



GUIDANCE NOTES ON

EQUIPMENT CONDITION MONITORING TECHNIQUES

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Foreword

Since the late 1970's, marine and offshore operators have increasingly applied various proactive maintenance techniques to prevent failures before they occur, detect the onset of failures, or discover failures before they impact system performance. There have been numerous advances in condition monitoring technology, trending, and increasingly more powerful planned maintenance software and machine diagnostics solutions as a result of increased computing power and networking. Beginning in 1978, ABS cooperated with Owners on developing and implementing preventative maintenance programs incorporating condition monitoring techniques. In 1984, ABS issued its first *Guide for Survey Based on Preventative Maintenance Techniques* with subsequent updates in 1985, 1987, 1995, and then inclusion in the *ABS Rules for Survey After Construction (Part 7)* in mid-2002. Since that date, updates have been made periodically with the most recent in the 2012 Rules.

Machinery systems continued to become larger and more complex, requiring operators with more specialized knowledge of the machinery and systems onboard. Accordingly, ABS published the *Guide for Survey Based on Reliability-Centered Maintenance (RCM Guide)* in December 2003 to provide vessel and other marine installation owners, managers and operators with requirements for the development of a maintenance program using techniques successfully applied in other industries for machinery systems within a maintenance philosophy referred to as Reliability-Centered Maintenance (RCM).

Subsequently, ABS published the *Guidance Notes on Reliability-Centered Maintenance (RCM Guidance Notes)* in July 2004 to provide supplementary information for the more effective application of the requirements of the *RCM Guide*. The *RCM Guidance Notes* provide information related to equipment failure, maintenance strategies, risk considerations, conducting and documenting an RCM analysis and sustaining an RCM program.

The purpose of these *Guidance Notes on Equipment Condition Monitoring Techniques* is to provide a single ABS document containing information related to the subject and to be used as a resource (supplement) for choosing appropriate condition monitoring techniques where referred to in Appendix 7-A-14 of the *ABS Rules for Survey After Construction (Part 7)* or the *ABS Guide for Surveys Based on Machinery Reliability and Maintenance Techniques*. Topics addressed include a summary of condition-monitoring techniques used in the marine industry, guidance on the selection of an appropriate technique, measurement frequency, personnel skills, company resources, and risk assessment. Also available is an electronic spreadsheet listing organized by the type and condition of the equipment being monitored.

Through the application of condition-monitoring techniques, Owners/managers/operators should be able to expect improved equipment and system reliability onboard their vessels or other marine installations. ABS recommends consideration is given to enrolling these vessels in either the Reliability-Centered Maintenance Program or the Preventative Maintenance Program to take advantage of the additional cost saving benefits for equipment maintenance together with receiving credit towards the ABS Continuous Survey – Machinery.

These Guidance Notes become effective on the first day of the month of publication.

Users are advised to check periodically on the ABS website www.eagle.org to verify that this version of these Guidance Notes is the most current.

We welcome your feedback. Comments or suggestions can be sent electronically by email to rsd@eagle.org.

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SECTION 1 General

1 Application

Condition-monitoring tasks may be applied to any equipment and machinery systems for which they are applicable. Both Appendix 7-A-14 of the *ABS Rules for Survey After Construction (Part 7)* and the *ABS Guide for Surveys Based on Machinery Reliability and Maintenance Techniques* should be referenced, as applicable, for equipment that is not permitted to be enrolled in the respective programs for reasons of statutory regulations or ABS survey policy.

If the machinery is intended to be enrolled in a Machinery Maintenance Program or the Preventative Maintenance Program, it is a prerequisite the machinery be on a Special Continuous Survey of Machinery (CMS) cycle.

2 Objective

These Guidance Notes provide supplementary information for condition monitoring, trending and diagnostics which can be used in conjunction with Appendix 7-A-14 of the *ABS Rules for Survey After Construction (Part 7)* and the *ABS Guide for Surveys Based on Machinery Reliability and Maintenance Techniques*.

Condition-monitoring tasks are scheduled activities used to monitor machine condition and to detect a potential failure in advance so that action can be taken to prevent that failure. These Guidance Notes summarize:

- i) The various condition-monitoring techniques applied to machinery
- ii) The condition-monitoring tasks most applicable for particular machinery
- iii) The effectiveness of condition-monitoring tasks
- iv) The failure condition monitored
- v) The framework for network based data collection

Improved equipment and machinery system reliability onboard vessels and other marine structures may be expected through the proper application of condition-monitoring tasks where condition-monitoring techniques are appropriate, applicable, and correctly implemented.

The principles summarized in these Guidance Notes follow the same principles as those applied in Appendix 7-A-14 of the *ABS Rules for Survey After Construction (Part 7)* and the *ABS Guide for Surveys Based on Machinery Reliability and Maintenance Techniques*.

3 Defining Condition-Monitoring Tasks

A condition-monitoring task is a scheduled task used to detect the potential onset of a failure so that action can be taken to prevent such failure. A potential failure is an identifiable condition that indicates that a functional failure is either about to occur or is in the process of occurring. Condition-monitoring tasks should only be chosen when a detectable potential failure condition will exist before failure and the applicable task has a reasonable probability of detecting the failure. The first maintenance types that should be considered are those recommended by the manufacturer. Condition monitoring tasks should only be considered if they can be proven to be applicable and effective.

Some condition-monitoring tasks may be identified from previous risk studies such as, HAZOPs, HAZIDs and FMEAs conducted during a system design. Failure-finding tasks may be considered to supplement some of the identified condition-monitoring tasks for increased robustness of the maintenance scheme. (See Appendix 5 of the *ABS Guide for Surveys Based on Machinery Reliability and Maintenance Techniques*.)

Note: At times condition-monitoring tasks are referred to by practitioners in some countries as “predictive maintenance” tasks. Section 3 provides additional details.

4 Definitions

The following definitions are applied to the terms used in these Guidance Notes.

ABS Recognized Condition Monitoring Company: This term refers to those companies which ABS has approved as External Specialists.

Baseline Data: The baseline data refer to *condition monitoring* indications – usually vibration records on rotating equipment – established with the *equipment item* or *component* operating in good order when the unit first entered the Program or the first condition-monitoring data collected following an overhaul or repair procedure that invalidated the previous baseline data. The baseline data are the initial condition monitoring data to which subsequent periodical condition-monitoring data are compared.

Cause: See “*failure cause*”.

CANopen network: CAN (Controller Area Network) is a standardized application for distributed automation systems based on transmitting time-critical process data, standardized data related to the system components and functional status.

CANbus: The data link layer of CANopen transmitting data between equipment, system controllers and data analyzers.

Component: The hierarchical level below *equipment items*. This is the lowest level for which the component can be identified for its contribution to the overall functions of the *functional group*; can be identified for its *failure modes*; is the most convenient physical unit for which the *preventative maintenance plan* or the spares holding requirement can be specified.

Condition Based Maintenance (CBM.) A maintenance plan, conducted on a frequent or real-time basis, which is based on the use of Condition Monitoring to determine when part replacement or other corrective action is required. This process involves establishing a baseline and operating parameters, then frequently monitoring the machine and comparing any changes in operating conditions to the baseline. Repairs or replacement of parts are carried out before the machinery fails based upon the use of the tools prescribed for CM.

Condition Monitoring (CM): Condition monitoring comprises scheduled diagnostic technologies used to monitor machine condition to detect a potential failure. Practitioners in some countries refer to this term as an “on-condition task” or “predictive maintenance”.

Consequence: The way in which the effects of a *failure mode* matter. Consequence can be expressed as the number of people affected, property damaged, amount of oil spilled, area affected, outage time, mission delay, dollars lost, etc. Regardless of the measure chosen, the consequences are expressed “per event”.

Effects: See “*failure effects*”.

