# Risk-Based Strategies for the Next Generation of Maintenance and Inspection Programs

Christopher M. Serratella

Ge Wang

Robert Conachey

American Bureau of Shipping, USA, cserratella@eagle.org
gwang@eagle.org, rconachey@eagle.org

## Abstract

*The maritime industry has seen an ever-increasing interest in applying risk-based approaches to better manage the integrity of ships and offshore units in service. The recent initiatives related to IMO in setting Goal Based Standards will also be reflected in justification of maintenance and inspection regimes for marine assets from a performance based standpoint. The development of risk-based strategies for the next generation of maintenance and inspection programs for various ship includes the application of Reliability-Centered Maintenance (RCM) for machinery systems and Risk-Based Inspection (RBI) for hull structures and fixed equipment systems.*

*By applying RCM principles, an operator can improve the reliability of its vessels' machinery system. Risk assessment techniques (FMECA) and RCM analysis are used to determine relevant failure modes and equipment criticality. These inputs provide a process feed for optimization of maintenance tasks for maximum uptime. Further, spares management can be optimized using the RCM process. A sustainment process is also discussed so the operator can keep preventative maintenance tasks current as the system ages, new failure modes are identified, or system modification occur.*

*RBI inspection planning includes risk assessment coupled with the understanding of applicable degradation mechanisms and consequence of failures in the structure in order to develop an inspection program for the asset. Structural analysis plays an important role in this process. For structures, analysis data generated as part of the design process is used to predict the likelihood of failure and account for the degradation that structures inevitably suffer. Combined with an assessment of consequence of failure, structure is risk ranked , inspection methods and frequencies optimized, and then aggregated into an RBI plan. Hence, this process can be regarded as a vehicle for incorporating design information in the inspection process in an integrated way. This represents a significant improvement in integrity management (IM) approach over traditional methods where there is little, if any, interaction between the design and in-service phases of the life of the asset. Further, targeted inspection and data collection of asset health for critical areas within the hull leads to risk reduction overall.*

## Keywords

Inspection; Maintenance; Risk; RBI; RCM; Optimization

## 1. Introduction

As analysis techniques become more sophisticated, ships and offshore structures have become more complex and innovative. As a result, their designs do not necessarily mimic those of their predecessors with certain aspects unique in their configuration. In particular, naval vessel design emphasizes minimum structural weight in order to maximize payload. Compounding this problem is the fact that many organizations differentiate between the "Capital Expenditure" and the "Operational Expenditure" segments. This can mean that design features which improve a vessel's operability, inspectability, and maintainability are rejected at the procurement stage in the interest of decreased initial costs and as a result, the traditional, prescriptive inspection and maintenance methods are no longer the most effective. It is imperative that those elements of the vessel's structure or machinery systems more prone to deterioration and damage be identified early in the design process.

While there remains a strong need for traditional rule-based and prescriptive approaches, marine assets are becoming more complex, have a higher degree of novelty, and many aspects of their designs are falling outside or ahead of the development of traditional Class Rules. Risk and reliability based technology is finding increased application given the current demands from clients for more flexibility in the way classification services are provided as well as the greater use of performance-based criteria. Ever-expanding technologies often require the abandonment of trusted methods, the stretching of boundaries, and the adoption of new unfamiliar procedures. Risk and reliability based design, operation, and integrity management programs are all becoming more commonplace in this environment.

In addition, the operator's control of the integrity management of its assets must now reach far beyond the minimum. Society now expects due diligence and proactive management from vessel operators. Today's organizations must also adapt to constant advances in technology while burdened with the mandate to do more with less as budgets grow leaner by the day.

Companies with effective asset integrity management programs strive to consider these facts throughout the life-cycle of that asset. The leading edge operators will ensure that operability and maintainability are considered from the initial concept and detailed design (How best can it be designed for optimum inspectability and maintainability?), construction (What can I do now to minimize future inspection and maintenance needs?), installation (What baseline am I starting with?), and onward through operation (What are my inspection and maintenance results telling me?) and potentially upgrading the asset (What can I do to improve performance?).

Traditional practice as exemplified by prescriptive Rules and standard methods lacks the flexibility to respond to these demands. Risk and reliability based methodologies allow systematic and rational ways for dealing with variations and deviations from the "standard" approach. These more advanced methods of maintenance and inspection strategy development follow along an evolutionary continuum that other industries are also following (Fig. 1, end of paper).

The American Bureau of Shipping (ABS) has been involved in the development of and the assistance with implementation of both RBI and RCM for the maintenance of Class. This paper will describe an approach to developing both Risk-Based Inspection and Reliability Centered Maintenance plans for vessel structures and machinery that have the potential to result in significantly improved asset integrity management and cost savings. The methods presented herein aim to support optimized life-cycle integrity management of ships and offshore units by utilizing risk and reliability based methods.

## 2. Risk Based Approaches

The marine and offshore industries are drawing upon the lead set by other industries (nuclear, aircraft, etc…), in the application of risk-based approaches for design and in-service inspection. Risk-based methodologies for inspection plan optimization originated in the nuclear industry in the 1970's and over the years have migrated into other industries, such as the downstream petrochemical industry in the 1980's and 1990's. These approaches are now moving into the upstream sector of the oil and gas industry and to a lesser extent, the shipping industry.

Of particular interest has been the application of risk based inspection (RBI) and reliability centered maintenance (RCM) techniques in which experience based data related to various degradation mechanisms as well as a better understanding of these degradation mechanisms as applied to set inspection and maintenance frequencies and scopes. The implementation of these risk and reliability based techniques into the development of a plan provides an alternative to prescriptive time-based inspection and maintenance planning.

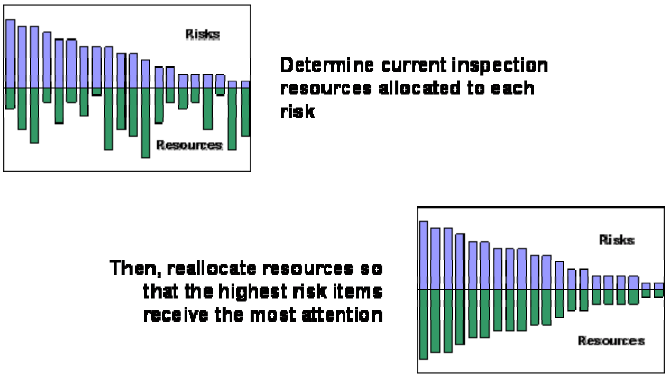
Figure 1 (end of paper) provides a schematic on the evolution of inspection and maintenance plan strategies. The compliance-based strategy (Phase 1), also referred to as rule-based, is generally representative of the traditional class or regulatory requirements. Inspection plans derived from such an approach have generally been developed based on years of experience and tend to provide a broader brush inspection plan and a minimum standard. These approaches are based on the experience obtained from inspections performed on unrestricted trading vessels. The condition or performance-based methods (Phases 2 and 3) represent the next logical step along the evolution from traditional methods. Degradation models and input from subsequent inspections are used to forecast the condition of the structure for fixed equipment. When the condition is predicted to reach a predefined threshold, inspections are conducted. This method relies heavily on the likelihood of structural degradation but does not explicitly include the associated consequences which is a key aspect of the next evolutionary step, the risk-based approach (Phase 4). The risk-based methods includes aspects of the condition-based methods using trending techniques to estimate likelihood, but it also factors in an estimation of the consequences of the structures degradation and potential failure, enabling the program resources to be optimized and focused towards inspecting those items which have a greater risk weight overall. Once those items are identified, optimum methods of inspection or maintenance are then are selected.

