

Guide for

Surveys Based on Machinery Reliability and Maintenance Techniques



January 2023



GUIDE FOR

...
**SURVEYS BASED ON MACHINERY RELIABILITY AND
MAINTENANCE TECHNIQUES
JANUARY 2023**

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Foreword (2023)

The mission of the American Bureau of Shipping (ABS) is to serve the public interest, as well as the needs of its clients, by promoting the security of life, property, and the natural environment. This is primarily accomplished through the development and verification of standards for the design, construction and operational maintenance of marine and offshore facilities. These standards or Rules are established from principles of naval architecture, marine engineering and other engineering principles that have been proven satisfactory by service experience and systematic analysis.

Marine and offshore operators are striving towards improved operational effectiveness and efficiency. To achieve this end requires a focus on maximizing uptime, establishing quantitative condition assessment, and improving the overall safety, planning, operations, maintenance and repair processes. This is accomplished with a lifecycle process executing operations and maintenance in a continuous improvement cycle. This cycle aims at improving asset operations with a balanced criticality and risk-based approach.

The Guidelines presented herein offer ABS clients methodologies for achieving classification notations applied to machinery reliability and maintenance management programs. This Guide describes the process and responsibilities for ABS review of design submittals, analysis processes, and resulting maintenance plans as applicable throughout lifecycle stages. The methodology presented relies heavily on risk and reliability assessment techniques as a way to better understand and anticipate machinery and operational issues related to these concepts.

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 *ABS Rules for Survey After Construction (Part 7)* in mid 2002. Machinery systems continue to become larger and more complex, requiring skilled operators with specialized knowledge of the machinery and systems onboard.

This Guide supersedes the *ABS Guide for Surveys Based on Reliability-Centered Maintenance* (2014).

This Guide updates Reliability Centered Maintenance (RCM) and includes two new reliability processes:

- Design for Reliability (DFR) utilizes reliability/risk analyses to improve reliability-related performance to a predetermined value. It also provides a structure for applying these reliability/risk analysis tools throughout the design process to provide the information needed by the designer to make more informed design or procurement decisions.
- Reliability Based Maintenance (RBM) is an alternative reliability process to Reliability Centered Maintenance (RCM). RBM utilizes risk and criticality of systems and equipment to determine the level of analysis needed for maintenance development. A machinery system is selected for evaluation, then the criticality or risk ranking of the equipment and components is determined. The maintenance task selection processes are then chosen based on this criticality.

The final result is a suite of reliability processes that support a comprehensive preventative maintenance plan as defined in Appendix 7-A1-14 of the *ABS Rules for Survey after Construction (Part 7)*.

The January 2023 edition of the Guide replaces the requirements for surveys after construction with references to Section 7-A1-14 of the *ABS Rules for Survey After Construction (Part 7)*.

This Guide becomes effective on the first day of the month of publication.

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

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



GUIDE FOR

SURVEYS BASED ON MACHINERY RELIABILITY AND MAINTENANCE TECHNIQUES

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SECTION 1 General

1 Application

This Guide provides techniques for owners and operators to leverage reliability principles into machinery design, maintenance plan development, and sustainment activities. Owners and operators maintaining their marine or offshore assets with advanced machinery maintenance practices may increase their reliability and/or operational availability. Additionally, the processes found in this Guide and the resulting preventative maintenance plan may provide an alternative for crediting of Special Periodical Survey of Machinery.

Early in the lifecycle, the reliability of components, systems, or combinative processes can be improved by selecting appropriate reliability-enhancing design strategies. These strategies focus on:

- Improving equipment and configuration reliability through their arrangements,
- Designing to simplify manufacturing and assembly,
- Forecasting the design needs anticipated for operations, maintenance,
- Generating a testing and evaluation plan to confirm and validate the changes in design.

These processes enable optimized design, integrated features, and/or technology that will support minimizing operational disruption from component failure, maintenance, inspection, and survey of equipment. Design changes and critical components or machinery identified during design analysis steps may have additional construction tolerances and manufacturing hold points (testing and validation). These requirements support the construction and manufacturing plan thereby addressing reliability throughout the process up to and including commissioning.

To support operational activities, planning must take place to develop an in-service maintenance plan. A systematic process coupling risk and reliability principles should be followed for maintenance alignment and justification. This should take into consideration equipment criticality, functional definitions with applicable failure management analysis, equipment history of performance, OEM recommendations, and spare parts management.

As a means to credit Continuous Survey, clients may enroll their equipment in the ABS Preventative Maintenance Program (PMP). This allows the operator to execute planned maintenance and condition-monitoring activities through an ABS approved program. ABS Surveyors can then utilize the results of these programs to provide crediting toward Special Periodical Survey Machinery requirements. This can reduce disruptions and minimize impact to operations from ABS Survey activities. The ABS Preventative Maintenance Program requirements are contained in Section 7-A1-14 of the *ABS Rules for Survey after Construction (Part 7)*.

The procedures and techniques described herein are applicable to maintained machinery and address multiple stages of equipment and asset lifecycle. No program for improved reliability supersedes the judgment of ABS during the design and approval process for certification of the machinery or systems as required by the applicable ABS Rules such as:

- *Rules for Building and Classing Marine Vessels (Marine Vessel Rules)*
- *Rules for Building and Classing Mobile Offshore Units (MOU Rules)*
- *Guide for Classification of Drilling Systems (CDS Guide)*

Nor does it waive ABS Surveyor attendance for damage, overhauls, operational tests, and verification of safety devices such as relief valves, over-speed trips, emergency shut-offs, low-oil pressure trips, etc., as required by the applicable Rules.

It is a prerequisite that the machinery enrolled in the programs outlined within this Guide be on a Special Continuous Survey of Machinery cycle.

2 Objective

The objectives of this Guide are to:

- Provide reliability based programs to address improved maintenance program performance. These efforts can provide increased asset value and result in improved asset safety and operational effectiveness. An additional benefit is a more clear definition of asset health so that unanticipated repairs are minimized and operations are less prone to delay.
- Provide requirements for improved reliability which seek to reduce the risk to personnel, vessels or marine structures, and the environment. This will potentially reduce the economic consequences due to a machinery failure which may otherwise occur more frequently without the application of a rational maintenance strategy, as provided for by this Guide.
- Foster effective asset management philosophies for new or existing assets and assist in providing credit toward the requirements of Special Periodical Survey of Machinery.

3 Definitions

The following definitions are applied to the terms used in this Guide.

ABS Recognized Condition Monitoring Company: The reference to this term refers to those companies whom ABS has identified as an Service Supplier to carry out condition monitoring on designated machinery.

Baseline Data: Refers to *condition monitoring* indications (ex. vibration records, temperature/pressure readings, etc.) 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 is 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 Based Maintenance (CBM): A maintenance plan, conducted on a frequent or real-time basis, which is based on the use of Condition Monitoring (CM) to determine when part replacement or other corrective action is required. This process involves establishing a baseline and operating parameters, then frequently monitoring the machine and comparing any changes in operating conditions to the baseline.

Repairs or replacement of parts are carried out before the machinery fails based upon the use of the tools prescribed for CM.

Condition Monitoring (CM): Scheduled diagnostic technologies used to monitor machine condition to detect a potential failure.

Confidence: 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, revenue lost, etc. Regardless of the measure chosen, the consequences are expressed "per event".

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

Criticality: 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).

Design for Maintenance and Inspection: A systematic design evaluation process used to improve maintenance efficiency and application in the design process. Incorporating future maintenance of the asset into the design is vital to maintaining the inherent reliability and capability of the process throughout its life.

Design for Manufacture and Assembly (DFMA): A systematic design evaluation process used to improve part design and part manufacture early in the design process. DFMA considers all aspects of the design, development, total parts, manufacturability, cost, assembly time and modularity to further enhance the overall design for manufacturability and quality.

Effects: See "failure effects".

End Effects: See "failure effects".

Environmental Standards: International, national and local laws and regulations or industry standards that must be complied with.

Equipment Items: The hierarchical level below *systems* comprised of various groups of machines or *components*.

Event: 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 basic equipment failure that results in the *failure mode*. For example, pump bearing seizure is one failure cause of the failure mode where a pump fails.

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

Failure Effects: 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 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 proactive strategy to manage failures and their effects to an acceptable risk. It consists of proactive maintenance tasks and/or one-time changes.

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

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).

Failure Modes and Effects Analysis (FMEA): A systematic process to identify potential failures to fulfill the intended function, to identify possible failure causes so the causes can be eliminated, and to locate the failure impacts so the impacts can be reduced.

Failure Modes, Effects and Criticality Analysis (FMECA): A variation of the FMEA that includes an explicit estimation of the severity of the consequences of the failure or a combination of the likelihood of the failure and severity of the consequences.

Frequency: The potential of an 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: 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*: Directly related to producing the primary output or product from a functional group/system/equipment item/component.
- *Secondary Function*: 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 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: 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): 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*”.

Maintained Machinery: Machines or equipment are maintained where lifecycle decisions involve the repair, overhaul, or replacement of the machinery or its sub-components. These activities restore system function. Pumps, electrical motors, switchgears, gears, generators, compressors, internal combustion engines, turbines, hydraulic cylinders, winches, windlasses, and control and alarm systems are examples of maintained machinery.

Maintenance Task Analysis: Maintenance planning strategy that reviews all previous asset performance records as well as pertinent asset records that detail the best approach for maintenance. These results are used to tailor decision making on maintenance task selection.

One-time Change: 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 defined set of circumstances under which the *functional group* is expected to operate. The operating context may include the physical and operational environment as well as the specified performance criteria of the functional group.

Operating Mode: The operational state the vessel or marine structure is in. For example, cruising at sea, entering or departing a port.

Original Equipment Manufacturer (OEM): Company that manufactures equipment or components which are purchased and by others.

P-F (Potential Failure) Interval: The time interval between the point at which the onset of failure can be detected and the point at which functional failure occurs.

Parallel Redundancy: Applies to *systems/equipment items* operating simultaneously where each system/equipment 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: The requirements *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.

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

Preventative Maintenance: Consists of all the maintenance tasks identified as necessary to provide an acceptable probability of survival to the end of a specified interval for the machinery systems. In IACS UR Z20, this is referred to as a “Planned Maintenance Scheme”. ABS Preventative Maintenance Program is defined in Section 7-A1-14, “Surveys Based on Preventative Maintenance Techniques” of the *ABS Rules for Survey after Construction (Part 7)*

Proactive Maintenance Task: 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: Chance failures caused by sudden stresses, extreme conditions, random human errors, etc. (i.e., failure is not predictable by time).

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

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

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

Risk: 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 table indicating the *risk* for an associated *frequency* and *consequence severity*.

Root Cause Analysis: An analysis that identifies the causal factors, intermediate causes and root causes of an incident and develops recommendations to address each level of the analysis.

Run-to-failure: 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: Methods that 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) assess the failure rate and failure pattern 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 confirm 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*, indicates the magnitude of the consequence.

Special Continuous Survey of Machinery (CMS): The requirements for Special Continuous Survey of Machinery are listed in the following Rules and Guides. Special Periodical Survey requirements are carried out in regular rotation to complete all of the requirements of the particular Special Periodical Survey within a five-year period. The proposed arrangements are to provide for survey of approximately 20% of the total number of survey items during each year of the five-year period, as referenced in:

- 7-2-1/7 “Continuous Surveys” (Vessels in Unrestricted Service) and 7-2-2/9 “Continuous Surveys” (Vessels in Great Lakes Service) of the *ABS Rules for Survey After Construction (Part 7)*.
- 7-2-2/1.5 “Continuous Surveys” (MOU) of the *ABS Rules for Building and Classing Mobile Offshore Units*
- 8-1/3 “Continuous Survey Program” of the *ABS Guide for the Classification of Drilling Systems*

Special Periodical Survey – Machinery: The requirements for a conventional ABS Special Periodical Survey – Machinery are listed in the following portions of the ABS Rules and Guides. Generally, this is considered 100% equipment crediting at Special Survey. There are Special Periodical Survey requirements in ABS Rules and Guides for specific vessel types, services, marine and offshore structures, such as:

- *ABS Rules for Survey After Construction (Part 7):*
 - 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” (7-6-2/3.1, All Vessels, 7-6-2/3.3, Tankers)
- *ABS Rules for Building and Classing Mobile Offshore Units:*
 - Section 7-2-2/1.3 “Special Periodical Surveys”
- *ABS Guide for Classification of Drilling Systems:*
 - 8-3/3 “Special Periodical Surveys”

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: Failure method that 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: Failure method that is dominated by end-of-useful life issues for equipment.

4 Program Conditions and Administration

For enrollment in any of the maintenance and reliability programs, 7-A1-14/3 of the *ABS Rules for Survey After Construction (Part 7)* are to be complied with including the following additional requirements:

4.1 Engineering Review

Where enrollment of machinery in any reliability program (Design for Reliability, Reliability Based Maintenance, or Reliability Centered Maintenance) is requested, the documented analyses and resulting in-service maintenance plan are to be submitted to the responsible ABS Engineering Office for approval. After implementation, if additional equipment is to be added to the programs, the analyses are to be submitted to the responsible ABS Engineering Office which performed the initial review. The requirements for the documentation to be submitted are listed in each Section of this Guide.

4.2 Implementation Survey

Implementation survey is to be carried out by the attending Surveyor within one year from the date of the approval letter approving the reliability analysis and resulting maintenance plan, as issued by the responsible ABS Engineering Office. The requirements for the implementation survey are listed in Section 6. This requirement is in addition to the Implementation Survey for ABS Preventative Maintenance Program per Appendices 7-A1-14/5.3 and 7-A1-14/17.5 as applicable in *ABS Rules for Survey After Construction (Part 7)*.

When this survey is carried out and the implementation found to be in order, a report confirming the implementation of the program is to be submitted by the attending ABS Surveyor. A class notation and survey status indicator will be assigned and distinguished in the *Record*, if appropriate, in accordance with 1/8.

4.3 Spares Holding

For assets enrolled in any reliability program, the Surveyor is to verify that an effective, computerized spares holding inventory and ordering system is established onboard at the Implementation Survey and at subsequent Annual Confirmation Surveys.

4.4 Sustainment

An effective sustainment program will collect, analyze, review and respond to in-service data throughout the life of the vessel so as to continually improve the maintenance plan. The results of the sustainment process are to be submitted to the attending Surveyor at the Annual Confirmation Survey and validated as part of survey process.

If the reliability analysis or resulting maintenance plans are revised as a result of the sustainment process, the attending Surveyor must be notified. The ABS Surveyor may require the analyses to be submitted to the responsible ABS Engineering Office that performed the initial review.

Reliability Based Maintenance (RBM) and Reliability Centered Maintenance (RCM) programs require an office audit be completed within five years after the date of enrollment of a vessel or after the crediting date of the previous special sustainment audit. The Surveyor will audit the shore office management plan to verify that the vessel's maintenance sustainment and continuous improvement activities are occurring and such activities are documented.

4.5 Annual Confirmation Survey

Simultaneously with each Annual Survey of Machinery for vessels on these programs, an Annual Confirmation Survey is to be performed by the attending Surveyor. This is to verify that the reliability program is being effectively implemented and is supporting execution of an approved maintenance program.

4.6 Cancellation of Program

The survey arrangement for machinery under this program may be cancelled by ABS if the program is not being satisfactorily carried out, either from the maintenance records or the general condition of the machinery, or when the agreed intervals between overhauls are exceeded.

Sale, change of management of the vessel, or transfer of class is to be cause for reconsideration of the approval.

The Owner may at any time cancel the survey arrangement for machinery under this program by informing ABS in writing. For this case, items which have been inspected under the program since the last Annual Survey may be credited for class at the discretion of the Surveyor. However, ABS will determine future survey requirements for machinery formerly enrolled as determined applicable by the Rules.

4.7 Overhauls and Damage Repairs

Damage, failure, deterioration or repair to machinery or equipment, which affects or may affect classification, is to be submitted by the Owners or their representatives for examination by a Surveyor at first opportunity. All repairs found necessary by the Surveyor are to be carried out to the Surveyor's satisfaction in accordance with Section 7-1-1/7.1 of the *ABS Rules for Survey After Construction (Part 7)*.

In the case of overdue conditions of class or a record of unrepaired damage which would affect the Machinery Reliability and Maintenance Program, the relevant items are to be surveyed to the requirements of Special Periodical Survey until the recommendation is fulfilled or the repair is carried out.

5 Application of Risk and Criticality in Decision Making

The purpose of a criticality analysis is to rank items with respect to risk. The risk can be measured qualitatively (e.g., high, medium, low) or quantitatively (e.g., \$15,000 per year). Risk can be considered as the product of two factors: 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:

- *Capital Investment*. Damage to and cost of repair of equipment
- *Community*. Effect on the public
- *Directional Control*. Complete loss or reduction of maneuverability
- *Explosion or Fire*. Damage to equipment and/or the vessel
- *Loss of Containment*. Amount of harmful substances released to the environment (cost of substance loss, the cleanup cost)
- *Operations*. Loss of hire, outage time of functions such as drilling, position mooring (station keeping), hydrocarbon production and processing, loading or unloading functions
- *Propulsion*. Complete loss or reduction of propulsive capability
- *Safety*. The number of people affected (injured or fatalities)

A sample risk matrix is shown in 1/5 TABLE 1 below. 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 (High to Low) 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 (e.g., multiples of 5 or 10).

TABLE 1
Risk Matrix Example Format

<i>Consequence Level</i>	<i>Likelihood of Failure</i>				
	<i>Improbable</i>	<i>Remote</i>	<i>Occasional</i>	<i>Probable</i>	<i>Frequent</i>
High	Medium	Medium	High	High	High
Medium High	Low	Medium	Medium	High	High

<i>Consequence Level</i>	<i>Likelihood of Failure</i>				
	<i>Improbable</i>	<i>Remote</i>	<i>Occasional</i>	<i>Probable</i>	<i>Frequent</i>
Medium Low	Low	Low	Medium	Medium	High
Low	Low	Low	Low	Medium	Medium

6 Reliability Assessment Team Requirements

The analysis processes supporting reliability are best performed by a multi-disciplinary team to bring together varying perspectives and technical strengths. A team approach verifies that all required information that is available within the vessel or marine structure and/or organization is considered in the analysis, as well as providing a thorough analysis of the risks of failure and effective maintenance tasks.

The specific composition of the team depends on the vessel or marine structure complexity, program scope and any applicable regulations. Some of the technical disciplines may require outside assistance (from within or outside the organization) as advisors, but a core team is essential for continuity.

The team should have the expertise to identify and analyze all of the factors and their implications to machinery function including explosion/fire, loss of containment and safety. If during the risk and criticality prioritization, failure scenarios are inaccurately characterized, the analysis could potentially affect maintenance efforts of related components, thus resulting in a hazardous situation or inefficient maintenance. Personnel with technical and risk analysis knowledge are essential for the program to function effectively.

The team will typically consist of individuals with experience and technical knowledge in the maintenance and inspection of machinery with the following disciplines:

- i)* Safety and health
- ii)* Reliability
- iii)* Operations
- iv)* Risk analyses
- v)* System process hazards
- vi)* Safety and health
- vii)* Materials of construction

The team members may also be tasked to:

- viii)* Participate and actively contribute in all risk analyses and reliability meetings and share their knowledge and experience for the analyses
- ix)* Validate the quality and veracity of the information available
- x)* Perform their specific tasks, keeping in mind the end goals of the reliability program

6.1 Client Activities and ABS Participation

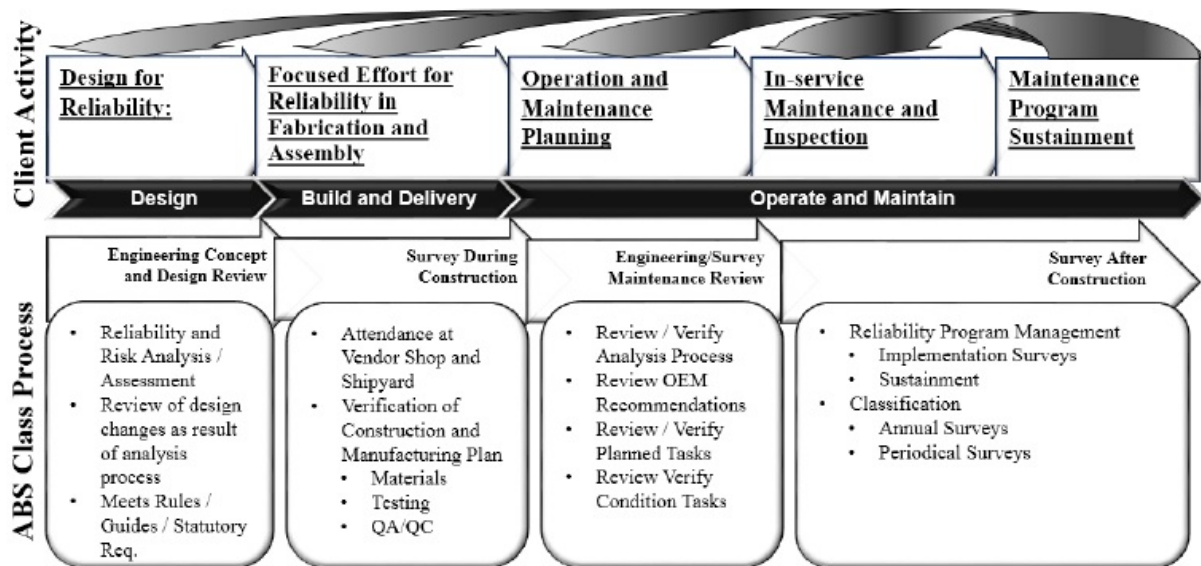
Conducting a reliability and risk assessment involves a team brainstorming session that provides a unique forum for designers, operational and safety personnel to discuss the design in a structured manner.

While ABS does not mandate that ABS personnel be part of this assessment team, as a participant, the ABS representative will be able to point out the issues that ABS considers to be relevant for the classification of the proposed design and thus should be discussed.

7 Coordination with Lifecycle Activities

The classification processes (engineering review, survey during construction, and survey after construction) coordinate with the lifecycle approaches as illustrated in 1/7 FIGURE 1. The objective is to align operator's in-service maintenance plan with the applicable survey requirements. For additional details on lifecycle activities, see Appendix A1.

FIGURE 1
Class Alignment with Client Programs



8 Classification Notations

The programs in this Guide are to be approved by an ABS Engineering Office. Upon completion of a satisfactory Implementation Survey, a "Certificate of Approval" is to be issued by the attending Surveyor. An optional notation, if appropriate, will be entered in the *Record*. In order to qualify for a notation assigned under this Guide requirements, a vessel is required to be assigned with a **PMP** notation in accordance with the Preventative Maintenance Program in Section 7-A1-14 of the *ABS Rules for Survey After Construction (Part 7)*.

Details on each phase of an asset lifecycle and the associated ABS processes are explained in the following Sections of this Guide. The lifecycle program must be aligned to the applicable lifecycle phases and activities that are summarized herein. Where the requirements of this guide are met and the Owner request, a vessel may be assigned with one of the following optional notations:

- i) An approved program in accordance with Section 2, "Design for Reliability" will be assigned and distinguished in the *Record* with the class notation **RBMD** with an approved program in accordance with Section 3, or **RCMD** with an approved program in accordance with Section 4.
- ii) An approved program in accordance with Section 3 "Reliability Based Maintenance" will be assigned and distinguished in the *Record* with the class notation **RBM**.
- iii) An approved program in accordance with Section 4 "Reliability Centered Maintenance" will be assigned and distinguished in the *Record* with the class notation **RCM**.

8.1 Program Enrollment Options for Asset, System, or Equipment

The processes associated with the programs described in this Guide can be applied holistically to the asset (comprised of multiple systems), specific systems or specific equipment(s) of a system(s) at the Owner's option.

TABLE 2
Program Definitions and Notations

Program	Definition	ABS Notation	Applicable Guide Section								
			ABS Engineering Submittal			Operational Documentation				ABS Surveys	
			DFR	RBM	RCM	Onboard Req.	PMP	Sustain	Annual Report	Implement	Annual Confirmation
			2/2	3/2	4/2	5/2	5/3	5/4	5/5	6/1	6/2
Design for Reliability	Design for reliability (DFR) utilizes reliability/risk analysis tools so that future reliability-related performance meet expectations. It also provides a structure for applying these reliability/risk analysis tools throughout the design process to provide the information needed by the operator to make more informed design decisions. ** DFR requires the addition of a reliability based or reliability centered maintenance program.	RBMD	✓	✓		✓	✓	✓	✓	✓	✓
		RCMD	✓		✓	✓	✓	✓	✓	✓	✓
Reliability Based Maintenance	A maintenance development process that will act as the foundation for applying selective reliability techniques, choosing and deploying a maintenance plan, and creating an effective reliability strategy to support an efficient maintenance environment	RBM		✓		✓	✓	✓	✓	✓	✓
Reliability Centered Maintenance	A systematic process coupling risk and reliability principles to create a maintenance plan by taking into consideration equipment criticality, functional definitions with applicable failure management analysis, OEM recommendations. To support the resulting maintenance plan, RCM also deploys a risk based analysis of spare parts and a sustainment plan.	RCM			✓	✓	✓	✓	✓	✓	✓
In order to qualify for a notation assigned under this Guide requirements, a vessel is required to be assigned with a PMP notation in accordance with the Preventative Maintenance Program in Appendix 7-A-14 of the <i>ABS Rules for Survey After Construction (Part 7)</i> . The below is for comparison with above reliability programs.											
Preventative Maintenance Program (see 7-A-14)	A program that consists of planned maintenance and/or condition-monitoring activities. Maintenance intervals and tasks follow OEM recommendations or documented operator experience.	PMP				✓	✓		✓	✓	✓

8.2 Machinery Status Indicators

Upon satisfactory completion of the Implementation Survey, the attending Surveyor shall advise Classification Documentation Center (CDC) to update the items covered by a Planned Maintenance plan are to be shown by a "PM" indicator, and the items covered by a Condition Monitoring plan are to be shown by a "CM" indicator. When equipment is covered by both PM and CM plans, items are shown by a "PM/CM" indicator. The owner is to confirm with the attending Surveyor that the vessel shows the correct indicators for the listed equipment.

