GUIDANCE NOTES ON

RELIABILITY-CENTERED MAINTENANCE

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Foreword

In recent years, there has been an increase in the use of proactive maintenance techniques by Owners for repair and maintenance of machinery onboard vessels and offshore structures. The resulting preventative maintenance programs developed as a result of applying these techniques are being used by the vessel's crew and shore-based repair personnel. There have been numerous advances in condition monitoring technology, trending, and increasingly more powerful planned maintenance software as a result of increased business competition. Since 1978, ABS has cooperated with Owners on developing and implementing preventative maintenance programs. 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 *Rule Requirements for Survey After Construction – Part 7* in mid-2002.

However, machinery systems have continued to become larger and more complex, requiring skilled operators with specialized knowledge of the machinery and systems onboard. The *Guide for Survey Based on Reliability-centered Maintenance* was issued in December 2003 to provide vessel and other marine structure Owners, managers and operators requirements for the development of a maintenance program using techniques applied in other industries for machinery systems within a maintenance philosophy referred to as Reliability-centered Maintenance (RCM). With the application of RCM principles, maintenance is evaluated and applied in a rational manner that provides the most value to a vessel's Owner/manager/operator. Accordingly, improved equipment and system reliability onboard vessels and other marine structures can be expected by the application of this philosophy.

The purpose of these Guidance Notes is to provide supplementary information for application of the requirements of the *Guide for Survey Based on Reliability-centered Maintenance*. Information related to equipment failure, maintenance strategies, risk considerations, conducting and documenting an RCM analysis and sustaining an RCM program is provided in the main section of these Guidance Notes. An Appendix providing an overview of various condition monitoring techniques is included. A brief example RCM analysis for three propulsion engine components is provided to demonstrate the procedure.

ABS welcomes comments and suggestions for improvement of this Guide. Comments or suggestions can be sent electronically to rdd@eagle.org.

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GUIDANCE NOTES ON
RELIABILITY-CENTERED MAINTENANCE

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SECTION 1 General

1 Objective

These Guidance Notes provide a summary of various maintenance techniques used in industry for machinery systems and how these techniques can be applied within a maintenance philosophy referred to as reliability-centered maintenance (RCM). With the application of RCM principles, maintenance will be evaluated and applied in a rational manner that provides the most value to a vessel's Owner/Operator. Accordingly, improved equipment and system reliability onboard vessels and other marine structures can be expected by the application of this philosophy.

An additional purpose of these Guidance Notes is to introduce RCM as a part of overall risk management. By understanding the risk of losses associated with equipment failures, a maintenance program can be optimized. This optimization is achieved by allocating maintenance resources to equipment maintenance according to risk impact on the vessel. For example, RCM analysis can be employed to:

i) Identify functional failures with the highest risk, which will then become the focus for further analyses

ii) Identify equipment items and their failure modes that will cause high-risk functional failures

iii) Determine maintenance tasks and maintenance strategies that will reduce risk to acceptable levels

The principles summarized in these Guidance Notes are applied in the *Guide for Survey Based on Reliability-centered Maintenance*.

2 Application

These Guidance Notes provide supplementary information for the use of the *Guide for Survey Based on Reliability-centered Maintenance* and apply to any machinery system for which a preventative maintenance plan applying risk-based principles is desired. It is applicable to both vessels and offshore facilities.

3 Defining Reliability-centered Maintenance

Reliability-centered maintenance is a process of systematically analyzing an engineered system to understand:

i) Its functions

ii) The failure modes of its equipment that support these functions

iii) How then to choose an optimal course of maintenance to prevent the failure modes from occurring or to detect the failure mode before a failure occurs

iv) How to determine spare holding requirements

v) How to periodically refine and modify existing maintenance over time

The objective of RCM is to achieve reliability for all of the operating modes of a system.

An RCM analysis, when properly conducted, should answer the following seven questions:

i) What are the system functions and associated performance standards?

ii) How can the system fail to fulfill these functions?

iii) What can cause a functional failure?

iv) What happens when a failure occurs?

v) What might the consequence be when the failure occurs?

vi) What can be done to detect and prevent the failure?

vii) What should be done if a maintenance task cannot be found?

Typically, the following tools and expertise are employed to perform RCM analyses:

i) Failure modes, effects and criticality analysis (FMECA). This analytical tool helps answer Questions 1 through 5.

ii) RCM decision flow diagram. This diagram helps answer Questions 6 and 7.

iii) Design, engineering and operational knowledge of the system

iv) Condition-monitoring techniques

v) Risk-based decision making (e.g., the frequency and the consequence of a failure in terms of its impact on safety, the environment and commercial operations)

Documenting and implementing the following formalize this process:

i) The analyses and the decisions taken

ii) Progressive improvements based on operational and maintenance experience

iii) Clear audit trails of maintenance actions taken and improvements made

Once these are documented and implemented, this process will be an effective system to ensure reliable and safe operation of an engineered system. Such a maintenance management system is called an RCM system.

4 Definitions

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

ABS Recognized Condition Monitoring Company: The reference to this term refers to those companies whom ABS has identified as an External Specialist. Please refer to Subsection 8/2.

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 is compared.

Cause: See *failure cause*.

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* can be specified.

Condition monitoring: Condition monitoring are those scheduled diagnostic technologies used to monitor machine condition to detect a potential failure. Also referred to as an on-condition task or predictive maintenance.

Confidence: Confidence is the analyst's/team's certainty of the risk evaluation.

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".

Corrective Measures: Corrective measures are engineered or administrative procedures activated to reduce the *likelihood* of a *failure mode* and/or its end *effect*.

Criticality: Criticality is a measure of risk associated with the *failure mode* and its *effects*. The *risk* can be measured qualitatively (e.g., high, medium, low) or quantitatively (e.g., $15,000 per year).

Current likelihood (frequency): The current likelihood (or frequency) of a *failure mode* occurring is based on no maintenance being performed or, in the case of existing *preventative maintenance plans*, the failure *frequency* with the existing plan in place.

Current risk: The resulting *risk* that results from the combination of the *severity* and the *current likelihood* (*severity* times *likelihood*).

Effects: See *failure effects*.

End Effects: See *failure effects*.

Environmental standards: Environmental standards are international, national and local laws and regulations or industry standards that the vessel must operate in conformance with.

Equipment items: The hierarchical level below *systems* comprised of various groups of *components*.

Event: An event is an occurrence that has an associated outcome. There are typically a number of potential outcomes from any one initial event ranging in *severity* from minor (trivial) to critical (catastrophic), depending upon other conditions and add-on events.

Evident failure mode: A *failure mode* whose *effects* become apparent to the operators under normal circumstances if the failure mode occurs on its own.

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 (e.g., 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 this Guide, the term *End Effects* applies only to the total loss or degradation of the functions related to propulsion and directional control, including the following consequences: loss of containment, explosion/fire, and/or 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 functions related to drilling operations, position mooring, hydrocarbon production and processing and/or import and export functions.

Failure-finding task: 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.

Failure management strategy: A failure management strategy is a proactive strategy to manage failures and their effects to an acceptable *risk*. It consists of *proactive maintenance tasks* and/or *one-time changes*.

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 (e.g., pump bearing seizes), but is typically described in terms of an observed effect of the equipment failure (e.g., pump fails off).

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*.

Hazard: Hazards are conditions that may potentially lead to an undesirable *event*.

Hidden Failure Mode: A *failure mode* whose *failure effects* do not become apparent to the operators under normal circumstances if the failure mode occurs on its own.

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

Level of indenture: A relative position within a hierarchy of *functions* for which each level is related to the functions in the level above. For the purposes of this Guide, the levels of indenture in descending order are: *functional group*, *systems*, *subsystems*, *equipment items* and *components*.

Likelihood: See *frequency*.

One-time change: One-time change is any action taken to change the physical configuration of a *component*, an *equipment item* or a *system* (redesign or modification), to change the method used by an operator or maintenance personnel to perform an operation or maintenance task, to change the manner in which the machinery is operated or to change the capability of an operator or maintenance personnel, such as by training.

Operating context: The operating context of a functional group is the circumstances under which the *functional group* is expected to operate. It must fully 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.

Operating mode: An operating mode is the operational state that the vessel or marine structure is in. For example, cruising at sea, entering or departing a port.

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.

Parallel redundancy: Parallel redundancy applies to *systems*/*equipment items* operating simultaneously. Each system has the capability to meet the total demand. In the event of a *functional failure* in one system/equipment item, the remaining system/equipment item will continue to operate, but at a higher capacity. For some arrangements, standby systems/equipment items may also be in reserve.

Performance and quality standards: Performance and quality standards are the requirements that *functional groups/systems/equipment items/components* are to operate at, such as minimum/maximum power or pressure, temperature range, fluid cleanliness, etc.

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.

Preventative maintenance plan: The preventative maintenance plan 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.

Projected likelihood: The *likelihood* (or *frequency*) of a *failure mode* occurring based on a maintenance task being performed or a *one-time change* implemented.

Projected risk: The resulting *risk* that results from the combination of the *consequence* and the *projected likelihood*.

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

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.

Risk Matrix: A risk matrix is a table indicating the *risk* for an associated *frequency* and *consequence severity*.

Run-to-failure: Run-to-failure is a failure management strategy that allows an *equipment item/component* to run until failure occurs, and then a repair is made.

Safeguards: See *corrective measures*.

Safety standards: Safety standards address the *hazards* that may be present in an *operating context* and specify the *safeguards (corrective measures)* that must be in place for the protection of the crew and vessel.

Servicing and Routine Inspection: These are simple tasks intended to (1) ensure that the failure rate and failure pattern remain as predicted by performing routine servicing (e.g., lubrication) and (2) spot accidental damage and/or problems resulting from ignorance or negligence. They provide the opportunity to ensure that the general standards of maintenance are satisfactory. 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.).

Severity: When used with the term *consequence*, severity indicates the magnitude of the consequence.

Special Continuous Survey of Machinery: The 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 *Rules for Survey After Construction – Part 7.*

Special Periodical Survey of Machinery: The requirements for a conventional Special Periodical Survey of Machinery are listed in 7-2-2/7 Special Periodical Surveys (Vessels in Great Lakes Service); 7-2-3/5 Special Periodical Surveys (Vessels in Rivers and Intracoastal Waterway Service); 7-6-2/3 Special Periodical Surveys – Machinery (3.1, All Vessels, 3.3, Tankers); 7-6-3/1 Special Periodical/Continuous Survey-Machinery-Year of Grace (Vessels in Great Lakes Service; 7-8-2 Shipboard Automatic and Remote-control Systems, Special Periodical Surveys; 7-9 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) of the *Rules for Survey After Construction – Part 7.* There are Special Periodical Survey requirements in other *Rules* and *Guides* for specific vessel types, services and marine structures not listed here.

Subsystems: An additional hierarchical level below *system,* comprised of various groups of *equipment items* for modeling complex *functional groups*.

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

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.

SECTION 2 Equipment Failure

1 Equipment Failure

A combination of one or more equipment failures and/or human errors causes a loss of system function. The following factors usually influence equipment failure:

i) Design error

ii) Faulty material

iii) Improper fabrication and construction

iv) Improper operation

v) Inadequate maintenance

vi) Maintenance errors

Note that maintenance does not influence many of these factors. Therefore, maintenance is merely one of the many approaches to improving equipment reliability and, hence, system reliability. RCM analyses focus on reducing failures resulting from inadequate maintenance. In addition, RCM aids in identifying premature equipment failures introduced by maintenance errors. In these cases, RCM analyses may recommend improvements for specific maintenance activities, such as improving maintenance procedures, improving worker performance, or adding quality assurance/quality control tasks to verify correct performance of critical maintenance tasks. While the objective of this document is to improve maintenance, RCM analyses may recommend design changes and/or operational improvements when equipment reliability cannot be ensured through maintenance.

To effectively improve equipment reliability through maintenance, design changes or operational improvement, one must have an understanding of potential equipment failure mechanisms, their causes and associated system impacts. Equipment failure should be defined as a state or condition in which a component no longer satisfies some aspect of its design intent (e.g., a functional failure has occurred due to the equipment failure). RCM focuses on managing equipment failures that result in functional failures.

To develop an effective failure management strategy, the strategy must be based on an understanding of the failure mechanism. Equipment will exhibit several different failure modes (e.g., 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. To help understand this relationship, Section 2, Table 1 examines typical hardware-related equipment failure mechanisms.

TABLE 1
Examples of Dominant Physical Failure Mechanisms for Hardware

Mechanical Loading Failure	*Wear*	*Corrosion*	*Temperature-related Failure*
• Ductile fracture • Brittle fracture • Mechanical fatigue	• Abrasive • Adhesive • Fretting • Pitting • Cavitation	• Galvanic • Uniform • Stress corrosion cracking	• Creep • Metallurgical transformation • Thermal fatigue

2 Equipment Failure Rate and Patterns

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

Statistically, failure rate is expressed in terms of operating time (or another pertinent operating parameter) elapsed before an item of equipment fails. Due to the variable nature of failure time, usually a failure density distribution is used to provide the probability of an item failing after a given operating time. Depending on the equipment failure mode, a variety of distributions (e.g., normal, exponential, Weibull, lognormal) are used to statistically model the probability of failure. Failure density distributions measure the probability of failure within a given interval (e.g., between time zero and 8,000 hours of operation). Section 2, Figure 1 provides example normal, exponential, and Weibull failure distributions.

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 are 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) Early wear-out

iv) 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 task intervals for certain types of maintenance tasks (e.g., rebuilding tasks).

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. Section 2, Figure 1 also identifies the MTTF for normal and exponential failure distributions.

MTTF data are helpful in determining when to perform certain types of maintenance tasks. For example, if the appropriate maintenance strategy is to rebuild an equipment item, the MTTF data can be used to help set the rebuilding task interval. If the MTTF is represented by a normal distribution and the interval is set at the MTTF, then one can assume that there is a 50% chance of the item failing before it is rebuilt. If the interval is set less than the MTTF, then the probability of the item failing before being rebuilt is less than 50%. If the interval is more than the MTTF, then the probability is more than 50%. The increase or decrease in probability as the interval is moved before or after the MTTF depends on the standard deviation of the distribution.

A more useful measurement, derived from the failure distribution, is the conditional failure rate or lambda (λ). 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 2 shows six classic conditional failure setup 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 (e.g., operating cycles).

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 (e.g., patterns C through F) is of little benefit and may actually increase failures as a result of infant mortality and/or human errors during maintenance tasks.

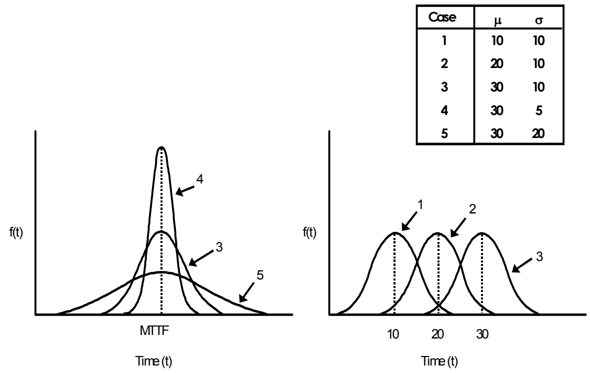
For most equipment failure modes, the specific failure patterns are not known and, fortunately, are not needed to make maintenance decisions. Nevertheless, certain failure characteristic information is needed to make maintenance decisions. These characteristics are:

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. (e.g., failure is not predictable by time).

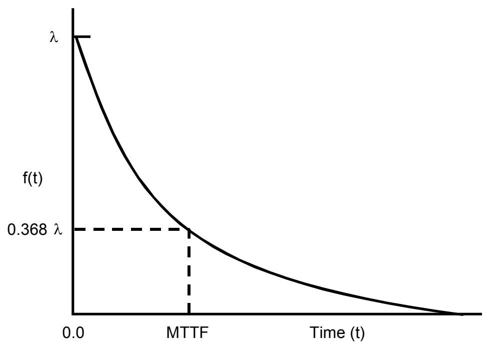
iii) *Wear-out failure* – dominated by end-of-useful life issues for equipment.

FIGURE 1
Normal, Exponential and Weibull Failure Distributions

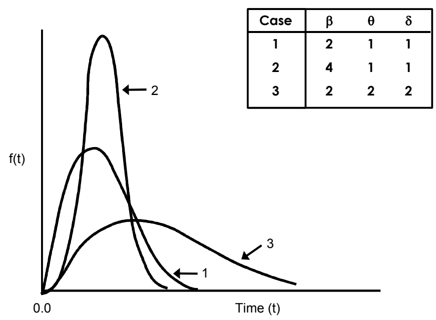


Case	μ	σ
1	10	10
2	20	10
3	30	10
4	30	5
5	30	20

Normal (continuous)



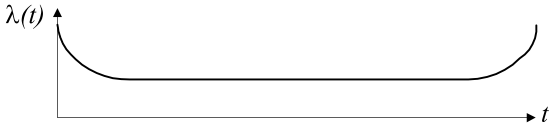
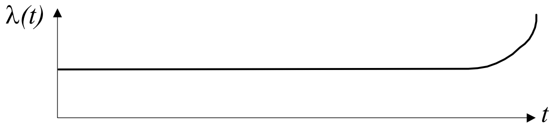
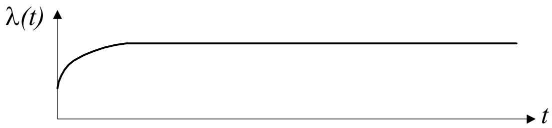
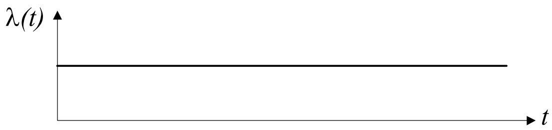
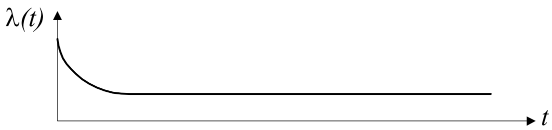
Exponential (continuous)



Case	β	θ	δ
1	2	1	1
2	4	1	1
3	2	2	2

Weibull (continuous)

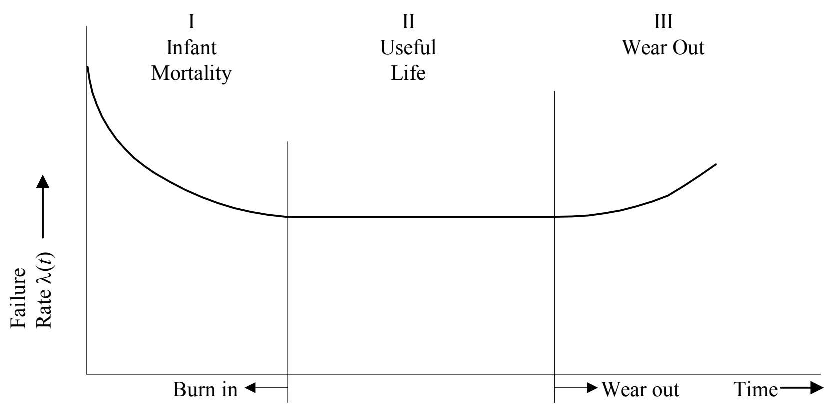
TABLE 2
Six Classic Failure Rate Patterns (1)

	**Pattern A – Bathtub:** Infant mortality, then a constant or increasing failure rate, followed by a distinct wear-out zone *Example*: overhauled reciprocating engine
	**Pattern B – Traditional Wear-out:** Constant or slowly increasing failure rate followed by a distinct wear-out zone *Example*: reciprocating engine, pump impeller
	**Pattern C – Gradual Rise with no Distinctive Wear-out Zone:** Gradually increasing failure rate, but no distinct wear-out zone *Example*: gas turbine
	**Pattern D – Initial Increase with a Leveling off:** Low failure rate initially, then a rapid increase to a constant failure probability *Example*: 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 *Example*: roller/ball bearings
	**Pattern F – Infant Mortality:** High infant mortality followed by a constant or slowly rising failure rate *Example*: 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.

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

FIGURE 2
Equipment Life Periods



By simply identifying which of the three equipment failure characteristics is representative of the equipment failure mode, one gains 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 (e.g., fail frequently) are usually best addressed by redesign rather than applying more frequent maintenance.

3 Failure Management Strategy

Understanding failure rates and failure characteristics allows the determination of an appropriate strategy for managing the failure mode (e.g., RCM refers to this as the failure management strategy). Developing and using this understanding is fundamental to RCM and critical 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 can actually increase overall failure rates by introducing infant mortality and/or human errors into otherwise stable systems.

In RCM, the failure management strategy can consist of:

i) Appropriate proactive maintenance tasks,

ii) Equipment redesigns or modifications, or

iii) Other operational improvements.

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 managed before it occurs. Equipment redesigns, modifications and operational improvements (RCM refers to these as one-time changes) are attempts to improve equipment whose failure rates are too high or for which proactive maintenance is not effective/efficient.

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 describe the risk-based decision tools and the RCM analysis process, and provide a more detailed discussion on determining effectiveness of the failure management strategy.

In addition to proactive maintenance tasks and one-time changes, servicing tasks and routine inspections may be critical to the failure management strategy. These activities help ensure 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 further described in the following Paragraphs.

3.1 Proactive Maintenance Tasks

Proactive maintenance tasks are divided into four categories.

3.1.1 Planned-maintenance Tasks

A planned-maintenance task (sometimes called preventative maintenance) is performed on 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 region. RCM further divides planned maintenance 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 of the fuel injectors would be an example. Section 3 provides additional details.
- *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. Section 3 provides additional details.

3.1.2 Condition-monitoring Tasks

A condition-monitoring task is a scheduled task used to detect the 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 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 4 provides additional details.

3.1.3 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. Usually, this approach is used when the condition-monitoring or planned-maintenance task is insufficient to achieve an acceptable risk by itself. Sections 7 and 8 provide further information on determining whether this failure management strategy achieves an acceptable level of risk.

3.1.4 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 checking the safety valve on a boiler. Section 5 provides additional details.

3.2 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 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.

3.3 One-time Changes

One-time changes are used to reduce the failure rate or manage failures in which appropriate proactive 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/or
- Operational improvements.

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

i) Faulty design and/or material

ii) Improper fabrication and/or construction

iii) Misoperation

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. For failure modes that have the highest risk, a one-time change is mandatory. 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 adding drain valves to appropriate lengths of piping to a tanker's deck cargo piping to prevent freezing and damage to the piping during vessel transits in freezing temperatures.
- *Operational improvements.* Operational improvements may be modifications to the operation of the equipment and/or modifications to the way in which maintenance is performed on the equipment. 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 noncontinuous rating name plate, the engine could be operated at a lower output closer to its continuous rating so as to reduce downtime for maintenance. (However, this action may cause the vessel to be unable to meet its schedules.)

3.4 Servicing and Routine Inspection

These are simple tasks intended to (1) ensure that the failure rate and failure pattern remain as predicted by performing routine servicing (e.g., lubrication) and (2) spot accidental damage and/or problems resulting from ignorance or negligence. They provide the opportunity to ensure that the general standards of maintenance are satisfactory. 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 Planned Maintenance

1 Introduction

Planned maintenance is a failure management strategy that restores the inherent reliability or performance of the equipment item. These tasks are best employed on equipment items suffering from age-related failure (e.g., wear-out failure characteristic).

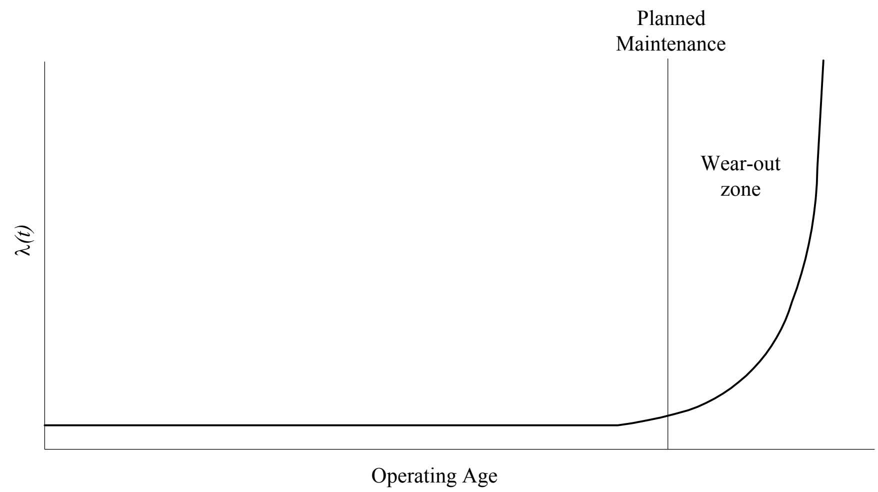
The basic principle of planned maintenance is that restoring or discarding the item at a specific time before failure is expected can best manage the probability of failure. Following this principle, the planned-maintenance tasks are performed at set intervals, regardless of whether or not a failure is impending. Restoring the item or discarding it and replacing it with a new item prevent the failure.

2 Age-To-Failure Relationship

The age-to-failure relationship (or wear-out failure characteristic) is distinctive in failure patterns A and B, discussed in Subsection 2/2. Other equipment failure modes may exhibit a less distinctive wear-out characteristic, such as that in failure pattern C. Conceptually, though, performing planned maintenance restores equipment reliability for these failure patterns.

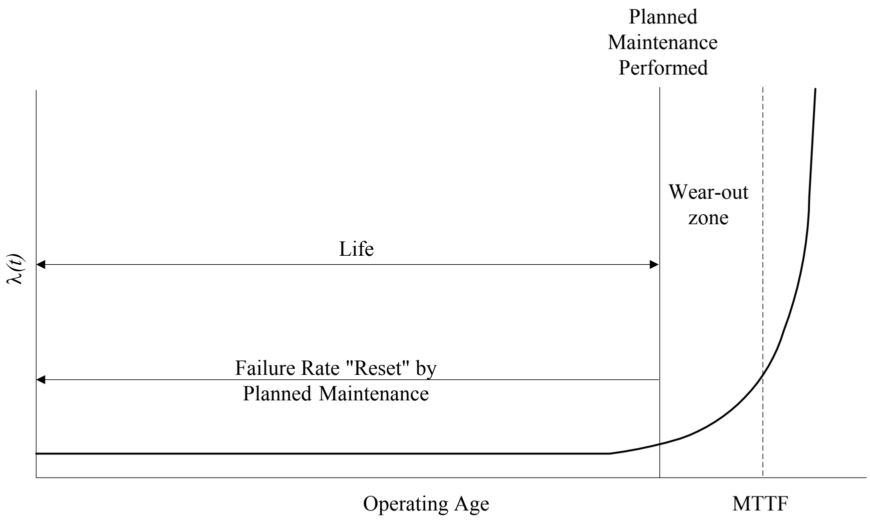
For planned maintenance to be effective in managing the failure, the failure mode must exhibit a clear life and most of the equipment items must survive to that life. Section 3, Figure 1 illustrates the wear-out period for failure pattern B.

FIGURE 1
Classic Failure Profile Used for Planned Maintenance



Planned maintenance provides an effective failure management strategy for wear-out failures because the conditional probability of failure is reduced to approximately its initial failure rate (e.g., failure rate at time zero). Section 3, Figure 2 illustrates the "resetting" of the failure rate curve that results from performing a planned-maintenance task.

FIGURE 2
Failure Profile Illustrating the Effect of Performing a Planned Task



The assumption is that the restoration and discard task restores the equipment item to nearly "new" condition. However, if the equipment failure mode exhibits both wear-in and wear-out failure patterns (e.g., failure pattern A), additional tasks or a one-time change may be required to manage the wear-in that is likely to occur after the planned-maintenance task (for example, the recommissioning of a gas turbine or a diesel engine after an extensive repair/overhaul).

3 Planned-maintenance Task Applicability and Effectiveness

For a planned-maintenance task to be considered applicable and effective, the following considerations must be made:

i) Is the task technically feasible to perform? The age-to-failure relationship must be reasonably consistent, and the task must be physically capable of being performed.

ii) Does the task reduce the probability of failure (and therefore the risk) to an acceptable level? The tasks must be carried out at an interval that is less than the age at which the equipment or component shows a rapid increase in its conditional probability of failure. Agreed-upon risk acceptance criteria should be determined and recorded.

iii) Is the task cost-effective? The cost of undertaking a task over a period of time should be less than the total cost of the consequences of failure.

When determining whether the planned-maintenance task should be a restoration or discard task, the following considerations must be made:

i) Does the task ensure the reliability and performance of the equipment? If the equipment is restored, it must be restored to a nearly new condition.

ii) Is the task cost-effective? The cost of restoring the equipment should be less than discarding the equipment and replacing it with a new item.

4 Determining Planned-maintenance Task Interval

One can determine the interval at which planned-maintenance tasks should be performed using a variety of methods:

i) Equipment manufacturer information

ii) Expert opinion

iii) Published reliability data

iv) Statistical analysis (e.g., Weibull) of actual failure history, including the MTTF data

Regulatory requirements (e.g., classification society Rules) should also be considered, especially if data are insufficient to determine a planned-maintenance interval. In addition, the potential consequence (e.g., the resulting effect) and the risk associated should be considered when determining a planned-maintenance interval. RCM employs two concepts when determining a planned-maintenance interval: safe life limit and economic life limit. These limits are illustrated in Section 3, Figures 3 and 4.

FIGURE 3
Safe Life Limit

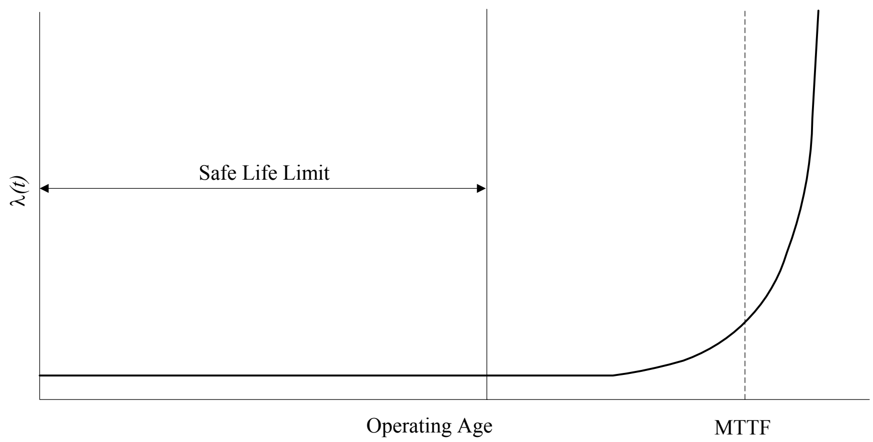
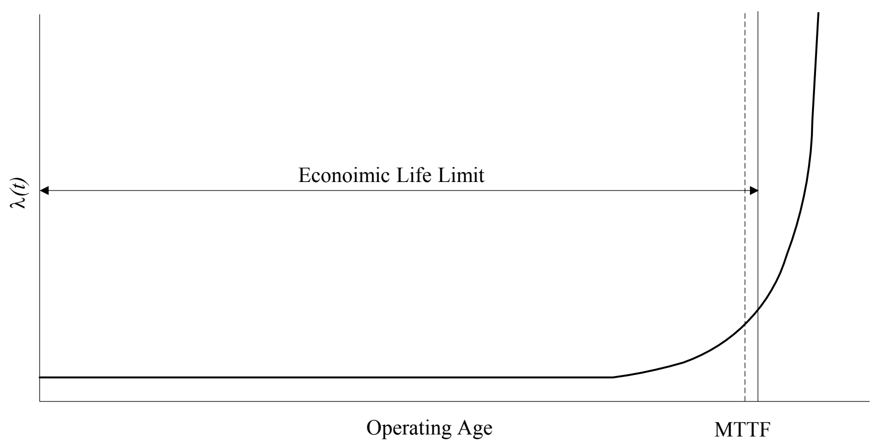


FIGURE 4
Economic Life Limit



If the failure mode could result in a severe safety or environmental effect or a highest-risk event, the planned-maintenance task interval is set using the safe limit concept. That is, the task interval is set to ensure there is little chance of failure occurring before the planned-maintenance task is performed. This usually means setting the interval well before the MTTF point.

The economic life limit is used for all other failure modes. In this model, the task interval is based on the economics of the task and the expected equipment life. In this case, the task interval may be before, at, or after the MTTF point.

Because few operations currently have enough data to determine optimal planned-maintenance task intervals, the initial task frequency is typically set at a conservative value (especially for highest-risk failure modes) and then optimized as the task is performed. However, performing planned maintenance too frequently can result in an increased failure rate. This increased failure rate results from human errors during the task and/or wear-in failures.

SECTION 4 Condition Monitoring (Predictive) Maintenance

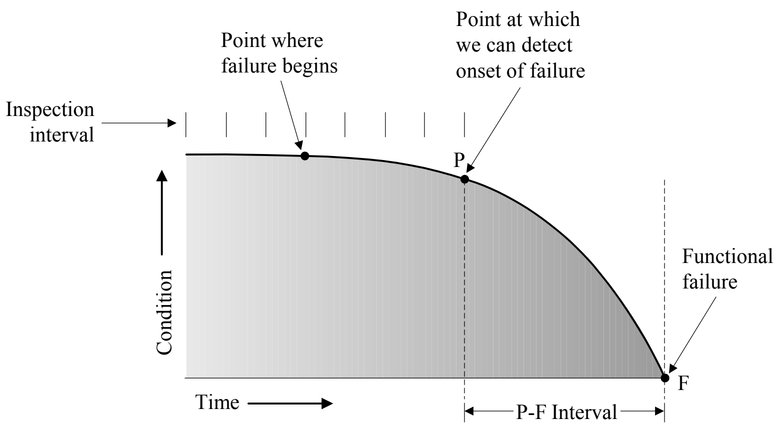
1 Potential Failure (P-F) Diagram

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 and/or to avoid the consequences. Section 4, Figure 1 illustrates the final stages of failure, called the P-F curve. Section 4, 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).

In practice, there are many ways of determining whether failures are in the process of occurring (e.g., 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). Tasks designed to detect potential failure are known as condition-monitoring tasks (see Subparagraph 2/3.1.2).

FIGURE 1
P-F Diagram



2 The P-F Interval

The time interval between Point P and Point F in Section 4, Figure 1 is called the "P-F interval". This is the warning period (e.g., 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.

For example, if the inspection interval is once per month and the P-F interval is six (6) months, the time between discovery of the potential failure and the occurrence of the functional failure is five (5) months. This is sometimes known as the available P-F interval. For a condition-monitoring task to be technically feasible, the available P-F interval must be longer than the time required to take action to prevent the functional failure (or minimize its effects).

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.

