



## **GUIDANCE NOTES ON**

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# **RELIABILITY-CENTERED MAINTENANCE**

**JULY 2004**

**American Bureau of Shipping  
Incorporated by Act of Legislature of  
the State of New York 1862**

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## Foreword

In recent years, there has been an increase in the use of proactive maintenance techniques by Owners for repair and maintenance of machinery onboard vessels and offshore structures. The resulting preventative maintenance programs developed as a result of applying these techniques are being used by the vessel's crew and shore-based repair personnel. There have been numerous advances in condition monitoring technology, trending, and increasingly more powerful planned maintenance software as a result of increased business competition. Since 1978, ABS has cooperated with Owners on developing and implementing preventative maintenance programs. In 1984, ABS issued its first *Guide for Survey Based on Preventative Maintenance Techniques* with subsequent updates in 1985, 1987, 1995 and then inclusion in the *Rule Requirements for Survey After Construction – Part 7* in mid-2002.

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

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

*ABS welcomes comments and suggestions for improvement of this Guide. Comments or suggestions can be sent electronically to [rdd@eagle.org](mailto:rdd@eagle.org).*

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# GUIDANCE NOTES ON RELIABILITY-CENTERED MAINTENANCE

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## SECTION 1 General

### 1 Objective

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

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

- i) Identify functional failures with the highest risk, which will then become the focus for further analyses
- ii) Identify equipment items and their failure modes that will cause high-risk functional failures
- iii) Determine maintenance tasks and maintenance strategies that will reduce risk to acceptable levels

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

### 2 Application

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

### 3 Defining Reliability-centered Maintenance

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

- i) Its functions
- ii) The failure modes of its equipment that support these functions
- iii) How then to choose an optimal course of maintenance to prevent the failure modes from occurring or to detect the failure mode before a failure occurs
- iv) How to determine spare holding requirements
- v) How to periodically refine and modify existing maintenance over time

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

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

- i) What are the system functions and associated performance standards?
- ii) How can the system fail to fulfill these functions?
- iii) What can cause a functional failure?
- iv) What happens when a failure occurs?
- v) What might the consequence be when the failure occurs?
- vi) What can be done to detect and prevent the failure?
- vii) What should be done if a maintenance task cannot be found?

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

- i) Failure modes, effects and criticality analysis (FMECA). This analytical tool helps answer Questions 1 through 5.
- ii) RCM decision flow diagram. This diagram helps answer Questions 6 and 7.
- iii) Design, engineering and operational knowledge of the system
- iv) Condition-monitoring techniques
- v) Risk-based decision making (e.g., the frequency and the consequence of a failure in terms of its impact on safety, the environment and commercial operations)

Documenting and implementing the following formalize this process:

- i) The analyses and the decisions taken
- ii) Progressive improvements based on operational and maintenance experience
- iii) Clear audit trails of maintenance actions taken and improvements made

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

## 4 Definitions

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

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

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

*Cause:* See *failure cause*.

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

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

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

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

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

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

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

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

**Effects:** See *failure effects*.

**End Effects:** See *failure effects*.

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

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

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

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

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

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

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

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

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

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

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

*FMECA:* The acronym for failure mode effects and criticality analysis.

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

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

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

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

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

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

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

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

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

*Likelihood:* See *frequency*.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

*Safeguards:* See *corrective measures*.

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

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

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

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

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

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

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

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

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

## SECTION 2 Equipment Failure

### 1 Equipment Failure

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

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

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

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

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

**TABLE 1**  
**Examples of Dominant Physical Failure Mechanisms for Hardware**

| <i>Mechanical Loading Failure</i>                                                                                              | <i>Wear</i>                                                                                                                                   | <i>Corrosion</i>                                                                                                     | <i>Temperature-related Failure</i>                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------|
| <ul style="list-style-type: none"> <li>• Ductile fracture</li> <li>• Brittle fracture</li> <li>• Mechanical fatigue</li> </ul> | <ul style="list-style-type: none"> <li>• Abrasive</li> <li>• Adhesive</li> <li>• Fretting</li> <li>• Pitting</li> <li>• Cavitation</li> </ul> | <ul style="list-style-type: none"> <li>• Galvanic</li> <li>• Uniform</li> <li>• Stress corrosion cracking</li> </ul> | <ul style="list-style-type: none"> <li>• Creep</li> <li>• Metallurgical transformation</li> <li>• Thermal fatigue</li> </ul> |

## 2 Equipment Failure Rate and Patterns

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

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

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

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

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

Another common statistical measure associated with these distributions is mean time to failure (MTTF). MTTF is the average life to failure for the equipment failure mode. Thus, it represents the point at which the areas under the failure distribution curve are equal above and below the point. Determining the MTTF will, therefore, depend on the type of failure distribution used to model the failure mode. Section 2, Figure 1 also identifies the MTTF for normal and exponential failure distributions.

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

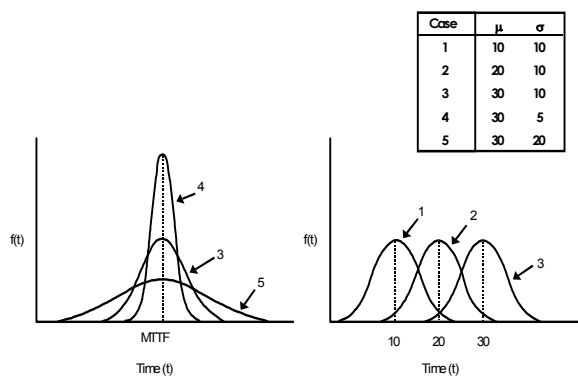
A more useful measurement, derived from the failure distribution, is the conditional failure rate or lambda ( $\lambda$ ). The conditional probability failure rate is the probability that a failure occurs during the next instant of time, given that the failure has not already occurred before that time.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