TABLE 3
Machinery Status Indicators

Maintenance Task Type Selection	Notations
	All
Combination Planned and Condition Monitoring	PM/CM
Planned Maintenance	PM
Condition Monitoring	CM

8.3 Equipment Certification

Equipment suppliers can also pursue equipment certification independently. This certification requires enrollment in ABS Type Approval Program while also achieving the requirements of Section 2. Type Approval for Reliability in Design:

- i) *ABS Type Approval Program.* For ABS Type Approval Program, see 1-1-4/7.7 of the *ABS Rules for Conditions of Classification (Part 1)*.
- ii) *Design for Reliability Procedure.* Submittal requirements per 2/3 of this Guide.

9 Sample Program Workflows

1/9 FIGURE 2 through 1/9 FIGURE 5 provide example workflows for each of the reference programs in this Guide.

FIGURE 2
Design for Reliability Process Workflow

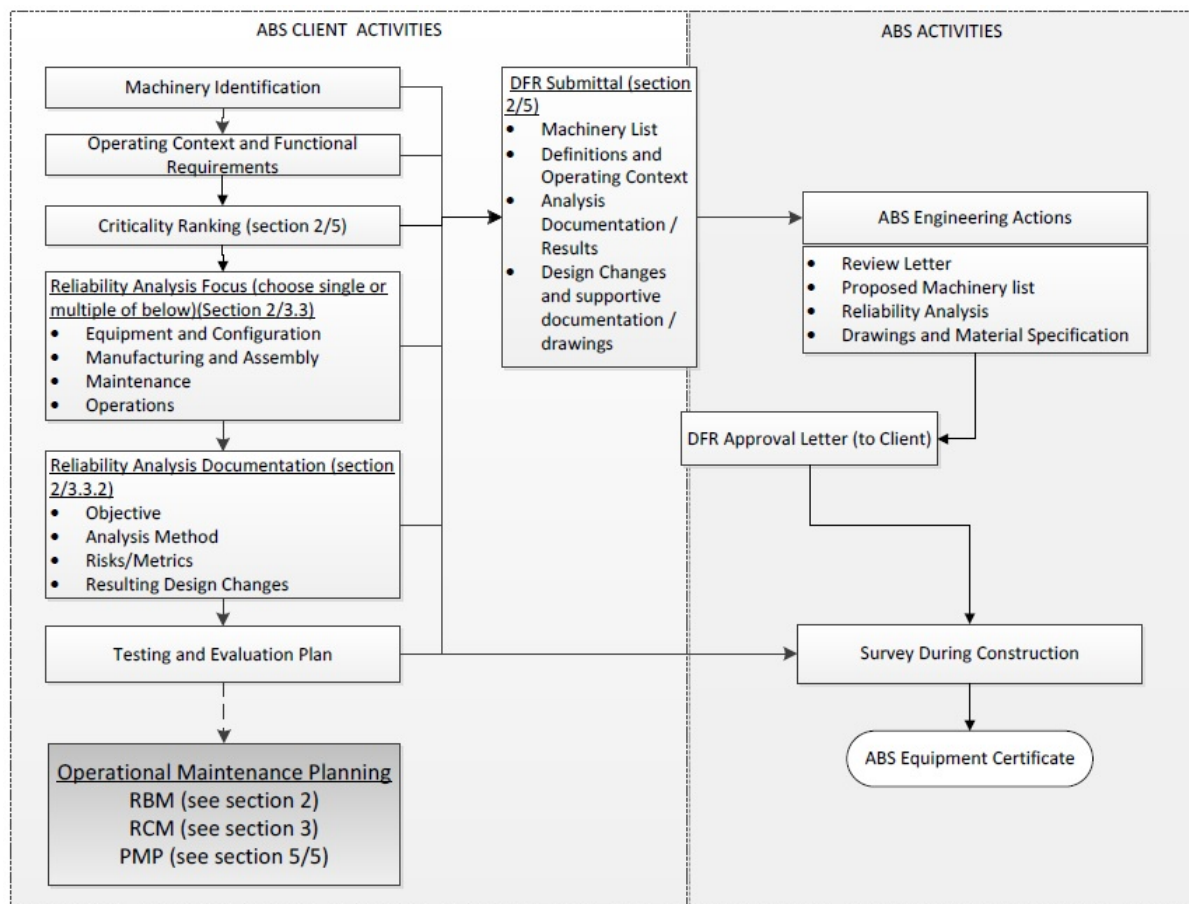


FIGURE 3
Reliability Based Maintenance Process Workflow

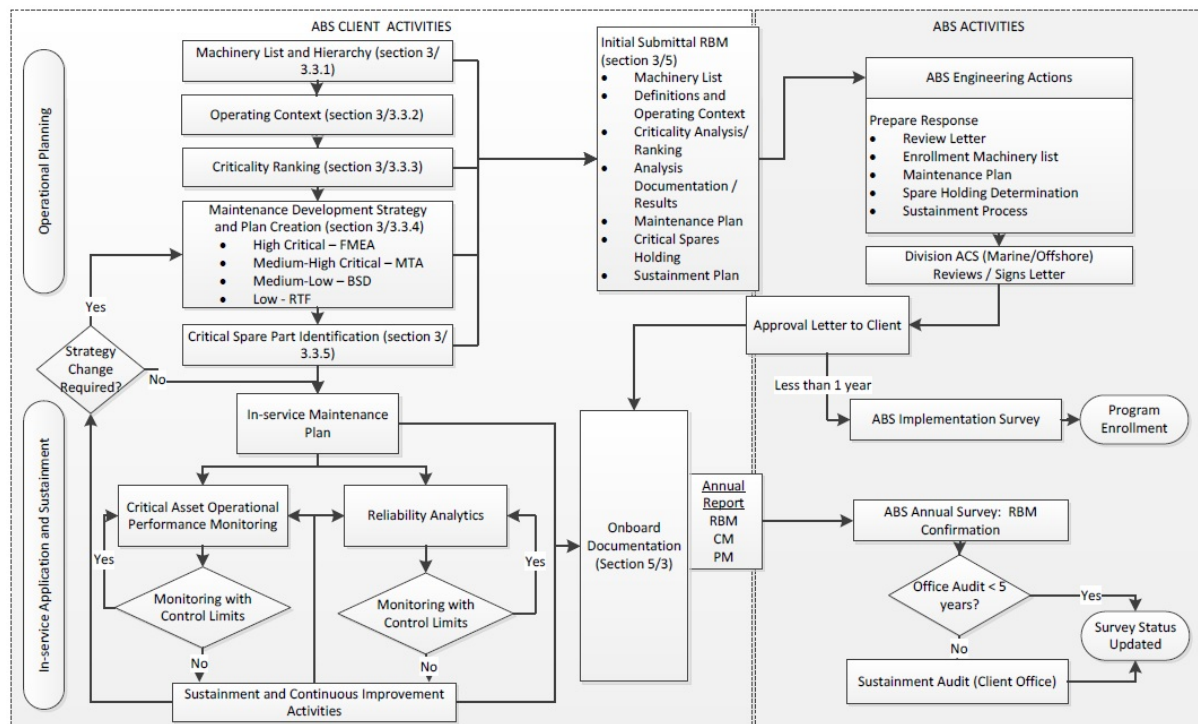


FIGURE 4
RCM Process Workflow

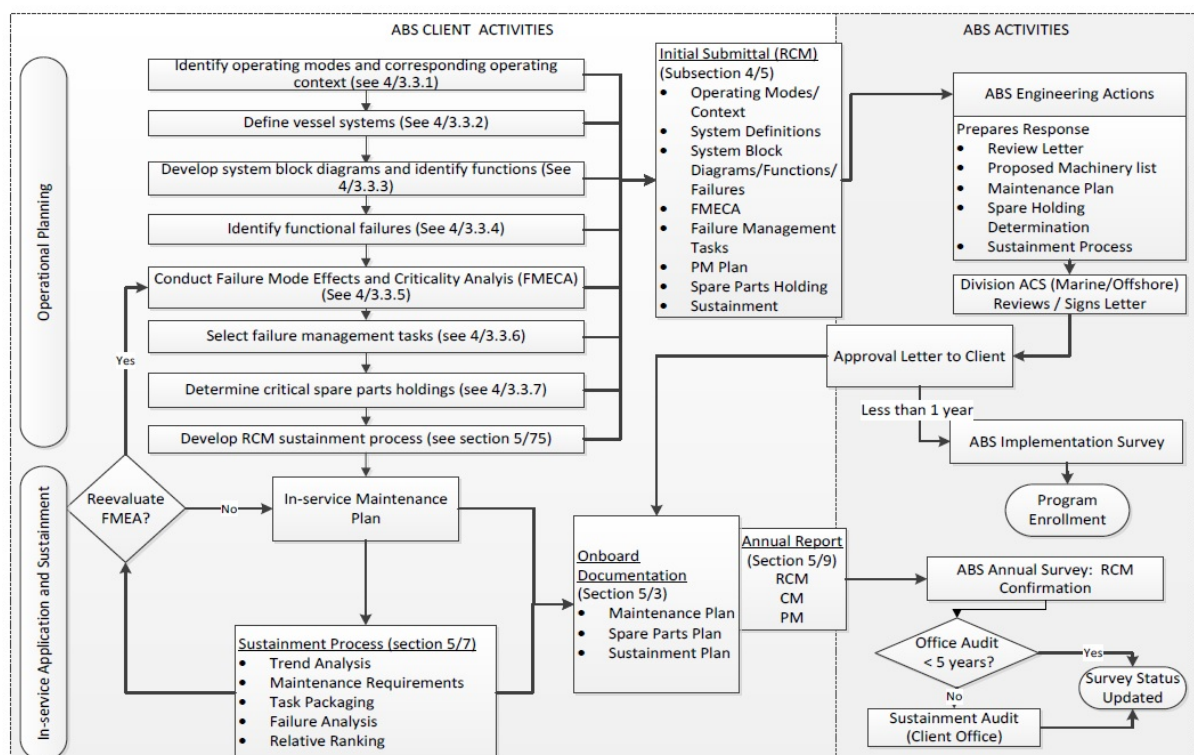
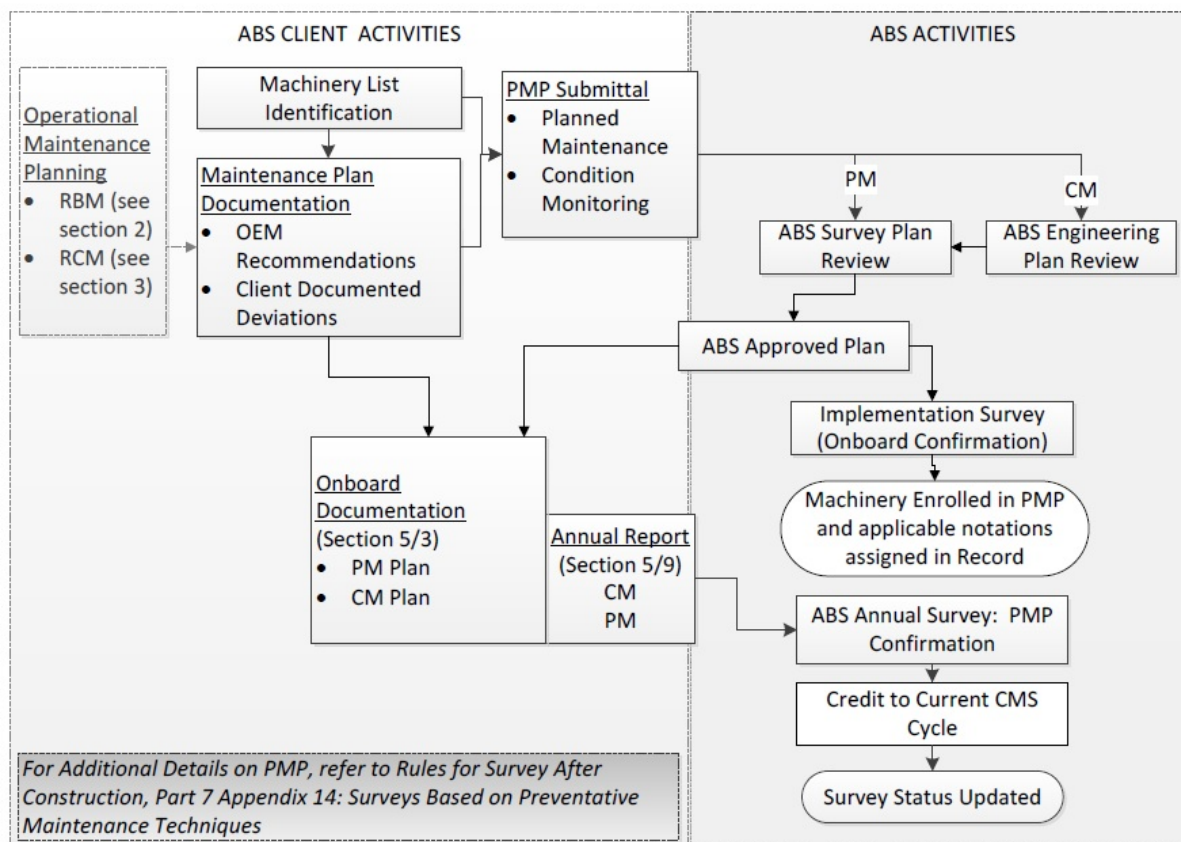


FIGURE 5
PMP Process Workflow



SECTION 2 Design for Reliability

1 Principles of Design for Reliability

Design for reliability (DFR) refers to the incorporation of reliability-enhancing strategies and practices into the design, manufacture and capital equipment procurement procedures. An engineering evaluation is used to verify the design is in accordance with applicable Rules, Guides and statutory regulations and the design reliability analysis is in accordance with the requirements of this Section.

The reliability criteria may be based on design, manufacture, material composition or phases of operation (transit, installation, commissioning and in-service) as selected by the submitter. Upon successful completion of the requirements of this Section, an appropriate notation per 1/8 may be assigned. Equipment suppliers can also pursue equipment certification independently as referenced in 1/8.3.

1.1 Age Requirements for DFR

Enrollment in Design for Reliability requires either:

- The equipment is manufactured and certified as part of new construction, or
- The equipment or components are manufactured and certified as part of a redesign and modification.

1.2 Limitations

1.2.1 Non-OEM supplied parts

Parts supplied by vendors other than the OEM are to be in accordance with Sections 2/2 and 2/3.

1.2.2 Changes to Design or Procedures

Change in the design or procedures as submitted in 2/3, requires the manufacturer to notify ABS of those changes for re-assessment and resulting effect on configuration, design, and validity of notation.

2 Analysis Requirements

2.1 Design for Reliability Overview

DFR utilizes reliability/risk analysis tools to verify improved reliability-related performance to a predetermined value provided by the designer. DFR also provides a process for applying these reliability/risk analysis tools throughout the design process and the information needed to make more informed design or procurement decisions. When chosen, a DFR is required to be performed at an appropriate level of analysis necessary at each design stage to support the decision-making needs.

2.2 Reliability Team

The team that supports the DFR process is to be documented in accordance with Reliability Team Requirements (see 1/6).

2.3 Procedures

2.3.1 Defining Design for Reliability Objectives

The key activities of DFR are initiated based on establishing the key objectives for improving reliability. The objectives for improving reliability via design changes are shown in 2/2.3.1 Table 1. The chosen path can employ one or a combination of the objectives described (A-D). All design for reliability activities are to establish a testing and evaluation plan which will validate function and reliability requirements.

Table 1
Reliability Objectives in Design

<i>A: Equipment and Configuration</i>	<i>B: Manufacturing and Assembly</i>	<i>C: Efficient Maintenance</i>	<i>D: Efficient Operations</i>
The inherent potential of an asset to perform reliably is referenced by the technology of the equipment employed and the degree of redundancy. The design processes are to evaluate the level of redundancy required to achieve targeted process availability.	Designing to help reliable manufacturing and assembly of the asset that helps lead to reliable performance. Equipment and process specifications are to anticipate sources of variability and try to minimize process sensitivity to such variability.	Incorporating future maintenance of the asset into the design is vital to maintaining the inherent reliability and capability of the process throughout its life.	Designers should consider the interaction between the operator and equipment with focus on designing systems that reduce likely human error. The designers must consider the environment in which the process is being operated to minimize equipment vulnerabilities. The environment includes location, maintenance envelope, and accessibility of the equipment.

2.3.2 Design for Reliability Analysis

The design phase analysis and any resulting changes help establish a baseline for inherent reliability of a system/machinery/component. The designer is to document the reasoning behind the selected method/tool used for reviewing and analyzing the design for reliability improvements. For additional details on design for reliability methods see Appendix A1. Documentation of the objective, method, references, and results should be submitted to ABS Engineering Office for review.

3 Plans and Data to be Submitted

The following information is to be submitted to ABS Engineering Office for review

3.1 For All Machinery Items to be Included

- i)* A list and description of machinery/items for analysis
- ii)* Design for Reliability statement of intent documenting the reason(s) for DFR analysis
- iii)* Item definition and operating context:
 - a)* Design basis documents that include the “operating envelope”, working environment, design life, etc.

- b)* Process or functional description
 - c)* General arrangement/layout drawings (post any design changes)
 - d)* Details of material specification to be utilized
- iv)* Criticality ranking:
 - a)* Components for assessment
 - b)* Factors for each component
- v)* *Analysis Process Documentation.* Design for Reliability can focus on multiple paths for improvement. Many industry methods exist for reliability and performance analysis (see Appendix A3). The submittal must include an explanation of the process and justification.
 - a)* Reliability objective definition
 - 1)* Reference path objective(s) from 2/2.3.1 Table 1
 - 2)* End state reliability goal (Probability, Interval, Stated Conditions)
 - b)* *Definition of Analysis Method.* If multiple methods utilized, submittal shall include items 2/3.1v)c) and 2/3.1v)d) for each method deployed.
 - c)* Risks or metrics analyzed (Quantitative or Qualitative)
 - d)* Reference showing justification for application
- vi)* Results of analysis
 - a)* Specified design changes
 - b)* Required maintenance to support reliability goal
 - c)* Estimate of design reliability improvement

To support survey activity in the shipyard and at vendor facilities, the following items are required for submittal:
- vii)* Material Specifications
- viii)* Inspection and Test Plan
- ix)* Quality Assurance Programs
- x)* Project assembly and construction “hold-points”

3.2 As Applicable for Each Item

- i)* Process flow diagrams (PFDs)
- ii)* Piping and instrumentation diagrams (P&IDs)
- iii)* Electrical one-line drawings and Electrical loads
- iv)* Instrumentation details and accompanying logic diagrams
- v)* System interface requirements
- vi)* Mechanical design drawings

SECTION 3

Reliability Based Maintenance

1 Principles of Reliability Analysis

1.1 Definition

Reliability Based Maintenance (RBM) is a process to develop a preventative maintenance plan. A machinery system is selected for evaluation, then the criticality or risk ranking of the equipment and components is determined. The maintenance task selection processes are then chosen based on this criticality.

Effective asset management can help achieve best in class maintenance and asset performance. Reliability based maintenance analysis can be applied to create the in-service maintenance plan and sustainment processes. This Guide provides the requirements for a process that can be created and managed by the client or executed in collaboration with ABS.

1.2 Tools and Expertise Employed to Perform RBM Analyses

- i) Design, engineering and operational knowledge of the system
- ii) Failure modes, effects and criticality analysis (FMECA), or similar reliability process
- iii) Condition-monitoring techniques with the understanding of their application
- iv) Risk-based decision making (i.e., the frequency and the consequence of a failure in terms of its impact on safety, the environment and commercial operations)

1.3 Process Documentation and Implementation

- 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

2 RBM Process Requirements

The analysis is to be conducted for all equipment and systems proposed for enrollment in the RBM Program. The Initial RBM Analysis is to be submitted to the responsible ABS Engineering Office for approval. Subsequently, Annual RBM reports are to be prepared for review by the attending Surveyor at the Annual Confirmation Survey.

2.1 Overview

An analysis of the systems proposed for enrollment applying RBM utilizes the system drawings; equipment item drawings; preventative maintenance instructions for systems, equipment items or

components; and operator experience. The final result of the analysis is a preventative maintenance plan for the selected systems and equipment items.

2.2 Reliability Team

The team members supporting the Reliability Based Maintenance process is to be documented in accordance with 1/6, “Reliability Team Requirements”.

2.3 Procedures

The requirements for the RBM procedure are shown in a process flow diagram in 1/9 FIGURE 4 and described further as follows. Additional support information on RBM is in Appendix A1.

2.3.1 System Selection and Machinery List Development

As the primary step of effective asset management in support of RBM, it is important to develop a formal process to clearly define the difference between assets and spare parts.

Each system selected for RBM analysis is to be defined. The system definition involves (1) partitioning the vessel’s functional groups into systems, subsystems (as necessary due to complexity), equipment items and components, and (2) further development of the narrative description for each functional group, system, equipment item and component.

2.3.2 Operating Context

To properly define operating characteristics, the various operating modes for the asset or equipment are to be identified. Operating contexts are to be developed for each level of the machinery hierarchy. An example of an operating mode, along with its operating context, is provided in .

2.3.3 Criticality Ranking

The process chosen is to be capable of prioritizing or ranking assets to optimize the utilization of maintenance resources based on factors such as: safety, quality, environmental impact, operational throughput, operational cost, and/or current system or equipment reliability.

2.3.4 Maintenance Development Strategy

Developing an effective maintenance strategy assists in improved reliability of an asset at the planned operational cost and coordinates the utilization of maintenance resources by dedicating them to the execution of high value maintenance activities. The criticality ranking drives which maintenance strategies should be applied to an asset, and results in a complete maintenance plan for later execution. The varying levels of maintenance plan development are determined from criticality analysis and ranking (see 3/2.3 Table 1):

- *Failure Modes Effects and Criticality Analysis (FMECA)*. This process analyzes asset sub-assemblies and components to identify failure modes and their accompanying causes and system effects. Each failure mode has a risk calculation performed to prioritize and quantify the level of mitigation required. Condition-monitoring or planned maintenance tasks are identified with a preference to apply non-disruptive predictive technologies as the primary option.
- *Maintenance Task Analysis (MTA)*. This process reviews all previous asset maintenance and performance records with the objective to reaffirm or select replacement value added maintenance tasks. The approach analyzes maintenance tasks and their alignment and coverage of failure modes in an effort to enhance their application.
- *Basic Strategy Development (BSD)*. This is a review of the current maintenance tasks and the affiliated job plans that are presently in place to develop a standard to be followed based on utilizing the current content. If no current content exists, Original Equipment Manufacturer (OEM) recommendations will be the baseline for standard development.

- *Run to Failure (RTF)*. This strategy allows the asset to operate until a failure occurs followed by replacement of the failed component(s). (See Note in 3/2.3 Table 1)

Table 1
Criticality Based Maintenance Alignment

<i>Equipment Criticality Tiers</i>	<i>Maintenance Development Alignment</i>			
	<i>FMECA</i>	<i>MTA</i>	<i>BSD</i>	<i>RTF*</i>
Top 25%	X			
Upper Middle 25%	O	X		
Lower Middle 25%		O	X	
Bottom 25%			O	X*

Legend: X – Recommended, O – Optional

* Note: Class items where RTF strategy is deployed require compliance with Special Periodical Survey

2.3.5 Critical Spare Part Identification

For the proposed maintenance schedules to be viable, it is essential that the spares that support the identified maintenance tasks in 3/3.2.3 are available at the appropriate time. There are procurement factors which can also drive classification of a spare part, deeming it more or less important. The primary factors that determine if a spare part is identified as critical are as follows:

- The component is directly linked to a failure mode that has a high risk calculation or failure consequence
- The component failure causes the asset to cease operation or operate at an unsatisfactory level of performance

2.3.6 In-service Application and Sustainment

Once assets are in operation, their performance is to be monitored. Critical assets are to be selected so that overall operation is satisfactory based on individual asset performance. The primary method to determine if the asset is operating or function efficiently is to monitor operational performance parameters with designated control limits. Similarly, a method to determine if the maintenance strategy is effective and appropriate is to monitor reliability analytics with designated control limits.

In the event it is determined that the asset is operating unsatisfactorily, functioning inefficiently, or the maintenance strategy is ineffective based on monitoring operational performance, a root cause analysis (RCA) should be performed to identify the corrective and preventative actions required to restore the asset to a functional condition.

3 Plans and Data to be Submitted

The following information is to be submitted to an ABS Engineering Office for review:

3.1 Items Selected for Analysis

- i) Criticality Analysis and Ranking
- ii) Design basis documents that include the “operating envelope“, working environment, design life, etc.
- iii) Process or functional description
- iv) General arrangement/layout drawings

3.2 Risk and Reliability Analysis

The Owner is to document the analysis tools used as part of each assessment. Submittals for the program are to provide results and descriptions of the analysis. The submittal is to include an explanation of the process and justification. Refer to Appendix A2, “Risk and Reliability Tools and Techniques”, for suggested analyses.

3.2.1 Analysis Objective Definition

- i) Analysis team members
- ii) Analysis/method utilized
- iii) Risks or metrics analyzed (quantitative or qualitative)
- iv) Reference showing justification for application
- v) Documented results of analysis

3.2.2 Analysis Results and Documentation

- i) Criticality Assessment
- ii) Identify components
- iii) Factors for each component
- iv) Criteria and scoring for each factor (with weighting)
- v) Scoring calculation for each component
- vi) Scoring calculation for assessment
- vii) Determine score groupings for bulk analysis

3.2.3 Failure Modes Effects Analysis (where applicable)

- i) Identification of failure modes and their causes
- ii) Evaluate the effects on the system of each failure mode
- iii) Identification of failure detection methods
- iv) Identification of corrective measures for failure modes

3.2.4 Maintenance Task Analysis (where applicable)

- i) Identification of maintenance tasks reviewed
- ii) Failure modes addressed by each task
- iii) Documentation on decision process for modification (trade-off study, FMEA, etc.)
- iv) Resulting maintenance changes

3.3 Maintenance Plan

3.3.1 List and Description of the Machinery

A table listing the owner’s equipment item name and the equivalent ABS Survey Manager name is to be provided for reference.

3.3.2 For Items to be enrolled in ABS Preventative Maintenance Program

- *Planned Maintenance*: Refer to Appendix 7-A1-14/13.5.1 of the *ABS Rules for Survey After Construction (Part 7)*
- *Condition Monitoring*: Refer to Appendix 7-A1-14/15.5.1 of the *ABS Rules for Survey After Construction (Part 7)*

3.4 Critical Spares Holding

For the proposed maintenance schedules to be viable, 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:

- i)* Parts necessary to perform tasks to correct each failure mode identified in the reliability analysis,
- ii)* Parts required as a result of work to correct “condition monitoring”, “planned maintenance”, “failure finding”, “any applicable and effective” and “run-to-failure” tasks.
- iii)* An evaluation of the effects on the functional group or system’s operational availability if an out-of-stock condition occurs.
- iv)* 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.
- v)* Lead time required for ordering a part out of stock.

