BIRO KLASIFIKASI INDONESIA

GUIDANCE FOR SURVEY BASED ON RELIABILITY-CENTERED MAINTENANCE

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Section 1

General

A. Application

The following are procedures and conditions under which a properly conducted Reliability-Centered Maintenance (RCM) analysis and the resulting preventative maintenance plan may be credited as satisfying the requirements of Continuous Class Renewal Survey of Machinery.

No preventative maintenance plan supersedes the judgment of the Surveyor, nor does it waive the Surveyor attendance for damage, representative overhaul of main engines, generator engines and steering gear, general electrical insulation condition and resistance tests, electrical devices functional tests, reduction gear teeth examinations, hydrostatic tests of pressure vessels, tests and verification of safety devices such as relief valves, overspeed trips, emergency shut-offs, low-oil pressure trips, etc., as required by the Rules for Classification and Survey, Volume I.

It is a prerequisite that the machinery in this program be on a Continuous Class Renewal Survey of Machinery (CMS) cycle.

B. Objective

The objective of this Guidance is to provide requirements which reduce the risk to personnel, the vessel or marine structure, other vessels or structures and the environment and which reduce the economic consequences due to a machinery failure which may otherwise occur more frequently if a rational maintenance strategy, as provided for by this Guidance, was not applied. This is achieved by applying the analysis methodology provided in this Guidance to develop a rational maintenance plan. 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.

With an effective preventative maintenance plan, credit towards the requirements of Continuous Class Renewal Survey of Machinery may be provided.

C. Classification Notations

The RCM Program is to be approved by BKI Head Office. Upon completion of a satisfactory Implementation Survey, a “Certificate of Approval for Reliability-centered Maintenance Program” is to be issued by the attending Surveyor. A notation, if appropriate, will be entered in the *Register*.

In general, any machinery systems subject to Class Renewal Survey according to the Rules for Classification and Survey, Volume I may be selected for RCM analysis and development of a preventative maintenance plan. There are other Class Renewal Survey requirements listed in other Rules and Guides not listed here for which machinery systems may be selected for analysis. The vessel’s Owner may specifically request review of other machinery not subject to Class Renewal Survey.

When the RCM Program is approved for the equipment related to:

i) The propulsion system, including as applicable: prime mover(s), reduction gears, shafting, propeller or other thrusting device, all auxiliary systems providing, cooling, control, electrical power, exhaust, fuel, lubrication and equipment related to the steering or other directional control system, the RCM Program will be assigned and distinguished in the *Register* with the Class Notation **RCM-PS.**

ii) The fire extinguishing system (see Section 3.C.1.1.4 Rules for Classification and Survey, Volume I), the RCM Program will be assigned and distinguished in the *Register* with the Class Notation **RCM-FF**

iii) The cargo handling (cargo pumps, associated piping for internal and independent tanks) and safety equipment (i.e., inert gas system, vapor emission control) for a tanker, liquefied gas carrier or chemical carrier, the RCM Program will be assigned and distinguished in the *Register* with the Class Notation **RCM (CARGO)**.

When the RCM Program is approved for both propulsion and fire extinguishing systems, the RCM Program will be assigned and distinguished in the *Register* with the Class Notation **RCM (MACH)**.

When the RCM Program is approved for systems and equipment used in connection with drilling and the drilling system and the drilling system is in compliance with the *Guide for the Certification of Drilling Systems*, the RCM Program will be distinguished in the *Register* with the class notation **RCM (CDS)**.

The Owner may select particular systems or equipment for which RCM analysis is desired. Any machinery items not covered by the RCM analysis are to be surveyed and credited in the usual way in accordance with the *Rules for Classification and Survey*.

D. Definitions

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

BKI Recognized Condition Monitoring Company. The reference to this term refers to those companies whom BKI has identified as an External Specialist.

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

Cause. See *failure cause*.

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

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

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

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

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

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

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

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

Effects. See *failure effects*.

End Effects. See *failure effects*.

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

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

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

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

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

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

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

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

Failure-finding task. A failure-finding task is a scheduled task used to detect *hidden failures* when no *condition-monitoring* or *planned-maintenance* task is applicable. It is a scheduled function check to determine whether an item will perform its required function if called upon.

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

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

FMECA. The acronym for Failure Mode Effects and Criticality Analysis.

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

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

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

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

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

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

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

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

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

Likelihood. See *frequency*.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Safeguards. See *corrective measures*.

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

Servicing and Routine Inspection. These are simple tasks intended to (1) ensure that the failure rate and failure pattern remain as predicted by performing routine servicing (e.g., lubrication) and (2) spot accidental damage and/or problems resulting from ignorance or negligence. They provide the opportunity to ensure that the general standards of maintenance are satisfactory. These tasks are not based on any explicit potential failure condition. Servicing and routine inspection may also be applied to items that have relatively insignificant failure *consequences*, yet should not be ignored (minor leaks, drips, etc.).

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

Continuous Class Renewal Survey of Machinery. The requirements for Continuous Class Renewal Survey of Machinery are listed in Rules for Classification and Surveys, Volume I, Section 3.B.1.3.6.

Class Renewal Survey – Machinery. The requirements for a conventional Class Renewal Survey – Machinery are listed in Rules for Classification and Surveys, Volume I, Section 3.B.1.3.

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

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

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

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

E. Program Conditions and Administration

A diagram for the administration of the RCM Program is shown in Figure 1.1. A summary of the Program requirements for each step of the process is provided along with a reference to the applicable Section in this Guidance.

For a Reliability-Centered Maintenance Program in lieu of a conventional Continuous Class Renewal Survey of Machinery to be accepted, the following conditions must be met:

1. Age of Vessel

There is no limit on the age of a vessel when entered into the program. However, a vessel applying for entrance into the Program will be subject to a review of the vessel's Survey Status records to ascertain the historical performance of the machinery which could affect the RCM Program. Provided there are no historical problems related to the maintenance of machinery (e.g., unscheduled repairs, inability to meet performance requirements), the vessel will be considered eligible. If a machinery item is identified with unsatisfactory performance (see Section 7.B), the vessel may still be considered eligible, provided more frequent surveys of the item are conducted, and/or a one-time change is made, resulting in satisfactory performance and confirmed by survey.

2. Surveys

Surveys related to the vessel are to be up-to-date, without outstanding recommendations which would affect machinery enrolled in the RCM Program. The machinery in the program is to be on a Continuous Class Renewal Survey of Machinery (CMS) cycle.

If the vessel is not on CMS, the Owner is to be advised that the vessel is to be entered in CMS. For machinery for which an outstanding recommendation exists, confirmation is to be made that repairs have been performed, or if repairs have not been performed, the Owner is to be notified that an outstanding recommendation exists.

Any machinery items not covered by the RCM Program are to be surveyed and credited in the usual way in accordance with the *Rules for Classification & Survey, Volume I.*

3. Damages

There is to be no record of unrepaired damage to the vessel or its machinery which would affect the vessel's ability to participate in the RCM Program.

4. Computerized System

The RCM analysis and preventative maintenance plan is to be programmed into and maintained by a computerized system. Details of the computerized system are to be submitted to the responsible BKI Head Office for approval. It is preferable that analyses and reports required in accordance with the RCM Program be submitted or available in an electronic format with the capability to be copied to CD-ROM or other acceptable electronic storage medium.

Computerized systems are to include back-up devices such as disks/tapes or CD-ROMs which are to be updated at regular intervals.

5. Engineering Review

Where enrollment of machinery in the RCM Program is requested, the initial RCM analysis and preventative maintenance plan are to be submitted to the responsible BKI Head Office for approval. If additional equipment is enrolled in the RCM Program, the analyses are to be submitted to the responsible BKI Head Office which performed the initial review. The requirements for the documentation to be submitted are listed in Section 2.

6. Survey and Maintenance Intervals

The resulting preventative maintenance plan will list maintenance tasks to be carried out. The intervals between routine maintenance, testing or overhauls are based on recommendations by manufacturers, documented operator's experience, application of failure-finding maintenance task interval and overview of condition-monitoring techniques, and/or potential-failure interval data (Appendix C and D), where applicable.

In general, the intervals for the preventative maintenance plan are not to exceed those specified for Continuous Class Renewal Survey of Machinery (CMS). However, for components where the maintenance is based on running hours, longer intervals may be accepted as long as the intervals are based on the manufacturer's recommendations.

However, if an approved preventative maintenance program applying condition-monitoring techniques is in effect, the machinery survey intervals based on the CMS cycle period may be extended.

7. Implementation Survey

The implementation survey is to be carried out by the attending Surveyor within one year from the date of the approval letter approving the RCM analysis and preventative maintenance plan, as issued by the responsible BKI Head Office. The requirements for the implementation survey are listed in Section 4.

When this survey is carried out and the implementation found to be in order, a report confirming the implementation of the RCM Program is to be submitted by the attending Surveyor to BKI, and the system may be put into service. A class notation will be assigned and distinguished in the *Register*, if appropriate, in accordance with Section 1.C.

8. Spares Holding

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 (see Sections 4 and 6).

9. Sustainment

An effective RCM sustainment program will collect, analyze, review and respond to in-service data throughout the life of the vessel so as to continually improve the preventative maintenance plan (see Section 2.F). The results of the sustainment process are to be submitted to the attending Surveyor at the Annual Confirmation Survey. If the RCM analysis or preventative maintenance plans are revised as a result of the sustainment process, the analyses are to be submitted to the responsible BKI Head Office that performed the initial review.

10. Annual Confirmation Survey

Simultaneously with each Annual Survey of Machinery for vessels on the RCM program, an Annual Confirmation Survey is to be performed by the attending Surveyor. This survey is to verify that the program is being correctly operated and that the machinery has been functioning satisfactorily since the previous survey.

11. Cancellation of Program

The survey arrangement for machinery under the RCM Program may be cancelled by BKI 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 or 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 the RCM Program by informing BKI 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, BKI will determine future survey requirements for machinery formerly enrolled in the RCM Program.

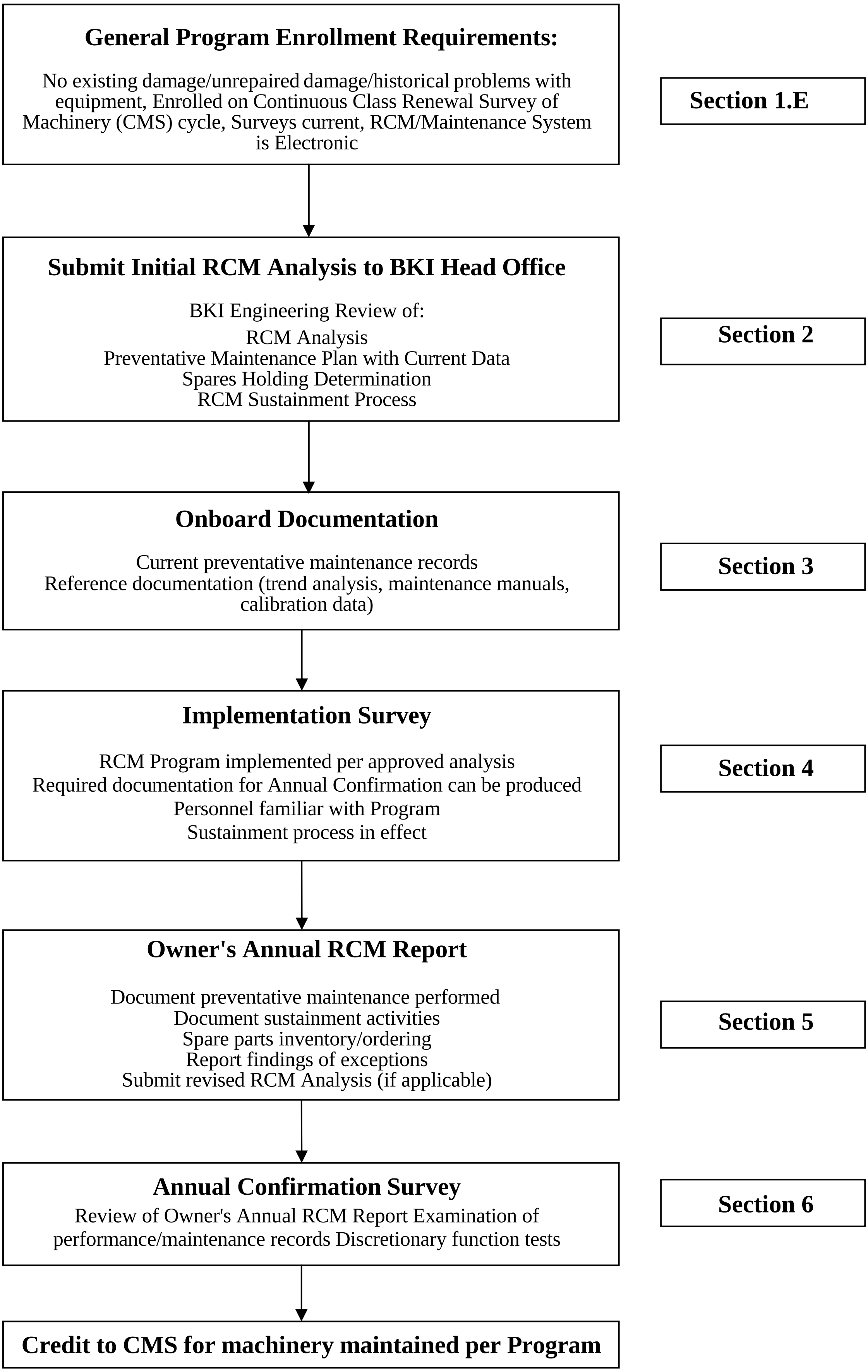

Fig. 1.1. Diagram for RCM Program Administration

Section 2

RCM Analysis Requirements

A. Introduction

The analysis consists of a Failure Mode Effects and Criticality Analysis (FMECA), a preventative maintenance plan, a spares holding plan and a sustainment process. The RCM sustainment process is to be designed so as to continually review and refine the preventative maintenance plan as the machinery ages, modifications are made during its service life or the operating context of the vessel changes.