## 3 Rationale and Benefits of RBI

RBI for hull structures is becoming more widely used within the offshore oil and gas industry. Slowly, such concepts are also seeing application via marine operators who see a way to tailor their inspection programs for a specific ship type and also to have a mechanism to adapt the program as the vessels age. Operators feel there are significant benefits in developing RBI plans that are tailored to their asset in regards to both design and operation. By taking this approach, the inspections are more targeted and the operational constraints better managed, resulting in a more optimized inspection program while maintaining the same level of safety.

Figure 2 demonstrates the basic purpose of RBI – to allocate resources in accordance with risk. In other words, the goal of a risk based inspection study is to ensure that the resources (inspection manpower and costs) are distributed to where the there is the most probable benefit to risk reduction.

Fig. 2 RBI Concepts



Determine current inspection resources allocated to each risk

Then, reallocate resources so that the highest risk items receive the most attention

Both the traditional approach to hull integrity (largely Class based) and an enhanced risk-based approach lead to the ultimate goal of confirming the hull structure is fit-for-purpose. For the risk-based approach, a major contributor to the development of such a plan is the foundation of experience from the Class rules which begins with the historical experience of the class society. The main drivers which have sparked industry's interest in RBI for hull structures are the potential benefits of implementing such a plan. There are significant benefits in developing a plan that is tailored to a specific class or type of vessel rather than following a rule based approach. The following provides a list of some key benefits from a risk-based inspection plan.

- Asset Specific Plan – The plan is tailored for the particular design and operational variables such that resources are focused on the highest risk components. This can influence, where possible, inspection frequency and/or compartment inspection sequencing, work scope, degree of connection sampling, etc… The advantage of this is more focused inspections, which target the critical components within the structure. The plan can also incorporate overall business requirements, such as required asset utilization or compartment downtime limitations.

- Demonstrable Basis for the Inspection Plan – A RBI plan provides rational basis for the extent and methods of inspections based on combining structural analysis and structural reliability results. This allows additional flexibility for inspection planning and execution as well as a better understanding on what items are critical and when they become critical.

- Formal Approach of Collecting Information and Assessing Inspection Results – In order for a RBI plan to be executed and updated, data must be captured in a format that can be organized and assessed to verify the condition of the hull. Often with typical inspection data, the inspections are completed and compared to prescribed acceptable limits to determine if mitigation is required. Generally, this is the extent of the data's usefulness. For RBI, the data collected from the inspections is used to validate and update the degradation models and determine if adjustments in future inspections are warranted (as a result, some form of electronic integrity data management tool is typically required to store and trend data).

- Potentially More Cost Effective – An RBI plan may provide justification to extend inspection frequencies where possible, which may reduce the number of inspection and associated costs. However, this may not always be the case. In some cases, inspection intervals for compartments may be reduced and inspection scopes more rigorous, offsetting any cost saving that may be obtained in other compartments. Regardless of the cost, an RBI plan provides means for risk reduction and a rational basis for the intervals and inspection scopes which are optimized based on the asset's service conditions.

### *3.1 RBI Methodology*

Structural reliability based methods can assist in providing a framework for quantifying loading and degradation mechanisms (such as fatigue and corrosion), through a systematic consideration of the probabilistic uncertainty in each degradation mechanism. Further, such methodologies allow for these mechanisms to be quantified in a time dependent manner. By applying structural reliability analysis and risk assessment techniques to inspection planning, the operator is given a tool by which he can justify the allocation of resources to those structural components with a higher risk profile, and at the same time potentially relax inspection activities for low risk components to optimize and target inspection efforts.

The overall approach to the development of the RBI plan involves the use of structural reliability methods which are then applied to determine the inspection intervals based on environmental loading as applied to strength considerations of the hull girder, stiffened and un-stiffened plate panel strength, and finally to welded connection fatigue life. By tracing the time-varying reliability index for these structural components, the risk-based inspection intervals can be determined. This methodology has been applied to several floating production units operating throughout the world under ABS Class.

Figure 3 (end of paper) shows the typical flow chart for this hull structure RBI methodology. The various boxes represent specific information or analysis necessary to develop the inspection plan. The plan development not only includes structural analysis results but also historical data, tank service condition data, condition summary, qualitative risk assessment, leak potentials, and information on all other external structures that may affect the hull inspection.

The process starts with an initial structural analysis of the hull, consisting of both strength and fatigue assessments. The analyses provide global stress and fatigue results in the "as-gauged" condition as well as local models of various critical areas to further refine the assessment. The results of these assessments allow the identification of specific critical areas of the structure that are more prone to high stress or fatigue damage, so that they can then be targeted in the inspection program. Additionally, the analysis facilitates the development of reliability models used to predict future response and select inspection intervals.

The "degradation models" are comprised of calibrated limit state equations for various failure modes and used within the reliability analysis draw upon the vessel's past history, structural analyses and the results of a qualitative risk analysis. The results from degradation model predictions, structural/fatigue analysis results and other factors are assessed and compared using probabilistic techniques to pre-defined reliability targets set by the risk assessment. The degradation models enable forecasting via time varying reliability methods to determine acceptable inspection intervals as well as most appropriate inspection methods for those selected intervals.

The reliability targets are driven by risk and the potential consequences identified as part of the qualitative risk assessment (Fig. 4, end of paper). The results from the degradation modeling and reliability analysis are inspection intervals for a component or system that will allow that component or system to maintain an acceptable level of reliability. These models and analyses are updateable so that the most recent condition information is used when determining the reliability level for both strength and fatigue.

The qualitative risk assessment identifies the potential consequences related to hull structural damage. Generally the assessment will incorporate a structured workshop similar to a hazard identification (HAZID) study where risks associated with the system are systematically identified and assessed. Other methods can also be used but study simplifications ultimately result in limitations in the plan (i.e., not all of the key aspects are covered in detail). The risk assessment is used to highlight and account for other factors that may impact hull integrity not necessarily covered by the strength and fatigue analyses or the reliability analysis (such as leak potential from pitting damage, coating breakdown, etc.).