Data Historian: A data historian is a type of database designed to archive automation and process data. They are designed to store high frequency data and data collecting on a regular basis. Historians are used to troubleshoot processes, optimize manufacturing, store data for regulatory compliance, etc. It does not store transactional or relational data.

Equipment Items: The hierarchical level below *systems* comprising various groups of *components*.

Failure Cause: The failure cause is the basic equipment failure that results in the *failure mode*. For example, pump bearing seizure is one failure cause of the failure mode “pump fails off”.

Failure Characteristic: The failure characteristic is the failure pattern (i.e., wear-in, random, wear-out) exhibited by the *failure mode*.

Failure Effects: Failure effects are the *consequences* that can result from a *failure mode* and its *causes*.

- **Local Effect:** The initial change in the system operation that would occur if the postulated failure mode occurs.
- **Next Higher Effect:** The change in condition or operation of the next higher level of indenture caused by the postulated failure mode. This higher level effect is typically related to the *functional failure* that could result.
- **End Effect:** The overall effect on the vessel that is typically related to the consequences of interest for the analysis (loss of propulsion, loss of maneuverability, etc.). For the purposes of these Guidance Notes, the term “End Effect” applies only to the total loss or degradation of the functions related to propulsion and directional control, including any of the following consequences: loss of containment, explosion/fire, reduction in safety occurring immediately after or a short time thereafter as a result of a failure mode. For offshore activities, these may be extended to include any functions related to drilling operations, position keeping, hydrocarbon production and processing, or import and export functions.

Failure Management Strategy: A failure management strategy is a proactive strategy to manage failures and their effects to an acceptable level of *risk*. It consists of *proactive maintenance tasks*, *run to failure for low risks*, or *one-time changes for high risks*.

Failure Mechanism: The failure mechanism describes how the *failure mode* may occur. One *failure mode* for a particular piece of equipment may have several failure mechanisms. The failure mechanism may vary during the life of the equipment as the failure rate pattern changes. See Subsection 2/3.

Failure Mode: The failure mode describes how equipment can fail and potentially result in a functional failure. Failure mode can be described in terms of an equipment failure cause (i.e., pump bearing seizes), but is typically described in terms of an observed effect of the equipment failure (i.e., pump fails off).

Failure Rate: The failure rate is the number of failures per unit time that can be expected to occur for the equipment.

FMECA: The acronym for “Failure Mode Effects and Criticality Analysis”.

Frequency: The frequency of a potential undesirable *event* is expressed as events per unit time, usually per year. The frequency should be determined from historical data if a significant number of events have occurred in the past. Often, however, risk analyses focus on events with more severe *consequences* (and low frequencies) for which little historical data exist. In such cases, the event frequency is calculated using risk assessment models.

Function: A function is what the *functional group*, *systems*, *equipment items*, and *components* are designed to do. Each function should be documented as a function statement that contains a verb describing the function, an object on which the function acts, and performance standard(s).

- **Primary Function.** A primary function is directly related to producing the primary output or product from a functional group/system/equipment item/component.
- **Secondary Function.** A secondary function is not directly related to producing the primary output or product, but nonetheless is needed for the functional group/system/equipment item/component.

Functional Failure: A functional failure is a description of how the equipment is unable to perform a specific *function* to a desired level of performance. Each functional failure should be documented in a functional failure statement that contains a verb, an object and the functional deviation.

Functional Group: A hierarchical level addressing propulsion, maneuvering, electrical, vessel service, and navigation and communications *functions*.

Indications (Failure Detection): Indications are alarms or conditions that the operator would sense to detect the *failure mode*.

Likelihood: See “frequency”.

MODBUS: is a common serial communications protocol for connecting industrial electronic devices such as sensors and programmable logic controllers (PLCs).

One Time Change: A maintenance strategy in which equipment or systems, which have been determined to present an unacceptable level of risk and have no potential mitigations, are replaced or significantly altered in order to provide an acceptable level of risk.

OPC Server: OPC (“OLE”PC) (Object Linking and Embedding for Process Control) is a software interface standard to allow Windows programs to communicate with industrial hardware devices.

Operating Context: The operating context of a functional group is the circumstances under which the *functional group* is expected to operate. It should describe the physical environment in which the functional group is operated, a precise description of the manner in which the functional group is operated and the specified performance capabilities of the functional group.

PM Program: A maintenance plan which uses time-based inspection, part replacement or overhauls in an effort to prevent equipment failures. Timing can be based on calendar days, cycles counter or equipment running hours. Such schedules are generally established by the machinery manufacturer and include lubrication servicing; filter, bearing and seal replacements; as well as major overhaul. This refers to the Preventative Maintenance Program requirements in Appendix 7-A-14, “ABS Surveys Based on Preventative Maintenance Techniques” of the *ABS Rules for Survey After Construction (Part 7)*. The ABS PM Program is based on IACS Unified Requirement Z20, although there are significant differences concerning equipment permitted to be enrolled.

P-F Interval: The Potential Failure interval is the time interval between the point at which the onset of failure can be detected and the point at which functional failure occurs. A condition-monitoring task should be performed at less than half of this interval.

Planned Maintenance: For the purposes of this Guide, planned maintenance is a scheduled maintenance task that entails discarding a *component* at or before a specified age limit, regardless of its condition at the time. It also refers to a scheduled maintenance task that restores the capability of an item at or before a specified age limit, regardless of its condition at the time, to a level that provides an acceptable probability of survival to the end of another specified interval. These maintenance tasks are also referred to as “scheduled discard” and “scheduled restoration”, respectively.

Potential Failure: A potential failure is an identifiable condition that indicates that a *functional failure* is either about to occur or is in the process of occurring.

Predictive Maintenance: See “condition monitoring”.

Preventative Maintenance: Preventative maintenance consists of all the maintenance tasks identified as necessary to provide an acceptable probability of survival to the end of a specified interval for the machinery systems. In IACS UR Z20, this is referred to as a “Planned Maintenance Scheme”.

Proactive Maintenance Task: A proactive maintenance task is implemented to prevent failures before they occur, detect the onset of failures or discover failures before they impact system performance.

PROFIBUS: PROFIBUS (Process Field Bus) is a standard for fieldbus communication in automation technology.

Random Failure: Random failure is dominated by chance failures caused by sudden stresses, extreme conditions, random human errors, etc. (i.e., failure is not predictable by time).

Reactive Maintenance: A maintenance strategy in which equipment is run until failure before corrective action is taken. This is useful for items which are low risk, low-cost and have no impact on operational, environmental or safety concerns as a result of failure.

Reliability: The probability that an item will perform its intended function for a specified interval under stated conditions.

Reliability Based Maintenance (RBM): A maintenance strategy development model that will act as the foundation for applying selective reliability techniques, choosing and deploying a maintenance plan, and creating an effective reliability strategy to support an efficient maintenance environment

RCM Guidance Notes: This refers to the *ABS Guidance Notes on Reliability-Centered Maintenance*.

Reliability Centered Maintenance (RCM): A process that is used to determine the most effective approach to maintenance. It involves identifying actions that when taken will reduce the probability of failure and which actions are most cost effective. ABS has developed a maintenance program which uses RCM analysis of installed equipment to develop a Maintenance Program, a spare parts holdings list and includes a sustainment plan.

Risk: Risk is composed of two elements, *frequency* and *consequence*. Risk is defined as the product of the frequency with which an event is anticipated to occur and the *severity* of the consequence of the event's outcome.

Special Continuous Survey of Machinery: The ABS requirements for Special Continuous Survey of Machinery are listed in 7-2-1/7 "Continuous Surveys" (Vessels in Unrestricted Service) and 7-2-2/9 "Continuous Surveys" (Vessels in Great Lakes Service) of the *ABS Rules for Survey After Construction (Part 7)*.