3 Condition-monitoring Maintenance Task Applicability and Effectiveness

For a condition-monitoring maintenance task to be considered applicable and effective, the following considerations must be made:

i) *Onset of failure must be detectable.* There must be some measurable parameter that can detect the deterioration in the equipment's condition. In addition, maintenance personnel must be able to establish limits to determine when corrective action is needed.

ii) *Reasonably consistent P-F interval.* The P-F interval must be consistent enough to ensure that corrective actions are not implemented prematurely or that failure occurs before corrective actions are implemented.

iii) *Practical interval in which condition-monitoring tasks can be performed.* The P-F interval must be sufficient to permit a practical task interval. For example, a failure with a P-F interval of minutes or hours is probably not a good candidate for a condition-monitoring maintenance task.

iv) *Sufficient warning so that corrective actions can be implemented.* The P-F interval must be 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.

v) *Reduces the probability of failure (and therefore the risk) to an acceptable level.* The tasks must be 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.

vi) *Must be cost-effective.* The cost of undertaking a task over a period of time should be less than the total cost of the consequences of failure.

Appendix 1 provides an overview of several condition-monitoring techniques.

4 Determining Condition-monitoring Maintenance Task Intervals

Condition-monitoring maintenance task intervals must 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 (e.g., manufacturer's recommendations)

ii) Published information about condition-monitoring tasks (e.g., Appendix 1, RCM texts)

iii) Historical data (e.g., current condition-monitoring task intervals)

4.1 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 $^1/_2$ [P-F interval]) does not provide sufficient time to 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.

4.2 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 (e.g., 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, adjust the task interval downward 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 Paragraph 4/4.1. 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?

4.3 Improving the Understanding of P-F Intervals

As data from condition-monitoring tasks are collected and corrective actions are implemented, a facility will improve its 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. We then know that the P-F interval for these pumps is probably at least six (6) weeks, and the task interval can be changed to three (3) weeks ($^1/_2$ of six weeks).

This is a rough form of age-exploration testing.

5 Establishing Condition-monitoring Maintenance Task Action Limits

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

i) Reperforming the condition-monitoring task to verify the results

ii) Altering the task interval to ensure closer monitoring of the equipment

iii) Initiating corrective actions to prevent the impending equipment failure

Establishing limits helps ensure that condition-monitoring tasks are effective in detecting and/or preventing the failure.

SECTION 5 Failure Finding Maintenance

1 Introduction

Failure-finding maintenance tasks are employed to discover equipment faults that are not detected during normal crew operations (e.g., hidden failures). Because these failures are hidden, if proper maintenance is not performed, a second failure must occur and a failure consequence realized before the equipment fault is detected. For example, a standby electrical generator failing to start on loss of power may only be discovered when the primary generator fails and power is lost.

Because these types of faults result in hidden failures, condition-monitoring or planned-maintenance tasks are typically not an effective failure management strategy. Failure-finding maintenance tasks usually involve a functional test of the equipment to ensure the equipment is available to perform its function(s) when demanded.

2 Statistical View of Hidden Failures

The purpose of a failure-finding task is to reduce the risk of multiple failures to an acceptable level by managing the frequency of occurrence of a multiple failure. Assuming that the multiple failure can only occur from the combination of a specific initiating event concurrent with the unavailability of the safety or backup system, the frequency of occurrence of a multiple failure is defined by the following equation:

$$F_{MF} = F_{IE} \cdot \bar{a}_{SYS} \qquad (1)$$

where

F_{MF} = frequency of occurrence of the multiple failure

F_{IE} = frequency of occurrence of the initiating event making the hidden failure evident

$\bar{a}_{SYS}$ = $(1 - a_{SYS})$, or the unavailability of the safety system or backup system

a_{SYS} = availability of the safety system or backup system

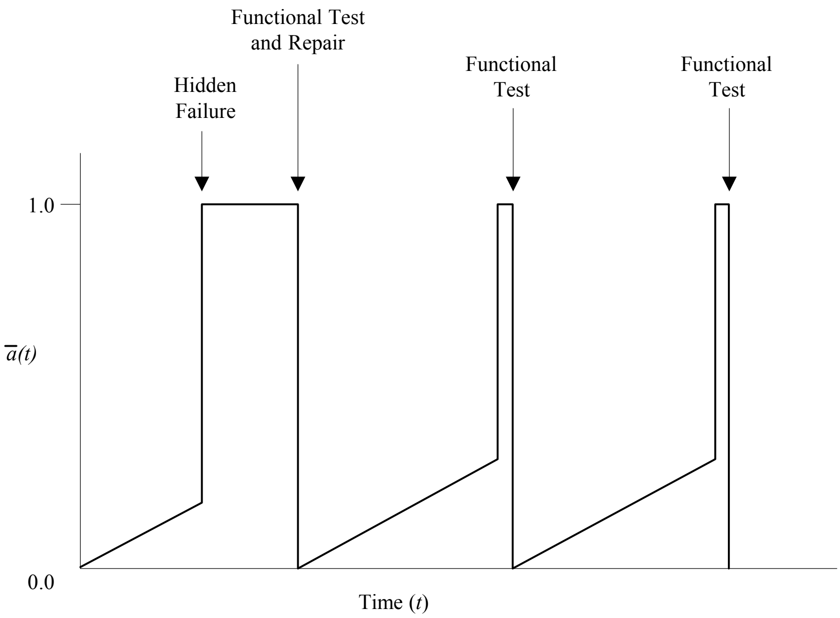
This equation can be rearranged to solve for the unavailability of the safety system or backup system:

$$\bar{a}_{SYS} = F_{MF}/F_{IE} \qquad (2)$$

An acceptable frequency of occurrence of a failure is achieved by ensuring that the unavailability of the equipment is less than what is needed to ensure the frequency of occurrence of a multiple failure is low enough to yield an acceptable risk of failure. For example, if the acceptable frequency of occurrence of a multiple failure for a specific event is 0.01/yr and the frequency of failure of the initiating event (e.g., F_{IE}) is 0.1/yr, then the acceptable unavailability for the hidden failure is 0.1.

Failure-finding tasks are effective in managing hidden failures because these tasks either (1) confirm that the equipment is functioning or (2) allow us to discover that the equipment has failed and needs repair. Once the task is performed, the unavailability of the safety system or backup system is "reset" to zero (or nearly zero). Then, as time progresses, the unavailability increases until the item fails or is retested again. If an exponential failure distribution is assumed, the failure rate is constant, which means the probability of the failure increases linearly (or at least nearly so over most reasonable time periods) at a slope equal to the failure rate (e.g., the probability of failure is a product of the failure rate and elapsed time). Section 5, Figure 1 illustrates the effect of failure-finding tasks.

FIGURE 1
Effect of a Failure-finding Task



3 Failure-finding Task Applicability and Effectiveness

For a failure-finding task to be considered effective, the following considerations must be made:

i) Must be no applicable or cost-effective condition-monitoring or planned-maintenance task that can detect or prevent the failure.

ii) Must be technically feasible to perform. The task must be practical to perform at the required interval and must not disrupt an otherwise stable system.

iii) Must reduce the probability of failure (and therefore the risk) to an acceptable level. The tasks must be carried out at an interval so that probability of multiple failures allows an acceptable risk level to be achieved. Agreed-upon risk acceptance criteria should be determined and recorded.

iv) Must not increase the risk of a multiple failure (e.g., when testing a relief valve, an over-pressure should not be created without the relief valve in service).

v) Must ensure that protective systems are tested in their entirety rather than as individual components that make up the system.

vi) Must be cost-effective. The cost of undertaking a task over a period of time should be less than the total cost of the consequences of failure.

4 Determining Failure-finding Maintenance Task Interval

The interval for failure-finding tasks can be determined:

i) Mathematically, using reliability equations, or

ii) Using general guidelines developed to ensure acceptable risk.

Regardless of the technique used, the key is to ensure that the unavailability of a safety system or backup system is low enough to ensure that frequency of occurrence of a multiple failure is sufficiently low to achieve an acceptable risk. For a given consequence resulting from a multiple failure, an acceptable frequency of occurrence for the multiple failure needs to be established. For example, an acceptable frequency of occurrence for a $1 million operational loss might be 0.01/yr and acceptable frequency of occurrence for a $100,000 operational loss could be 0.1/yr. In both cases, the risk is equivalent ($10,000/yr).

These two techniques for setting failure-finding task intervals are briefly explained in the following paragraphs

4.1 Mathematical Determination of Failure-finding Task Interval

The highest-risk hidden failures usually require that the failure-finding task interval be mathematically determined. This is generally done by assuming the hidden failure is random and, therefore, is best modeled using the exponential distribution. This assumption is usually valid for the following reasons:

i) If the failure has a wear-in failure characteristic, then either a one-time change or a condition-monitoring task is usually employed to manage the failure.

ii) If the failure has a wear-out failure characteristic, then a condition-monitoring task or a planned-maintenance task should be applied to manage the failure.

To determine a failure-finding task interval, the equation for the frequency of a multiple failure and the equation for the unavailability of the hidden failure are combined as follows:

The equation for the frequency of occurrence of a multiple failure is:

$$F_{MF} = F_{IE} \cdot \bar{a}_{SYS} \quad (3)$$

To determine the maximum unavailability allowed to achieve an acceptable risk level, F_{MF} is set equal to the acceptable frequency (F_{ACC}) for the consequence being evaluated. Equation 3 is rearranged and unavailability ($\bar{a}_{SYS}$) is then solved for as shown in Equations 4a and 4b:

$$\bar{a}_{SYS} = F_{MF}/F_{IE} \quad (4a)$$

$$\bar{a}_{SYS} = F_{ACC}/F_{IE} \quad (4b)$$

The following additional assumptions are often true and will produce the simplification shown in Equation 5.

i) The distribution of the failures is exponential.

ii) The conditional failure rate times the test interval time ($\lambda \times$ test interval) is less than 0.1.

iii) The time to conduct a failure-finding task is short when compared to the length of time that the system is available.

iv) The time to conduct a repair of the system is short when compared to the length of time that the system is available.

v) The multiple failure can only occur from the combination of the specified initiating event concurrent with the unavailability of the backup or safety system.

$$T = \frac{2 \cdot F_{ACC} \cdot MTTF}{F_{IE}} \quad \text{.......(5)}$$

where

T = test interval

F_{ACC} = acceptable frequency of occurrence of the multiple failure

F_{IE} = frequency of occurrence of the initiating event making the hidden failure evident

$MTTF$ = mean time to failure for the system with the hidden failure

4.2 Using Guidelines to Determine the Failure-finding Task Interval

Guidelines are developed and documented for determining the failure-finding task interval. This usually involves the following:

i) Establishing rules for determining required unavailability of the hidden failure based on the risk of the hidden failure

ii) Estimating the MTTF of the hidden failure

iii) Determining the test interval using a table based on Equation 5

Section 5, Tables 1 and 2 provide examples of the acceptable probability rules and failure-finding test interval.

TABLE 1
Example of Failure-finding Task Interval Rules

Risk of Hidden Failure	*Unavailability Required*
Very High	< 0.0001
High	> 0.0001 to 0.001
Moderate	> 0.001 to 0.01
Low	> 0.01 to 0.05

TABLE 2
Example of Failure-finding Task Intervals Based on MTTF

Unavailability Required	*Failure-finding Task Interval (as % of MTTF)*
0.0001	0.02
0.001	0.2
0.01	2
0.05	10

When applying this guideline approach, the user must be aware of the assumptions used in developing the rules and task intervals, and ensure that the assumptions are valid.

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SECTION 6 Consideration of Risks

1 Risks In General

Risk can be considered in two parts: how often a loss event occurs (frequency) and how severe the effects are (consequence).

Frequency of a loss is usually expressed in loss events per year. The frequency can either be determined from past data (if a large number of events have occurred) or calculated using risk analysis tools (if few data records exist).

Consequence can be expressed in terms of a combination of a loss event's impact on the following example consequences:

i) *Capital investment.* Damage to and cost of repair of equipment

ii) *Community.* Effect on the public

iii) *Directional control.* Complete loss or reduction of maneuverability

iv) *Explosion or fire.* Damage to equipment and/or the vessel

v) *Loss of containment.* Amount of harmful substances released to the environment (the cleanup costs)

vi) *Operations.* Loss of hire, outage time of functions such as drilling, position mooring (station keeping), hydrocarbon production and processing, loading or unloading functions

vii) *Propulsion.* Complete loss or reduction of propulsive capability

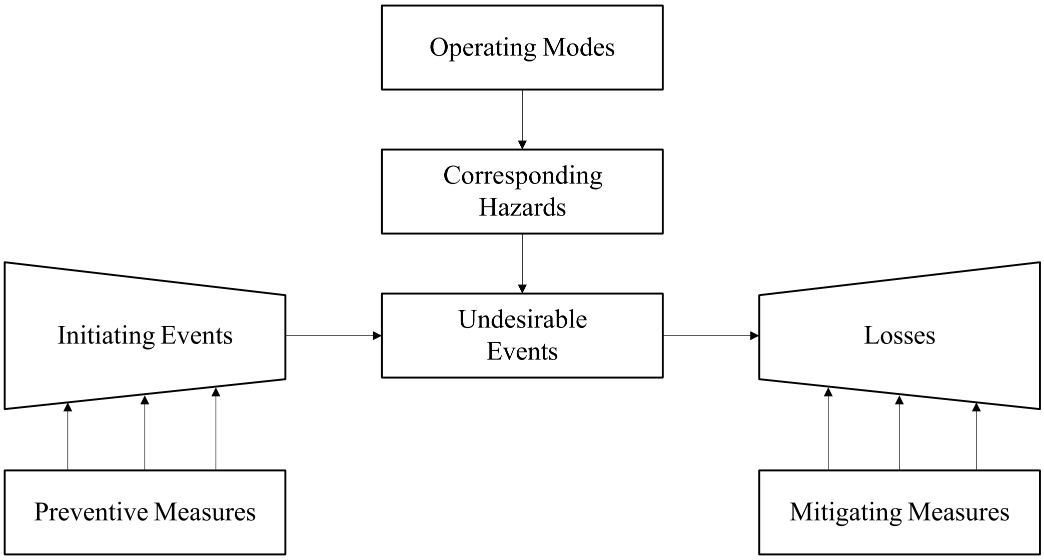
viii) *Safety.* The number of people affected (injured or fatalities)

Having identified the risk of a loss event, ship designers, operators, insurers and regulators should deploy preventative or mitigative measures or both to the extent that the risk can be reduced to an acceptable level.

Depending on the operating modes of the vessel or marine structure (ocean transit, cargo discharge, etc.), loss events associated with each operating mode may differ. Thus, identifying the operating mode is the essential first step in addressing risks for vessels. A general risk model to illustrate this concept is shown in Section 6, Figure 1.

The operating modes represent the different operating contexts and environments for the vessel. The hazards can then be determined based on the operating modes. The initiating events are specific equipment failures, human errors or external events (e.g., lightning strike) that potentially result in an undesired event. Preventative measures are engineered safeguards (e.g., alarms) or management systems (e.g., personnel training) to prevent an initiating event from propagating into the undesired event. Undesired events are the immediate results of an initiating event and hazard on the vessel (e.g., collision, allision). The losses are the ultimate impact resulting from the undesired event and are usually measured in terms of the consequences listed in Subsection 6/1. The mitigating measures are the engineered safeguards and management systems that reduce or control the loss. Section 6, Figure 2 provides an example of the risk model, illustrating vessel operation in restricted waters.

FIGURE 1
The General Risk Model



2 Vessels and Their Risks

It is possible to comprehensively postulate loss events associated with each operating mode. Indeed, many loss events are already well known and identified, implicitly or explicitly, in classification society Rules and International Maritime Organization (IMO) regulations. Typically, this includes events such as structural failure, loss of stability, loss of propulsion, fire, etc. Consider "loss of propulsion" as an example. Preventative measures must be provided to make the propulsion machinery as reliable as possible, so as to prevent the loss of propulsion. On the other hand, mitigative measures must also be provided so that in the event of loss of propulsion, consequences such as collision, grounding, pollution, etc., can be mitigated. The extent to which preventative and mitigative measures should be provided depends on the risk level and the acceptable risk level.

Until now, classification society Rules and IMO regulations provide for reduction of risks for vessels primarily through hardware design, provision of facilities and in-service inspection. There are issues that traditionally are not explicitly covered. For example:

i) They are not specific as to the operating modes of the vessel.

ii) The risk levels have not been quantified nor, in fact, have acceptable risk criteria been defined.

iii) It is only in more recent years that operational measures (e.g., safety management and crew training) have been included as tools to reduce risks. More appear necessary, particularly in measures to mitigate consequences.

iv) Maintenance is not emphasized as a means of preventing loss events.

Risk acceptance criteria are discussed in general terms in the following Subsection.

3 Risk Characterization

A sample risk matrix is shown in Section 6, Figure 3. A risk matrix is an efficient way to characterize the risk of loss events. A risk matrix is simply a grid of cells that corresponds to defined consequence (severity) and frequency categories into which the loss events can be placed. The consequence and frequency categories are defined broadly enough to help one easily determine an appropriate risk cell for a loss event, but narrow enough to provide varying degrees of resolution for decision making. In many cases, frequency and consequence levels on a risk matrix are graduated by an order of magnitude.

Severity levels can be defined for several types of loss consequences from the list of examples in Subsection 6/1. Section 6, Table 1 lists five (5) consequences (directional control, propulsion, loss of containment, fire/explosion and safety) and defines four severity levels for each consequence. An appropriate severity level term for the consequence is to be chosen and defined prior to the risk analysis. For each severity level, several example descriptors are listed. Some descriptors are shown repeated between adjacent severity levels. Some studies use numerals (e.g., 1, 2, 3, 4). The descriptor chosen to describe a particular severity level may vary from analysis to analysis. For example, one analysis may choose the descriptors hazardous and critical to describe the two highest severity levels while another analysis may choose critical and catastrophic.

A listing of example frequency categories is shown in Section 6, Figure 3. Frequency categories are typically expressed in units of events per year. An example frequency category from Section 6, Figure 3 is Occasional, corresponding to a range of 0.01 to 0.1 events per year (a range of 1 event every 100 years to 1 event every 10 years). Sometimes, it is hard to obtain a perspective on the smaller frequency categories (e.g., Remote: 0.001 events per year to 0.01 events per year, or from 1 event every 1,000 years to 1 event every 100 years). These tiny frequencies can be better understood when one looks at multiple vessels over longer periods of time. For example, a loss event that has occurred twice across a fleet of 100 vessels over the last 20 years corresponds to a frequency of 0.001 events per year.

The risk-based decision-making aspect of a risk matrix is seen in the lines of constant risk. Each cell in the risk matrix corresponds to a defined risk level. Cells with similar risk levels are grouped together to form a line of constant risk. All of the cells on a risk matrix should be categorized into relevant lines of constant risk. Risk-based action levels to address the loss event are based on the risk level represented by the line of constant risk. Usually, the actions necessary to address loss events in each risk level are predefined.

In Section 6, Figure 3, there are three lines of constant risk. These are denoted by the different shades in the risk matrix (High Risk, Medium Risk and Low Risk). Referring to Section 6, Figure 3, if the consequence of a loss event were estimated as Hazardous and the frequency estimated as Probable, the loss event falls within a line of constant risk categorized as High Risk. Based on the action levels defined for this risk level, the loss event would be addressed by either a redesign or a one-time change.

Once the risk of the loss event has been identified from the risk matrix, a risk reduction action consistent with the required action level should be selected. Typically, maintenance tasks such as condition monitoring and planned maintenance will only reduce the frequency of occurrence of a loss event, while equipment redesign actions and one-time changes may reduce both the frequency and consequence. Essential to the risk-based task selection process is an assessment of the impact that the task has on the loss event. The ultimate objective should be to select an efficient, feasible task to reduce the risk level of the loss event to an acceptable level of risk (e.g., low risk or medium risk).

FIGURE 2
Example Risk Model

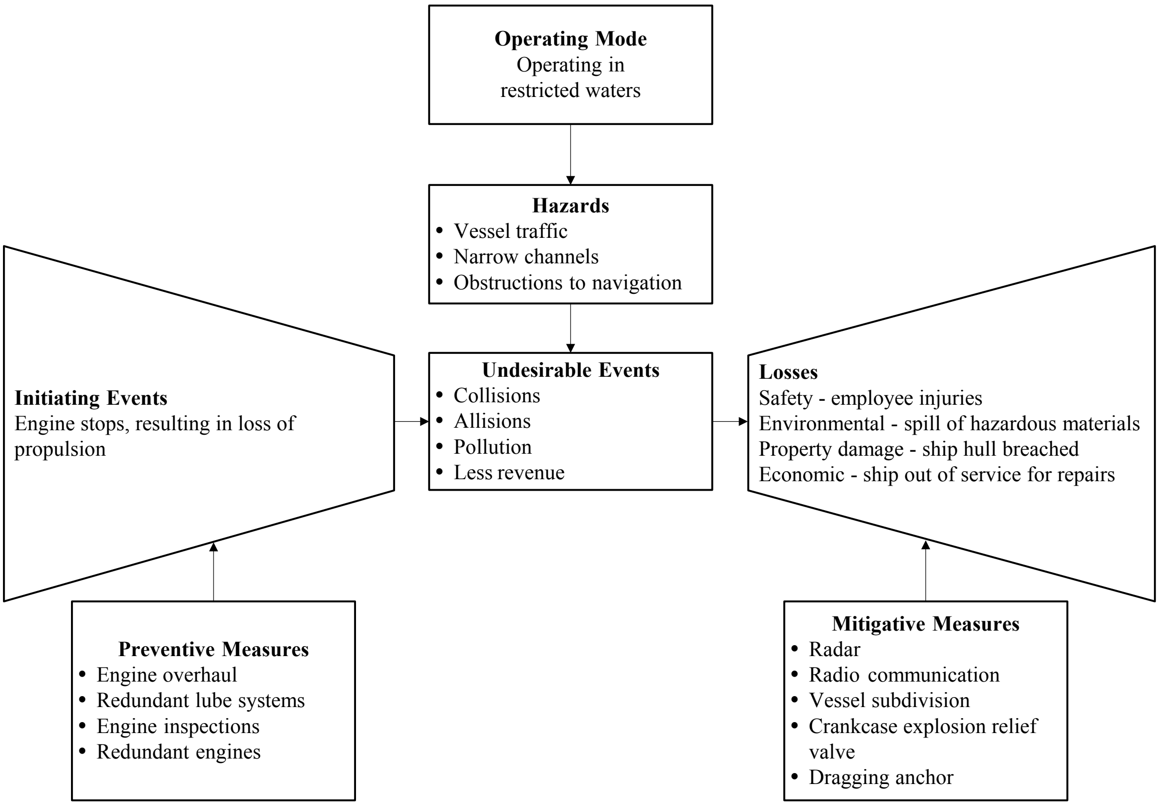
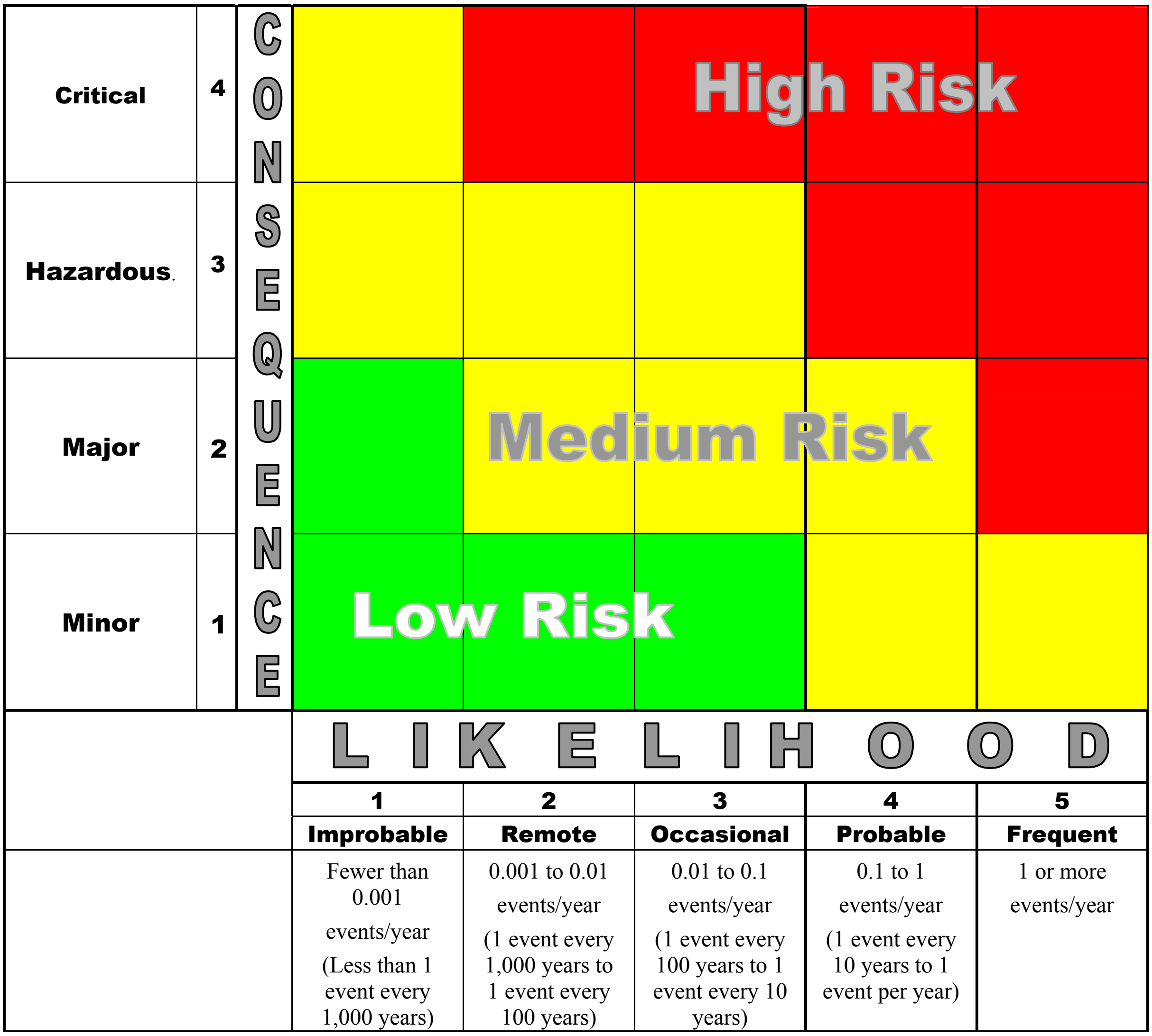
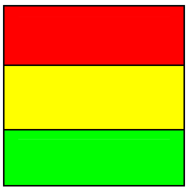


FIGURE 3
Sample Risk Matrix





High Risk – Redesign or other one-time change required to reduce risk

Medium Risk – One or more maintenance tasks are acceptable to reduce risk (e.g., condition monitoring, preventive maintenance)

Low Risk – Run-to-failure (no maintenance) is acceptable

TABLE 1
Example Consequence (Severity) Categories

Example Descriptors for Severity Level	Directional Control, Propulsion, etc.	Explosion/Fire	Loss of Containment	Safety [1]
Minor, Negligible	Function is not affected, no significant operational delays. Nuisance.	No damage to affected equipment or compartment, no significant operational delays.	Little or no response necessary	Minor impact on personnel/No impact on public
Major, Marginal, Moderate	Function is not affected, however, failure detection/corrective measures not functional. OR Function is reduced, resulting in operational delays.	Affected equipment is damaged, operational delays	Limited response of short duration	Professional medical treatment for personnel/No impact on public
Critical, Hazardous, Major, Significant	Function is reduced, or damaged machinery, significant operational delays	An occurrence adversely affecting the vessel's seaworthiness or fitness for service or route	Serious/significant commitment of resources and personnel	Serious injury to personnel/Limited impact on public
Catastrophic, Critical	Complete loss of function	Loss of vessel or results in total constructive loss	Complete loss of containment. Full scale response of extended duration to mitigate effects on environment.	Fatalities to personnel/Serious impact on public

Notes:

1 Safety losses are not intended to be compared to other losses to determine monetary equivalency.

SECTION 7 Conducting and Documenting an RCM Analysis

1 Introduction

The following procedures provide guidance for conducting RCM analyses. RCM analyses are to be performed in a step-by-step fashion. The basic elements of an RCM analysis process are as follows:

i) Identify operating modes and corresponding operating contexts

ii) Define vessel systems

iii) Develop system block diagrams and identify functions

iv) Identify functional failures

v) Conduct a failure modes, effects and criticality analysis (FMECA)

vi) Select a failure management strategy

vii) Determine spare parts holdings

viii) Document the analysis

The procedures to perform the RCM analysis are shown in Section 7, Figure 1, along with the cross-reference to the corresponding Subsection/Paragraph of this Section.

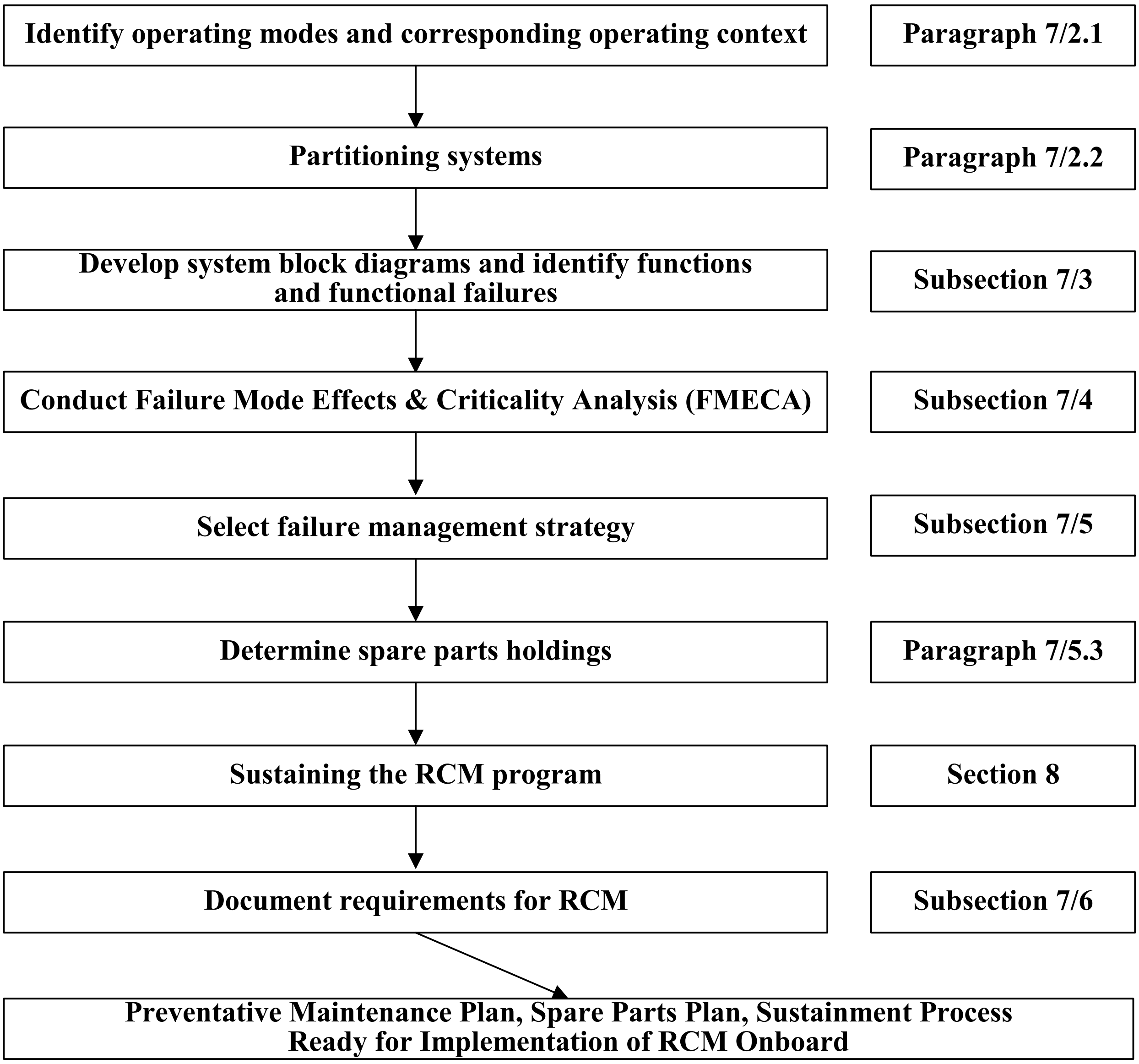
2 Defining Systems

In order to efficiently and thoroughly perform an RCM analysis, each system must be thoroughly defined. This activity involves (1) defining the operating characteristics for the ship as a whole and then for each system and (2) partitioning the vessel into functional groups, then into specific systems and then into equipment items. These distinctions are needed to clearly define the boundaries and operational intent of each system that is subject to RCM analysis.

2.1 Defining Ship Operating Characteristics

The operating characteristics of the vessel are the foundation for RCM failure management strategy decisions. Poorly defined or incomplete operating characteristics will result in an improper failure management strategy. To properly define operating characteristics, the various operating modes for the vessel must be identified. Next, the operating modes are used to define the operating context for each functional group. The following Subparagraphs describe operating modes and operating context in more detail.

FIGURE 1
Diagram for RCM Analysis



2.1.1 Operating Mode

An operating mode of a vessel or marine structure is the operational state that the vessel is in. Each operating mode influences the manner in which the shipboard systems and machinery are to be operated. This in turn dictates the development of operating contexts for individual functional groups.

The following example operating modes are typical for ships:

- Normal seagoing conditions at full speed
- Maximum permitted operating speed in congested waters
- Maneuvering alongside
- Cargo handling

The following example operating modes are typical for mobile offshore drilling units and offshore oil and gas production facilities:

- Drilling operations
- Position mooring or station keeping
- Relocation/Towing
- Hydrocarbon production and processing
- Import and export functions

2.1.2 Operating Context

The operating context of a functional group is the circumstances under which the system is expected to operate. It must fully describe:

i) The physical environment in which the functional group is operated

ii) A precise description of the manner in which the functional group is used

iii) The specified performance capabilities of the functional group as well as the required performance of any additional functional groups within which the functional group is embedded

Some of the important factors that must be considered in the development of the operating context for a functional group are:

i) *Serial redundancy.* Applies to arrangements for which an identical standby system/equipment exists to support an operating functional group. In the event of failure of the operating system, the standby system is activated. The operating contexts for the running system/equipment and standby system/equipment are different. For example, a functional failure in the operating system/equipment will likely be evident, while a functional failure in the standby system/equipment will likely be hidden.

ii) *Parallel redundancy.* Applies to systems/equipment operating simultaneously. Each system has the capability to meet the total demand. In the event of a functional failure in one system/equipment, the remaining systems/equipment will continue to operate, but at a higher capacity. In some arrangements, standby systems/equipment may also be in reserve.

iii) *Performance and quality standards.* Systems/equipment may be required to perform at a certain performance level or to provide a service with a certain quality level (e.g., compressed air supplied at specified quantity at certain pressure within certain temperature ranges and humidity limits).

iv) *Environmental standards.* As required by international, national and local laws and regulations (e.g., for an engine emission standard, the operating context of a functional group's impact or potential impact on the environment must be considered).

v) *Safety standards.* Hazards that might be present in an operating context and the safeguards that must be in place for protection of the crew should be specified.

vi) *Shift arrangements.* For oceangoing vessels, it is assumed the propulsion machinery is operating continuously, except when the vessel is docked. On the other hand, the ship's service electrical power system is operating continuously. System arrangements and maintenance strategies must be carefully developed so as to ensure system availability.