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 are special conditions for steam turbines, internal combustion engines, electrical switchgear and power distribution panels and permanently installed monitoring equipment (see Section 2.H).

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

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

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 BKI Head Office for approval. Subsequently, Annual RCM Sustainment Analyses, if applicable, are to be prepared for review by the attending Surveyor at the Annual Confirmation Survey. If additional equipment is enrolled in the RCM Program, or the preventative maintenance plan is revised as a result of sustainment processes, the analyses are to be submitted to the responsible BKI Head Office which reviewed the Initial RCM Analysis.

Additional standards and reference publications are listed in Appendix A.

B. RCM Team Setup

An RCM-based preventative maintenance plan is best performed by a multi-disciplinary team that synergistically brings together different perspectives and technical strengths. A team approach ensures that all required information that is available within the vessel or marine structure and/or organization is considered in the RCM analysis, as well as providing a wider perception of the risks of failure and effective maintenance tasks.

The specific composition of the team varies depending on the complexity of the vessel or marine structure, scope of the RCM Program and any applicable regulatory requirements. Some of the disciplines will be called from within or outside the organization as advisors, but a core team is essential for continuity.

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

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

i) Maintenance and inspection of machinery

ii) Degradation and failure mechanisms of machinery

iii) Reliability

iv) Operations

v) Risk analysis

vi) Production process hazards (if applicable)

vii) Safety and health

viii) Materials of construction

Participation in the team of a representative with knowledge of RCM analyses in other vessels/marine structures will ensure consistency throughout the organization and/or industry, as well as provide wider experience of risks and preventative maintenance practices.

Among the duties of the RCM team members are:

i) To participate and proactively contribute in all required risk analysis and RCM meetings to ensure their knowledge is easily tapped for the RCM analyses

ii) To validate the quality and veracity of the information available

iii) To perform their specific RCM tasks, keeping in mind the end goals of the RCM Program

C. Procedures

The procedures necessary to perform the RCM analysis are shown in Figure 2.1, along with the cross-reference to the corresponding Subsection of this Section.

D. Initial RCM Analysis Submittal

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.

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

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

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

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

The functional interdependence of the selected systems within functional groups shall be described through the use of block diagrams (see Section 2.D.3) 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 (see Section 2.D.4).

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

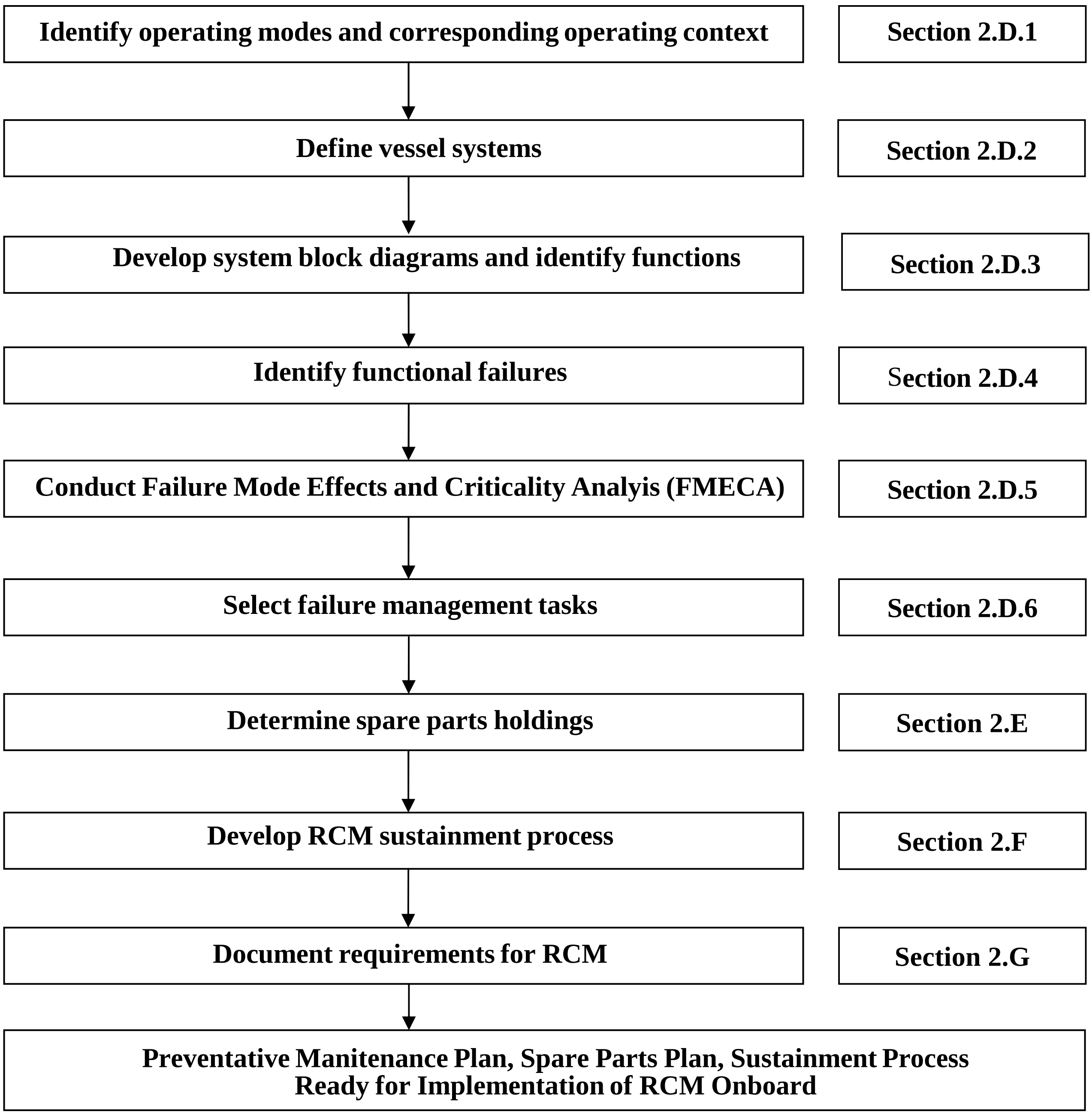

Fig. 2.1. Diagram for RCM Analysis

For each operating mode, the operating context under which the functional group is expected to operate is to be fully described 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 indenture. An example of an operating mode, along with its operating context, is provided in Table 2.1.

2. 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 described in Section 2.D.1 for each functional group, system, equipment item and component. An example partitioning for a vessel's machinery is provided in Figure 2.2.

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

- A general description of operation and structure
- The functional relationship among the system/equipment items/components
- Acceptable functional performance limits of the system/equipment items/components for each operating mode considered in Section 2.D.1
- Constraints

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

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.

Function lists may be submitted by providing a list similar to that shown in Table 2.2.

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:

- The partitioning of the functional group into systems, equipment items and components
- All appropriate labeled inputs and outputs and identification numbers by which each system is consistently referenced
- 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 Figure 2.3.

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 Table 2.2, as follows:

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.

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 overspeed 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:

- *Environment integrity.* Equipment fluid or gaseous emissions limits subject to MARPOL or other regulations
- *Safety, structural integrity.* Vibration, structural deflection, limits; safety of human operators/maintenance personnel
- *Control, containment, comfort.* Equipment control, containment of fluids/gases in system, personal comfort of personnel
- *Appearance.* Appearance of equipment to the operators/public
- *Protection.* Devices to protect equipment from overspeed, high pressure or high temperature
- *Economy, efficiency.* Fuel efficiency, lubricating oil consumption
- *Supplementary functions.* Other functions unique to the functional group/system/equipment item/component

4. Identification of Functional Failures

A list of functional failures for each function identified in Section 2.D.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:

- No or none of the function
- Less than prescribed output of function
- More than prescribed output of function
- Intermittent operation of the function
- Premature operation of the function
- Failure to operate function at a prescribed time
- Failure to cease operation of the function at a prescribed time
- 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 Table 2.2.

5. Failure Mode Effects and Criticality Analysis (FMECA)

The FMECA shall be considered using the bottom-up approach, starting from the lowest level of indenture identified during the system partitioning performed in Section 2.D.2. A sample bottom- up

FMECA format is shown in Table 2.3.

The FMECA procedure is divided into the following steps:

- Identify all potential failure modes and their causes (Section 2.D.5.1)
- Evaluate the effects on the system of each failure mode (Section 2.D.5.2)
- Identify failure detection methods (Section 2.D.5.3)
- Identify corrective measures for failure modes (Section 2.D.5.4)
- Assess the frequency and severity of important failures for criticality analysis, where applicable (Section 2.D.5.5)

5.1. 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 B. The user is cautioned that other failure modes may exist that are not listed in Appendix B. The failure modes listed in Appendix B 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:

- *Wear-in failure* is to be used for failures associated with manufacturing defects and installation, maintenance or startup errors;
- *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
- *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 in Section 2.D.6 to aid in the selection of appropriate failure management task(s).

5.2. Failure Effects

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

- 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.
- 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.
- 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 (see Section 2.D.5.4), 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.

5.3. Failure Detection

The following information is to be included in the Failure Detection/Corrective Measures column of the FMECA Worksheet (Table 2.3):

- 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.
- Where the failure detection is not evident, the term *hidden* is to be indicated.

5.4. Corrective Measures

The following information is to be included in the Failure Detection/Corrective Measures column of the FMECA Worksheet (Table 2.3):

- 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).
- 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.

5.5. 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:

- *Quantitative.* This approach is to be used if reliability data are available. When used, the source of the data and the operating context is to be provided.
- *Qualitative.* Where quantitative data are 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 (see Section 2.D.1) 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 Table 2.4.

A descriptor is be used to define each severity level. Example descriptors and example definitions for each severity level have been listed in Table 2.4. 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 Table 2.5.

A risk matrix is to be developed using the example format in Table 2.6. 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 (loss of containment, explosion/fire, safety) 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 are needed before the risk can be used in the failure management strategy in Section 2.D.6. Low confidence is to be noted in the report for the affected failure mode.

6. Selection of the Failure Management Tasks

A simplified task selection flow diagram is shown in Figure 2.4 for illustrative purposes along with the cross reference to the applicable item in this subparagraph for each step in the process.

All assessed failure modes are to be evaluated in accordance with the RCM Task Selection Flow Diagram in Figure 2.5. 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 Figure 2.5.

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.

Table 2.7 provides a listing of suggested failure management tasks for the failure characteristics identified in Section 2.D.5.1.

Maintenance task selections are to be displayed in a Task Selection Table using a format similar to Table 2.8.

Special conditions for steam turbines, internal combustion engines, electrical switchgear and power distribution panels enrolled in the RCM Program, and for permanently installed monitoring equipment are listed in Section 2.I.

6.1. High and Low Risk Characterizations

Failure modes with the high risk ranking typically cannot achieve an acceptable level of risk through maintenance alone. Generally, to achieve an acceptable level of risk, a redesign of the equipment item/component or the manner in which it is operated is needed. Therefore, a one-time change is required to reduce the risk. When the one-time change is identified, it is to be noted on the FMECA Corrective Measures column, and the FMECA is to be updated and any applicable failure modes reevaluated using Figure 2.5.