Special Periodical Survey – Machinery: The requirements for a conventional ABS Special Periodical Survey – Machinery are listed in the following portions of the of the ABS Rules:

- *ABS Rules for Survey After Construction (Part 7):*
 - 7-2-2/7 "Special Periodical Surveys" (Vessels in Great Lakes Service) and 7-2-3/5 "Special Periodical Surveys" (Vessels in Rivers and Intracoastal Waterway Service)
 - 7-6-2/3 "Special Periodical Surveys – Machinery" (7-6-2/3.1, All Vessels, 7-6-2/3.3, Tankers)
 - 7-6-3/1 "Special Periodical/Continuous Survey-Machinery-Year of Grace" (Vessels in Great Lakes Service)
 - Section 7-8-2 "Shipboard Automatic and Remote-control Systems, Special Periodical Surveys"
 - Part 7, Chapter 9 "Survey Requirements for Additional Systems and Services" (Cargo Refrigeration, Hull Condition Monitoring System, Quick Release System, Thrusters and Dynamic Positioning System, and Vapor Emission Control System)
- *ABS Rules for Building and Classing Mobile Offshore Drilling Units:*
 - 7-2-5/9 "Special Periodical Survey – Machinery", 7-2-5/11 "Special Periodical Survey – Electrical Equipment", and 7-2-5/13 "Special Periodical Survey – Special Features (All Types)"
- There are Special Periodical Survey requirements in other ABS Rules and Guides for specific vessel types, services and marine structures not listed here.

Systems: The hierarchical level below *functional group*, comprising various groups of *equipment items*.

TCP/IP: TCP/IP (Transmission Control Protocol and Internet Protocol) is the computer networking model and set of communications protocols used on the internet and similar computer networks.

Wear-in Failure: Wear-in failure is dominated by "weak" members related to problems such as manufacturing defects and installation/maintenance/startup errors. It is also known as "burn in" or "infant mortality".

Wear-out Failure: Wear-out failure is dominated by end-of-useful life issues for equipment.

5 Machinery Condition Monitoring Techniques

A summary of the machinery condition monitoring techniques listed in these Guidance Notes including the applicable equipment and a reference to the paragraph is listed in Section 1, Table 1.

TABLE 1
Machinery Condition Monitoring Applications

Technique	Reference	Roller Bearings	Journal Bearings	Belt Drives	Circuit Breakers	Diesel Generators	Electric Motors	Electrical Systems	Gears	Heat Exchangers	Heavy Equipment/ Cranes	Pumps	Reciprocating Equipment	Steering Gears	Tanks, Piping	Transformers	Turbine (Gas or Steam)
Temperature Measurements	4																
Point temperature devices	2.3	x	x	x	x	x	x	x	x	x	x	x		x	x	x	
Infrared photography	2.4	x	x	x	x	x	x	x	x	x	x	x		x	x	x	
Dynamic Monitoring	5																
Time wave form analysis	2.1	x	x	x		x	x		x			x	x	x			x
Broad band vibration analysis	2.2	x	x	x		x	x		x			x	x	x			x
Spectrum analysis	2.3	x	x	x		x	x		x			x	x	x			x
Shock pulse analysis	2.4	x ⁽¹⁾				x ⁽²⁾											
Ultrasonic analysis	2.5	x							x								
Other Techniques	2.6	See Section 5, Table 3															
Technique	Reference	Electrical Insulating Oil	Grease	Hydraulic Oil	Lubricating Oil	Various Elements	Oil Additives	Fuel Oil	Cable in insulated oil	Circuit Breakers	Compressors	Diesel Engines	Gas Turbines	Hydraulic Systems	Reduction Gears, Transmissions	Transformers	Turbine Generators
Oil Analysis	6																
Atomic emissions spectroscopy	2.1			x	x	x	x				x			x			
Dielectric strength tests	2.2						x		x	x						x	
Ferrogaphy	2.3		x	x	x						x	x	x	x	x		
Infrared and ultraviolet spectroscopy	2.4	x		x	x					x				x		x	x
Moisture measurement	2.5	x ⁽³⁾		x	x												
Kinematic viscosity test	2.6			x	x						x	x	x	x	x		x
Microbial analysis	2.7				x			x			x	x	x		x		x
Particle counter	2.8		x	x	x						x	x	x	x	x		
Total acid/Total base number	2.9	x		x	x						x	x	x	x	x	x	x
Sediment tests	2.10	x							x	x						x	
Other techniques	2.11	See Section 6, Table 3															
Technique	Reference	Atmospheric Corrosion Monitor	Cathodic Protection Monitoring	Electrical Generating Systems	Freshwater or Seawater Cooling	Underwater/Under Sea Structures	Cathodic Protection Monitoring	Electrical Generating Systems	Freshwater or Seawater Cooling	Underground/Under Sea Structures							
Corrosion Monitoring	7																
Coupon testing	2.1	x	x	x	x	x	x	x	x	x							
Corrometer (electrical resistance)	2.2	x	x	x	x	x	x	x	x	x							
Potential monitoring ⁽⁴⁾	2.3			x		x		x		x							

TABLE 1 (cont'd)
Machinery Condition Monitoring Applications

Technique	Reference	Weld defects	Gas porosity	Surface shrinkage	Lack of weld penetration	Cracks, Crack formation	Subsurface defects in plates, shafts, castings	Intergranular corrosion	Corrosion fatigue	Stress Corrosion	Hydrogen embrittlement	Surface cracks	Surface defects	Embrittlement	Defects in pressure boundary, Leaks	Metal thickness loss due to wear, corrosion or both	Lamination	Corrosion
Nondestructive Testing	8																	
X-ray radiography	2.1	x	x		x	x	x	x										
Liquid dye penetrants	2.2					x			x	x	x	x	x	x				
Ultrasonic leak detection	2.3														x			
Ultrasonic Flaw Detection	2.4	x	x					x		x						x		
Magnetic Particle Inspection ⁽⁵⁾	2.5			x		x			x	x	x						x	
Eddy Current Testing	2.6															x		x
Acoustic Emission	2.7					x												
Hydrostatic and Pneumatic Testing	2.8														x			
Visual Inspection – Borescope	2.9	x				x						x						
Other Techniques	2.10	See Section 8, Table 2																
Technique	Reference	Strain	Surface and shallow subsurface defects	Pipe and Tube thickness	Wear	Fatigue	Plastic deformation	Stress	Oxide films									
Nondestructive Testing	8																	
X-ray radiography	2.1																	
Liquid dye penetrants	2.2																	
Ultrasonic leak detection	2.3																	
Ultrasonic Flaw Detection	2.4			x														
Magnetic Particle Inspection ⁽⁵⁾	2.5		x		x	x												
Eddy Current Testing	2.6	x	x	x	x													
Acoustic Emission	2.7				x	x	x	x										
Hydrostatic and Pneumatic Testing	2.8																	
Visual Inspection – Borescope	2.9				x	x			x									

TABLE 1 (cont'd)
Machinery Condition Monitoring Applications

Technique	Reference	DC Armatures	Induction/synchronous motors	Flow or machine output restrictions	Machinery misalignment	Battery wet cell deterioration	Resistance of equipment insulation	Synchronous field poles	Motor winding resistance	Various coils/coil groups	Compressors	Pumps	Motor operated valves	Wound rotor electric motors		
Electrical Testing	9															
Megohmmeter Testing	2.1						x									
High Potential Testing	2.2							x								
Surge Testing	2.3	x	x					x		x						
Power Signature Analysis	2.4			x	x						x	x	x			
Motor Circuit Analysis	2.5	x	x						x					x		
Battery Impedance Testing	2.6					x										
Technique	Reference	Loose or worn parts	Fluid or gas leaks	Missing parts	Poor electrical connections	Poor pipe connections	Bearings	Steam leaks	Pressure relief valve leaks	Coupling leaks	Overloaded pumps	Poor mechanical Alignment	Heat	Scaling	Roughness changes	
Observation and Surveillance	10															
Visual Inspection	2.1	x	x	x	x	x										
Audio Inspection	2.2						x	x	x	x	x	x				
Touch Inspections	2.3												x	x	x	
Performance Trending	11	Monitoring of equipment or system performance indicators for trending														
Engine Performance Monitoring/Diagnostics	12	Monitoring of engine parameters so as to optimize performance or alert operator of impending maintenance														

Notes:

- 1 This technique is reported to work well on bearings by themselves but has some serious limitation on bearings in gearboxes, pumps, motors, etc., because of the other “normal” frequencies that are in most common machines, such as blade pass frequency, gear mesh frequency, and slot pass frequency, for example.
- 2 Internal combustion engine valves or components for which metal-to-metal contact is a source of wear.
- 3 Use the Coulometric Karl Fischer Titration Method for Insulating Liquids (ASTM D1533-00(2005) or ISO 12937-00 *Petroleum products – Determination of water – Coulometric Karl Fischer titration method.*)
- 4 It is reported potential monitoring is best suited to use on stainless steel, nickel-based steel alloys and titanium materials
- 5 Suitable for ferromagnetic materials only
- 6 Reported to be suitable for hydraulic pipes and tubes.