2.1.3 Developing Operating Contexts of Vessels

Operating contexts are to be developed to different degrees of detail at each level. At each level of functional breakdown, an operating context statement should be written for that level, amplifying the operating context written for the preceding level. At the lower levels of the functional breakdown, more detail is included in the operating context statement because at this level, the focus is on the systems and equipment that make up the functional group. Specific performance parameters are necessary to clearly define functions for the functional group and then to determine what constitutes a failure and what effects such failures will have upon specific equipment performance, overall system operation and, ultimately, the vessel's roles.

- *Vessel level.* Operating contexts must first be developed for the vessel. They are normally generic to a vessel type. This should include first a physical description of the vessel, the vessel type and the cargoes to be carried, the performance standard of the vessel (speed, maneuverability, fuel capacity and consumption, etc.) and the cargo handling capability. Statements are to be made on the primary roles (e.g., to carry cargo from point A to point B in a certain time, cargo preservation), secondary roles (e.g., crew habitability), and the safety and environmental roles of the vessel.

- *Functional group level.* The vessel-level operating context is then used to develop an operating context for each functional group level (e.g., machinery and utilities, then propulsion functional group). The operating contexts at a given functional group level must include all of the operational characteristics needed to define the operating context for the next highest level. For example, the operating contexts for the propulsion, maneuvering, electrical, vessel service, and navigation and communication functional groups must include all of the operating characteristics included in the machinery and utilities functional groups. In addition, an operating context must be developed for each vessel's operating mode. As an example, the operating context for the propulsion functional group may be developed in a structured manner, as shown in Section 7, Table 1. Section 7, Table 2 shows an example operating context for the diesel engine within the propulsion functional group.

TABLE 1
Example Operating Context of Propulsion Functional Group

Operating Context of Propulsion Functional Group				
The propulsion system consists of a *Manufacturer* Diesel Type *Model Number* low-speed diesel engine rated 16,860 kW Maximum Continuous Rating (MCR) at 91 RPM, coupled directly to a shaft supported by one intermediate bearing and two stern tube bearings, and driving a fixed pitched propeller.				
	Operating Modes			
Common Characteristics	*At Sea*	*In Congested Waters*	*Maneuvering Alongside*	*Cargo Handling*
Environmental Parameters	Nominal ambient air temperature: 25°C. Range from –29°C to 45°C Barometric air press (dry) 101.3 kPa Absolute Nominal seawater inlet temperature: 32°C. Range from –2°C to 50°C	Depending on geographical location	Depending on geographical location	Not used
Manner of Use	Propels vessel at 20 knots at 85% of MCR. Capable of continuous operation for up to 22 days. Single-engine installation	Propels vessel from 2 to 10 knots, with reversing and stopping capabilities	Propels vessel from 2 to 10 knots, with reversing and stopping capabilities, and assists in mooring	Not used
Performance Capability	To output 16,860 kW @ 91 RPM; controllable from bridge, centralized control station and locally	To output at 30 to 85 RPM; reversing at 63 RPM, controllable from bridge, centralized control station and locally	To output at 30 to 85 RPM; reversing at 63 RPM, controllable from bridge, centralized control station and locally	Not Applicable

TABLE 2
Example Operating Modes and Operating Context

Operating Context of Diesel Engine				
The propulsion system consists of a *Manufacturer* Diesel Type *Model Number* low-speed diesel engine rated 16,860 kW Maximum Continuous Rating (MCR) at 91 RPM, coupled directly to a shaft supported by one intermediate bearing and two stern tube bearings, and driving a fixed pitched propeller.				
	Operating Modes			
Common Characteristics	*At Sea*	*In Congested Waters*	*Maneuvering Alongside*	*Cargo Handling*
Environmental Parameters	Nominal ambient air temperature: 25°C. Range from –29°C to 45°C Barometric air press (dry) 101.3 kPa Absolute Nominal seawater inlet temperature: 32°C, 2.0-2.5 bar. Range from –2°C to 50°C Cooling FW nominal temperature: 25°C, 2.0-2.5 bar. Max. temp. 90°C L.O. max. supply temp. 60°C, 4.3 bar with exception of Camshaft L.O. max. supply temp. 50°C, 4 bar F.O. supply max. temp. 150°C at 4 bar.	Dependent on geographical location If ports to visit are known, list environmental parameter ranges.	Dependent on geographical location If ports to visit are known, list environmental parameter ranges	Not used
Manner of Use	Propels vessel at 20 knots at 85% of MCR. Capable of continuous operation for up to 22 days. Single-engine installation	Propels vessel from 2 to 10 knots, with reversing and stopping capabilities	Propels vessel from 2 to 10 knots, with reversing and stopping capabilities, and assists in mooring	Not used
Performance Capability	To output 16,860 kW @ 91 RPM; controllable from bridge, centralized control station and locally	To output at 30 to 85 RPM; reversing at 63 RPM, controllable from bridge, centralized control station and locally	To output at 30 to 85 RPM; reversing at 63 RPM, controllable from bridge, centralized control station and locally	Not Applicable

2.2 Partitioning Systems

Because a vessel is made up of many complex systems and subsystems, it is helpful to divide the vessel into functional groups and then into specific systems, subsystems, equipment items and, finally, components within each functional group.

2.2.1 Partitioning a Vessel into Functional Groups

Partitioning a vessel into functional groups is accomplished using a top-down approach. For most vessels, the top level includes these top-level functional groups:

- Hull
- Machinery and utilities
- Cargo handling

In most cases, partitioning of these high-level functional groups is necessary to identify major systems for analysis. For example, machinery and utilities should be further divided into the following functional groups:

- Propulsion functional group
- Maneuvering functional group
- Electrical functional group
- Ship service functional group (e.g., bilge, ballast, firefighting, steam)
- Navigation and communication functional group

Each functional group should be partitioned using a top-down approach. This is done until a level is reached at which functions are identified with discrete physical units, such as a single system or equipment item. This is sometimes called the level of indenture. The level of indenture is of vital importance as it significantly affects the amount of time and effort required to complete a satisfactory analysis. An analysis carried out at too high a level can become too superficial, while one taken at too low a level can become too cumbersome.

The level of indenture will vary depending on the complexity of a system. Highly complex systems will have a large number of failure modes and will tend to be analyzed at lower levels. The level of indenture should be such that the following can be identified for the functional group:

i) Physical boundaries

ii) Functions and functional failures

iii) Discrete equipment items

2.2.2 Partitioning a Functional Group into Equipment Items

Once a satisfactory level of partitioning functional groups has been completed, each functional group is partitioned into specific equipment items. Again, one or two levels of indenture may be needed to satisfactorily divide a functional group into equipment items. The level of indenture chosen for equipment items should be such that the equipment:

i) Can be identified for its contribution to the overall functions of the functional group

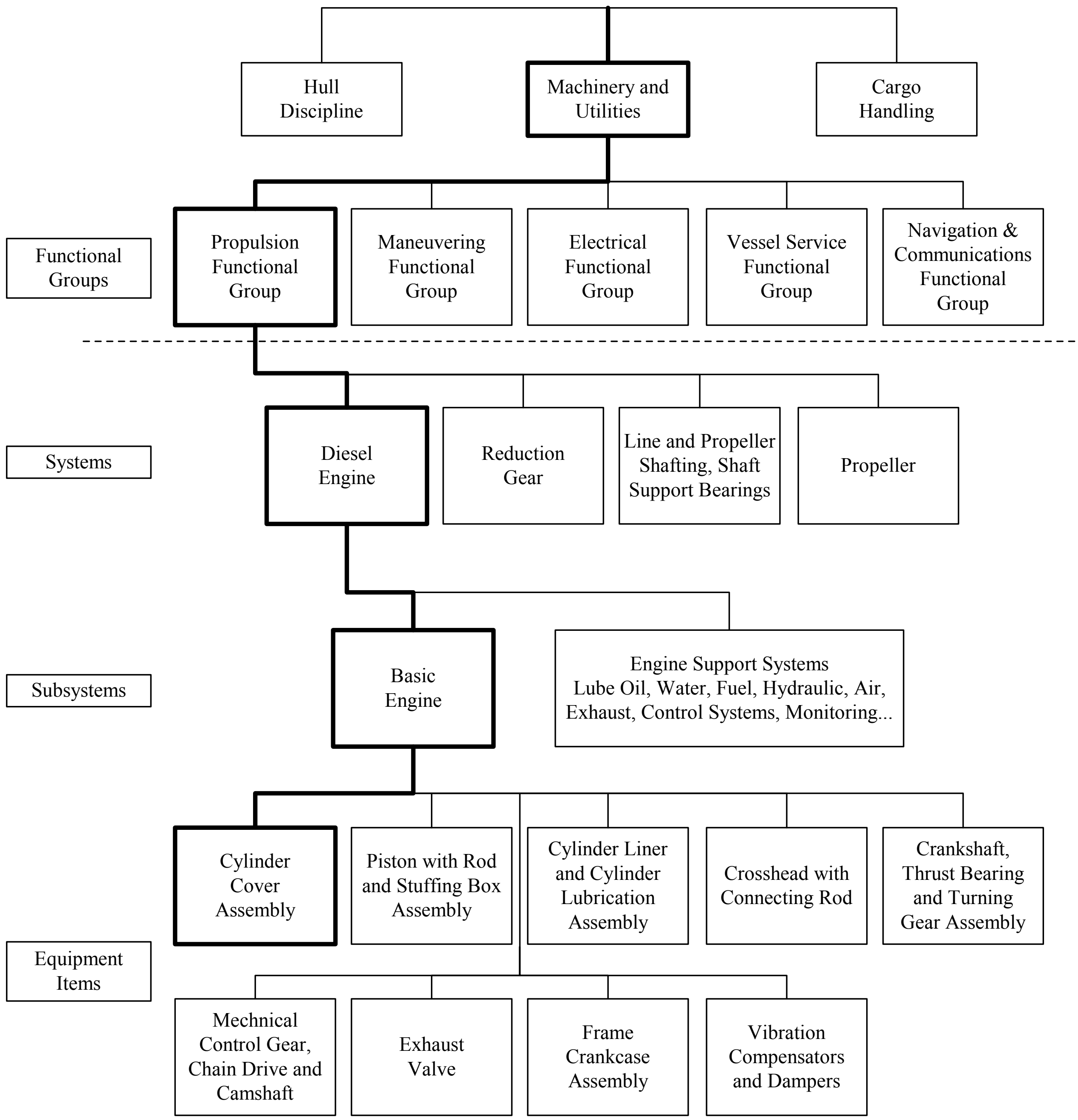
ii) Can be identified for its failure modes

iii) Is the most convenient physical unit for which maintenance can be specified

Section 7, Figure 2 shows an example of partitioning of functional groups and their associated equipment items.

Note: RCM analyses tend to be performed at too low an indenture level because of the mistaken belief that a failure mode can only be identified at the level of the component. In fact, failure modes can be identified from higher levels too, except that identification at the higher levels will be less structured than that at the lower level.

FIGURE 2
Example Partitioning of Functional Groups



2.2.3 Selection of Functional Groups for Analysis

It may be necessary to identify an order of priority for the analysis of the functional groups so that resources may be targeted most productively. In general, one of the following methods is used to select groups for analysis:

i) *Engineering judgment*. This approach relies on the undocumented experience of subject matter experts to select the group. Typically, in selecting a group, a team will subjectively consider the following issues: number of failures that have occurred, the amount of maintenance resources, the opportunity to improve performance and the potential to reduce costly downtime maintenance (e.g., dry-docking maintenance). Once the selection and priorities are determined, the team should document the rationale for its decision.

ii) *Simple analytical approaches.* A more analytical method for selecting functional groups is to use simple analysis tools, such as Pareto analysis and relative ranking. These tools provide the selection team with a structured methodology for ranking the different issues considered during the selection process. When using the Pareto analysis, the team would collect data related to each issue being considered. For example, if number of failures is important, the team would look to collect failure data for each group and then rank each group based on the number of failures. When using relative ranking, the team develops a scoring system that is used to score each issue. The scores are then tabulated and evaluated to rank the groups.

iii) *Risk assessment.* The most comprehensive approach is to perform a risk assessment or use an available risk assessment to select and rank functional groups. Whether the risk assessment is a detailed quantitative analysis or high-level profiling analysis (as used for enterprise risk management), the risk assessment data can be used to identify the groups that have unacceptable risk and those that have the highest risk. The unacceptable risk data can be used to determine if further detailed analysis, such as RCM analysis, is warranted. Then, the group risk ranking can be used to prioritize the groups for analysis (e.g., groups with highest risk are analyzed first). In addition, the risk assessment should be reviewed to determine if there are equipment failures that can be impacted by improved maintenance and if these failures are major contributors to the risk. For example, in reviewing the risk assessment for a group, one might discover that the major contributor to risk is operational errors. For this group, an RCM analysis might not be the best analytical method to reduce the risk. However, highest risk groups in which equipment failures are a major risk contributor are good candidates for RCM analysis.

Regardless of which approach is used to select groups, the following considerations should be made:

i) The expected cost savings over the predicted remaining life of the equipment should be balanced against the cost of the analysis

ii) The human resources required to undertake each analysis must be identified and their availability ascertained.

3 Defining Functions and Functional Failures

Once the operating mode for the vessel and the operating context for a functional group have been defined, the RCM analysis team uses this information to define the functions needed for the functional group to successfully operate so that all relevant vessel functions are maintained. When defining functions for a functional group, the applicable operating modes must be considered because functions can vary with the different operating modes. It is important that all functions be identified. Failure to identify all functions can result in important failures (e.g., failures that affect system and vessel performance) being overlooked.

Once the functions are defined, functional failures (e.g., different loss functions that can occur due to failures) are defined. Functional failures can reflect the total loss of function (e.g., provides no compressed air) or partial loss of function (e.g., provides compressed air at reduced pressure and flow). The following paragraphs explain how to identify functions and functional failures in more detail.

3.1 Identifying Functions for a Functional Group

Once the operating characteristics and partitioning have been completed, the next task is to list the functions associated with the chosen functional group and its associated equipment. The functions are identified based on the operating context of the functional group as well as the equipment that is included in the functional group. To ensure that all functions are identified and completely defined, it is important that functions be stated in terms of what the functional group must do/provide for the vessel to operate properly (in the given operating mode), and not how individual equipment items operate. For example, a function for the propulsion group might be "to provide X horsepower at Y RPM to the propeller", even though the engine itself may be capable of producing more horsepower and operating at a higher RPM.

One method for identifying functions is to develop a functional block diagram of the system. A functional block diagram is a graphical representation of the system operation. It typically contains (1) the inputs (e.g., raw materials, energy sources) entering the system boundary, (2) the blocks representing the functions that occur within the system boundary, and (3) the outputs (e.g., materials, energy, signals) leaving the boundary. In addition, arrows are used to depict the flow of materials, energy, signals, etc., between functional blocks and into and out of the system. Within the boundary, each block represents a primary or secondary function that must be provided for the system to convert the inputs into outputs. Therefore, each function block and its associated outputs represent a function that must be provided for the system to properly operate. Section 7, Figure 3 provides an example functional block diagram.

Each function should be documented as a function statement that contains a verb, an object and a performance standard. The performance standard is to describe the minimum acceptable requirement rather than the design capability. Performance standards must be clearly defined or quantified. They are used to define failure, which forms the basis of the maintenance decision-making process. Functions are to be categorized as follows:

- *Primary functions* — These functions are the reasons why the system/equipment exists. For example, the primary functions of the diesel engine are to provide power to drive the propeller from 0 to 91 RPM with output from 0 to 16,860 kW. The minimum acceptable output is 9,000 kW to maintain a minimum vessel speed of 7 knots.
- *Secondary functions* — Most systems/equipment will have secondary functions that will generally be less obvious than the primary functions, although their failure may sometimes have worse consequences. The following functional categories can be helpful in determining secondary functions:

  Environment integrity

  Safety, structural integrity

  Control, containment, comfort

  Appearance

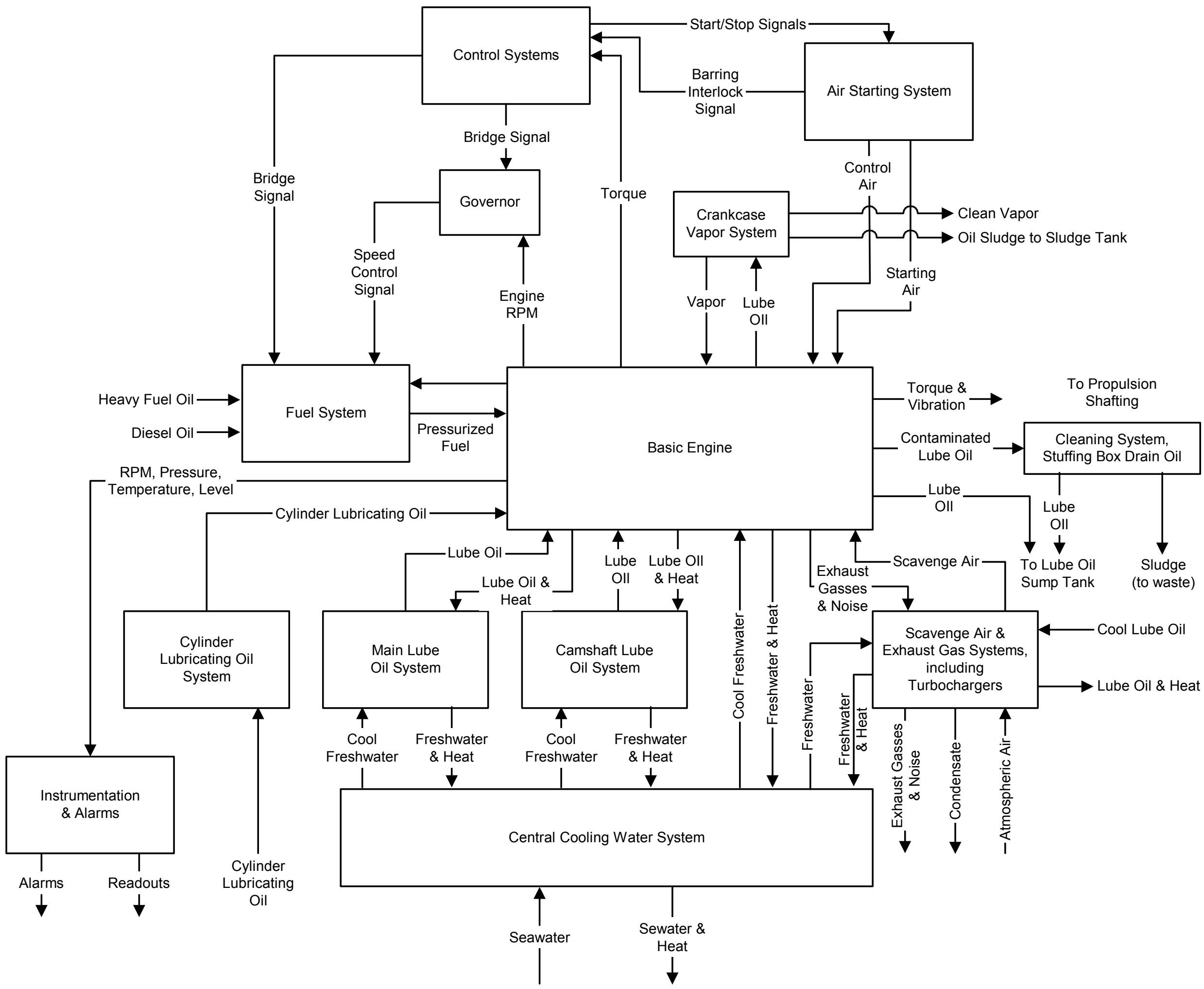
  Protection

  Economy, efficiency

  Supplementary functions

For example, some of the secondary functions of a diesel engine are to have acceptable engine emissions in accordance with some standard, to have a vibration level that will not affect structural integrity, etc.

FIGURE 3
Example System Block Diagram



The most important of the secondary functions relates to protection and protective devices. Protection and protective devices work in one of the following five ways:

i) To draw the operator's attention to abnormal conditions

ii) To shut down the equipment in the event of a failure

iii) To eliminate or relieve abnormal conditions that follow a failure and that might otherwise cause more serious damage

iv) To take over from a function that has failed

v) To prevent a dangerous situation from arising in the first place

When listing the functions of any system/equipment, the functions of ALL of the associated protective devices must be listed. These devices must receive special attention.

3.2 Identifying Functional Failures for a Functional Group

For each function in the functional group, a series of functional failures must be identified. In general, each function will have at least two functional failures. A functional failure can be a complete loss of function or partial loss of function. The partial loss of function is usually represented by deviations in the performance standard. Example functional failures for the function "to provide 16,860 kW at 91 RPM to the propeller" are:

- *Total loss of function*

  No power to the propeller

- *Partial loss of function*

  Provides less than 16,860 horsepower to the propeller

  Provides more than 16,860 horsepower to the propeller

  Provides less than 35 RPM to the propeller

  Provides more than 91 RPM to the propeller

Functional failures can be identified from functions by applying the following guides to each function:

- No or none of the function
- Less of each performance standard parameter
- More of each performance parameter
- Premature operation of the function
- Failure to cease operation of the function (e.g., function operates too long)
- Intermittent operation of the function
- Other functional failures appropriate for the functional group

Each functional failure should be documented in a functional failure statement that contains a verb, an object and the functional deviation. An example function and functional failure list is shown in Section 7, Table 3.

TABLE 3
Example Function and Functional Failure List

Equipment Item: Low speed diesel engine for main propulsion, driving a controllable pitch propeller

Function			*Functional Failure*	
Item No.	*Function Statement*	*Function Type*	*Item No.*	*Functional Failure Statement*
1	Transmit 16,860 kW of power at 91 rpm to the propulsion shafting	Primary	1.1	No transmission of power to the propulsion shafting
			1.2	Transmits less than 16,860 kW of power to the propulsion shafting
			1.3	Transmits more than 16,860 kW of power to the propulsion shafting
			1.4	Operates at less than 91 rpm (Reduce rpm)
			1.5	Operates at more than 91 rpm
2	Exhaust engine gases after the turbochargers are to be in the range 275 to 325°C	Secondary	2.1	Exhaust gases are less than 275°C
			2.2	Exhaust gases are more than 325°C
3	Provide engine overspeed protection at 109 rpm	Secondary	3.1	No activation of overspeed protection
			3.2	Overspeed protection activates at less than 109 rpm
			3.3	Overspeed protection activates at more than 109 rpm
			3.4	Overspeed protection activates and cannot be reset

4 Conducting an FMECA

Once potential functional failures have been identified, the next step in the RCM analysis is to conduct an FMECA. The purpose of this step is to establish the cause-and-effect relationship among potential equipment failures, functional failures and the end effect of the functional failures, and to evaluate the criticality of the postulated failure mode.

This information is vital to determine the following:

- When a failure management strategy is needed
- What type of failure management strategy is best used to manage the failure mode (e.g., one-time change, planned maintenance or run-to-failure)
- The importance of the failure management strategy

4.1 Identifying Failure Modes and Effects with an FMECA

There are two basic approaches for conducting an FMECA: a bottom-up approach and a top-down approach. Either method can be successfully used in an RCM analysis, and each has its strengths and weaknesses. The key attribute of both approaches is that they are inductive analysis techniques that guide the RCM analysis team in establishing the cause-and-effect relationship needed to define maintenance requirements and discover other improvements. The following Subparagraphs describe each approach.

4.1.1 Bottom-up FMECA Approach

The bottom-up approach is performed by explicitly analyzing each equipment item of interest. This approach focuses on determining what effects different equipment failure modes have on the operation of the system. The bottom-up approach determines whether the equipment failure mode results in a local effect that causes a functional failure that causes an end effect of interest. Following are the steps for performing a bottom-up FMECA:

i) Select an equipment item for analysis

ii) Identify the potential failure modes for the equipment item

iii) Select a failure mode for evaluation

iv) Determine the failure characteristic (e.g., wear-in, random, wear-out) for the failure mode

v) Determine the local, next higher level and end effects for the postulated failure mode

vi) If the end effect results in a consequence of interest, determine the causes of the failure mode

vii) Determine the criticality of the failure mode using the risk decision tool

viii) Repeat steps as necessary until all equipment items and associated failure modes have been evaluated

When performing a bottom-up FMECA, the failure causes are the basic equipment failures that result in the failure mode, and the next higher-level effect typically identifies the resulting functional failure. Section 7, Table 4 provides an example of a bottom-up FMECA.

The bottom-up approach helps ensure that all equipment items are analyzed and all plausible equipment failure modes are considered. In addition, a standard list of failure modes can be developed for common equipment items, thus making the analysis somewhat easier to perform and helping to ensure consistency between RCM teams. Appendix 2 of the *Guide for Survey Based on Reliability-Centered Maintenance* provides a listing of suggested failure modes for marine machinery equipment and components.

4.1.2 Top-down FMECA Approach

The top-down approach is performed by analyzing each function and its associated functional failures. This approach focuses on determining what effects different functional failures have on the operation of the system and then what equipment failures (e.g., failure mode) can result in the functional failure. The top-down approach determines whether the functional failure results in an end effect of interest and then determines which equipment failures can cause the functional failure. Following are the steps for performing a top-down FMECA:

i) Select a function for analysis

ii) Select a functional failure for evaluation

iii) Determine the local and end effects for the postulated functional failure

iv) If the end effect results in a consequence of interest, determine the equipment failures that can result in the functional failure

v) Determine the failure characteristic (e.g., wear-in, random, wear-out) for the failure mode

vi) Determine the criticality of the failure mode using the risk decision tool

vii) Repeat steps until all functions and functional failures are evaluated

Section 7, Table 5 shows an example of a top-down FMECA.

TABLE 4
Example Bottom-up FMECA Worksheet

No.: 15	**Description:** Camshaft Lube Oil Pump					
Item	**Failure Mode**	**Causes**	**Failure Characteristic**	**Local Effects**	**Functional Failures**	**End Effects**
15.1	Fails off while running (on-line pump) (evident)	Pump motor failure Pump seizure Pump motor control failure Pump coupling failure	Random failure, Wear-out failure Random failure, Wear-out failure Random failure, Wear-out failure Wear-out failure	Interruption of lubrication to the camshaft, requiring the standby pump to be started	No flow of lubricant to the camshaft	Brief shutdown of the engine until standby lube oil pump is started
15.2	Starts prematurely/ operates too long (standby pump)					No effect of interest
15.3	Operates at degraded head/flow performance (on-line pump) (evident)	Worn pump gears	Wear-out failure	Insufficient pressure or flow of lubricant to the camshaft, resulting in a low pressure alarm and requiring standby pump to be started	Flows less than 10.3 m^3/hr of lubricant to the camshaft Flows lubricant to the camshaft at a pressure less than 4 bar	Brief engine shut down until the standby pump is operating

No.: 15	**Description:** Camshaft Lube Oil Pump				
Item	**Matrix**	**Severity**	**Current Likelihood**	**Current Risk**	**Failure Detection/ Corrective Measures**
15.1	Propulsion	Minor	Remote	Low	Upon low pressure, sensor sends signal to automatic changeover controller which starts standby pump
15.2					
15.3	Propulsion	Minor	Remote	Low	Upon low pressure, sensor sends signal to automatic changeover controller which starts standby pump

TABLE 5
Example Top-down FMECA Worksheet

No.: 25	**Description:** Transmit 16,860 kW at 91 RPM to the propulsion shafting				
Item	**Functional Failure**	**Failure Causes**	**Failure Characteristic**	**Local Effects**	**End Effects**
25.1a	No transmission of torque to the propulsion shafting	External rupture of the cylinder cover (evident)	Wear-in, Random, Wear-out	High engine vibration, requiring a shutdown Rupture of fuel oil line, releasing fuel oil into the engine room Catastrophic release of cylinder pressure, causing shrapnel to be released in the engine room Partial loss of containment of cooling water	Potential injury to personnel if hit by shrapnel Damage to cylinder cover and/or piston Vessel out of service for a time to make repairs
25.1b		Loosened piston rod studs at the crosshead (evident)	Wear-out	Relative motion between two parts, fretting Studs eventually break if left undetected	Engine damage due to a loose piston rod Vessel out of service for a time to make repairs
25.1c		Restricted oil passageway in the piston rod (hidden)	Wear-out	Overheating of piston crown, potentially causing piston failure	Damage to the piston Vessel out of service for a time to make repairs

No.: 15	**Description:** Camshaft Lube Oil Pump				
Item	**Matrix**	**Severity**	**Current Likelihood**	**Current Risk**	**Failure Detection/ Corrective Measures**
25.1a	Safety	Major	Improbable	Medium	Engine noise, exhaust fume odor, and engine vibration will alert the operator to the failure
	Property Damage	Major	Improbable	Medium	
	Economic	Major	Improbable	Medium	
25.1b	Property Damage	Moderate	Remote	Medium	Visual inspection during normal engine shutdowns
	Economic	Moderate	Occasional	Medium	
25.1c	Property Damage	Moderate	Remote	Medium	
	Economic	Moderate	Remote	Medium	

4.2 Considerations in Identifying Failure Modes and Failure Effects with an FMECA

Regardless of which FMECA approach is used, the FMECA must identify the equipment failures that cause functional failures, which will result in end effects of interest so that proper failure management strategies can be determined. To ensure that the FMECA accomplishes this purpose, the following issues must be considered:

4.2.1 Identifying Failure Modes

A comprehensive list of failure modes causing each functional failure must be generated:

i) Failures that have previously occurred on similar equipment

ii) Any other failure modes that have not yet occurred but are considered probable, including those being suppressed by the current preventative maintenance program

iii) Failure modes that are possible but considered unlikely (included to show that they have been considered)

When performing a bottom-up FMECA, the following guide phrases may be used to help develop a list of failure modes to be considered:

i) Premature operation

ii) Failure to operate at a prescribed time

iii) Intermittent operation

iv) Failure to cease operation at a prescribed time

v) Loss of output or failure during operation

vi) Degraded output or operational capability

vii) Other unique failure conditions

Failure causes, such as normal wear and tear, corrosion, abrasion, erosion, fatigue, etc., should be recorded in sufficient detail to enable an appropriate failure management strategy to be identified. Failures caused by human error should be included if firm evidence exists to support such failures, or if operator error can induce significant consequences. It is important to ensure that the causes are sufficiently identified so that the subsequent maintenance recommendations address the cause of failure rather than its symptoms.

4.2.2 Identifying Failure Effects

Failure effects should be identified at three levels:

i) Local effects are effects local to the system/equipment being analyzed and should include the following:

- Failure detection methods (alarms, test indicators)
- Reduced level of performance
- Whether a standby system/equipment can provide the same function

ii) Next higher effects are effects on the larger system to which the system/equipment forms a part and should include the following:

- Potential physical damage to the system/equipment
- Potential secondary damage to either other equipment in the system or unrelated equipment in the vicinity

iii) End effects are effects on the vessel and should include the following:

- Threats to safety and the environment
- Operational effectiveness of the vessel
- Downtime needed to repair the damage

4.3 End Effect Considerations

Upon identification of the end effects, the following information should be included:

i) Mitigation of the consequences of failure before implementing maintenance (e.g., bringing a standby system online, reconfiguring the system) and the estimated time for such action

ii) Defective item repair action (e.g., repair primary and secondary damages as applicable, personnel needed, whether dry-docking or shore support is required, time to perform repair)

iii) Spare part identification

4.3.1 Level of Indenture Considerations

For the chosen functional group, FMECA should be conducted on systems or equipment at a lower convenient indenture level, typically the level at which maintenance is performed. However, experience has shown that if more than 20 to 30 failure modes can be identified at an indenture level, a lower indenture level should be chosen.

4.3.2 Maintenance Considerations

The FMECA shall be performed assuming zero-based maintenance (e.g., no proactive maintenance tasks are being performed) for which the data for probability of failure is not available. This is necessary to ensure that the need for a failure management strategy is determined. For application to existing maintenance programs, the probability of failure is to be based on the current maintenance program.

4.4 Assessing the Criticality of Failure Modes and Effects in an FMECA

The purpose of the criticality analysis is to rank, based on the best available data, each potential failure mode identified during the FMECA according to the combined influence of severity classification and its probability of occurrence. This allows the comparison of each failure mode to all other failure modes with respect to risk. The process highlights the risk associated with each failure mode.

The consequence categories, frequency categories and risk matrix described in Section 6 should be used for this assessment. In determining the frequency category (probability of occurrence), the following approaches may be taken:

i) *Quantitative.* This should be used if reliability data are available. If used, the source of the data and the operating context should be noted.

ii) *Qualitative.* Where quantitative data are not available to determine the probability of occurrence, engineering judgment can be applied based on previous experience.

The following procedure should be used to determine the qualitative risk associated with a failure mode:

i) *Severity classification.* Identify both the consequence of the end effect resulting from each failure mode and the severity category allocated in applying the example shown in Section 6, Table 1. For failure modes that do not directly result in an end effect (e.g., failure of a protective device), the criticality analysis will take account of the multiple failures and assume that the protected function experiences failure with the protective device in the failed state.

ii) *Probability of occurrence.* Derive the probability of occurrence of each failure mode for those failure modes identified in the FMECA. Determine the probability of failure in accordance with 7/4.3.2. See Section 6, Figure 3.

iii) *Risk matrix.* Obtain the risk level from Section 6, Figure 3 by plotting the severity classification and probability of occurrence on this matrix.

The criticality ranking (e.g., the risk) for each failure mode/end effect pair is then used in an RCM decision flow chart to determine the proper failure management strategy. Section 7, Tables 4 and 5 include examples of the criticality ranking.

5 Selecting a Failure Management Strategy

At the level of each system/equipment item for which FMECA has been conducted, the failure modes assessed to have high, medium or low risks are evaluated in accordance with the RCM Task Selection Flow Diagrams in Section 7, Figures 4 and 5. Figure 4 is a simplified flow diagram to illustrate the failure management strategy. Figure 5 is to be used to determine the failure management strategy when conducting the analysis. Section 7, Table 6 provides suggested failure management tasks for the failure characteristics identified in the FMECA. It should be noted that the answers to the questions posed in the RCM Task Selection Flow Diagram are only relevant for the operating mode under consideration. "Normal Operating Conditions" (NOC) will be repeatedly used throughout this section and should be taken to mean the normal operating condition with respect to the relevant operating mode.