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

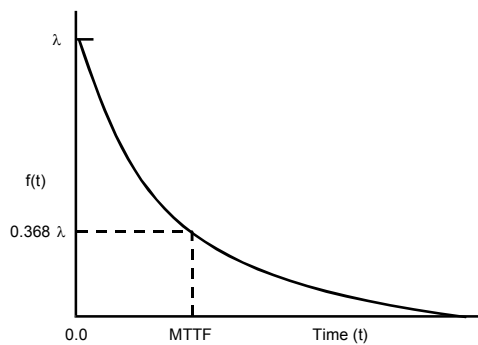
For most equipment failure modes, the specific failure patterns are not known and, fortunately, are not needed to make maintenance decisions. Nevertheless, certain failure characteristic information is needed to make maintenance decisions. These characteristics are:

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

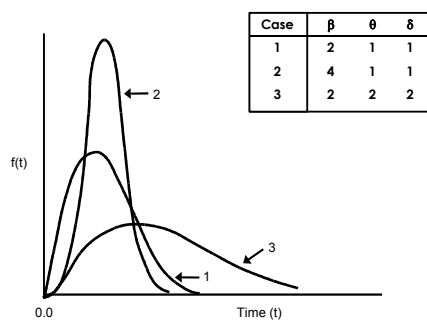
**FIGURE 1**  
**Normal, Exponential and Weibull Failure Distributions**



**Normal (continuous)**

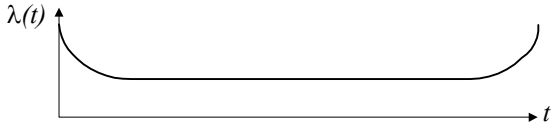
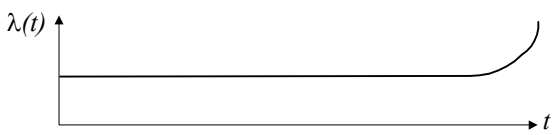
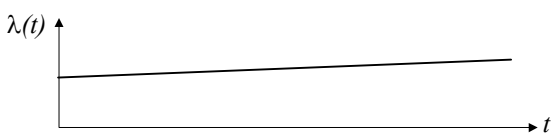
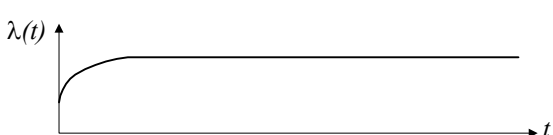
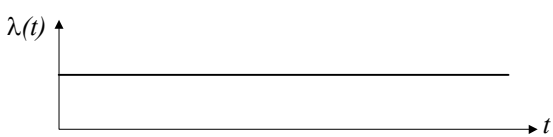
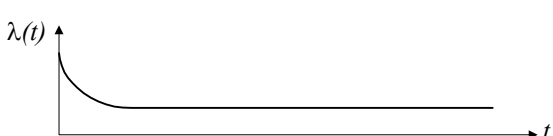


**Exponential (continuous)**



**Weibull (continuous)**

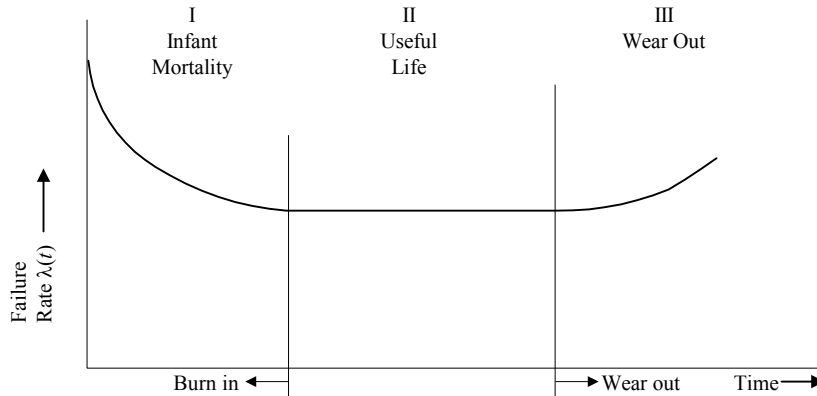
**TABLE 2**  
**Six Classic Failure Rate Patterns <sup>(1)</sup>**

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

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

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

**FIGURE 2**  
**Equipment Life Periods**



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

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

### 3 Failure Management Strategy

Understanding failure rates and failure characteristics allows the determination of an appropriate strategy for managing the failure mode (e.g., RCM refers to this as the failure management strategy). Developing and using this understanding is fundamental to RCM and critical to improving equipment reliability. It is no longer considered to be true that the more an item is overhauled, the less likely it is to fail. Unless there is a dominant age-related failure mode, age limits do little or nothing to improve the reliability of complex items. Sometimes, scheduled overhauls can actually increase overall failure rates by introducing infant mortality and/or human errors into otherwise stable systems.

In RCM, the failure management strategy can consist of:

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

The purpose of the proactive maintenance tasks in the failure management strategy is to (1) prevent failures before they occur or (2) detect the onset of failures in sufficient time so that the failure can be managed before it occurs. Equipment redesigns, modifications and operational improvements (RCM refers to these as one-time changes) are attempts to improve equipment whose failure rates are too high or for which proactive maintenance is not effective/efficient.

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

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

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

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

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

### 3.1 Proactive Maintenance Tasks

Proactive maintenance tasks are divided into four categories.