SECTION 2 Equipment Failure

1 Introduction

An abridged introduction to equipment failure theory is presented in this Section. For additional information on this topic, please refer to Section 2 of the *RCM Guidance Notes*.

The theory presented in this section can be applied to systems, comprised of two or more equipment.

2 Equipment Failure

A combination of one or more equipment failures, human errors, or both causes a loss of system function. The following factors may influence the likelihood of equipment failure:

- i) Design error
- ii) Faulty material
- iii) Improper fabrication and construction
- iv) Improper installation
- v) Improper operation
- vi) Inadequate maintenance
- vii) Maintenance errors

Note that maintenance influences only some of these factors. Therefore, proper and timely maintenance is merely one of the many approaches that can be used to improve equipment reliability and, hence, system reliability. In certain cases, condition-monitoring tasks may aid in identifying impending equipment failures introduced by maintenance errors or machinery degradation.

To effectively improve equipment reliability through maintenance, design changes, or operational improvement, an understanding of potential equipment failure mechanisms, their causes and associated system impacts is required. Equipment failure should be defined as a state or condition in which a component no longer satisfies some aspect of its design intent (i.e., a functional failure has occurred due to the equipment failure). Condition-monitoring tasks can identify impending equipment/component failures that may result in functional failures.

An effective failure management strategy should be based on an understanding of the failure mechanism. Equipment will exhibit several different failure modes (i.e., how the equipment fails). Also, the failure mechanism may be different for the different failure modes, and the failure mechanisms may vary during the life of the equipment.

3 Equipment Failure Rate and Patterns

Depending on the dominant system failure mechanisms, system operation, system operating environment, and system maintenance, specific equipment failure modes may exhibit a variety of failure rates and patterns.

3.1 Failure Rate

Statistically, failure rate is expressed in terms of operating time (or another pertinent operating parameter) elapsed before an item of the equipment fails. Due to the variable nature of failure time, a failure density distribution is often used to provide the probability of an item failing after a given operating time. Depending on the equipment failure mode, a variety of distributions (i.e., normal, exponential, Weibull, lognormal) are used to statistically model the probability of failure.

A common failure distribution used to model equipment failures is the Weibull distribution. This distribution is used when equipment exhibits a constant failure rate for a portion of its life followed by increasing failure rate due to wear-out. In addition, Weibull analysis is used when there is a small number of failure data. A Weibull plot can be used to determine if the failure is due to:

- i) Infant mortality or wear-in
- ii) Random
- iii) Wear-out

This information is helpful in determining an appropriate maintenance strategy. The Weibull plot can also be correlated between the probability of failure and operating time. These data can be helpful in establishing intervals for certain types of maintenance tasks (i.e., rebuilding tasks).

3.2 Failure Rate

Another common statistical measure associated with these distributions is mean time to failure (MTTF). MTTF is the average life to failure for the equipment failure mode. Thus, it represents the point at which the areas under the failure distribution curve are equal above and below the point. Determining the MTTF will, therefore, depend on the type of failure distribution used to model the failure mode.

3.3 Conditional Probability Failure Rate

A more useful measurement, derived from the failure distribution, is the conditional probability failure rate, $\lambda(t)$. The conditional probability failure rate is the probability that a failure occurs during the next instant of time, given that the failure has not already occurred before that time. The conditional failure rate, therefore, provides additional information about the survival life and is used to illustrate failure patterns. Section 2, Table 1 shows six classic conditional failure rate patterns. The vertical axis represents the conditional failure rate as a function of time ($\lambda(t)$), and the horizontal axis represents the operating time (t) or another variable (i.e., operating cycles).

3.4 Equipment Failure Models and Failure Patterns

Understanding that equipment failure modes can exhibit different failure patterns has important implications when determining appropriate maintenance strategies. For example, rebuilding or replacing equipment items that do not have distinctive wear-out regions (i.e., Patterns C through F) is of little benefit and may actually increase failures as a result of infant mortality, human errors or both during maintenance tasks.

For most equipment failure modes, the specific failure patterns are not known and, fortunately, are not needed to make maintenance decisions. Nevertheless, certain failure characteristic information is needed to make maintenance decisions. These characteristics are:

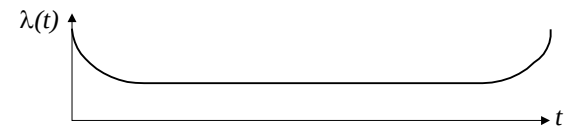
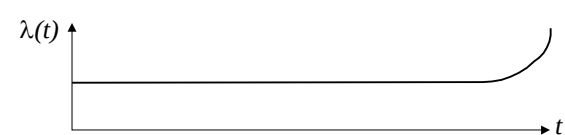
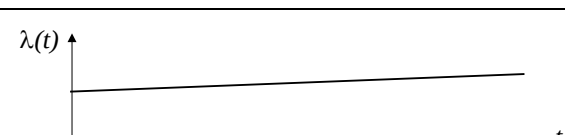
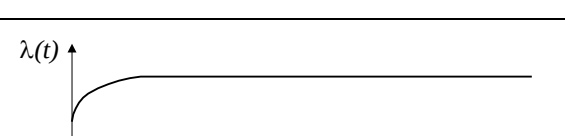
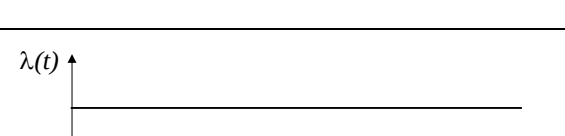
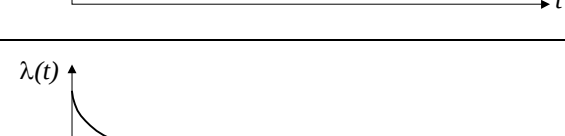
- i) *Wear-in failure* – dominated by “weak” members related to problems such as manufacturing defects and installation/maintenance/startup errors. Also known as “burn in” or “infant mortality” failures.
- ii) *Random failure* – dominated by chance failures caused by sudden stresses, extreme conditions, random human errors, etc. (i.e., failure is not predictable by time).
- iii) *Wear-out failure* – dominated by end-of-useful life issues for equipment.

These failure characteristics are best illustrated by failure Pattern A, shown in Section 2, Figure 1.

Simply identifying which of the three equipment failure characteristics is representative of the equipment failure mode, provides insight into the proper maintenance strategy. For example, if an equipment failure mode exhibits a wear-out pattern, rebuilding or replacing the equipment item may be an appropriate strategy. However, if an equipment failure mode is characterized by wear-in failure, replacing or rebuilding the equipment item may not be advisable.