TABLE 6
Failure Characteristic and Suggested Failure Management Tasks

Equipment Item/Component Failure Characteristic	*Suggested Failure Management Task*
Wear-in failure	Eliminate or reduce wear-in Condition-monitoring task to detect onset of failure One-time change or redesign
Random failure	Condition-monitoring task to detect onset of failure Failure-finding task to detect hidden failure One-time change or redesign
Wear-out failure	Condition-monitoring task to detect onset of failure Planned-maintenance task Failure-finding task to detect hidden failure

FIGURE 4
Simplified Task Selection Flow Diagram

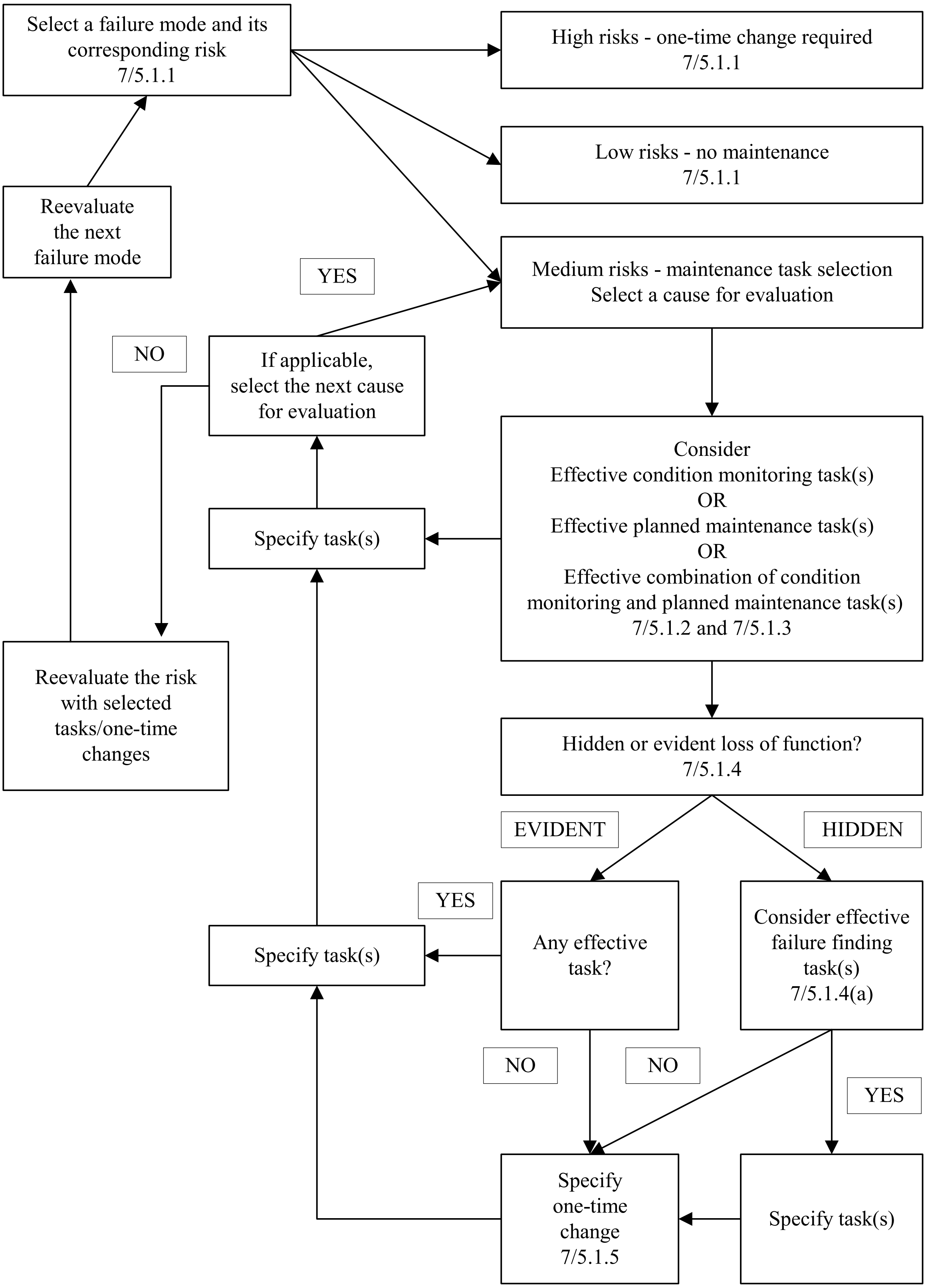


FIGURE 5
RCM Task Selection Flow Diagram

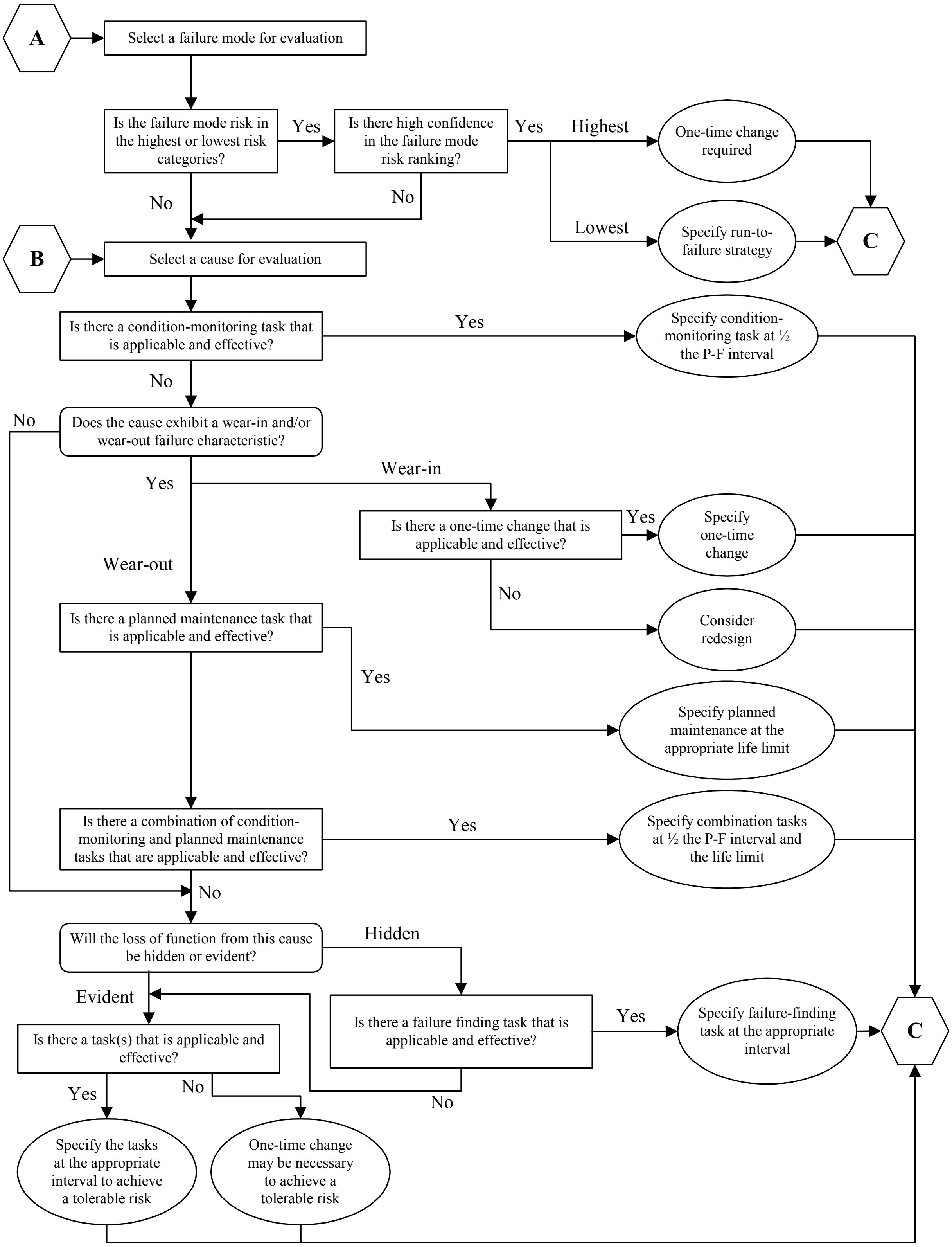
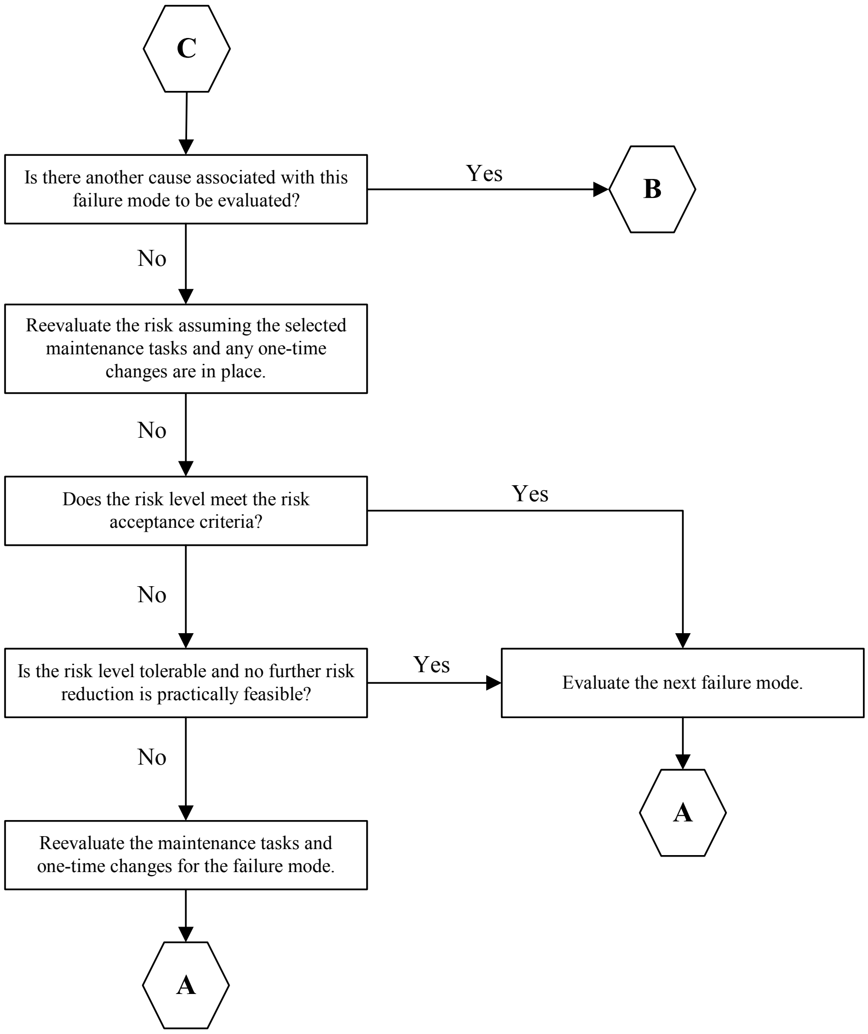


FIGURE 5 (continued)
RCM Task Selection Flow Diagram



5.1 RCM Task Selection Flow Diagram

The purpose of the Task Selection Flow Diagram is to assist in selecting the most appropriate failure management strategy to prevent or detect a specific failure mode.

5.1.1 First Selection Decision

Decide whether the risk associated with the failure mode is the highest or lowest risk and determine the confidence in the decision.

- *Highest risk.* A failure mode with the highest risk typically cannot achieve an acceptable level of risk through maintenance alone. In general, to achieve an acceptable level of risk, a fundamental change in how the equipment is designed or operated is needed. Therefore, a one-time change is required to reduce the risk. Once the one-time change is identified, the FMECA should be updated and any applicable failure modes reevaluated using the RCM Task Selection Flow Diagram.
- *Lowest risk.* A failure with the lowest risk is a low-priority failure and, therefore, is acceptable without any failure management strategy for most organizations.

- *Confidence in the risk characterization.* High confidence indicates the team is relatively certain that the risk is properly characterized and, therefore, can be used in the RCM flow diagram without any further discussion. Low confidence indicates that the team is uncertain and that additional data (about the probability or consequence of the failure) are needed before the risk can be used in the decision-making process. To be conservative, the failure mode is then assumed to have a medium/moderate risk characterization and is evaluated through the entire RCM Task Selection Flow Diagram.

5.1.2 Second Selection Decision

Condition-monitoring tasks are first considered because these tasks typically are the best choice technically and usually the most cost-effective. In determining if the failure mode can be managed by a condition-monitoring task, the team must select a specific task and then determine an appropriate task interval. The following provide criteria for making these decisions.

5.1.2(a) Maintenance task selection criteria. For a condition-monitoring task to be selected, it must first be applicable and effective. When determining the applicability and effectiveness, the following should be considered:

i) Must be practicable to implement (e.g., the required maintenance task interval and accessibility for carrying out the task are operationally feasible)

ii) Must have a high degree of success in detecting the failure mode

iii) Must be cost-effective. The cost of undertaking a task over a period of time should be less than the total cost of the consequences of failure. The costs should include man-hours, spares, tools and facilities, and should be assessed on the basis of through-life costs.

Next, the team must evaluate the potential risk reduction resulting from implementing the condition-monitoring task. This is accomplished by determining the reduction in risk that is anticipated if the task is implemented. In general, proactive maintenance tasks will reduce the probability of the failure mode occurring rather than the severity of the consequence. The reduced risk is then compared to the risk acceptance criteria to determine whether the task should be selected.

If the risk reduction does not achieve an acceptable level of risk, the failure mode is further analyzed to determine if other maintenance tasks or a one-time change is needed to manage the failure.

5.1.2(b) Maintenance task interval determination. Ideally, proactive maintenance task intervals are determined using actual failure data, but this is not realistic for most organizations. Therefore, the task frequency must be determined from the following sources listed in ascending order of priority and documented:

- Generic P-F interval data
- Manufacturers' recommendations
- Current task intervals
- Team experience

For condition-monitoring tasks, the task interval must give enough warning of the failure to ensure action can be taken in time to avoid the consequences. The maintenance task interval must be set at less than half the anticipated P-F interval.

5.1.3 Third Selection Decision

If condition monitoring does not provide an effective failure management strategy, the team must then use its knowledge of the failure characteristics to evaluate the need for other proactive maintenance tasks or one-time change. If the failure mode exhibits a wear-in failure characteristic, the team considers a one-time change or redesign of the equipment item as a means to manage the failure. If the failure mode exhibits a wear-out failure characteristic, the team first considers planned maintenance to manage the failure. The team must select the task and task interval.

5.1.3(a) Maintenance task selection criteria. As for a condition-monitoring task, a planned-maintenance task must first be applicable and effective to be selected. When determining the applicability and effectiveness, the following should be considered:

- Must be practicable to implement (e.g., the required maintenance task interval and accessibility for carrying out the task are operationally feasible)
- Must have a high degree of success in preventing the failure mode
- Must be cost-effective. The cost of undertaking a task over a period of time should be less than the total cost of the consequences of failure. The costs should include man-hours, spares, tools and facilities, and should be assessed on the basis of through-life costs.

Next, the team must evaluate the potential risk reduction resulting from implementing the planned-maintenance task just as in the condition-monitoring task.

5.1.3(b) Maintenance task interval determination. Ideally, proactive maintenance task intervals are determined using actual failure data, but this is not realistic for most organizations. Therefore, the task frequency must be determined from the following sources listed in ascending order of priority and documented:

- Generic failure data
- Manufacturers' recommendations or failure data
- Current task intervals
- Team experience

For planned maintenance to be effective, there must be a clear life for the item, and most items must survive this life, after which the conditional probability of failure increases significantly. The life can be determined based on information from the equipment manufacturer, expert opinion, published reliability data, actuarial analysis, etc.

If the risk reduction does not achieve an acceptable level of risk, the failure mode is further analyzed to determine if a combination of planned-maintenance and condition-monitoring tasks can achieve an acceptable risk. If a combination does provide an appropriate failure management strategy, the failure mode is further analyzed in accordance with the maintenance task selection criteria above.

5.1.4 Fourth Selection Decision

Decide whether the failure mode is an evident or a hidden failure mode.

- *Evident failures* — An evident failure is one that will eventually become evident to the operating crew under normal operating conditions (NOC) (e.g., the loss of function will be noticed at some future, indefinite time without any further incident or intervention).

- *Hidden failures* — A hidden failure is a failure that will not become evident to the operating crew under NOC if the failure mode occurs on its own. Normally, hidden failures only become apparent after a second but related failure or event occurs. For example, the failure of a protective device that is not fail-safe is a typical hidden failure. Although there will be no immediate consequences of a hidden failure, the consequence of such a failure will be an increased risk of multiple failures. The ultimate safety, environmental or operational implications must therefore be considered fully and recorded as possible failure effects.

If the failure is hidden and there is no condition monitoring, planned maintenance or combination of tasks that will provide an acceptable risk level, the team must determine if a failure-finding task is needed to manage the failure.

5.1.4(a) Maintenance task selection criteria. As for condition-monitoring and planned-maintenance tasks, a failure-finding task must first be applicable and effective to be selected. When determining the applicability and effectiveness, the following should be considered:

- Must be practicable to implement (e.g., the required maintenance task interval and accessibility for carrying out the task are operationally feasible)
- Must have a high degree of success in discovering the hidden failure mode
- Must be cost-effective. The cost of undertaking a task over a period of time should be less than the total cost of the consequences of failure. The costs should include man-hours, spares, tools and facilities, and should be assessed on the basis of through-life costs.

Next, the team must evaluate the potential risk reduction resulting from implementing the failure-finding task just as in the condition-monitoring and planned-maintenance tasks.

5.1.4(b) Maintenance task interval determination. Ideally, proactive maintenance task intervals are determined using actual failure data, but this is not realistic for most organizations. Therefore, the task frequency must be determined from the following sources listed in ascending order of priority and documented:

- Generic failure data
- Manufacturers' recommendations or failure data
- Current task intervals
- Team experience

For failure-finding tasks, availability and reliability information, where possible, is to be used to set failure-finding intervals, T. For example, T can be determined by the following equation:

$$T = \frac{2 \cdot F_{ACC} \cdot MTTF}{F_{IE}} \qquad (1)$$

where

T	=	test interval
F_{ACC}	=	acceptable frequency of occurrence of the multiple failure
F_{IE}	=	frequency of occurrence of the initiating event making the hidden failure evident
$MTTF$	=	mean time to failure for the system with the hidden failure

As a guide, the unavailability for safety and environmental functions should be not more than 0.05%; for operational functions, not more than 2.0%; and for non-operational functions, not more than 10%. Also, the team should consider regulatory requirements.

5.1.5 One-time Changes

If the failure is evident or it is hidden and there is no failure-finding task that will provide an acceptable risk level, the team must decide if risk cannot be practically reduced to the low risk level and then determine which of the tasks (or combination of tasks) provides the best failure management strategy. If the team determines that the risk can and should be lower than what can be achieved with maintenance, the team should consider one-time changes to manage the failure. To evaluate the effectiveness of one-time changes, the team should determine the potential changes and consider the following:

- Does the one-time change reduce the risk to an acceptable level?
- If not, does the one-time change reduce the risk to a tolerable level with no further risk reduction reasonably possible?
- Is the one-time change cost-effective? That is, is the cost reasonable for the resulting risk reduction?
- Are any of the other maintenance tasks discussed more effective, or can they result in more risk reduction than the one-time change?

5.1.6 Rounds and Routine Servicing

In addition, the team should examine rounds and routine inspection tasks. These important tasks help ensure the failure rate curve for the failure mode (that is the basis for the proactive maintenance tasks and risk characterization) is not altered (e.g., premature wear-out of a bearing because of lack of lubrication).

5.2 Maintenance Task Allocation and Planning

5.2.1 Task Categories

The maintenance tasks derived from the RCM analysis are to be allocated in accordance with the following categories:

Category A — Can be undertaken at sea by the vessel's crew

Category B — Must be undertaken alongside by equipment vendors or with use of dockside facilities

Category C — Must be undertaken in a dry dock facility

5.2.2 Task Interval Adjustment

Task intervals derived from the RCM analysis need not be in alignment with the current calendar-based maintenance schedule. Therefore, the team should integrate these task intervals into a common maintenance schedule. For this purpose, RCM task intervals may have to be adjusted to a shorter or longer interval depending on the criteria given below.

- Tasks with safety/environmental consequences should only be adjusted to a shorter task interval to ensure that safety and containment are not compromised
- Tasks with operational consequences may be adjusted to a longer or shorter task interval. However, when adjusting to a longer interval, the team should obtain the approval of the responsible person in the shipping company.

5.2.3 Overall Maintenance Schedule

Category B and C task intervals should then be organized to derive an overall maintenance schedule. This is done by adjusting the RCM task intervals (Category B and C tasks only) using the criteria specified in Category B so that the tasks can coincide with the vessel's port calling and dry-docking schedules. An example maintenance task summary with the necessary information is indicated in Section 7, Table 7.

5.3 Spares Holding

For the proposed maintenance schedules to be viable, it is essential that the spares that support the identified maintenance tasks are available at the appropriate time. The spares holding requirement is to be developed based on the following considerations:

- The list of parts necessary to perform tasks to correct each failure mode identified in the RCM analysis, along with the parts required as a result of remedial work to correct "condition-monitoring", "planned-maintenance", "failure-finding", "any applicable and effective" and "run-to-failure" tasks.
- An evaluation of the effects on the functional group or system's operational availability if an out-of-stock condition occurs.
- Assessment for those parts whose use can be preplanned. For those parts whose use cannot be preplanned, determine the quantity necessary to achieve the desired operational availability.

Section 7, Figure 6 is to be applied to select the most appropriate spares holding to achieve the desired level of the End Effects. Section 7, Figure 6A has been provided to illustrate a spares holding determination example. An example spares holding determination summary with the necessary information is indicated in Section 7, Table 8.

5.3.1 Stock-out Effect on End Effects

Determine whether the stock-out and further failure will result in End Effects, such as degradation or loss of propulsion, fire, etc. When determining the effect, consider the direct and indirect effects of the stock-out under normal circumstances. The following define direct and indirect effects and normal circumstances.

- *Direct effect.* If the spare is not available and the associated maintenance tasks cannot be carried out, the corresponding failure mode will eventually lead to an End Effect(s) if failure occurs.
- *Indirect effect.* If the spare is not available and the associated maintenance tasks cannot be carried out, the corresponding failure mode will not lead to an End Effect(s), unless a further failure occurs.
- *Normal circumstances.* The item is operating within context and without a failure occurring.

If the stock-out has no effect, then no spares holding is required.

5.3.2 Spares Holding Decisions

The following decision-making process is to be used to select the most appropriate strategy for spares when a stock-out or a stock-out and further failure will result in End Effects:

For the case when:

- The parts requirements can be anticipated before failure occurs or there is sufficient warning time for the parts to be ordered.
- Lead-time for parts order is consistent over the life cycle of the equipment item or component.

Then order parts before demand occurs.

If ordering parts before demand occurs is not acceptable, then consideration is to be given to holding parts onboard or in storage depots, provided:

- The risk of a stock-out is reduced to an acceptable level.
- The cost and storage basis to hold the parts is feasible.

When neither of the two above strategies is feasible, then the following is to be considered:

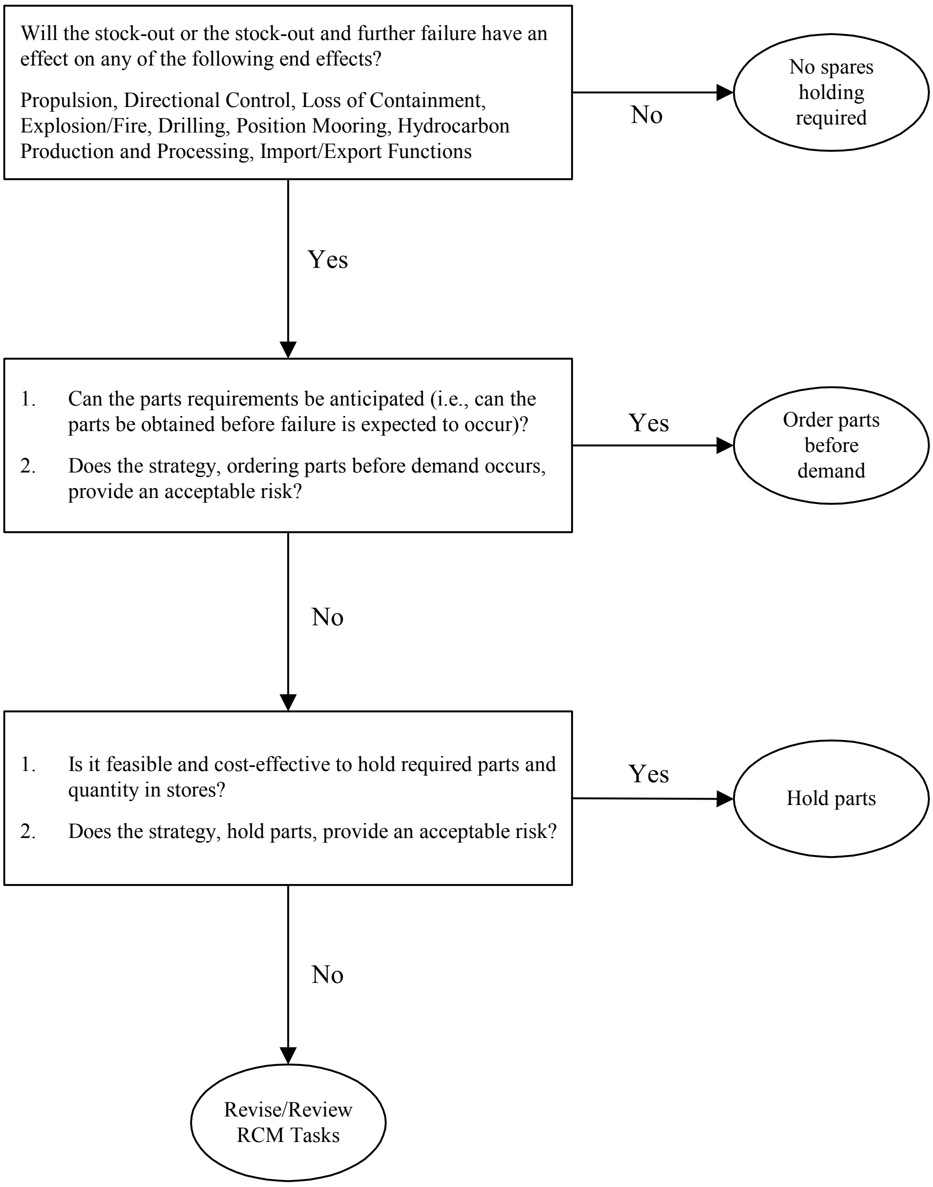
- If the stock-out will result in End Effect(s) (either direct or indirect), it is mandatory to review the RCM analysis with a view to revising the maintenance task.
- If the stock-out will only have a non-operational effect, it is desirable to review the RCM analysis with a view to revising the maintenance task.

TABLE 7
Summary of Maintenance Tasks

Maintenance Category: **Category A, B or C**
Functional Group: **Indicate group name, e.g., Propulsion**
System: **Indicate system name**
Equipment Item: **Indicate equipment item name**
Component: **Indicate component name**

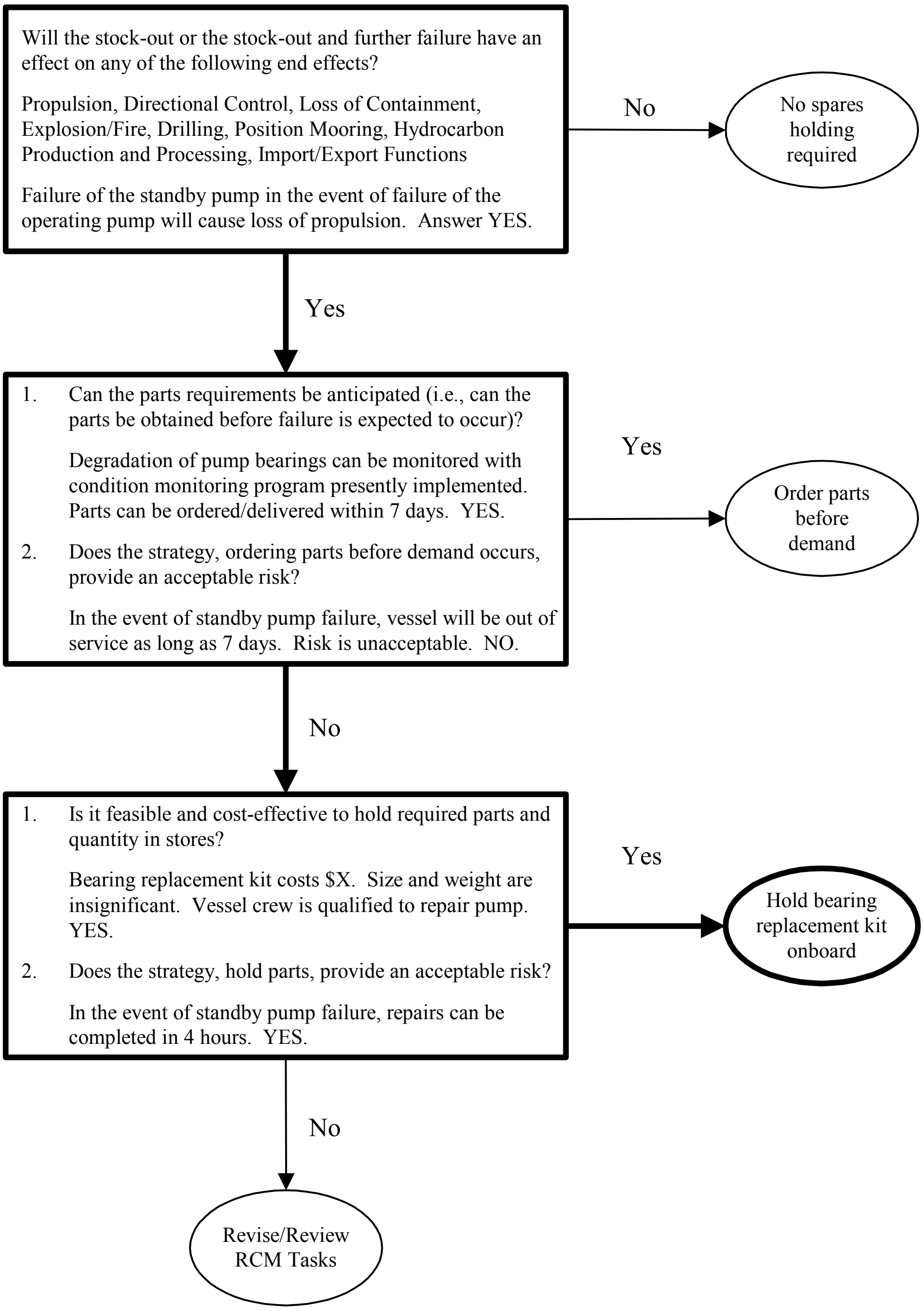
Task	*Task Type*	*Item No.*	*Risk*		*Frequency*	*Procedure No. or Class Reference*	*Comments*
			Current	*Projected*			
Visual inspection of the cooling water passages with a borescope	CM	1.3, 1.5	Medium	Low	2,000 hr	MA 901-3.1	Inspection is to detect corrosion, erosion, cracking and plugging
Visual inspection of the exhaust port with a borescope	CM	1.4	Medium	Medium	2,000 hr	MA 901-2.2	
Visual inspection of the injection port with a borescope	CM	1.6	Medium	Medium	2,000 hr	MA 901-2.1	
Removal and function testing of the cylinder puncture valve	CM	1.2	Medium	Medium	4,000 hr	MA 911-2	
Replacement of the cylinder cover o-ring	PM	1.1	Medium	Medium	8,000 hr	MA 901-1	
Removal and function testing of the cylinder relief valve	CM	1.2	Medium	Medium	8,000 hr	MA 911-2	

FIGURE 6
Spares Holding Decision Flow Diagram (1)



1 Adapted from the diagram in *Ministry of Defense, Requirements for the Application of Reliability-centered Maintenance to HM Ships, Submarines, Royal Fleet Auxiliaries, and Other Naval Auxiliary Vessels*, Naval Engineering Standard NES 45, Issue 3, September 1999.

FIGURE 6A
Example of Use of Spares Holding Decision Flow Diagram



Example Operating Context and Analysis. A Fuel Oil piping system is provided with two fuel oil supply pumps arranged in parallel redundancy. Each pump is sized so as to supply heavy fuel oil to the main propulsion engine and two of the three diesel generator engines operating at their maximum continuous rating. The pumps are operated as follows: the No. 1 pump is operated for one week at a time with the No. 2 pump on standby. After one week, the No. 1 pump is secured and put on standby and the No. 2 pump is operated for one week. Anticipated annual service hours for both pumps are the same.

TABLE 8
Summary of Spares Holding Determination

Maintenance Category: **Category A, B or C**
Functional Group: **Indicate group name, e.g., Propulsion**
System: **Indicate system name**
Equipment Item: **Indicate equipment item name**
Component: **Indicate component name**

				Risk due to stock-out				
Task	*Task Type*	*Item No.*	*Stock-out Effect*	*Order parts before demand*	*Hold parts*	*Revise/Review RCM Tasks*	*Procedure No. or Class Reference*	*Spare Parts Identification*
Visual inspection of the cooling water passages with a borescope	CM	1.3, 1.5	Yes	Low			MA 901-3.1	-Cooling water connection O-rings
Removal and function testing of the cylinder puncture valve	CM	1.2	Yes		Medium		MA 911-2	-Cleaning solvent -Valve seat O-rings -Cooling water connection O-rings
Replacement of the cylinder cover o-ring	PM	1.1	Yes	Medium			MA 901-1	-Cylinder cover sealing ring -Cooling water connection O-rings
Removal and function testing of the cylinder relief valve	CM	1.2	Yes	Medium			MA 911-2	-Cleaning solvent -Valve seat O-rings -Cooling water connection O-rings

6 Documenting RCM Analyses

The information used in and the results from each RCM analysis step must be documented. The entire RCM analysis should be documented for the following reasons:

- *To provide defendability.* For most organizations, management approval is required before implementing the RCM results. To facilitate this approval, the analysis process and results must be documented and available for management review.
- *To provide auditability.* The RCM results will impact areas of concern for regulators and classification societies. Therefore, documentation is needed so that these organizations can review and audit the RCM analysis.
- *To establish a baseline.* For some organizations, the RCM analysis may be the first systematic analysis that has been performed. A documented RCM analysis provides an excellent tool for establishing a baseline for system operation. This information can be used to evaluate the effect of changes (e.g., has the operation really been improved) as well as to perform other risk management activities (e.g., incident investigations, safety case).
- *To preserve corporate memory.* Much knowledge is represented on most RCM teams. Documenting the RCM analysis provides a means of capturing some of the teams' knowledge.
- *To ensure a living RCM program.* As the RCM results are implemented and data are collected, the RCM analysis should be updated periodically. This updating provides an opportunity for the RCM team to reevaluate decisions based on actual failure data and to consider other improvements (e.g., new condition-monitoring technology). Without a documented RCM analysis, updating the results can be time-consuming and expensive. In fact, most organizations will fail at keeping the RCM program "evergreen" if the RCM analyses are not documented.