The results from this assessment are used to adjust the individual component target reliabilities up or down on a risk basis which in turn influences the required inspection intervals. In addition, POD curves as well as cost-benefit analysis play a role in determining the optimum inspection method and degree of inspection (number of like details to be inspected).

Lastly, input from the operations personnel and risk results generated during the exercise provides a forum to identify key or critical inspection locations as well as help understand potential consequences (i.e., impact to operations) related to the structural integrity of the hull (see Figures 5 and 6, end of paper).

The final stage of the process is the development of a forward-looking risk based structural inspection plan for the asset. The key to this part of the RBI is the development of a general rule set for combining the results of the qualitative risk ranking, structural analysis results as well as the degradation and reliability model results. A systematic approach is utilized which uses the strength and fatigue reliability as the primary basis (i.e., starting point) for setting the intervals and then draws upon other data such as sampling inspections, critical inspection points, outstanding issues as well as general Class requirements to adjust the inspection frequency intervals. When considering ships, these adjustments will be done within the typical 5-year Class cycle.

### *3.2 RBI Study Results*

A brief summary of the conclusions drawn from the study include a determination of an optimized inspection schedule for the hull structure as well as the definition of various areas requiring increased scrutiny, hereafter defined as "critical areas". These critical areas are made up of a series of key locations that have been deemed to require monitoring above and beyond the typical Class requirements of visual examination and UT gauging. They are made up of strength (yielding and buckling), damage, and fatigue sensitive areas within the hull.

As an example within this paper, the focus will be on the fatigue sensitive locations. For the fatigue sensitive locations (4 areas determined from the RBI study), the plan covers enhanced connection sampling requirements for these locations. Example connections include the following which will be targeted for critical area monitoring and enhanced inspection:

- Upper transverse frame cross-ties on the 2$^{nd}$ frame aft of the OTB in the cargo block tanks
- Horizontal Girder (HG) Bracket at HG No. 3 (forward HG brackets at 2$^{nd}$ frame aft of OTB in cargo block tanks
- Horizontal Girder Backup Bracket at HG No. 2 Side Shell longitudinals above the upper HG)

Typical examples of critical areas found in the study are summarized in Table 1 (end of paper).

## 4. Reliability Centered Maintenance

When considering machinery and rotating equipment, Reliability Centered Maintenance is technique applied as a parallel to RBI defined above.

By applying Reliability-centered maintenance (RCM) principles, maintenance is evaluated and applied in a rational manner that provides the most value to a vessel's owner/operator. Accordingly, improved equipment and system reliability on board vessels and other marine structures can be expected by applying this philosophy. In recent years RCM based maintenance has been increasingly applied by vessel owner/operators, particularly in the offshore oil and gas industry. Successful users have experienced improved system reliability with consequent increased revenues.

RCM is also a part of overall risk management so that the risk of undesirable end events associated with equipment failures can be effectively managed by the maintenance program. This failure management is achieved by allocating maintenance resources to equipment maintenance according to risk impact on the vessel. For example, RCM analysis can be employed to:

- Identify functional failures with the highest risk, which will then be focused on for further analyses;
- Identify equipment items and their failure modes that will cause high-risk functional failures; and
- Determine a maintenance strategy that will reduce risk to acceptable levels.

A brief overview of the RCM process as applied in the *Guide for Survey Based on Reliability-centered Maintenance* (*RCM Guide*) by the American Bureau of Shipping (ABS) is provided (ABS 2003). The *RCM Guide* lists the requirements for the ABS RCM Program, a voluntary Program that enables vessel operators to receive credit towards certain machinery survey requirements in order to maintain a vessel's classification. A companion document to the *RCM Guide, Guidance Notes on Reliability-centered Maintenance* was published to provide additional information related to maintenance and risk analysis (ABS 2004).

### *4.1 Overview of RCM Principles*

RCM is a process of systematically analyzing an engineered system to understand:

- system functions and impact of functional failures
- equipment failure modes and causes that can result in functional failures
- optimal strategy for managing potential failures, including maintenance to prevent the failures from occurring or to detect potential failures before a failure occurs, and
- spares holding requirements.

ABS requires the following analytical tools to be employed when performing the RCM analyses:

- Failure modes, effects, and criticality analysis (FMECA),
- RCM task selection flow diagram,
- Risk-based decision making tools (e.g., risk matrix).

In addition, the following system expertise is needed to successfully and efficiently perform the analysis:

- Design, engineering, and operational knowledge of the system,
- Condition-monitoring techniques, planned maintenance actions, failure finding techniques,
- Other proactive maintenance practices (e.g., lubrication).

**Equipment failure basics**

Since 1978, ABS has cooperated with owners/operators on developing and implementing preventative maintenance programs. The *RCM Guide* provides owner/operators a process to create an effective preventative maintenance program applying risk principles and a maintenance task methodology.

The RCM analysis process uses these tools and expertise to help establish the cause effect relationship between equipment failures and system performance (e.g., the FMECA) and then determine an effective failure management strategy (e.g., RCM task selection).

A combination of one or more equipment failures and/or human errors causes a loss of system function. Specifically, one of the focuses of reliability improvement is to manage the equipment failures that impact system performance (e.g., losses of system function). Therefore, an understanding of the factors that influence equipment failures is needed. The following factors usually influence equipment failure:

- Design error
- Faulty material
- Improper fabrication and construction
- Improper operation
- Inadequate maintenance
- Maintenance errors

Therefore, maintenance is merely one of the many approaches to improving equipment reliability and hence system reliability. RCM analyses focus in reducing failures resulting from inadequate maintenance. In addition during the RCM analysis process, some equipment failures may be identified as the result of maintenance errors. In these cases the results of RCM analyses may suggest improvements for specific maintenance activities, such as improving the manner in which the maintenance procedures are carried out, improving worker performance through additional training or required skill level, or adding quality assurance/quality control tasks during the maintenance procedure to verify correct performance of critical maintenance tasks. Furthermore, RCM analyses may recommend design changes and/or operational improvements when equipment reliability cannot be ensured through maintenance.

### Equipment failure rate and patterns

One of the key concepts of RCM is that all equipment failures are not the same; therefore, the maintenance tasks necessary to prevent failures may require different strategies in order to successfully manage them. In fact, 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.

First, let's discuss the failure rate. The conditional probability failure rate or lambda ($\lambda$) 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.

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

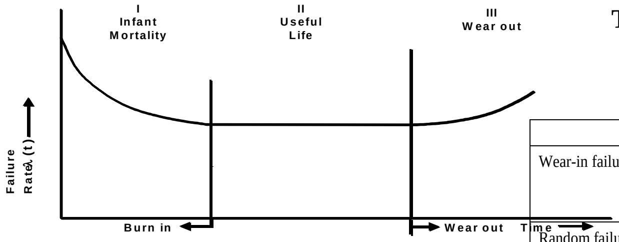
**Wear-in failure** – also known as "burn in" or "infant mortality" failures.