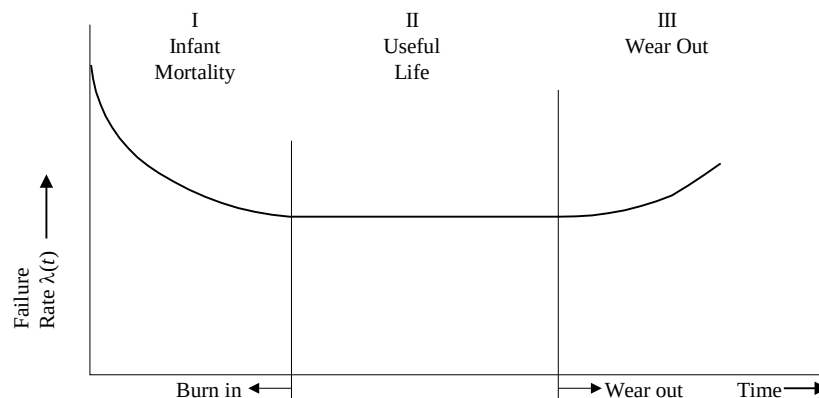
Finally, a basic understanding of failure rate helps in determining whether maintenance or equipment redesign is necessary. For example, equipment failure modes that exhibit high failure rates (i.e., fail frequently) may be best addressed by redesign rather than applying more frequent maintenance.

TABLE 1
Six Classic Failure Rate Patterns ⁽¹⁾

	Pattern A – Bathtub: Infant mortality, then a constant or increasing failure rate, followed by a distinct wear-out zone <i>Example:</i> overhauled reciprocating engine
	Pattern B – Traditional Wear-out: Constant or slowly increasing failure rate followed by a distinct wear-out zone <i>Example:</i> reciprocating engine, pump impeller
	Pattern C – Gradual Rise with no Distinctive Wear-out Zone: Gradually increasing failure rate, but no distinct wear-out zone <i>Example:</i> gas turbine
	Pattern D – Initial Increase with a Leveling-off: Low failure rate initially, then a rapid increase to a constant failure probability <i>Example:</i> complex equipment under high stress with test runs after manufacture or restoration, such as hydraulic systems
	Pattern E – Random Failure: Constant failure rate in all operating periods <i>Example:</i> roller/ball bearings
	Pattern F – Infant Mortality: High infant mortality followed by a constant or slowly rising failure rate <i>Example:</i> electronic components

Reference 1: *Reliability-centered Maintenance*, F. Stanley Nowlan and Howard F. Heap, December 29, 1978, U.S. Department of Commerce, National Technical Information Service.

FIGURE 1
Equipment Life Periods



4 Failure Management Strategy

Understanding failure rates and failure characteristics allows the determination of an appropriate strategy for managing the failure mode (i.e., the *ABS Guide for Surveys Based on Machinery Reliability and Maintenance Techniques* refers to this as the failure management strategy; and Appendix 7-A-14 of the *ABS Rules for Survey After Construction (Part 7)*, refers to this as preventative maintenance). Developing and using this understanding is fundamental to improving equipment reliability. It is no longer considered to be true that the more an item is overhauled, the less likely it is to fail. Unless there is a dominant age-related failure mode, age limits do little or nothing to improve the reliability of complex items. Sometimes, scheduled overhauls may increase overall failure rates by introducing infant mortality, human errors or both into otherwise stable systems.

The failure management strategy can consist of:

- i) Appropriate proactive maintenance tasks,
- ii) Equipment redesigns or modifications, or
- iii) Other operational improvements.

For a preventative maintenance plan developed for the PM Program, items ii) and iii) would not be considered as there is no provision for this.

The purpose of the proactive maintenance tasks in the failure management strategy is to (1) prevent failures before they occur or (2) detect the onset of failures in sufficient time so that the failure can be mitigated before it occurs. Equipment redesigns, modifications, and operational improvements are attempts to improve reliability of equipment whose failure rates are too high or for which proactive maintenance is considered to be ineffective or too costly.

The key issues in determining whether a specific failure management strategy is effective are the following:

- i) Is the failure management strategy technically feasible?
- ii) Is an acceptable level of risk achieved when the failure management strategy is implemented?
- iii) Is the failure management strategy cost-effective?

Sections 7 and 8 in the *RCM Guidance Notes* describe the risk-based decision tools and the RCM analysis process, and provide a more detailed discussion on determining the effectiveness of the failure management strategy.

In addition to proactive maintenance tasks and one-time changes, servicing tasks and routine inspections may be important elements within the failure management strategy. These activities help determine that the equipment failure rate and failure characteristics are as anticipated. For example, the failure rate and failure pattern for a bearing drastically changes if it is not properly lubricated.

These proactive maintenance tasks, run-to-failure, one-time changes, and servicing and routine inspections are summarized in the following Paragraphs.

4.1 Proactive Maintenance Tasks

Proactive maintenance tasks are divided into four categories.

4.1.1 Planned-maintenance Tasks

A planned-maintenance task is performed at a specified interval, regardless of the equipment's condition. The purpose of this type of task is to prevent functional failure before it occurs. Many times this type of task is applied when no condition-monitoring task is identified or justified, and the failure mode is characterized with a wear-out pattern. Planned maintenance can be divided into the following two subcategories:

- **Restoration Task.** A scheduled task that restores the capability of an item at or before a specified interval (age limit) to a level that provides a tolerable probability of survival to the end of another specified interval. For the case of scheduled restoration of a diesel engine, rebuilding the fuel injectors would be an example.

- **Discard Task.** A scheduled task involving discarding an item at or before a specified age limit regardless of its condition at the time.

Note that the terms “restoration” and “discard” can be applied to the same task. For example, if a diesel engine’s cylinder liners are replaced with new ones at fixed intervals, the replacement task could be described as scheduled discard of the cylinder liner or scheduled restoration of the diesel engine.

4.1.2 Condition-monitoring Tasks

A condition-monitoring task is a scheduled task used to detect the potential onset of a failure so that action can be taken to prevent the functional failure. A potential failure is an identifiable condition that indicates that a functional failure is either about to occur or is in the process of occurring. Condition-monitoring tasks should only be chosen when a detectable potential failure condition will exist before failure. When choosing maintenance tasks, condition-monitoring tasks should be considered first, unless a detectable potential failure condition cannot be identified. Condition-monitoring tasks are also referred to as “predictive maintenance”. Section 3 provides additional details.

4.1.3 Combination of Tasks

Where the selection of either condition-monitoring or planned-maintenance tasks on their own do not seem capable of reducing the risks of the functional failure of the equipment, it may be necessary to select a combination of both maintenance tasks.

4.1.4 Failure-finding Tasks

A failure-finding task is a scheduled task used to detect hidden failures when no condition-monitoring or planned-maintenance task is applicable. It is a scheduled function check to determine whether an item will perform its required function if called upon. Most of these items are standby or protective equipment. An example would be testing the safety valve on a boiler.

4.2 Run-to-failure

Run-to-failure is a failure management strategy that allows an equipment item to run until failure occurs and then a repair or replacement is made. This maintenance strategy is acceptable only if the risk of a failure is acceptable without any proactive maintenance tasks. An example would be permitting a local pressure gauge on a cooling water line, also fitted with a remote-reading pressure gauge, to fail.

4.3 One-time Changes

One-time changes are used to reduce the failure rate or manage failures in which appropriate maintenance tasks are not identified or cannot effectively and efficiently manage the risk. The basic purpose of a one-time change is to alter the failure rate or failure pattern through:

- Equipment redesigns or modification, and
- Operational improvements, or both.

One-time changes most effectively address equipment failure modes that result from the following failure mechanisms:

- i) Faulty design, materials, or both
- ii) Improper fabrication, construction, or both
- iii) Mis-operation
- iv) Maintenance errors

These failure mechanisms often result in a wear-in failure characteristic, and thus, require a one-time change.