3.5 Sustainment Plan

The plan for continued improvement shall be submitted to the ABS Engineering Office. The results of the sustainment activities must be maintained onboard for verification at annual surveys. See 5/4.

SECTION 4

Reliability Centered Maintenance

1 Principles of Reliability Centered Maintenance

1.1 Definition

Reliability centered maintenance is a process of systematically analyzing an engineered system or maintained machinery 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 mode 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

1.2 Objective

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?

1.3 Tools and Expertise

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

- i)* Failure modes, effects and criticality analysis (FMECA).
- ii)* RCM decision flow diagram.
- 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)

1.4 Reliability Centered Maintenance Overview

By using RCM principles, maintenance is evaluated and applied in a rational manner. Functional failures with the highest risk are identified and then focused on. Equipment items and their failure modes that will cause high-risk functional failures are identified for further analyses. Maintenance tasks and maintenance strategies that will reduce risk to acceptable levels are determined. Spare parts inventories are determined based on the maintenance tasks developed and a risk assessment. An RCM sustainment procedure is instituted to continually monitor and optimize maintenance. Accordingly, improved equipment and system reliability can be expected.

The primary objective of RCM analysis is to provide a comprehensive, systematic and documented investigation which establishes important failure conditions of the machinery system(s), maintenance tasks or system/equipment redesigns chosen to reduce the frequency of such occurrences, and the rationale for spares inventory. There may be special conditions for steam turbines, internal combustion engines, electrical switchgear and power distribution panels and permanently installed monitoring equipment.

Additional benefits for the Owner/Operator of the vessel or marine structure which are beyond the scope of this Guide are:

- To provide data to generate comprehensive training, operational and maintenance programs and documentation; and
- To provide the results of the study into the asset's failure characteristics so as to assist in an assessment of levels of risk proposed for the asset operations.

2 Process Requirements

The analysis is to be conducted for all equipment and systems proposed for enrollment in the RCM Program. The Initial RCM Analysis is to be submitted to the responsible ABS Engineering Office for approval. Subsequently, Annual RCM reports are to be prepared for review by the attending Surveyor at the Annual Confirmation Survey.

2.1 Overview

A detailed study of the system(s) or machine(s) subject to RCM analysis is to be made through the use of system drawings; equipment item drawings; documents containing maintenance requirements for systems, equipment items or components; and operator experience.

2.2 Reliability Team

A list of team members supporting the Reliability-Centered Maintenance process is to be documented in accordance with Reliability Team Requirements (see 1/6).

2.3 Procedures

2.3.1 Operating Modes and Context

To properly define operating characteristics, the various operating modes for the asset or equipment are to be identified. Operating contexts are to be developed for each level of the machinery hierarchy. An example of an operating mode, along with its operating context, is provided in A1/9 TABLE 2.

2.3.2 System Definition

Each system selected for RCM analysis is to be defined. The system definition involves (1) partitioning the asset's functional groups into systems, subsystems (as necessary due to complexity), equipment items and components, and (2) further development of the narrative description for each functional group, system, equipment item and component.

2.3.3 System Block Diagrams and Functions

The functions for the functional groups, systems, equipment items and components are to be identified. When identifying functions, the applicable operating modes and the operating context is to be listed. All functions are to be identified.

Block diagrams are to be developed showing the functional flow sequence of the functional group, both for technical understanding of the functions and operation of the system and for subsequent analysis. As a minimum, the block diagram is to contain:

- i) The partitioning of the functional group into systems, equipment items and components
- ii) All appropriate labeled inputs and outputs and identification numbers by which each system is consistently referenced
- iii) All redundancies, alternative signal paths and other engineering features that provide “fail-safe” measures

2.3.4 Identification of Functional Failures

A list of functional failures for each function identified in 4/2.3.3 is to be identified for each functional group, system, equipment item and component.

Each functional failure is to be documented in a functional failure statement that contains a verb, object and the functional deviation. Example Functions and Functional Failures are given in A1/9 TABLE 3.

2.3.5 Failure Mode Effects and Criticality Analysis (FMECA)

The FMECA is to be considered using the bottom-up approach, starting from the lowest level of detail identified during the system partitioning. A sample bottom-up FMECA format is shown in A1/9 TABLE 4.

2.3.6 Selection of the Failure Management Tasks

All causes of each failure mode are to be evaluated. Appropriate failure management tasks are to be selected for all corrective measures. All manufacturers’ maintenance recommendations are to be considered during the selection of the failure management tasks. If changes or deletions to the manufacturers’ recommendations are made, these are to be documented in the analysis.

The Task Type is to be identified as follows: Condition Monitoring (CM), Planned Maintenance (PM), Combination of CM and PM (CM/PM), Failure Finding (FF), One-time Change (OTC), Run-to-Failure (RTF), Any Applicable and Effective Task (AAET).

2.3.7 Critical Spares Holding Determination

For the proposed maintenance schedules to be viable, it is essential the spares that support the identified maintenance tasks are available at the appropriate time.

2.3.8 Sustainment Plan

For the sustainment planning, the plan for continued improvement shall be submitted to the ABS Engineering Office. The results of the sustainment activities must be maintained onboard for verification at annual surveys. See 5/4.

3 Plans and Data to be Submitted

3.1 RCM Analysis Documentation

For each step, the following topics are to be documented:

- i) The results of the analysis step
- ii) The decision tools used

- iii)* Any other pertinent information related to the step (e.g., assumptions, equipment excluded from the analysis)

Based on the maintenance tasks identified in the RCM analysis, a maintenance plan is to be developed and documented in accordance with Subsection 5/3.

The documentation for the FMECA analysis, maintenance and spares holding plans and sustainment process are to be preferably in an electronic format, although paper copies will be accepted.

The following information is to be submitted to an ABS Engineering Office for review.

3.1.1 Operating Modes/Context

Operating modes, as applicable, within normal design environmental conditions (see 4/2.3.1).

3.1.2 System Definitions

A narrative description for each level of indenture and the corresponding functional requirements is to be documented (see 4/2.3.2).

3.1.3 System Block Diagrams/Functions/Failures

The functions for the functional groups, systems, equipment items and components are to be identified (see 4/2.3.3).

A list of functional failures for each function identified is to be identified for each functional group, system, equipment item and component (see 4/2.3.4).

3.1.4 FMECA

The failure modes effects and criticality analysis shall be conducted as specified in 4/2.3.5 and following documentation submitted:

- i)* Identification of failure modes and their causes
- ii)* Evaluate the effects on the system of each failure mode
- iii)* Identification of failure detection methods
- iv)* Identification of corrective measures for failure modes
- v)* Criticality analysis

3.1.5 Failure Management Tasks

Appropriate failure management tasks are to be selected for all corrective measures (see 4/2.3.6). A maintenance task summary with the information indicated in A1/9 TABLE 10 is to be submitted.

3.1.6 Critical Spare Parts Holding

A spare parts holding determination summary with the information indicated in A1/9 TABLE 11 is to be submitted. 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 parts necessary to perform tasks to correct each failure mode identified in the reliability analysis as follows:

- i)* Parts necessary to perform tasks to correct each failure mode identified in the reliability analysis.
- ii)* 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.
- iii)* An evaluation of the effects on the functional group or system’s operational availability if an out-of-stock condition occurs.

- iv) 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.
- v) Lead time required for ordering a part out of stock

3.1.7 Sustainment Plan

The procedures and processes used by the operator to sustain the preventative maintenance plan are to be developed and submitted (see 4/2.3.8).

3.2 Maintenance Plan

3.2.1 List and Description of the Machinery

A table listing the owner's equipment item name and the equivalent ABS Survey Manager name is to be provided for reference.

3.2.2 For Items to be Enrolled in ABS Preventative Maintenance Program

- *Planned Maintenance*: Refer to 7-A1-14/13.5.1 of the *ABS Rules for Survey After Construction (Part 7)*
- *Condition Monitoring*: Refer to 7-A1-14/15.5.1 of the *ABS Rules for Survey After Construction (Part 7)*

3.2.3 For Items on Alternate Applicable Maintenance Tasking

The applicable items from 4/3.2 and the maintenance sheet(s) for each machine/system considered.

SECTION 5

In-Service Application and Operations

1 Principles of Maintenance and Sustainment

Owners and operators are to maintain their vessels and marine structures with updated machinery maintenance practices, which may increase the reliability and/or operational availability. Proper documentation is to be maintained and available onboard with an effective sustainment program in place.

In some cases, the chosen maintenance practices may include equipment and/or system firmware or software updates via cyber-enabled systems. Refer to the *ABS Guidance Notes on the Application of Cybersecurity Principles to Marine and Offshore Operations – Volume 1: Cybersecurity* for information on this topic.

2 Onboard Documentation

The Chief Engineer or maintenance supervisor shall be the responsible person onboard the vessel or offshore floating unit in charge of the Maintenance Program. If a computerized system is used for storing the maintenance documentation and maintenance program, access is to be controlled with user authorizations as directed by the Chief Engineer or Maintenance Supervisor. The following information is to be available onboard.

2.1 All Programs

- i) A copy of the ABS approval letter for program enrollment (RBM, RCM, PMP).
- ii) A copy of the reviewed maintenance plan (PM and CM)
- iii) All records showing compliance with the program, including a copy of the most recent Owner's annual report are to be made available for review by the Surveyor at the Annual Survey – Machinery.

2.2 Condition Monitoring

The latest up-to-date information required in 7-A1-14/15.7.1 of the *ABS Rules for Survey After Construction (Part 7)*.

2.3 Planned Maintenance

The latest up-to-date information required in 7-A1-14/13.7.1 of the *ABS Rules for Survey After Construction (Part 7)*.

2.4 Any Other Applicable and Effective Tasks

The applicable items listed in 5/2.1, 5/2.2 and 5/2.3.

2.5 Spares Holding

If enrolled in RCM or RBM, records for required critical spare parts, inventory on hand and ordering procedures to procure additional spare parts are to be readily available.

2.6 Sustainment

If enrolled in RCM or RBM, records of sustainment activities in accordance with 5/4 are to be readily available.

3 Preventative Maintenance Program

A properly conducted preventative maintenance plan may allow enrolled equipment to be credited as satisfying the requirements of Special Continuous Survey of Machinery. Increased operational testing may be required to satisfy Survey requirements.

This plan must be in accordance with Section 7-A1-14 “Surveys Based on Preventative Maintenance Techniques” of the *ABS Rules for Survey After Construction (Part 7)*.

4 Sustainment Activities

The RBM and RCM Programs require ABS Engineering Office review of sustainment planning. The results of the sustainment activities must be maintained onboard for verification by the attending Surveyor at annual surveys.

4.1 Sustainment Documentation Requirements

For sustainment plans applying the following items, the item must include at a minimum:

- i) *Trend Analysis*. Condition and Performance monitoring tasks are specified for trend analysis.
 - Equipment identification;
 - Data to be collected; and,
 - Pre-determined limits identified for the data when the condition-monitoring tasks are developed indicating those maintenance actions to be taken when data are outside of the limits.
- ii) *Maintenance Plan Review*
 - *Maintenance Requirement Document Reviews*. Documents containing maintenance requirements for systems, equipment items or components are to be reviewed at least annually to identify outdated maintenance processes, techniques or technologies, or to bring attention to obsolete tools and outdated spare parts.
 - *Task-packaging Reviews*. 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 intervals to verify that as maintenance tasks are added, deleted or modified, optimum packaged intervals are maintained
 - *Age-exploration Tasks*. When insufficient age-to-failure data is available or assumed data is used during the initial RCM or RBM analysis, age exploration tasks are to be designed and implemented
- iii) *Failures*. A record is to be maintained of failure analyses conducted, and any changes to the affected maintenance task(s) or one-time changes to the equipment item/component.
- iv) *Relative Ranking Analysis*. A relative ranking analysis can be developed for those items having the highest operational cost or cost impact.
- v) *Sustainment Result Implementation*

- A record is to be maintained of the results of other activities conducted that result in changes to the reliability analysis and/or maintenance tasks. The attending ABS Surveyor must be notified of these changes. The ABS Surveyor may require the analysis or task changes be submitted to the responsible ABS Engineering Office that performed the initial review.
- 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 or RBM 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.

5 Annual Reporting Requirements

In addition to the onboard documentation, the Owner or designated representative (Chief Engineer or Maintenance Supervisor) is to present an Annual Report to the attending Surveyor for review and verification at the time of the Annual Confirmation Survey covering the following:

5.1 Annual Reliability Programs Report

The annual report is to be submitted in a paper or electronic format. Prior to submitting electronic reports, the submitter is to confirm the attending Surveyor has the necessary software to review the reports.

5.1.1 Equipment Item Changes

If the machinery included in the Program has changed, this is to be stated. Any machinery to be added to the system is subject to the requirements of the Program and approval by the responsible ABS Engineering Office and the attending Surveyor. Also, the asset's Owner is to advise Corporate Document Classification and the attending Surveyor of any machinery to be deleted from the Program.

5.1.2 Maintenance Plan Changes

If during the sustainment process the time intervals for maintenance task needs to be altered, then documentation that supports the change in interval are to be submitted to the attending Surveyor for review and acknowledgement.

5.1.3 Maintenance Plan Details

- Condition Monitoring Tasks: 7-A1-14/15.5.1(a) of the ABS Rules for Survey After Construction (Part 7)*
- Planned Maintenance Tasks: 7-A1-14/13.5.1(a) of the ABS Rules for Survey After Construction (Part 7)*

5.1.4 Sustainment Activities

Records of sustainment activities are to be available for the ABS Surveyor and a summary included in the annual report. The results of relative ranking analyses, trend analyses, maintenance requirements document reviews, task packaging reviews, age exploration tasks and failure investigations of all unscheduled maintenance and/or breakdowns are to be provided. Sustainment activities can be conducted ashore as long as some shipboard personnel, who have been participating in the RCM program aboard the subject vessel or marine structure, are involved in the sustainment activities.

5.1.5 Report Exceptions

The Owner is to advise the attending Surveyor of all machinery for which maintenance is not indicated, is incomplete, or when additional monitoring is needed for machinery with vibration readings above those in the approved baseline. If either of the above mentioned situations occurs, the condition of the machinery is to be to the satisfaction of the attending Surveyor.

SECTION 6 Surveys

1 Implementation Survey (2023)

Implementation Surveys of machinery based on RBM or RCM reliability maintenance techniques are to comply with the requirements of Section 7-A1-14 of the *ABS Rules for Survey After Construction (Part 7)*.

1.1 Preventative Maintenance Requirements

1.1.1 Planned Maintenance (2023)

Planned Maintenance plans are to be reviewed by the attending Surveyor. The survey will be in accordance with 7-A1-14/11.1 of the *ABS Rules for Survey After Construction (Part 7)*.

1.1.2 Condition Monitoring (2023)

Condition Monitoring plans are to be approved by the responsible ABS Engineering Office. The survey will be in accordance with 7-A1-14/11.3 and 7-A1-14/11.5 of the *ABS Rules for Survey After Construction (Part 7)*.

2 Annual Requirements

2.1 Annual Confirmation Surveys (2023)

Surveys of machinery that have been accepted for surveys based on RBM or RCM reliability maintenance techniques are to comply with the requirements of Section 7-A1-14 of the *ABS Rules for Survey After Construction (Part 7)*.

1 Information

1.1 Program Entry and Fees

Fees include the cost of the initial review and entry into the program. For information regarding entry into the program, contact:

Classification and Documentation Center

American Bureau of Shipping

1701 City Plaza Dr

Spring, TX 77389

Attn: Assistant Chief Surveyor

Telephone: 281-877-6000

1.2 Service Supplier

For information on becoming an ABS Service Supplier, please contact:

American Bureau of Shipping

1701 City Plaza Dr

Spring, TX 77389

Attn: Service Supplier Coordinator

Telephone: 281-877-6000

2 ABS Offices Responsible for Machinery Reliability and Maintenance Programs

ABS Corporate

American Bureau of Shipping

1701 City Plaza Dr

Spring, TX 77389

Attn: Director, Asset Integrity Management

ABS North American Region
American Bureau of Shipping
1701 City Plaza Dr
Spring, TX 77389

Attn: Manager, ABS Programs

ABS Europe and Africa Region
ABS House
No. 1 Frying Pan Alley
London, E1 7HR, England

Attn: Manager, Machinery Engineering Services

ABS Middle East Region
Al Joud Center 1st Floor, Suite #111
Sheikh Zayed Road
P.O. Box 24860,
Dubai United Arab Emirates

Attn: Manager, Machinery Engineering Services

ABS Greater China Region
5th Floor, Silver Tower
No.85 Taoyuan Road
Huang Pu District

Shanghai, 200021 P.R. China

Attn: Manager, Machinery Engineering Services

ABS North Pacific Region

11th Floor,

Kyobo Life Insurance Building, 7,

Chungiang-Daero,

Jung-Gu, Busan, 48939,

Republic of Korea

Attn: Manager, Machinery Engineering Services

ABS South Pacific Region

438 Alexandra Road,

#10-00 Alexandra Point,

Singapore 119958

Republic of Singapore

Attn: Manager, Machinery Engineering Services

APPENDIX 1

Guidance on Lifecycle Reliability Principles

1 General

This Appendix provides details and sample lifecycle reliability processes that can be created and managed by the client or executed in collaboration with ABS.

2 Detailed Lifecycle Reliability

Reliability processes can be applied in multiple phases of an asset's lifecycle. To improve the inherent reliability of an asset, ABS recommends a multi-step process to achieve a client's reliability objectives (see A1/2 FIGURE 1). These activities align with the Asset Life Cycle.

FIGURE 1
Lifecycle Maintenance Management Activities



Details on each phase of an asset life and the associated ABS processes are explained in the proceeding sections of this Guide. The lifecycle program must be aligned to the applicable lifecycle phases and activities that are summarized herein.

Additionally, this program must support the class requirements associated with our engineering and survey work processes.

3 Design for Reliability and Procurement Strategies

3.1 Overview of Design for Reliability

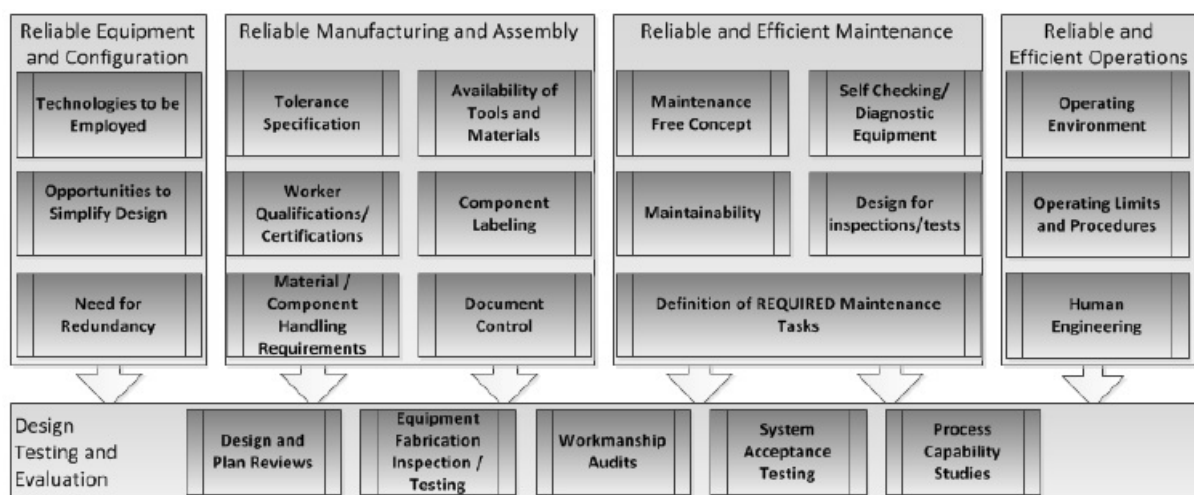
DFR utilizes reliability/risk analyses to improve reliability-related performance to a predetermined value. It also provides a structure for applying these reliability/risk analysis tools throughout the design process to provide the information needed by the designer to make more informed design or procurement decisions. The fundamental premise of this procedure is to perform the appropriate level of analysis necessary at each stage to support the decision-making needs. This could enable optimized design, integrated features, and/or technology that will support minimizing operational disruption from maintenance, inspection, and survey of equipment. The design approach can seek to achieve a number of objectives:

- Improving equipment and configuration reliability through their arrangements,
- Designing to simplify manufacturing and assembly,
- Forecasting the design needs anticipated for operations, maintenance, and inspection,
- Generating a testing and evaluation plan to confirm and validate the changes in design

Clients supporting and engaging OEMs in developing schemes for equipment and system designs may also produce data/information to monitor and potentially extend the lifecycle of key equipment. This will allow the client to procure more than just quality components but also an OEM supplying supportive services and capabilities that enable an optimized and Class approved maintenance scheme. This combined approach provides better performance and reliability while avoiding disruptive activities and assisting in making better informed maintenance decisions.

Procurement specifications are an essential and integral tool during the design phase of an asset lifecycle. It is also understood that input into the OEM Procurement Specification that illustrates the features of their equipment and services that can contribute to the project wide vision for asset reliability is required. Well-developed procurement specifications for critical equipment can help establish an asset base and OEM partner program which will help provide the technical and support infrastructure necessary to effectively implement a world class reliability program.

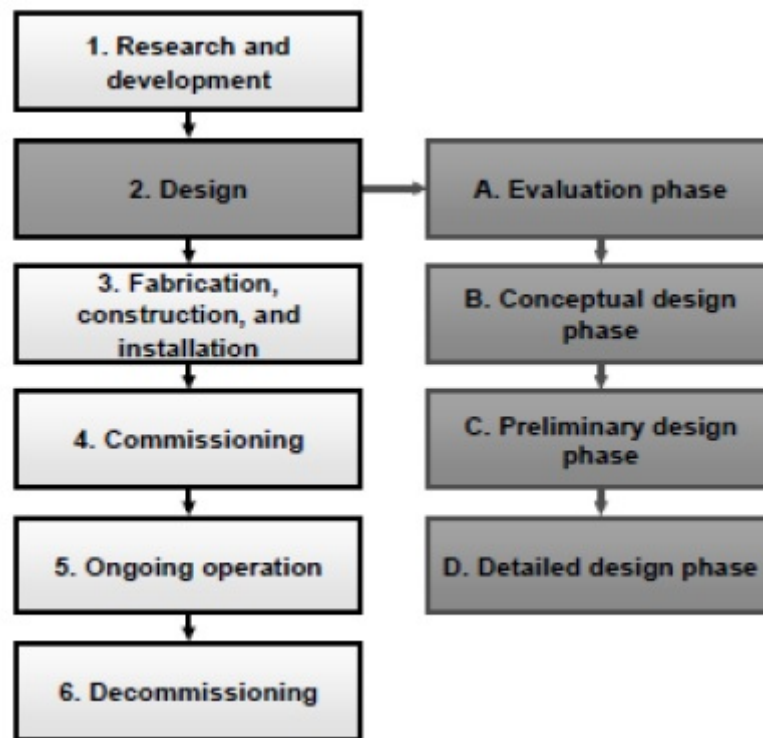
FIGURE 2
Design for Reliability Process



3.2 Design Phases

Design involves selecting and applying technologies to meet operational needs. The engineering design process consists of four phases: Evaluation, Conceptual, Preliminary, and Detailed.

FIGURE 3
Asset Lifecycle – Design Phase



3.2.1 Evaluation Phase

The evaluation phase is the beginning phase of the design process. It involves assessing the general needs/requirements for the new process/system/component and evaluates the technologies that may be employed to satisfy those needs/requirements. The key determinations from this phase are whether this project should be pursued, specific objectives for the project, and the fundamental project direction.

3.2.2 Conceptual Phase

The conceptual phase is an intermediate phase of the design process. This requires the investigation and proposal of the “best” type of process configuration for the project. It involves choices of general types of processes, interconnections between equipment, ranges of expected operating conditions, and the operating environments.

3.2.3 Preliminary Phase

The preliminary phase is another intermediate phase of the design process. This phase expands the conceptual design by finalizing choices about the types and numbers of various components/equipment, produces drawings that define component/equipment configuration, defines process parameters, and evaluates impacts of tie-ins to other systems and processes. A key step in the preliminary phase is the specific preplanning for how the asset will be operated and maintained.

3.2.4 Detailed Phase

The detailed phase is the final stage of the design process. It involves final choices about specific components of the process and the layout. This requires the development of a complete

specification of the process including complete documentation of the design, preparation of equipment files, development of commissioning and operating procedures/instructions, development and scheduling of planned maintenance and operator tasks for the process, as well as selection of spare parts stocking strategy for the process.

FIGURE 4
Application of DFR in Design Phases

Strategy	Evaluation Phase	Conceptual Phase	Preliminary Phase	Detailed Phase
Design for reliable equipment/configuration	✓	✓	✓	✓
Design for reliable manufacturing/assembly			✓	✓
Design for reliable and efficient maintenance	✓		✓	✓
Design for reliable and efficient operations	✓	✓	✓	✓
Proving designs through testing and evaluation				✓

3.3 Design For Reliability (DFR) Approaches

The key activities of DFR are initiated based on establishing the key objectives for improving reliability. The objectives for improving reliability via design changes are shown in A1/2 FIGURE 1. The chosen path can employ one or a combination of the objectives described (A-D). All design for reliability activities need to establish a testing and evaluation plan to validate function and reliability requirements. Sample approaches that align with these objectives are covered in the following Subsections.

TABLE 1
Reliability Objectives in Design

<i>A: Equipment and Configuration</i>	<i>B: Manufacturing and Assembly</i>	<i>C: Efficient Maintenance</i>	<i>D: Efficient Operations</i>
The inherent potential of an asset to perform reliably is referenced by the technology of the equipment employed and the degree of redundancy. The design process needs to evaluate the level of redundancy required to achieve targeted process availability.	Designing to help reliable manufacturing and assembly of the asset that helps lead to reliable performance. Equipment and process specifications need to anticipate sources of variability and try to minimize process sensitivity to such variability.	Incorporating future maintenance of the asset into the design is vital to maintaining the inherent reliability and capability of the process throughout its life.	Designers should consider the interaction between the operator and equipment with focus on designing systems that reduce likely human error. The designers must consider the environment in which the process is being operated to minimize equipment vulnerabilities. The environment includes location, maintenance envelope, and accessibility of the equipment.