**Random failure** – dominated by chance failures caused by sudden stresses, extreme conditions, random human errors, etc. (e.g., failure is not predictable by time) during the "useful life" of the equipment.

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

These failure characteristics are best illustrated by the failure pattern identified in Figure 7. 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.

**Figure 7: Equipment Life Periods**



Understanding that equipment failure modes can exhibit different failure patterns have important implications when determining appropriate maintenance strategies. The literature has indicated there are six different failure patterns (Nowlan/Heap 1978, Moubray 1997, and Smith 1993). We have listed the failure characteristic(s) as follows:

- Pattern A – Bathtub Curve – Wear-In, Random Failure, Wear-Out
- Pattern B – Traditional Wear-Out – Random Failure, Wear Out
- Pattern C – Gradual Rise with no Distinctive Wear-out Zone - Random Failure
- Pattern D – Initial Increase with a Leveling Off – Random Failure
- Pattern E – Random – Random Failure
- Pattern F – Infant Mortality- Wear-In, Random Failure

A basic understanding of failure rate helps in determining whether maintenance or equipment redesign is necessary and provides insight into frequency of maintenance tasks. Once one begins to understand how equipment fails and its failure rate and pattern, an understanding of maintenance task types and their relationship to the failure characteristics is needed.

### *4.2 Overview of Maintenance Task Types*

One of the primary objectives of the RCM analysis is to define a set of proactive maintenance tasks needed to manage potential equipment failures that can impact critical system performance. These tasks can manage these potential failures by:

- Detecting onset of failure with sufficient time to allow corrective action before the failure occurs, e.g. *condition monitoring tasks,*
- Preventing the failures before they occur, which are referred to in the RCM Program as *planned maintenance tasks,*
- Discovering and correcting hidden failures before they impact system performance, e.g. *failure finding tasks*.
- Applying operational restrictions or some other action, e.g. *any applicable and effective task.*

In addition, the RCM analysis might indicate the failure does not warrant any proactive maintenance and run-to-failure is acceptable. Also, RCM analyses should include routine servicing tasks to ensure the assumed failure rate and failure pattern are valid. Table 2 summarizes the relationship between failure characteristic and suggested maintenance tasks.

**Table 2 Failure Characteristic and Suggested Failure Management Tasks**

| *Failure Characteristic* | *Suggested Failure Management Task* |
|---|---|
| Wear-in failure | Eliminate or reduce wear-in<br>Condition-monitoring task to detect onset of failure<br>One-time change or redesign |
| Random failure | Condition-monitoring task to detect onset of failure<br>Failure-finding task to detect hidden failure<br>One-time change or redesign |
| Wear-out failure | Condition-monitoring task to detect onset of failure<br>Planned-maintenance task<br>Failure-finding task to detect hidden failure |

### *4.3 RCM Analysis Process*

ABS reviewed the RCM analysis literature and concluded that what was available would need to be modified for marine applications. We also decided that the procedures would be in conformance with SAE JA 1011, Evaluation Criteria for Reliability-Centered Maintenance (RCM) Processes (Society of Automotive Engineers 1999). We believed evaluation of risk was necessary in order to rank the relative importance of the failures analyzed, so we incorporated risk in the failure modes and effects analysis adopting the approach in the IMO International Code for High Speed Craft (IMO 2001). We also felt it necessary to include a process to determine spare parts requirements using risk assessment. Any successful long-term maintenance program must include a feedback mechanism so we included requirements for a sustainment procedure. Accordingly, the basic steps of the RCM analysis process are:

1. Identify operating modes and corresponding operating context
2. Define vessel systems
3. Develop system block diagrams and identify functions
4. Identify functional failures
5. Conduct failure modes, effects, and criticality analysis (FMECA)
6. Select failure management tasks
7. Determine spare parts holdings
8. Develop RCM sustainment process
9. Document the analysis
10. Implement RCM Onboard

### Step Nos. 1 through 4 – System Modeling, Functions and Functional Failures

For this part of the analysis, how the vessel is to be operated (operating mode) and the manner in which the vessel's machinery systems are operated (operating context) are determined. The vessel's systems are modeled as a hierarchy for the purposes of performing the FMECA. For consistency, ABS has named these hierarchy levels, in descending order as follows: functional group, system, sub-system, equipment item, and component. A component is defined as:

- the lowest level that can be identified for its contribution to the overall functions of the functional group,
- being identifiable for its failure modes, and
- the most convenient physical unit that can be considered for the preventative maintenance plan.

The system block diagrams serve as an aid to visualize the hierarchical structure and identify the various system functions. Then, the various functional failures associated with each function are identified.

### Step No. 5 – Conduct FMECA

For Step No. 5, ABS requires the application of a bottom-up FMECA. An example format is shown in Table 3. We selected the bottom-up format instead of the top-down format because during development of the preventative maintenance plan for each system component, there is less of a chance a component will be omitted. The top-down format is useful when designing new systems to determine the risk associated with various functional failures. If one chooses to apply the top-down format for existing systems, it is necessary to identify all system functions otherwise it is likely a component may be omitted that contributes to that system function.

**Table 3: Example Bottom-up FMECA Worksheet**

| | | | | | | |
|---|---|---|---|---|---|---|
| **No.:** XX | **Description:** Pump | | | | | |
| **Item** | **Failure Mode** | **Causes** | **Failure Characteristic** | **Local Effects** | **Functional Failures** | **End Effects** |

| | | | | | |
|---|---|---|---|---|---|
| **No.:** XX | **Description:** Pump | | | | |
| **Item** | **Matrix** | **Severity** | **Current Likelihood** | **Current Risk** | **Failure Detection/ Corrective Measure** |

For some operating modes/contexts these failure modes may not be applicable and can be indicated so in the analysis. In some cases the failure modes listed may not have been considered by the analysis team. ABS has provided a list of suggested failure modes for ten groups of equipment and components in Appendix 2 of the *RCM Guide*.

ABS decided for consistency among analyses received to require the End Effect descriptions to be the effect on the functional group(s). A consolidated example format from the *RCM Guide* is shown in Table 4 (end of paper). The severity level is defined for at least four levels from no effect, two progressive functional degradations to complete loss of function. Four levels is the minimum to ensure meaningful risk ranking. An additional severity level or two may be considered but greater care is necessary in severity level definition. The traditional approach is to define severity levels based on an order of magnitude in economic terms (i.e. $10,000, $100,000, etc.). Some would consider the approach in the *RCM Guide* as determining the intermediate effect, not the end effect. However, as part of the certification process it is straightforward for determining failure effects on functional groups when a component failure occurs. Attempting to determine the ultimate end effects from a vessel's complete loss of propulsion, such as grounding and considering other end effects such as pollution caused by rupture of the fuel oil storage tanks, loss of revenue, etc., is much more subjective and therefore difficult to evaluate. Such end effects would be dependent on the operating mode of the vessel, geographic location, etc. If desired, the owner/operator can extend the analysis to assess business risks.