Failure modes with the low risk ranking are a low priority failure and, therefore, a no maintenance strategy is acceptable, provided existing/appropriate maintenance task strategies for corrective measures are provided so as to ensure the continued low risk for the equipment item/component being analyzed.

However, for low risk rankings with low confidence, the maintenance task strategy is to be conducted for a medium risk characterization (see Section 2.D.6.2).

6.2. Medium Risk Characterizations and Maintenance Task Selection

For medium risk characterizations and low risk characterizations with low confidence, all causes for all failure modes are to be evaluated using the RCM Task Selection Flow Diagram in Figure 2.5.

A condition-monitoring task(s) is to be considered initially. If such a task is selected, it must be practicable to implement (e.g., the task interval and accessibility for carrying out the task are operationally feasible); have a high degree of success in detecting the failure mode; and reduce the frequency of occurrence of the failure mode.

The task interval selected must provide sufficient warning of the failure to ensure maintenance can be performed prior to the actual failure. The task interval is to be set at less than half of the anticipated Potential-Failure interval. The task interval is to be determined from the following sources (in ascending order) and documented:

- Manufacturer's recommendations
- Current condition-monitoring task intervals
- Documented Owner/Operator experience if proposing changes to current intervals

Guidance for determining the Potential-Failure interval has been provided in Appendix D.

If condition-monitoring tasks are not effective or applicable, a planned-maintenance task is to be considered. If the cause of the failure mode is attributable to wear-in failure characteristics, consideration to a one-time change or redesign of the equipment item/component is to be considered. If the failure mode is attributable to wear-out failure characteristics, a planned-maintenance task is to be considered. The criterion for selection of the planned-maintenance tasks is the same as listed for condition-monitoring tasks.

If the frequency of occurrence of the failure mode cannot be reduced by condition-monitoring or planned-maintenance tasks alone, a combination of condition-monitoring and planned- maintenance tasks can be considered to reduce the frequency of occurrence of the failure mode.

6.3. Hidden and Evident Functional Failures and Maintenance Task Selection

For evident failure modes, if no applicable or effective maintenance task can be applied, then a one-time change may be necessary to achieve an acceptable risk.

For hidden failure modes, an effective failure-finding task is to be applied at an appropriate interval. If no effective failure-finding task can be applied or any other applicable and effective task (such as servicing and routine inspection), then a one-time change may be necessary to achieve an acceptable risk.

Suggested failure-finding task interval data has been provided in Appendix C.

6.4. Reevaluation of Risk

The risk is to be reevaluated with the selected maintenance tasks and any one-time changes. The resulting risk is to be acceptable with no further risk reduction practically feasible. If the resulting risk is not acceptable, the maintenance task selections and one-time changes are to be reevaluated. These are to be noted in the Task Selection Table (see Table 2.8).

6.5. Maintenance Task Allocation and Planning

The maintenance tasks identified in each step in Section 2.D.6.1 through 2.D.6.3 are to be organized in accordance with the following suggested categories:

Category A – Can be undertaken at sea by the vessel's personnel

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

Category C – Must be undertaken in a dry dock facility

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 ensure End Effects are not compromised.

A maintenance task summary with the information indicated in Table 2.9 is to be submitted.

E. 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:

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

Figure 2.6 is to be applied to select the most appropriate spares holding to achieve the desired level of the End Effects. Figure 2.6A has been provided to illustrate a spares holding determination example. A spares holding determination summary with the information indicated in Table 2.10 is to be submitted.

1. Stock-out Effect on End Effects

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

Direct effect. If the spare is not available and the associated maintenance tasks cannot be carried out, the corresponding failure mode will eventually lead to an End Effect(s) if failure occurs.

Indirect effect. If the spare is not available and the associated maintenance tasks cannot be carried out, the corresponding failure mode will not lead to an End Effect(s), unless a further failure occurs.

Normal circumstances. The item is operating within context and without a failure occurring. If the stock-out has no effect, then no spares holding is required.

2. Spares Holding Decisions

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

For the case when:

The parts requirements can be anticipated before failure occurs or there is sufficient warning time for the parts to be ordered;

Lead-time for parts order is consistent over the life cycle of the equipment item or component;

Then order parts before demand occurs.

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

The risk of a stock-out is reduced to an acceptable level, and

The cost and storage basis to hold the parts is feasible.

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

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

If the stock-out will only have a non-operational effect, it is desirable to review the RCM analysis with a view to revising the maintenance task.

F. RCM Sustainment

The preventative maintenance plan based on the RCM analysis is dynamic. The vessel operator is required to 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.

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 RCM and maintenance programs

Sustainment efforts are to be organized such that the results can be effectively used to support the RCM analysis and preventative maintenance plan updates. The following Paragraphs can be applied, as appropriate, to RCM sustainment.

1. Trend Analysis

A trend analysis provides an indication for systems or components that may be in the process of degrading. The measurement factors used for trending may be as follows:

- Equipment downtime
- Equipment item/component vibration levels
- Other condition-monitoring parameters such as temperatures, pressures, power, etc.
- The results of chronic root cause failure analyses

When performing trend analyses, it is the change in value, rather than the values themselves that is important. Statistical measures, such as mean and standard deviations, may be used to establish performance baselines and comparing current performance levels to established control levels. Performance parameters can then be monitored and investigations of causes for those parameters that exceed control limits. After the problem has been characterized, the related RCM analysis is to be reviewed and updated as necessary. Other corrective actions should also be considered and implemented, if necessary, to reduce the causes of performance deviations.

In particular, trend analyses are to be established for repeat equipment failures.

2. Maintenance Requirements Document Reviews

Documents containing mainte to identify outdated maintenance processes, techniques or technologies, nance requirements for systems, equipment items or components are to be reviewed at least annually 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 life-cycle costs. In addition, service bulletins from equipment manufacturers are to be reviewed and evaluated for impact on the RCM program. Service bulletins can provide beneficial information such as new condition-monitoring techniques and life limits for components.

3. Task Packaging Reviews

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

4. Age Exploration Tasks

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

5. Failures

When the knowledge of occurrence of unpredicted system or equipment failures becomes available, an appropriate response or corrective action is to be determined. An example process is shown in Figure 2.7.

A root cause analysis or other appropriate structured process is to be performed first to develop an understanding of the failure. The analysis is to 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 or potential failure
- Classifying the event and convening a trained team suitable for addressing the issues posed by this event
- Gathering data to understand how the event happened
- Performing a root cause failure analysis to understand why it happened
- Generating corrective actions to keep it (and similar events) from recurring
- Verifying that corrective actions are implemented

- Putting all of the data related to this event into an information system for trending purposes

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

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

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

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

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

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

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

6. Relative Ranking Analysis

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

- Maintenance man-hours
- Maintenance man-hours per operating hour
- Maintenance actions per operating hour
- Cost of lost production
- 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.

7. Other Activities

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

8. Sustainment Process Results

Changes to the RCM analysis and/or preventative maintenance tasks may be required as a result of the sustaining efforts. The possible changes are as follows:

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

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

G. Documentation Requirements

1. RCM Analysis Documentation

The information used in and the results from each RCM analysis step in Section 2.D.1 through D.6 is to be developed and documented as follows:

- The operating modes considered (see Section 2.D.1 and Table 2.1)
- Operating context for each level of indenture for all operating modes.
- Functional group definition along with narrative description (see Section 2.D.2 and Figure 2.2)
- Identification of all functions and categorization for each level of indenture along with corresponding functional failures (see Section 2.D.3, 2.D.4 and Table 2.2)
- Functional interdependence of the systems within functional groups described through the use of block diagrams or fault tree diagrams (see Section 2.D.3 and Figure 2.3)
- Failure mode effects and criticality analysis providing the information in Table 2.3 (see Section 2.D.5)
- Selection of failure management tasks providing the information in Table 2.8 (see Section 2.D.6)

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

- The results of the analysis step
- The decision tools used
- Any other pertinent information related to the step (e.g. assumptions, equipment excluded from the analysis)

Based on the preventative maintenance tasks identified in the RCM analysis, a preventative maintenance plan is to be developed and documented in accordance with Section 2.G.1.1 through 2.G.1.5.

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

1.1. For Items Covered by Condition-monitoring Tasks

i) A list and description of the machinery covered including:

- Method of data collection and analysis tools
- Nominal rpm
- Horsepower
- Location and orientation of sensor attachments which are to be permanently marked on machinery

ii) Sampling procedures for fluid analysis, as applicable

iii) Organization chart identifying areas of responsibility

iv) Schedule of data collection

v) Type and model of data collection instrument, including sensor and attachment method and calibration schedule

vi) Acceptance criteria of data

vii) *Baseline data.* Initial or baseline data are to be recorded. For the case of vibration data, the data is to be recorded in the presence of the Surveyor and/or a representative specialist of an BKI Recognized Condition Monitoring Company and are to be compared to the acceptable vibration levels shown in an applicable standard, such as SNAME’s T&R Bulletin 3-42 “Guidelines for the Use of Vibration Monitoring for Preventative Maintenance.” The Owner is to be notified of all machinery that does not meet acceptance criteria (i.e., machinery with high vibration levels).

viii) Preventative maintenance sheet(s) for each machine to be considered

1.2. For Items Covered by Planned-maintenance Tasks

i) A list and description of the machinery

ii) Organization chart identifying areas of responsibility

iii) Schedule of servicing and overhaul

iv) Description of the work to be performed at each interval

v) Machinery identification method and record-keeping procedures

vi) Preventative maintenance sheet(s) for each machine to be considered

1.3. For Items Covered by a Combination of Condition-monitoring and Planned- Maintenance Tasks

The applicable items from Sections 2.G.1.1 (all) and 2.G.1.2 [iii), iv) and v)].

1.4. For Items Covered by Failure-finding Tasks

The applicable items from Sections 2.G.1.1 [i) through vi)] and 2.G.1.2 [iii), iv) and v)] and the failure-finding maintenance sheet(s) for each machine/system considered.

1.5. For Items Covered by any other Applicable and Effective Tasks

The applicable items from Section 2.G.1.2 [i) through v)] and the maintenance sheet(s) for each machine/system considered.

2. Spares Holding Documentation

The spares holding documentation is to be a summary. The documentation is to provide the following information:

- There is to be identification between the maintenance task listed and the RCM analysis (e.g., Item Nos. in the RCM analysis).
- The task type is to be listed (e.g., 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).
- If a stock-out or a stock-out and further failure will have an effect on the End Effects.
- The risk due to a stock-out is identified along with the appropriate spare parts strategy (e.g., Order parts before demand, Hold parts in storage, Revise RCM maintenance tasks, Review RCM maintenance tasks, No spares holdings required).
- The maintenance procedure is listed.

An example Spares Holding Determination summary is shown in Table 2.10.

3. RCM Sustainment Documentation

The sustainment process is to be designed so as to allow verification by the attending Surveyor at the annual Survey for those processes applied.

The sustainment documentation is to be maintained onboard by the vessel/rig/facility operators. The sustainment process(es) applied by the operator are to be readily available for review by the attending Surveyor at the Annual Survey.

3.1. Trend Analysis

Data is to be collected periodically for all equipment items/components for which condition- monitoring tasks are specified for trend analysis. Limits are to be identified for the data when the condition-monitoring tasks are developed to indicate those maintenance actions to be taken when the data are outside of the limits. (See Section 2.F.1)

3.2. Maintenance Requirement Document Reviews

A record is to be maintained indicating which maintenance documents have been reviewed for updates and when the review occurred. (See Section 2.F.2)

3.3. Task-packaging Reviews

A record is to be maintained indicating when task-packaging reviews were conducted and what maintenance tasks were added, deleted or modified. (See Paragraph 2.F.3)

3.4. Age-exploration Tasks

A record is to be maintained of the results of the age-exploration tasks conducted and any resulting changes to the affected maintenance task(s). (See Section 2.F.4)

3.5. 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. (See Section 2,F.5)

3.6. Relative Ranking Analysis

A record is to be maintained of relative ranking analyses conducted and any changes to the affected maintenance task(s). (See Section 2.F.6)

3.7. Other Activities

A record is to be maintained of the results of other activities conducted that result in changes to the RCM analysis and/or preventative maintenance tasks. (See Section 2.F.7).

H. Special Conditions For Certain Equipment

1. Steam Turbine

The main propulsion turbine rotor journal bearings, thrust bearings and flexible couplings are to be opened up for examination. The low pressure exhaust trunk is to be opened for examination of the last row of low pressure and astern wheels. Providing vibration readings, lubrication oil analysis and rotor position checks and turbine operating records are reviewed and all considered satisfactory by the Surveyor, the lifting of the main propulsion turbine casings may be waived at alternate, subsequent Class Renewal Surveys.