6.1 Documenting RCM Analysis Steps

Each analysis step should be completely documented. For each step, the following topics should be documented:

- The results of the analysis step,
- Any decision tools used (e.g., risk matrix), and
- Any pertinent information related to the step (e.g., equipment excluded).

The following subparagraphs provide guidance on documenting each analysis step.

6.1.1 Defining Systems

Many of the results of the defining system step can be documented in either a tabular or paragraph format. The following items should be documented:

- Description of the relevant operating modes for the vessel
- Functional group breakdown and each group boundary
- Functional group and equipment partitioning
- Decision tools/criteria used to select functional groups for analysis
- Analysis priority for the selected functional group and the basis for those decisions
- Operating context for each selected functional group

6.1.2 Identifying Functions and Functional Failures

Functions can be documented as a functional block diagram or in tabular format. Each function statement must include a verb, an object and a performance standard. Functional failures are documented in a similar fashion and must be clearly associated with the relevant functions. The following must be documented:

- Primary functions
- Secondary functions, including all protective functions
- Functional failures related to primary and secondary functions

6.1.3 Conducting an FMECA

Documentation for this step includes:

- A description of how the FMECA was conducted
- A description of the risk-based decision tools used to assess criticality
- The FMECA worksheets

The risk-based decision tools are typically documented in a tabular format that includes:

- A description of consequence categories
- A description of the probability categories
- The risk matrix with risk levels identified

The FMECA is documented in a tabular format that includes:

- The equipment failure mode/cause
- The functional failure
- The end effect resulting from the functional failure
- The criticality associated with the failure mode and the resulting functional failure

6.1.4 Selecting a Failure Management Strategy

Documentation for this step should include:

- The RCM decision diagram
- The task selection worksheets

The RCM decision diagram should clearly identify:

- When a one-time change is required or should be considered
- Types and order of maintenance tasks to be considered
- When run-to-failure is an acceptable failure management strategy

The task selection worksheets are typically documented in a tabular format that includes:

- Relevant equipment failure mode/cause and criticality information from the FMECA
- Decision point in the RCM decision diagram that is the basis for the proposed task or one-time change
- Proposed tasks and their associated interval

- Proposed one-time changes
- Evaluation of the risk reduction anticipated from implementing the proposed task and/or change

In addition, RCM documentation should include:

- A description of the RCM analysis process followed
- The composition of the analysis team
- Any analysis assumptions or exclusions

6.2 Example RCM Analysis

An example RCM analysis is provided in Appendix 2. The RCM analysis includes examples for each step listed in Paragraph 7/6.1.

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SECTION 8 Sustaining the RCM Program

1 Introduction

A maintenance program that is based on the RCM philosophy must be dynamic. This is especially true during the early stages of a new program when it is based on limited information. The vessel operator must be prepared to collect, analyze, review and respond to in-service data throughout the operating life of the vessel in order to continually refine the maintenance program. The procedures and processes used to monitor, analyze, update and refine the maintenance program through RCM analysis will sustain the program. These procedures and processes are to be identified in the RCM program plan.

The basis for the decisions made during an RCM analysis are not static. As the maintenance program experiences changes because of equipment and system modifications and modernization, reviewing and refining the maintenance program must occur continuously. An organized information system is necessary to capture the data from the performance of the maintenance tasks (selected during the previous RCM analyses) as well as from data from other analyses, such as periodic root cause failure analyses. This information is used to determine what refinements and modifications need to be made to the initial maintenance program. Secondly, it is used to determine the need for taking other actions, such as product improvement or operational changes. Monitoring and adjusting existing maintenance tasks, developing emergent requirements and periodically assessing RCM-generated maintenance requirements meet these two purposes. Analysts use this new information to revise RCM analyses, which subsequently may reflect a need for changes to the maintenance program.

2 Sustaining the Analysis

The objective of the sustainment process is to:

- Continually monitor and optimize the current maintenance program
- Delete unnecessary requirements
- Identify adverse failure trends
- Address new failure modes
- Improve overall efficiency and effectiveness of the maintenance programs

Sustainment efforts should be organized such that the results can be effectively used to support the RCM analysis updates. Following are a list of RCM sustainment processes that can be applied, as appropriate.

2.1 Trend Analysis

A trend analysis provides an indication for systems or components that may be in the process of degrading. The measurement factors used for trending may be the same factors listed in Paragraph 8/2.6. Other trending factors that can be used include condition-monitoring parameters (temperatures, pressures, power, etc.) or the results of chronic root cause failure analyses. When performing trend analyses, it is the change in value, rather than the values themselves, which is important. Statistical measures, such as mean and standard deviations, may be used to establish performance baselines and for comparing current performance levels to established control levels. Performance parameters can then be monitored and causes investigated for those parameters that exceed control limits. After the problem has been characterized, the related RCM analysis should be reviewed and updated as necessary. Other corrective action should also be considered and implemented, if necessary, to reduce the causes of performance deviations.

Specifically, trend analysis should be established for the following:

- Repeat equipment failures
- Comparing machinery reliability before and after implementation of the RCM-derived maintenance tasks

2.2 Maintenance Requirements Document Reviews

Documents containing maintenance requirements should be reviewed periodically to identify outdated maintenance processes, techniques or technologies, or to bring attention to obsolete tools and outdated supplies. These document reviews provide opportunities to update maintenance requirements that will improve effectiveness or reduce life-cycle costs. In addition, service bulletins from equipment manufacturers should be reviewed and evaluated for impact on the RCM program. Service bulletins can provide beneficial information, such as new condition-monitoring techniques and life limits for components.

2.3 Task Packaging Reviews

Task packaging is the process of incorporating a number of RCM-derived maintenance tasks, each of which has a discrete engineering interval, into optimum uniform intervals such as maintenance performed during a vessel's scheduled dry-docking. When maintenance tasks are modified and updated, they continue to be placed back into the same packaged intervals. However, over time, the original packaged interval may no longer be optimal. Task packaging reviews should be conducted periodically to evaluate the packaged maintenance intervals to ensure that as maintenance tasks are added, deleted or modified, optimum packaged intervals are maintained.

2.4 Age Exploration Tasks

When insufficient age-to-failure data are available or assumed data are used during the initial RCM analysis, age exploration tasks may be designed and implemented. An effective RCM program will necessarily impose frequent changes to an age exploration program, such as adding new equipment, deleting completed or unproductive tasks, or adjusting task intervals. The result of the age exploration tasks is a better understanding of the system or equipment's wear-out region of the failure characteristics curve (see Subsection 3/2 and Section 3, Figure 2), which can be fed back for use in updating the RCM analysis. The RCM analysis should provide guidance for implementing age exploration tasks.

2.5 Failures

A successful RCM program has a process to address failures (loss events) and other unpredicted events, and to determine the appropriate response or corrective action. An example of such a process is shown in Section 8, Figure 1.

A root cause analysis should be performed first to develop an understanding of the failure. By employing a structured process, the analysis can identify areas such as maintenance, operations, design, human factors, etc., that require further analysis. The key steps in a root cause failure analysis include:

- Identifying the failure/loss event or potential failure/loss event
- Classifying the event and convening a trained team suitable for addressing the issues posed by this event
- Gathering data to understand how the event happened
- Performing a root cause failure analysis to understand why it happened
- Generating corrective actions to keep it (and similar events) from recurring
- Verifying that corrective actions are implemented
- Putting all of the data related to this event into an information system for trending purposes

The failure may be addressed by corrective actions for which an RCM analysis is not necessary. Examples of non-RCM corrective actions include technical publication changes and design changes.

The root cause analysis may reveal problems that may need immediate attention. Issuing inspection bulletins, applying temporary operational restrictions and implementing operating safety measures are examples of interim actions.

The results produced from reviewing the RCM analysis will be a factor that should be considered in determining a response to the failure. It is necessary that an RCM review be part of the overall methodology. The RCM review and update, if required, will determine if changes in maintenance requirements are necessary. The review will indirectly aid in determining if corrective actions are necessary. Decisions not to update the RCM analysis should be documented for audit purposes. During the RCM review, the following questions should be addressed:

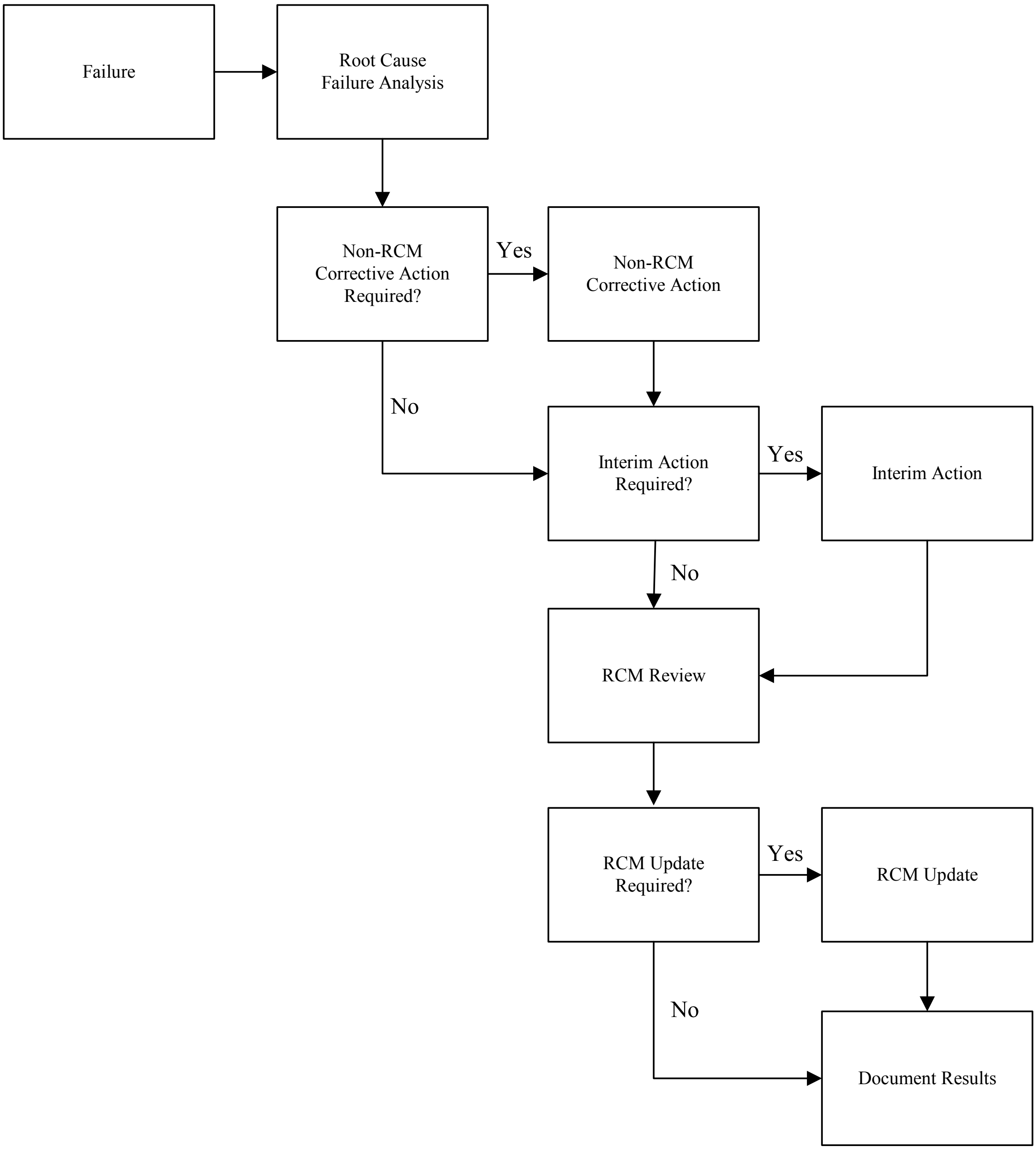
- Is the failure mode already covered?
- Are the failure consequences correct?
- Are the reliability data accurate?
- Is the existing task (or requirement for no task) adequate?
- Are the related costs accurate?

When new failure modes or failure modes previously thought unlikely to occur are determined to be significant, the RCM analysis is to be updated. The existing analysis for a failure mode may also be determined to be correct or inadequate. Inadequate analyses can result for any number of reasons, such as revision of mission requirements or changes to operator or maintenance procedures.

Failures and other unpredicted events are available from several sources, including the following examples:

- Defect reports issued by maintenance engineering or the vessel's crew
- Defects discovered during routine vessel repairs in a shipyard
- Vendor and original equipment manufacturer reports related to inspections, rework, or overhauls
- Design changes, which may be in the form of a single item change or a major system modification
- Results of tests (such as certification tests or tests performed during the course of a failure investigation or some other unrelated event) that may require RCM review and update

FIGURE 1
Process to Address Failures and Unpredicted Events (1)



1 *Guidelines for the Naval Aviation Reliability-centered Maintenance Process*, Published by Direction of Commander, Naval Air Systems Command, NAVAIR 00-25-403, 01 February 2001.

2.6 Relative Ranking Analysis

A relative ranking analysis can be developed for those items having the highest operational cost or cost impact. The following measurement factors can be considered in developing this ranking:

- Maintenance man-hours
- Maintenance man-hours per operating hour
- Equipment downtime
- Maintenance actions per operating hour
- Cost of lost production
- Cost of repair

The identification of the highest contributors entails detailed data analyses and communication with operators and maintainers. This analysis is limited to identifying only the worst performing items, not those in the process of degradation. Some items by their very nature and use may appear at the top of the list. Further RCM analyses of these items may prove to be beneficial, and other analysis techniques, such as root cause analysis, may need to be employed to improve performance.

2.7 Other Activities

Changes to the RCM analysis and/or preventative maintenance tasks may be required as a result of internal audits by the operator.

3 Results of Sustaining Efforts

Changes to the RCM analysis or existing maintenance tasks may be required as a result of the sustaining efforts. A list of these possible changes is as follows:

- It may be determined that an existing maintenance task is not being performed at its most effective interval. By collecting information through sustaining efforts, the data necessary to refine the assumptions used to establish the interval during the initial RCM analysis can be used to adjust the task interval and thereby improve the interval's effectiveness.
- Sustaining efforts may also identify maintenance tasks that need to be added, deleted or modified.
- Sustaining efforts may also generate a requirement to modify age exploration tasks currently taking place.

Other changes that may occur as a result of sustaining efforts include system or equipment redesign, or operational changes or restrictions.

4 Assessment of RCM Program Effectiveness

To measure the effectiveness of the RCM program, the performance parameters identified in the RCM program plan are to be monitored. The RCM analyses should have established the units of performance measurement for the equipment under evaluation. The feedback from the effectiveness assessments can be used to provide justification for the continued use of RCM to management. Examples of effectiveness assessments are cost avoidance, maintenance performed and operational availability.

Cost avoidance compares the operational and maintenance (O&M) costs related to the original maintenance program of an item along with the item's availability with the O&M costs and availability that result after the application of an RCM analysis.

The man-hours expended in performing scheduled and unscheduled maintenance may provide an indication of the maintenance program's effectiveness. Comparison of man-hours expended prior to implementation of RCM-generated tasks with man-hours expended afterward may provide a useful measure. A similar approach may be used for measuring the effectiveness of the sustaining efforts.

The effectiveness of RCM-generated tasks may also be measured by the availability of the equipment or system before and after implementation of the RCM program. Certain equipment operating without the benefit of an RCM program may require extensive unscheduled maintenance, which negatively impacts availability. Also, equipment that is subject to too much maintenance will also affect availability.

Other relevant maintenance metrics that can be used to monitor the RCM program include:

- Compliance with the RCM maintenance plan
- Safety performance metrics (e.g., number of recordable incidents, incident rate)
- Environmental performance metrics (e.g., permit exceedances, average emission rates)
- Miles/ton of fuel
- Asset downtime
- Number of breakdowns
- Port maintenance days
- Comparison of actual maintenance costs to budgeted maintenance costs

SECTION 9 RCM Applied to Existing Preventative Maintenance Plans

1 General

RCM analyses can be conducted for existing machinery systems. The vessel's Owners/Operators will have considerable operating and maintenance knowledge and experience with the equipment to be analyzed. The current proactive/preventative maintenance plan is satisfactory, but possibly excessive. The RCM analysis results can be used to:

- Verify the suitability of the existing preventative maintenance plan
- Identify equipment failure modes not addressed by the system design or by the existing maintenance plan
- Identify unnecessary maintenance activities

There are numerous methods presently available seeking to "streamline" RCM analyses. These methods all seek to reduce the time and effort required to perform the RCM analysis. Any analysis that does not address all failure modes of the system being analyzed may result in the development of a preventative maintenance plan that is inadequate with the risk that a preventable consequence may occur. Therefore, any RCM analysis performed should consider all failure modes.

2 System Templates

Many marine systems and equipment installed on various vessel types are similar in arrangement and purpose. As an aid to Owners/Operators, the Bureau has developed several templates for piping systems and equipment. These templates are partially completed Failure Modes and Effects Analyses. They provide the following information:

- High level system schematic
- Detailed system schematic
- Listing of system functions and suggested functional failures
- Failure modes and effects analysis including:

  System equipment item/component

  Suggested failure mode

  Possible causes

  Local effects

  Functional failure

  End effects

  Failure detection and corrective measures (indications and safeguards)

These templates will reduce the time necessary to perform a thorough analysis and provide the Bureau with a consistent analysis from various Owners/Operators. However, individual vessel classes may have features not shown on these templates or failure modes unique to their equipment. It is the Owner/Operator's responsibility to verify and revise as necessary the templates to be representative of the actual systems onboard.

The templates have been developed for the operating mode Normal Seagoing Conditions at Full Speed. Analyses for the remaining operating modes listed in 2/4.1 of the *Guide for Survey Based on Reliability-centered Maintenance* are to be completed by the Owner/Operator.

APPENDIX 1 Overview of Condition-monitoring Techniques

1 Introduction

Equipment failures are many times preceded by an advanced warning period, and maintenance techniques used to detect this warning are known as condition-monitoring (CM) tasks. More specifically, CM tasks are maintenance techniques that are used to detect the onset of an equipment failure so that the failure can be prevented or the consequences associated with the failure can be mitigated by providing the opportunity for preemptive action to be taken.

This Appendix provides:

i) Descriptions of and specific examples for general CM categories

ii) A discussion of factors that should be considered when selecting a CM technique

2 General Condition-monitoring Categories

Following are brief descriptions of some general CM categories. They are intended to provide an introduction to different types of CM tasks. Descriptions of selected CM techniques for each of these categories are provided in Subsection A1/4.

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

ii) *Dynamic Monitoring.* Dynamic monitoring (e.g., spectrum analysis, shock pulse analysis) involves measuring and analyzing energy emitted from mechanical equipment in the form of waves such as vibration, pulses and acoustic effects. Measured changes in the vibration characteristics from equipment can indicate problems such as wear, imbalance, misalignment and damage.

iii) *Oil Analysis.* Oil analysis (e.g., ferrography, particle counter testing) can be performed on different types of oils such as lubrication, hydraulic or insulation oils. It can indicate problems such as machine degradation (e.g., wear), oil contamination, improper oil consistency (e.g., incorrect or improper amount of additives) and oil deterioration.

iv) *Corrosion Monitoring.* Corrosion monitoring (e.g., coupon testing, corrometer testing) helps provide an indication of the extent of corrosion, the corrosion rate and the corrosion state (e.g., active or passive corrosion state) of material.

v) *Nondestructive Testing.* Nondestructive testing involves performing tests (e.g., x-ray, ultrasonic) that are noninvasive to the test subject. Many of the tests can be performed while the equipment is online.

vi) *Electrical Testing and Monitoring.* Electrical condition-monitoring techniques (e.g., high potential testing, power signature analysis) involve measuring changes in system properties such as resistance, conductivity, dielectric strength and potential. Some of the problems that these techniques will help detect are electrical insulation deterioration, broken motor rotor bars and a shorted motor stator lamination.

vii) *Observation and Surveillance.* Observation and surveillance condition-monitoring techniques (e.g., visual, audio and touch inspections) are based on human sensory capabilities. They can serve as a supplement to other condition-monitoring techniques. These techniques will help detect problems such as loose/worn parts, leaking equipment, poor electrical/pipe connections, steam leaks, pressure relief valve leaks and surface roughness changes.

viii) *Performance Monitoring.* Monitoring equipment performance is a condition-monitoring technique that predicts problems by monitoring changes in variables such as pressure, temperature, flow rate, electrical power consumption and/or equipment capacity.

3 Selecting a Condition-monitoring Technique

Prior to assigning a CM task, several factors need to be considered so that an effective and technically/economically feasible approach can be chosen. The following paragraphs provide guidance on several of these factors.

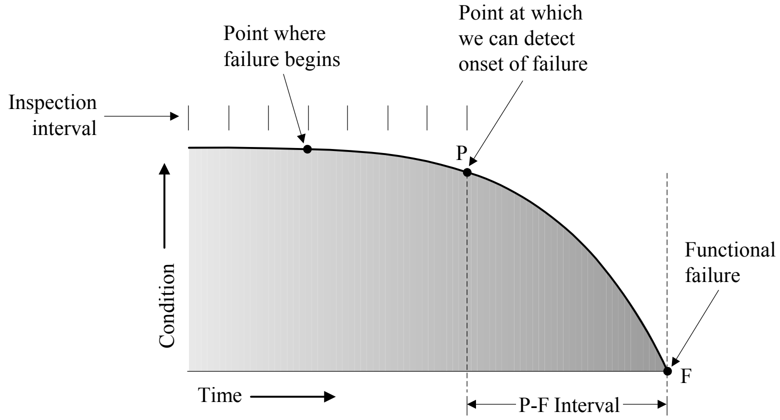
3.1 Condition Being Detected

The condition or operating performance of the equipment must be understood so that the point of onset of failure can be defined. Also, parameter(s) that can be measured/observed and represent the equipment's condition must be understood so that an appropriate CM task can be selected.

3.2 P-F Interval

The warning period during which CM tasks can be used to detect the onset of a failure is known as the P-F interval (e.g., the interval between the point at which the onset of failure becomes detectable and the point at which the condition deteriorates into a functional failure – see Appendix 1, Figure 1).

FIGURE 1
P-F Diagram



Understanding the P-F interval plays an important role in selecting the CM task frequencies. Too high a task frequency can result in wasted resources. Too low a task frequency can result in the inability to take corrective actions due to the onset of failure being discovered late in the P-F interval, or the task frequency being longer than the P-F interval, thus resulting in the P-F interval not being detected.

The consistency of the P-F interval also needs to be considered. If the interval varies consistently within a range, then the shortest interval needs to be considered when assigning a CM task frequency. If the interval range is wildly inconsistent, then it might not be possible to establish a meaningful CM task interval (or consider continuous monitoring, if practical).

Even if equipment is determined to be operating in the P-F interval, the interval might not be long enough to provide an opportunity to respond and to reduce or eliminate the consequences of the functional failure.

3.3 Measurement Precision/Sensitivity

The measurement precision and sensitivity of the CM technique being used need to be understood because they affect the reaction time available to reduce or eliminate the consequences of the functional failure. Take the example of using ultrasonic testing versus human auditory sense as a CM approach. If both of these CM techniques were used in the same service, ultrasonic testing will provide more precision and sensitivity (e.g., can detect less intense noises). Therefore, it will consistently provide more reaction time once the onset of failure is detected. Of course, other variables (e.g., economic, available resources) might drive the use of the human auditory sense.

3.4 Skills

CM techniques require varying skill levels, so this must be taken into consideration when selecting tasks. An investment might have to be made to train personnel, or outside sources might need to be contracted to perform the tasks.

3.5 Resources versus the Risk

The risk of the equipment functional failure must also be taken into account when assigning CM tasks. Risk is the combination of the effect and the likelihood of an undesired event. Effects may include safety, health, economic, environmental or other types of potential losses. Likelihood addresses the probability of a single occurrence of the undesired event (e.g., equipment failures) or the average frequency of occurrence of the undesired event. For example, a machine that fails twice per year causing $100,000 in lost production per failure event has the same risk as a machine that fails 10 times per year causing $20,000 in lost production per event. Over a year's time, the failure of each machine results in $200,000 in lost production. The economic risk associated with operating these two machines is equal. Using this example, the risk of operating the two machines is reduced to an annual cost (dollars per year).

If the risk of a functional failure is less than the cost of the CM task, then it might not be economically feasible to perform the task.

3.6 Environment, Location and Portability

The physical feasibility of performing a CM task must also be considered. For example, equipment located in hazardous environments may preclude human inspections. Also, some CM techniques might not be feasible because the equipment being observed is located in tight areas, or the measuring equipment being used might be cumbersome and difficult to transport to certain areas.

4 Summary of Selected Condition-monitoring Techniques

Following are brief descriptions of selected CM techniques for each of the general CM technique categories described in Subsection A1/2. The following sections do not contain complete listings of CM techniques. However, the more common techniques have been included. In addition, the technique information provided (e.g., P-F interval, application) is representative of data/experience from a variety of industries. Therefore, this information should be carefully evaluated before using it to determine the application and interval of a CM technique.

4.1 Temperature Measurement Condition-monitoring Techniques

4.1.1 Thermocouple

This is the measurement of the temperature of an object using thermocouples applied to the surface or the interior. This form of condition monitoring results in an electrical current being generated in the thermocouple, which is converted to a temperature readout by an instrument.

4.1.2 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

Advantages of this technique include the following:

i) The test is simple and no special training is required to observe the results.

ii) The paint retains the color of the highest temperature reached, providing a permanent record.

Disadvantages of this technique include the following:

i) Once the paint color changes, it does not change back to the original color.

ii) The effective life of an application of the paint is usually one (1) or two (2) years, or until the paint changes color.

4.1.3 Infrared Thermography

This noncontact technique uses infrared scanners to measure the temperature of heat-radiating surfaces within the line of sight of the scanner. (*Note:* Infrared radiation is emitted from all objects above the temperature of absolute zero [-273°C]). The scanner 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 results in 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 scanners are available for a wide range of temperature sensitivities and resolutions. This technique can be used to scan elevated, large, distant or hot surfaces.

Typical P-F interval: days to months

Skill level: trained and experienced technician

Advantages of this technique include the following:

i) Scanners can be portable and are generally considered easy to operate.

ii) It provides dramatic images of the object's temperature profile.

iii) It provides noncontact testing (e.g., safe to measure energized 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.

Disadvantages of this technique include the following:

i) Equipment costs are considered moderate to expensive.

ii) Interpretation of the results requires training and experience.

iii) The scanners do not measure well through metal or glass housings or barriers.

4.2 Dynamic Monitoring Condition-monitoring Techniques

4.2.1 Time Waveform Analysis

Time waveform analysis can identify a wide range of mechanical instabilities, including problems such as chipped, cracked or broken teeth; pump cavitation; misalignment; looseness; and/or eccentricity. This technique uses an oscilloscope connected to the output of a vibration analyzer or real-time analyzer. Through manipulation of the analyzer output signal, the oscilloscope can generate a wave form representing vibration in the dynamic system being monitored. This technique can be used to monitor gearboxes, pumps and roller bearings.

Typical P-F interval: weeks to months

Skill level: trained and experienced technician

Advantages of this technique include the following:

i) The analysis is effective when looking for beats, pulses, instabilities and a multitude of other conditions of interest.

ii) The technique often provides more information than frequency analysis.

Disadvantages of this technique include the following:

i) The time waveforms can be complex and confusing.

ii) Testing can consume a considerable amount of time.

iii) Personnel need considerable practice and experience to interpret complex waveforms.

4.2.2 Spectrum Analysis

Spectrum analysis transforms data that are in the time domain to the frequency domain, using the fast Fourier transform algorithm, by either the data collector itself or a host computer. After the data are collected and transformed (e.g., organized by frequency), they are compared to the baseline or expected values. Problems are identified by comparing a device's current spectra to its previous spectra to detect changes in amplitude at selected frequencies. This technique can be used to monitor shafts, gearboxes, belt drives, compressors, engines, roller bearings, journal bearings, electric motors, pumps and turbines.

Typical P-F interval weeks to months

Skill level: trained and experienced technician

Advantages of this technique include the following:

i) The equipment is portable and easy to use.

ii) Software is available that makes the mathematical transformation of the data rapid and accurate.

iii) Small performance changes in the equipment being tested can be identified by these tests.

iv) Characteristic frequencies usually allow the user to isolate the problem to a component.

One *disadvantage* of this technique is that random noise and vibrations of nearby equipment can interfere with the tests.

4.2.3 Shock Pulse Analysis

Shock pulse analysis measures the impact of rollers with the raceway and produces a shock pulse reading that changes as the conditions within the bearing deteriorate. This technique uses a shock pulse analyzer that is set up specifically for the type and size of bearings being tested and is fed a signal from an accelerometer placed on a bearing housing. It can identify issues such as lubricant problems, problems with oil seals and packings and incorrect bearing installation and/or alignment. This technique can be used to monitor roller bearings, impact tools and internal combustion engine valves.

Typical P-F interval: weeks to months

Skill level: trained and experienced technician

Advantages of this technique include the following:

i) Test equipment is portable and easy to operate.

ii) Test results are essentially immediate.

iii) The sensitivity of the test is generally considered better than conventional vibration analysis.

Disadvantages of this technique include the following:

i) The test is limited to roller-type bearings.

ii) The test is highly dependent on accurate bearing size and speed information.

4.2.4 Ultrasonic Analysis

When used as a dynamic monitoring technique, ultrasonic analysis helps detect changes in sound patterns caused by problems such as wear, fatigue and deterioration in moving parts. Ultrasound (e.g., high-frequency sound waves that are above human perception from 20 kHz to 100 kHz) is detected by an ultrasonic translator and converted to audible or visual output. *[Note: See ultrasonic testing as a nondestructive condition-monitoring technique (A1/4.5.3) for its other capabilities.]* This technique can be used to monitor bearing fatigue or wear.

Typical P-F interval: highly variable

Skill level: trained skilled worker

Advantages of this technique include the following:

i) Tests are quick and easy to do.

ii) The location of the noise source can be pinpointed accurately.

iii) Equipment is portable and monitoring can be done from a long range.

One *disadvantage* of this technique is that random noise and vibrations of nearby equipment can interfere with the tests.

4.3 Oil Analysis Condition-monitoring Techniques

4.3.1 Ferrography

Ferrography is a technique that identifies the density and size ratio of particles in oil or grease caused by problems such as wear, fatigue and/or corrosion. A representative sample is diluted with a fixer solvent and then passed over an inclined glass slide that is subjected to a magnetic field. The magnetic field provides separation of the ferrous particles (ferrous particles align with the magnetic field lines) and distributes them along the length of the slide (nonmagnetic and nonmetallic particles are distributed randomly along the slide). The total density of the particles and the ratio of large-to-small particles indicate the type and extent of wear. Analysis of the test sample is done by bichromatic, microscopic examination using both reflected and transmitted light sources (which may be used simultaneously). Green, red and polarized filters are also used to distinguish the size, composition, shape and texture of both metallic and nonmetallic particles. An electron microscope can also be employed in the analysis to determine particle shapes and provide an indication of the cause of failure. This technique can be used to analyze grease and oil used in diesel and gasoline engines, gas turbines, transmissions, gearboxes, compressors and hydraulic systems.

Typical P-F interval:	months
Skill level:	trained semiskilled worker to take the sample and experienced technician to perform and interpret the analysis

Advantages of this technique include the following:

i) Ferrography is more sensitive than many other tests at identifying early signs of wear.

ii) The slide provides a permanent record and allows the measurement of particle size and shape.

Disadvantages of this technique include the following:

i) The test is time-consuming and requires expensive equipment.

ii) In-depth analysis requires an electron microscope.

iii) The primary target is limited to ferromagnetic particles.

4.3.2 Particle Counter

Particle counter testing monitors particles in both lubricating and hydraulic oils caused by problems such as corrosion, wear, fatigue and contaminants. There are several types of particle counting tests available. Two in particular are light extinction and light scattering particle counters. In a light extinction particle counter test, an incandescent light shines on an object cell that the oil sample fluid moves through under controlled flow and volume conditions. A particle counter (e.g., photo diode) receives the light passing through the sample and, based on the amount of light blocked, it indicates the number of particles in a predetermined size range. A direct reading of the ISO cleanliness value can be determined from this test.

In a light scattering particle counter test, a laser light shines on an object cell that the oil sample fluid moves through under controlled flow and volume conditions. When opaque particles pass through the laser, the scattered light created is measured and translated into a particle count by a photo diode. A direct reading of the ISO cleanliness value can be determined from this test.

This technique can be used to analyze oil used in engines, compressors, transmissions, gearboxes and hydraulic systems.

Typical P-F interval: weeks to months

Skill level: trained skilled worker

Advantages of this technique include the following:

i) Test results are quickly available.

ii) Tests are accurate and reproducible.

iii) Tests are more accurate than graded filtration.

Disadvantages of this technique include the following:

i) The tests are dependent on good fluid conditions and are hampered by air bubbles, water contamination and translucent particles.

ii) The tests provide no information on the chemical nature of the contamination.

4.3.3 Sediment Tests (ASTM D-1698)

Sediment testing provides information about sediment (e.g., inorganic sediment from contamination and organic sediment from oil deterioration or contamination) and soluble sludge from electrical insulating oil deterioration. It involves the use of a centrifuge to separate sediment from oil, and the sediment-free portion is subject to further steps (e.g., dilution, precipitation and filtration) to measure the soluble sludge. The total sediment is weighed and then baked to remove the organics, which provides an organic/inorganic composition. This technique can be used to analyze petroleum-based insulating oils in transformers, breakers and cables.

Typical P-F interval: weeks

Skill level: electrician to take the sample and trained laboratory technician to perform and interpret the analysis

Advantages of this technique include the following:

i) The test is relatively quick and easy to complete.

ii) Samples can be taken online.

Disadvantages of this technique include the following:

i) Only low-viscosity oil can be sampled.

ii) Testing must be performed in a laboratory.