The other element of risk is the likelihood or frequency of the failure mode. Many efforts have been made and are currently underway to collect failure rate data for machinery. Obtaining quantitative failure data is problematic: published data is scant, reliability databases are available only to subscribing members of an industry, manner of data collection is unknown, failure modes are not identified, etc. ABS decided to take a qualitative approach by recommending frequency *ranges* as shown in Table 5. As the FMECA is developed, we believe the team members can estimate failure mode frequencies based on events occurring within their operating fleet or collective memory.

**Table 5: Probability of Failure (i.e., Frequency, Likelihood) Criteria Example Format**

| ***Likelihood Descriptor*** | ***Description*** |
|---|---|
| Improbable | Fewer than 0.001 events **or** < 1 event per 1000 vessels per year |
| Remote | 0.001 to 0.01 events **or** 1 event per 100 to 1000 vessels per year |
| Occasional | 0.01 to 0.1 events **or** 1 event per 10 to 100 vessels per year |
| Probable | 0.1 to 1 events **or** 1 event per 1 to 10 vessels per year |
| Frequent | 1 or more events **or** >1 event per vessel per year |

### Step No. 6 – Select Failure Management Tasks

There are several RCM task selection flow diagrams in the literature (Ministry of Defence (UK) 1999, Moubray 1997, Naval Air Systems Command (USA) 2001, Society of Automotive Engineers 1999). ABS considered all of them and adapted the appropriate features from them for application to the marine industry. The RCM Task Selection Flow Diagram is shown in Figure 8 (end of paper).

The ABS task selection process is similar to other selection processes with respect to requiring one-time changes for failure modes with the highest risk, and a run-to-failure strategy for failure modes with the lowest risk. For failure modes with risks between the extremes, maintenance task types in the following order are considered: condition monitoring, planned maintenance, combination condition monitoring and planned maintenance, any applicable and effective task, or one-time change. For hidden failure modes, failure finding tasks are specified.

Unlike other published task selection flow processes we have included additional procedures as shown in the continuation for Figure 8. These include a procedure to specify a maintenance task(s) to address all causes associated with the failure mode for evaluation. The risk is re-evaluated for the selected maintenance tasks and any one-time changes associated with a failure mode. If the risk level meets the acceptance criteria, the next failure mode is evaluated. If not, the maintenance tasks and one-time changes are re-evaluated to seek a reduction in the risk to acceptable criteria. These criteria would include: a reduction in or at least the same level of risk compared to no maintenance or present maintenance tasks; the failure mode does not result in the highest risk occurring.

### *Step No. 7 – Spare Parts Holdings*

An additional feature of the ABS RCM Program is a requirement for the selection of spare parts applying risk principles. We adapted the approach from Figure 14.1 of NES 45 (Ministry of Defence (UK) 1999). As with the FMECA, the operating context of the equipment is an important factor in determining spare parts holdings.

### Step No. 8 – Sustainment Process

Any successful maintenance program needs to be dynamic to address modifications to systems and their respective equipment and effects of aging for the life of the machinery. A process for providing feedback is necessary and is referred to as RCM sustainment.

The objective of the sustainment process is to:

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

ABS has listed several sustainment tools in the *RCM Guide* as an aid to the vessel owner/operator when conducting the sustainment process. These are:

- Trend analysis
- Maintenance requirements document reviews
- Task packaging reviews
- Age exploration tasks
- Failures
- Relative ranking analysis
- Other activities

## 5. Conclusions

Responsible fleet managers are turning more frequently to risk and reliability informed machinery maintenance and structural inspection approaches based upon maintenance history, system analysis and risk analysis.

***For hull structures***, a system for the rational development of a structural maintenance program based on risk principles utilizing graphical display tools and relational databases has the following advantages:

- Asset specific inspection plans, customized to target the most critical areas of the hull structure
- Application of inspection resources based on historical information and consequence of failure
- Ability to change the inspection plan as the vessel ages, with quantitative justification
- Potential cost savings
- Permanent record of complete structural history

- Potential for trending of structural failures against a fleet of vessels

***For machinery and rotating equipment***, we have described some of the processes used in the *RCM Guide* such as risk assessment techniques, failure management task selection and sustainment. We have also described some of the approaches we have taken to address issues such as consistency among analyses received from different owner/operators, lack of quantitative data and identifying consequences objectively. RCM is a relatively new maintenance approach in the marine industry and time will be needed before the industry becomes familiar with the processes. The *RCM Guide* provides a thorough and sound basis while maintaining a practical approach to current marine maintenance practices.

We believe over time as the marine industry becomes familiar with the application of RCM techniques, vessel owners/operators will see the same benefits of other industries that have embraced RCM. Some of the benefits that vessel owners/operators can expect are:

- An integrated program to address safety and environmental concerns;
- Increased integrity and reliability of critical machinery and components;
- More cost-effective maintenance; and
- Improved understanding of equipment failures and their impact on vessel performance.

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Figure 1: Evolution of Inspection and Maintenance Strategies