#### 3.1.1 Planned-maintenance Tasks

A planned-maintenance task (sometimes called preventative maintenance) is performed on a specified interval, regardless of the equipment's condition. The purpose of this type of task is to prevent functional failure before it occurs. Many times this type of task is applied when no condition-monitoring task is identified or justified, and the failure mode is characterized with a wear-out region. RCM further divides planned maintenance into the following two subcategories:

- *Restoration task.* A scheduled task that restores the capability of an item at or before a specified interval (age limit) to a level that provides a tolerable probability of survival to the end of another specified interval. For the case of scheduled restoration of a diesel engine, rebuilding of the fuel injectors would be an example. Section 3 provides additional details.
- *Discard task.* A scheduled task involving discarding an item at or before a specified age limit regardless of its condition at the time. Note that the terms "restoration" and "discard" can be applied to the same task. For example, if a diesel engine's cylinder liners are replaced with new ones at fixed intervals, the replacement task could be described as scheduled discard of the cylinder liner or scheduled restoration of the diesel engine. Section 3 provides additional details.

#### 3.1.2 Condition-monitoring Tasks

A condition-monitoring task is a scheduled task used to detect the onset of a failure so that action can be taken to prevent the functional failure. A potential failure is an identifiable condition that indicates that a functional failure is either about to occur or in the process of occurring. Condition-monitoring tasks should only be chosen when a detectable potential failure condition will exist before failure. When choosing maintenance tasks, condition-monitoring tasks should be considered first, unless a detectable potential failure condition cannot be identified. Condition-monitoring tasks are also referred to as "predictive maintenance." Section 4 provides additional details.

### 3.1.3 Combination of Tasks

Where the selection of either condition-monitoring or planned-maintenance tasks on their own do not seem capable of reducing the risks of the functional failure of the equipment, it may be necessary to select a combination of both maintenance tasks. Usually, this approach is used when the condition-monitoring or planned-maintenance task is insufficient to achieve an acceptable risk by itself. Sections 7 and 8 provide further information on determining whether this failure management strategy achieves an acceptable level of risk.

### 3.1.4 Failure-finding Tasks

A failure-finding task is a scheduled task used to detect hidden failures when no condition-monitoring or planned-maintenance task is applicable. It is a scheduled function check to determine whether an item will perform its required function if called upon. Most of these items are standby or protective equipment. An example would be checking the safety valve on a boiler. Section 5 provides additional details.

## 3.2 Run-to-failure

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

## 3.3 One-time Changes

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

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

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

- i) Faulty design and/or material
- ii) Improper fabrication and/or construction
- iii) Misoperation
- iv) Maintenance errors

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

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

- *Equipment redesign or modifications.* Redesign or modifications entail physical changes to the equipment or system. An example would be adding drain valves to appropriate lengths of piping to a tanker's deck cargo piping to prevent freezing and damage to the piping during vessel transits in freezing temperatures.
- *Operational improvements.* Operational improvements may be modifications to the operation of the equipment and/or modifications to the way in which maintenance is performed on the equipment. Operational improvements usually entail changing the operating context, changing operating procedures, providing additional training to the operator or maintainer, or any combination thereof. For example, in the case of a main propulsion engine provided with a noncontinuous rating name plate, the engine could be operated at a lower output closer to its continuous rating so as to reduce downtime for maintenance. (However, this action may cause the vessel to be unable to meet its schedules.)

### **3.4 Servicing and Routine Inspection**

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

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## SECTION 3 Planned Maintenance

### 1 Introduction

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

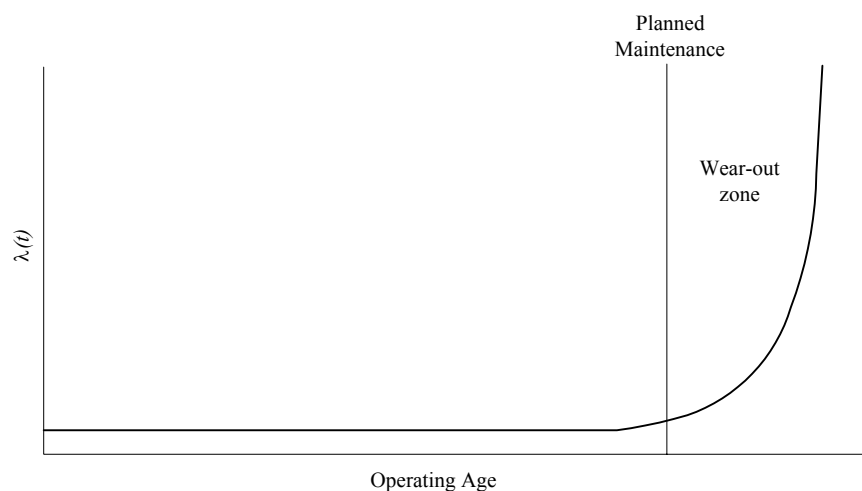
The basic principle of planned maintenance is that restoring or discarding the item at a specific time before failure is expected can best manage the probability of failure. Following this principle, the planned-maintenance tasks are performed at set intervals, regardless of whether or not a failure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