4.3.4 Atomic Emissions Spectroscopy

Atomic emissions spectroscopy identifies problems such as corrosion, wear metals, contaminants and additives in lubrication and hydraulic oil samples by measuring the characteristic radiation emitted when samples are subjected to high energy and temperature conditions. The test results are in parts per million (ppm) for a wide variety of elements of interest, including iron, aluminum, chromium, copper, lead, tin, nickel and silver, and components of oil additives such as boron, zinc, phosphorus and calcium. This technique can be used to analyze oil used in diesel and gasoline engines, compressors, transmissions, gearboxes and hydraulic systems.

Typical P-F interval: weeks to months

Skill level: trained semiskilled worker to take the sample and experienced technician to perform and interpret the analysis

Advantages of this technique include the following:

i) The tests are fairly low cost.

ii) The tests yield rapid and accurate results.

iii) The range of elements identified is large.

Disadvantages of this technique include the following:

i) The tests do not identify the wear process that contaminated the oil.

ii) Large particles in the sample may not be counted in the results.

4.3.5 Infrared Spectroscopy

Infrared spectroscopy involves placing an oil sample in a beam of infrared light and then measuring the absorbent light energy at various specific wavelengths to determine the level of an element in a sample without destroying the sample. Mathematical manipulations of the absorption data result in a "fingerprint" of the sample oil, which can be compared to prior samples or standards by intelligent software. The analysis can provide information about oil deterioration, oxidation, water contamination or oil additives. This technique can be applied to turbine generators, sulfur hexafluoride or nitrogen sealed systems, transformer oils and breakers.

Typical P-F interval: weeks to months

Skill level: trained semiskilled worker to take the sample and trained laboratory technician to perform and interpret the analysis

Advantages of this technique include the following:

i) Data can be used to determine ASTM parameters.

ii) The test is highly repeatable.

iii) Data can be used to generate a total acid number (TAN) and a total base number (TBN).

Disadvantages of this technique include the following:

i) Test equipment manufacturers are not consistent in the processing of data.

ii) Typically, the test is limited to about 1000 ppm water contamination.

4.3.6 Potentiometric Titration – Total Acid Number (TAN)

Potentiometric titration – TAN is used to determine the extent of breakdown in lubrication or hydraulic oil by determining the level of acidity in an oil sample. The test involves mixing the oil sample with solvents and water and then measuring the change in the electrical conductivity as the mixture is titrated with potassium hydroxide (KOH). The more KOH a sample uses, the higher the acid number and oil deterioration. This technique can be used to test oil used in diesel/gasoline engines, gas turbines, transmissions, gearboxes, compressors, hydraulic systems and transformers.

Typical P-F interval: weeks to months

Skill level: trained semiskilled worker to take the sample and trained laboratory technician to perform and interpret the analysis

Advantages of this technique include the following:

i) The test can be performed on any color oil.

ii) The test is considered accurate within 15%.

Disadvantages of this technique include the following:

i) The test is limited to petroleum-based oils.

ii) Some of the chemicals used to complete the tests are hazardous.

4.3.7 Karl Fischer Titration Test (ASTM D-1744)

The Karl Fischer titration test measures moisture in a lubrication or hydraulic oil sample, which is an indicator of a degraded oil condition, by measuring electrical current flow between two electrodes immersed in the sample solution. Karl Fischer reagent is metered into the sample until all of the entrained water is reacted with the reagent. Results are reported in ppm of water. This technique can be used to analyze oil in enclosed oil systems such as engines, gearboxes, transmissions, compressors, hydraulic systems, turbines and transformers.

Typical P-F interval: days to weeks

Skill level: trained lab technician

Advantages of this technique include the following:

i) The test is accurate for small quantities of water contamination.

ii) The test can be completed fairly quickly.

iii) Results are repeatable.

Disadvantages of this technique include the following:

i) Considerable skill is required to interpret the results.

ii) Automated equipment is relatively expensive and not portable.

4.3.8 Kinematic Viscosity

The kinematic viscosity test provides an indication of oil deterioration over time or contamination of the oil by fuel or other oils. The test measures the fluids resistance to flow under known pressure and temperature conditions and involves forcing a sample to flow through a capillary viscometer. Based on the test results, the dynamic viscosity of the oil sample can be calculated. This technique can be used to test oil used in diesel/gasoline engines, turbines, transmissions, gearboxes, compressors and hydraulic systems.

Typical P-F interval: weeks to months

Skill level: trained semiskilled worker to take the sample and trained laboratory technician to perform and interpret the analysis

Advantages of this technique include the following:

i) The test can be used for most lubricating oils, both transparent and opaque.

ii) Results are repeatable.

Disadvantages of this technique include the following:

i) The test is not done in the field.

ii) Flammable solvents are used.

4.3.9 Dielectric Strength Tests

Dielectric strength tests are used to measure the insulating quality of electrical insulating oils. Potential quality deterioration is often caused by contamination or oil breakdown. The test is performed by subjecting the sample to an electrical stress at a given temperature by passing voltage through the sample. This technique can be used to test insulating oils in transformers, breakers and cables.

Typical P-F interval: months

Skill level: electrician to take the sample and trained laboratory technician to perform and interpret the analysis

Advantages of this technique include the following:

i) The test is rapid and relatively simple.

ii) The equipment does not need to be offline to perform the test.

Disadvantages of this technique include the following:

i) The sampling technique can affect the test results.

ii) The test must be completed in the lab.

iii) The materials and equipment used to complete the test are hazardous.

4.4 Corrosion Monitoring Condition-monitoring Techniques

4.4.1 Coupon Testing

Coupon testing involves placing sacrificial coupons, which are usually made from low-carbon steel or from a grade of material that duplicates the material of construction of the equipment being monitored, into the process so that the corrosion from the equipment can be monitored. The coupons are periodically measured and observed to understand the process environment's effect on these test pieces. Measurements include checking weight loss, dimensional changes and physical damage such as pitting. This technique can be used to perform tests at petroleum refineries, process plants, underground/undersea structures, water distribution systems and electrical generating plants, and for cathodic protection monitoring, abrasive slurry transport and atmospheric corrosion monitoring.

Typical P-F interval: months

Skill level: trained and experienced technician

Advantages of this technique include the following:

i) Corrosion effects can be accurately predicted when the environment is consistent over the test period.

ii) Testing is relatively inexpensive and yields vivid examples of the corrosion to expect.

Disadvantages of this technique include the following:

i) Testing can take a long time to complete.

ii) Determining the corrosion rates can take several weeks or months of testing.

iii) The tests involve working directly with the potentially hazardous corrosive material streams.

4.4.2 Corrometer

Corrometer testing helps measure the corrosion rate of equipment by monitoring the change in the electrical resistance of a sample material. As the sample material's cross-section is reduced due to corrosion, the electrical resistance of the sample will increase. The measured resistance change corresponds to the total metal loss and can be converted to a corrosion rate. This technique can be used to perform tests at petroleum refineries, process plants, underground/undersea structures, water distribution systems, paper mills and electrical generating plants, and for cathodic protection monitoring, abrasive slurry transport and atmospheric corrosion monitoring.

Typical P-F interval: months

Skill level: trained and experienced technician

Advantages of this technique include the following:

i) Portable equipment is available.

ii) Testing works in many environments.

iii) Testing can be made continuous with an online monitor.

iv) Results are easily converted to corrosion rates.

Disadvantages of this technique include the following:

i) Portable equipment does not provide permanent records.

ii) The test does not typically indicate changes in the corrosion rate.

4.4.3 Potential Monitoring

Potential monitoring helps identify the corrosion state (e.g., active or passive) of material by monitoring localized corrosion and indicating when active corrosion is in progress. This test takes advantage of the fact that metals in an active corrosion state (e.g., higher corrosion rate) have a different electrical potential than when they are in a passive corrosion state (e.g., lower corrosion rate). A voltmeter is used to measure the potential of the sample area. This technique can be used to perform monitoring at chemical process plants, paper mills, pollution control plants, electrical utilities and desalination plants. The technique is best suited to stainless steel, nickel-based alloys and titanium.

Typical P-F interval: varies depending on material and rate of corrosion

Skill level: trained and experienced technician

Advantages of this technique include the following:

i) The test provides a rapid response to change.

ii) Localized corrosive effects are monitored.

Disadvantages of this technique include the following:

i) The test does not provide corrosion rates.

ii) Testing is influenced by changes in temperature and acidity.

4.5 Nondestructive Testing Condition-monitoring Techniques

4.5.1 X-ray Radiography

X-ray radiography helps identify surface and subsurface flaws caused by problems such as stress, corrosion, inclusions, fatigue, poor or incomplete welds and trapped gases. In addition, it can be used to locate semiconductor faults and loose wires. The technique produces a radiograph by passing X rays through opaque materials and producing an image of those materials on film or a cathode ray tube. Typically, film exposed to X rays is darkest where the object is thinnest or absorbs the least radiation. This technique can be used to analyze welds, steel structures, plastic structures and metallic wear components of engines, compressors, gearboxes, pumps and shafts.

Typical P-F interval: months

Skill level: trained and experienced technician to take the radiographs and trained and experienced technician or engineer to interpret the radiographs

Advantages of this technique include the following:

i) The technique examines the inside of test materials to locate hidden flaws (e.g., areas that cannot be seen externally).

ii) The technique provides a permanent record of the test.

Disadvantages of this technique include the following:

i) Sometimes several views are required to locate the flaw.

ii) The test is not very sensitive to crack-type flaws.

4.5.2 Liquid Dye Penetrant

The use of liquid dye penetrants can help detect surface discontinuities or cracks due to problems such as fatigue, wear, surface shrinkage and grinding. The technique involves applying liquid dye penetrant to a test surface and then allowing sufficient time for the dye to penetrate the surface. Next, excess penetrant is removed from the surface, and the surface is retreated with a developer that draws the penetrant to the surface revealing the location of imperfections. Liquid penetrants are categorized according to the type of dye (e.g., visible dye, fluorescent penetrant and dual sensitivity penetrant) and the type of processing (e.g., water washable, postemulsified or solvent removed) required to remove the dye from the surface. This technique can be used to analyze ferrous and nonferrous materials such as welds, machined surfaces, steel structures, shafts, boilers, plastic structures and compressor receivers.

Typical P-F interval: days to months

Skill level: trained and experienced technician

Advantages of this technique include the following:

i) Visible dye penetrant kits are cheap (*Note*: fluorescent kits are more sensitive but more expensive).

ii) Surface problems on nonferrous materials can be detected.

Disadvantages of this technique include the following:

i) Testing will not work on highly porous materials.

ii) The technique is not conducive to online testing.

iii) Experienced personnel are required to evaluate the results.

iv) A dark work area is required for fluorescent dye testing.

4.5.3 Ultrasonic Analysis

Ultrasonic analysis helps detect changes in sound patterns caused by problems such as leaks, wear, fatigue or deterioration. Ultrasound (e.g., high-frequency sound waves that are above human perception from 20 kHz to 100 kHz) is detected by an ultrasonic translator and converted to audible or visual output. *[Note: See ultrasonic analysis as a dynamic condition-monitoring technique (A1/4.2.4) for its other capabilities.]* This technique can be used to detect leaks in pressure/vacuum systems and underground pipes or tanks, and to detect static discharge.

Typical P-F interval: highly variable

Skill level: trained skilled worker

Advantages of this technique include the following:

i) The tests are quick and easy to do.

ii) The location of the noise source can be pinpointed accurately.

iii) Equipment is portable and monitoring can be done from a long range.

Disadvantages of this technique include the following:

i) Some tests can only be done under vacuum.

ii) In general, test results do not indicate the size of a leak.

4.5.4 Ultrasonic Transmission

Ultrasonic testing using a transmission technique helps to detect surface and subsurface discontinuities caused by problems such as fatigue, heat treatment, inclusions, and lack of penetration and gas porosity welds. It can also measure thickness in test subjects. The test involves using one of the available transmission techniques to apply an ultrasound signal to a test object and then receiving the signal back and analyzing it for changes that might indicate the presence of discontinuities in the test object. Ultrasonic techniques include pulse echo, transmission, resonance and frequency modulation. This technique can be used to inspect ferrous and nonferrous welds, steel structures, boilers, tubes, plastic structures and vessels/tanks.

Typical P-F interval: weeks to months

Skill level: trained and experienced technician

One *advantage* of this technique is that the tests are applicable to a majority of materials.

One *disadvantage* of this technique is that the test results do not clearly distinguish between types of defects.

4.5.5 Magnetic Particle Inspection

Magnetic particle inspection helps detect the location of surface/near-surface cracks and discontinuities caused by problems such as fatigue, wear, inclusions, laminations, heat treatment, hydrogen embrittlement, seams and corrosion. The technique involves magnetizing the test piece and spraying it with a solution containing very fine iron particles. Discontinuities on the surface of the test piece will cause the iron particles to accumulate and form an indication of the flaw. The results are then interpreted. This technique can be used to analyze ferromagnetic metals such as vessels/tanks, welds, machined surfaces, shafts, steel structures and boilers.

Typical P-F interval: days to months

Skill level: trained and experienced technician

Advantages of this technique include the following:

i) The test is reliable.

ii) The test is sensitive.

iii) The test is widely used.

Disadvantages of this technique include the following:

i) The test is limited to detecting surface imperfections.

ii) The test is time-consuming.

iii) The test is not applicable as an online test.

4.5.6 Eddy Current Testing

Eddy current testing helps detect surface and subsurface flaws caused by problems such as wear, fatigue and stress, and it helps detect dimensional changes that result from problems such as wear, strain and corrosion. It can also help determine material hardness. The technique involves applying high-frequency alternating current to conductive material test objects and inducing eddy currents around discontinuities. The electrical effects in the test part are amplified and shown on a cathode ray tube or a meter. This technique can be used to analyze boilers, heat exchangers, hydraulic tubes, hoist ropes, railroad lines and overhead conductors.

Typical P-F interval: weeks

Skill level: trained and experienced technician

Advantages of this technique include the following:

i) The test can be performed on a wide variety of conductive materials.

ii) Permanent records can be made via data recorders.

One *disadvantage* of this technique is that nonferrous materials respond poorly to the test.

4.5.7 Acoustic Emission

Acoustic emission testing monitors the plastic deformation and crack formation caused by problems such as fatigue, stress and wear. The technique involves subjecting the test object to loads and listening to the audible stress waves that result. The test results can be displayed on a cathode ray tube or an x-y recorder. This technique can be used to test structures, pressure vessels, pipelines and mining excavations.

Typical P-F interval: weeks

Skill level: trained and experienced technician

Advantages of this technique include the following:

i) The test can be performed remotely in relation to the flaws and can cover the entire structure.

ii) Active flaws can be detected.

iii) Relative loads used in testing can be used to estimate failure loads in some cases.

Disadvantages of this technique include the following:

i) The test object has to be loaded.

ii) Some electrical and mechanical noises can interfere with the results.

iii) Results analysis can be difficult.

4.5.8 Hydrostatic Testing

Hydrostatic testing helps detect breaches in a system's pressure boundaries caused by problems such as fatigue, stress and wear. The testing involves filling a system to be tested with water or the operating fluid, sealing the system, and increasing the pressure to approximately 1.5 times the system's operating pressure. Then, the pressure is held for a defined period while inspections and monitoring are conducted for visible leaks, a system pressure drop and makeup water/operating fluid additions. The principle of hydrostatic testing can also be used with compressed gases. This technique can be used to test components (e.g., tanks, vessels, pipelines) and completely assembled systems that contain pressurized fluids or gases.

Typical P-F interval: days to weeks

Skill level: trained skilled worker

One *advantage* of this technique is that the results are easy to interpret.

Disadvantages of this technique include the following:

i) The test has the potential to overpressurize and damage the system.

ii) The test will not identify defects that have not penetrated a pressure boundary.

iii) The test is not applicable as an online test.

4.5.9 Visual Inspection – Borescope

Visual inspections with a borescope allow internal inspections of the surface of narrow tubes, bores, pipes, chambers of engines, pumps, turbines, compressors, boilers, etc. The inspection helps locate and orient surface cracks, oxide films, weld defects, corrosion, wear and fatigue flaws. The borescope provides a system to channel light from an external light source to illuminate parts not easily visible to the naked eye, and it also provides a means to photograph and/or magnify the illuminated surface of interest.

Typical P-F interval: weeks

Skill level: trained and experienced technician

Advantages of this technique include the following:

i) The equipment provides excellent views.

ii) The parts being examined can be photographed and magnified.

Disadvantages of this technique include the following:

i) The inspection is limited to surface conditions.

ii) The lens systems are often inflexible.

iii) Technicians can suffer eye fatigue during prolonged inspections.

4.6 Electrical Testing and Monitoring Condition-monitoring Techniques

4.6.1 Megohmmeter Testing

A megohmmeter can be used to test the insulation resistance of electrical circuits. The technique involves applying a known voltage to electrical circuits of the equipment being tested and measuring the current flow. Based on the leakage current flowing to ground, the resistance of the equipment insulation can be determined.

Typical P-F interval: months to years

Skill level: technician or engineer

One *advantage* of this technique is that it is simple and well understood.

One *disadvantage* of this technique is that online testing cannot be conducted.

4.6.2 High Potential Testing

High potential testing helps detect motor winding ground wall insulation deterioration. The test involves applying high direct current voltage to the stator windings in graduated steps to help determine the voltage at which nonlinearity in the test current or a drop in the insulation resistance occurs. If the insulation withstands a specified voltage, it is considered to be safe, and the motor can be returned to service. Also, trending the voltage at which the current becomes nonlinear or the resistance drops can be used to predict the remaining motor life. This technique can be applied to AC and DC motors.

Typical P-F interval:	weeks
Skill level:	experienced electrical technician

One *advantage* of this technique is that the test results usually correlate with surge comparison tests.

Disadvantages of this technique include the following:

i) Motors must be offline for testing.

ii) The test voltage can be destructive to motor parts.

4.6.3 Surge Testing

Surge testing helps identify insulation faults in induction/synchronous motors, DC armatures, synchronous field poles and various coils or coil groups. The technique involves using a high-frequency transient surge applied to two separate but equal parts of a winding, and then the resulting reflected waveforms are compared on an oscilloscope. Normally, if no problems are detected at twice the operating voltage, plus 1,000 volts, the winding is considered good.

Typical P-F interval:	weeks to months
Skill level:	trained and experienced test operator

One *advantage* of this technique is that the test is portable.

Disadvantages of this technique include the following:

i) The test is complex and expensive.

ii) Careful repetition is required to determine the location or severity of a fault.

4.6.4 Power Signature Analysis

Power signature analysis can be used to detect motor problems such as broken rotor bars, broken/cracked end rings, flow or machine output restrictions and machinery misalignment. This online technique involves monitoring current flow in one of the power leads at the motor control center or starter. The electrical current variations identified in the test indicate changing machine operating conditions and can be trended over time. Also, line frequencies can be compared with motor frequencies to help detect various motor flaws. This technique can be used to analyze AC induction motors, synchronous motors, compressors, pumps and motor-operated valves.

Typical P-F interval	weeks to months
Skill level:	experienced electrician to connect the test equipment and experienced technician to perform the analysis and interpret the data

Advantages of this technique include the following:

i) Testing is conducted online.

ii) Test readings can be taken remotely for large or high-speed machines.

Disadvantages of this technique include the following:

i) Equipment is expensive.

ii) Analysis results are complex and often subjective.

4.6.5 Motor Circuit Analysis

A motor circuit analysis helps to yield a complete picture of motor conditions by performing a series of tests. The test applies voltage at the motor control center power bus to measure resistance to ground, circuit resistance, capacitance to ground, inductance, rotor influence, DC bar-to-bar and polarization index/dielectric absorption. The results can identify changes in conductor path resistance caused by loose or corroded connections and loss of copper (turns) in the stator; phase-to-phase inductance caused by magnetic interaction between the stator and rotor; stator inductance affected by rotor position, rotor porosity and eccentricity, stator turn, and coil and phase shorting; and winding cleanliness/resistance to ground. This technique can be used to analyze electric motors (e.g., DC, AC induction, synchronous and wound rotor).

Typical P-F interval: weeks to months

Skill level: experienced electrical technician to perform the test

Advantages of this technique include the following:

i) The test is low voltage and nondestructive.

ii) Tests can be performed at the motor control center, which does not require motor disassembly.

One *disadvantage* of this technique is that the test cannot be performed online.

4.6.6 Battery Impedance Testing

Battery impedance testing helps detect battery cell deterioration. The test involves injecting an AC signal between the battery posts and measuring the resulting voltage. The battery impedance is then calculated and compared to (1) the battery's last test and (2) the impedance of other batteries in the same bank. If the comparison results are outside a certain percentage, then this could indicate a cell problem or capacity loss.

Typical P-F interval: weeks

Skill level: experienced electrical technician to perform the test

One *advantage* of this technique is that the test can be performed online.

One *disadvantage* of this technique is that the tests are lengthy for large batteries.

4.7 Observation and Surveillance Condition-monitoring Techniques

4.7.1 Visual Inspection

Visual inspection practices are the oldest and most common CM techniques employed in industry. Human observation helps identify a broad range of potential problems, including loose or worn parts; leaks of lubricating oils, hydraulic fluids and process liquids; missing parts; poor electrical or pipe connections; etc. Inspection standards are easy to establish and communicate to assigned personnel. Essentially, all machines and equipment in the industrial setting can be monitored with this technique. Also, human sensory-based inspections can verify the results from other CM techniques.

Typical P-F interval: varies widely

Skill level: trained semiskilled workers are normally required

One *advantage* of this technique is that the versatility of human observation combined with experience can identify an extremely wide range of problem types.

One *disadvantage* of this technique is that unless inspections are scheduled and recorded, observers can become so familiar with their surroundings that changes of interest go unnoticed.

4.7.2 Audio Inspections

Audio inspection practices are common CM techniques employed in industry. The monitoring of machinery and equipment by listening to it operate helps identify a broad range of potential problems, including worn high-friction bearings, steam leaks, pressure relief valve leaks or discharges, coupling leaks, excessive loading on pumps, poor mechanical equipment alignment, etc. Humans are particularly sensitive to new or changed sounds and are easily taught to report and investigate unusual sounds. This technique is often a supplemental inspection to visual inspections. Also, human sensory-based inspections can verify the results from other CM techniques.

Typical P-F interval: varies widely

Skill level: trained semiskilled workers are normally required

One *advantage* of this technique is that the versatility of human hearing combined with experience can identify an extremely wide range of problem sounds.

One *disadvantage* of this technique is that the inspections must be assigned so that the inspectors gain sufficient experience to be able to detect new or changed noises.

4.7.3 Touch Inspections

Using touch as an inspection technique can be extremely useful. Heat, scaling and roughness changes can all be detected by touch. Human touch is extremely sensitive and able to differentiate surface finish differences not discernable by eye. This technique is often a supplemental inspection to visual inspections. Also, human sensory-based inspections can verify the results from other CM techniques.

Typical P-F interval: varies widely

Skill level: trained semiskilled workers are normally required

One *advantage* of this technique is that the hands and fingers are extremely sensitive to surface finish and to heat.

One *disadvantage* of this technique is that the inspectors can be burned by touching hot objects and can be injured or shocked by touching operating equipment.

4.8 Performance Condition-monitoring Technique

4.8.1 Performance Trending

Performance trending as a CM technique involves collecting and analyzing data on pressure, temperatures, flow rates or electrical power consumption for the process, machinery and/or equipment of interest. Data are often collected by operations personnel for other reasons (e.g., quality control programs) and may already be available for analysis. Performance trend data are often coupled with other test results to confirm the identification of problems (e.g., equipment degradation, performance deterioration). Monitoring the performance indicators over a long period of time can provide indications of improper maintenance or poor operations practices. Virtually all industrial machines can be monitored in this fashion, and targets for data collection include diesel and gasoline engines, pumps, motors, compressors, etc. Data are often already collected for other reasons, and test data can also be used to optimize performance. In addition, most of the computer control equipment (e.g., distributed control systems, programmable logic controller) has data analysis and alarming features that can be used to trend equipment performance.

Typical P-F interval: varies widely

Skill level: trained semiskilled workers are normally required

One *advantage* of this technique is that the data are often already collected.

One *disadvantage* of this technique is that baseline data may not exist, which necessitates longer time periods to develop trends.

5 Condition-monitoring Technique Matrices

To assist in selecting CM techniques for application, three different CM matrices have been developed by the Bureau. The matrices provide guidance on which CM techniques are applicable to (1) specific failure conditions, (2) ship equipment and (3) ship components. The following listing briefly describes the information provided by each matrix and how the matrix can be used.

5.1 Failure Condition Matrix

This matrix provides the user with the ability to find applicable CM techniques for a given failure condition, regardless of the equipment or component type. For example, if the user wanted to find CM techniques applicable to bearing failures, regardless of the type of equipment/component, this matrix can be used. The matrix includes four columns: *Condition*, *Technique*, *P-F Interval* and *Skill*.

i) *Condition.* This column lists different failure conditions (e.g., bearing damage, corrosion), regardless of the type of equipment/component.

ii) *Technique.* This column lists the different CM techniques that can be used to detect the failure condition listed in the *Condition* column.

iii) *P-F Interval.* This column lists the typical P-F interval for the CM technique and failure condition.

iv) *Skill.* This column lists the skill level required for the CM technique.

5.2 Ship Equipment Matrix

This matrix provides the user with the ability to find applicable CM techniques for ship equipment items and their related failure conditions. For example, this matrix can be used to find related CM techniques for pumps and then for a specific failure condition, such as bearing failure. This matrix contains five columns: *Ship Product Model Equipment*, *Condition*, *Technique*, *P-F Interval* and *Skill*.

i) *Ship Product Model Equipment.* This column lists ship equipment items based on ABS' ship product model for equipment. For most of the equipment, all components of the equipment item are considered part of the equipment item. For example, the equipment item "pump" includes failure conditions and CM data (e.g., technique) for all typical components that make up a pump (e.g., motor, gear reducer and pump head).

ii) *Condition.* This column lists different failure conditions (e.g., bearing damage, corrosion) considered applicable for a given equipment item.

iii) *Technique.* This column lists the different CM techniques that can be used to detect the failure condition listed in the *Condition* column.

iv) *P-F Interval.* This column lists the typical P-F interval for the CM technique and failure condition.

v) *Skill.* This column lists the skill level required for the CM technique.

5.3 Matrix C: Ship Component Matrix

This matrix provides the user with the ability to find applicable CM techniques for ship components and their related failure conditions. For example, this matrix can be used to find related CM techniques for a motor (that is part of a pump) and then for a specific failure condition, such as bearing failure. This matrix contains five columns: *Ship Product Model Component*, *Condition*, *Technique*, *P-F Interval* and *Skill*.

i) *Ship Product Model Component.* This column lists ship components based on ABS' ship product model for components. This list consists of discrete components that may or may not be included in an equipment item.

ii) *Condition.* This column lists different failure conditions (e.g., bearing damage, corrosion) considered applicable for a given component.

iii) *Technique.* This column lists the different CM techniques that can be used to detect the failure condition listed in the *Condition* column.

iv) *P-F Interval.* This column lists the typical P-F interval for the CM technique and failure condition.

v) *Skill.* This column lists the skill level required for the CM technique.

6 Sources

The information provided in this document and in the CM matrices was based on review of several CM publications. The primary sources of this information were as follows:

Moubray, J., *Reliability-centered Maintenance*, Butterworth-Heinemann Ltd, Oxford, England, 1991.

Preventive/Predictive Maintenance, "Section 8 – Predictive Maintenance," Marshall Institute, 1998.

Reliability Centered Maintenance Guide for Facilities and Collateral Equipment, "Chapter 4 – Predictive Testing & Inspection (PT&I) Technologies," National Aeronautics and Space Administration, February 2000.

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APPENDIX 2 Example RCM Analysis of a Low Speed Diesel Engine

This Appendix provides an example RCM analysis for selected portions of a propulsion low-speed diesel engine. The purpose of this Appendix is to illustrate the RCM analysis process outlined in Section 7. Please note that this Appendix does not include RCM analysis data for the entire engine, nor does it contain all of the information that should be provided in a complete RCM analysis report. Specifically, this Appendix includes excerpts of the RCM analysis sections for the basic engine, the governor system and the camshaft lubrication system.

1 Overview of the RCM Analysis Process

A team, including personnel familiar with the operation, maintenance and engineering of a low-speed diesel engine and personnel with expertise in the RCM analysis process, should perform the RCM analysis. The team may refer to engine design manuals, engine schematics and their knowledge and expertise to perform the analysis.

The RCM analysis process outlined in Section 7 was followed. The following paragraphs briefly describe the RCM activities and provide example results for each RCM analysis step.

1.1 Identify Operating Modes and Corresponding Operating Context

The vessel's operating modes were first identified to define the operating context for the vessel. These operating modes included operating at sea, operating in restricted waters, maneuvering in port and cargo handling.

Based on the operating modes, operating contexts were developed for the top three levels of indenture. First, the operating context for the machinery and utilities were developed. These provide the basis for the functional groups' operating context. Likewise, the functional groups' operating context formed the basis for the major system operating context. Appendix 2, Tables 1, 2 and 3 provide examples of the operating contexts for the machinery and utilities, propulsion functional group and diesel engine system for the at-sea operating mode.

1.2 Define Vessel Systems

The vessel is first partitioned into disciplines and functional groups beginning with hull, machinery and utilities, and cargo handling. The propulsion group was selected for analysis and then further partitioned to the system level. The system-level partitioning includes two indenture levels: subsystems and equipment items. Appendix 2, Figure 1 provides an example partitioning diagram for the discipline, functional group, system, subsystem and equipment item levels.

This partitioning establishes the boundaries for each discipline and lower levels of indenture. In addition, the partitioning provides a basic structure for defining the vessel's operating characteristics.

TABLE 1
Machinery and Utilities Operating Characteristics

Operating Context of Machinery and Utilities Discipline	
The vessel will be propelled by a single low-speed diesel engine directly connected to the shafting with a fixed-pitch propeller. Electrical power will be provided by three ship's service diesel generators… *A general description of the remainder of the disciplines would be included here.*	
Common Characteristics	**Operating Mode** **At Sea**
Environmental Parameters	Ambient air temperature design range: –29°C to 52°C, 25°C nominal Barometric air pressure (dry): 101.3 kPa absolute Seawater Inlet temperature: –2°C to 38°C, 32°C nominal
Manner of Use	Operate continuously 24 hours per day for up to 22 days at 85% maximum continuous rating (MCR), 280 days per year
Performance Capability	Required MCR power to be developed by the Machinery System for propulsion: 16,860 kW Reversible engine Propel ship at 20 knots up to Sea State 3 Conditions Fuel: Intermediate fuel oils IFO 380 and IFO 180 Compliance with ABS Rules, SOLAS, MARPOL, etc.
	Other common characteristics associated with machinery and utilities not relevant to propulsion are also to be listed above if an RCM for the entire Discipline is to be performed.

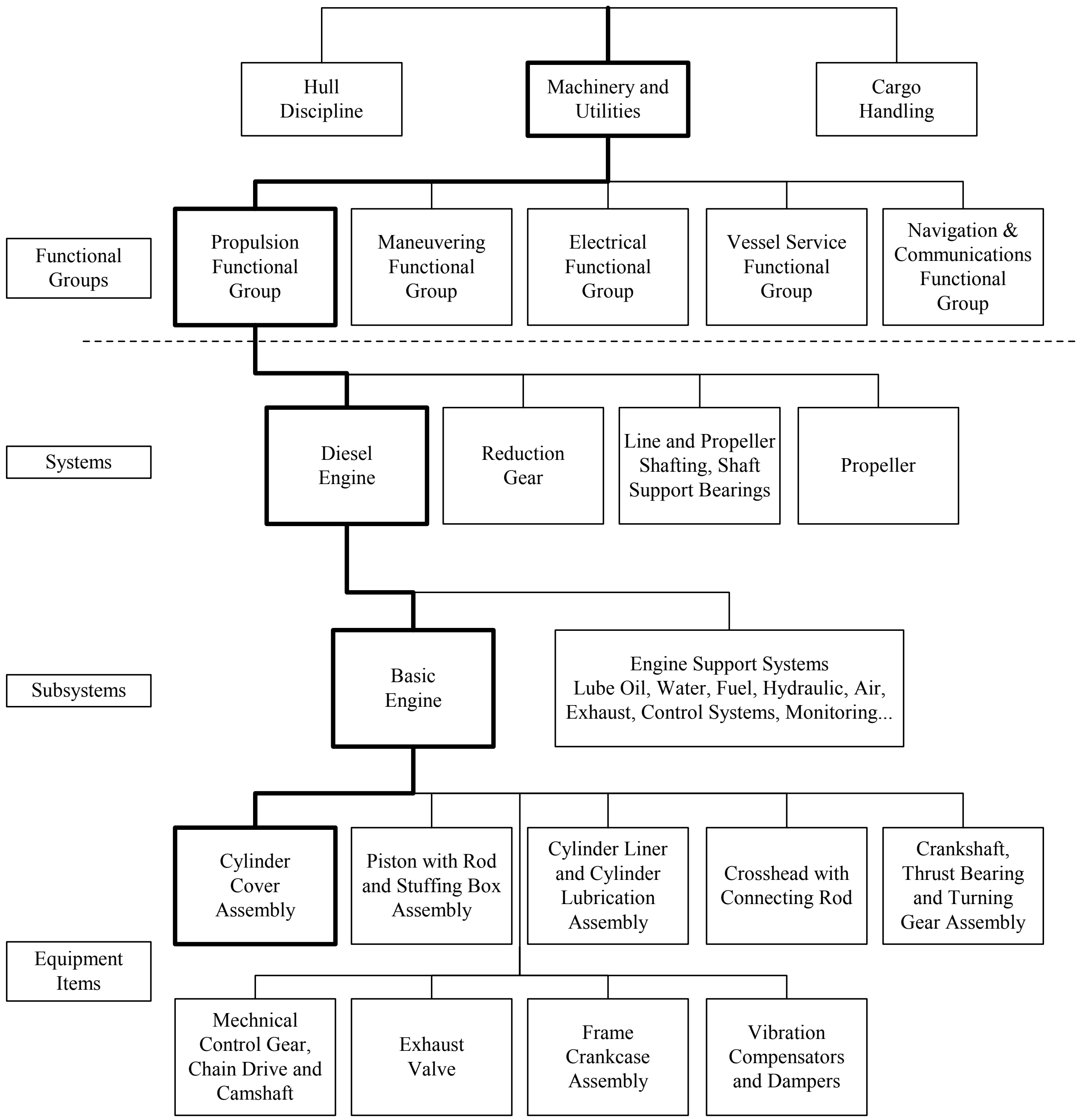
TABLE 2
Propulsion Functional Group Operating Characteristics

Operating Context of Propulsion Functional Group	
The propulsion system consists of a *Manufacturer's Name* Diesel Type *Model Number* low-speed diesel engine rated 16,860 kW maximum continuous rating (MCR) at 91 RPM, coupled directly to a shaft supported by one intermediate bearing and two stern tube bearings and driving a fixed-pitched propeller.	
Common Characteristics	**Operating Mode** **At Sea**
Environmental Parameters	Ambient air temperature design range: –29°C to 52°C, 25°C nominal Barometric air pressure (dry): 101.3 kPa absolute Seawater Inlet temperature: –2°C to 38°C, 32°C nominal
Manner of Use	Operate continuously 24 hours per day for up to 22 days at 85% MCR, 280 days per year Single engine installation Controllable from the bridge, centralized control station in machinery space and locally
Performance Capability	Required MCR power to be developed by the Propulsion Functional Group for propulsion: 16,860 kW at 91 RPM Fuel: Intermediate fuel oils IFO 380 and IFO 180 Reversible engine Propel ship at 20 knots up to Sea State 3 Conditions Maintain propulsion at following vessel angles of inclination: 15° static and 22.5° dynamic, athwartship 5° static and 7.5° dynamic, fore-and-aft Compliance with ABS Rules, SOLAS, MARPOL, etc.
	Other common characteristics associated with the line and propeller shafting, shaft support bearings and propeller not relevant to the diesel engine are also to be listed above if an RCM for the entire Functional Group is to be performed.