3.3.1 Design for Reliable Equipment/Configuration Approaches

- i) *Critical System/Equipment Functions.* Reliability work focuses on preserving system/component functions. The important process/system/component functions need to be clearly and completely defined if reliability efforts are to be successful.
 - Functions
 - Mission time (service life)
 - Life cycle operating conditions (each mode of operation)
 - Environments
 - Transients
- ii) *Life Characteristics of Components.* The reliability of systems and processes are ultimately dependent on the reliability of the components that comprise the systems/processes, as well as the reliability of the people who interact with the equipment. Being able to describe the life characteristics of components is critical to assuring reliability-related performance of those components.
 - Equipment failure fundamentals. A basic understanding of how equipment fails and the prominent component failure mechanisms for classes of equipment
 - Statistical characterizations. A statistical description of component life over a period of operation, including failure rate, failure density, and reliability characterizations
- iii) *Effects of Component/System Configuration.* Understanding the life characteristics of individual components alone is not enough. The arrangement of the components in a system/ process also strongly influences system/process reliability-related performance. Being able to select appropriate component configurations to enhance reliability-related performance for specific applications is important in the design process.
 - Basic Component/System Configurations (Series/Parallel)
 - Active Redundancy
 - Standby Redundancy/Safeguards
- iv) *Best Practices for Reliable Equipment/Configuration.* In each decision, project engineers need to be aware of the key issues that drive component reliability.
 - Establishing suitability of service
 - Specifying Service Life
 - Using Novelty and Complexity in Equipment/applications Prudently
 - Incorporating Damage Tolerance
 - Managing Performance Trade-offs
 - Documenting the Design

3.3.2 Design for Reliable Manufacturing/Assembly Approaches

- i) *Multi-disciplined Teams and Early Input.* The designer should incorporate a multi-disciplined team approach from project inception.
- ii) *Reduction of Parts.* Simplify the design as much as possible (use the minimum number of parts and have parts made with the minimum number of fabrication operations).
- iii) *Connections and Flexible Parts.* The designer should work to reduce the number of flexible parts and interconnections.
- iv) *Fabrication.* The designer should take steps to design for ease of fabrication.

- v) *Mistake-proof Product Design and Assembly.* Design the product such that the assembly process is unambiguous (by designing components so that they can only be assembled one way).
- vi) *Geometric Dimensions and Tolerances.* Geometric dimensioning and tolerances contributes to the most economical and effective production of parts with features that offer function and have proper relationships. The design process must also specify the acceptable tolerances of manufactured components and the assembly of components.
- vii) *Assembly Complexity.* Design the components such that the assembly of the parts is as simple as possible.
- viii) *Design Tools.* Provide the designer with the right tools to perform the work.
- ix) *Leadership.* The company's leadership should acquire an intimate, detailed knowledge of all the tools and should have "hands-on" experience on project teams.
- x) *Outside Organizations.* Companies use outside organizations for what Deming called profound knowledge.
- xi) *Training.* People will not think of new ways to do their jobs or use new rules without training.
- xii) *Worker Qualifications/Certifications.* The design process must specify any qualifications or certifications that workers must have to manufacture or assemble the components.
- xiii) *Handling Requirements.* Any special handling requirements for components must be specified and controlled.
- xiv) *Availability of Tools/Materials.* The design specifications must be consistent with the tools and materials that will be available to manufacture or assemble components.
- xv) *Component Labeling.* The design specification should include labeling requirements for components and materials so that they can be easily and properly identified by personnel.
- xvi) *Documentation.* The design process must specify and control documentation and use appropriate Language in doing so.
- xvii) *Customer Operations.* Design with the customer's operations in mind.

3.3.3 Design for Reliable and Efficient Maintenance Approaches

- i) *Maintenance-free Concept.* The most reliable and least costly (especially over a lifecycle) maintenance task is the one that never has to be performed; therefore, equipment or equipment components that require no maintenance (e.g., sealed bearings) or have extended frequency between maintenance intervals (e.g., the new engines that run thousands of hours before the first tune-up) should be evaluated and used whenever possible.
- ii) *Self-checking Equipment.* Equipment that possesses self-checking and diagnostic features that identify failures (preferably prior to system degradation) is the next best option. This potentially provides the opportunity to correct problems prior to impacting system performance or to reduce the downtime required for troubleshooting the problem (especially for complex systems).
- iii) *Maintainability Issues.* To confirm that maintenance tasks can be performed reliably and efficiently, the design should be evaluated to assess whether common maintainability issues have been introduced into the design. For example, a checklist could be used to evaluate the design to verify that maintainability issues, such as equipment accessibility, adjustments, equipment labeling, etc., have been appropriately included in the design.
- iv) *Design for Inspections/Tests.* For equipment on which inspection and tests are going to be performed, the ability to perform the inspection and test in an efficient and reliable manner should be incorporated into the design. For example, if corrosion is a failure of

interest, the process can be designed to have on-line analysis of the corrosion via instrumentation and to accommodate on-stream inspections (by providing cut outs in the insulation for corrosion monitoring). Similar applications exist for other condition monitoring technologies such as on-line vibration monitoring.

- v) *Definition of Required Maintenance Tasks.* Defining the maintenance tasks for the system during the design phase is beneficial because it helps (1) allocate maintenance resources prior to startup and operation of the process, (2) identify equipment failure modes targeted for maintenance, thus providing the designers with the opportunity to adapt the design (e.g., eliminate the failure mode if possible), (3) identify maintenance technology requirements that need to be incorporated into the design (e.g., vibration taps on rotating equipment), and (4) develop lists of tasks that should be evaluated for maintainability issues. This process should result in a list of applicable and effective planned maintenance tasks for the process. This list is generally developed using reliability analysis tools such as risk derived maintenance, reliability-centered maintenance (RCM), or risk-based inspection.
- vi) *Maintenance Procedures.* Maintenance procedures are among the key elements for ensuring reliable performance of the personnel maintaining the system. Developing maintenance procedures during the design phase helps to (1) identify maintenance training requirements, (2) reduce the unreliable performance caused by mistakes during equipment maintenance, and (3) define the approved method for maintaining the system.
- vii) *Maintenance Training.* Providing maintenance personnel with adequate training equips each team member with the knowledge necessary to adequately maintain the system. Developing some of the training content during the design phase will help the design team define any special requirements (e.g., education, experience, physical strength) for maintenance personnel. Defining such requirements will help to provide the future maintenance team with the expertise to maintain the system and enhance reliability.
- viii) *Computerized Maintenance Management System.* A computerized maintenance management system (CMMS) provides a means to organize and track vast amounts of data to provide useful information to maintenance personnel. The system can help to (1) facilitate the planning and scheduling of work, (2) control work orders, (3) track necessary preventive maintenance, and (4) provide continuous accurate reporting for better decision making. Managing these types of maintenance tasks can greatly enhance system reliability by reducing maintenance costs and increasing maintenance efficiency.

3.3.4 Design for Reliable and Efficient Operations Approaches

- i) *Operating Environment.* The operating environment can create both equipment vulnerabilities and error-likely situations. The design must anticipate the range of environmental conditions (e.g., temperature, humidity, vibration) to which the process and its operators will be exposed.
- ii) *Operating Limits.* The operating limits of the system (i.e., manufacturing process tolerances) can impact the reliable performance of a system. For reliable performance, the design process must confirm that (1) the system and individual equipment items are designed to satisfy current (as well as anticipated) operating limits and (2) the operating limits of the system and its equipment are defined and documented.
- iii) *Operating Procedures.* Operating procedures are among the key elements for ensuring reliable performance of the personnel operating the system. Developing operating procedures during the design phase (and evaluating the procedures and design together) is needed to (1) ensure that the design is compatible with the anticipated operation, (2) help reduce the unreliable performance caused by misoperation of the equipment, and (3) define the approved method for operating the system.
- iv) *Human Engineering Issues.* Another aspect of designing a process for reliable and efficient operation is to reduce situations that will likely lead to human errors. Workplace

layout, workload, and tolerance of the system to errors are three major areas of the design where error-likely situations can be addressed. Each of these areas should be evaluated to identify potential errors that may result in unreliable system performance. The design can then be modified to help eliminate the error and/or mitigate its consequence.

- v) *Operations Training.* Providing operators with adequate training equips personnel with the knowledge necessary to operate the process. Developing some of the training materials during the design phase will help the design team to understand how potential process upsets or emergency situations may occur and how an operator is expected to respond. Knowledge of this information allows the design team to make modifications to reduce the opportunity for these upset/emergency situations and incorporate additional safeguards or alternate measures that can be taken to prevent or mitigate the effects of undesirable consequences.
- vi) *Material Logistics.* Involves the movement of material into, within, and from an asset, and is critical to efficient operation. Considering logistics planning during the design phase will help to ensure that packaging, warehousing, receiving, and loading facilities are located with adequate attention to material movement requirements. Incorporating these issues into the design will help to minimize congestion, safety hazards, operating inefficiencies, and high cost that are so often associated with poor logistics planning.
- vii) *Definition of Staffing Requirements/Operating Basis.* Providing an adequate number of trained personnel to operate the process is very important to system reliability. Also, determining the number of shifts of operation and shift rotations for the facility during the design phase will help to ensure that the design incorporates specific features to prevent various types of human errors that are more likely to occur during certain shifts.
- viii) *Visual Management.* Incorporating visual management into the design process can greatly enhance system reliability. A workplace that is cluttered, dirty, and disorganized is a breeding ground for accidents, misplaced items, machine downtime, defects, rework, and scrap. Visual management allows individuals and teams to achieve “visual order,” which consists of implementing simple, low-cost, high-impact mechanisms that share vital information rapidly, accurately, and completely, without the need to speak or read a word.
- ix) *Error-proof Operations.* Designing the process so that specific operational errors cannot be made inherently improves system reliability. Errors create waste, which interrupts process flow. The system should be designed so that the process automatically detects abnormal conditions during critical operations and alerts the operators or shuts down the process.

3.3.5 Proving Designs through Testing and Evaluation Approaches

- i) *Design Reviews.* A team knowledgeable about the design, requirements, and design standards assesses the design’s compliance with published design standards and codes, and verifies adherence to good engineering practices.
- ii) *Component/Fabricated Parts Tests and Inspections.* Critical components and fabricated parts are tested and inspected before higher-level assembly to verify that required component and fabricated part design specifications have been achieved.
- iii) *Workmanship Audits.* Installation processes are field-verified to confirm that the fabricated parts and critical components are assembled and configured according to the design specifications.
- iv) *System/Subsystem Acceptance Testing.* As each subsystem is assembled, the subsystem is tested to verify performance and adherence with design specifications. The system itself is tested to verify performance before actual production.
- v) *Process Capability Testing.* The system is operated as intended, and capability and efficiency measurements are made to verify performance within expected design parameters.

management of assets versus spare parts and items such as work order data are not too granular. Industry examples for defining an asset are listed below:

- It is related to a defined business desire or requirement to track maintenance costs
- It is regularly maintained in order to preserve the function for which it was acquired
- It is repaired rather than replaced when it fails
- It is within the scope of regulatory requirement to track performance or maintenance history

5.3 Operating Modes and Context

To properly define operating characteristics, the various operating modes for the asset or equipment is to be identified. The operating modes are used to define the operating context for each item identified in machinery list as follows:

- The physical environment in which the functional group is operated
- A precise description of the manner in which the functional group is used
- The specified performance requirements of the functional group as well as the required performance of any additional functional groups within which the functional group is interfaced

The development of the operating context is to consider system arrangements, performance or quality standards, environmental standards, safety standards and manner of operation. Operating contexts are to be developed for each level of the machinery hierarchy. An example of an operating mode, along with its operating context, is provided in A1/9 TABLE 2.

All operating modes, as applicable, within normal design environmental conditions are to be considered. The following operating modes are typical for ships:

- i)* Normal seagoing conditions at full speed
- ii)* Maximum permitted operating speed in congested waters
- iii)* Maneuvering alongside
- iv)* Cargo handling

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

- i)* Drilling operations
- ii)* Position mooring or station keeping
- iii)* Relocation/towing
- iv)* Hydrocarbon production and processing
- v)* Import and export functions

The functional interdependence of the selected systems within functional groups shall be described through the use of block diagrams or fault-tree diagrams or in a narrative format to enable failure effects to be understood. A list of failure modes for each of the systems to be analyzed is to be developed.

5.4 Criticality Ranking Execution

The ability to prioritize or rank assets to optimize the utilization of resources, from both strategic and tactical perspectives, is a key concept of RBM. This process is the prioritization of all assets based on critical factors such as safety, quality, environmental impact, operational throughput, operation cost, and/or current reliability. Steps in executing criticality assessment are as follows:

- Components for criticality assessment (e.g., disruptive survey requirements, failure leading to shutdown)
- Factors for each component (e.g., operational throughput, utilization, quality, detection risk)
- Criteria and scoring for each factor
- Weighting for each factor
- Scoring calculation for each component
- Scoring calculation for assessment
- Determine score groupings for bulk analysis (e.g., classification, percentile, quartile)

5.5 Maintenance Development Strategy

Developing an effective maintenance plan assists in the uptime reliability of an asset at the planned operational cost and coordinates the utilization of maintenance resources by dedicating them to the execution of high value maintenance activities. The criticality ranking drives which maintenance strategies should be applied to an asset, and results in a complete maintenance plan for later execution. The varying levels of maintenance strategy are described below in order from the most effective to the least effective:

- *Failure Modes and Effects Analysis (FMEA)*. This process is a review of asset sub-assemblies and components to identify failure modes followed by their causes and effects. Each failure mode has a risk calculation performed to prioritize and quantify the level of remediation required. Remediation tasks are developed where non-disruptive predictive technologies are to be applied as the primary option.
- *Maintenance Task Analysis (MTA)*. This process reviews all previous asset maintenance and performance records with the objective to reaffirm or select replacement value added maintenance tasks. The process starts with review of maintenance tasks and intervals and then identifying failure modes addressed by each task. Tasks are then revised or replaced based on the consequence and feasibility of the tasks to remedy or monitor the failure mode.
- *Basic Strategy Development (BSD)*. This strategy is a review of the current maintenance tasks and the affiliated job plans that are already in place to develop a standard to be followed based on utilizing the current content. If no current content exists, Original Equipment Manufacturer (OEM) recommendations will be the baseline for standard development.
- *Run to Failure (RTF)*. This strategy allows the asset to operate until a failure occurs followed by replacement of the failed component(s).

The application of each of these strategies is to be aligned to the previously conducted criticality analysis and ranking.

5.6 Critical Spare Part Identification

The scope for identification of critical spare parts is to be focused on component failure as it impacts operations. There are procurement factors which can also drive classification of a spare part, deeming it more or less important. The primary factors that determine if a spare part is identified as critical are as follows:

- The component is directly linked to a failure mode that has a high risk calculation or failure consequence.
- The component failure causes the asset to cease operation or operate at an unsatisfactory level of performance.

6 Reliability Centered Maintenance

6.1 Overview

A detailed study of the systems subject to RCM analysis is to be made through the use of system drawings; equipment item drawings; documents containing maintenance requirements for systems, equipment items or components; and operator experience.

6.2 Operating Modes and Context

6.2.1 Operating Modes

To properly define operating characteristics, the various operating modes for the asset or equipment is to be identified. The operating modes are used to define the operating context for each item identified in machinery list as follows:

- The physical environment in which the functional group is operated
- A precise description of the manner in which the functional group is used
- The specified performance requirements of the functional group as well as the required performance of any additional functional groups within which the functional group is interfaced

The development of the operating context is to consider system arrangements, performance or quality standards, environmental standards, safety standards and manner of operation. Operating contexts are to be developed for each level of the machinery hierarchy. An example of an operating mode, along with its operating context, is provided in A1/9 TABLE 2.

All operating modes, as applicable, within normal design environmental conditions are to be considered. The following operating modes are typical for ships:

- i)* Normal seagoing conditions at full speed
- ii)* Maximum permitted operating speed in congested waters
- iii)* Maneuvering alongside
- iv)* Cargo handling

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

- i)* Drilling operations
- ii)* Position mooring or station keeping
- iii)* Relocation/towing
- iv)* Hydrocarbon production and processing
- v)* Import and export functions

The functional interdependence of the selected systems within functional groups shall be described through the use of block diagrams or fault-tree diagrams or in a narrative format to enable failure effects to be understood. A list of failure modes for each of the systems to be analyzed is to be developed.

6.2.2 Operating Context

To properly define operating characteristics, the various operating modes for the asset or equipment must be identified. To define the operating context for each functional group, the operating modes are to be used.

For each operating mode, the operating context under which the functional group is expected to operate is to be fully described as follows:

- 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 requirements of the functional group as well as the required performance of any additional functional groups within which the functional group is interfaced.

The development of the operating context is to consider system arrangements, performance or quality standards, environmental standards, safety standards and manner of operation. Operating contexts are to be developed for each level of the machinery hierarchy. An example of an operating mode, along with its operating context, is provided in A1/9 TABLE 2.

6.3 System Definition

Each system selected for RCM analysis is to be defined. The system definition involves (1) partitioning the vessel's functional groups into systems, subsystems (as necessary due to complexity), equipment items and components, and (2) further development of the narrative description for each functional group, system, equipment item and component. An example partitioning for a vessel's machinery is provided in A1/9 FIGURE 8.

A narrative description for each level of the hierarchy and the corresponding functional requirements is to be developed, providing the following information:

- i)* A general description of operation and structure
- ii)* The functional relationship among the system/equipment items/components
- iii)* Acceptable functional performance limits of the system/equipment items/components for each operating mode considered
- iv)* Constraints

The partitioning is to be performed using a top-down approach until a level of detail is reached for which functions are identified with equipment items or components. The level of detail should be such that the equipment item or component:

- 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.

6.4 System Block Diagrams and Functions

The functions for the functional groups, systems, equipment items and components are to be identified. When identifying functions, the applicable operating modes and the operating context is to be listed. All functions are to be identified.

Function lists may be submitted by providing a list similar to that shown in A1/9 TABLE 3.

6.4.1 Block Diagrams

Block diagrams are to be developed showing the functional flow sequence of the functional group, both for technical understanding of the functions and operation of the system and for subsequent analysis. As a minimum, the block diagram is to contain:

- i)* The partitioning of the functional group into systems, equipment items and components;

- ii) All appropriate labeled inputs and outputs and identification numbers by which each system is consistently referenced;
- iii) All redundancies, alternative signal paths and other engineering features that provide “fail-safe” measures.

It may be necessary to create a different set of block diagrams for each operational mode

An example system block diagram is shown in A1/9 FIGURE 9.

6.4.2 System Functions

When identifying the function, the performance standard is to describe the minimum acceptable requirement for the operating context rather than the system or component’s design capability. Performance standards must be clearly defined or quantified, as they are used to define failure. Functions are to be categorized, as shown in A1/9 TABLE 3, as follows:

- i) *Primary Functions.* These functions are the reasons why the functional group/system/equipment item/component exist. For example, the primary function of the Propulsion Functional Group is to provide propulsion for a vessel; the primary function of the system, diesel engine, is to provide power to propel a vessel.
- ii) *Secondary Functions.* These functions are in addition to the primary functions. Examples of secondary functions for a diesel engine in the Propulsion Functional Group include emissions requirements for exhaust gases, fuel efficiency requirements and safety systems, such as over-speed trips and cylinder relief valves. The following functional categories are listed with some examples, as an aid in determining secondary functions for systems to be analyzed:
 - a) *Environment Integrity.* Equipment fluid or gaseous emissions limits subject to MARPOL or other regulations
 - b) *Safety, Structural Integrity.* Vibration, structural deflection, limits; safety of human operators/maintenance personnel
 - c) *Control, Containment, Comfort.* Equipment control, containment of fluids/gases in system, personal comfort of personnel
 - d) *Appearance.* Appearance of equipment to the operators/public
 - e) *Protection.* Devices to protect equipment from overspeed, high pressure or high temperature
 - f) *Economy, Efficiency.* Fuel efficiency, lubricating oil consumption
 - g) *Supplementary Functions.* Other functions unique to the functional group/system/equipment item/component

6.5 Identification of Functional Failures

A list of functional failures for each function identified in 4/2.3 is to be identified for each functional group, system, equipment item and component. Functional failures are to be identified using the following suggested failures, as appropriate:

- i) No or none of the function
- ii) Less than prescribed output of function
- iii) More than prescribed output of function
- iv) Intermittent operation of the function
- v) Premature operation of the function
- vi) Failure to operate function at a prescribed time

- vii) Failure to cease operation of the function at a prescribed time
- viii) Other functional failures appropriate for the functional group

Each functional failure is to be documented in a functional failure statement that contains a verb, object and the functional deviation. The functional failures are to be shown with the function lists similar to the example list in A1/9 TABLE 3.

6.6 Failure Mode Effects and Criticality Analysis (FMECA)

The FMECA is to be considered using the bottom-up approach, starting from the lowest level of detail identified during the system partitioning. A sample bottom-up FMECA format is shown in A1/9 TABLE 4.

The FMECA procedure is divided into the following steps:

- i) Identify all potential failure modes and their causes;
- ii) Evaluate the effects on the system of each failure mode;
- iii) Identify failure detection methods;
- iv) Identify corrective measures for failure modes;
- v) Assess the frequency and severity of important failures for criticality analysis, where applicable.

6.6.1 Identification of Failure Modes

A failure mode is the manner by which a failure is observed. It generally describes the way the failure occurs and its impact on the equipment or system. All of the equipment item or component-related causes of the identified failure modes are to be identified. Example lists of failure modes for various equipment items and components are provided in Appendix A4. The user is cautioned that other failure modes may exist that are not listed in Appendix A4. The failure modes listed in Appendix A4 can be used to describe the failure of any equipment item or component in sufficiently specific terms. When used in conjunction with performance specifications governing the inputs and outputs on the system block diagram, all potential failure modes can thus be identified and described. Failure shall be assumed by one possible failure mode at a time with the exception of “hidden failures” in which a second failure must occur in order to expose the “hidden failure”.

A failure mode in an equipment item or component could also be the failure cause of a system failure. Since a failure mode may have more than one cause, all potential independent causes for each failure mode shall be identified. The failure characteristic for the failure mode is to be identified as follows:

- i) *Wear-in failure* is to be used for failures associated with manufacturing defects and installation, maintenance or startup errors;
- ii) *Random failure* is to be used for failures associated with random failures caused by sudden stresses, extreme conditions, random human errors or any failure not predictable by time; and
- iii) *Wear-out failure* is to be used for failures associated with end-of-useful life issues for equipment.

The failure mode may have multiple failure characteristics. The identification of the failure characteristic(s) is used to aid in the selection of appropriate failure management task(s).

6.6.2 Failure Effects

The effects of the failure for each failure mode are to be listed as follows:

- i)* The Local Effect is to describe the initial change in the equipment item or component operation when the failure mode occurs; failure detection methods, if any, are to be identified and availability of standby system/equipment to provide the same function.
- ii)* The Functional Failure is to describe the effect of the failure mode on the system or functional group; such as potential physical damage to the system/equipment item; or potential secondary damage to either other equipment items in the system or unrelated equipment items in the vicinity.
- iii)* The End Effect is to describe the overall effect on the vessel addressing propulsion, directional control, environment, fire and/or explosion. For offshore drilling units and offshore oil and gas production facilities, the End Effects would address drilling, position mooring, hydrocarbon production and processing and import/export functions. One failure mode may result in multiple end effects.

For failures in systems with corrective measures, the corrective measures are to be shown to be immediately effective or brought online with negligible time delay. If operator action is required to bring the corrective measure(s) online, the effects of operator delay are to be considered. It is to be assumed for the analysis that the corrective measure is successful.

Where the failure detection is not evident (e.g., hidden) and the system can continue with its specific operation, the analysis is to be extended to determine the effects of a second failure, which in combination with the first undetectable failure may result in a more severe effect. It is to be assumed for the analysis that any corrective measure(s) provided is (are) successful unless that corrective measure is the second failure whose effects are being analyzed.

The actions required to repair a defective component or equipment item are to be indicated in the End Effect. The information is to include repair of equipment item or component, repairs to other equipment affected by the failure mode, personnel needed, special repair facilities and time to perform the repair.

6.6.3 Failure Detection

The following information is to be included in the Failure Detection/Corrective Measures column of the FMECA Worksheet (A1/9 TABLE 4):

- i)* The failure detection means, such as visual or audible warning devices, automatic sensing devices, sensing instrumentation or other unique indications, if applicable. The term “evident” is to be indicated.
- ii)* Where the failure detection is not evident, the term “hidden” is to be indicated.

6.6.4 Corrective Measures

The following information is to be included in the Failure Detection/Corrective Measures column of the FMECA Worksheet (A1/9 TABLE 4):

- i)* Provisions that are features of the design at any level to nullify the effects of a failure mode (e.g., standby systems that allow continued and safe operation, safety devices, monitoring or alarm provisions which permit restricted operation or limit damage; and alternate modes of operation).
- ii)* Provisions which require operator action to circumvent or mitigate the effects of the failure mode shall be provided. The possibility and resulting effects of operator error shall be considered if the corrective action or the initiation of the redundant equipment item requires operator input, when evaluating the means to eliminate the local failure effects.

6.6.5 Criticality Analysis

The criticality analysis is used to rank the risk associated with each failure mode identified during the FMECA by assessing the severity of the End Effect and the likelihood of failure based on the

best available data. This allows the comparison of each failure mode to all other failure modes with respect to risk.

The likelihood of failure can be determined using either of these two approaches:

- i) *Quantitative.* This approach is to be used if reliability data is available. When used, the source of the data and the operating context is to be provided.
- ii) *Qualitative.* Where quantitative data is not available to determine the likelihood of failure, engineering judgment can be applied based on previous experience.

The probability of failure is to be based on current failure rate data for equipment items/components operating in similar operating modes and operating contexts for the existing maintenance tasks. If this data is not available, then the failure rate is to be estimated based on an assumption that no maintenance is performed.

The severity level for consequences attributable to functional losses (as applicable), loss of containment, explosion/fire and safety are to be described and defined using the format shown in A1/9 TABLE 5. A descriptor is to be used to define each severity level. Example descriptors and example definitions for each severity level have been listed in A1/9 TABLE 5. Four severity levels are recommended to be defined.