### 2 Age-To-Failure Relationship

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

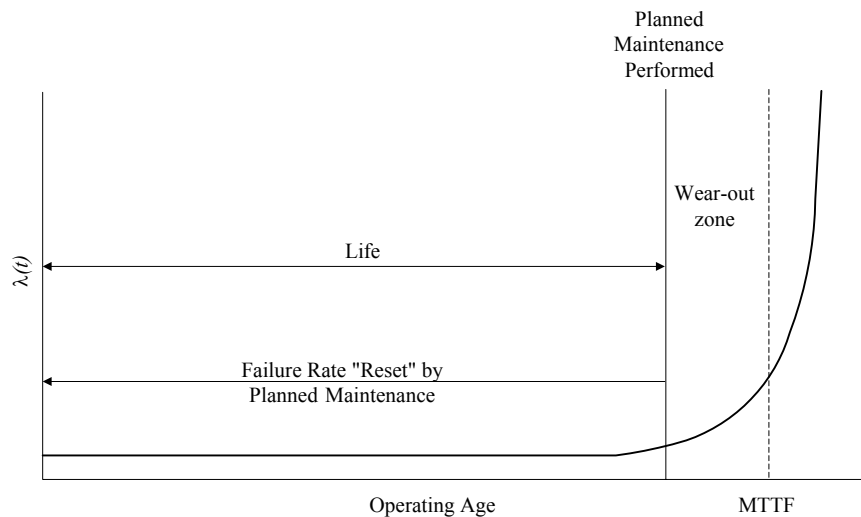
For planned maintenance to be effective in managing the failure, the failure mode must exhibit a clear life and most of the equipment items must survive to that life. Section 3, Figure 1 illustrates the wear-out period for failure pattern B.

**FIGURE 1**  
**Classic Failure Profile Used for Planned Maintenance**



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

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



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

### 3 Planned-maintenance Task Applicability and Effectiveness

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

- i) Is the task technically feasible to perform? The age-to-failure relationship must be reasonably consistent, and the task must be physically capable of being performed.
- ii) Does the task reduce the probability of failure (and therefore the risk) to an acceptable level? The tasks must be carried out at an interval that is less than the age at which the equipment or component shows a rapid increase in its conditional probability of failure. Agreed-upon risk acceptance criteria should be determined and recorded.
- iii) Is the task cost-effective? The cost of undertaking a task over a period of time should be less than the total cost of the consequences of failure.

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

- i) Does the task ensure the reliability and performance of the equipment? If the equipment is restored, it must be restored to a nearly new condition.
- ii) Is the task cost-effective? The cost of restoring the equipment should be less than discarding the equipment and replacing it with a new item.

## 4 Determining Planned-maintenance Task Interval

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

- i) Equipment manufacturer information
- ii) Expert opinion
- iii) Published reliability data
- iv) Statistical analysis (e.g., Weibull) of actual failure history, including the MTTF data

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

**FIGURE 3**  
**Safe Life Limit**

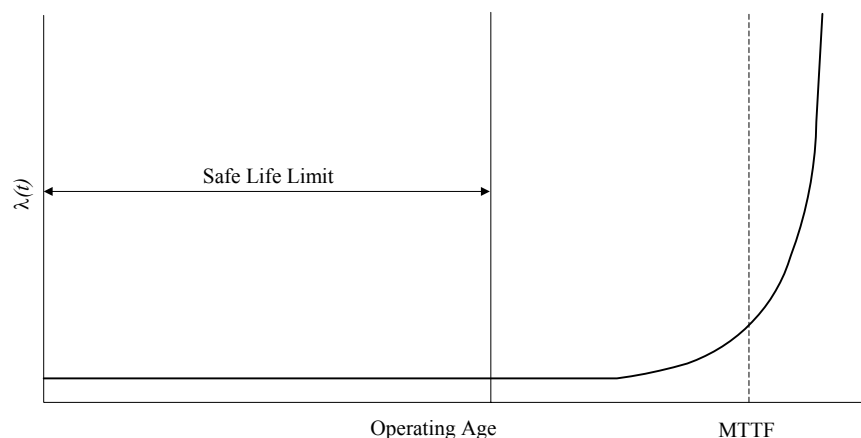
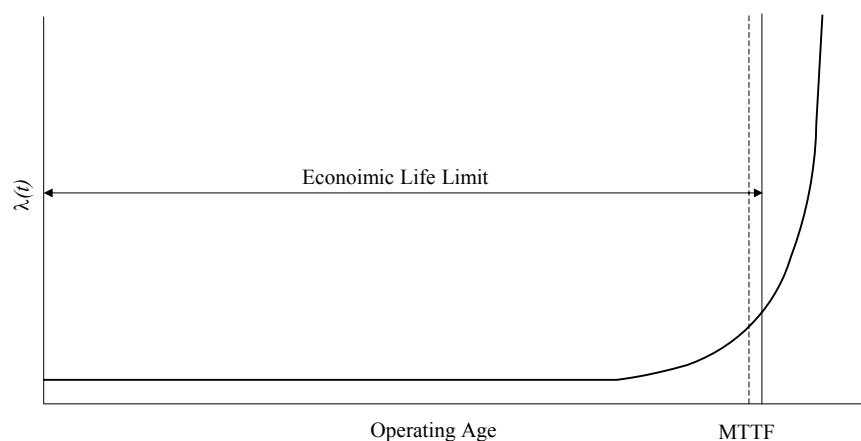


**FIGURE 4**  
**Economic Life Limit**



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

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

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

## SECTION 4 Condition Monitoring (Predictive) Maintenance

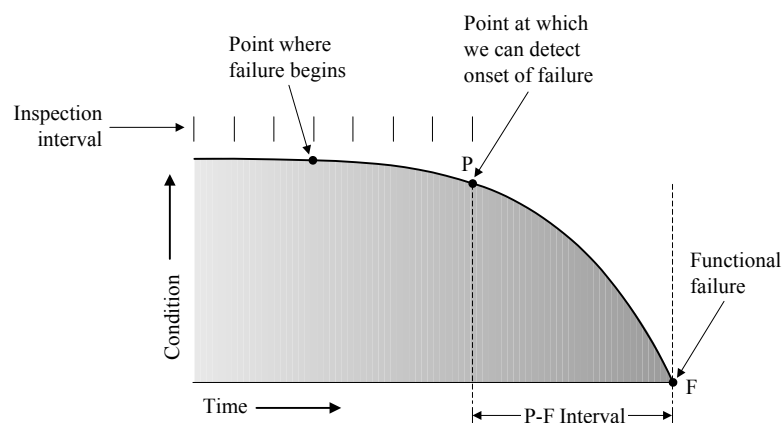
### 1 Potential Failure (P-F) Diagram

Although many failure modes are not age-related, most of them give some sort of warning that they are in the process of occurring or about to occur. If evidence can be found that something is in the final stages of a failure, it may be possible to take action to prevent it from failing completely and/or to avoid the consequences. Section 4, Figure 1 illustrates the final stages of failure, called the P-F curve. Section 4, Figure 1 illustrates how a condition deteriorates to the point at which it can be detected (Point P) and then, if it is not detected and corrected, continues to deteriorate until it reaches the point of functional failure (Point F).