On turbines where variable or abnormal readings are noted, readings are to be recorded by the vessel's personnel more frequently, as appropriate, to properly monitor the performance range or establish the trend.

The turbines are to be operationally tested.

2. Internal Combustion Engines

Machine condition monitoring of internal combustion engines must provide detailed engine analysis, as well as the information provided in Section 2.G.1. The following data must be recorded at least monthly, unless indicated otherwise.

- *i)* Operating time (running hours)
- *ii)* Power output (MCR)
- *iii)* Rpm
- *iv)* Cylinder pressure as function of crank angle
- *v)* Injection pressure as function of crank angle
- *vi)* Cylinder liner and piston ring wear (on basis of compression/firing pressures or proximity readings)
- *vii)* Scavenging air pressures and temperatures
- *viii)* Lubricating oil and cylinder oil consumption
- *ix)* Bearing temperatures (main, crank pin, crosshead and internal thrust, as fitted)
- *x)* Cylinder exhaust temperatures
- *xi)* Turbocharger vibration and T/C rpm
- *xii)* Lubricating oil analysis (quarterly)
- *xiii)* Crankshaft deflection readings for medium/slow speed diesel engines (quarterly).

For machines for which variable or abnormal readings are noted, readings are to be recorded by the vessel's personnel more frequently, as appropriate, to properly monitor the performance range or establish the trend.

3. Electrical Switch Gear and Power Distribution Panels

Condition-monitoring plans for electrical equipment are to include examination of panels, switchboards, transformers and other essential electrical apparatus by infrared photographic thermography during each five-year survey cycle while the circuit is energized and under normal work loads. A report describing the results of the survey, as well as periodic insulation resistance records must be retained onboard for review by the attending the Surveyor.

4. Permanently Installed Monitoring Equipment

Permanently installed electronic analyzing equipment used for condition-monitoring tasks is to comply with the requirements regarding testing and certification of automatic and remote control systems for use onboard vessels.

I. Condition-monitoring Techniques

BKI will consider all appropriate applications of condition-monitoring techniques. For those cases where the BKI is unfamiliar with the technique or a new technology has been developed or is being applied in a new manner, BKI will request information from the manufacturer concerning theory of operation and experimental test results.

Table. 2. 1. Example Operating Modes and Operating Context

<table>
<tr><th colspan="5">Operating Context of Diesel Engine</th></tr>
<tr><td colspan="5">The propulsion system consists of a Manufacturer Diesel Type Model Number low-speed diesel engine rated 16,860 kW Maximum Continuous Rating (MCR) at 91 RPM, coupled directly to a shaft supported by one intermediate bearing and two stern tube bearings, and driving a fixed pitched propeller.</td></tr>
<tr><td rowspan="2">Common Characteristics</td><td colspan="4">Operating Modes</td></tr>
<tr><td>At Sea</td><td>In Congested Waters</td><td>Maneuvering Alongside</td><td>Cargo Handling</td></tr>
<tr><td>Environmental Parameters</td><td>Nominal ambient air temperature: 25°C. Range from –29°C to 45°C
Barometric air press (dry) 101.3 kPa Absolute
Nominal seawater inlet temperature:
32°C, 2.0-2.5 bar. Range from –2°C to 50°C
Cooling FW nominal temperature:
25°C, 2.0-2.5 bar. Max. temp. 90°C
L.O. max. supply temp. 60°C,
4.3 bar with exception of Camshaft L.O. max. supply temp. 50°C,
4 bar
F.O. supply max. temp. 150°C at
4 bar.</td><td>Dependent on geographical location
If ports to visit are known, list environmental parameter ranges.</td><td>Dependent on geographical location
If ports to visit are known, list environmental parameter ranges</td><td>Not used</td></tr>
<tr><td>Manner of Use</td><td>Propels vessel at 20 knots at 85% of MCR. Capable of continuous operation for up to 22 days. Single-engine installation</td><td>Propels vessel from 2 to 10 knots, with reversing and stopping capabilities</td><td>Propels vessel from 2 to 10 knots, with reversing and stopping capabilities, and assists in mooring</td><td>Not used</td></tr>
<tr><td>Performance Capability</td><td>To output 16,860 kW @ 91 RPM; controllable from bridge, centralized control station and locally</td><td>To output at 30 to 85 RPM; reversing at 63 RPM, controllable from bridge, centralized control station and locally</td><td>To output at 30 to 85 RPM; reversing at 63 RPM, controllable from bridge, centralized control station and locally</td><td>Not Applicable</td></tr>
</table>

Table. 2.2. Example Function and Functional Failure List

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

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

Table. 2.3. Example Bottom-up FMECA Worksheet

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

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

Table. 2. 4. Example Consequence/Severity Level Definition Format

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

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

Table. 2. 4. Example Consequence/Severity Level Definition Format (continued).

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

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

Table. 2.5. Probability of Failure (i.e., Frequency, Likelihood) Criteria Example Format

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

Note:

1 See Section 2.D.5.5 for determining probability of failure.

Table. 2.6. Risk Matrix Example Format

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

Table. 2.7. Failure Characteristic and Suggested Failure Management Tasks

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

Table. 2.8. Example Maintenance Task Selection Worksheet

Table. 2.9. Summary of Maintenance Task

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

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

Table. 2.10. Summary of Spares Holding Determination

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

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

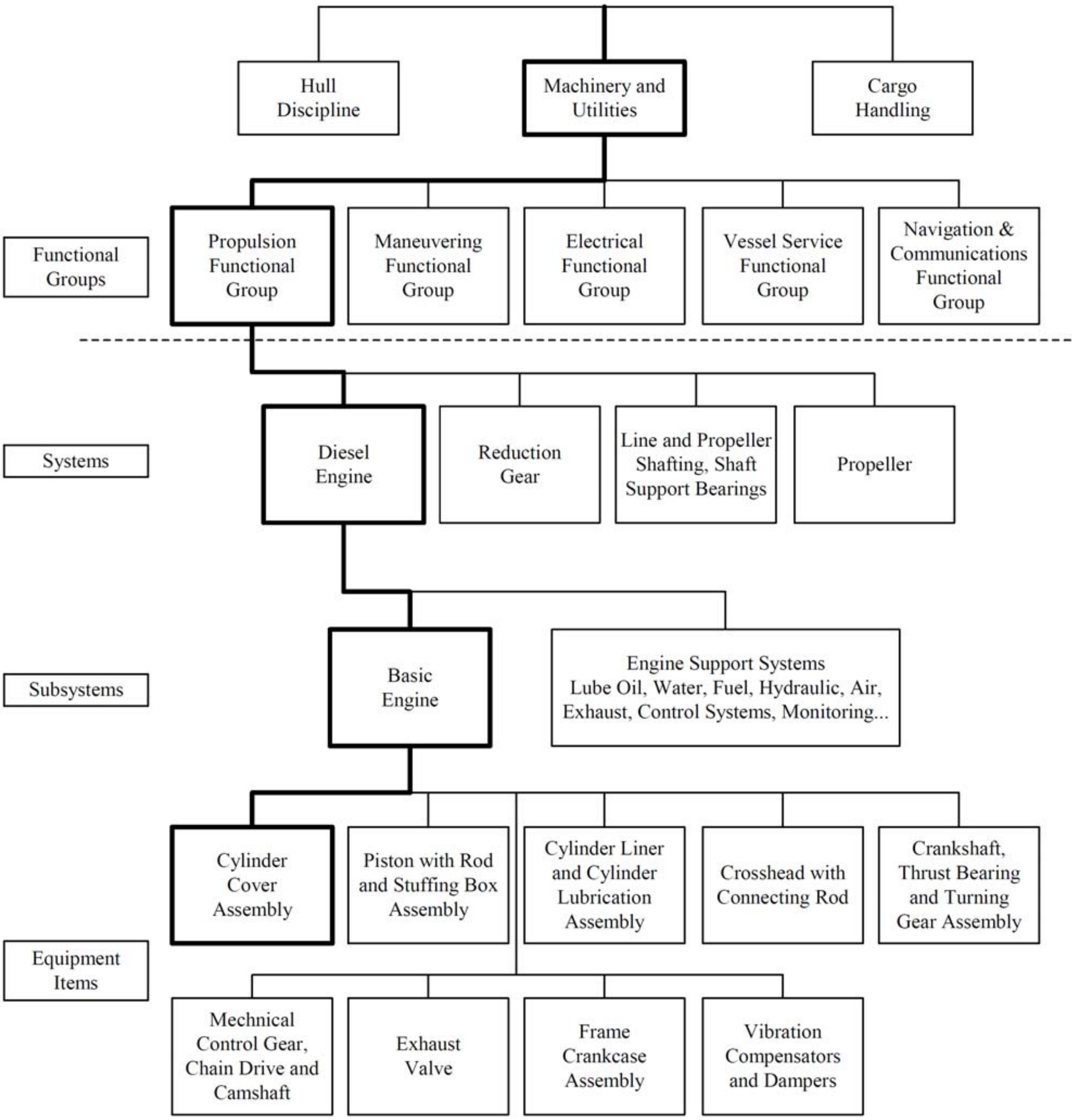

Fig. 2.2. Example Partitioning of Fuctional Groups

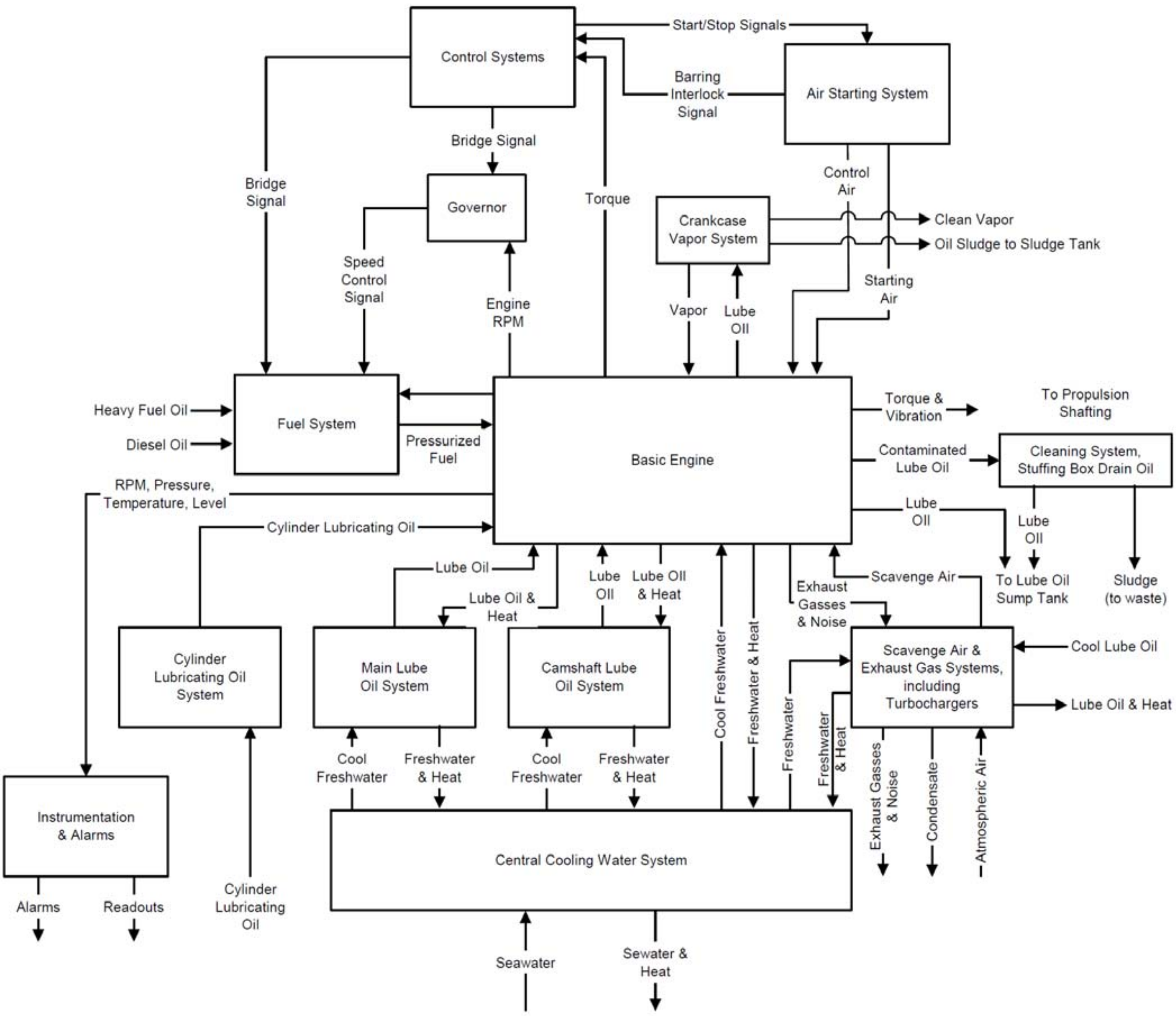

Fig. 2.3. Example System Block Diagram

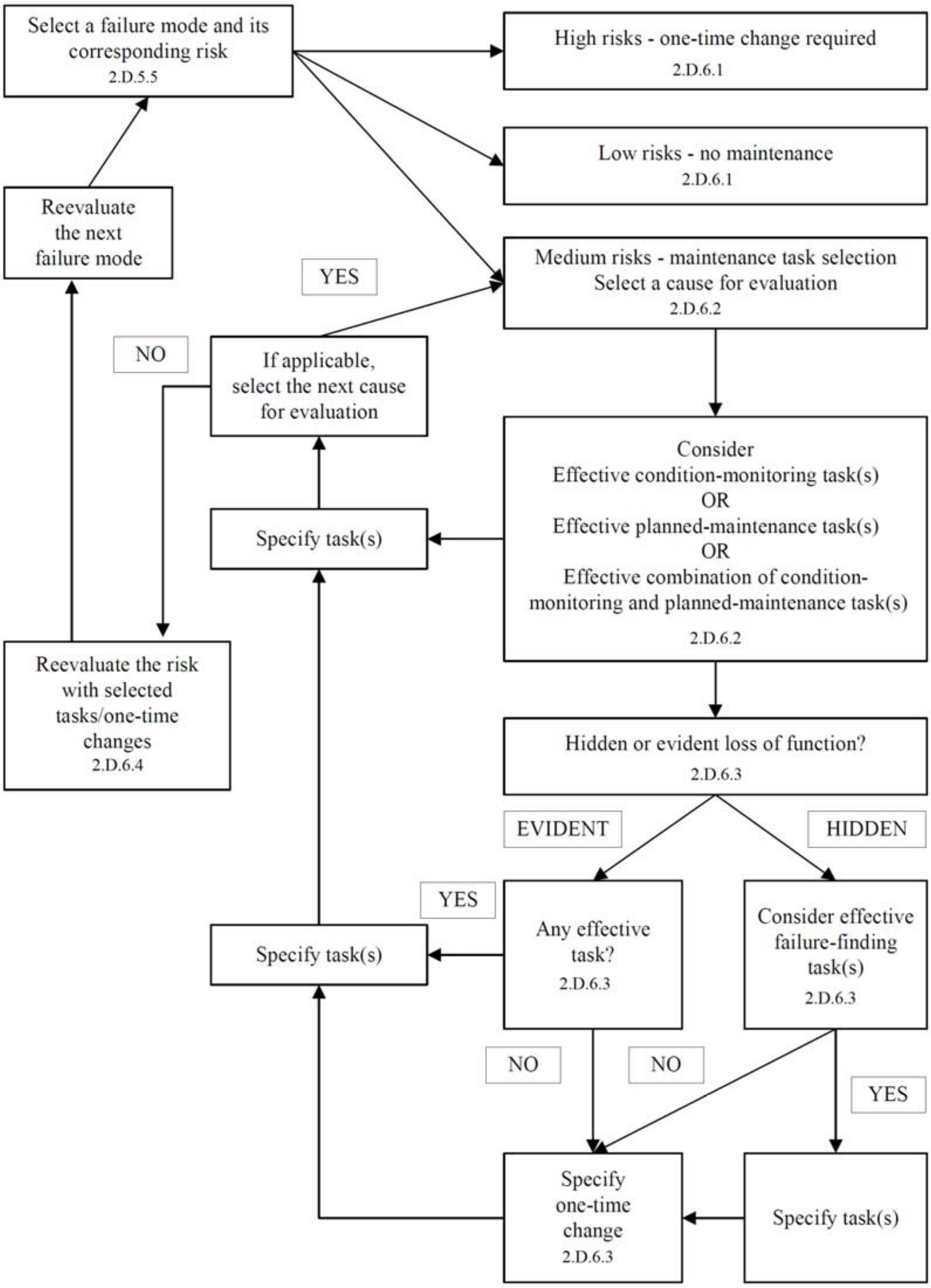

Fig. 2.4. Simplified Task Selection Flow Diagram

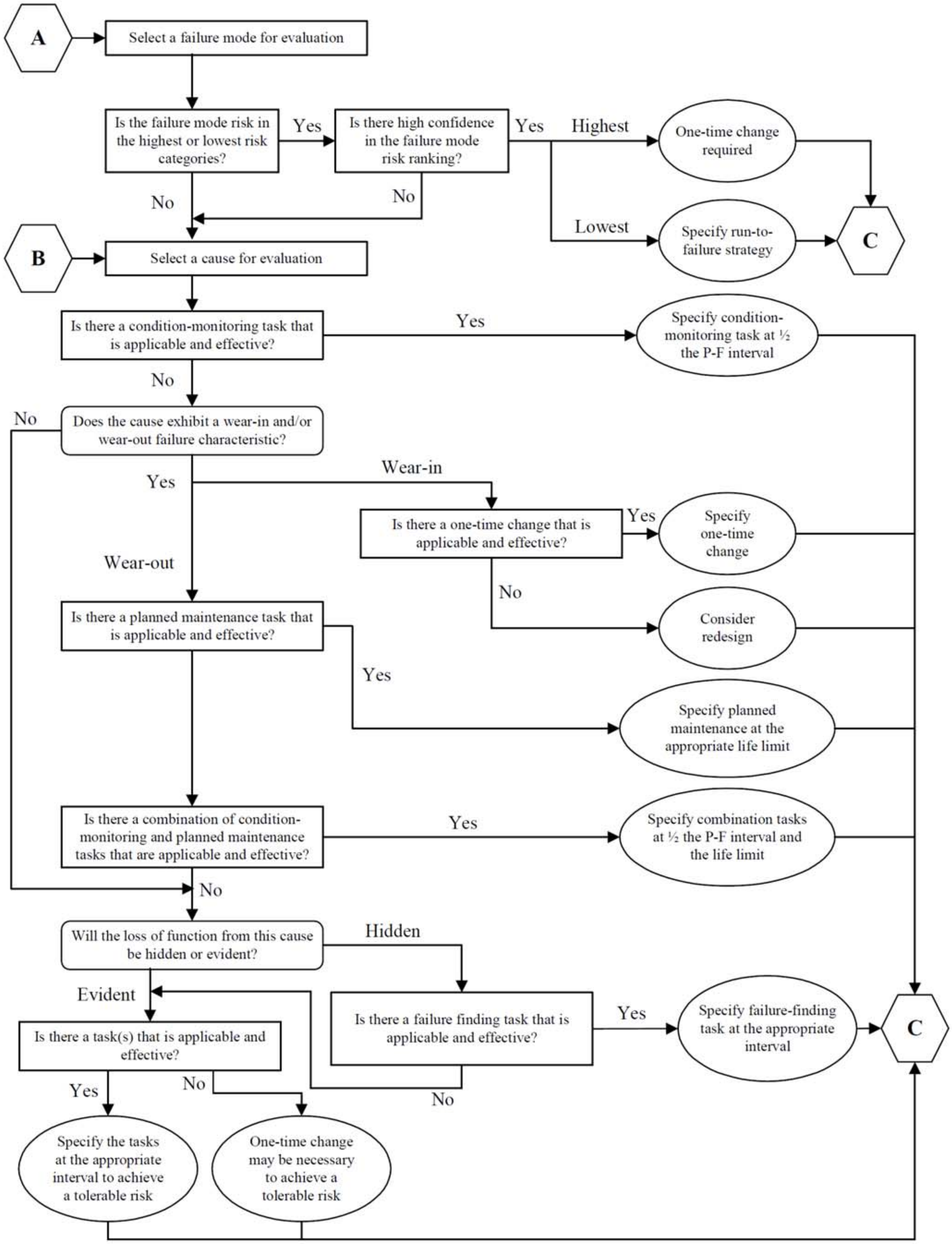

Fig. 2.5. RCM Task Selection Flow Diagram

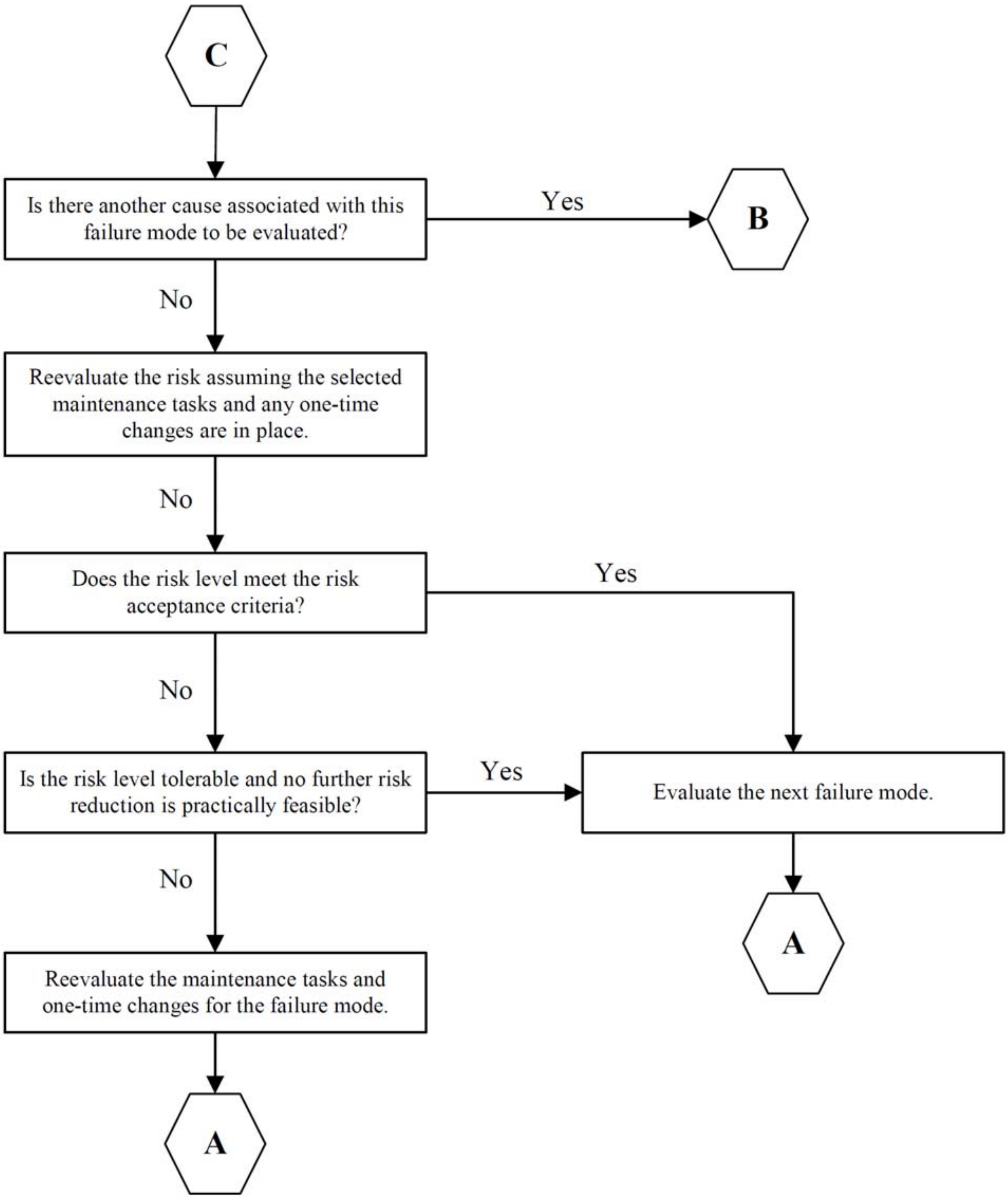

Fig. 2.5. RCM Task Selection Flow Diagram (continued).