For the likelihood of failure, five likelihoods are recommended to be described and defined. Ranges based on the number of events per year are to be provided. However, other frequencies using events per operating hour or other practical unit of time may be applied. An example format listing descriptors and definitions is shown in A1/9 TABLE 6.

A risk matrix is to be developed using the example format in A1/9 TABLE 7. Each cell in the risk matrix is to be assigned a priority descriptor (high, medium, low, etc.). Other risk rankings, such as a priority number or criticality number, may be used. A minimum of three risk rankings are to be provided. The lowest risk ranking is to signify acceptable risk and the highest risk ranking is to signify an unacceptable risk. A risk matrix is to be developed for the functional groups and consequence categories. During the development of the risk matrix, the risk ranking for certain likelihoods and severity levels may vary when comparing the functional groups and consequence categories. For such cases, separate risk matrices for the functional groups/consequence categories are to be submitted.

For each failure mode, the FMECA is to indicate all functional losses, severity, probability of failure and their resulting risk. The consequence categories (i.e. loss of containment, explosion/fire, safety, etc.) are to be considered in the FMECA when the failure mode directly initiates a consequence (e.g., a broken fuel oil pipe spraying oil on a hot surface would lead to a fire).

The confidence in the risk characterization is to be assessed. A high confidence in the risk characterization indicates the risk is properly characterized and can be used without any further discussions. A low confidence indicates uncertainty, and that additional data about the frequency of occurrence or severity of the End Effect is needed before the risk can be used in the failure management strategy. Low confidence is to be noted in the report for the affected failure mode.

6.7 Selection of the Failure Management Tasks

All assessed failure modes are to be evaluated in accordance with the RCM Task Selection Flow Diagram in A1/9 FIGURE 10. The purpose of this diagram is to assist in selecting the most appropriate maintenance task strategy to prevent or detect a specific failure mode.

All causes of each failure mode are to be evaluated.

Appropriate failure management tasks are to be selected for all corrective measures by applying A1/9 FIGURE 10.

All manufacturers' maintenance recommendations are to be considered during the selection of the failure management tasks. If changes or deletions to the manufacturers' recommendations are made, these are to be documented in the analysis.

6.7.1 Maintenance Task Allocation and Planning

The maintenance tasks identified in each step are to be organized in accordance with the following suggested categories:

- *Category A* – Can be undertaken on location (at sea, offshore) by the onboard 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

Alternative categories to those suggested are to be fully described in a manner similar to the descriptions above.

The Task Type is to be identified as follows: Condition Monitoring (CM), Planned Maintenance (PM), Combination of CM and PM (CM/PM), Failure Finding (FF), One-time Change (OTC), Run-to-Failure (RTF), Any Applicable and Effective Task (AAET).

The RCM analysis may identify identical maintenance tasks addressing different failure modes with different intervals on the same equipment item or component. The task intervals developed may not be in alignment with the present in-use calendar-based maintenance schedule. Accordingly, the task intervals may be integrated into a common maintenance schedule as an aid to personnel scheduling efficiencies. If tasks are integrated, the RCM task intervals may only be adjusted to shorter intervals to avoid compromising of End Effects.

6.8 Spares Holding Determination

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:

- i) 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.
- ii) An evaluation of the effects on the functional group or system's operational availability if an out-of-stock condition occurs.
- iii) 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.

6.8.1 Out-of-Stock Effect on End Effects

Determination is to be made whether the out-of-stock condition and subsequent 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 out-of-stock under normal circumstances. The following define direct and indirect effects and normal circumstances.

- i) *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.

- ii) 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.
- iii) Normal Circumstances.* The item is operating within context and without a failure occurring.

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

6.9 Spares Holding Decisions

The following decision-making process is to be used to select the most appropriate strategy for spares when an out-of-stock condition will directly or indirectly result in End Effects:

- i)* In the following cases, the parts are to be ordered before demand occurs:
 - 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;
- ii)* 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 an out-of-stock is reduced to an acceptable level, and
 - The cost and storage basis to hold the parts is feasible.
- iii)* When neither of the two above strategies is feasible, then the following is to be considered:
 - If the out-of-stock 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 out-of-stock will only have a non-operational effect, it is desirable to review the RCM analysis with a view to revising the maintenance task.

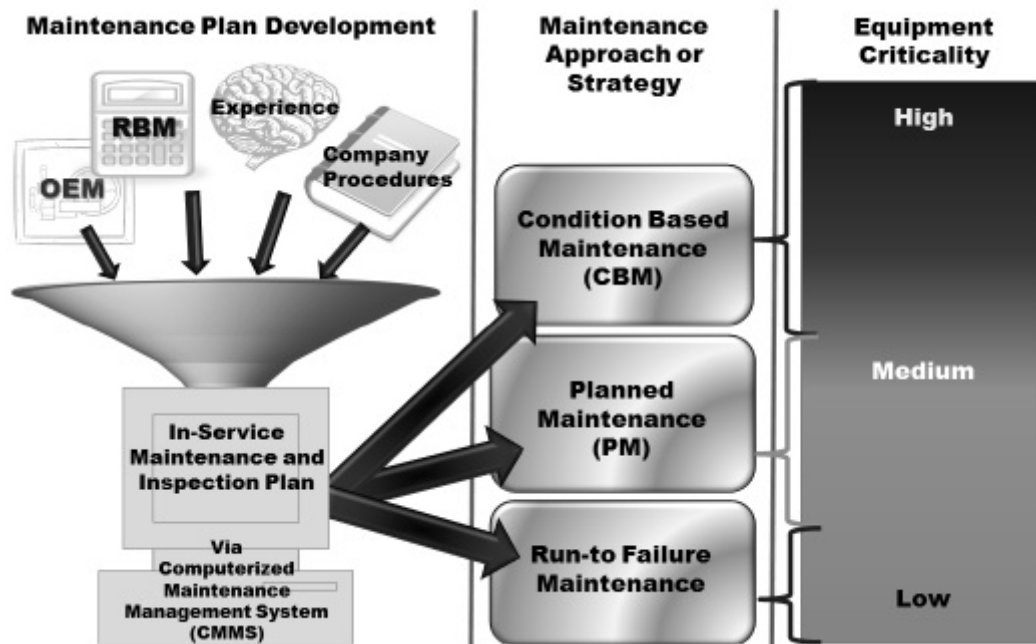
6.10 Sustainment Plan

For the sustainment planning, the plan for continued improvement shall be submitted to the ABS Engineering Office. The results of the sustainment activities must be maintained onboard for verification at annual surveys. See A1/8 for more information.

7 Maintenance Alignment

Following successful completion of the reliability analyses, maintenance leaders must choose the best path for operational execution. The identified failure mode knowledge coupled with the operator's experience is used for selection of proper maintenance task types. These maintenance task types are Condition based, Planned, and Run-to-Failure. Utilizing a criticality assessment for reference, the tasks can be properly risk aligned for a best in class maintenance plan.

FIGURE 6
Maintenance Alignment



7.1 Condition Based Maintenance

Condition based maintenance, also known as predictive maintenance, is a failure management strategy, with tasks conducted on a frequent or real-time basis, which is based on the use of Condition Monitoring (CM) to determine when corrective action or part replacement is required. This process involves establishing a baseline and operating parameters, then periodically monitoring the machine and comparing any changes in operating conditions to the baseline. Repairs or replacement of parts are carried out before the machinery fails based upon the use of the tools prescribed for CM.

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 or observed and represent the equipment's condition must be understood so that an appropriate condition monitoring (CM) task can be selected.

7.2 Planned Maintenance

Planned maintenance is a failure management strategy that restores the inherent reliability or performance of the equipment item. 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. 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 potential of failure.

7.3 Run-to-Failure Maintenance

Run-to-failure is a failure management strategy that allows an equipment item to run until failure occurs and then a repair or replacement is made. This maintenance strategy is acceptable only if the risk of failure is acceptable. An example would be permitting a local pressure gauge on a cooling water line, also fitted with a remote-reading pressure gauge, to fail.

8 Principles of In-service Application and Sustainment

For the operational phase the asset, the in-service maintenance and inspection plan developed in the previous step will be executed. To support effective and efficient asset management, maintenance must be dynamic and supported by a documented sustainment plan. This plan should be organized such that the results can be effectively used to provide feedback to revisit the reliability and integrity analysis as well as any determined updates for modifications to the in-service maintenance and inspection plan.

The vessel operator should collect, analyze, review and respond to in-service data throughout the operating life of the vessel in order to continually improve the maintenance plan. The procedures and processes used by the operator to sustain the preventative maintenance plan are to be developed and submitted to ABS for review.

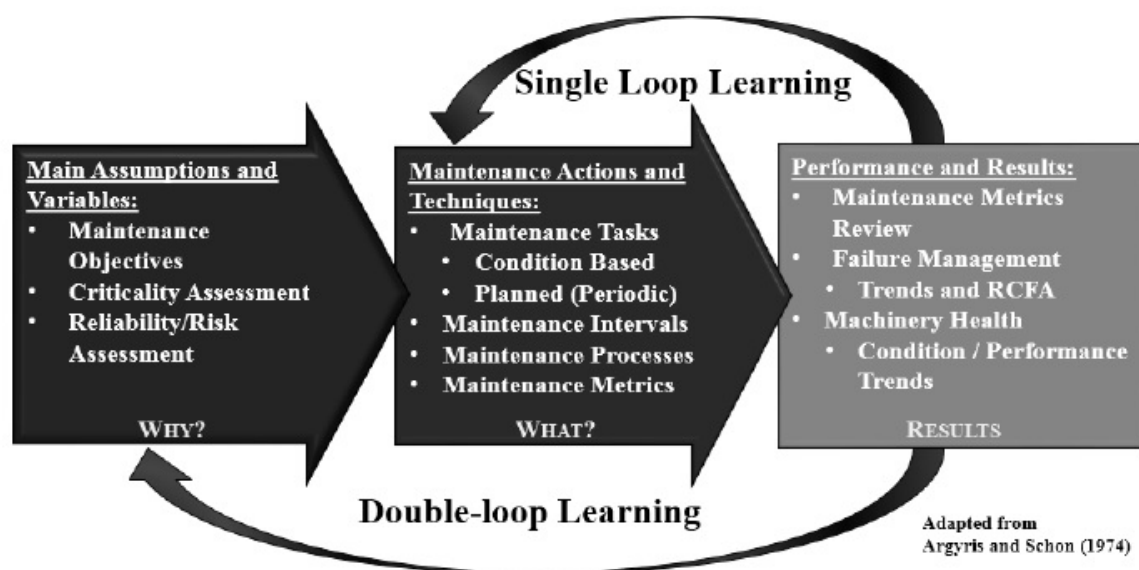
The objective of the sustainment process is to:

- 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 and maintenance programs and supporting analysis
- Identify opportunities for learning and training

Sustainment efforts are to be organized such that the results can be effectively used to support the reliability and integrity analysis and maintenance plan updates. The feedback can support two levels of learning (see A1/8 FIGURE 7):

- i) Provide learning opportunities for changing and improving maintenance application, and
- ii) Revisiting the assumptions and objectives that initiated the maintenance planning process.

FIGURE 7
Sustainment Learning Loop



8.1 Examples of In-service Application and Sustainment

8.1.1 Asset Monitoring Selection

Once assets are in operation, their performance is to be monitored. Critical assets are to be selected so that overall operation is satisfactory based on individual asset performance.

8.1.2 Asset Operational Performance Monitoring

The primary method to determine if the asset is operating or function efficiently is to monitor operational performance with designated control limits. Unique critical process parameters will have to be developed for each asset specific to its designed operation or function as well as available parameters that can be monitored. Control limits should be established for each indicator based on expected operational performance. Operational performance should be tracked with control charts using minimum and/or maximum set points as the control limits. Examples of critical process parameters are as follows:

- Cycles
- Differential pressure
- Flow rate
- Program logic control set points
- Revolution per Minute (RPM)
- Temperature

8.1.3 Asset Reliability Analytics Monitoring

The primary method to determine if the maintenance strategy is effective and appropriate is to monitor reliability analytics with designated control limits. Primary reliability analytics indicators that to be used are listed below:

- Failure Code Analysis (FCA)
- Mean Cost to Repair (MCTR)
- Mean Time Between Failure (MTBF)
- Mean Time to Repair (MTTR)

The primary source for the data to calculate these indicators will be stored in the CMMS work order history. Control limits should be established for each indicator based on expected performance levels. The control limits for FCA and MTBF will focus on rate of failure while MCTR and MTTR will focus on cost and effort for repair, respectively. Analytics should follow a recognized standard (ex. ISO 14224).

8.1.4 Root Cause Analysis (RCA)

In the event it is determined that the asset is operating or functioning inefficiently based on monitoring operational performance, root cause analysis should be performed to identify the corrective and preventative actions required to return the operation or function to a satisfactory level and achieve the desired control limits. 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
- RCA is to follow a recognized practice and additional information can be found in Section 5 of the *ABS Guidance Notes on Investigation of Marine Incidents*.

8.1.5 Proactive Maintenance Improvement

In the event it is determined that the maintenance strategy is ineffective based on monitoring or RCA, a maintenance review and updates should be performed to enhance the strategy and achieve the desired control limits. Typically maintenance programs have been developed using a combination of recommendations issued by the OEM and developed over time by the local maintenance staff based on experience.

The intent is to review the existing maintenance strategy for opportunities to:

- Identify and remove low value tasks that do not address failure modes
- Revise fixed time intervals based on task type, asset usage, environment, operating histories, and industry practices
- Replace calendar based intrusive tasks with operational run time or condition based non-intrusive tasks
- Strengthen work packages (e.g., task instructions, parts, tools)
- Shift tasks from maintenance to operations when the program would be better served by having operators perform the task during routine surveillance
- Evaluate repeat failures and develop proactive strategies to minimize the occurrence of the failures

9 Reference Tables and Figures

- TABLE 2 Example Operating Modes and Operating Context
- TABLE 3 Example Function and Functional Failure List
- TABLE 4 Example Bottom-up FMECA Worksheet
- TABLE 5 Example Consequence/Severity Level Definition Format
- TABLE 6 Probability of Failure (i.e., Frequency, Likelihood) Criteria Example Format
- TABLE 7 Risk Matrix Example Format
- TABLE 8 Failure Characteristic and Suggested Failure Management Tasks
- TABLE 9 Example Maintenance Task Selection Worksheet
- TABLE 10 Summary of Maintenance Tasks
- TABLE 11 Summary of Spares Holding Determination
- FIGURE 8 Example Partitioning of Functional Groups
- FIGURE 9 Example System Block Diagram

- FIGURE 10 RCM Task Selection Flow Diagram
- FIGURE 11 Spares Holding Decision Diagram

TABLE 2
Example Operating Modes and Operating Context

<i>Operating Context of Diesel Engine</i>				
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.				
Common Characteristics	<i>Operating Modes</i>			
	<i>At Sea</i>	<i>In Congested Waters</i>	<i>Maneuvering Alongside</i>	<i>Cargo Handling</i>
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 range	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 3
Example Function and Functional Failure List

<i>Function</i>			<i>Functional Failure</i>	
<i>Item No.</i>	<i>Function Statement</i>	<i>Function Type</i>	<i>Item No.</i>	<i>Functional Failure Statement</i>
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

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

TABLE 4
Example Bottom-up FMECA Worksheet

<i>Item</i>	<i>Failure Mode</i>	<i>Causes</i>	<i>Failure Characteristic</i>	<i>Local Effects</i>	<i>Functional Failures</i>	<i>End Effects</i>	<i>Matrix</i>	<i>Severity</i>	<i>Current Likelihood</i>	<i>Current Risk</i>	<i>Failure Detection/ Corrective Measures</i>
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	Propulsion	Minor	Remote	Low	Upon low pressure, sensor sends signal to automatic changeover controller which starts standby pump
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	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 shutdown until the standby pump is operating	Propulsion	Minor	Remote	Low	Upon low pressure, sensor sends signal to automatic changeover controller which starts standby pump

TABLE 5
Example Consequence/Severity Level Definition Format

<i>Severity Level</i>	<i>Descriptions for Severity Level</i>	<i>Definition for Severity Level</i>	<i>Applicable to Functional Groups for</i>
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 Function
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	
<i>Severity Level</i>	<i>Descriptions for Severity Level</i>	<i>Definition for Severity Level</i>	<i>Applicable to Consequence Category of</i>
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	
<i>Severity Level</i>	<i>Descriptions for Severity Level</i>	<i>Definition for Severity Level</i>	<i>Applicable to Consequence Category of</i>
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	
<i>Severity Level</i>	<i>Descriptions for Severity Level</i>	<i>Definition for Severity Level</i>	<i>Applicable to Consequence Category of</i>
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 (i.e., Frequency, Likelihood) Criteria Example Format

<i>Likelihood Descriptor*</i>	<i>Description</i>
Improbable	Fewer than 0.001 events/year
Remote	0.001 to 0.01 events/year 0.01 to 0.1 events/year
Occasional	
Probable	0.1 to 1 events/year
Frequent	1 or more events/year

* Note: See A1/6.6.5 for determining probability of failure

TABLE 7
Risk Matrix Example Format

<i>Severity Level</i>	<i>Likelihood of Failure</i>				
	<i>Improbable</i>	<i>Remote</i>	<i>Occasional</i>	<i>Probable</i>	<i>Frequent</i>
4	Medium	Medium	High	High	High
3	Low	Medium	Medium	High	High
2	Low	Low	Medium	Medium	High
1	Low	Low	Low	Medium	Medium

TABLE 8
Failure Characteristic and Suggested Failure Management Tasks

<i>Equipment Item/Component Failure Characteristic</i>	<i>Suggested Failure Management Task</i>
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

TABLE 9
Example Maintenance Task Selection Worksheet

<i>Failure Mode</i>	<i>Failure Char.</i>	<i>Hidden/Evident</i>	<i>Effects</i>			<i>Risk Characterization ⁽¹⁾</i>			<i>Task Selection ⁽²⁾</i>			
			<i>Local</i>	<i>Functional Failure</i>	<i>End</i>	<i>S</i>	<i>CL</i>	<i>CR</i>	<i>Proposed Action(s)</i>	<i>PL</i>	<i>PR</i>	<i>Disposition</i>
External leak	Wear-out	Evident	Release of hazardous material	Loss of containment	Potential severe injury to employees	Major	Remote	Medium	Delete rebuilding task	Remote	Medium	Consider deleting the rebuilding task
									1. Reduce vibration analysis interval to 1 week 2. Maintain visual inspection at 1 week	Remote	Medium	
									1. Reduce vibration analysis interval to 1 week 2. Reduce visual inspection interval to daily	Extremely remote	Low	1. Reduce vibration analysis interval to 1 week 2. Reduce visual inspection interval to daily

Failure Mode	Failure Char.	Hidden/ Evident	Effects			Risk Characterization ⁽¹⁾			Task Selection ⁽²⁾			
			Local	Functional Failure	End	S	CL	CR	Proposed Action(s)	PL	PR	Disposition
Degraded head	Wear-out	Evident	Reduced flow of material	Transfer time too long	Production rate reduced	Minor	Remote	Low	Delete all tasks	Remote	Low	
									1. Delete vibration analysis 2. Maintain rebuilding at 1 year interval	Remote	Low	
									1. Maintain vibration analysis at 1 month 2. Delete rebuilding task	Remote	Low	Team has low confidence that vibrational analysis will always detect degraded performance
									1. Maintain vibration analysis at 1 month 2. Increase rebuilding task interval to 2 years	Remote	Low	1. Maintain vibration analysis at 1 month 2. Increase rebuilding task interval to 2 years

* Note:

1) Risk Characterization abbreviations are: S is severity; CL is current likelihood; CR is current risk

2) Task Selection abbreviations are: PL is projected likelihood; PR is projected risk

TABLE 10
Summary of Maintenance Tasks

<i>Task</i>	<i>Task Type</i>	<i>Item No.</i>	<i>Risk</i>		<i>Frequency</i>	<i>Procedure No. or Class Reference</i>	<i>Comments</i>
			<i>Unmitigated</i>	<i>Mitigated</i>			
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	PM	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	PM	1.2	Medium	Medium	8,000 hr	MA 911-2	

Note:

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

TABLE 11
Summary of Spares Holding Determination

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

Note:

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

FIGURE 8
Example Partitioning of Functional Groups

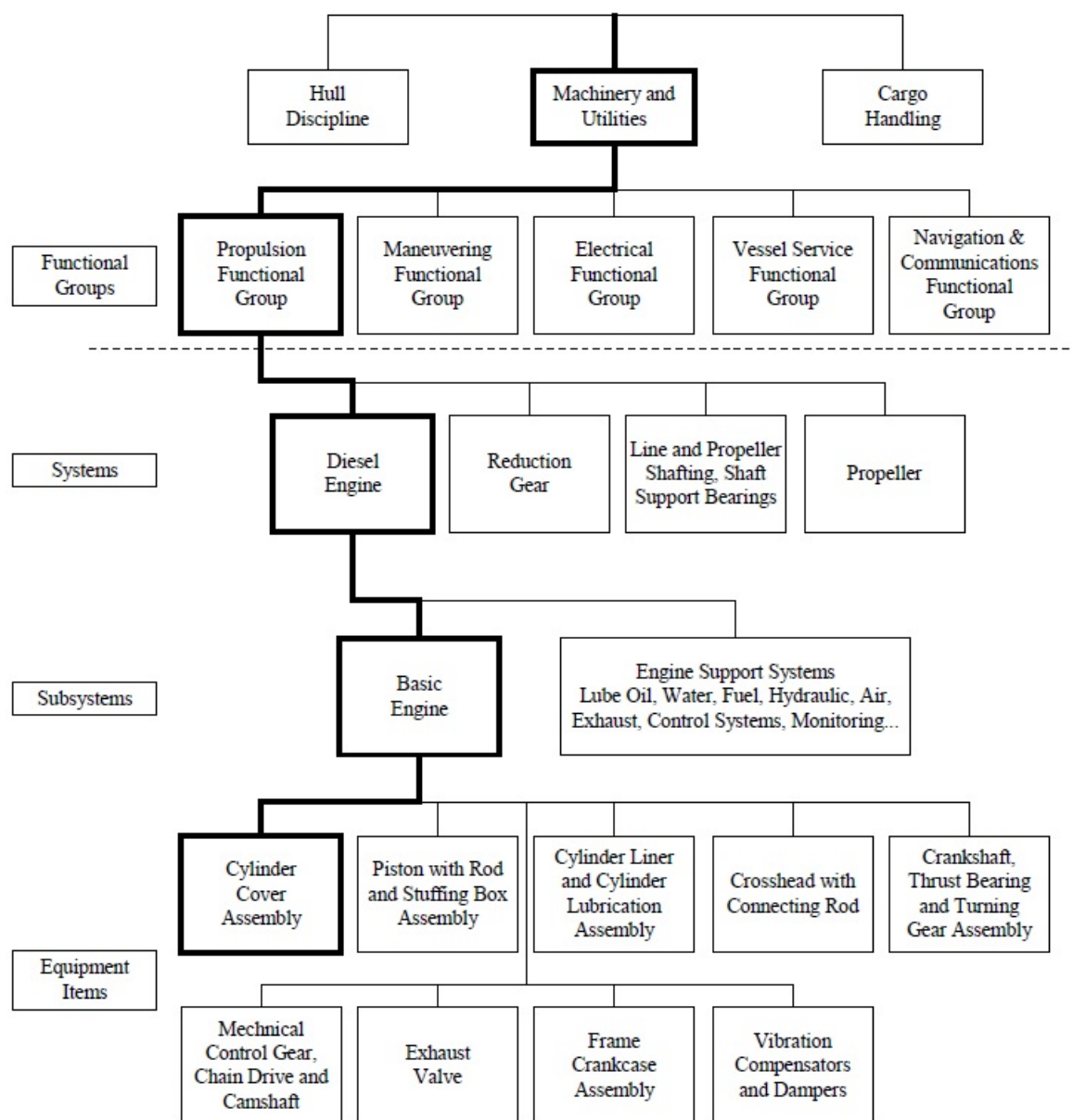


FIGURE 9
Example System Block Diagram

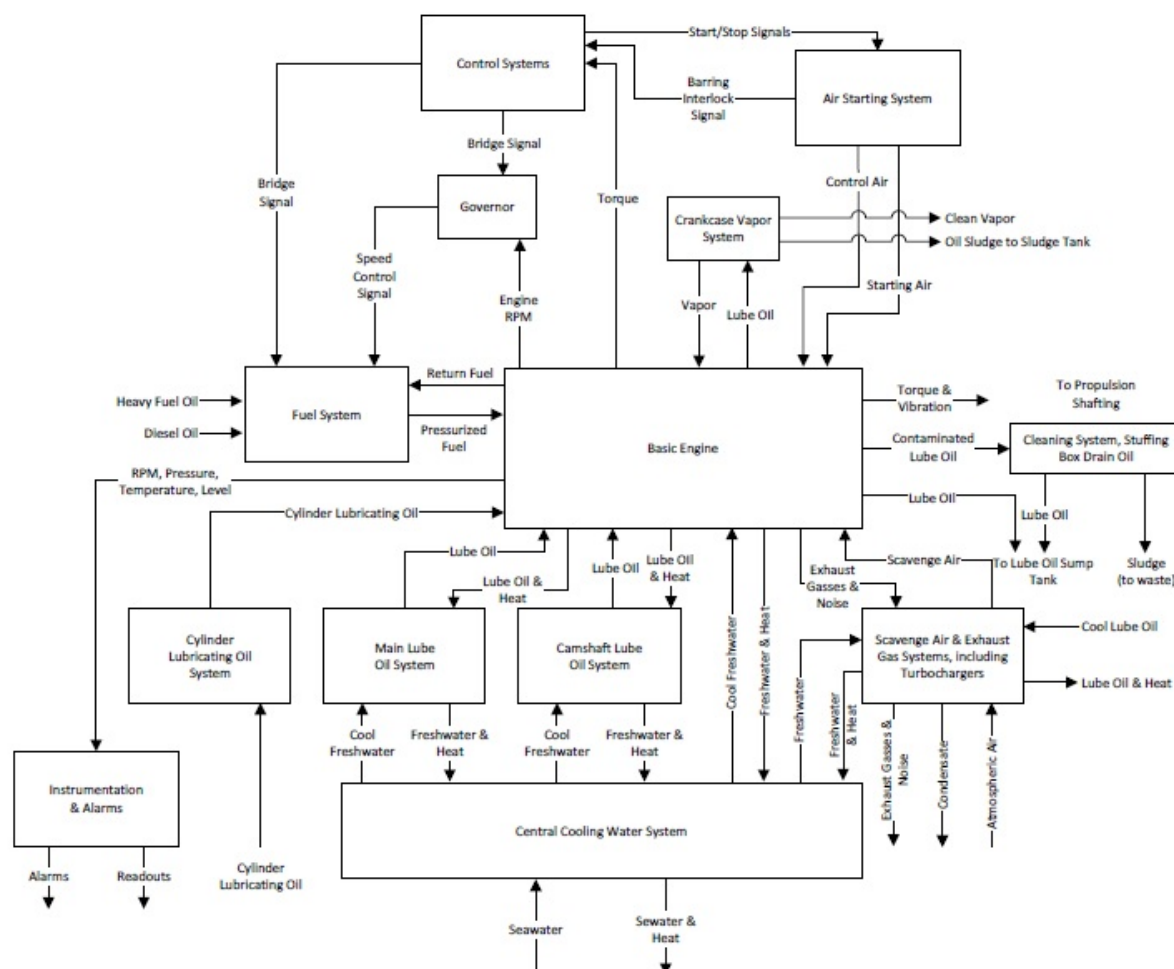


FIGURE 10
(continued) RCM Task Selection Flow Diagram

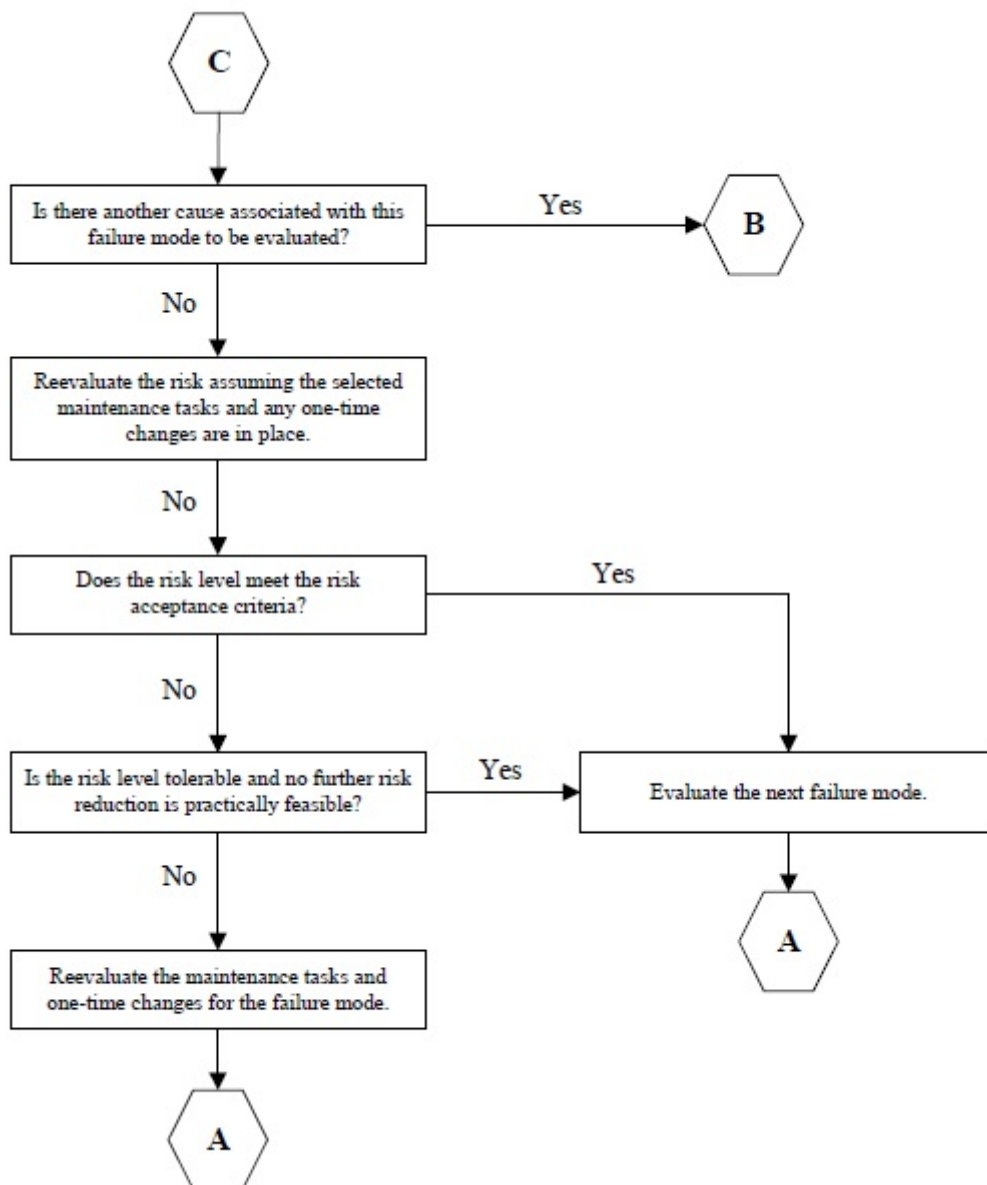
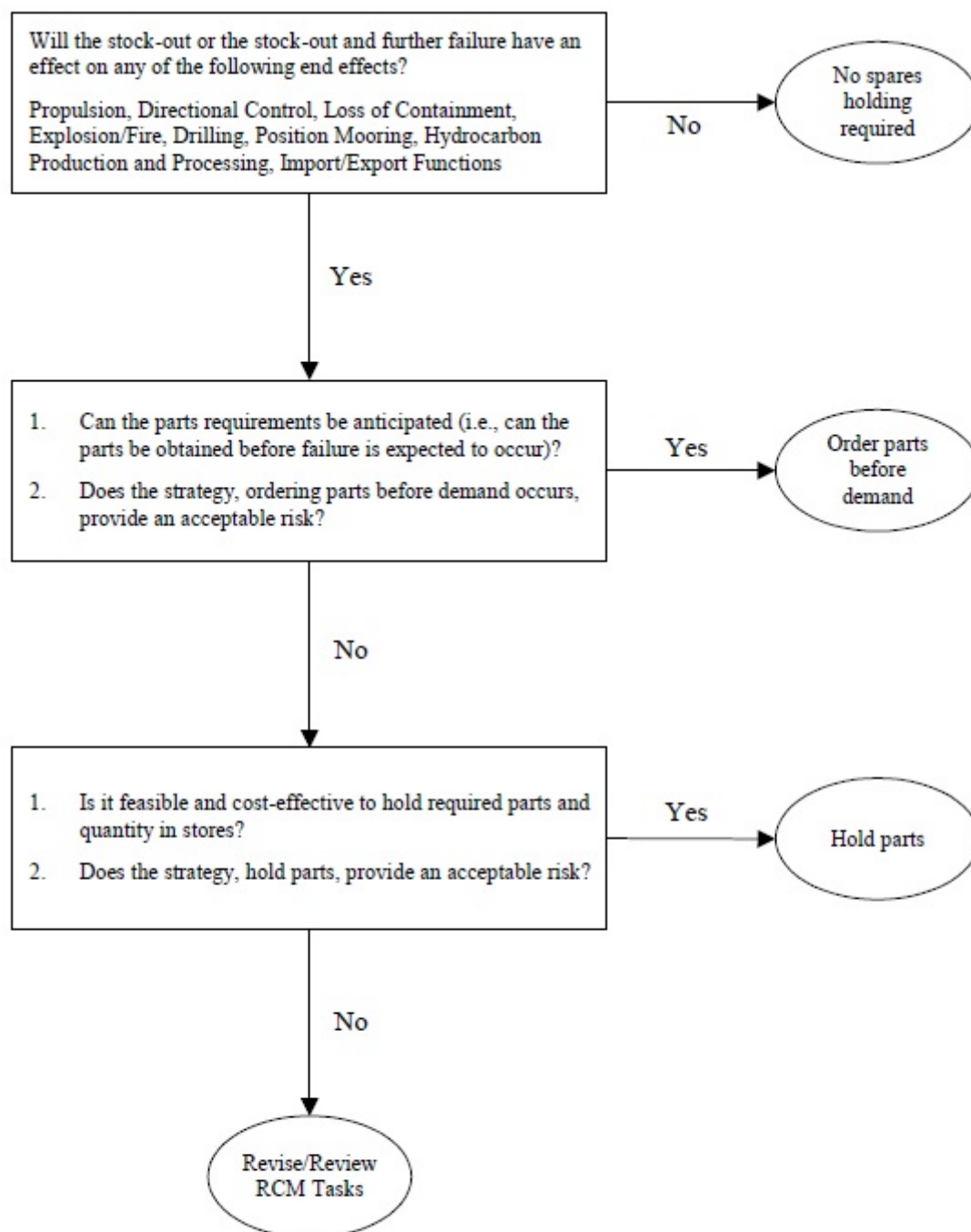


FIGURE 11
Spares Holding Decision Flow Diagram ⁽¹⁾



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.

APPENDIX 2

Reliability Tools and Techniques

Additional references related to many of these techniques can be found in Appendix A3. The list below is for sample purposes and not all inclusive of risk and reliability analysis methods:

1 Equipment Criticality Assessment

- i)* Components for criticality assessment (e.g., Disruptive Survey Requirements, Failure leading to shutdown)
- ii)* Factors for each component (e.g., operational throughput, utilization, quality, detection risk)
- iii)* Criteria and scoring for each factor
- iv)* Weighting for each factor
- v)* Scoring calculation for each component
- vi)* Scoring calculation for assessment
- vii)* Determine score groupings for bulk analysis (e.g., classification, percentile, and quartile)

2 Reliability, Availability, Maintainability Study (RAM)

- i)* Define the objectives and scope
- ii)* Define boundaries for the study
- iii)* Collecting and collating data
- iv)* Equipment performance data
 - a)* System configurations
 - b)* Equipment/system uptime
 - c)* Maintenance resources
 - d)* Spares constraints
- v)* Preparation
 - a)* Prepare a study basis
 - b)* Build the model in stages
 - c)* Verify model operation at each stage
- vi)* Results
 - a)* Compare overall results with expectations
 - b)* Perform sensitivity analyses

3 Reliability Data Management (Bad Actor Analysis)

This can provide the low hanging fruit necessary to gain instant traction with improving maintenance practices. The start of this process is by analyzing the appropriate data sources available:

- i) CMMS work order history (cost and count)
- ii) Spare Parts Usage (cost and count)
- iii) CMMS failure code history
- iv) Operational performance data (rate and units)
- v) Manufacturing alarms and faults (PLC data)
- vi) Overall Equipment Effectiveness (OEE)
- vii) PdM reports and trends
- viii) Maintenance or operations personnel interviews

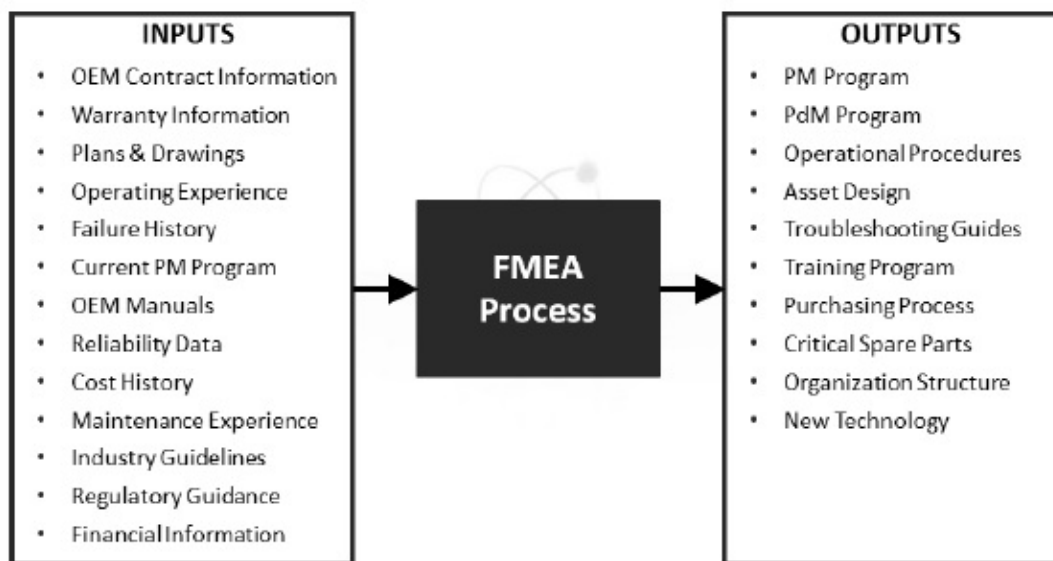
Identified areas of concern should then undergo a Pareto analysis or a Structured Root Cause Failure Analysis (RCA).

4 Failure Modes and Effects Analysis (FMEA)

FMEA is a detailed and orderly process that is built on a functional analysis of the maintainable items used in a system. The FMEA process should address the following key questions:

- i) *Function:* What is the equipment system, subsystem, or component designed to do? How is the system being used (operations, capacity vs. design, etc.)?
- ii) *Functional Failure:* How can each system, subsystem, or component fail?
- iii) *Failure Mode:* What event causes each failure?
- iv) *Effect:* What happens when each failure occurs? How do we know? What is the impact on the operation?
- v) *Principal Cause:* What is the root or principal cause or causes of each failure?
- vi) *Prevention:* What can be done to predict or prevent each failure?
- vii) *Options:* Identify the most cost effective Corrective Actions and Preventive Actions including changes, additions, and/or modifications to the existing Reliability Strategy (PMs or PdMs).

FIGURE 1
FMEA Process



5 Hazard Identification Study (HAZID, HAZOP)

- i) Define the type of HAZID conducted and the date(s) in which the study was conducted. (examples include Guideword, What-if, and Deviation).
- ii) Provide the risk matrix used for the HAZID and what key identifiers were used for identification and gradation of high risk items.
- iii) Identify key personnel who participated in the preliminary HAZID and their qualifications.
- iv) Document high risk items that were discovered and/or identified through the HAZID process along with recommendations and actions that were suggested to be taken to lower the risk.
- v) Include items identified to be within the As Low As Reasonably Practicable (ALARP) region in the HAZID
- vi) Document actions taken to mitigate high risk items identified through the HAZID, these changes and their effect on later studies shall be discussed in the RMP and included in the Management of Change.

6 Preventative Maintenance Optimization (PMO)

A key element of success is properly evaluating current planned maintenance and improvements for the future. The key drivers of concern on the existing maintenance plan:

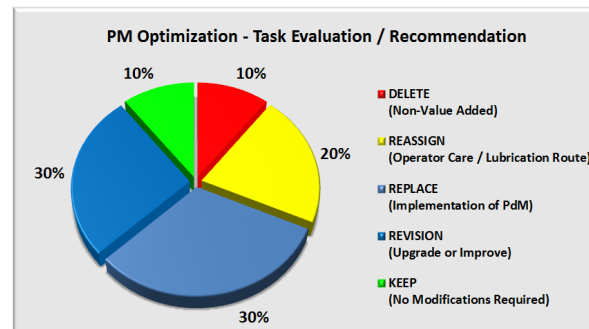
- i) Current PM tasks are generic and ineffective
- ii) Too many labor hours spent on invasive PM inspections
- iii) Components are replaced prematurely (still in good condition)
- iv) Too much operational downtime required to perform PMs

Additionally, maintenance management teams should approach current strategy with the following questions:

- i) PMs are not effective at detecting failures proactively
- ii) PMs are not focused on protecting required functions

- iii) PMs appear to be more of a documentation exercise
- iv) Failures occur after PMs (incorrect rebuilds or adjustments)

FIGURE 2
PM Optimization

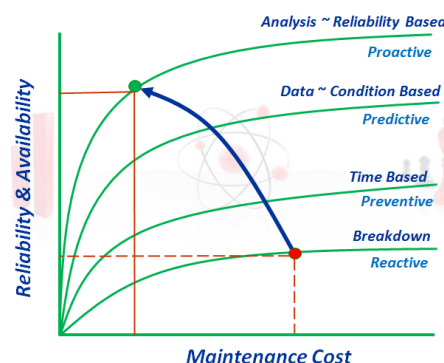


7 Applications of Predictive Technologies

Multiple paths exist for determining the right application of maintenance. For critical equipment and components tracking condition and performance can lead to trending and forecasting future failures. Predictive Maintenance (PdM) is the effective use of technologies/tools to measure an asset parameter (condition or performance) that will point to asset failure. These tools will lead to a reliable operations and maintenance plan

- *Condition Based Maintenance.* Monitoring of any parameter that will allow evaluation of the asset's current and/or future condition.
- *Performance Monitoring.* Evaluation of an asset's operating parameters (e.g., pressure, temp, flow, speed) through trend analysis that will allow forecasting asset failure.

FIGURE 3
Maintenance Strategy



8 Inventory and Part Stocking Management

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:

- i) Order parts before demand occurs in cases where:
 - 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 lifecycle of the equipment item or component.

- ii)* 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.
- iii)* 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.

9 Continuous Improvement Process

A sustainment program is required to continue the efficacy of the program while striving for a best practice program. The process includes the following objectives:

- i)* Continually monitor and optimize the current maintenance program
- ii)* Delete unnecessary requirements
- iii)* Identify adverse failure trends
- iv)* Address new failure modes
- v)* Improve overall efficiency and effectiveness of the maintenance programs

10 Structured Root Cause Failure Analysis

Root Cause Failure Analysis (RCFA) is a method or series of actions taken to find out why a particular failure or problem exists and correcting those causes. This is accomplished as a structured process using many available methods of problem solving.

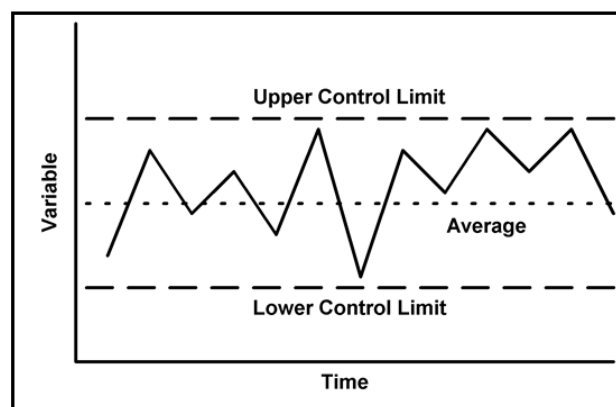
10.1 RCFA Approach

- i)* Focus on repetitive failures.
- ii)* Understand the root cause(s) and prevent them in the future.
- iii)* Address the cause instead of the symptom – change from reactive to proactive.
- iv)* Not to place blame – “just the facts” & they will speak for themselves. Focus on process.

11 Control Charting

Collect data over time and look for averages. Set control limits and trend data for “out of control” patterns. These patterns are visible as points outside the control limits, trends up/down, or points always over or under average.

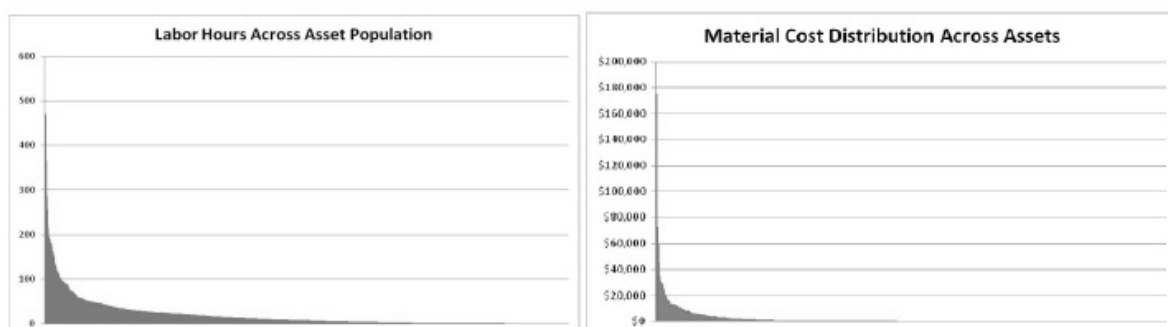
FIGURE 4
Sample Control Chart



12 Pareto Analysis

Pareto is a statistical technique to separate the vital few from the trivial many. The general theme as applied to reliability is that a large majority of problems (80%) are produced by a few key causes (20%).

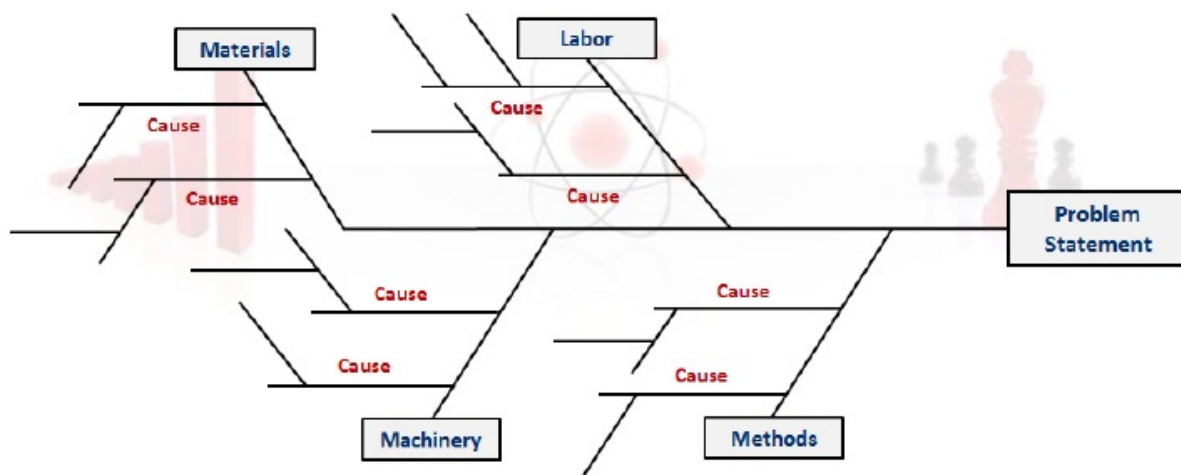
FIGURE 5
Sample Pareto Charts



13 Cause and Effects Analysis

- Step 1: Develop a precise Problem Statement: Put your statement in a box (“fish head”), and draw main causal line as the “fish spine”
- Step 2: Select Cause Categories to be used and add to diagram as “fins”, drawn off the causal line (“spine”) and label
- Step 3: On each Cause Category line (fin), add specific Cause lines off the fin
- Step 4: Pursue each Cause line back to its Root Cause

FIGURE 6
Sample Cause and Effect Fishbone Diagram



14 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 as follows:

- i) Equipment downtime
- ii) Equipment item/component condition monitoring levels (vibration, thermography, tribology, etc.)
- iii) Other condition-monitoring parameters related to performance (temperatures, pressures, power, etc.)
- iv) The results of chronic root cause failure analyses

15 Maintenance Requirements Document Reviews

Documents containing maintenance requirements for systems, equipment items or components are to be reviewed at least annually to identify outdated maintenance processes, techniques or technologies, or to bring attention to obsolete tools and outdated spare parts. These document reviews provide opportunities to update maintenance requirements that will improve effectiveness or reduce lifecycle costs.

16 Task Packaging

Task packaging is the process of bundling a number of derived maintenance tasks into optimum uniform intervals such as maintenance performed during a vessel's scheduled dry-docking. Task packaging reviews should be conducted periodically to evaluate the packaged maintenance intervals to verify that as maintenance tasks are added, deleted or modified, optimum packaged intervals are maintained.

17 Age Exploration Tasks

When insufficient age-to-failure data are available or assumed data are used during the initial reliability based analysis, age exploration tasks are to be designed and implemented. An effective reliability based 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, which can be fed back for use in updating the analysis.

18 Failure Management

When the knowledge of occurrence of unpredicted system or equipment failures becomes available, an appropriate response or corrective action is to be determined. A root cause analysis or other appropriate structured processes are performed to develop an understanding of the failure and to identify areas that require further analysis such as maintenance, operations, design, human factors, etc.

19 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:

- i)* Maintenance labor hours
- ii)* Maintenance labor hours per operating hour
- iii)* Maintenance actions per operating hour
- iv)* Cost of lost production
- v)* Cost of repair

Based on a comparison of high operational cost systems on the vessel, unit or facility or similar systems on other vessels, units or facilities, analyses can be performed to improve operational performance by investigating methods to quickly diagnose failures, detect potential failures before developing into equipment failures, analyzing overhaul intervals and optimizing equipment operation.

APPENDIX 3 Additional Resources

Additional references related to Reliability Techniques, Failure Mode Effect Analysis (FMEA) and FMECAs may be found in the following publications:

1 Related Standards

ABS Guidance Notes on Risk Assessment Applications for the Marine and Offshore Industries

ABS Guide for Failure Mode Effect Analysis

ABS Guide for Surveys Using Risk Based Inspection for the Offshore Industry

International Code of Safety for High-Speed Craft, 2000, IMO London, 2001. Annex 3, Use of probability concept. Annex 4, Procedures for failure mode and effects analysis.

SAE JA1011, Evaluation Criteria for Reliability-Centered Maintenance (RCM) Processes. Society of Automotive Engineers, 1999.

SAE JA1012, A Guide to Reliability-Centered Maintenance (RCM). Society of Automotive Engineers, 2002.

2 Related Publications

Anderson, Ronald T. and Neri, Lewis, "Reliability-Centered Maintenance: Management and Engineering Methods," Elsevier Applied Science, London and New York, 1990.

Jones, Richard B., "Risk-Based Management: A Reliability-Centered Approach," Gulf Publishing Company, Houston, TX, 1995.

Moubray, John, "Reliability-centered Maintenance-2nd edition", New York, Industrial Press Inc. 1997 (Chapter 4).

Smith, Anthony M., "Reliability-Centered Maintenance," New York, McGraw-Hill, 1993 (Chapter 5).

Zwengelstein, G., "Reliability Centered Maintenance, A Practical Guide for Implementation," Hermes, Paris, 1996.

3 Condition Monitoring and Dynamic Monitoring Standards

References to selected condition monitoring and vibration measurement standards are listed below. These are applicable to some of the techniques listed under Vibration Analysis in A6/3.3.3 TABLE 4 "Dynamic Monitoring". The latest edition of the standard is applicable.