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

If a potential failure is detected between Point P and Point F, it may be possible to take action to prevent the functional failure (or at least to minimize the effects). Tasks designed to detect potential failure are known as condition-monitoring tasks (see Subparagraph 2/3.1.2).

**FIGURE 1  
P-F Diagram**



## 2 The P-F Interval

The time interval between Point P and Point F in Section 4, Figure 1 is called the “P-F interval”. This is the warning period (e.g., the time between the point at which the potential failure becomes detectable and the point at which it deteriorates into a functional failure). If a condition-monitoring task is performed on intervals longer than the P-F interval, the potential failure may not be detected. On the other hand, if the condition-monitoring task is performed too frequently compared to the P-F interval, resources are wasted.

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

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

## 3 Condition-monitoring Maintenance Task Applicability and Effectiveness

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

- i) *Onset of failure must be detectable.* There must be some measurable parameter that can detect the deterioration in the equipment’s condition. In addition, maintenance personnel must be able to establish limits to determine when corrective action is needed.
- ii) *Reasonably consistent P-F interval.* The P-F interval must be consistent enough to ensure that corrective actions are not implemented prematurely or that failure occurs before corrective actions are implemented.
- iii) *Practical interval in which condition-monitoring tasks can be performed.* The P-F interval must be sufficient to permit a practical task interval. For example, a failure with a P-F interval of minutes or hours is probably not a good candidate for a condition-monitoring maintenance task.
- iv) *Sufficient warning so that corrective actions can be implemented.* The P-F interval must be long enough to allow corrective actions to be implemented. This can be determined by subtracting the task interval from the expected P-F interval and then judging whether sufficient time remains to take necessary corrective actions.
- v) *Reduces the probability of failure (and therefore the risk) to an acceptable level.* The tasks must be carried out at an interval so that the probability of failure allows an acceptable risk level to be achieved. Agreed-upon risk acceptance criteria should be determined and recorded.
- vi) *Must be cost-effective.* The cost of undertaking a task over a period of time should be less than the total cost of the consequences of failure.

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

## 4 Determining Condition-monitoring Maintenance Task Intervals

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

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

### 4.1 Condition-monitoring Task Interval

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

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

### 4.2 Initial Condition-monitoring Task Intervals

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

- i) If an existing condition-monitoring task is being performed and has proven to be effective (e.g., no unexpected failures have occurred), use the existing task interval as the initial default task interval.
- ii) If an existing condition-monitoring task is being performed and some functional failures have occurred, adjust the task interval downward based on the experience.
- iii) If there is no existing condition-monitoring task being performed or a new condition-monitoring task is being proposed, the task interval will have to be based on the team's estimate of the P-F interval and guidelines provided in Paragraph 4/4.1. The following questions can help the team estimate the P-F interval:
  - How quickly can the condition deteriorate and result in a functional failure? Will it deteriorate in minutes, hours, days, weeks, months or years?
  - What is the capability of the condition-monitoring task in detecting the onset of failure? High or low?
  - How confident is the team in its judgment?

### 4.3 Improving the Understanding of P-F Intervals

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

This is a rough form of age-exploration testing.

## 5 Establishing Condition-monitoring Maintenance Task Action Limits

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

- i) Reperforming the condition-monitoring task to verify the results
- ii) Altering the task interval to ensure closer monitoring of the equipment
- iii) Initiating corrective actions to prevent the impending equipment failure

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

## SECTION 5 Failure Finding Maintenance

### 1 Introduction

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

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

### 2 Statistical View of Hidden Failures

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

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

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

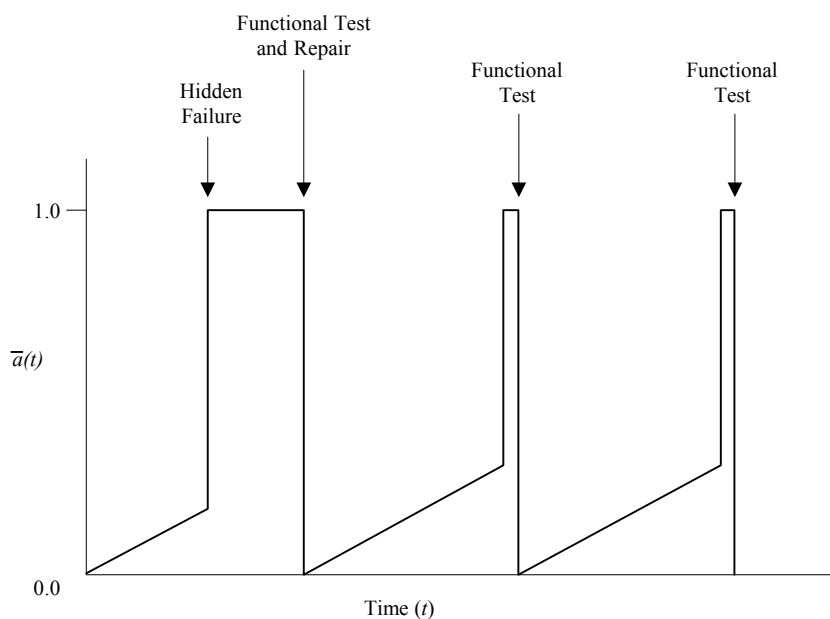
This equation can be rearranged to solve for the unavailability of the safety system or backup system:

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

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

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

**FIGURE 1**  
**Effect of a Failure-finding Task**



### 3 Failure-finding Task Applicability and Effectiveness

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

- i) Must be no applicable or cost-effective condition-monitoring or planned-maintenance task that can detect or prevent the failure.
- ii) Must be technically feasible to perform. The task must be practical to perform at the required interval and must not disrupt an otherwise stable system.
- iii) Must reduce the probability of failure (and therefore the risk) to an acceptable level. The tasks must be carried out at an interval so that probability of multiple failures allows an acceptable risk level to be achieved. Agreed-upon risk acceptance criteria should be determined and recorded.
- iv) Must not increase the risk of a multiple failure (e.g., when testing a relief valve, an over-pressure should not be created without the relief valve in service).
- v) Must ensure that protective systems are tested in their entirety rather than as individual components that make up the system.
- vi) Must be cost-effective. The cost of undertaking a task over a period of time should be less than the total cost of the consequences of failure.

## 4 Determining Failure-finding Maintenance Task Interval

The interval for failure-finding tasks can be determined:

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

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

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

### 4.1 Mathematical Determination of Failure-finding Task Interval

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

- i) If the failure has a wear-in failure characteristic, then either a one-time change or a condition-monitoring task is usually employed to manage the failure.
- ii) If the failure has a wear-out failure characteristic, then a condition-monitoring task or a planned-maintenance task should be applied to manage the failure.

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

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

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

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

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

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

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

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

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

where

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

#### 4.2 Using Guidelines to Determine the Failure-finding Task Interval

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

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

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

**TABLE 1**  
**Example of Failure-finding Task Interval Rules**

| <i>Risk of Hidden Failure</i> | <i>Unavailability Required</i> |
|-------------------------------|--------------------------------|
| Very High                     | < 0.0001                       |
| High                          | > 0.0001 to 0.001              |
| Moderate                      | > 0.001 to 0.01                |
| Low                           | > 0.01 to 0.05                 |

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

| <i>Unavailability Required</i> | <i>Failure-finding Task Interval (as % of MTTF)</i> |
|--------------------------------|-----------------------------------------------------|
| 0.0001                         | 0.02                                                |
| 0.001                          | 0.2                                                 |
| 0.01                           | 2                                                   |
| 0.05                           | 10                                                  |

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

## SECTION 6 Consideration of Risks

### 1 Risks In General

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

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

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

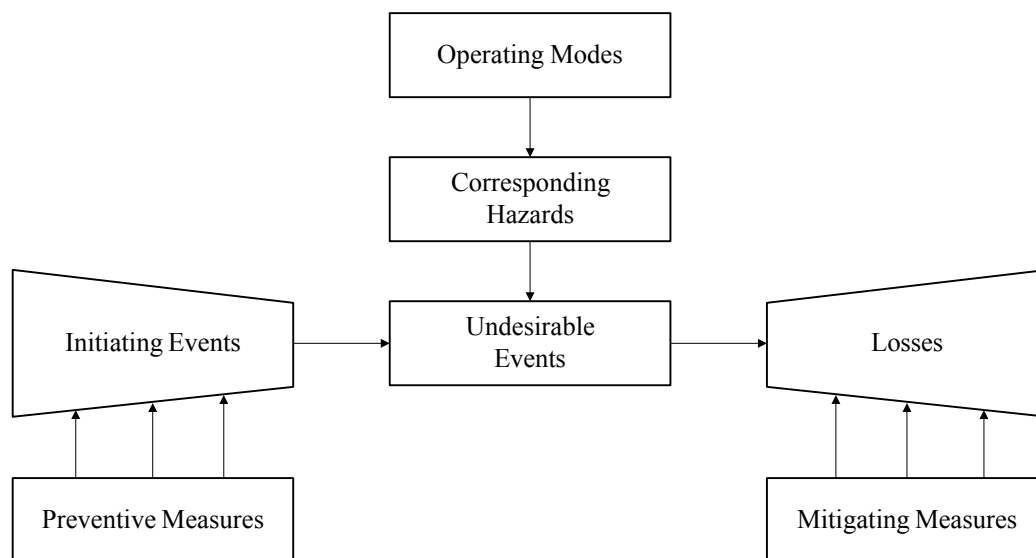
- i) *Capital investment.* Damage to and cost of repair of equipment
- ii) *Community.* Effect on the public
- iii) *Directional control.* Complete loss or reduction of maneuverability
- iv) *Explosion or fire.* Damage to equipment and/or the vessel
- v) *Loss of containment.* Amount of harmful substances released to the environment (the cleanup costs)
- vi) *Operations.* Loss of hire, outage time of functions such as drilling, position mooring (station keeping), hydrocarbon production and processing, loading or unloading functions
- vii) *Propulsion.* Complete loss or reduction of propulsive capability
- viii) *Safety.* The number of people affected (injured or fatalities)

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

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

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

**FIGURE 1**  
**The General Risk Model**



## 2 Vessels and Their Risks

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

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

- i) They are not specific as to the operating modes of the vessel.
- ii) The risk levels have not been quantified nor, in fact, have acceptable risk criteria been defined.
- iii) It is only in more recent years that operational measures (e.g., safety management and crew training) have been included as tools to reduce risks. More appear necessary, particularly in measures to mitigate consequences.
- iv) Maintenance is not emphasized as a means of preventing loss events.