When no maintenance strategy can be found that is both applicable and effective in detecting or preventing failure, a one-time change should be considered. The following briefly describes each type of one-time change:

- *Equipment Redesign or Modifications.* Redesign or modifications entail physical changes to the equipment or system. An example would be mitigating main engine bearing damage caused by no or low lube oil flow by adding a low pressure sensor in the lubricating oil pump outlet that would start a standby pump to maintain lube oil flow to the main engine bearings.
- *Operational Improvements.* Operational improvements are: changes in the way equipment is operated, modifications in the way maintenance is performed on the equipment, or both. Operational improvements usually entail changing the operating context, changing operating procedures, providing additional training to the operator or maintainer, or any combination thereof. For example, in the case of a main propulsion engine provided with a non-continuous rating nameplate, the engine could be operated at a lower output closer to its continuous rating so as to reduce downtime for maintenance.

4.4 Servicing and Routine Inspection

These are simple tasks intended to: (1) maintain the failure rate and failure pattern as predicted by performing routine servicing (i.e., lubrication, filter changing, other replenishment tasks); (2) spot accidental damage; (3) spot problems resulting from ignorance or negligence or (4) respond to unsatisfactory condition monitoring techniques results.. They provide the opportunity to maintain the general standards of maintenance at a satisfactory level. These tasks are not based on any explicit potential failure condition. Servicing and routine inspection may also be applied to items that have relatively insignificant failure consequences, yet should not be ignored (minor leaks, drips, etc.).

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SECTION 3 Condition-monitoring (Predictive) Maintenance

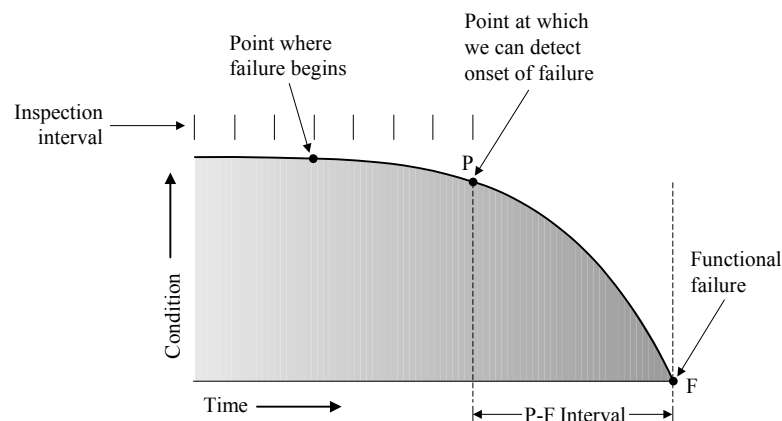
1 Potential Failure (P-F) Diagram

Although many failure modes are not age-related, most of them give some sort of warning that they are in the process of occurring or about to occur. If evidence can be found that something is in the final stages of a failure, it may be possible to take action to prevent it from failing completely so as to avoid the consequences. Section 3, Figure 1 illustrates the final stages of failure, called the P-F curve. Section 3, Figure 1 illustrates how a condition deteriorates to the point at which it can be detected (Point P) and then, if it is not detected and corrected, continues to deteriorate until it reaches the point of functional failure (Point F). (A functional failure is a description of how the equipment is unable to perform a specific *function* to a desired level of performance.)

In practice, there are many ways of determining whether failures are in the process of occurring (i.e., hot spots showing deterioration of furnace refractories or electrical insulation, vibrations indicating imminent bearing failure, increasing level of contaminants in lubricating oil).

If a potential failure is detected between Point P and Point F, it may be possible to take action to prevent the functional failure (or at least to minimize the effects) before the failure occurs. Tasks designed to detect potential failure are known as condition-monitoring tasks (see 2/4.1.2).

**FIGURE 1
P-F Diagram**



2 Selection of Task Frequency

The time interval between Point P and Point F in Section 3, Figure 1 is called the “P-F interval”. This is the warning period (i.e., the time between the point at which the potential failure becomes detectable and the point at which it deteriorates into a functional failure). If a condition-monitoring task is performed on intervals longer than the P-F interval, the potential failure may not be detected. On the other hand, if the condition-monitoring task is performed too frequently compared to the P-F interval, resources are wasted.

Industry practice is to select an interval of about one-half of the P-F interval. In the event the condition degrades, the condition-monitoring task will be performed prior to a functional failure occurring at Point F.

It should be noted that the P-F interval can vary in practice, and in some cases, it can be very inconsistent. In these cases, a task interval should be selected that is substantially less than the shortest of the likely P-F intervals.

Technology improvements have eased the storage limitations for large quantities of condition monitoring data collected on a continual basis instead of periodically. Additionally, this data can be transmitted ashore via satellite for analysis by the equipment manufacturer or another third party service firm. The analyst can verify satisfactory operation of the equipment or system and in the event of degradation occurring, notify the operator of the affected component with suggestions for verifying and repairing the component.

3 Condition-monitoring Maintenance Categories

Condition-monitoring maintenance techniques can be organized into the following categories:

- Temperature measurements
- Dynamic monitoring
- Oil analysis
- Corrosion monitoring
- Nondestructive testing
- Electrical testing
- Observation and surveillance

Sections 4 through 10 provide overviews of these categories together with listings of commonly used techniques in the marine industry. Tables of other related techniques applied in shore-based industries are also provided for consideration.

4 Condition-monitoring Maintenance Task Applicability and Effectiveness

For a condition-monitoring maintenance task to be considered applicable and effective, the following should be taken into account:

- Onset of failure is detectable.* There is some measurable parameter that can detect the deterioration in the equipment's condition. In addition, maintenance personnel should be able to establish limits to determine when corrective action is needed.
- Reasonably consistent P-F interval.* The P-F interval is such that corrective actions are not implemented prematurely or that failure occurs before corrective actions are implemented.
- Practical interval in which condition-monitoring tasks can be performed.* The P-F interval is sufficient to permit a practical task interval. For example, a failure with a P-F interval of minutes or hours would not be an appropriate candidate for manually collected data from a condition-monitoring maintenance task. However, an automated device that assesses condition very frequently with ability to shut down the equipment would be appropriate to install.
- Sufficient warning so that corrective actions can be implemented.* The P-F interval is long enough to allow corrective actions to be implemented. This can be determined by subtracting the task interval from the expected P-F interval and then judging whether sufficient time remains to take necessary corrective actions.
- Reduces the probability of failure (and therefore the risk) to an acceptable level.* The tasks are carried out at an interval so that the probability of failure allows an acceptable risk level to be achieved. Agreed-upon risk acceptance criteria should be determined and recorded.
- Cost-effectiveness.* The cost of undertaking a task over a period of time should be less than the total cost of the consequences of failure.

5 Determining Condition-monitoring Maintenance Task Intervals

Condition-monitoring maintenance task intervals should be determined based on the expected P-F interval. The following sources may be referred to as an aid to determine the P-F interval:

- i) Expert opinion and judgment (i.e., manufacturer's recommendations)
- ii) Published information about condition-monitoring tasks (i.e., Appendix 1, RCM texts)
- iii) Historical data (i.e., estimated MTTF from existing data, current condition-monitoring task intervals)

5.1 Condition-monitoring Task Interval

The interval for a condition-monitoring task should be set at no more than half the expected P-F interval and should be adjusted based on the following considerations:

- i) Reduce the task interval if the P-F interval minus the task interval (based on $\frac{1}{2}$ [P-F interval]) does not provide sufficient time to stop the equipment and implement corrective actions.
- ii) Reduce the task interval if there is low confidence in the "guesstimate" of the expected P-F.
- iii) Reduce the task interval for higher risk failure modes.
- iv) Set the task interval at half the expected P-F interval (or slightly above) for lower risk failure modes.