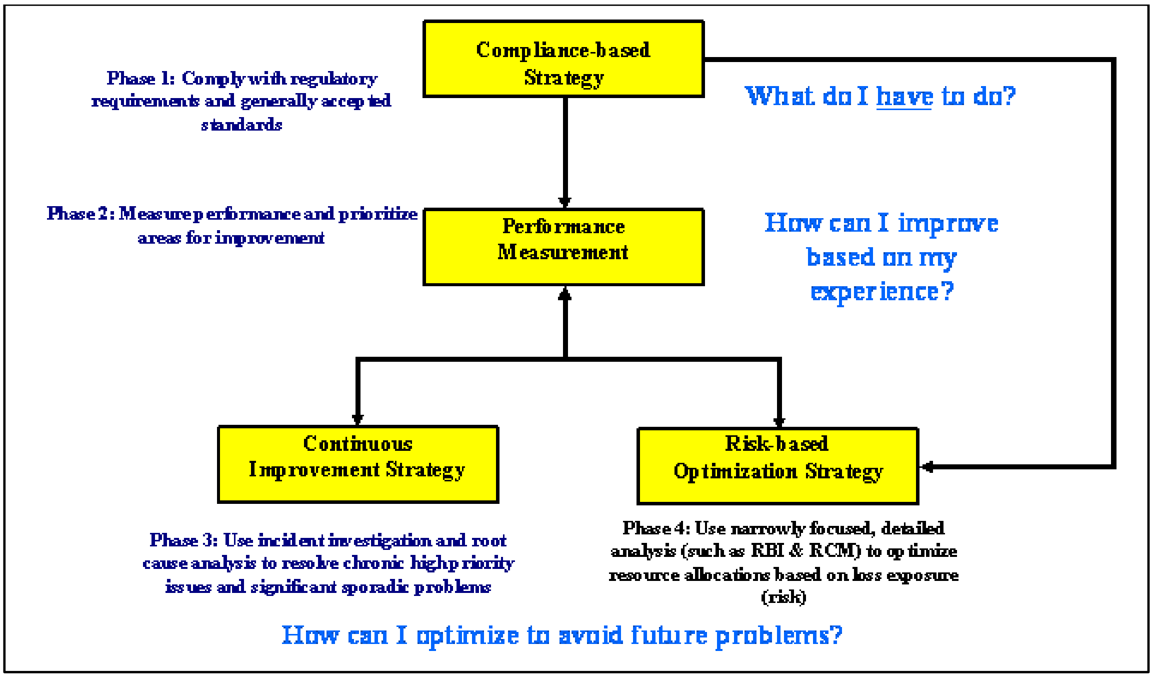
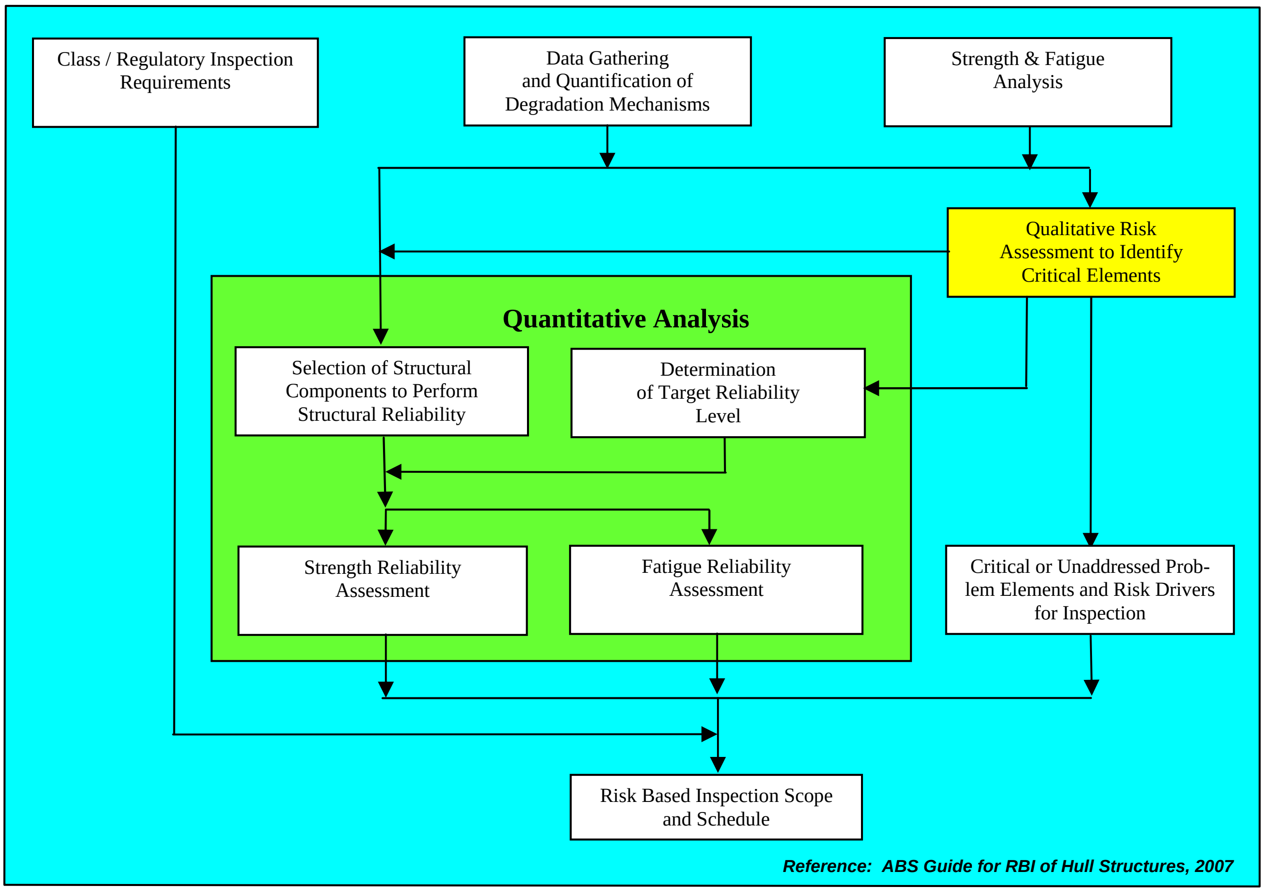