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

### 3 Risk Characterization

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

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

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

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

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

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

**FIGURE 2**  
**Example Risk Model**

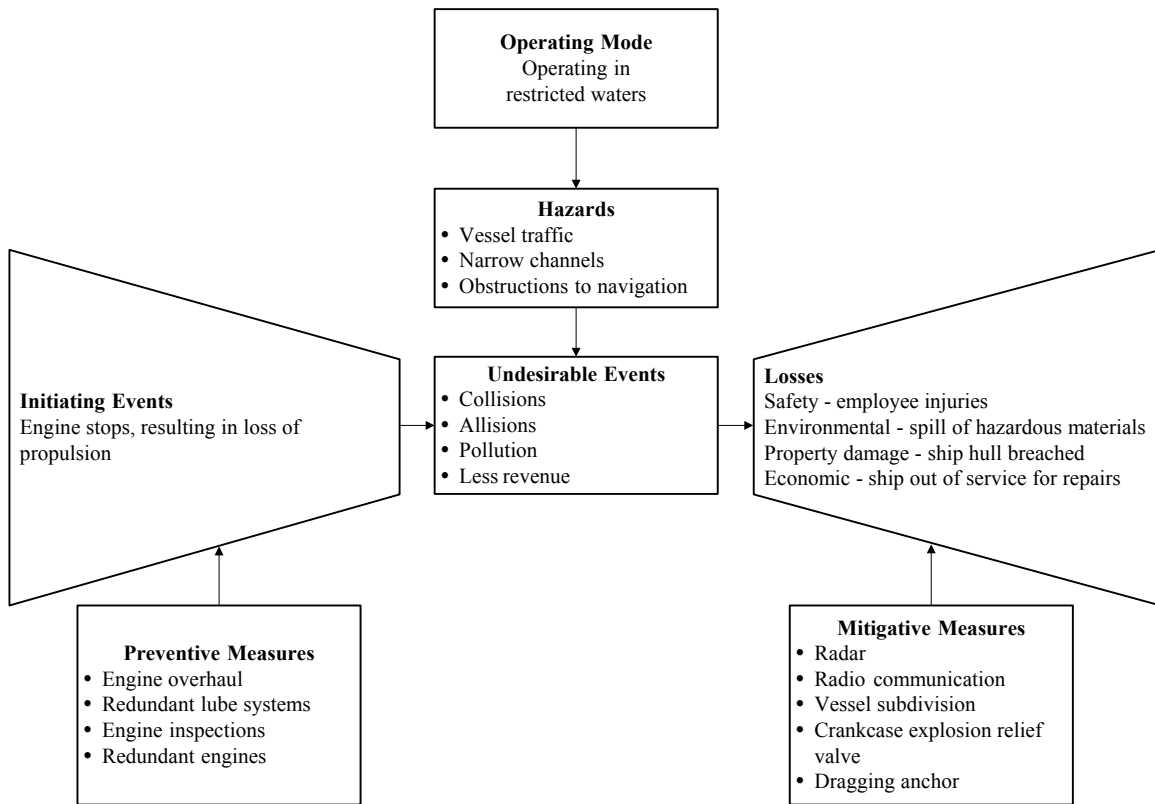
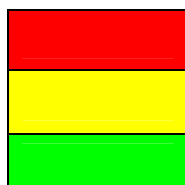


**FIGURE 3**  
**Sample Risk Matrix**

|           |   |                                                     |                                                                       |                                                                                     |                                                                                |                                                                      |                       |  |  |
|-----------|---|-----------------------------------------------------|-----------------------------------------------------------------------|-------------------------------------------------------------------------------------|--------------------------------------------------------------------------------|----------------------------------------------------------------------|-----------------------|--|--|
| Critical  | 4 | C<br>O<br>N<br>S<br>E<br>Q<br>U<br>E<br>N<br>C<br>E |                                                                       |                                                                                     | High Risk                                                                      |                                                                      |                       |  |  |
| Hazardous | 3 |                                                     |                                                                       |                                                                                     |                                                                                |                                                                      |                       |  |  |
| Major     | 2 |                                                     |                                                                       | Medium Risk                                                                         |                                                                                |                                                                      |                       |  |  |
| Minor     | 1 |                                                     | Low Risk                                                              |                                                                                     |                                                                                |                                                                      |                       |  |  |
|           |   |                                                     | L I K E L I H O O D                                                   |                                                                                     |                                                                                |                                                                      |                       |  |  |
|           |   |                                                     | 1                                                                     | 2                                                                                   | 3                                                                              | 4                                                                    | 5                     |  |  |
|           |   |                                                     | Improbable                                                            | Remote                                                                              | Occasional                                                                     | Probable                                                             | Frequent              |  |  |
|           |   |                                                     | Fewer than 0.001 events/year<br>(Less than 1 event every 1,000 years) | 0.001 to 0.01 events/year<br>(1 event every 1,000 years to 1 event every 100 years) | 0.01 to 0.1 events/year<br>(1 event every 100 years to 1 event every 10 years) | 0.1 to 1 events/year<br>(1 event every 10 years to 1 event per year) | 1 or more events/year |  |  |



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

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

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

**TABLE 1**  
**Example Consequence (Severity) Categories**

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

Notes:

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

## SECTION 7 **Conducting and Documenting an RCM Analysis**

### **1 Introduction**

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

- i) Identify operating modes and corresponding operating contexts
- ii) Define vessel systems
- iii) Develop system block diagrams and identify functions
- iv) Identify functional failures
- v) Conduct a failure modes, effects and criticality analysis (FMECA)
- vi) Select a failure management strategy
- vii) Determine spare parts holdings
- viii) Document the analysis