TABLE 3
Diesel Engine System Operating Characteristics, Modes and Context

<table>
<tr><th colspan="5">Operating Context of Diesel Engine</th></tr>
<tr><td colspan="5">The propulsion system consists of a Manufacturer Diesel Type Model Number low-speed diesel engine rated 16,860 kW Maximum Continuous Rating (MCR) at 91 RPM, coupled directly to a shaft supported by one intermediate bearing and two stern tube bearings, and driving a fixed pitched propeller. Two (2) conventional turbochargers Manufacturer and Model Number installed.</td></tr>
<tr><th rowspan="2">Common Characteristics</th><th colspan="4">Operating Modes</th></tr>
<tr><th>At Sea</th><th>Operating in Restricted Waters</th><th>Maneuvering in Port</th><th>Cargo Handling</th></tr>
<tr><td>Environmental Parameters</td><td>Nominal ambient air temperature: 25°C. Range from –29°C to 45°C
Barometric air press (dry) 101.3 kPa Absolute
Nominal seawater inlet temperature:
32°C, 2.0-2.5 bar. Range from –2°C to 50°C
Cooling FW nominal temperature:
25°C, 2.0-2.5 bar. Max. temp. 90°C
L.O. max. supply temp. 60°C,
4.3 bar with exception of Camshaft L.O. max. supply temp. 50°C, 4 bar
F.O. supply max. temp. 150°C at 4 bar.</td><td>Dependent on geographical location
If ports to visit are known, list environmental parameter ranges.</td><td>Dependent on geographical location
If ports to visit are known, list environmental parameter ranges</td><td>Not used</td></tr>
<tr><td>Manner of Use</td><td>Propels vessel at 20 knots at 85% of MCR. Capable of continuous operation of 24 hours per day for up to 22 days, 280 days per year. Single-engine installation</td><td>Propels vessel from 2 to 10 knots, with reversing and stopping capabilities for up to 72 hours maximum.</td><td>Propels vessel from 2 to 10 knots, with reversing and stopping capabilities, and assists in mooring for up to 4 hours maximum.</td><td>Not used</td></tr>
<tr><td>Performance Capability</td><td colspan="3">To output up to MCR of 16,860 kW @ 91 RPM; reversible to maximum speed of 63 RPM. Controllable from bridge, centralized control station in machinery space and locally.
Maintain propulsion at following vessel angles of inclination:
15° static and 22.5° dynamic, athwartship
5° static and 7.5° dynamic, fore-and-aft
Fuel: Intermediate fuel oils IFO 380 and IFO 180
Specific fuel consumption: 171 g/kW-hr maximum at 85% MCR
Fuel oil lower calorific value: 42707 kJ/kg or 10200 kcal/kg
Lube oil consumption, system oil: 9 kg/cylinder 24 hours
Cylinder oil: 1.1-1.6 g/kWh
Gases
Exhaust gas flow: 136200 kg/h, Exhaust gas temperature 250°C
Air consumption: 37.0 kg/s
Crankcase vapors: X kg/h
Controls signal, alarm, and readout details listed here along with parameters
Compliance with ABS Rules, SOLAS, MARPOL, etc.</td><td>Not Applicable</td></tr>
</table>

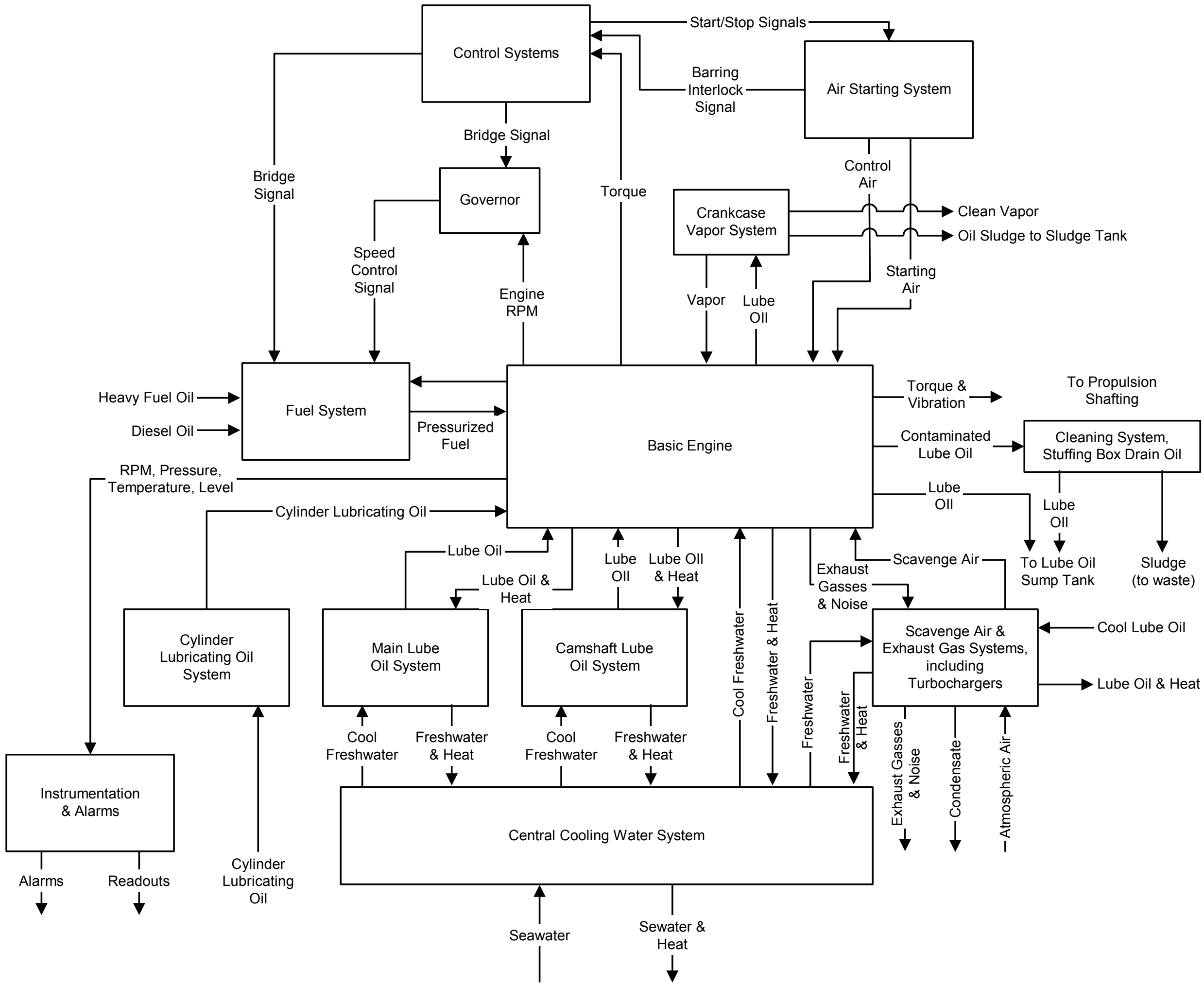
FIGURE 1
Example Partitioning Diagram



1.3 Develop System Block Diagrams, Identify Functions and Functional Failures

To identify the functions needed, the team first identifies the operating mode to be considered in the analysis. The "at-sea" operating mode is selected for this example analysis. Using the at-sea operating characteristics as a basis, a functional block flow diagram was developed for the propulsion functional group. Appendix 2, Figure 2 provides the portion of the functional block diagram for the low-speed diesel engine. This functional block diagram includes both primary and secondary functions for the engine.

FIGURE 2
Example System Block Diagram



The functional block diagram is used to identify the functions needed for the engine to properly operate at sea. The outputs from each functional block represent the functions that must be provided and are used to develop specific function statements. Each function statement must include a verb representing the functionality required, a noun on which the functionality is performed and performance parameters (when possible). Functional failures are then identified for each function statement. The functional failures include total and partial loss of each function. Partial losses of each function are determined by postulating deviations from each performance parameter in the function statement. Appendix 2, Table 4 provides an example of the functions and functional failures for the low-speed diesel engine.

TABLE 4
Example Function and Functional Failure List

Subsystem: Low speed diesel engine for main propulsion, driving a controllable pitch propeller

Function			*Functional Failure*	
Item No.	*Function Statement*	*Function Type*	*Item No.*	*Functional Failure Statement*
1	Transmit 16,860 kW of power at 91 rpm to the propulsion shafting	Primary	1.1	No transmission of power to the propulsion shafting
			1.2	Transmits less than 16,860 kW of power to the propulsion shafting
			1.3	Transmits more than 16,860 kW of power to the propulsion shafting
			1.4	Operates at less than 91 rpm (Reduce rpm)
			1.5	Operates at more than 91 rpm
2	Transmit 200 N-m of torque at 91 rpm to the control system	Primary	2.1	No transmission of torque to the control system
			2.2	Transmits less than 200 N-m of torque to the control system
			2.3	Transmits more than 200 N-m of torque to the control system
			2.4	Operates at less than 91 rpm
			2.5	Operates at more than 91 rpm
3	Meter fuel to engine at 171 g/kW-hr, at 4 bar pressure, and 150°C temperature (max.)	Primary	3.1	No metering of fuel to the engine
			3.2	Meters less than 171 g/kW-hr of fuel to the engine
			3.3	Meters more than 171 g/kW-hr of fuel to the engine
			3.4	Meters fuel to the engine at a pressure less than 4 bar
			3.5	Meters fuel to the engine at a pressure more than 4 bar
			3.6	Meters fuel to the engine at a temperature less than 50°C
			3.7	Meters fuel to the engine at a temperature more than 150°C
4	Flow 43.2 kg/s of combustion air to the engine at 1,000 mbar (inlet), 25°C temperature, and Z condition	Primary	4.1	No flow of combustion air
			4.2	Flows less than 43.2 kg/s of combustion air
			4.3	Flows more than 43.2 kg/s of combustion air
			4.4	Flows inlet combustion air at a pressure less than 800 mbar
			4.5	Flows inlet combustion air at a pressure more than 1,200 mbar
			4.6	Flows combustion air at a temperature less than 15°C
			4.7	Flows combustion air at a temperature more than 30°C
			4.8	Fails to condition combustion air (dry air)

TABLE 4 (continued)
Example Function and Functional Failure List

Function			*Functional Failure*	
Item No.	*Function Statement*	*Function Type*	*Item No.*	*Functional Failure Statement*
5	Exhaust engine gases and noise after the turbochargers are to be in the range 275 to 325°C and less than 100 decibels	Secondary	5.1	No exhausting of gases
			5.2	Exhausting gases to a location other than exhaust pipe outlet
			5.3	Exhaust gases are more than 325°C
			5.4	Exhaust gases are less than 275°C
			5.5	Exhaust gas noise level exceeds 100 decibels
6	Remove, separate and discharge X m^3/hr vapors from the engine crankcase	Secondary – Environmental	6.1	No removal or discharge of crankcase vapors
			6.2	Removes and discharges less than X m^3/hr crankcase vapors
			6.3	Removes and discharges more than X m^3/hr crankcase vapors
			6.4	No separation of lube oil, air, and oil sludge
			6.5	Inadequate separation of sludge from return oil
			6.6	Inadequate separation of return oil from sludge
			6.7	Inadequate separation of oil from air
			6.8	Inadequate separation of sludge from air
			6.9	Inadequate separation of air from oil
			6.10	Inadequate separation of air from sludge
7	Remove and clean contaminated lube oil and return cleaned lube oil to the lube oil sump tank	Secondary – Environmental	7.1	No removal of the contaminated lube oil
			7.2	Removes less than X m^3/hr of the contaminated lube oil
			7.3	Removes more than X m^3/hr of the contaminated lube oil
			7.4	Inadequate cleaning of the contaminated lube oil
			7.5	No return of cleaned lube oil to the lube oil sump tank
			7.6	Returns less than Y m^3/hr of cleaned lube oil to the lube oil sump tank
			7.7	Returns more than Y m^3/hr of cleaned lube oil to the lube oil sump tank
8	Contain and return fuel leakage to fuel storage	Secondary-Environmental	8.1	Fails to contain leaked fuel
			8.2	Fails to return leaked fuel
9	Remove and discharge 2,850 kW of heat from the engine	Secondary – Structural	9.1	No removal or discharge of heat from the engine
			9.2	Removes and discharges less than 2,850 kW of heat from the engine
			9.3	Removes and discharges more than 2,850 kW of heat from the engine
10	Provide vibration isolation between the engine and torsional coupling	Secondary – structural	10.1	Fails to isolate vibration

TABLE 4 (continued)
Example Function and Functional Failure List

Function			*Functional Failure*	
Item No.	*Function Statement*	*Function Type*	*Item No.*	*Functional Failure Statement*
11	Contain fuel	Secondary – Structural	11.1	Partial loss of containment of fuel
			11.2	Total loss of containment of fuel
12	Contain combustion air	Secondary – Structural	12.1	Partial loss of containment of combustion air
			12.2	Total loss of containment of combustion air
13	Contain engine vapors and combustion gases and pressure	Secondary – Structural	13.1	Partial loss of containment of engine vapors, combustion gases, and pressure
			13.2	Total loss of containment of engine vapors, combustion gases, and pressure
14	Contain exhaust gases	Secondary – Structural	14.1	Partial loss of containment of exhaust gases
			14.2	Total loss of containment of exhaust gases
15	Contain seawater	Secondary – Structural	15.1	Partial loss of containment of seawater
			15.2	Total loss of containment of seawater
16	Contain freshwater	Secondary – Structural	16.1	Partial loss of containment of freshwater
			16.2	Total loss of containment of freshwater
17	Contain lube oil	Secondary – Structural	17.1	Partial loss of containment of lube oil
			17.2	Total loss of containment of lube oil
18	Contain oil sludge	Secondary – Structural	18.1	Partial loss of containment of oil sludge
			18.2	Total loss of containment of oil sludge
19	Contain starting air	Secondary – Structural	19.1	Total loss of containment of starting air
			19.2	Partial loss of containment of starting air
20	Provide support for engine assemblies	Secondary – Structural	20.1	Inadequate support of engine assemblies
21	Maintain engine speed at a constant 91 rpm	Secondary – Control	21.1	Erratic control of engine rpm
			21.2	Controls engine speed at less than 91 rpm
			21.3	Controls engine speed at more than 91 rpm
22	Provide monitoring of engine and engine system pressures, temperature and rpm	Secondary – Control	22.1	No pressure readout
			22.2	False low pressure readout
			22.3	False high pressure readout
			22.4	No temperature readout
			22.5	False low temperature readout
			22.6	False high temperature readout
			22.7	No rpm readout
			22.8	False low rpm readout
			22.9	False high rpm readout

TABLE 4 (continued)
Example Function and Functional Failure List

Function			*Functional Failure*	
Item No.	*Function Statement*	*Function Type*	*Item No.*	*Functional Failure Statement*
23	Provide alarming on engine and engine system pressures, temperatures and tank levels	Secondary – Protection	23.1	No pressure alarms
			23.2	False low pressure alarm
			23.3	False high pressure alarm
			23.4	No temperature alarm
			23.5	False low temperature alarm
			23.6	False high temperature alarm
			23.7	No tank level alarm
			23.8	False low tank level alarm
			23.9	False high tank level alarm
24	Provide overspeed protection at 110 rpm	Secondary – Protection	24.1	No activation of protection
			24.2	Activation of protection at less than 110 rpm
			24.3	Activation of protection at more than 110 rpm
25	Provide monitoring of fuel rack position	Secondary – Protection	25.1	No indication of fuel rack position
			25.2	False indication of fuel rack position
26	Flow 400 m^3/hr of clean lubricant to the main engine and turbochargers at 4.3 bar and 45°C temperature to the main engine	Secondary – Protection	26.1	No flow of lubricant to the main engine
			26.2	Flows less than 400 m^3/hr of lubricant to the main engine and turbochargers
			26.3	Flows more than 400 m^3/hr of lubricant to the main engine and turbochargers
			26.4	Flows lubricant to the main engine and turbochargers at a pressure less than 3.5 bar
			26.5	Flows lubricant to the main engine and turbochargers at a pressure more than 5 bar
			26.6	Flows lubricant to the main engine and turbochargers at a temperature less than 40°C
			26.7	Flows lubricant to the main engine and turbochargers at a temperature more than 50°C
			26.8	Fails to adequately clean main engine and turbochargers lubricant
27	Flow lube oil at 400 m^3/hr from the main engine to the lube oil sump tank	Secondary – Protection	27.1	No flow of lubricant from the main engine to the lube oil sump tank
			27.2	Flows less than 400 m^3/hr flow of lubricant from the main engine to the lube oil sump tank
			27.3	Flows more than 400 m^3/hr flow of lubricant from the main engine to the lube oil sump tank
			27.4	Flows contaminated lubricant from the main engine to the lube oil sump tank

TABLE 4 (continued)
Example Function and Functional Failure List

Function			*Functional Failure*	
Item No.	*Function Statement*	*Function Type*	*Item No.*	*Functional Failure Statement*
28	Flow 10.3 m^3/hr of clean lubricant to the camshaft at 4 bar and 45°C temperature	Secondary – Protection	28.1	No flow of lubricant to the camshaft
			28.2	Flows less than 10.3 m^3/hr of lubricant to the camshaft
			28.3	Flows more than 10.3 m^3/hr of lubricant to the camshaft
			28.4	Flows lubricant to the camshaft at a pressure less than 3.5 bar
			28.5	Flows lubricant to the camshaft at a pressure more than 4.5 bar
			28.6	Flows lubricant to the camshaft at a temperature less than 40°C
			28.7	Flows lubricant to the camshaft at a temperature more than 50°C
			28.8	Fails to adequately clean camshaft lubricant
29	Engage the barring interlock	Secondary – Protection	29.2	Fails to engage barring interlock when demanded
			29.1	Engages barring interlock prematurely
			29.3	Fails to disengage barring interlock
30	Provide starting air at 0.75 m^3 and 30 bar pressure when demanded	Secondary-Protection	30.1	No starting air when demanded
			30.2	Flows less than 0.75 m^3 of starting air when demanded
			30.3	Flows more than 0.75 m^3 of starting air when demanded
			30.4	Flows starting air at a pressure less than 30 bar when demanded
			30.5	Flows starting air at a pressure more than 30 bar when demanded
			30.6	Stops flowing starting air when demanded
			30.7	Flows starting air prematurely
31	Prepare engine for maintenance while at sea	Secondary-Protection	31.1	Inability to bar the engine
			31.2	Incorrect barring position

1.4 Conducting the FMECA

The bottom-up failure modes, effects and criticality analysis (FMECA) approach is applied, using the Example Consequence/Severity Level Definitions in Appendix 2, Table 5, the Probability of Failure Criteria Example in Appendix 2, Table 6 and the Example Risk Matrix in Appendix 2, Table 7.

The example FMECA was performed on selected equipment items from the following systems represented in the partitioning diagrams in Appendix 2, Figure 1:

- *Basic engine.* cylinder liner, including cylinder lubrication passageways and cooling jacket
- *Governor system.* governor rpm input signal, governor bridge input signal, governor output linkages
- *Camshaft lubrication system.* camshaft lube oil pump (duty)

Appendix 2, Table 8 provides an example FMECA worksheet. This table contains a header that identifies the equipment item or component being evaluated and 12 major columns: *Item, Failure Mode, Causes, Failure Characteristic, Local Effects, Functional Failures, End Effects, Matrix, Severity, Current Likelihood, Current Risk* and *Failure Detection/Corrective Measures*. *Item* is used to link the equipment item or component with the failure mode under investigation. In this example, the cylinder liner is Equipment Item No. 3 and there have been eight failure modes identified, numbered 3.1, 3.2 … 3.8. *Matrix* identifies the consequence/severity level definition table, e.g., Propulsion, Loss of Containment, Safety and Explosion/Fire. The definitions for the remaining column headings are provided in Subsection 1/4.

TABLE 5
Example Consequence/Severity Level Definition Format

Severity Level	*Descriptions for Severity Level*	*Definition for Severity Level*	*Applicable to Functional Groups for*
1	Minor, Negligible,	Function is not affected, no significant operational delays. Nuisance.	Propulsion Directional Control Drilling Position Mooring (Station Keeping) Hydrocarbon Production and Processing Import and Export Functions
2	Major, Marginal, Moderate	Function is not affected, however, failure detection/corrective measures not functional. OR Function is reduced, resulting in operational delays.	
3	Critical, Hazardous, Significant	Function is reduced, or damaged machinery, significant operational delays	
4	Catastrophic, Critical	Complete loss of function	

TABLE 5 (continued)
Example Consequence/Severity Level Definition Format

Severity Level	*Descriptions for Severity Level*	*Definition for Severity Level*	*Applicable to Consequence Category of*
1	Minor, Negligible	Little or no response necessary	Loss of Containment
2	Major, Marginal, Moderate	Limited response of short duration	
3	Critical, Hazardous, Significant	Serious/significant commitment of resources and personnel	
4	Catastrophic, Critical	Complete loss of containment. Full scale response of extended duration to mitigate effects on environment.	

Severity Level	*Descriptions for Severity Level*	*Definition for Severity Level*	*Applicable to Consequence Category of*
1	Minor, Negligible	Minor impact on personnel/ No impact on public	Safety
2	Major, Marginal, Moderate	Professional medical treatment for personnel/No impact on public	
3	Critical, Hazardous, Significant	Serious injury to personnel/ Limited impact on public	
4	Catastrophic, Critical	Fatalities to personnel/Serious impact on public	

Severity Level	*Descriptions for Severity Level*	*Definition for Severity Level*	*Applicable to Consequence Category of*
1	Minor, Negligible	No damage to affected equipment or compartment, no significant operational delays.	Explosion/Fire
2	Major, Marginal, Moderate	Affected equipment is damaged, operational delays	
3	Critical, Hazardous, Significant	An occurrence adversely affecting the vessel's seaworthiness or fitness for service or route	
4	Catastrophic, Critical	Loss of vessel or results in total constructive loss	

TABLE 6
Probability of Failure (e.g., Frequency, Likelihood) Criteria Example Format

Likelihood Descriptor [(1)]	*Description*
Improbable	Fewer than 0.001 events/year
Remote	0.001 to 0.01 events/year
Occasional	0.01 to 0.1 events/year
Probable	0.1 to 1 events/year
Frequent	1 or more events/year

Note

1 See Subsection 6/3 for determining probability of failure.

TABLE 7
Risk Matrix Example Format

Severity Level	*Likelihood of Failure*				
	Improbable	*Remote*	*Occasional*	*Probable*	*Frequent*
4	Medium	High	High	High	High
3	Low	Medium	High	High	High
2	Low	Low	Medium	High	High
1	Low	Low	Low	Medium	Medium

TABLE 8
Example Bottom-up FMECA Worksheet

No.: 3	Description: Cylinder liner, including cylinder lubrication passageways and cooling jacket										
Item	**Failure Mode**	**Causes**	**Failure Charac-teristic**	**Local Effects**	**Functional Failures**	**End Effects**	**Matrix**	**Severity**	**Current Likelihood**	**Current Risk**	**Failure Detection/ Corrective Measures**
3.1	Leak in the cylinder liner between cooling water jacket and cylinder (evident)	Cylinder liner cracking Loss of cooling water in local areas causing liner overheating	Wear-in Random	Loss of compression in the affected cylinder, causing reduced engine performance Exhaust gases enter jacket cooling water system Cooling water leaking into cylinder, resulting in abnormal increase in freshwater makeup rate	Partial loss of containment of freshwater Transmits less than 16,860 kW of power at 91 rpm to the propulsion shafting	Propulsion is reduced, resulting in long vessel delays	Propulsion	Severity Level 3	Occasional	High	Jacket water expansion tank level will rise setting off high level alarm (engine operating) Cooling water pressure will fluctuate (standby and operation) Water will exit indicator cocks during blow-down prior to starting engine (standby)
3.2	Rupture of the cylinder liner	No credible cause									
3.3	Deformed/ damaged cylinder liner (e.g., badly scored/ scuffed) (evident)	Debris in the lube oil Normal liner wear Cylinder oil feed rate improperly adjusted (HE) Restricted cylinder oil passageways (hidden) (linked from 3.5) Degraded lube oil (e.g., improper lube oil viscosity or total base number)	Random Wear-out	Loss of compression of the affected cylinder, causing reduced engine performance Excessive consumption of cylinder lube oil during combustion	Transmits less than 16,860 kW of power at 91 rpm to the propulsion shafting Partial loss of containment of engine vapors, combustion gases and pressure	Propulsion is reduced, resulting in. long vessel delays	Propulsion	Severity Level 3	Occasional	High	Increased cylinder exhaust temperature Fire in scavenge air space Exhaust gas blow-by into scavenge air space

TABLE 8 (continued)
Example Bottom-up FMECA Worksheet

No.: 3	Description: Cylinder liner, including cylinder lubrication passageways and cooling jacket										
Item	**Failure Mode**	**Causes**	**Failure Charac-teristic**	**Local Effects**	**Functional Failures**	**End Effects**	**Matrix**	**Severity**	**Current Likelihood**	**Current Risk**	**Failure Detection/ Corrective Measures**
3.4	Worn cylinder liner (evident)	Normal use Cylinder oil feed rate improperly adjusted (HE) Degraded lube oil (e.g., improper lube oil viscosity or total base number) Under-cooling of scavenge air allowing condensation on cylinder liner and causing poor cylinder lube oil film	Wear-in Random Wear-out	Loss of compression in the affected cylinder, causing reduced engine performance Excessive consumption of lube oil during combustion	Transmits less than 16,860 kW of power at 91 rpm to the propulsion shafting Partial loss of containment of engine vapors, combustion gases and pressure	Propulsion is reduced, resulting in vessel delays	Propulsion	Severity Level 2	Occasional	Medium	Increased exhaust temperature level for affected cylinder Exhaust gas blow-by into scavenge air space
3.5	Restricted cylinder oil passage-ways (hidden)	Lube oil contaminants and carbon buildup	Random Wear-out	Uneven cylinder liner wear or "clover leafing"	Transmits less than 16,860 kW of power at 91 rpm to the propulsion shafting Partial loss of containment of engine vapors, combustion gases and pressure	Propulsion is reduced, resulting in long vessel delays	Propulsion	Severity Level 3	Occasional	High	Increased exhaust temperature level for affected cylinder Exhaust gas blow-by into scavenge air space

TABLE 8 (continued)
Example Bottom-up FMECA Worksheet

No.: 3	Description: Cylinder liner, including cylinder lubrication passageways and cooling jacket										
Item	**Failure Mode**	**Causes**	**Failure Charac-teristic**	**Local Effects**	**Functional Failures**	**End Effects**	**Matrix**	**Severity**	**Current Likelihood**	**Current Risk**	**Failure Detection/ Corrective Measures**
3.6	Fouled scavenge air port (evident)	Normal buildup of material from the exhaust gases	Random Wear-out	Insufficient air fed to the engine, resulting in inefficient combustion and excessive smoking of the engine	Transmits less than 16,860 kW of power at 91 rpm to the propulsion shafting Flows less than 43.2 kg/s of combustion air	Propulsion is reduced, resulting in vessel delays	Propulsion	Severity Level 2	Occasional	Medium	Increased exhaust temperature level for affected cylinder
3.7	External leak of the cooling water jacket (evident)	Improper treatment of the freshwater, causing accelerated corrosion Overheating of cooling water jacket Seal rings at bottom of cylinder liner leak, allowing cooling water into scavenge air space	Wear-in Random Wear-out	Release of cooling water to the atmosphere/scavenge air, resulting in excessive consumption of freshwater and potentially insufficient cooling water being delivered to the engine's cylinder	Removes and discharges less than 2,850 kW of heat from the engine Partial loss of containment of freshwater	Propulsion is reduced, resulting in long vessel delays	Propulsion	Severity Level 3	Remote	Medium	Release of water will alert operators to the failure
3.8	Restricted/ scaled cooling water jacket passage-ways (evident)	Improper treatment of the cooling water Debris in the cooling water	Random Wear-out	Overheating of cylinder, potentially resulting in the cylinder liner cracking and/or scoring of the liner	Transmits less than 16,860 kW of power at 91 rpm to the propulsion shafting	Propulsion is reduced, resulting in long vessel delays	Propulsion	Severity Level 3	Remote	Medium	Cylinder cooling water temperature will increase, potentially alerting the operator to the failure

TABLE 8 (continued)
Example Bottom-up FMECA Worksheet

No.: 12	**Description:** Governor rpm input signal										
Item	**Failure Mode**	**Causes**	**Failure Charac-teristic**	**Local Effects**	**Functional Failures**	**End Effects**	**Matrix**	**Severity**	**Current Likelihood**	**Current Risk**	**Failure Detection/ Corrective Measures**
12.1	Fails with no signal (evident)	Speed sensor failure Loose/broken wire connection Loss of control power	Random	Governor increases engine speed, resulting in overspeed protective device tripping and the engine stopping	Controls engine speed at more than 91 rpm No transmission of power to the propulsion shafting No transmission of torque to the control system	Complete loss of propulsion	Propulsion	Severity Level 4	Improbable	Medium	Overspeed protective device trips and stops the engine
12.2	Fails with a low signal (evident)	Speed sensor failure Loose/broken wire connection	Random	Governor increases engine speed, resulting in overspeed protective device tripping and the engine stopping	Controls engine speed at more than 91 rpm No transmission of power to the propulsion shafting No transmission of torque to the control system	Complete loss of propulsion	Propulsion	Severity Level 4	Improbable	Medium	Overspeed protective device trips and stops the engine

TABLE 8 (continued)
Example Bottom-up FMECA Worksheet

No.: 12	**Description:** Governor rpm input signal										
Item	**Failure Mode**	**Causes**	**Failure Charac-teristic**	**Local Effects**	**Functional Failures**	**End Effects**	**Matrix**	**Severity**	**Current Likelihood**	**Current Risk**	**Failure Detection/ Corrective Measures**
12.3	Fails with a high signal (evident)	Speed sensor failure	Random	Governor slows the engine down, resulting in reduced vessel speed or the engine shutting down	Controls engine speed at less than 91 rpm Transmits less than 16,860 kW of power to the propulsion shafting No transmission of power to the propulsion shafting Transmits less than 200 N-m of torque to the control system No transmission of torque to the control system	Function is reduced. resulting in operational delays	Propulsion	Severity Level 3	Improbable	Low	Officer on watch will notice reduction in engine speed
12.4	Fails to respond to an input change (evident)	Speed sensor failure Governor electronic failure	Random	Governor maintains engine at current speed, resulting in incorrect vessel speed	Controls engine speed at less than 91 rpm Transmits less than 16,860 kW of power to the propulsion shafting Controls engine speed at more than 91 rpm Transmits more than 16,860 kW of power to the propulsion shafting	Function is reduced or increased. resulting in operational delays	Propulsion	Severity Level 3	Improbable	Low	Officer on watch will notice engine speed is not as ordered

TABLE 8 (continued)
Example Bottom-up FMECA Worksheet

No.: 12 — **Description:** Governor rpm input signal

Item	Failure Mode	Causes	Failure Charac-teristic	Local Effects	Functional Failures	End Effects	Matrix	Severity	Current Likelihood	Current Risk	Failure Detection/ Corrective Measures
12.5	Erratic signal (evident)	Speed sensor failure Loose wire connection Governor electronic failure	Random	Erratic engine speed, resulting in erratic vessel speed	Controls engine speed at less than 91 rpm Transmits less than 16,860 kW of power to the propulsion shafting Controls engine speed at more than 91 rpm Transmits more than 16,860 kW of power to the propulsion shafting	Function is reduced or increased, resulting in operational delays	Propulsion	Severity Level 3	Improbable	Low	Officer on watch will notice engine speed is not as ordered

TABLE 8 (continued)
Example Bottom-up FMECA Worksheet

No.: 13 **Description:** Governor bridge input signal

Item	Failure Mode	Causes	Failure Charac-teristic	Local Effects	Functional Failures	End Effects	Matrix	Severity	Current Likelihood	Current Risk	Failure Detection/ Corrective Measures
13.1	Fails with no signal (evident)	Bridge control failure Loose/broken wire connection Governor electronic failure	Random	Governor reduces engine speed to zero (e.g., engine stops)	No transmission of power to the propulsion shafting No transmission of torque to the control system	Complete loss of propulsion	Propulsion	Severity Level 4	Remote	High	
13.2	Fails with a low signal (evident)	Bridge control failure Loose wire connection Governor electronic failure	Random	Governor reduces engine speed	Controls engine speed at less than 91 rpm Transmits less than 16,860 kW of power to the propulsion shafting Reduce rpm	Function is reduced, resulting in operational delays	Propulsion	Severity Level 3	Remote	Medium	
13.3	Fails with a high signal (evident)	Bridge control failure Governor electronic failure	Random	Governor increases engine speed, resulting in the overspeed protective device tripping and the engine stopping	Controls engine speed at more than 91 rpm No transmission of power to the propulsion shafting No transmission of torque to the control system	Complete loss of propulsion	Propulsion	Severity Level 4	Improbable	Medium	Overspeed protective device trips and stops the engine

TABLE 8 (continued)
Example Bottom-up FMECA Worksheet

No.: 13 | **Description:** Governor bridge input signal

Item	Failure Mode	Causes	Failure Charac-teristic	Local Effects	Functional Failures	End Effects	Matrix	Severity	Current Likelihood	Current Risk	Failure Detection/ Corrective Measures
13.4	Erratic signal (evident)	Bridge control failure Governor electronic failure Loose wire connection	Random	Erratic engine speed, resulting in erratic vessel speed	Controls engine speed at less than 91 rpm Transmits less than 16,860 kW of power to the propulsion shafting Controls engine speed at more than 91 rpm Transmits more than 16,860 kW of power to the propulsion shafting	Function is reduced or increased, resulting in operational delays	Propulsion	Severity Level 3	Improbable	Low	Officer on watch will notice engine speed is not as ordered