Fig. 3 Hull RBI Plan Methodology



*Reference: ABS Guide for RBI of Hull Structures, 2007*

Fig. 4 Qualitative Risk Assessment

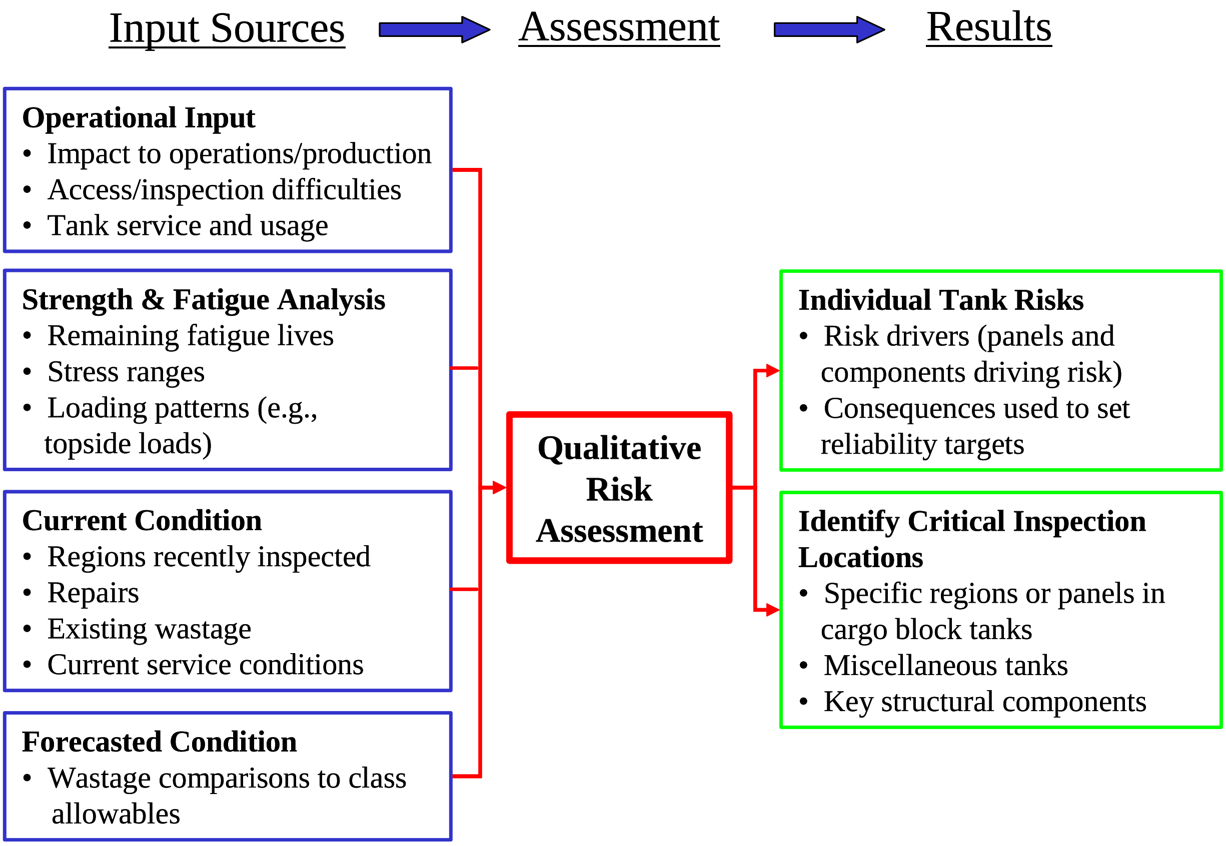


Fig. 5 Use of Reliability Targets to Set Inspection Interval

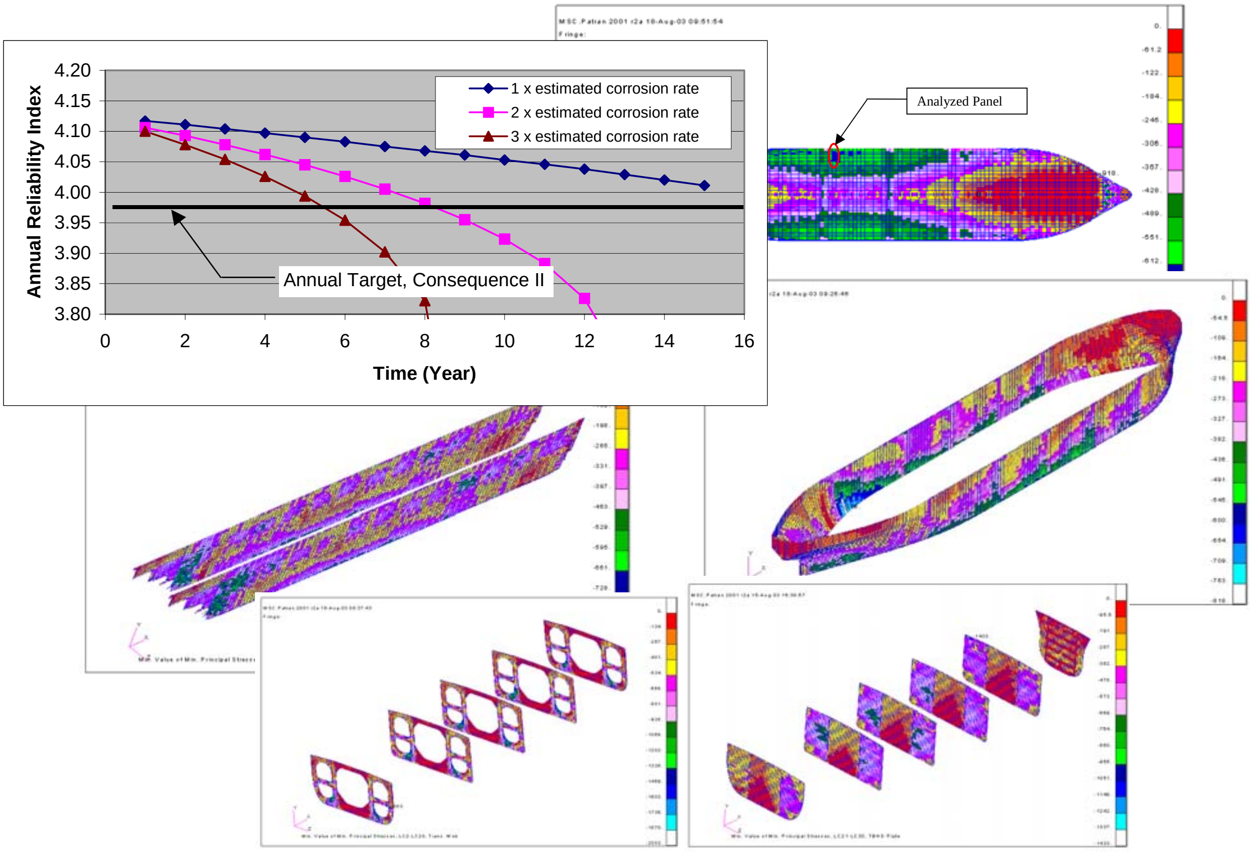


Fig. 6 Use of Reliability Targets to Determine Optimum Inspection Method w/Varying POD