ISO 7919: Mechanical vibration of non-reciprocating machines -- Measurements on rotating shafts and evaluation criteria; **Part 1:** General guidelines; **Part 2:** Land-based steam turbines and generators in excess of 50 MW with normal operating speeds of 1500 r/min, 1800 r/min, 3000 r/min and 3600 r/min; **Part 3:** Coupled industrial machines; **Part 4:** Gas turbine sets; **Part 5:** Machine sets in hydraulic power generating and pumping plants.

ISO 10055: Mechanical vibration -- Vibration testing requirements for shipboard equipment and machinery components

ISO 10816-1: Mechanical vibration -- Evaluation of machine vibration by measurements on non-rotating parts -- **Part 1:** General guidelines; **Part 2:** Land-based steam turbines and generators in excess of 50 MW with normal operating speeds of 1500 r/min, 1800 r/min, 3000 r/min and 3600 r/min; **Part 3:** Industrial machines with nominal power above 15 kW and nominal speeds between 120 r/min and 15 000 r/min when measured in situ; **Part 4:** Gas turbine driven sets excluding aircraft derivatives; **Part 5:** Machine sets in hydraulic power generating and pumping plants; **Part 6:** Reciprocating machines with power ratings above 100 kW.

ISO 13373-1: Condition monitoring and diagnostics of machines – Vibration condition monitoring -- **Part 1:** General procedures

ISO 13379: Condition monitoring and diagnostics of machines – General guidelines on data interpretation and diagnostics techniques

ISO 13380: Condition monitoring and diagnostics of machines – General guidelines on using performance parameters

ISO 17359: Condition monitoring and diagnostics of machines – General guidelines

Society of Naval Architects and Marine Engineers T&R Bulletin 3-42, “Guidelines for the Use of Vibration Monitoring for Preventive Maintenance”

APPENDIX 4

Suggested Failure Modes for Marine Machinery Equipment and Components

This Appendix provides a listing of suggested failure modes for use in a FMECA. Failure modes are provided for marine machinery equipment and components. The hierarchy and grouping of equipment and components is based on the ABS ship product model hierarchy and groupings.

Equipment-level failure modes are presented first. These failure modes are based on deviations from the equipment functions. Failure modes are provided for:

<i>Equipment</i>	<i>Table No.</i>
Electrical equipment	A4/ TABLE 1
Mechanical equipment	A4/ TABLE 2
Piping equipment	A4/ TABLE 3
Control equipment	A4/ TABLE 4
Lifting equipment	A4/ TABLE 5

Component-level failure modes are based on standard mechanical and electrical failure modes. Failure modes are provided for:

<i>Component</i>	<i>Table No.</i>
Electrical components	A4/ TABLE 6
Mechanical components	A4/ TABLE 7
Piping components	A4/ TABLE 8
Structural components	A4/ TABLE 9
Rigging components	A4/ TABLE 10

This listing is provided for guidance only and is not to be considered complete when performing the FMECA. Due to the unique applications required for particular marine applications, other failure modes may be present and are to be considered in the FMECA.

TABLE 1
Electrical Equipment

<i>Equipment Item</i>	<i>Suggested Failure Modes</i>	<i>Equipment Item</i>	<i>Suggested Failure Modes</i>
Battery	• External leak • Fails with no output voltage/current • Fails with low output current • Fails with low output voltage • Reduced discharging time	Generator	• Produces high voltage • Produces low voltage • Produces high current • Produces low current • Fails to start on demand • Starts prematurely • Fails to stop on demand/operates too long • Produces no voltage • Unable to share load/current when running in parallel
Converter	• Fails with no output voltage/current • Fails with low output voltage • Fails with high output voltage • Fails with low output hertz • Fails with high output hertz • Low insulation resistance	Motor controller	• Fails with no output voltage/current • Fails to transfer correctly • Fails with low output/current • Operates prematurely • Operates too long
Console	• Fails with no output voltage/current • Fails to transfer correctly • Fails with low output/current • Transfers prematurely • Fails to transfer on demand	Switchboard	• Fails with no output voltage/current • Fails to switch on demand • Switches prematurely • Erratic/incorrect indicators
Distribution board	• Fails with no output voltage/current • Fails to transfer correctly • Fails with low output/current • Transfers prematurely • Fails to transfer on demand • Erratic/incorrect indicators	Transformer	• Fails with no output voltage/current • Fails with low output voltage/current • Fails with high output voltage/current

<i>Equipment Item</i>	<i>Suggested Failure Modes</i>	<i>Equipment Item</i>	<i>Suggested Failure Modes</i>
Electric motor	• Fails to start on demand • Fails off while operating • Starts prematurely • Fails to stop on demand/operates too long • Operates with high vibration level • Operates at degraded torque/rotational speed • Operates with unbalanced phases	Uninterruptible power supply	• Fails with no output voltage/current • Fails to transfer correctly • Fails with low output voltage • Fails with high output voltage • Operates prematurely • Fails to operate on demand • Operates too long • Operates too short
Electrical swivel	• Fails with no output voltage/current • Fails with low output/current • Fails to rotate		

TABLE 2
Mechanical Equipment

<i>Equipment Item</i>	<i>Suggested Failure Modes</i>	<i>Equipment Item</i>	<i>Suggested Failure Modes</i>
Blower	• External leak/rupture • Fails to start on demand • Fails off while operating • Starts prematurely • Fails to stop on demand/operates too long • Operates at degraded flow/head performance • No flow/head • Operates with high vibration/noise level	Coupling (elastomeric, metallic, hydraulic apply failure modes as appropriate)	• Fails to transmit torque • Degraded torque transmission • Overheats • Operates with high vibration/noise level • External leak • External rupture • Loosened
Brake	• Fails to engage on demand • Fails to disengage on demand/engages too long • Engages prematurely • Disengages prematurely • Operates at degraded braking performance	Damping unit (mechanical-type)	• Structural damage (cracked, fractured, deformed) • Loosened • Sticks

<i>Equipment Item</i>	<i>Suggested Failure Modes</i>	<i>Equipment Item</i>	<i>Suggested Failure Modes</i>
Capstan	• Fails to start on demand • Fails off while operating • Fails to stop on demand/operates too long • Starts prematurely • Operates too slow • Operates too fast • Operates at degraded torque	Damping unit (hydraulic- or pneumatic-type)	• Internal spring blades broken • Wear at spring contact • Loosened connection between damper and crankshaft • Insufficient oil supply to damper • Dynamic seal failure • Structural damage (cracked, fractured, deformed)
Clutch	• Fails to engage on demand • Fails to disengage on demand/engages too long • Engages prematurely • Disengages prematurely • Operates at degraded torque transmission performance	Diesel engine	• External leak/rupture • Fails to start on demand • Fails off while operating • Fails to stop on demand/operates too long • Starts prematurely • Operates too slow • Operates too fast • Operates with high vibration level • Operates at degraded torque • Exhaust emissions exceed limits
Connector	• External leak • External rupture		
Gas turbine	• External leak/rupture • Fails to start on demand • Fails off while operating • Fails to stop on demand/operates too long • Starts prematurely • Operates too slow • Operates too fast • Operates with high vibration level • Operates at degraded torque • Exhaust emissions exceed limits	Paddle wheel	• Structural damage (cracked, fractured, deformed) • Operates too slow (absorbs too much power from prime mover) • Operates too fast (develops insufficient thrust) • Operates with high vibration level • Operates at degraded power

<i>Equipment Item</i>	<i>Suggested Failure Modes</i>	<i>Equipment Item</i>	<i>Suggested Failure Modes</i>
Gear unit	• External leak/rupture • Fails to transmit power • Operates too slow • Operates too fast • Operates with high vibration level • Operates at degraded torque	Propeller	• Structural damage (cracked, fractured, deformed) • Operates too slow (absorbs too much power from prime mover) • Operates too fast (develops insufficient thrust) • Operates with high vibration level • Operates at degraded power • Thrust opposite to ordered direction (controllable pitch)
Hydraulic motor	• External leak/rupture • Fails to start on demand • Fails off while operating • Fails to stop on demand/operates too long • Starts prematurely • Operates too slow • Operates too fast • Operates with high vibration level • Operates at degraded torque	Quick release	• External leak/rupture • Prematurely releases • Fails to release on demand
Motion compensator	• Structural damage (cracked, fractured, deformed) • Improper transfer of torsional motion • Improper transfer of linear motion	Rotary table	• External leak/rupture • Structural damage (cracked, fractured, deformed) • Fails to rotate • Operates too slow • Operates too fast • Operates at degraded torque
Optical signal sensor	Structural damage (cracked, fractured, deformed) Fails to rotate Fails to sense rotation-dirty, signal, tape missing Fails to transmit signal		

<i>Equipment Item</i>	<i>Suggested Failure Modes</i>	<i>Equipment Item</i>	<i>Suggested Failure Modes</i>
Spark ignition engine	• External leak/rupture • Fails to start on demand • Fails off while operating • Fails to stop on demand/operates too long • Starts prematurely • Operates too slow • Operates too fast • Operates with high vibration level • Operates at degraded torque	Thruster	• Structural damage (cracked, fractured, deformed) • External leak • Fails to start on demand • Fails off while operating • Fails to stop on demand/operates too long • Fails to steer on demand/steers unpredictably • Steering operates at degraded output • Starts prematurely • Operates at degraded output • Operates with high vibration level
Steam engine	• External leak/rupture • Fails to start on demand • Fails off while operating • Fails to stop on demand/operates too long • Starts prematurely • Operates too slow • Operates too fast • Operates at degraded torque	Tong	• Structural damage (e.g., cracked, fractured, deformed) • Fails to rotate • Fails to grip • Operates too slow • Operates too fast • Operates at degraded torque
Steering Gear	• Fails to start on demand • Fails off while operating • Fails to stop on demand/operates too long • Starts prematurely • Operates at degraded output • Operates with high vibration level • Internal leak • External leak	Turbocharger	• External leak/rupture • Fails to start on demand • Fails off while operating • Fails to stop on demand/operates too long • Starts prematurely • Operates too slow • Operates too fast • Operates with high vibration level • Fails to supply sufficient combustion air

<i>Equipment Item</i>	<i>Suggested Failure Modes</i>	<i>Equipment Item</i>	<i>Suggested Failure Modes</i>
Vibration damper	• Internal spring blades broken • Wear at spring contact • Loosened connection between damper and crankshaft • Insufficient oil supply to damper • Dynamic seal failure • Structural damage (cracked, fractured, deformed)	Windlass	• Structural damage (cracked, fractured, deformed) • Fails to start on demand • Fails off while operating • Fails to stop on demand/operates too long • Starts prematurely • Operates too slow • Operates too fast • Operates with high vibration level • Operates at degraded torque
Winch	• Structural damage (cracked, fractured, deformed) • Fails to start on demand • Fails off while operating • Fails to stop on demand/operates too long • Starts prematurely • Operates too slow • Operates too fast • Operates with high vibration level • Operates at degraded torque		

TABLE 3
Piping Equipment

<i>Equipment Item</i>	<i>Suggested Failure Modes</i>	<i>Equipment Item</i>	<i>Suggested Failure Modes</i>
Blowout preventer (drilling/protection)	• External leak/rupture • Internal leak • Fails to close on demand • Ram closes prematurely • Choke/kill valve fails to close on demand • Choke/kill valve closes/opens prematurely	Deaerator	• External leak/rupture • Plugged/choked inlet • Plugged/choked outlet
Boiler	• External leak/rupture • Tube leak/rupture • Tube plugged/choked • Tube fouled • Overfired • Underfired • Exhaust emissions exceed limits	Deck water seal (inert gas system semi-dry type)	• Plugged/choked venturi pipeline • Plugged/choked pipeline connecting the holding tank to seal loop • External leak/rupture • Fails to demist inert gas
Burner	• External leak/rupture • Plugged/choked • Fouled • Overfired • Underfired • Exhaust emissions exceed limits	Deck water seal (inert gas system wet type)	• Plugged/choked water inlet/outlet • External leak/rupture • Fails to demist inert gas

<i>Equipment Item</i>	<i>Suggested Failure Modes</i>	<i>Equipment Item</i>	<i>Suggested Failure Modes</i>
Compressor	• External leak/rupture • Fails to start on demand • Fails off while operating • Starts prematurely • Fails to stop on demand/operates too long • Operates at excessive head/flow performance • Operates at degraded head/flow performance • Operates at excessive temperature performance • Contaminants carried over into compressed gas	Distiller(production trays or packing as applicable)	• External leak/rupture • Tray rupture • Tray plugged • Tray collapse • Packed bed plugged • Bed support collapse • Contracting surface fouled
Cooler/heat exchanger (shell and tube)	• External leak/rupture • Shell plugged/choked • Shell side fouled • Tube leak/rupture • Tube plugged/choked • Tube fouled	Diverter	• External leak/rupture • Internal leak • Plugged/choked • Fails to change position on demand • Premature changing of positions
Cooler/heat exchanger (plate type)	• External leak/rupture • Internal leak • Plugged/choked inlet/outlet	Dryer(refrigerant air dryer)	• External leak/rupture • Plugged/choked • Fouled heat transfer surfaces
Ejector	• External leak/rupture • Plugged/choked • Degraded flow performance • Misdirected	Heater	• External leak/rupture • Tube leak/rupture • Tube plugged/choked • Tube fouled • Overfired • Underfired • Exhaust emissions exceed limits

<i>Equipment Item</i>	<i>Suggested Failure Modes</i>	<i>Equipment Item</i>	<i>Suggested Failure Modes</i>
Evaporator(freshwater distiller, flash type)	• External leak/rupture • Plugged/choked inlet • Plugged/choked outlet • Heat transfer surface fouled • Carryover	Incinerator	• External leak/rupture • Tube leak/rupture • Tube plugged/choked • Tube fouled • Overfired • Underfired • Degraded combustion performance
Exhaust valve	• External leak/rupture • Plugged/choked • Fails to open on demand • Fails to close on demand • Fails to reseat • Opens prematurely • Closes prematurely	Inert gas generator	• External leak/plugged • Plugged/choked • Internal leak • Fails to operate on demand • Operates too long • Degraded quality of inert gas • Degraded capacity of inert gas
Filter	• External leak/rupture • Blinded/plugged internal element • Internal element rupture	Injectors	• External leak/rupture • Plugged/choked • Fails to operate on demand • Operates prematurely • Fails closed • Fails open • Operates at degraded performance (volume, spray pattern)
Fired pressure vessel	• External leak/rupture • Tube leak/rupture • Tube plugged/choked • Tube fouled • Overfired • Underfired • Exhaust emissions exceed limits	Intake valve	• External leak/rupture • Plugged/choked • Fails to open on demand • Fails to close on demand • Fails to reseat • Opens prematurely • Closes prematurely
Fluid swivel	• External leak/rupture • Internal leak • Fails to rotate • Rotates when not required	Non-return valve	• External leak/rupture • Plugged/choked • Fails to open on demand • Fails to close on demand

<i>Equipment Item</i>	<i>Suggested Failure Modes</i>	<i>Equipment Item</i>	<i>Suggested Failure Modes</i>
Nozzle	• External leak/rupture • Plugged/choked • Misdirected • Operates with degraded spray pattern	Rupture disc	• External leak/rupture • Internal leak • Plugged/choked • Fails to rupture on demand • Ruptures prematurely
Pressure-vacuum valve	• External leak/rupture • Plugged/choked • Fails to open on demand (pressure) • Fails to close on demand (pressure) • Fails to reseal (pressure) • Opens prematurely (pressure) • Closes prematurely (pressure) • Fails to open on demand (vacuum) • Fails to close on demand (vacuum) • Fails to reseal (vacuum) • Opens prematurely (vacuum) • Closes prematurely (vacuum)	Safety/relief valve	• External leak/rupture • Internal leak • Plugged/choked • Fails to open on demand • Fails to reseal • Opens prematurely • Closes prematurely
Pump	• External leak/rupture • Fails to start on demand • Fails to stop on demand • Fails off while running • Operates at degraded head/flow performance	Scrubber	• External leak/rupture • Plugged/choked inlet • Plugged/choked outlet • Fouled contact surfaces • Channeling of fluids
Purifier(centrifugal type)	• External leak/rupture • Internal leak • Plugged/choked • Operates at degraded purification performance	Separator(for oily water)	• External leak/rupture • Plugged/choked inlet • Plugged/choked outlet • Discharge exceeds limits

<i>Equipment Item</i>	<i>Suggested Failure Modes</i>	<i>Equipment Item</i>	<i>Suggested Failure Modes</i>
Regulating valve	• External leak/rupture • Internal leak • Plugged/choked • Fails to open • Fails to close • Fails to change position/spurious position • Opens prematurely • Closes prematurely	Strainer	• External leak/rupture • Blinded/plugged internal element • Internal element rupture
Reservoir/tank	• External leak/rupture • Plugged/choked inlet • Plugged/choked outlet		
Unfired pressure vessels	• External leak/rupture • Plugged/choked inlet • Plugged/choked outlet • Coil leak/rupture • Plugged/choked coil • Coil fouled	Valve	• External leak/rupture • Internal leak • Fails to open • Fails to close • Fails to change position/spurious operation • Opens prematurely • Closes prematurely

TABLE 4
Control Equipment

<i>Equipment Item</i>	<i>Suggested Failure Modes</i>	<i>Equipment Item</i>	<i>Suggested Failure Modes</i>
Actuator	• Fails with no output signal • Fails with low output signal • Fails with high output signal • Fails to respond to an input signal change • Spurious output signal	Protective device	• Fails to detect and activate • False detection and activation • Causes incorrect action
Analyzer	• External leak/rupture • Tap plugged/choked • Fails with no output signal • Fails with low output signal • Fails with high output signal • Fails to respond to an input change • Spurious output signal	Release device	• Fails to detect and activate • False detection and activation • Causes incorrect action
Indicator	• External leak/rupture • Tap plugged/choked • Fails with no output signal • Fails with low output signal • Fails with high output signal • Fails to respond to an input change • Spurious output signal	Sensor	• External leak/rupture • Tap plugged/choked • Fails with no output signal • Fails with low output signal • Fails with high output signal • Fails to respond to an input change • Spurious output signal

TABLE 5
Lifting Equipment

<i>Equipment Item</i>	<i>Suggested Failure Modes</i>	<i>Equipment Item</i>	<i>Suggested Failure Modes</i>
Boom	• Cracked • Fractured • Deformed • Worn • Corroded • Loosened • Sticking	Drawworks	• Cracked structural member • Fractured structural member • Deformed structural member • Worn structural member • Corroded structural member • Loosened • Sticking • Fails to operate on demand • Fails to stop on demand/ operates too long • Starts prematurely • Stops prematurely • Degraded lifting performance
Crane	• Cracked structural member • Fractured structural member • Deformed structural member • Worn structural member • Corroded structural member • Loosened • Sticking • Fails to operate on demand • Fails to stop on demand/ operates too long • Starts prematurely • Stops prematurely • Degraded lifting performance	Elevator	• Cracked structural member • Fractured structural member • Deformed structural member • Worn structural member • Corroded structural member • Loosened • Sticking • Fails to operate on demand • Fails to stop on demand/ operates too long • Starts prematurely • Stops prematurely • Degraded lifting performance

<i>Equipment Item</i>	<i>Suggested Failure Modes</i>	<i>Equipment Item</i>	<i>Suggested Failure Modes</i>
Davit	• Cracked structural member • Fractured structural member • Worn structural member • Deformed structural member • Corroded structural member • Loosened • Sticking	Hoist	• Cracked structural member • Fractured structural member • Deformed structural member • Worn structural member • Corroded structural member • Loosened • Sticking • Fails to operate on demand • Fails to stop on demand/ operates too long • Starts prematurely • Stops prematurely • Degraded lifting performance
Derrick	• Cracked structural member • Fractured structural member • Deformed structural member • Worn structural member • Corroded structural member • Loosened • Vibrating		

TABLE 6
Electrical Components

<i>Equipment Item</i>	<i>Suggested Failure Modes</i>	<i>Equipment Item</i>	<i>Suggested Failure Modes</i>
Cable	• Cracked • Fractured • Corroded/oxidized • Kinked/pinched • Short circuited • Open circuited	Fixture	• Corroded/oxidized • Fails opened • Fails closed • Short circuit
Circuit breaker	• Corroded/oxidized • Fails opened • Fails closed • Short circuit	Fuse	• Corroded/oxidized • Fails opened • Fails closed • Short circuit
Disconnect	• Corroded/oxidized • Fails opened • Fails closed • Short circuit		

TABLE 7
Mechanical Components

<i>Equipment Item</i>	<i>Suggested Failure Modes</i>	<i>Equipment Item</i>	<i>Suggested Failure Modes</i>
Bearing	• Cracked • Contaminated • Fractured • Worn • Corroded • Loosened/Excessive play • Binding/Sticking • Vibrating	Connecting rod	• Cracked • Fractured • Worn • Deformed • Corroded • Loosened • Sticking • Vibrating • Plugged/choked passageways (internal to the rod)
Blade	• Cracked • Fractured • Worn • Deformed • Corroded • Loosened • Sticking	Crankcase	• Cracked • Fractured • Worn • Deformed • Corroded • Loosened • Leaking • Vibrating
Bolt	• Cracked • Fatigue • Fractured • Fretting • Worn • Deformed • Corroded • Loosened • Sticking • Vibrating	Crankcase explosion relief valve	• External leak/rupture • Plugged/choked • Fails to open on demand • Opens prematurely

<i>Equipment Item</i>	<i>Suggested Failure Modes</i>	<i>Equipment Item</i>	<i>Suggested Failure Modes</i>
Casing	• Cracked • Fractured • Worn • Deformed • Corroded • Vibrating • Leaking	Crosshead	• Cracked • Fractured • Worn • Deformed • Corroded • Loosened • Sticking • Vibrating • Plugged/choked passageways
Chock	• Cracked • Fractured • Worn • Deformed • Corroded • Loosened • Sticking	Cylinder	• Cracked • Fractured • Worn • Deformed • Corroded • Leaking
Cylinder head	• Cracked • Fractured • Worn • Deformed • Corroded • Leaking	Key	• Cracked • Fractured • Worn • Deformed • Corroded • Loosened • Vibrating
Diaphragm	• Cracked • Fractured • Worn • Deformed • Corroded • Leaking • Sticking	Nut	• Cracked • Fractured • Worn • Deformed • Corroded • Loosened • Sticking • Vibrating

<i>Equipment Item</i>	<i>Suggested Failure Modes</i>	<i>Equipment Item</i>	<i>Suggested Failure Modes</i>
Gear wheel	• Cracked • Fractured • Worn • Deformed • Corroded • Loosened • Sticking • Vibrating	Pin	• Cracked • Fractured • Worn • Deformed • Corroded • Loosened • Sticking • Vibrating
Impeller	• Cracked • Fractured • Worn • Deformed • Corroded • Vibrating	Pipe scraper	• Cracked • Fractured • Worn • Deformed • Corroded • Loosened • Sticking • Vibrating
Journal	• Cracked • Fractured • Worn • Deformed • Corroded	Piston	• Cracked • Fractured • Worn • Deformed • Corroded • Loosened • Seized • Sticking
Piston rod	• Cracked • Fractured • Worn • Deformed • Corroded • Loosened • Sticking • Vibrating • Plugged/choked passageways (internal to the rod)	Scavenging air valve	• External leak/rupture • Internal leak • Plugged/choked • Fails to open on demand • Fails to close on demand • Opens prematurely • Closes prematurely

<i>Equipment Item</i>	<i>Suggested Failure Modes</i>	<i>Equipment Item</i>	<i>Suggested Failure Modes</i>
Rack	• Cracked • Fractured • Deformed • Corroded • Loosened	Scavenge relief device	• External leak/rupture • Internal leak • Plugged/choked • Fails to open on demand • Fails to reseal • Opens prematurely • Closes prematurely
Ram	• Cracked • Fractured • Worn • Deformed • Corroded • Loosened • Sticking	Scavenger unit	• Adds too little reacting chemical to drilling mud • Adds too much reacting chemical to drilling mud • Unable to remove sufficient contaminants from drilling mud
Rotor	• Cracked • Fractured • Worn • Deformed • Corroded • Loosened • Sticking • Vibrating	Seal	• Cracked • Fractured • Worn • Deformed • Corroded • Loosened • Leaking • Vibrating
Rudder pintle	• Cracked • Fractured • Worn • Deformed • Corroded • Loosened • Sticking • Vibrating	Shaft	• Cracked • Fractured • Worn • Deformed • Corroded • Loosened • Sticking • Vibrating

<i>Equipment Item</i>	<i>Suggested Failure Modes</i>	<i>Equipment Item</i>	<i>Suggested Failure Modes</i>
Rudder stock	• Cracked • Fractured • Worn • Deformed • Corroded • Loosened • Vibrating	Tensioner ring	• Cracked • Fractured • Worn • Deformed • Corroded • Loosened • Sticking
Tie rod	• Cracked • Fractured • Worn • Deformed • Corroded • Loosened • Vibrating	Turbine disc	• Cracked • Fractured • Worn • Deformed • Corroded • Loosened • Vibrating
Tiller	• Cracked • Fractured • Worn • Deformed • Corroded • Loosened • Sticking • Vibrating	Turret shaft	• Cracked • Fractured • Worn • Deformed • Corroded • Loosened • Sticking • Vibrating

TABLE 8
Piping Components

<i>Equipment Item</i>	<i>Suggested Failure Modes</i>	<i>Equipment Item</i>	<i>Suggested Failure Modes</i>
Expansion joint	• Cracked • Fractured • Deformed • Kinked/pinched • Corroded • Loosened • Leaking • Sticking • Vibrating	Kelly cock	• Leaking • Internal leak • Plugged/choked • Cracked • Fractured • Deformed • Corroded • Sticking • Fails to close on demand • Closes prematurely
Flange	• Cracked • Fractured • Worn • Corroded • Loosened • Leaking • Vibrating	Kelly	• Leaking • Plugged/choked • Cracked • Fractured • Deformed • Worn • Loosened
Flexible hose	• Cracked • Fractured • Deformed • Kinked/pinched • Twisted • Corroded • Loosened fittings • Leaking • Vibrating	Manifold	• Cracked • Fractured • Worn • Deformed • Corroded • Loosened • Leaking • Plugged/choked • Vibrating

<i>Equipment Item</i>	<i>Suggested Failure Modes</i>	<i>Equipment Item</i>	<i>Suggested Failure Modes</i>
Fusible plug	• Cracked • Fractured • Deformed • Corroded • Loosened • Leaking • Vibrating • Activates at a lower set point • Activates at a higher set point	Overboard discharge	• Cracked • Fractured • Worn • Corroded • Loosened • Leaking • Plugged/choked • Vibrating
Pipe	• Cracked • Fractured • Worn • Deformed • Corroded • Loosened • Leaking • Plugged/choked • Vibrating	Spraying nozzle	• Cracked • Fractured • Worn • Corroded • Loosened • Leaking • Plugged/choked • Vibrating

<i>Equipment Item</i>	<i>Suggested Failure Modes</i>	<i>Equipment Item</i>	<i>Suggested Failure Modes</i>
Pipe fitting	• Cracked • Fractured • Worn • Scored • Deformed • Corroded • Loosened • Leaking • Plugged/choked • Vibrating	Tube	• Cracked • Fractured • Worn • Deformed • Corroded • Loosened • Leaking • Plugged/choked • Vibrating
Sight flow glass	• Cracked • Fractured • Worn • Corroded • Loosened • Leaking • Plugged/choked • Blinded/blocked sight glass • Vibrating		

TABLE 9
Structural Components

<i>Equipment Item</i>	<i>Suggested Failure Modes</i>	<i>Equipment Item</i>	<i>Suggested Failure Modes</i>
Bed plate	• Cracked • Fractured • Worn • Deformed • Corroded • Loosened • Leaking • Vibrating	Rudder	• Cracked • Fractured • Worn • Deformed • Corroded • Loosened • Sticking • Vibrating
Bilge well	• Cracked • Fractured • Worn • Deformed • Corroded • Loosened • Leaking • Vibrating	Sea chest	• Plugged/choked inlet • Plugged/choked outlet • Cracked • Fractured • Corroded
Connector	• Cracked • Fractured • Worn • Deformed • Corroded • Loosened • Leaking • Sticking • Vibrating	Stern tube	• Cracked • Fractured • Worn • Deformed • Corroded • Loosened • Leaking
Foundation	• Cracked • Fractured • Worn • Deformed • Corroded • Loosened • Vibrating	Thrust block	• Cracked • Fractured • Worn • Deformed • Corroded • Loosened

TABLE 10
Rigging Components

<i>Equipment Item</i>	<i>Suggested Failure Modes</i>	<i>Equipment Item</i>	<i>Suggested Failure Modes</i>
Block	• Cracked • Fractured • Worn • Deformed • Corroded • Loosened	Shackle	• Cracked • Fractured • Worn • Deformed • Corroded • Loosened
Deadline anchor	• Cracked • Fractured • Worn • Deformed • Corroded • Loosened • Sticking • Vibrating	Spreader beam	• Cracked • Fractured • Deformed • Corroded • Loosened
Hook	• Cracked • Fractured • Worn • Deformed • Corroded • Loosened • Sticking	Swivel	• Cracked • Fractured • Worn • Deformed • Corroded • Loosened • Sticking

<i>Equipment Item</i>	<i>Suggested Failure Modes</i>	<i>Equipment Item</i>	<i>Suggested Failure Modes</i>
Pulley	• Cracked • Fractured • Worn • Deformed • Corroded • Loosened • Sticking • Vibrating	Wire rope	• Cracked • Fractured • Worn • Deformed • Corroded • Loosened at a connection • Kinked
Ring	• Cracked • Fractured • Worn • Deformed • Corroded • Loosened		

Failure-finding Maintenance Task Interval

1 Introduction

Failure-finding maintenance tasks are employed to discover equipment faults that are not detectable during normal system operations. These equipment faults are referred to as 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 item to confirm that the equipment is available to perform its function(s) when demanded. When a hidden failure occurs, if an appropriate failure-finding maintenance task is not performed, when a second failure occurs, a functional failure will result before the hidden failure is detected. For example, a failure that has occurred in a standby electrical generator may only be discovered when the primary generator fails, the standby generator fails to start and electrical power is lost.