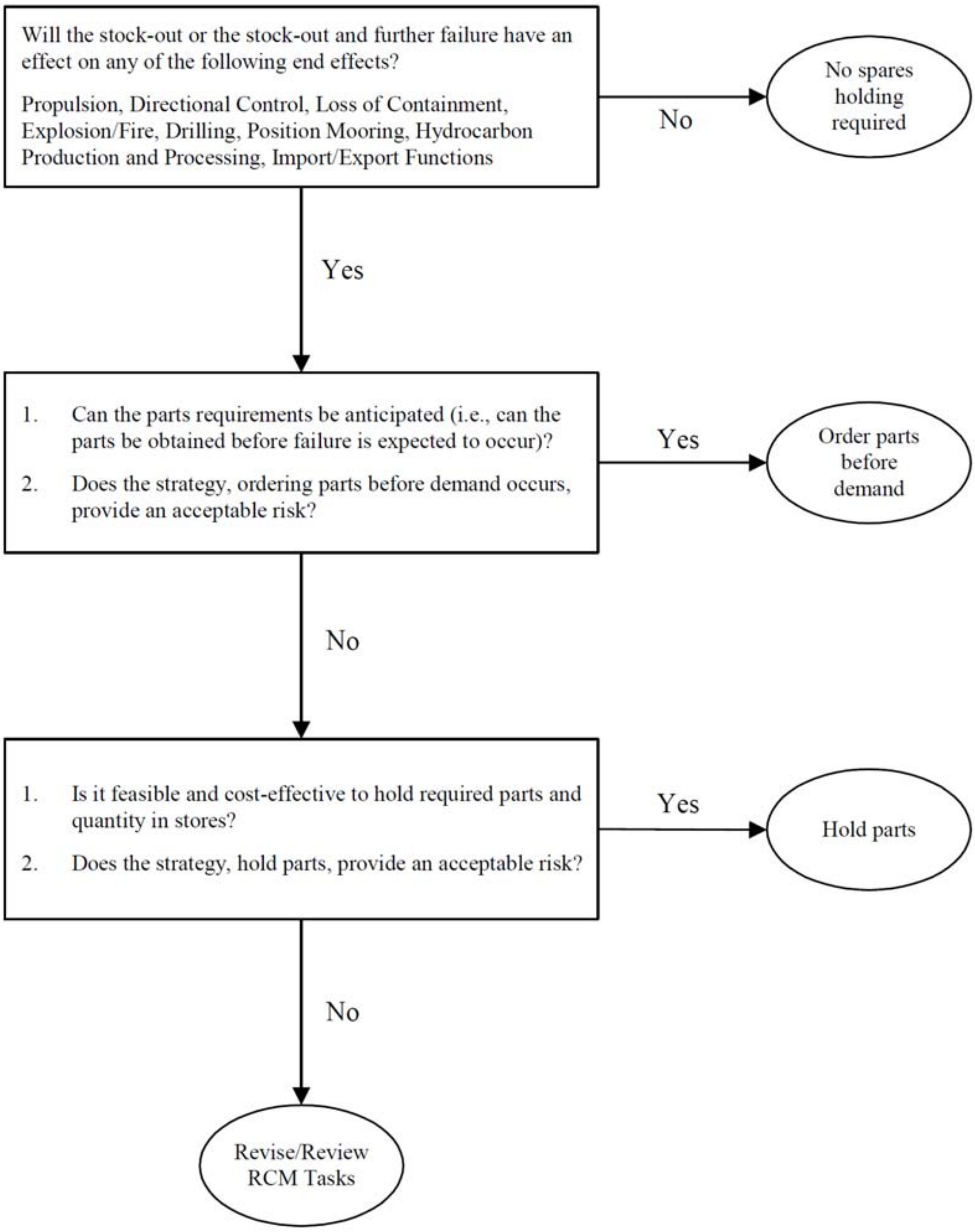

Fig. 2.6. Spares Holding Decision Flow Diagram[1]

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

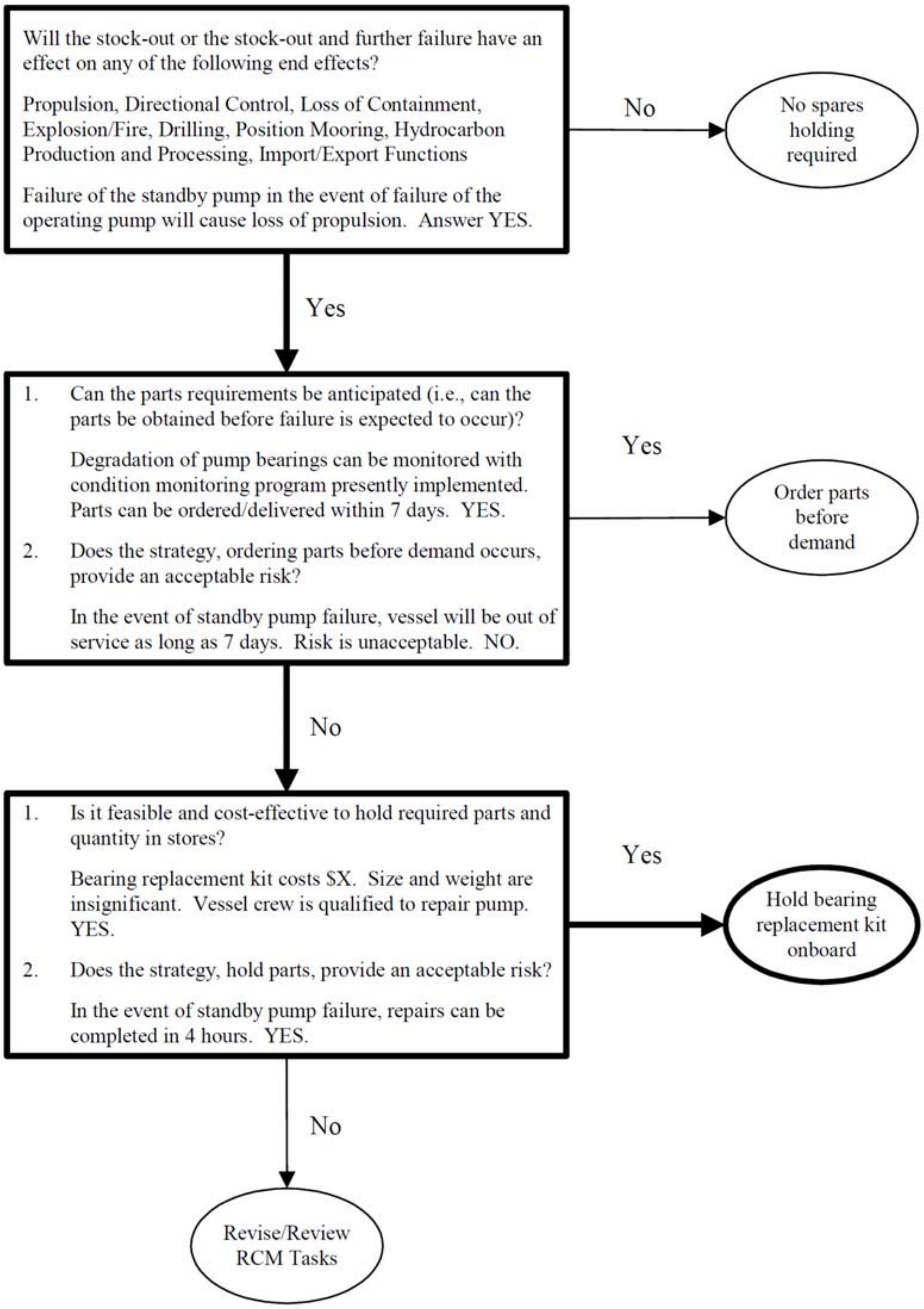

Fig. 2.6A. Example of Use of Spares Holding Decision Flow Diagram

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

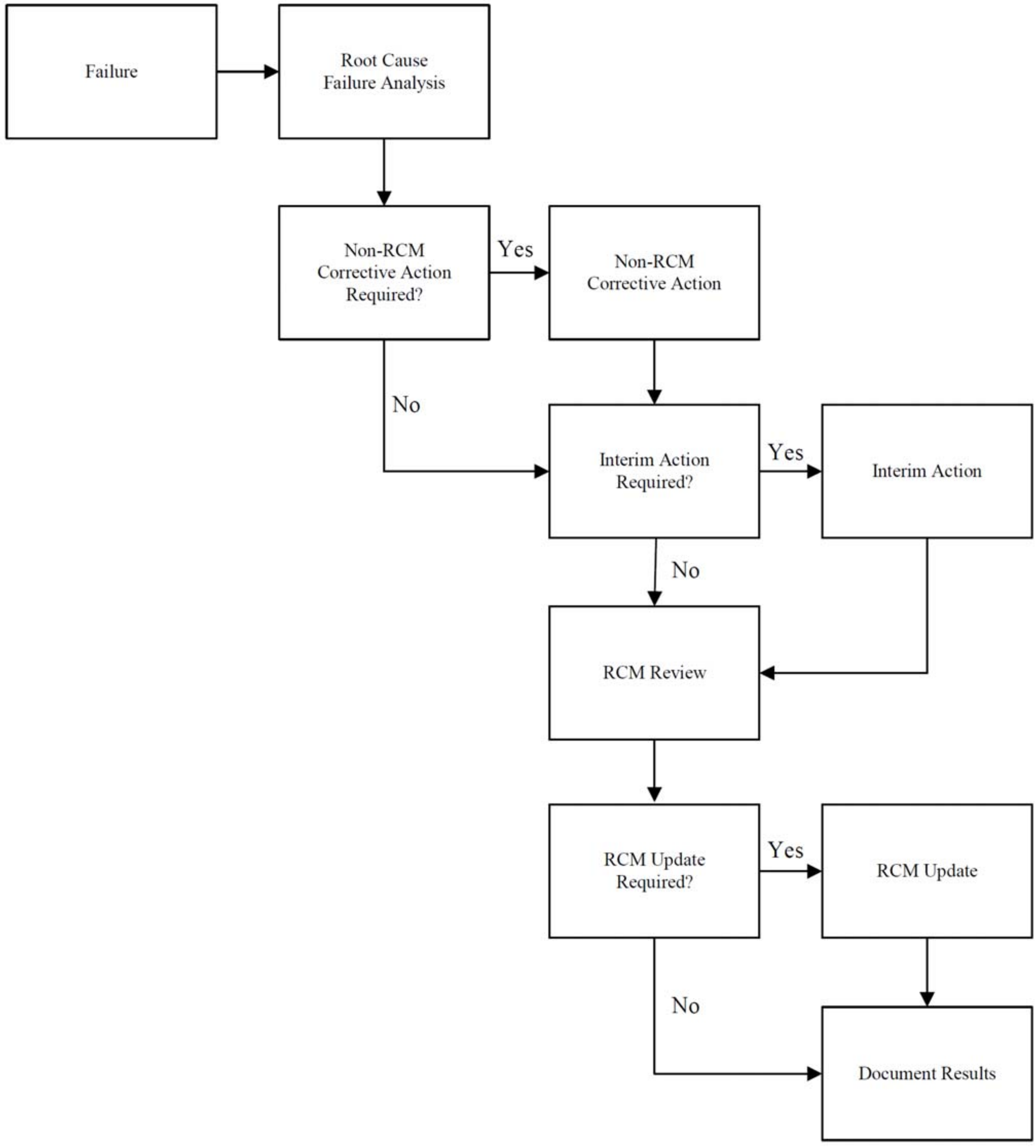

Fig. 2.7. Process to Address Failure and Unpredicted Event[1]

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

Section 3

Onboard Documentation

A. Onboard Documentation

The chief engineer shall be the responsible person onboard the vessel in charge of the Reliability-centered Maintenance Program. If a computerized system is used for updating the maintenance documentation and maintenance program, access is to be permitted only by the chief engineer or other authorized persons. The following information is to be available onboard.

1. Condition-monitoring Tasks

i) The latest up-to-date information required in 2.G.1.1.

ii) For vessels with onboard vibration meters or FFT vibration analyzers, manuals supplied by manufacturers for use of data collectors and computer programs, as well as guidance for machine operating and diagnosis of machine faults.

iii) Condition-monitoring data, including all data since the last opening of the machine and the original baseline data.

iv) Reference documentation (trend investigation procedures, etc. (see Section 2.F).

v) Records of lube oil analysis, rotor positioning readings, interstage bleed system pressures and vibration readings are to be recorded by the vessel's personnel at least on a quarterly basis and retained onboard for review annually by the attending Surveyor.

vi) Complete vibration data, as specified in 2.F.1.1, are to be taken at least quarterly, or more frequently when warranted by abnormal conditions and operational parameters, reviewed by a representative specialist of BKI Recognized Condition Monitoring Company and retained onboard for review annually by the attending Surveyor.

vii) If the vessel includes internal combustion engines in the program, the data outlined in 2.H.2 must be retained onboard for review annually by the attending Surveyor.

viii) Calibration date of measuring equipment. Calibration is to be in accordance with the manufacturer's recommendations or annually, whichever is more frequent.

ix) Any repairs or changes to any machines must be reported, and a summation and analysis of all unscheduled maintenance and/or breakdowns of monitored equipment (see Section 2.F).

x) 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. Planned-maintenance Tasks

i) The latest up-to-date information required in 2.G.1.2.

ii) A copy of the manufacturer's service manuals and/or shipyard's maintenance instructions.

iii) Reference documentation (trend investigation procedures, etc. (see Section 2.F).

iv) All records showing compliance with the program (including repairs and renewals carried out) are to be made available for review by the attending Surveyor at the Annual Survey – Machinery.