5.2 Initial Condition-monitoring Task Intervals

Because few organizations will have detailed knowledge about the equipment failure mode P-F interval, the following guidelines can be used to establish initial condition-monitoring task intervals:

- i) If an existing condition-monitoring task is being performed and has proven to be effective (i.e., no unexpected failures have occurred), use the existing task interval as the initial default task interval.
- ii) If an existing condition-monitoring task is being performed and some functional failures have occurred, reduce the task interval based on the experience.
- iii) If there is no existing condition-monitoring task being performed or a new condition-monitoring task is being proposed, the task interval will have to be based on the team's estimate of the P-F interval and guidelines provided in 3/5.1. The following questions can help the team estimate the P-F interval:
 - How quickly can the condition deteriorate and result in a functional failure? Will it deteriorate in minutes, hours, days, weeks, months, or years?
 - What is the capability of the condition-monitoring task in detecting the onset of failure? High or low?
 - How confident is the team in its judgment?

5.3 Improving the Understanding of P-F Intervals

As data from condition-monitoring tasks are collected and corrective actions are implemented, vessel operators will improve their understanding of the P-F interval. For example, assume that vibration testing is performed weekly on pumps in similar service. On several occasions, the vibration analysis detects the onset of failures. However, due to scheduling delays, corrective action is not taken for an additional six (6) to eight (8) weeks. During this period of delay, the pumps continue to operate properly. The P-F interval for these pumps is then known to be probably at least six (6) weeks, and the task interval can be changed to three (3) weeks ($\frac{1}{2}$ of six weeks).

5.4 Additional Guidance

Additional information is available in the *ABS Guide for Surveys Based on Machinery Reliability and Maintenance Techniques* by referring to:

- Appendix 4, "Suggested Failure Modes for Marine Machinery Equipment and Components", providing additional guidance for estimating initial P-F intervals and establishing P-F intervals based on collected failure data.
- Appendix 5, "Failure-finding Maintenance Task Interval", providing additional guidance for estimating initial P-F intervals and establishing P-F intervals based on collected failure data.

6 Condition Monitoring Technician Skill Level

The condition monitoring techniques in the following sections list the necessary skill level for the personnel taking and collecting data. The skill levels are categorized into four levels as follows:

- i) *No Specific Training Needed* – Collecting and recording of data are simple and require minimal or little training to use equipment.
- ii) *Trained Semi-skilled Worker to Take the Readings* – Collecting and recording of data require training in the use of the equipment. The personnel require some training for interpretation of data results to verify data is correct and relevant.
- iii) *Trained Skilled Worker or Trained Lab Technician* – Collecting and recording of data require comprehensive training in the use of the equipment. The personnel require training for interpretation of data results to verify data is correct and relevant.
- iv) *Trained and Experienced Technician* – Collecting and recording of data require comprehensive training in the use of the equipment. Experience is necessary to properly collect or evaluate data for special or unusual equipment installations or when evaluating unusual or suspect data. The personnel also require training for interpretation of data results to verify data is correct and relevant.

7 Establishing Condition-monitoring Maintenance Task Action Limits

Another aspect of a condition-monitoring maintenance task is establishing action limits. This involves establishing limits that result in corrective actions when they are exceeded. The actions may involve any of the following:

- i) Re-performing the condition-monitoring task to verify the results
- ii) Altering the task interval for closer/lesser monitoring of the equipment as warranted
- iii) Initiating corrective actions to prevent the impending equipment failure

Establishing limits should heighten the effectiveness of condition-monitoring tasks in detecting and preventing the failure.

SECTION 4 Temperature Measurements

1 Introduction

Temperature measurement (i.e., sensors, thermography) helps detect potential failures related to a temperature change in equipment. Measured temperature changes can indicate problems such as excessive mechanical friction (i.e., faulty bearings, inadequate lubrication), degraded heat transfer (i.e., fouling in a heat exchanger), or poor electrical connections (i.e., loose, corroded, or oxidized connections).

2 Temperature Measurement Techniques

2.1 Point Temperature Overview

Point temperature measurement refers to the temperature of an object using a device applied to its surface or the interior.

A comparison of several characteristics of temperature sensors is provided in Section 4, Table 1. The selection of an appropriate device is dependent on the purpose for obtaining the temperature. For example, are the temperature data collected to be used for system (process) control or are the temperatures taken only periodically?

TABLE 1
Comparison of Temperature Measurement Techniques

Device Type	Output/Sensitivity	Range °C	Accuracy $\pm$ °C	Robustness	Cost ⁽¹⁾
Thermocouple	40 μ V/°C	-270 to 2300	1.5 to 2.2	High	Low
Resistance Temperature Detector (RTD)	0.385 Ω /°C (Pt) 0.806 Ω /°C (Ni) 0.039 Ω /°C (Cu)	-200 to 600	0.2 (Pt) 0.5 (Ni) 0.7 (Cu)	Medium	Medium (Pt) Low (Ni)
Thermistor	-70 to -1500 Ω /°C	-50 to 200	0.2	High	Medium
Gauges Bimetallic Magnetic	Displacement	-100 to 300	2	High	Low
Paint/Stickers	Color change	-30 to 1200	1 to 20	Medium	Low
Infrared Thermography	Color or gray scale image	-20 to 500 (1500 with filter)	Varies with camera	High	Medium - High

* Note: Low Cost on the order of US\$10's, Medium Cost on the order of US\$100's, High Cost on the order of US\$1,000's.

Reference: Developed from www.capgo.com/Resources/Temperature/ and http://www.minco.com/uploadedFiles/Products/sensors_ts103a_full.pdf

2.2 Installation Considerations

Temperature measurement accuracy can be affected by the placement of the device on or in the equipment and the power supply or signal wires. Following is a listing of various sources of temperature measurement error to consider when selecting, locating, and installing a device:

- i) Device calibration errors are attributable to offset, scale, and linearity errors. Additionally, each of these errors can drift with time and temperature cycling. Hysteresis can be noticed with some devices such as bimetallic gauges.
- ii) Thermal gradients can occur especially when measuring fluids with poor thermal conductivity, such as air, most liquids and non-metallic solids (i.e. insulation, onboard processing systems).
- iii) Heat conduction in device leads can allow heat to flow into or out of the device body. Use the thinnest wires practical for device installation. Place the wires in or adjacent to the object measured. Minimize the thermal gradient along the device wires by placing the wires at an angle to the gradient.
- iv) Radiation can contribute to errors in temperature measurement. To reduce this effect the device should be provided with a coating highly reflective of infrared radiation, shielded if possible, and in good thermal contact with the material or object being measured.
- v) For those devices that require excitation power such as Resistance Temperature Detectors (RTDs) and thermistors, device self-heating can occur. In some cases the self-heating effect can be calibrated. In other cases a lower excitation power can be applied or consideration given to turning off excitation power between readings.
- vi) Thermal contact with the material or object being measured is vital. Parasitic thermal connections such as the device's lead conduction, direct contact with other materials, such as air, and radiant energy transfer can affect measurements.
- vii) The thermal time constant refers to the time it takes for a device to reach 63% of the way to the new temperature. This varies from device to device. If rapid temperature changes are anticipated, consider using a device with a low thermal time constant; improve thermal contact, reduce the device's thermal mass, and compensate the readings by applying an inverse matching filter.
- viii) Read-out errors can be reduced by calibrating the readout device against a known reference and calibrating the total device-readout system against a known reference.
- ix) Electrical noise or interference can induce errors. This can be reduced by use of shielded twisted pair cable, installing wire away from power cables, transformers, and other electrical machinery, installing low pass filters into the measuring device, and avoiding ground loops.
- x) At times, condensation in the device and wiring can collect, particularly for installations cycling through the dew point. The device and wiring should be sealed. Evaporating condensation can lead to measurement errors.
- xi) Some devices such as film type RTDs can be affected by mechanical stress. The device should not be subject to deformation after installation. Avoid the use of adhesives in attaching devices. The differences in coefficient of linear expansion will induce mechanical stress. Use devices less sensitive to stress, such as thermocouples.
- xii) Calibration can be applied so that the devices provide correct results.

2.3 Point Temperature Devices

Point temperature devices used in the marine industry are listed in the following Subparagraphs. A brief explanation is provided of the theory of operation along with the advantages and disadvantages for each device.