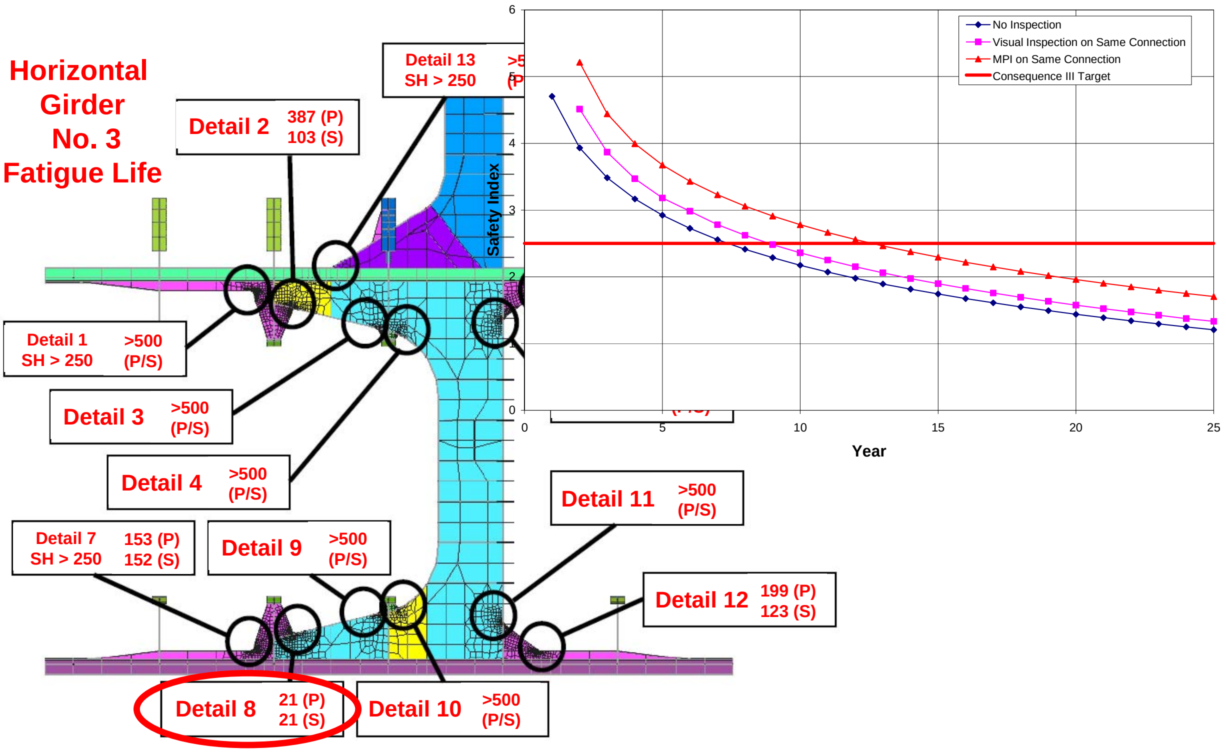


Table 1 Example RBI Critical Areas with Actions

| Applicable Location | Description | Impact | Actions & Responsibilities |
|---|---|---|---|
| Wing Tanks | Cracks detected in cross ties of 2$^{nd}$ frame aft of OTB | fatigue reliability | The typical inspection sampling is 4 similar connections (i.e., inspections of connections in same tank and/or other tanks under similar loading conditions. Up-sampling required if a crack is found as part of the inspection of 4 connections in order to obtain an acceptable reliability level.. |
| Wing Tanks | Cracks detected in side longitudinal connections | fatigue reliability | Check at key locations near SL46. Up-sampling required if a crack is found as part of the inspection of these connections in order to obtain an acceptable reliability level. |
| 2S, 4P, 4S and Fore Peak | Severe localized wastage in way of critical connections (i.e., crane pedestal, stair tower, turret arms and strut) and deck to hull connections | safety | If severe wastage is observed, technical support must be informed of condition and provided thickness measurements and diagrams showing effected region. This type of deterioration will be addressed on a case-by-case basis to determine the type of mitigation required. |
| Wing Tanks | Localized buckling LBH local plate paneling (i.e., around regions which have been reinforced) | strength reliability | This has been deemed a strength critical area per the reliability calculations. Close visual inspection for signs of buckling is required during scheduled wing tank inspections. |

## Table 4: Example Consequence/Severity Level Definition Format

| **Severity Level** | **Example Descriptors for Severity Level** | **Directional Control, Propulsion, etc.** | **Explosion/Fire** | **Loss of Containment** | **Safety [(1)]** |
|---|---|---|---|---|---|
| 1 | Minor,<br>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 |
| 2 | Major,<br>Marginal,<br>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 |
| 3 | Critical,<br>Hazardous,<br>Major,<br>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 |
| 4 | Catastrophic,<br>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: Safety losses are not intended to be compared to other losses to determine monetary equivalency.*

**Figure 8:  RCM Task Selection Flow Diagram**

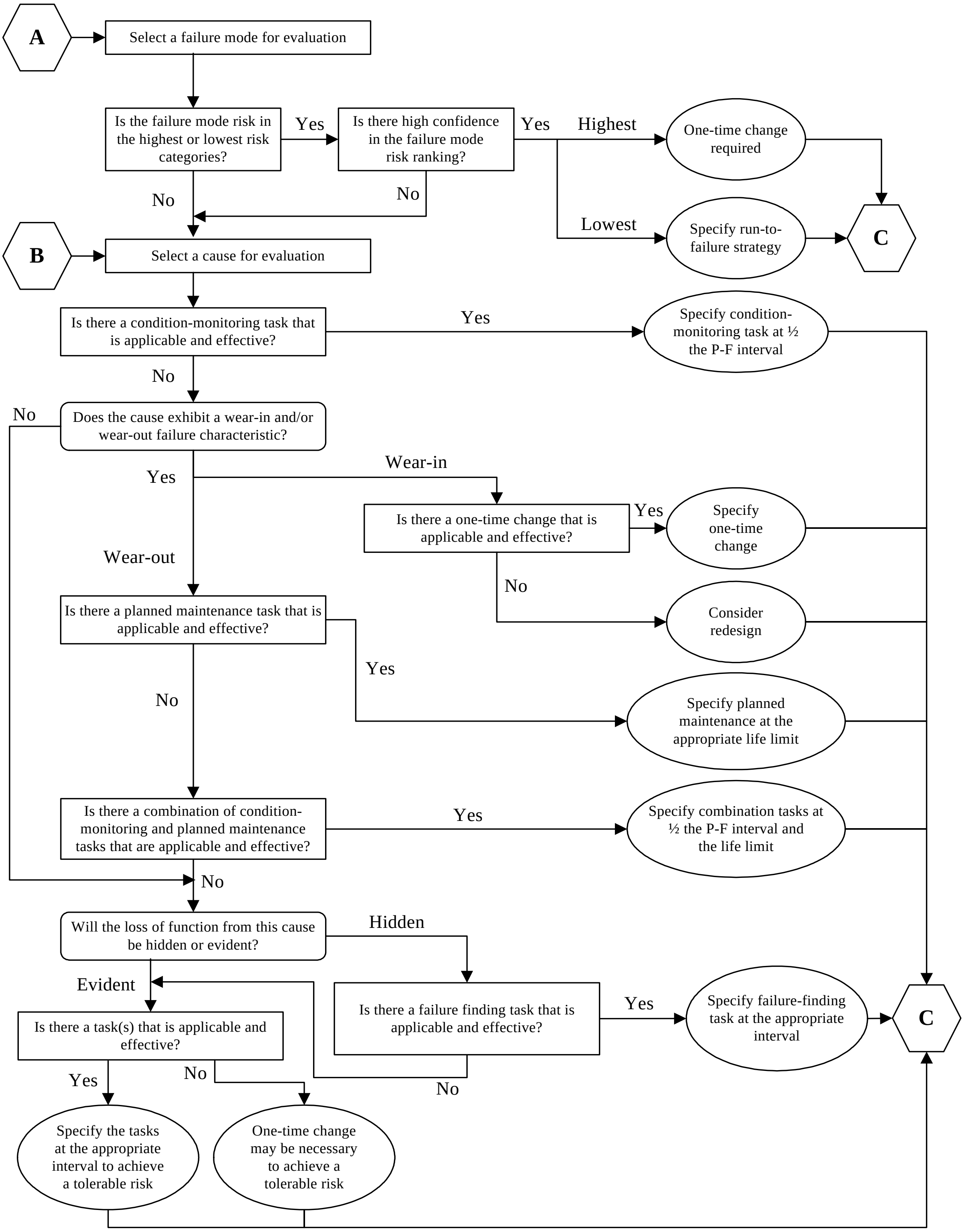


**Figure 8 (continued): RCM Task Selection Flow Diagram**