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

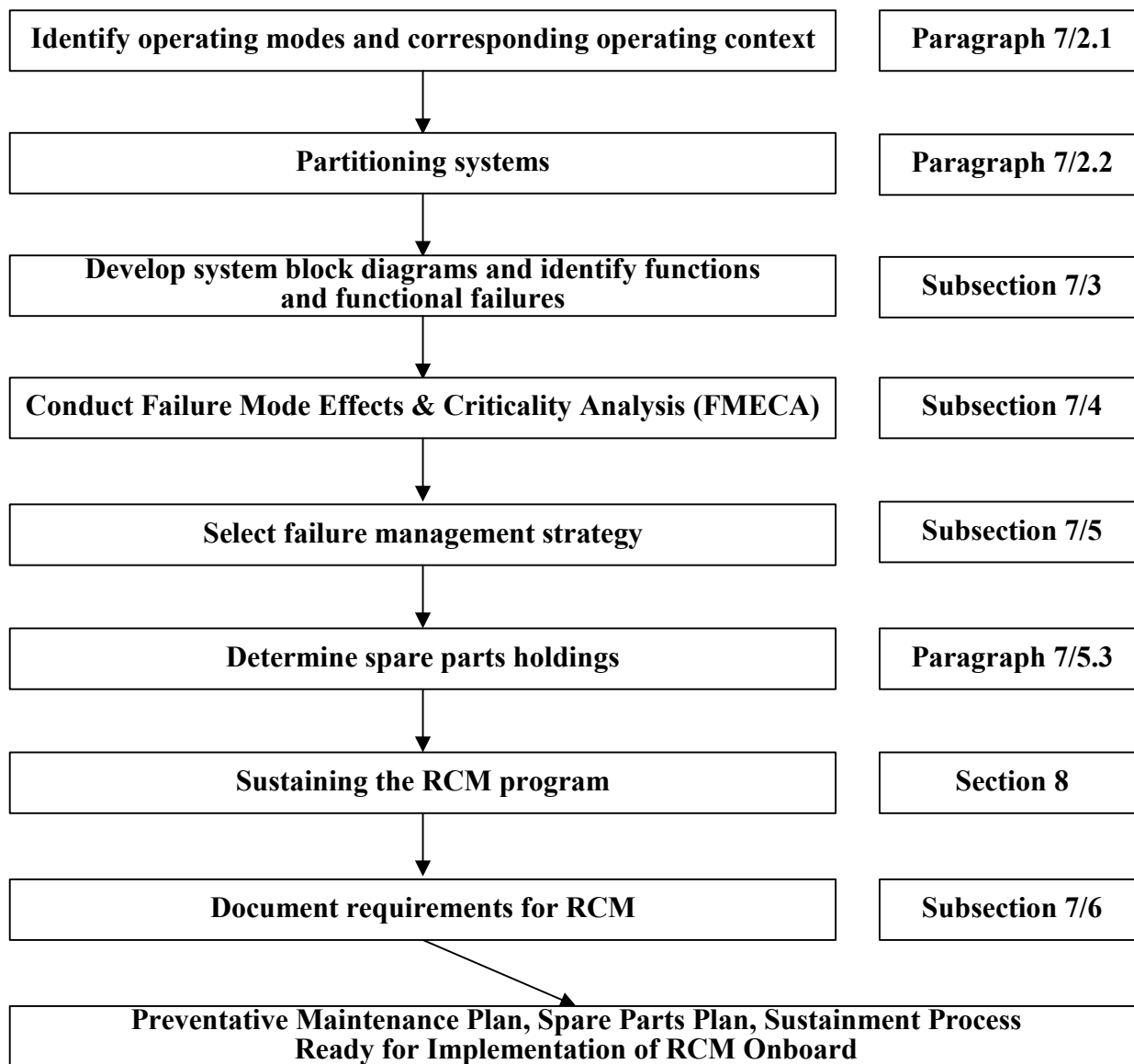
### **2 Defining Systems**

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

#### **2.1 Defining Ship Operating Characteristics**

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

**FIGURE 1**  
**Diagram for RCM Analysis**



### 2.1.1 Operating Mode

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

The following example operating modes are typical for ships:

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

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

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

### 2.1.2 Operating Context

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

- i) The physical environment in which the functional group is operated
- ii) A precise description of the manner in which the functional group is used
- iii) The specified performance capabilities of the functional group as well as the required performance of any additional functional groups within which the functional group is embedded

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

- i) *Serial redundancy.* Applies to arrangements for which an identical standby system/equipment exists to support an operating functional group. In the event of failure of the operating system, the standby system is activated. The operating contexts for the running system/equipment and standby system/equipment are different. For example, a functional failure in the operating system/equipment will likely be evident, while a functional failure in the standby system/equipment will likely be hidden.
- ii) *Parallel redundancy.* Applies to systems/equipment operating simultaneously. Each system has the capability to meet the total demand. In the event of a functional failure in one system/equipment, the remaining systems/equipment will continue to operate, but at a higher capacity. In some arrangements, standby systems/equipment may also be in reserve.
- iii) *Performance and quality standards.* Systems/equipment may be required to perform at a certain performance level or to provide a service with a certain quality level (e.g., compressed air supplied at specified quantity at certain pressure within certain temperature ranges and humidity limits).
- iv) *Environmental standards.* As required by international, national and local laws and regulations (e.g., for an engine emission standard, the operating context of a functional group's impact or potential impact on the environment must be considered).
- v) *Safety standards.* Hazards that might be present in an operating context and the safeguards that must be in place for protection of the crew should be specified.
- vi) *Shift arrangements.* For oceangoing vessels, it is assumed the propulsion machinery is operating continuously, except when the vessel is docked. On the other hand, the ship's service electrical power system is operating continuously. System arrangements and maintenance strategies must be carefully developed so as to ensure system availability.