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 failures 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:

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

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

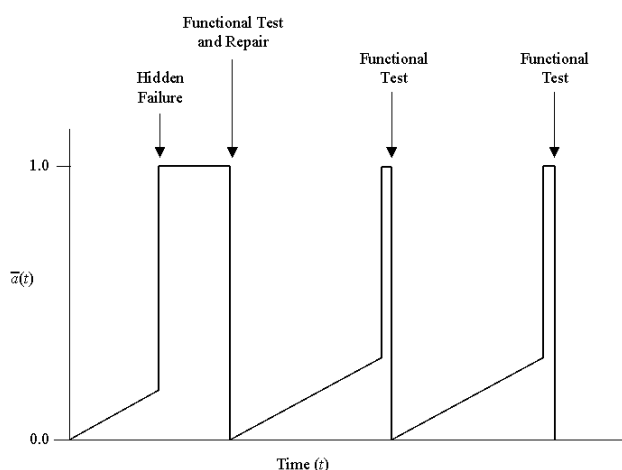
This equation can be rearranged to solve for the unavailability of the safety system or backup system:

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

An acceptable frequency of occurrence of a failure is achieved by keeping the unavailability of the equipment at less than what is needed so that 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 (i.e., 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 the operator to discover 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 (i.e., the probability of failure is a product of the failure rate and elapsed time). Appendix 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 test protective systems 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:

- Mathematically using reliability equations, or
- Using general guidelines developed to provide acceptable risk.

Regardless of the technique used, the key is to keep the unavailability of a safety system or backup system low enough so that 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:

- 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.
- 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.

- The distribution of the failures is exponential
- The conditional failure rate times the test interval time ($\lambda \times \text{test interval}$) is less than 0.1
- The time to conduct a failure-finding task is short when compared to the length of time that the system is available
- The time to conduct a repair of the system is short when compared to the length of time that the system is available
- The multiple failure can only occur from the combination of the specified initiating event concurrent with the unavailability of the backup or safety system

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

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 Failure-finding Task Interval

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

- Establishing rules for determining required unavailability of the hidden failure based on the risk of the hidden failure
- Estimating the MTTF of the hidden failure
- Determining the test interval using a table based on Equation 5

Appendix 5, Tables 1 and 2 provide examples of the acceptable probability rules and failure-finding task interval

TABLE 1
Example of Failure-finding Task Interval Rules

<i>Risk of Hidden Failure</i>	<i>Unavailability Required ($\bar{a}_{SYS}$)</i>
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

<i>Unavailability Required ($\bar{a}_{SYS}$)</i>	<i>Failure-finding Task Interval (as % of MTTF)</i>
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 verify that the assumptions are valid.

5 Failure-finding Maintenance Task Intervals

In determining the intervals in Appendix 5, Table 3, the following inputs were used:

- The failure rate data (MTTF) for the safety systems and alarms is based on 10,000 hours per year.
- The estimated frequency of occurrence of multiple failures is 0.01 (1 failure per 100 vessels per year).
- The estimated frequency of occurrence of the initiating event is 0.1 (1 failure per 10 vessels per year).

The test interval is determined by applying Equation (5).

TABLE 3
Failure-finding Maintenance Task Interval Estimates

<i>Equipment Item</i>	<i>Safety System</i>	<i>Task Interval</i>	<i>Alarm</i>	<i>Task Interval</i>	<i>Controls</i>	<i>Task Interval</i>
	<i>MTTF Failure per 104 hrsMonths</i>	<i>Months</i>	<i>MTTF Failure per 104 hrs</i>	<i>Months</i>	<i>MTTF Failure per 104 hrs</i>	<i>Months</i>
Main Engine	0.5778	4.2	1.7307	1.4	0.5570	4.3
Boiler	0.4482	5.4	0.5104	4.7	0.0137	175.2
Diesel Generator	0.2928	8.2	0.4599	5.2	0.0920	26.1
Steam Turbo Generator	0.0933	25.7	0.0868	27.6	0.0020	1200.0
Pumps	0.4003	6.0	0.1632	14.7	N/A	N/A
Air Compressors	0.1503	16.0	0.0337	71.2	N/A	N/A
Purifiers	0.7980	3.0	0.2539	9.5	N/A	N/A
Heat Exchangers	0.3213	7.5	0.0751	32.0	N/A	N/A
Pipe/valves	0.6555	3.7	0.0725	33.1	N/A	N/A
Deck Machinery	0.1645	14.6	0.0453	53.0	N/A	N/A
Tanks	0.3809	6.3	0.3705	6.5	N/A	N/A
Mooring Equipment	0.0216	111.1	N/A	N/A	N/A	N/A
Cargo Winch	0.0233	103.0	0.0059	406.8	N/A	N/A
Oil Content Monitor	N/A	N/A	0.1049	22.9	N/A	N/A
Steering Gear						
Emergency Diesel Gen						

Note:

N/A – Data Not Available

APPENDIX 6

Overview of Condition-monitoring Techniques and Potential-Failure Interval Data

1 Introduction

This Appendix provides a brief listing of condition-monitoring techniques that may be considered during the development of the preventative maintenance plan. A list of potential failure data is also provided for guidance. Additional information can be found in the *ABS Guidance Notes on Equipment Condition Monitoring Techniques*.

2 Condition Monitoring Categories

Numerous condition-monitoring techniques have been developed to indicate the condition of certain functions of equipment.

It is the responsibility of the Owner/Operator to select the most effective and appropriate technique.

The listings provided are representative of the techniques for that category. There may be other techniques available that are as effective.

The condition-monitoring techniques have been organized into the following categories and subcategories:

TABLE 1
Condition Monitoring Categories

<i>Condition Monitoring Categories</i>	<i>Subcategory</i>	<i>Table No.</i>
Corrosion Monitoring	Coupon Testing	A6/3.3.3 TABLE 2
	Corrometer	
	Potential Monitoring	
Thermography	Contact	A6/3.3.3 TABLE 3
	Non-Contact	
Dynamic Monitoring	Vibration Analysis	A6/3.3.3 TABLE 4
Oil Analysis and Tribology	Wear Particle Analysis	A6/3 TABLE 5
	Chemical Analysis	
	Viscosity	
	Dielectric Strength	

<i>Condition Monitoring Categories</i>	<i>Subcategory</i>	<i>Table No.</i>
Nondestructive Testing	Radiography	A6/3 TABLE 6
	Dye Penetrant	
	Ultrasonic	
	Magnetic Particle Inspection	
	Eddy Current Testing	
	Acoustic Emission	
	Hydrostatic Testing	
	Visual Inspection	
Electrical Condition Monitoring	Megohmmeter Testing	A6/3 TABLE 7
	High Potential Testing	
	Surge Testing	
	Conductor Complex Impedance	
	Power Signature Analysis	
	Radio Frequency Monitoring	
	Power Factor Testing	
	Starting Time and Current	
	Motor Circuit Analysis	
	Battery Impedance Testing	
Performance Monitoring	Temperature Monitoring	A6/3 TABLE 8
	Flow Monitoring	
	Pressure Monitoring	

2.1 Corrosion Monitoring

The corrosion monitoring category refers to any technique used to measure the corrosion rate or loss of material.

2.2 Thermography

The thermography category refers to those techniques that measure internal and/or external temperature or the rate of temperature change.

2.3 Dynamic Monitoring

Dynamic monitoring refers to those techniques which detect potential failures, in particular those associated with rotating equipment, which cause abnormal amounts of energy to be emitted in the form of waves such as vibration, pulses and acoustic effects. There are numerous proprietary dynamic monitoring instruments and software packages available. These have been developed to assess the condition of certain elements within equipment, such as bearing wear.

2.4 Oil Analysis and Tribology

Oil analysis refers to techniques to monitor the quantity of contaminants and additives in lubricating oils and fuel oils. Tribology refers to the study of the design, friction, wear and lubrication of interacting surfaces in relative motion, such as bearings. Some oil analyses also address wear particle size and shape.

2.5 Nondestructive Testing

The nondestructive testing category refers to numerous techniques that assess the condition of the material in a component in equipment with regard to internal or surface defects, for example, cracks or cavities.

2.6 Electrical Condition Monitoring

The electrical condition monitoring category refers to numerous techniques, some proprietary, that assess changes in resistance, conductivity, dielectric strength and potential.

2.7 Performance Monitoring

The performance monitoring category addresses simple, common techniques used to assess the operating condition of the equipment, namely temperature, flow, pressure, power and torque.

2.8 Tabular Listing of Techniques

The condition-monitoring techniques are organized as indicated in A6/2 TABLE 1 above.

There may be alternative names for the techniques listed under the Technique column, particularly if the technique uses a proprietary technology.

The Fixed/Portable Equipment column indicates whether the hardware that the technique uses can be a part of the equipment that it is monitoring (for example, fixed) or if it is carried to the equipment, monitoring occurs, and then the hardware is removed (for example, portable). In some cases, the hardware may be fixed or portable, depending upon the application of the equipment being monitored.

The P-F Interval column is provided for guidance only, regarding the order of magnitude of the frequency of monitoring. The P-F interval is dependent on the equipment type, operating mode and operating context.

The Skill column is provided for guidance related to the skill level required for the operator. The following skill descriptions are listed in ascending skill level:

- No specific training needed
- Trained semi-skilled worker
- Trained skilled worker
- Electrician
- Experienced electrician, technician, electrical technician
- Trained laboratory technician
- Trained and experienced technician and test operator
- Engineer
- Experienced engineer

3 Guidance for Condition-monitoring Interval Determination

3.1 Introduction

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 an equipment item 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.

The time interval between the point at which one can detect onset of failure, the Potential Failure, and the point at which functional failure occurs, the Failure, is called the P-F interval. This is the warning period (i.e., the time between the point at which the potential failure becomes detectable and the point at which it

deteriorates into a functional failure). If a condition-monitoring task is performed on intervals longer than the P-F interval, the potential failure may not be detected. On the other hand, if the condition-monitoring task is performed too frequently compared to the P-F interval, resources are wasted.

3.2 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:

- *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.
- *Reasonably consistent P-F interval.* The P-F interval must be consistent enough so that corrective actions are not implemented prematurely or that failure occurs before corrective actions are implemented.
- *Practical interval in which condition-monitoring tasks can be performed.* The P-F interval 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.
- *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.
- *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.
- *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.

3.3 Determining Condition-monitoring Maintenance Task Intervals

Condition-monitoring maintenance task intervals must be determined based on the expected P-F interval. Use the following sources to help determine the P-F interval:

- Expert opinion and judgment including manufacturer's recommendations;
- Published information about condition-monitoring tasks;
- Historical data.

3.3.1 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:

- 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.
- Reduce the task interval if there is low confidence in the estimate of the expected P-F.
- Reduce the task interval for higher risk failure modes.
- Set the task interval at half the expected P-F interval (or slightly above) for lower risk failure modes.

3.3.2 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:

- If an existing condition-monitoring task is being performed and has proven to be effective (i.e., no unexpected failures have occurred), use the existing task interval as the initial default task interval.
- If an existing condition-monitoring task is being performed and some functional failures have occurred, adjust the task interval downward based on the experience.
- 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. 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?

3.3.3 Improving the Understanding of P-F Intervals

As data from condition-monitoring tasks are collected and the sustainment process is implemented, operating personnel will improve their understanding of the P-F interval. For example, assume that vibration testing is performed weekly on pumps in similar service. On several occasions, the vibration analysis detects the onset of failures, however, due to scheduling delays, corrective action is not taken for an additional six (6) to eight (8) weeks. During this period of delay, the pumps continue to operate properly. It is then known 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 (6) weeks). This is a rough form of age-exploration testing.

TABLE 2
Corrosion Monitoring

<i>Condition</i>	<i>Condition Monitoring Subcategory</i>	<i>Technique</i>	<i>Fixed/Portable Equipment</i>	<i>P-F Interval</i>	<i>Skill</i>
General corrosion	Coupon Testing	Coupon Testing	Fixed	Months	Trained and experienced technician
Localized corrosion					
General corrosion	Corrometer	Corrometer	Fixed	Months	Trained and experienced technician
Localized corrosion					
Stress-corrosion cracking	Potential Monitoring	Potential Monitoring	Fixed	Varies depending on material and rate of corrosion	Trained and experienced technician
Pitting corrosion					
Selective phase corrosion					
Impingement attack					

TABLE 3
Thermography

<i>Condition</i>	<i>Condition Monitoring Subcategory</i>	<i>Technique</i>	<i>Fixed/Portable Equipment</i>	<i>P-F Interval</i>	<i>Skill</i>
Monitoring of internal/external temperature Hot or Cold spots/Heat loss caused by: - Corroded/oxidized/loose electrical connections - Damaged/failed/missing insulation - Damaged/malfunctioning electrical/mechanical equipment - Inadequate cooling - Inadequate lubrication - Misalignment/conditions leading to localized overloading of electrical/mechanical equipment - Overheated/overloaded electrical/mechanical equipment	Contact	Thermometer/RTD/Thermocoupl	Fixed	Weeks to months	No specific training needed
		Temperature indicating paint/crayon/decal	Fixed and/or Portable	Weeks to months	No specific training needed
	Non-contact	Infrared	Portable	Days to months	Trained and experienced technician

TABLE 4
Dynamic Monitoring

<i>Condition</i>	<i>Condition Monitoring Subcategory</i>	<i>Technique</i>	<i>Fixed/Portable Equipment</i>	<i>P-F Interval</i>	<i>Skill</i>
Wear Imbalance Misalignment Mechanical looseness Bearing damage Structural resonance Fatigue Shaft damage (e.g., bent) Belt flaws Sheave and pulley flaws Gear damage Flow turbulence Cavitation	Vibration Analysis	Spectrum Analysis ⁽¹⁾	Fixed or Portable	Weeks to months	Trained and experienced technician
Bearing damage Bearing wear Inadequate roller bearing lubrication Gear damage		Waveform Analysis (2) (Time Waveform Analysis)	Fixed or Portable	Weeks to months	Trained and experienced technician
Corona in switchgear Leaks in pressure and vacuum systems Bearing wear Cavitation Bearing damage Faulty steam trap		Shock Pulse Analysis, Peak Value (Peak Vue) Analysis, Spike Energy TM	Fixed or Portable	Weeks to months	Trained and experienced technician
		Ultrasonic	Portable	Highly variable	Trained skilled worker

Notes:

- 1 This technique is suitable for steady state conditions.
- 2 Waveform analysis is suitable for transient conditions, slow beats, pulses, amplitude modulations, frequency modulations and instabilities.
- 3 Suggested standards are listed in parentheses. Other applicable standards may be used to conduct the testing.
- 4 Refer to A6/3.3.3 TABLE 3 “Thermography” for additional condition-monitoring techniques related to electrical equipment.
- 5 This test stresses the insulation systems and can induce premature failure in marginal motors. This test is not recommended as a routinely repeated condition-monitoring technique, but as an acceptance test.

TABLE 5
Oil Analysis and Tribology

<i>Condition</i>	<i>Condition Monitoring Subcategory</i>	<i>Technique ⁽¹⁾</i>	<i>Fixed/Portable Equipment</i>	<i>P-F Interval</i>	<i>Skill</i>
Wear Fatigue Corrosion particles Particles in lubricating oil	Wear Particle Analysis	Ferrography	Portable	Months	Trained semi-skilled worker to take the sample and experienced technician to perform and interpret the analysis
Wear Fatigue Corrosion Lubricating oil contamination Particles in hydraulic oil		Particle Counting	Portable	Weeks to months	Trained skilled worker

<i>Condition</i>	<i>Condition Monitoring Subcategory</i>	<i>Technique ⁽¹⁾</i>	<i>Fixed/Portable Equipment</i>	<i>P-F Interval</i>	<i>Skill</i>
Oil contamination Oil deterioration	Chemical Analysis	Sediment (ASTM D-1698)	Portable	Weeks	Trained semi-skilled worker to take the sample and trained laboratory technician to perform and interpret the analysis
Presence of wear metals Oil additive depletion Oil contamination Corrosion		Atomic Emission Spectroscopy	Portable	Weeks to months	Trained semi-skilled worker to take the sample and experienced technician to perform and interpret the analysis
Electrical insulating oil deterioration Electrical insulating oil oxidation Electrical insulating oil additive depletion		Infrared Spectroscopy, including FT-IR (ASTM D 117-02)	Portable	Weeks to months	Trained semi-skilled worker to take the sample and experienced technician to perform and interpret the analysis
Lubricating oil deterioration		Total Acid Number/Base Number (ASTM D664 (Acid Number). ASTM D4739, ASTM D2896, ISO 3771 (Base Number))	Portable	Weeks to months	Trained semi-skilled worker to take the sample and trained laboratory technician to perform and interpret the analysis
Water contamination		Moisture (ASTM D 1533, ISO 12937-00 (Electrical))	Portable	Days to weeks	Trained semi-skilled worker to take the sample and/or perform simpler analysis procedures. Trained laboratory technician to perform the more complex analysis procedures

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Oil viscosity changes	Viscosity	Kinematic viscosity (ASTM D 445, DIN 51562)	Portable	Weeks to months	Trained semi-skilled worker to take the sample and trained laboratory technician to perform and interpret the analysis
Insulating oil contamination	Dielectric Strength	Dielectric Strength (ASTM D 117-02)	Portable	Months	Trained semi-skilled worker to take the sample and trained laboratory technician to perform and interpret the analysis

Note:

1. Suggested standards are listed in parentheses. Other applicable standards may be used to conduct the testing.

TABLE 6
Nondestructive Testing

<i>Condition</i>	<i>Condition Monitoring Subcategory</i>	<i>Technique</i>	<i>Fixed/Portable Equipment</i>	<i>P-F Interval</i>	<i>Skill</i>
Subsurface defects Lack of weld penetration Gas porosity in welds Intergranular corrosion	Radiography	Radiography	Portable	Months	Trained and experienced technician to take the radiographs and trained and experienced technician or engineer to interpret the radiographs
Surface defects Surface cracks Corrosion fatigue Corrosion stress embrittlement Hydrogen embrittlement	Dye Penetrant	Dye Penetrant	Portable	Days to months	Trained and experienced technician OR Trained skilled worker

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Subsurface defects Lack of weld penetration Gas porosity in welds Intergranular corrosion Stress corrosion Metal thickness loss due to wear and/or corrosion	Ultrasonic	Ultrasonic	Portable	Weeks to months	Trained and experienced technician
Shallow subsurface defects Corrosion fatigue Corrosion stress Surface shrinkage Fatigue Wear Lamination Hydrogen embrittlement	Magnetic Particle Inspection	Magnetic Particle Inspection	Portable	Days to months	Trained and experienced technician
Surface and shallow subsurface defects Tube thickness Wear Strain Corrosion Metal thickness loss due to wear and/or corrosion	Eddy Current Testing	Eddy Current Testing	Portable	Weeks	Trained and experienced technician
Plastic deformation Crack formation Fatigue Stress Wear	Acoustic Emission	Acoustic Emission	Portable	Weeks	Trained and experienced technician
Defects in pressure boundary	Hydrostatic Testing	Hydrostatic Testing	Portable	Days	Trained skilled worker
Surface cracks Oxide films Corrosion Wear Fatigue Weld defects	Visual Inspection - Borescope/ Endoscope/ Fiberscope	Visual Inspection - Borescope/ Endoscope/ Fiberscope	Portable	Weeks	Trained and experienced technician

TABLE 7
Electrical Condition Monitoring ⁽¹⁾

<i>Condition</i>	<i>Condition Monitoring Subcategory</i>	<i>Technique</i>	<i>Fixed/Portable Equipment</i>	<i>P-F Interval</i>	<i>Skill</i>
Insulation resistance	Megohmmeter Testing	Megohmmeter Testing	Portable	Months to years	Technicians or engineers
Motor winding insulation deterioration	High Potential Testing (HIPOT)	High Potential Testing (HIPOT)	Portable	Note 2	Experienced electrical technician
Insulation deterioration	Surge Testing	Surge Testing	Portable	Note 2	Trained and experienced test operator
Loose motor connections Corroded motor connections Motor winding deterioration	Conductor Complex Impedance	Conductor Complex Impedance (Testing of resistance, capacitive impedance and inductive impedance of motors)	Portable	Weeks to months	Experienced electrical technician to perform the test and experienced engineer to analyze and interpret the data
Rotor damage Broken rotor bars End rings damage Bad cage joints Shorted lamination Single phasing Phase imbalance Wear or deterioration of machine clearances Machinery alignment	Power Signature Analysis	Power Signature Analysis (Motor Current Signature Analysis)	Portable	Weeks to months	Experienced electrician to connect the test equipment and experienced technician to perform the analysis and interpret the data
Broken windings	Radio Frequency Monitoring	Radio Frequency Monitoring	Portable	Weeks to months	Experienced electrician to connect the test equipment and experienced technician to perform the analysis and interpret the data
Insulation deterioration (leakage) Cable moisture	Power Factor Testing	Power Factor Testing	Fixed/Portable	Months	Experienced electrical technician to perform the test and experienced engineer to analyze and interpret the data
Misalignment Excessive mechanical friction Motor deterioration	Starting Time and Current	Starting Time and Current	Portable	Unknown	Experienced electrical technician

<i>Condition</i>	<i>Condition Monitoring Subcategory</i>	<i>Technique</i>	<i>Fixed/Portable Equipment</i>	<i>P-F Interval</i>	<i>Skill</i>
Broken rotor bars Broken shorting rings High resistance between bars and rings Uneven rotor-stator gap Rotor misposition Rotor deterioration Rotor shorted	Motor Circuit Analysis	Motor Circuit Analysis	Portable	Weeks to months	Experienced electrical technician to perform the test
Battery cell deterioration	Battery Impedance Testing	Battery Impedance Testing	Portable	Weeks	Experienced electrical technician to perform the test

Note:

- 1 Refer to A6/3.3.3 TABLE 3 “Thermography” for additional condition-monitoring techniques related to electrical equipment.
- 2 This test stresses the insulation systems and can induce premature failure in marginal motors. This test is not recommended as a routinely repeated condition-monitoring technique, but as an acceptance test.

TABLE 8
Performance Monitoring

<i>Condition</i>	<i>Condition Monitoring Subcategory</i>	<i>Technique</i>	<i>Fixed/Portable Equipment</i>	<i>P-F Interval</i>	<i>Skill</i>
Heat transfer deterioration	Temperature Monitoring	Temperature Monitoring	Fixed/Portable	Days to weeks	Trained semi-skilled worker
Performance deterioration					
Performance deterioration	Flow Monitoring	Flow Monitoring	Fixed/Portable	Days to weeks	Trained semi-skilled worker
Performance deterioration	Pressure monitoring	Pressure monitoring	Fixed/Portable	Days to weeks	Trained semi-skilled worker
Leaks					
Plugging					
Power output	Power output	Power meter (torque meter)	Fixed/Portable	Days to weeks	Trained skilled worker