2.3.1 Thermocouple

A thermocouple consists of two wires of dissimilar metals joined near the measurement point (junction), a reference junction, and a measuring device. The output is a small voltage measured between the two wires which is converted to a temperature readout by an instrument.

- *Typical P-F interval:* Provides a continuous output, data recorded several times per day
- *Skill level:* No specific training needed

2.3.1(a) *Advantages.* Advantages of this technique include the following:

- i) Thermocouples can be rugged and immune to shock and vibration.
- ii) They are useful over a wide temperature range.
- iii) No excitation power or self heating is required.
- iv) They can be made very small.

2.3.1(b) *Disadvantages.* Disadvantages of this technique include the following:

- i) They produce a low, non-linear output signal. This requires a sensitive and stable measuring device able to provide a reference junction compensation and linearization.
- ii) A higher level of care is required when determining installation location to minimize potential noise sources.
- iii) The measuring device requires good noise rejection capability.

2.3.2 Resistance Temperature Detectors (RTDs)

A resistance temperature detector (RTD) consists of a stretched, fine wire coil supported and protected in a ceramic tube together with a measuring device. Film RTDs consist of a thin metal film on a ceramic or glassy substrate. The electrical resistance of metals changes with temperature in a predictable and repeatable phenomenon. RTDs made from platinum are the most accurate, but nickel and copper RTDs are also available with somewhat less accuracy. See Section 4, Table 1.

- *Typical P-F interval:* Provides a continuous output, data recorded several times per day
- *Skill level:* No specific training needed

2.3.2(a) *Advantages.* Advantages of this technique include the following:

- i) They are useful over a smaller temperature range.
- ii) They produce a larger and more linear output signal when compared to thermocouples.

2.3.2(b) *Disadvantages.* Disadvantages of this technique include the following:

- i) RTDs are less robust than thermocouples when installed in locations subject to shock and vibration.
- ii) They produce a low, non-linear output signal. This requires a sensitive and stable measuring device able to provide a reference junction compensation and linearization.
- iii) A higher level of care is required when determining installation location to minimize potential noise sources.
- iv) The measuring device requires good noise rejection capability.

2.3.3 Thermistor

Thermistor temperature sensors are manufactured from sintered metal oxide in a ceramic matrix that changes electrical resistance when temperature changes. These devices are sensitive to small temperature changes but highly non-linear [see 4/2.3.1(b)i)]. Thermistors are reliable, rugged and easy to use. It is reported there is a lack of interchangeability between manufacturers, which limits their application in industry.

The typical P-F interval and skill level are the same as for thermocouples and RTDs.

2.3.4 Bimetallic and Magnetic Temperature Sensors

A bimetallic temperature sensor is a mechanical element constructed from two different metals bonded together. As the temperature changes, the two metals expand at different expansion rates causing movement at the free end of the bimetallic pair.

Magnetic temperature sensors refer to devices fitted with magnets to allow attachment of the temperature gauge to any ferrous metallic object for which its local temperature is desired.

- *Typical P-F interval:* Provides a continuous output, data recorded several times per day (permanently installed)
Weeks to months (magnetic – not permanently installed)
- *Skill level:* No specific training needed

2.3.5 Temperature-indicating Paint

This contact measurement technique is used to indicate the surface temperature of objects upon which a special paint has been applied. The paint will change colors as the surface temperature of the monitored object increases, and it retains the color of the highest temperature the surface has encountered. This technique can be used to locate hot spots and insulation failures.

- *Typical P-F interval:* Weeks to months
- *Skill level:* No specific training needed

2.3.5(a) *Advantages.* Advantages of this technique include the following:

- The test is simple and no special training is required to observe the results.
- The paint retains the color of the highest temperature reached, providing a permanent record.

2.3.5(b) *Disadvantages.* Disadvantages of this technique include the following:

- Once the paint color changes, it does not change back to the original color.
- The effective life of an application of the paint is usually one (1) or two (2) years, or until the paint changes color.

2.4 Infrared Thermography

This non-contact technique uses infrared cameras to measure the temperature of heat-radiating surfaces within the line of sight of the camera. [Note: Infrared radiation is emitted from all objects above the temperature of absolute zero (-273°C)]. The camera measures temperature variations on the surface of the object being monitored and converts the temperature data into video or audio signals that can be displayed or recorded in a wide variety of formats for future analysis. This form of condition monitoring produces color or gray-scale images that identify temperature differences in the surface being examined. The sensitivity of the technique is affected by the reflectivity of the object being observed. The cameras are available for a wide range of temperature sensitivities and resolutions. This technique can be used to scan elevated, large, distant, or hot surfaces.

Recommended limits vary for particular applications. However, $\pm$ one full color band from that associated with the normal temperature range of operation is usually a satisfactory envelope.

Section 4, Figures 1 through 8 show several types of equipment with thermograph images to demonstrate how this technique can be applied. Note that the commentary provided with each figure is for illustrative purposes only. Interpretations of thermographs require an understanding of the equipment's design, function, operating characteristics and its operating context within the system. Infrared thermography should only be performed in a diagnostic function by trained, certified and experienced personnel. Using thermography techniques to validate repairs or check general area temperatures is applicable, but should be done with caution and with a full knowledge of the limitations.

Infrared cameras utilize two ranges of the infrared band:

- Long wave length (8 to 14 μm) for temperatures below the ambient temperature,
- Short wave length (2 to 5 μm) for temperatures above the ambient temperature.

Infrared cameras have to be programmed with the emissivity factor of the object being evaluated. Emissivity is a measure of an object's ability to emit radiation. For example, the emissivity of a black body, which is a perfect emitter and absorber, is 1. The camera will only measure the true temperature if the emissivity correction is accurate.

The thermal image quality can be affected by the following factors:

- The distance between the camera and the object.
- Excess humidity in the measured environment from rain or condensed steam, for example.
- Extraneous radiation emitted from surrounding objects or bright sunlight.
- The presence of insulation material between the camera and the object.
- The shape (such as angular relation to the camera) and surface condition.

When considering the performance of an infrared camera, the following characteristics are recommended for consideration:

- *Accuracy* – The measure of the difference between the true temperature and the measured temperature.
- *Environmental Temperature* – The temperature range in which the camera may be safely operated.
- *Spatial Resolution* – The measure of the fineness of detail directly proportional to the number of pixels representing the image.
- *Spot Size Ratio* – The ratio representing the maximum distance the camera can be from a target of a given size and still maintain temperature measurement accuracy.
- *Temperature Range* – Temperature measurement from -40°C to 2000°C is possible with modern cameras. Many cameras are capable of -20°C to 500°C and with the use of a filter extending the upper range to 1500°C .
- *Thermal Resolution* – The smallest difference in temperature possible to be expressed between two measurements.
- *Thermal Sensitivity* – The smallest change in radiation level the instrument is capable of registering expressed in terms of temperature.

Typical P-F interval: Minutes* to months (* for permanently mounted cameras)

Skill level: Trained and experienced technician

2.4.1 Advantages

Advantages of this technique include the following:

- i) Cameras can be portable and are generally considered easy to operate.
- ii) It provides dramatic images of the object's temperature profile.
- iii) It provides non-contact testing (i.e., safe to measure energized electrical systems, can measure object without disturbing its temperature).
- iv) The temperature of large surface areas can be observed quickly and continuously.
- v) A wide variety of equipment options is available, including various lenses and zoom-view capabilities.
- vi) Test data can be recorded, printed, logged, or fed to other digital equipment.

2.4.2 Disadvantages

Disadvantages of this technique include the following:

- i) Equipment costs are considered moderate to expensive. Price ranges from US\$400 to 10,000 depending on instrument sensitivity and various features. (American Infrared, <http://www.americaninfrared.com/Home.asp>)
- ii) Interpretation of the results requires training and experience.
- iii) The cameras do not measure well through metal or glass housings or barriers.