3. Combination of Condition-monitoring and Planned-maintenance Tasks

i) The latest up-to-date information required in 2.G.1.3.

ii) The applicable items listed in 3.A.1 and 3.A.2.

4. Failure-finding Tasks

i) The latest up-to-date information required in 2.G.1.4.

ii) The applicable items listed in 3.A.1 and 3.A.2.

5. Any Other Applicable and Effective Tasks

i) The latest up-to-date information required in 2.G.1.5.

ii) The applicable items listed in 3.A.1 and 3.A.2.

6. Spares Holding

Records for required spare parts, inventory and ordering procedures to procure additional spare parts are to be readily available.

7. RCM Sustainment

Records of sustainment activities in accordance with Section 2.F are to be readily available.

Section 4
Implementation Survey

A. General

Administrative and certification requirements for the implementation survey are listed in Section 1.E.7.

The Surveyor is to verify the following:

i) The RCM Program is implemented according to the approved documentation (see Section 2) and is adapted to the type and complexity of the components/systems on board

ii) The RCM Program is producing the documentation required for the Annual Confirmation Survey (see Section 3) and the requirements for surveys and testing for retention of class are complied with

iii) The onboard personnel are familiar with the RCM Program

iv) An RCM sustainment process is in effect to support the RCM analysis updates

For the case of vessels that are due to be placed in service or have recently been delivered so that little or no scheduled maintenance has been performed, the Surveyor is to verify items i), ii) and iv) are available and the onboard personnel have been trained to implement the RCM Program, item iii).

Section 5

Owner's Annual RCM Report

A. General

The Annual Confirmation of the Reliability-Centered Maintenance Program will be carried out by the attending Surveyor, who will confirm the Program is being effectively implemented onboard (see Section 3). The vessel's Owner or qualified representative is to present an Annual Reliability-Centered Maintenance Report containing the following information to the attending Surveyor for review and verification at the time of the Annual Confirmation Survey. Any reports submitted without the information required in Sections 5.B through 5.H, as applicable, will be returned without action to the submitter. The annual report is to be submitted in an electronic format. Prior to submitting electronic reports, arrangements are to be made to ensure the attending Surveyor has the necessary software to review the reports.

If the machinery included in the Reliability-Centered Maintenance Program has changed, this is to be stated. Any machinery to be added to the system is subject to the requirements of Section 1.E.5 and 1.E.9 and Section 2 and approval by the responsible BKI Head Office and the attending Surveyor. Also, the vessel's Owner is to advise the responsible BKI Head Office and the attending Surveyor of any machinery to be deleted from the RCM Program.

The information to be included with the annual report is detailed in the following Subsections.

B. Condition-monitoring Tasks – Annual

i) A summary list of all machinery covered under Condition Monitoring, clearly stating the overall condition of the machinery based on the most recent condition-monitoring data (i.e., Satisfactory, Marginal, Suspect, Unacceptable, etc.) compared to the acceptance criteria [see 2.G.1.1vi) and vii)]. For condition-monitoring tasks using vibration data, for the report, this data must have been collected within three months of the Annual Confirmation date of the report by vessel personnel or the BKI Recognized Condition Monitoring Company.

ii) Machinery identification procedure.

iii) Preventative maintenance sheet(s) for each machine.

iv) Original baseline data for machine.

v) Condition-monitoring data including all data since last opening of the machine.

vi) Vibration spectral data must be reviewed by a representative specialist of the BKI Recognized Condition Monitoring Company.

vii) Full trend analysis (including spectral analysis for vibration) of machinery displaying operating parameters exceeding acceptable tolerances. Also, alarm criteria.

viii) Relevant operational data during data recording, such as sea state, machine temperature, other equipment affecting the data, etc. should be included.

ix) Quarterly spectral data vibration meter readings recorded by vessel personnel. The type of recording device, method of data collection and calibration of the data collector must be provided [see 2.G.1.1v) and 3.A.1viii)].

C. Planned-maintenance Tasks – Annual

i) A summary list of all machinery covered under Planned Maintenance, including a complete description of work completed on each machine since the last annual report.

ii) Machinery identification procedure.

iii) Preventative maintenance sheet(s) for each machine.

iv) Exceptions, notes and comments noted during work.

v) Modifications and justifications to the schedule, such as might be recommended by a machinery manufacturer's technical bulletin or the RCM sustainment process.

vi) Full trend analysis of machinery displaying operating parameters exceeding acceptable tolerances.

vii) Summary and analysis of machines that failed prior to scheduled maintenance or servicing.

D. For Items Covered by a Combination of Condition- monitoring and Planned-Maintenance Tasks

The applicable items from Sections 5.B (all) and 5.C [i), iv), v) and vii)].

E. For Items Covered by Failure-finding Tasks

The applicable items from Sections 5.B [i) through vi)] and 5.C [iii), iv), v) and vii)] and the failure-finding maintenance sheet(s) for each machine/system considered.

F. For Items Covered by any other Applicable and Effective Tasks

The applicable items from Section 5.C [i) through vi)] and the maintenance sheet(s) for each machine/system considered.

G. RCM Sustainment

Evidence of sustainment activities described in Section 2.F is to be 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. Changes to the RCM analysis and or the preventative-maintenance tasks along with other changes resulting in equipment redesign or operational changes or restrictions as a result of sustainment are to be submitted to the responsible BKI Head Office which performed the initial review and provided to the attending Surveyor.

H. Report Exceptions

For condition-monitoring tasks, readings are to be compared to the acceptance criteria [see 2.G.1.1vi)] or for the case of vibration data, the baseline readings [see 2.G.1.1vii)] in the initial report. The Owner is to be advised that maintenance or additional monitoring is needed for machinery with readings above those in the acceptance criteria or the reference standard referred to in 2.G.1.1vii), as applicable. Machinery unavailable for measurements are to be noted and the Owner advised that readings are to be submitted for review. In the meantime, the condition of the machinery is to be to the satisfaction of the attending Surveyor.

For planned-maintenance tasks, the Owner is to be advised of all machinery for which periodic maintenance is not indicated or is incomplete as per the initial planned-maintenance report. In the meantime, the condition of the machinery is to be to the satisfaction of the attending Surveyor.

Section 6

Annual Confirmation Survey of RCM Program

A. Survey Requirements

Simultaneously with each Annual Survey – Machinery, for vessels on a Reliability-Centered Maintenance Program, an Annual Confirmation Survey is to be performed by the attending Surveyor. The purpose of this survey is to verify that the program is being correctly operated and that the machinery has been functioning satisfactorily since the previous survey.

The survey is to include the following:

i) A general examination of the items concerned is to be carried out.

ii) The Surveyor is to review the Owner's annual report (see Section 5).

iii) The performance and maintenance records are to be examined to verify that the machinery has functioned satisfactorily since the previous survey or action has been taken in response to machinery operating parameters exceeding acceptable tolerances and the overhaul intervals have been maintained.

iv) Written details of breakdown or malfunction are to be made available.

v) Description of repairs carried out is to be examined. Any machinery part which has been replaced with a spare due to damage is to be retained onboard, where possible, until examined by a Surveyor.

vi) At the discretion of the Surveyor, function tests, confirmatory surveys and random check readings, where condition-monitoring equipment is in use, are to be carried out as far as practicable and reasonable for equipment items/components, the failure of which has been identified as resulting in the highest severity for the consequences listed in this Guide.

Upon satisfactory completion of the above requirements, the Reliability-Centered Maintenance Program will be accepted by the BKI for its continued use.

The Surveyor may credit to the CMS any machines that were overhauled and tested in the presence of and to the satisfaction of the attending Surveyor.

Additionally, any machinery that has been overhauled in accordance with a planned-maintenance task may be credited to the CMS by the attending Surveyor after a satisfactory operational test.

Any machinery that has acceptable machine conditions by application of condition-monitoring tasks listed in the preventative maintenance plan may be credited to the CMS by the attending Surveyor after a satisfactory operational test. Special consideration is given for the opening of main propulsion steam turbines, in accordance with Section 2.H.1 of this Guide.

Section 7

Overhauls and Damage Repairs

A. Overhauls

The Surveyor is to attend and report on representative overhauls of the main and auxiliary machinery. Following overhauls, new baseline data is to be recorded in the presence of an BKI Recognized Condition Monitoring Company within six months of the overhaul and included in the Annual Report. Documentation on overhauls of items covered by the Reliability-Centered Maintenance Program is to be reported and signed by the chief engineer.

B. Damage Repairs

All damage to components/machinery is to be reported to BKI. Repairs of such damaged components/machinery under the Reliability-Centered Maintenance Program are to be carried out to the satisfaction of the Surveyor, in accordance with Rules for Classification and Surveys, Volume I, Section 2.C.5.2, Section 3.B.2.1 and 3.B.2.2.

Any repair and corrective action regarding machinery under the Reliability-Centered Maintenance Program is to be recorded and the repair verified by the attending Surveyor at the Annual Confirmation Survey.

In the case of overdue outstanding recommendations or a record of unrepaired damage which would affect the Reliability-Centered Maintenance Program, the relevant items are to be kept out of the program until the recommendation is fulfilled or the repair is carried out.

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Appendix A

Additional Resources

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

1. Related Standards

1. *Guidance Notes on Risk Assessment Application for the Marine and Offshore Oil and Gas Industries*

2. *Guide for Failure Mode Effect Analysis*

3. *Guidance for Risk Evaluations for the Classification of Marine-Related Facilities*

4. *Guide for Surveys Using Risk Based Inspection for the Offshore Industry*

5. 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.

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

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

2. Related Publications

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

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

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

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

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

3. Condition Monitoring and Dynamic Monitoring Standards

1. 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 Table D.3 "Dynamic Monitoring". The latest edition of the standard is applicable.

2. **ISO 7919:** Mechanical vibration of non-reciprocating machines -- Measurements on rotating shafts and evaluation criteria; **Part 1: (1996)** General guidelines; **Part 2: (2001)** 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: (1996)** Coupled industrial machines; **Part 4: (1996)** Gas turbine sets; **Part 5: (1997)** Machine sets in hydraulic power generating and pumping plants.

3. **ISO 10055:1996** Mechanical vibration **--** Vibration testing requirements for shipboard equipment and machinery components

4. **ISO 10816-1:** Mechanical vibration **--** Evaluation of machine vibration by measurements on non- rotating parts **-- Part 1: (1995)** General guidelines; **Part 2: (2001)** 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: (1998)** 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: (1998)** Gas turbine driven sets excluding aircraft derivatives; **Part 5: (2000)** Machine sets in hydraulic power generating and pumping plants; **Part 6: (1995)** Reciprocating machines with power ratings above 100 kW.

