperature / pressure changes, or flow changes.*
- *Some applications may warrant specifying top, middle or bottom of pipe* or areas of where more than one phase of a substance is present.
- *Areas where accelerated corrosion / erosion mechanisms* have been identified
- *Areas susceptible to cavitation.*

Applications

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

2. *Ultrasonics.* UT techniques are applicable to metal components including weld deposits. Specialized applications for plastics or composite materials are common. When 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.

3. *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.

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

5. *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.

6. *Eddy Current.* Eddy current techniques are used to detect internal defects such as cracks, seams, holes, or lamination 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.

Limitations

1. *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 sq in.) 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.

2. *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.

3. *Radiography.* Effective use of radiography mandates expensive equipment, extensive safety precautions and skilled technicians to interpret the images. Ex-

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pensive tracking and security for radiation sources are 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 percent penetration.

4. *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 overspray 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.

5. *Hydrostatic Testing*. Cleanliness and chemistry control of the fluid must be consistent with the operating standards of the system. Close attention should be given to controlling system thermodynamic parameters during the test to prevent overpressurization of the system. Overpressurization could lead to unintended damage to the system. Individual component hydros do not ensure system integrity. A final hydro of the completed system is used to ensure the integrity of the assembled system's pressure boundary.

6. 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.

7. *Eddy Current* - Eddy Currents tend to flow parallel to tile 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, and so is limited to shallow subsurface and surface defects.

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11 Conclusions

Management of maintenance activities at facilities on military installations is a complex and expensive task. This report presents a variety of techniques that can monitor equipment condition and anticipate failure. For some noncritical, inexpensive, and easily replaced components, run-to-failure method may be an acceptable practice. For large, complicated, expensive, mission-critical items, run-to-failure may be unacceptable. Maintenance to maximize service life of equipment or components and surveillance of performance degradation can allow repairs/replacement without interruption of mission-critical activities. For certain installations, it may be more economical to use contract services to maintain infrequent, complex, and expensive equipment and processes.

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