TABLE 8 (continued)
Example Bottom-up FMECA Worksheet

No.: 14 **Description:** Governor output linkages

Item	Failure Mode	Causes	Failure Charac-teristic	Local Effects	Functional Failures	End Effects	Matrix	Severity	Current Likelihood	Current Risk	Failure Detection/ Corrective Measures
14.1	Actuator fails to respond on demand (evident)	Governor electronic failure Internal actuator failure Broken linkage connection to actuator	Random Wear-out	No adjustment of engine speed, resulting in incorrect speed	Transmits less than 16,860 kW of power to the propulsion shafting Transmits more than 16,860 kW of power to the propulsion shafting Controls engine speed at less than 91 rpm Controls engine speed at more than 91 rpm	Function is reduced or increased, resulting in operational delays	Propulsion	Severity Level 3	Improbable	Low	Officer on watch will notice engine speed is not as ordered

TABLE 8 (continued)
Example Bottom-up FMECA Worksheet

No.: 14	**Description:** Governor output linkages										
Item	**Failure Mode**	**Causes**	**Failure Charac-teristic**	**Local Effects**	**Functional Failures**	**End Effects**	**Matrix**	**Severity**	**Current Likelihood**	**Current Risk**	**Failure Detection/ Corrective Measures**
14.2	Spurious response of actuator (evident)	Governor electronic failure Internal actuator failure	Random Wear-out	Erratic engine speed, resulting in erratic vessel speed	Controls engine speed at less than 91 rpm Transmits less than 16,860 kW of power to the propulsion shafting Controls engine speed at more than 91 rpm Transmits more than 16,860 kW of power to the propulsion shafting Erratic control of engine rpm	Function is reduced or increased, resulting in operational delays	Propulsion	Severity Level 3	Improbable	Low	Officer on watch will notice engine speed is not as ordered
14.3	Loosened output linkage (evident)	Engine vibration during normal use Wear between linkage parts over time	Random Wear-out	Incorrect adjustment of fuel rack, resulting in engine speed hunting Seizure of output linkage (evident)	Controls engine speed at less than 91 rpm Transmits less than 16,860 kW of power to the propulsion shafting Controls engine speed at more than 91 rpm Transmits more than 16,860 kW of power to the propulsion shafting	Function is reduced or increased, resulting in operational delays	Propulsion	Severity Level 3	Remote	Medium	Officer on watch will notice engine speed is not as ordered

TABLE 8 (continued)
Example Bottom-up FMECA Worksheet

No.: 14	Description: Governor output linkages										
Item	**Failure Mode**	**Causes**	**Failure Charac-teristic**	**Local Effects**	**Functional Failures**	**End Effects**	**Matrix**	**Severity**	**Current Likelihood**	**Current Risk**	**Failure Detection/ Corrective Measures**
14.4	Seizure of output linkage (evident)	Lack of routine lubrication of linkages Loosened output linkage (evident)	Random Wear-out	Failure to adjust fuel rack, resulting in improper engine speed	Controls engine speed at less than 91 rpm Transmits less than 16,860 kW of power to the propulsion shafting Controls engine speed at more than 91 rpm Transmits more than 16,860 kW of power to the propulsion shafting	Function is reduced or increased, resulting in operational delays	Propulsion	Severity Level 3	Remote	Medium	Officer on watch will notice engine speed is not as ordered
14.5	Fractured linkage (evident)	Lack of routine lubrication of linkages Manufacturing/ metallurgical flaws	Wear-in Random Wear-out	Failure to adjust fuel rack, resulting in improper engine speed	Controls engine speed at less than 91 rpm Transmits less than 16,860 kW of power to the propulsion shafting Controls engine speed at more than 91 rpm Transmits more than 16,860 kW of power to the propulsion shafting	Function is reduced or increased, resulting in operational delays	Propulsion	Severity Level 3	Remote	Medium	Officer on watch will notice engine speed is not as ordered

TABLE 8 (continued)
Example Bottom-up FMECA Worksheet

No.: 15 | **Description:** Camshaft lube oil pump (duty)

Item	Failure Mode	Causes	Failure Charac-teristic	Local Effects	Functional Failures	End Effects	Matrix	Severity	Current Likelihood	Current Risk	Failure Detection/ Corrective Measures
15.1	External leak/ rupture (evident)	Mechanical seal rupture/failure Pump housing gasket failure Pump housing erosion	Wear-in Random Wear-out	Release of lube oil in machinery space. If leak is large, standby pump will start.	Partial loss of containment of lube oil Total loss of containment of lube oil No flow of lubricant to the camshaft	Little or no response necessary	Loss of contain-ment	Severity Level 1	Remote	Low	Standby lube oil pump will start and resume function Oil spill tray around pump will collect and drain spilled lube oil
15.2	Fails off while running (evident)	Pump motor failure Pump seizure Pump motor control failure Pump coupling failure	Random Wear-out	Interruption of lubrication to the camshaft. The standby pump will start	None	No effect of interest					Standby lube oil pump will start and resume function
15.3	Fails to stop on demand (evident)	Defective motor controller or relay switch	Random Wear-out	Pump continues to operate	Flows more than 400 m^3/hr of lubricant to the main engine and turbochargers	No effect of interest					
15.4	Operates at degraded head/flow performanc e (evident)	Worn pump gears Leak/rupture of pump housing Suction blockage	Random Wear-out	Insufficient pressure or flow of lubricant to the camshaft, resulting in a low pressure alarm and standby pump started	Flows less than 400 m^3/hr of lubricant to the camshaft Flows lubricant to the camshaft at a pressure less than 3.5 bar	No effect of interest					Standby lube oil pump will start and resume function

1.5 Selecting a Failure Management Strategy

Using the information from the bottom-up FMECA, an appropriate failure management strategy is developed, referring to Subsection 7/5 and the RCM Task Selection Flow Diagram in Section 7, Figure 5.

The results of the maintenance task determinations are recorded in a tabular format. Appendix 2, Table 9 provides an example maintenance task selection worksheet developed from the FMECA in Appendix 2, Table 8. This maintenance task table contains 14 columns. The first 10 columns are copied from the FMECA table. The next four columns are: *Proposed Action(s), PL (Projected Likelihood), PR (Projected Risk)* and *Disposition*. The *Proposed Action(s)* lists the various failure management strategies either currently being applied or proposed to be applied to reduce the likelihood of the particular failure mode. *Disposition* is used to indicate whether the current maintenance strategies are retained or discontinued, if proposed strategies are not implemented, or any other related comments. The definitions for the remaining column headings are listed in Subsection 1/4.

The Task Selection Worksheet is organized by the Item No. for the Equipment Item and Failure Mode. Failure Modes that are considered unlikely in the FMECA are not listed. Some Failure Modes may require several failure management strategies to address all causes. Entries in *Disposition* may not be completed until the Summary of Maintenance Tasks is completed. See A2/1.6.

TABLE 9
Example Maintenance Task Selection Worksheet

No.: 3	Description: **Cylinder liner, including cylinder lubrication passageways and cooling jacket**												
Item	Failure Mode	Failure Char.	H/E[1]	Effects			Risk Characterization [2]			Task Selection [3]			
				Local	Functional failure[4]	End	S[5]	CL	CR	Proposed Action(s)	PL	PR	Disposition
3.1	Leak in the cylinder liner between cooling water jacket and cylinder	Wear-in Random	H	Loss of compression in the affected cylinder, causing reduced engine performance Exhaust gases enter jacket cooling water system Cooling water leaking into cylinder, resulting in abnormal increase in freshwater makeup rate	1.2, 16.1	Propul-sion is reduced result-ing in long vessel delays	Propul sion SL-3	Occa-sional	High	Hydrostatic pressure test the cylinder liner before each installation (ABS Rules 4-2-1/Table 2)	Remote	Medium	Required for all orders/ABS
										Metallurgical testing of cylinder liner to ensure correct properties (ABS Rules 4-2-1/Table 1)	Remote	Medium	Required for all orders/ABS
										Turn engine at least one revolution prior to starting, check if indicator valves on cylinders leaks fluid	Remote	Medium	In operating instructions
3.3	Deformed/ damaged cylinder liner (e.g., badly scored/ scuffed)	Random Wear-out	H	Loss of compression of the affected cylinder, causing reduced engine performance Excessive consumption of cylinder lube oil during combustion	1.2, 13.1	Propul-sion is reduced result-ing in long vessel delays	Propul sion SL-3	Occa-sional	High	Visual inspection of the cylinder liner with a borescope via the scavenge port – 2000 hr	Remote	Medium	

1 Abbreviations are: E is evident, H is hidden
2 Risk Characterization abbreviations are: S is severity; SL is severity level, CL is current likelihood; CR is current risk
3 Task Selection abbreviations are: PL is projected likelihood; PR is projected risk
4 Functional failure Item Nos. are listed in Appendix 3/Table 4
5 Severity Levels are listed in Appendix 3, Table 5

TABLE 9 (continued)
Example Maintenance Task Selection Worksheet

No.: 3		Description: **Cylinder liner, including cylinder lubrication passageways and cooling jacket**											
Item	Failure Mode	Failure Char.	H/E	Effects			Risk Characterization (1)			Task Selection (2)			
				Local	Functional failure	End	S	CL	CR	Proposed Action(s)	PL	PR	Disposition
3.4	Worn cylinder liner	Wear-in Random Wear-out	H	Loss of compression in the affected cylinder, causing reduced engine performance Excessive consumption of lube oil during combustion	1.2, 13.1	Propul-sion is reduced result-ing in vessel delays	Propul sion SL- 2	Occa-sional	Medium	Visual inspection of the cylinder liner with a borescope via the scavenge port – 2000 hr	Remote	Medium	
										Recondition the cylinder liner – 8000 hr	Remote	Low	
3.5	Restricted cylinder oil passage-ways	Random Wear-out	H	Uneven cylinder liner wear or "clover leafing"	1.2, 13.1	Propul-sion is reduced result-ing in long vessel delays	Propul sion SL- 3	Occa-sional	High	Preventative Maintenance plan for lube oil service system	Remote	Medium	Develop detailed instructions for this task

TABLE 9 (continued)
Example Maintenance Task Selection Worksheet

No.: 3		Description: **Cylinder liner, including cylinder lubrication passageways and cooling jacket**											
Item	Failure Mode	Failure Char.	H/E	Effects			Risk Characterization (1)			Task Selection (2)			
				Local	Functional failure	End	S	CL	CR	Proposed Action(s)	PL	PR	Disposition
3.6	Fouled scavenge air port	Random Wear-out	H	Insufficient air fed to the engine, resulting in inefficient combustion and excessive smoking of the engine	1.2, 4.2	Propul-sion is reduced, resulting in vessel delays	Propul sion SL-2	Occa-sional	Medium	Clean the scavenge air ports-4000 hr	Remote	Low	
3.7	External leak of the cooling water jacket	Wear-in Random Wear-out	E	Release of cooling water to the atmosphere/scavenge air, resulting in excessive consumption of freshwater and potentially insufficient cooling water being delivered to the engine's cylinder	9.2, 16.1	Propul-sion is reduced, resulting in long vessel delays	Propul sion SL-3	Remote	Medium	Cooling water analysis-1000 hr	Remote	Medium	
										Clean the freshwater cooling system-8000 hr	Remote	Medium	
3.8	Restricted/ scaled cooling water jacket passage-ways	Random Wear-out	E	Overheating of cylinder, potentially resulting in the cylinder liner cracking and/or scoring of the liner	1.2	Propul-sion is reduced, resulting in long vessel delays	Propul sion SL-3	Remote	Medium	Cooling water analysis-1000 hr	Remote	Medium	
										Clean the freshwater cooling system-8000 hr	Remote	Medium	

TABLE 9 (continued)
Example Maintenance Task Selection Worksheet

No.: 12		Description: **Governor rpm input signal**											
Item	Failure Mode	Failure Char.	H/E	Effects			Risk Characterization (1)			Task Selection (2)			
				Local	Functional failure	End	S	CL	CR	Proposed Action(s)	PL	PR	Disposition
12.1	Fails with no signal	Random	E	Governor increases engine speed, resulting in overspeed protective device tripping and the engine stopping	1.1, 2.1, 21.3	Complete loss of propulsion	Propul sion SL-4	Improb-able	Medium	Functional check of overspeed device-8000 hr	Improb-able	Medium	
										Functional check of speed setting system, engine with bridge control system-4000 hr	Improb-able	Medium	
12.2	Fails with a low signal	Random	E	Governor increases engine speed, resulting in overspeed protective device tripping and the engine stopping	1.1, 2.1, 21.3	Complete loss of propulsion	Propul sion SL-4	Improb-able	Medium	Functional check of overspeed device-8000 hr	Improb-able	Medium	
										Functional check of speed setting system, engine with bridge control system-4000 hr	Improb-able	Medium	

TABLE 9 (continued)
Example Maintenance Task Selection Worksheet

No.: 12		Description: **Governor rpm input signal**												
Item	Failure Mode	Failure Char.	H/E	Effects			Risk Characterization (1)			Task Selection (2)				
				Local	Functional failure	End	S	CL	CR	Proposed Action(s)	PL	PR	Disposition
12.3	Fails with a high signal	Random	E	Governor slows the engine down, resulting in reduced vessel speed or the engine shutting down	1.1, 1.2, 2.1, 2.2, 21.2	Function is reduced, resulting in operational delays	Propul-sion SL-3	Improb-able	Low	Functional check of speed setting system, engine with bridge control system-4000 hr	Improb-able	Low	
12.4	Fails to respond to an input change	Random	E	Governor maintains engine at current speed, resulting in incorrect vessel speed	1.2, 1.3, 21.2, 21.3	Function is reduced or increased, resulting in operational delays	Propul-sion SL-3	Improb-able	Low	Functional check of speed setting system, engine with bridge control system-4000 hr	Improb-able	Low	
12.5	Erratic signal	Random	E	Erratic engine speed, resulting in erratic vessel speed	1.2, 1.3, 21.2, 21.3	Function is reduced or increased, resulting in operational delays	Propul-sion SL-3	Improb-able	Low	Functional check of speed setting system, engine with bridge control system-4000 hr	Improb-able	Low	

TABLE 9 (continued)
Example Maintenance Task Selection Worksheet

No.: 13		Description: **Governor bridge input signal**											
Item	Failure Mode	Failure Char.	H/E	Effects			Risk Characterization (1)			Task Selection (2)			
				Local	Functional failure	End	S	CL	CR	Proposed Action(s)	PL	PR	Disposition
13.1	Fails with no signal	Random	E	Governor reduces engine speed to zero (e.g., engine stops)	1.1, 2.1	Complete loss of propulsion	Propulsion SL-4	Remote	High	Functional check of speed setting system, engine with bridge control system-4000 hr	Improbable	Medium	
13.2	Fails with a low signal	Random	E	Governor reduces engine speed	1.2, 21.2	Function is reduced, resulting in operational delays	Propulsion SL-3	Remote	Medium	Functional check of speed setting system, engine with bridge control system-4000 hr	Improbable	Medium	
13.3	Fails with a high signal	Random	E	Governor increases engine speed, resulting in the overspeed protective device tripping and the engine stopping	1.2, 2.1, 21.3	Complete loss of propulsion	Propulsion SL-4	Improbable	Medium	Functional check of overspeed device-8000 hr	Improbable	Medium	
										Functional check of speed setting system, engine with bridge control system-4000 hr	Improbable	Medium	
13.4	Erratic signal	Random	E	Erratic engine speed, resulting in erratic vessel speed	1.2, 1.3, 21.2, 21.3	Function is reduced or increased, resulting in operational delays	Propulsion SL-3	Improbable	Low	Functional check of speed setting system, engine with bridge control system-4000 hr	Improbable	Low	

TABLE 9 (continued)
Example Maintenance Task Selection Worksheet

No.: 14		Description: **Governor output linkages**												
Item	Failure Mode	Failure Char.	H/E	Effects			Risk Characterization [1]			Task Selection [2]				
				Local	Functional failure	End	S	CL	CR	Proposed Action(s)	PL	PR	Disposition
14.1	Actuator fails to respond on demand	Random Wear-out	E	No adjustment of engine speed, resulting in incorrect speed	1.2, 1.3, 21.2, 21.3	Function is reduced or increased, resulting in operational delays	Propul-sion SL-3	Improb-able	Low	Inspect and lubricate linkages-4000 hr	Improb-able	Low	
										Change governor oil-4000 hr	Improb-able	Low	Considered lube oil analysis, not practical
										Functional check of speed setting system, engine with bridge control system-4000 hr	Improb-able	Low	
14.2	Spurious response of actuator	Random Wear-out	E	Erratic engine speed, resulting in erratic vessel speed	1.2, 1.3, 21.1, 21.2, 21.3	Function is reduced or increased, resulting in operational delays	Propul-sion SL-3	Improb-able	Low	Inspect and lubricate linkages-4000 hr	Improb-able	Low	
										Functional check of speed setting system, engine with bridge control system-4000 hr	Improb-able	Low	
14.3	Loosened output linkage	Random Wear-out	E	Incorrect adjustment of fuel rack, resulting in engine speed hunting Seizure of output linkage	1.2, 1.3, 21.2, 21.3	Function is reduced or increased, resulting in operational delays	Propul-sion SL-3	Remote	Medium	Inspect and lubricate linkages-4000 hr	Improb-able	Low	
										Change governor oil-4000 hr	Improb-able	Low	Considered lube oil analysis, not practical

TABLE 9 (continued)
Example Maintenance Task Selection Worksheet

No.: 14	Description: **Governor output linkages**													
Item	Failure Mode	Failure Char.	H/E	Effects			Risk Characterization (1)			Task Selection (2)				
				Local	Functional failure	End	S	CL	CR	Proposed Action(s)	PL	PR	Disposition
14.4	Seizure of output linkage	Random Wear-out	E	Failure to adjust fuel rack, resulting in improper engine speed	1.2, 1.3, 21.2, 21.3	Function is reduced or increased, resulting in operational delays	Propulsion SL-3	Remote	Medium	Inspect and lubricate linkages-4000 hr	Improbable	Low	
										Change governor oil-4000 hr	Improbable	Low	Considered lube oil analysis, not practical
14.5	Fractured linkage	Wear-in Random Wear-out	E	Failure to adjust fuel rack, resulting in improper engine speed	1.2, 1.3, 21.2, 21.3	Function is reduced or increased, resulting in operational delays	Propulsion SL-3	Remote	Medium	Inspect and lubricate linkages-4000 hr	Improbable	Low	
										Change governor oil-4000 hr	Improbable	Low	Considered lube oil analysis, not practical

TABLE 9 (continued)
Example Maintenance Task Selection Worksheet

No.: 15		Description: **Camshaft lube oil pump (duty)**												
Item	Failure Mode	Failure Char.	H/E	Effects			Risk Characterization (1)			Task Selection (2)				
				Local	Functional failure	End	S	CL	CR	Proposed Action(s)	PL	PR	Disposition	
15.1	External leak/ rupture	Wear-in Random Wear-out	E	Release of lube oil in machinery space. If leak is large, standby pump will start.	17.1, 17.2, 26.1, 26.2, 26.4	Little or no response necessary	Loss of contain ment SL-1	Remote	Low	None			Run-to-failure	
15.2	Fails off while running	Random Wear-out	E	Interruption of lubrication to the camshaft. The standby pump will start	26.1	No effect	Propulsion SL-1	Remote	Low	Functional test of the standby pump and pump controls-1000 hrs	Improb-able	Low	Duty pump run continuously until failure Include this task in the standby pump task list	
15.4	Operates at degraded head/flow perform-ance	Random Wear-out	E	Insufficient pressure or flow of lubricant to the camshaft, resulting in a low pressure alarm and standby pump started	26.2, 26.4	No effect	Propulsion SL-1	Remote	Low	Functional test of the standby pump and pump controls-1000 hrs	Improb-able	Low		

1.6 Summary of Maintenance Tasks

The maintenance tasks selected for the failure modes listed for the equipment items/components in Appendix 2, Table 9 may be repeated. Accordingly, those maintenance tasks for an equipment item or component listed several times in the maintenance task selection worksheet are consolidated to a single task listing with a reference to the applicable Item Nos. for the equipment item/component and various Failure Modes in Appendix 2, Table 10, “Summary of Maintenance Tasks”. The maintenance tasks will need to be allocated in accordance with where the maintenance can be performed (e.g., onboard, at the dock by equipment vendors or in a dry dock facility). For this example, we have created a separate Table for each *Maintenance Category*. The *Task Type* is to be identified using the format in 2/4.6.5 of the *ABS Guide for Survey Based on Reliability-centered Maintenance*. The *Current Risk* and the *Projected Risk* are listed for comparison to determine the risk reduction as a result of the implementation of the proposed maintenance tasks. If the risk varies for two or more failure modes for a given task, the highest risk is to be listed. A *Procedure No. or Class Reference* column is provided to list equipment vendors’ procedures or ABS Rules requirements by reference number. The *Comments* column is used to record notes concerning the task, how the frequency was determined if several frequencies were proposed for the same task, and any other information. See Subsection 7/5.2.

TABLE 10
Summary of Maintenance Tasks

Maintenance Category[1]:	**Category A**
Functional Group:	**Propulsion**
System:	**Diesel Engine**
Equipment Item:	**Basic Engine**
Component:	**Cylinder liner, including cylinder lubrication passageways and cooling jacket**

Task	*Task Type[2]*	*Item No.*	*Risk*		*Frequency*	*Procedure No. or Class Reference*	*Comments*
			Current	*Projected*			
Turn engine at least one revolution prior to starting, check if indicator valves on cylinders leaks fluid	AAET	3.1	High	Medium	Perform before engine startup	*List the Task Procedure No. or Operating Instruction No. here*	
Visual inspection of the cylinder liner with a borescope via the scavenge port	CM	3.3, 3.4,	High	Medium	2000 hr		Inspection is to detect corrosion, erosion, cracking and plugging
Preventative Maintenance plan for lube oil service system	PM	3.5	High	Medium	8000 hrs		Develop detailed procedures for this task
Clean the scavenge air ports	PM	3.6	Medium	Low	4000 hr		May be required sooner based on results of inspection of cylinder liner
Cooling water analysis	CM	3.7, 3.8	Medium	Medium	1000 hr		Use results for water treatment as necessary
Clean the freshwater cooling system	PM	3.7, 3.8	Medium	Medium	8000 hr		
Recondition the cylinder liner	PM	3.4	Medium	Low	8000 hr		To restore honing pattern to cylinder walls and therefore ability to hold lube oil

1 Category A – Can be undertaken at sea by the vessel's personnel
Category B – Must be undertaken alongside by equipment vendors or with use of dockside facilities
Category C – Must be undertaken in a dry dock facility

2 CM – Condition monitoring
PM – Planned maintenance
FF – Failure finding
AAET – Any applicable and effective task
OTC – One time change

TABLE 10 (continued)
Summary of Maintenance Tasks

Maintenance Category[1]: **Category B**
Functional Group: **Propulsion**
System: **Diesel Engine**
Equipment Item: **Basic Engine**
Component: **Cylinder liner, including cylinder lubrication passageways and cooling jacket**

Task	*Task Type[2]*	*Item No.*	*Risk*		*Frequency*	*Procedure No. or Class Reference*	*Comments*
			Unmitigated	*Mitigated*			
Hydrostatic pressure test the cylinder liner before each installation	FF	3.1	High	Medium	Perform before installation	ABS Rules 4-2-1/Table 2	To ensure no cracks or porosity in cylinder liner
Metallurgical testing of cylinder liner to ensure correct properties	OTC	3.1	High	Medium	Perform at time of manufacture	ABS Rules 4-2-1/Table 1	

Maintenance Category[1]: **Category A**
Functional Group: **Propulsion**
System: **Diesel Engine**
Equipment Item: **Engine Support – Lube Oil**
Component: **Camshaft Lube Oil Pump (standby)**

Task	*Task Type[2]*	*Item No.*	*Risk*		*Frequency*	*Procedure No. or Class Reference*	*Comments*
			Unmitigated	*Mitigated*			
Functional test of the standby pump and pump controls	FF	15.2, 15.4	Low	Low	1000 hrs		This duty pump's operating context is to run until a failure occurs, then standby is started.

1 Category A – Can be undertaken at sea by the vessel's personnel
Category B – Must be undertaken alongside by equipment vendors or with use of dockside facilities
Category C – Must be undertaken in a dry dock facility

2 CM – Condition monitoring
PM – Planned maintenance
FF – Failure finding
AAET – Any applicable and effective task
OTC – One time change

TABLE 10 (continued)
Summary of Maintenance Tasks

Maintenance Category[1]: **Category A**
Functional Group: **Propulsion**
System: **Diesel Engine**
Equipment Item: **Engine Support-Control**
Component: **Governor**

Task	*Task Type[2]*	*Item No.*	*Risk*		*Frequency*	*Procedure No. or Class Reference*	*Comments*
			Unmitigated	*Mitigated*			
Functional check of overspeed device	FF	12.1, 12.2, 13.3	Medium	Medium	8000 hr	*List the Task Procedure No. or Operating Instruction No. here*	
Functional check of speed setting system, engine with bridge control system	FF	12.1, 12.2, 12.3, 12.4, 13.1, 13.2, 13.3, 13.4, 14.1, 14.2	High	Medium	4000 hr		
Inspect and lubricate linkages	PM	14.1, 14.2, 14.3, 14.4, 14.5	Medium	Low	4000 hr		
Change governor oil	PM	14.1, 14.3, 14.4, 14.5	Low	Low	4000 hr		Lube oil analysis was considered

1 Category A – Can be undertaken at sea by the vessel's personnel
Category B – Must be undertaken alongside by equipment vendors or with use of dockside facilities
Category C – Must be undertaken in a dry dock facility

2 CM – Condition monitoring
PM – Planned maintenance
FF – Failure finding
AAET – Any applicable and effective task
OTC – One time change

1.7 Summary of Spares Holding Determination

From those tasks listed in Appendix 2, Table 10, "Summary of Maintenance Tasks" that require spare parts or any other consumables necessary to perform the maintenance or test, a Summary of Spares Holding Determination is created as shown in Appendix 2, Table 11. This table is arranged similarly to the Summary of Maintenance Tasks with the exception that information related to a *Stock-out Effect*, the *Risk due to stock-out* and *Spare Parts Identification* are listed. The Spares Holding Decision Flow Diagram is shown in Section 7, Figure 6 and the spares holding considerations described in Paragraph 7/5.3.

Spare Parts required for Category A maintenance (undertaken at sea by vessel's personnel) are listed. For Category B maintenance, no listings are provided because the hydrostatic and metallurgical tests would be performed by the vendor.

TABLE 11
Summary of Spares Holding Determination

Maintenance Category[(1)]:: **Category A**
Functional Group: **Propulsion**
System: **Diesel Engine**
Equipment Item: **Basic Engine**
Component: **Cylinder liner, including cylinder lubrication passageways and cooling jacket**

Task	*Task Type*[(2)]	*Item No.*	*Stock-out Effect*	*Risk due to stock-out* *Order parts before demand*	*Hold parts*	*Revise/Review RCM Tasks*	*Procedure No. or Class Reference*	*Spare Parts Identification*
Visual inspection of the cylinder liner with a borescope via the scavenge port	CM	3.3, 3.4,	Yes		Medium		*List the Task Procedure No. or Operating Instruction No. here*	*List Spare parts identification data here* Parts and equipment necessary for borescope inspection
Preventative Maintenance plan for lube oil service system	PM	3.5	Yes	Medium				Parts and equipment necessary for tasks
Clean the scavenge air ports	PM	3.6	Yes		Medium			Parts and equipment necessary for cleaning
Cooling water analysis	CM	3.7, 3.8	Yes		Medium			Parts and equipment necessary for analysis
Clean the freshwater cooling system	PM	3.7, 3.8	Yes	Medium				Parts and equipment necessary for cleaning
Recondition the cylinder liner	PM	3.4	Yes	Medium				Parts and equipment necessary for tasks

1 Category A – Can be undertaken at sea by the vessel's personnel
Category B – Must be undertaken alongside by equipment vendors or with use of dockside facilities
Category C – Must be undertaken in a dry dock facility

2 CM – Condition monitoring
PM – Planned maintenance
FF – Failure finding
AAET – Any applicable and effective task
OTC – One time change

TABLE 11 (continued)
Summary of Spares Holding Determination

Maintenance Category[1]:: **Category A**
Functional Group: **Propulsion**
System: **Diesel Engine**
Equipment Item: **Engine Support-Control**
Component: **Governor**

Task	*Task Type[2]*	*Item No.*	*Stock-out Effect*	*Risk due to stock-out*			*Procedure No. or Class Reference*	*Spare Parts Identification*
				Order parts before demand	*Hold parts*	*Revise/Review RCM Tasks*		
Functional check of overspeed device	FF	12.1, 12.2, 13.3	Yes	Medium				Parts and equipment necessary for tasks
Functional check of speed setting system, engine with bridge control system	FF	12.1, 12.2, 12.3, 12.4, 13.1, 13.2, 13.3, 13.4, 14.1, 14.2	Yes	Medium				Parts and equipment necessary for tasks
Inspect and lubricate linkages	PM	14.1, 14.2, 14.3, 14.4, 14.5	Yes	Low				
Change governor oil	PM	14.1, 14.3, 14.4, 14.5	No					

1 Category A – Can be undertaken at sea by the vessel's personnel
Category B – Must be undertaken alongside by equipment vendors or with use of dockside facilities
Category C – Must be undertaken in a dry dock facility

2 CM – Condition monitoring
PM – Planned maintenance
FF – Failure finding
AAET – Any applicable and effective task
OTC – One time change

2 Supplemental RCM Analysis Results

Upon completion of the RCM analysis, additional analyses may be conducted to assess what types of maintenance tasks are to be performed and how the risk will be affected.

2.1 Review of RCM Analysis Results

This example RCM analysis of the basic engine (cylinder liner), the governor system (two input signals and output linkages) and the camshaft lubrication system [lube oil pump (duty)] identified 13 tasks to be performed to prevent or detect the listed failure modes. In addition, one one-time change was also developed (see Appendix 2, Table 10) and one run-to-failure maintenance strategy was accepted (see Appendix 2, Table 9, Item 15.1).

Appendix 2, Table 12 provides a breakdown of maintenance tasks by task type. For a larger analysis, we would expect on-condition-monitoring tasks to have the highest percentage of the tasks. However, because of the components chosen for this example, planned-maintenance tasks predominate.

The one-time change addresses verification of metallurgical properties for the engine cylinder liner.

TABLE 12
Breakdown of Maintenance Tasks

Task Type	*Number of Tasks*	*Percentage of Tasks*
Condition monitoring	2	13
Planned maintenance	6	40
Failure finding	4	27
Any applicable and effective	1	7
Run-to-failure	1	7
Surveillance	0	0
Servicing	0	0
One time change	1	7

2.2 Analysis of Risk Reduction

The benefits of employing the suggested maintenance tasks and one-time changes can be seen in the anticipated reduction in risk. Appendix 2, Tables 13 and 14 summarize the risk associated with the example analysis for each of the two types of losses analyzed (e.g., propulsion and loss of containment). The number in the matrix cells indicates the number of loss events with the cell's corresponding frequency and severity. CR indicates the number of Current Risk events, and PR indicates the number of Projected Risk events. The data in Appendix 2, Tables 13 and 14 are obtained from Appendix 2, Table 9. The Current Risk and the Projected Risk for each failure mode is tabulated. For cases where several tasks are selected for a failure mode, the task with the highest risk is used in the tables. From the example analysis, it can be seen from a qualitative aspect that there will be a reduction in overall risk by applying the selected maintenance tasks.

The risk reduction from a quantitative aspect can best be estimated in the following manner. Appendix 2, Tables 15 and 16 provide the current frequency, projected frequency and frequency reduction for the two types of losses evaluated. Because the frequency categories are ranges, ranges with an upper and lower bound represent the frequencies. These tables were developed from the data presented in Appendix 2, Tables 13 and 14.

To determine the frequency reduction for Severity Level 4 for Propulsion in Appendix 2, Table 15, we refer to the Severity Level 4 row in Appendix 2, Table 13. To calculate the Current Events/yr upper bound in Appendix 2, Table 15, Severity Level 4, we note there is one Current Risk in the "Remote" column and three Current Risks in the "Improbable" column of Appendix 2, Table 13. The frequency range for Remote is 0.001 to 0.01 events/yr and for Improbable, <0.001 events/yr. The Current Events/yr upper bound is 1 * (0.01) + 3 * (0.001) = 0.013 and Current Events/yr lower bound is 1 * (0.001) + 3 * (0.000) = 0.001. The Projected Events/yr is calculated similarly. The Frequency reduction is determined by subtracting the Projected Events/yr from the Current Events/yr for the upper bound and for the lower bound. For Severity Level 4, the proposed maintenance tasks are projected to reduce the frequency of a Severity Level 4 event by 0.001 to 0.009 events/yr. If an economic value is assigned to the Severity Level, an annual economic risk reduction can be estimated.

TABLE 13
Propulsion Category Risk Matrix

Severity Level	*Likelihood of Failure*				
	Improbable	*Remote*	*Occasional*	*Probable*	*Frequent*
4	**PR – 4, CR – 3**	**CR – 1**			
3	**PR – 10, CR – 6**	**PR – 5, CR – 6**	**CR – 3**		
2		**PR – 2**	**CR – 2**		
1	**PR – 2**	**CR – 2**			

TABLE 14
Loss of Containment Risk Matrix

Severity Level	*Likelihood of Failure*				
	Improbable	*Remote*	*Occasional*	*Probable*	*Frequent*
4					
3					
2					
1		**PR – 1, CR – 1**			

Risk	*Shade*
High	
Medium	
Low	

TABLE 15
Expected Event Frequencies for Propulsion

		Severity Categories			
		Severity Level 1	*Severity Level 2*	*Severity Level 3*	*Severity Level 4*
Current Events/yr	*Upper Bound*	0.02	0.2	0.366	0.013
	Lower Bound	0.002	0.02	0.036	0.001
Projected Events/yr	*Upper Bound*	0.002	0.02	0.06	0.004
	Lower Bound	0	0.002	0.005	0.0
Frequency Reduction Events/yr	*Upper Bound*	0.018	0.18	0.306	0.009
	Lower Bound	0.002	0.018	0.031	0.001

TABLE 16
Expected Event Frequencies for Loss of Containment

		Severity Categories			
		Severity Level 1	*Severity Level 2*	*Severity Level 3*	*Severity Level 4*
Current Events/yr	*Upper Bound*	0.01			
	Lower Bound	0.001			
Projected Events/yr	*Upper Bound*	0.01			
	Lower Bound	0.001			
Frequency Reduction Events/yr	*Upper Bound*	0			
	Lower Bound	0			

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