5. **ISO 13373-1:2002** Condition monitoring and diagnostics of machines – Vibration condition monitoring **-- Part 1**: General procedures

6. **ISO 13379:2003** Condition monitoring and diagnostics of machines – General guidelines on data interpretation and diagnostics techniques

7. **ISO 13380:2002** Condition monitoring and diagnostics of machines – General guidelines on using performance parameters

8. **ISO 17359:2003** Condition monitoring and diagnostics of machines – General guidelines

9. **Society of Naval Architects and Marine Engineers T&R Bulletin 3-42, 1987**, "Guidelines for the Use of Vibration Monitoring for Preventive Maintenance"

Appendix B

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 BKI 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:

Equipment	*Table No.*
Electrical equipment	Table. B.1
Mechanical equipment	Table. B.2
Piping equipment	Table. B.3
Control equipment	Table. B.4
Lifting equipment	Table. B.5

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

Component	*Table No.*
Electrical components	Table. B.6
Mechanical components	Table. B.7
Piping components	Table. B.8
Structural components	Table. B.9
Rigging components	Table. B.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. B. 1. Electrical Equipment

Equipment Item	*Suggested Failure Modes*	*Equipment Item*	*Suggested Failure Modes*
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 • Procedures 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 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
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	Uninterruptable 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. B.2. Mechanical Equipment

Equipment Item	*Suggested Failure Modes*	*Equipment Item*	*Suggested Failure Modes*
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
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		

Table. B.2. Mechanical Equipment (continued)

Equipment Item	*Suggested Failure Modes*	*Equipment Item*	*Suggested Failure Modes*
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
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		

Table. B.2. Mechanical Equipment (continued)

Equipment Item	*Suggested Failure Modes*	*Equipment Item*	*Suggested Failure Modes*
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

Table. B.2. Mechanical Equipment (continued)

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. B.3. Piping Equipment

Equipment Item	*Suggested Failure Modes*	*Equipment Item*	*Suggested Failure Modes*
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
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

Table. B.3. Piping Equipment (continued)

Equipment Item	*Suggested Failure Modes*	*Equipment Item*	*Suggested Failure Modes*
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
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	Nonreturn valve	• External leak/rupture • Plugged/choked • Fails to open on demand • Fails to close on demand

Table. B.3. Piping Equipment (continued)

Equipment Item	*Suggested Failure Modes*	*Equipment Item*	*Suggested Failure Modes*
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 reseat (pressure) • Opens prematurely (pressure) • Closes prematurely (pressure) • Fails to open on demand (vacuum) • Fails to close on demand (vacuum) • Fails to reseat (vacuum) • Opens prematurely (vacuum) • Closes prematurely (vacuum)	Safety/relief valve	• External leak/rupture • Internal leak • Plugged/choked • Fails to open on demand • Fails to reseat • 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
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		

Table. B.3. Piping Equipment (continued)

Equipment Item	*Suggested Failure Modes*	*Equipment Item*	*Suggested Failure Modes*
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. B.4. Control Equipment

Equipment Item	*Suggested Failure Modes*	*Equipment Item*	*Suggested Failure Modes*
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. B.5. Lifting Equipment

Equipment Item	*Suggested Failure Modes*	*Equipment Item*	*Suggested Failure Modes*
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 operated 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 operated 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 operated on demand • Fails to stop on demand/ operates too long • Starts prematurely • Stops prematurely • Degraded lifting performance
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 operated 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. B.6. Electrical Components

Equipment Item	*Suggested Failure Modes*	*Equipment Item*	*Suggested Failure Modes*
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. B.7. Mechanical Components

Equipment Item	*Suggested Failure Modes*	*Equipment Item*	*Suggested Failure Modes*
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 • Opens prematurelyOpens
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

Table. B.7. Mechanical Components (continued)

Equipment Item	*Suggested Failure Modes*	*Equipment Item*	*Suggested Failure Modes*
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
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

Table. B.7. Mechanical Components (continued)

Equipment Item	*Suggested Failure Modes*	*Equipment Item*	*Suggested Failure Modes*
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
Rack	• Cracked • Fractured • Deformed • Corroded • Loosened	Scavenge relief device	• External leak/rupture • Internal leak • Plugged/choked • Fails to open on demand • Fails to reseat • 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

Table. B.7. Mechanical Components (continued)

Equipment Item	*Suggested Failure Modes*	*Equipment Item*	*Suggested Failure Modes*
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. B.8. Piping Components

Equipment Item	*Suggested Failure Modes*	*Equipment Item*	*Suggested Failure Modes*
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
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

Table. B.8. Piping Components (continued)

Equipment Item	*Suggested Failure Modes*	*Equipment Item*	*Suggested Failure Modes*
Pipe	• Cracked • Fractured • Worn • Deformed • Corroded • Loosened • Leaking • Plugged/choked • Vibrating	Spraying nozzle	• Cracked • Fractured • Worn • Corroded • Loosened • Leaking • Plugged/choked • Vibrating
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. B.9. Structural Components

Equipment Item	*Suggested Failure Modes*	*Equipment Item*	*Suggested Failure Modes*
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. B.10. Rigging Components

Equipment Item	*Suggested Failure Modes*	*Equipment Item*	*Suggested Failure Modes*
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
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		

Appendix C

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 ensure 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 ensuring that the unavailability of the equipment is less than what is needed to ensure the frequency of occurrence of a multiple failure is low enough to yield an acceptable risk of failure. For example, if the acceptable frequency of occurrence of a multiple failure for a specific event is 0.01/yr and the frequency of failure of the initiating event (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). Figure. C.1 illustrates the effect of failure-finding tasks.

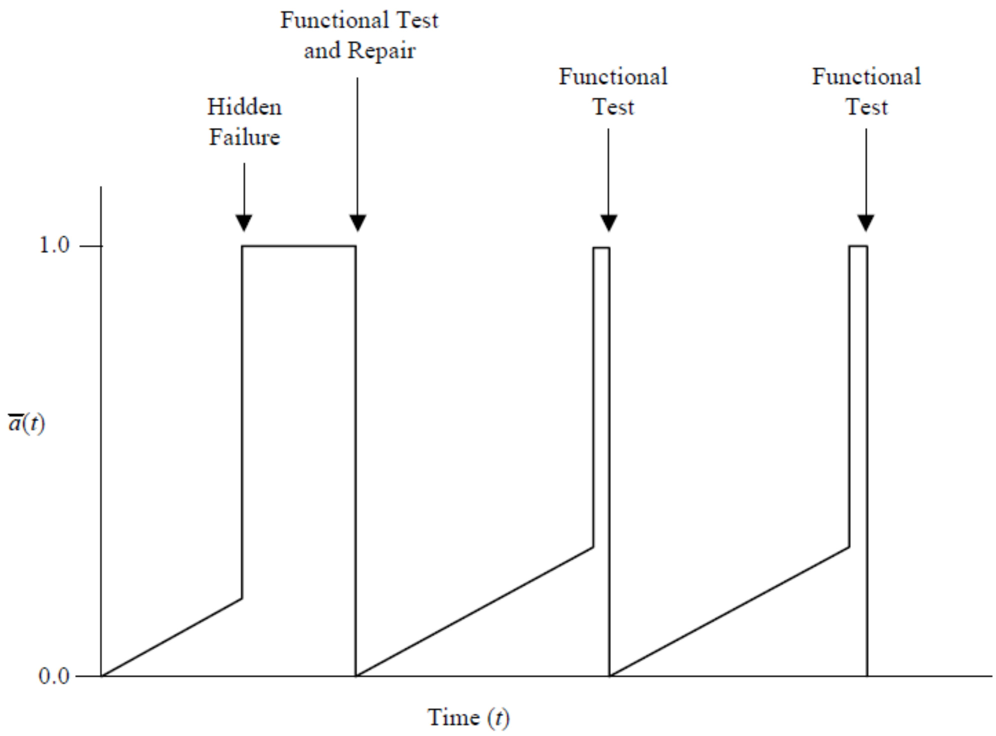

Fig. C.1. Effect of a Failure-Finding Task

3. Failure-finding Task Applicability and Effectiveness

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

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

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

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

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

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

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

4. Determining Failure-finding Maintenance Task Interval

The interval for failure-finding tasks can be determined:

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

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

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

4.1 Mathematical Determination of Failure-finding Task Interval

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

- 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 ($\lambda \times$ 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

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

where

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

4.2. Using Guidelines to Determine 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

Tables. C.1 and C.2 provide examples of the acceptable probability rules and failure-finding task interval.

Table. C.1. Example of Failure-finding Task Interval Rules

Risk of Hidden Failure	*Unavailability Required ($\bar{a}_{SYS}$)*
Very High	< 0.0001
High	> 0.0001 to 0.001
Moderate	> 0.001 to 0.01
Low	> 0.01 to 0.05

Table. C.2. Example of Failure-finding Task Intervals Based on MTTF

Unavailability Required ($\bar{a}_{SYS}$)	*Failure-finding Task Interval (as % of MTTF)*
0.0001	0.02
0.001	0.2
0.01	2
0.05	10

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

5. Failure-finding Maintenance Task Intervals

In determining the intervals in Table. C.3, the following inputs were used:

i) The failure rate data (MTTF) for the safety systems and alarms is based on 10,000 hours per year.

ii) The estimated frequency of occurrence of multiple failures is 0.01 (1 failure per 100 vessels per year).

iii) 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. C.3. Failure-finding Maintenance Task Interval Estimates

Equipment Item	*Safety System*	*Task Interval*	*Alarm*	*Task Interval*	*Controls*	*Task Interval*
	MTTF Failure per 10^4 hrs	*Months*	*MTTF Failure per 10^4 hrs*	*Months*	*MTTF Failure per 10^4 hrs*	*Months*
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 D

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.

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:

Condition Monitoring Categories	*Subcategory*	*Table No.*
Corrosion Monitoring	Coupon Testing	Table. D.1
	Corrometer	
	Potential Monitoring	
Thermography	Contact	Table. D.2
	Non-Contact	
Dynamic Monitoring	Vibration Analysis	Table. D.3
Oil Analysis and Tribology	Wear Particle Analysis	Table. D.4
	Chemical Analysis	
	Viscosity	
	Dielectric Strength	
Nondestructive Testing	Radiography	Table. D.5
	Dye Penetrant	
	Ultrasonic	
	Magnetic Particle Inspection	
	Eddy Current Testing	
	Acoustic Emission	
	Hydrostatic Testing	
	Visual Inspection	

Condition Monitoring Categories	*Subcategory*	*Table No.*
Electrical Condition Monitoring	Megohmeter Testing	Table. D.6
	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	Table. D.7
	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 the Table 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 to ensure 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 and guidelines provided in D.3.3.1. The following questions can help the team estimate the P-F interval:

  How quickly can the condition deteriorate and result in a functional failure? Will it deteriorate in minutes, hours, days, weeks, months or years?

  What is the capability of the condition-monitoring task in detecting the onset of failure? High or low?

  How confident is the team in its judgment?

3.3.3. Improving the Understanding of P-F Intervals

As data from condition-monitoring tasks are collected and the sustainment process is implemented (see Section 2.F), 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 (see Section 2.F.4).

Table. D.1. Corrosion Monitoring

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

Table. D.2. Thermography

Condition	*Condition Monitoring Subcategory*	*Technique*	*Fixed/Portable Equipment*	*P-F Interval*	*Skill*
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/ Thermocouple	Fixed	Weeks to months	No specific training needed
	Contact	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. D.3. Dynamic Monitoring

Condition	*Condition Monitoring Subcategory*	*Technique*	*Fixed/Portable Equipment*	*P-F Interval*	*Skill*
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	Vibration Analysis	Spectrum Analysis[1]	Fixed or Portable	Weeks to months	Trained and experienced technician
		Waveform Analysis[2] (Time Waveform Analysis)	Fixed or Portable	Weeks to months	Trained and experienced technician
Bearing damage Bearing wear Inadequate roller bearing lubrication Gear damage		Shock Pulse Analysis, Peak Value (Peak Vue) Analysis, Spike Energy™	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		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.

Table. D.4. Oil Analysis and Tribology

Condition	*Condition Monitoring Subcategory*	*Technique* [1]	*Fixed/Portable Equipment*	*P-F Interval*	*Skill*
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
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	Chemical Analysis	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 simplier analysis procedures. Trained laboratory technician to perform the more complex analysis procedures

Table. D.4. Oil Analysis and Tribology (continued)

Condition	*Condition Monitoring Subcategory*	*Technique (1)*	*Fixed/Portable Equipment*	*P-F Interval*	*Skill*
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

Notes:

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

Table. D.5. Nondestructive Testing

Condition	*Condition Monitoring Subcategory*	*Technique*	*Fixed/Portable Equipment*	*P-F Interval*	*Skill*
Subsurface defects Lack of weld penetration Gas porosity in welds Intergrannular 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
Subsurface defects Lack of weld penetration Gas porosity in welds Intergrannular 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

Table. D.5. Nondestructive Testing (continued)

Condition	*Condition Monitoring Subcategory*	*Technique*	*Fixed/Portable Equipment*	*P-F Interval*	*Skill*
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. D.6. Electrical Condition Monitoring[(1)]

Condition	*Condition Monitoring Subcategory*	*Technique*	*Fixed/Portable Equipment*	*P-F Interval*	*Skill*
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 Coil reversal or open circuit	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
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
Misalignment Excessive mechanical friction Motor deterioration	Starting Time and Current	Starting Time and Current	Portable	Unknown	Experienced electrical technician

Table. D.6. Electrical Condition Monitoring[1] (continued)

Condition	*Condition Monitoring Subcategory*	*Technique*	*Fixed/Portable Equipment*	*P-F Interval*	*Skill*
Broken rotor bars Broken shorting rings High resistance between bars and rings Uneven rotor-stator gap Rotor misposition Rotor deterioration	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

Notes:

1. Refer to Table D.2 "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. D.7. Performance Monitoring

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

Table. D.8. Suggested P-F Intervals

Equipment Item	*Controls* *Failure per 10^4 hrs*	*Test Interval* *Months*
Main Engine	0.5570	4.3
Boiler	0.0137	175.2
Diesel Generator	0.0920	26.1
Steam Turbo Generator	0.0020	1200.0