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Reliability Centered Maintenance - Methodologies

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United Space Alliance, LLC (USA) is the Space Processing Operations Contractor (SPOC) for NASA at Kennedy Space Center (KSC), Marshall Space Flight Center (MSFC), and Johnson Space Center (JSC) and in that role uses Reliability-Centered Maintenance (RCM) to optimize maintenance practices for the upkeep of tens of thousands of pieces of critical ground support, launch, and flight control equipment. USA has an institutionalized RCM process with a company policy, functional organization procedures, periodic review of performance, and metrics to track the performance. In addition, regular management reviews of RCM programs are promulgated to provide corrective and proactive direction that will ensure appropriate implementation of the RCM program.

1. INTRODUCTION

Reliability Centered Maintenance, RCM, is a process that identifies the optimum mix of applicable and effective maintenance tasks needed to maintain the inherent design reliability of systems and equipment at minimum cost. RCM provides logic for determining objective evidence needed to select the appropriate type of maintenance (*e.g.* predictive, preventive, or corrective). The process also is used to extend task periodicity, select alternative maintenance tactics (*e.g.* redesign, *etc.*), or eliminate unnecessary scheduled maintenance requirements based on operating experience. RCM is a proven process that increases system availability by achieving its inherent reliability and safety while reducing maintenance cost. Major benefits have been achieved by focusing on maintenance that preserves function, eliminates duplicate tasks, and decreases incidental damage through the broader use of non-intrusive inspection and predictive monitoring techniques. Other benefits include improved operating performance, increased safety, environmental protection, and a longer productive life for expensive items.

The USA Reliability Centered Maintenance program differs from traditional RCM programs because various methodologies are utilized to take advantage of their respective strengths for each application. Based on operational experience, USA has customized the traditional RCM methodology into a streamlined lean logic path and has implemented the use of statistical tools to drive the process. There are two RCM methodologies in practice – Classical and Streamlined - and both incorporate statistical tools. Regardless of the method, the USA RCM process takes you through a series of questions about a particular failure mode, which leads to one of five possible outcomes for dealing with a failure mode – predictive, preventive, failure-finding, redesign, and "run-to-failure". All USA RCM methodologies meet the requirements defined in SAE JA1011, Evaluation Criteria for Reliability-Centered Maintenance (RCM) Processes.

A sound analysis is produced by a team effort using the knowledge and expertise of the design and systems engineer, technician, and RCM mentor/analyst. The people who design, operate, and maintain the systems and equipment all participate in the RCM analyses. The USA Reliability Centered Maintenance Team serves as a central point of contact for RCM expertise, tools, analysts, and educational materials. It is the resource providing training, facilitation, analysis, and mentoring in RCM for any organization. The team also provides evaluations and recommendations for RCM products and tools, and networks with outside industries in this field.

2. RCM BASICS

RCM examines the different ways a system can fail and the appropriate maintenance tactics to manage that type of failure. Using RCM decision logic, the analyst can determine the best maintenance strategy for a particular failure mode. The RCM analysis process gives judicious

consideration to determining (a) the exact system or equipment function, (b) the functional failures that are likely to occur, (c) the likely consequences of these functional failures, and (d) the actions that can be taken to prevent these functional failures. Based on these considerations, the particular types of maintenance strategies, rather than being applied independently, are integrated to obtain maximum benefit of their respective strengths. Consequently, hardware and equipment operability and efficiency are maximized within given constraints.

There are a number of fundamental principles that characterize RCM. First and foremost, RCM is function-oriented. It seeks to preserve system or equipment function rather than merely maintaining operability for its own sake. Also, RCM prioritizes system functions by being more concerned with maintaining system functions than individual component functions.

RCM is reliability-centered. It is more concerned with conditional probability of failure at specific age brackets than with simple failure rate. Additionally, RCM recognizes that design – not maintenance – controls inherent reliability, and that the inherent design reliability is rarely achieved in use. Maintenance feedback can attain the original design reliability and hence improve operational reliability.

RCM is driven first by safety, which must be assured at any cost, and thereafter by economics, whereby cost-effectiveness becomes the guiding principle.

Last, but not least, RCM is a Living Process. It gathers data from the results achieved and feeds provides lessons learned feedback to improve design and future maintenance. This feedback loop is an important part of the Proactive Maintenance element of the RCM program.

The prominent benefits of an RCM program are the following:

- **Reliability** – RCM places significant emphasis on achieving equipment inherent reliability, mainly through the feedback of maintenance experience and equipment condition data.
- **Cost** – Although there are initial investments in technological tools, training, and baselining of equipment condition, the increases in maintenance costs are temporary. Over time, reactive maintenance costs as well as total maintenance costs decrease as failures are prevented and preventive maintenance tasks are replaced by condition monitoring.
- **Scheduling** – A condition-monitoring program forecasts maintenance and provides time for planning, procuring replacement parts, and arranging environmental and operational conditions prior to maintenance. RCM, through the implementation of Predictive Test & Inspection (PT&I) practices, reduces the unnecessary maintenance performed by a solely time scheduled maintenance program.
- **Efficiency/Productivity** – RCM's multi-faceted approach promotes the most efficient use of resources. The equipment is maintained as required based on its functional characteristics and the consequences of its failure.

The traditional approach to RCM acknowledges three types of maintenance tasks plus run-to-failure. The maintenance tasks are time-directed (Preventive Maintenance), condition-directed (Predictive Testing and Inspection), and failure-finding (one of several aspects of Proactive Maintenance). Time-directed tasks are scheduled as appropriate. Condition-directed tasks are performed when conditions indicate they are needed. Failure-finding tasks detect hidden functions that have failed without giving evidence of a pending failure. Additionally, Run-to-failure, often called Reactive Maintenance, is applied to small non-critical items, as a conscious decision. The RCM methodology identifies the optimum mix of applicable and effective maintenance tasks needed to maintain the inherent design reliability of systems and equipment at minimum cost. Further, RCM provides the basis for providing objective evidence in the selection of the appropriate maintenance strategy for a particular equipment or system.

The four acknowledged maintenance strategies are defined as follows:

- **Condition-Based Maintenance** – Maintenance tasks that are performed to detect impending failures by using non-intrusive testing techniques, visual inspection, and performance data to assess equipment condition.
- **Preventive Maintenance** – Maintenance tasks that are performed to minimize the probability and severity of lost or degraded functions. These tasks are performed on a recurring basis related to calendar time, equipment age, or operating time without regard to equipment condition.
- **Failure-Finding** – Maintenance tasks that determine if a piece of equipment has failed when it would not be evident to the operator during normal operations. Failure-finding tasks are performed on a time and/or cycle basis to determine if a hidden functional failure has already occurred so the equipment can be repaired and is available to perform its function.
- **Corrective Maintenance (Run-to-Failure)** – Maintenance tasks that are performed after a failure has occurred to restore an item to a specific level of performance.

A true RCM process answers the following seven questions in the sequence shown:

1. What are the functions and associated desired standards of performance of the asset in its present operating context (functions)?
2. In what ways can it fail to fulfill its functions (functional failures)?
3. What causes each functional failure (failure modes)?
4. What happens when each failure occurs (failure effects)?
5. In what way does each failure matter (failure consequences)?
6. What should be done to predict or prevent each failure (proactive tasks and task intervals)?
7. What should be done if a suitable proactive task cannot be found (default actions)?

Furthermore, a true RCM method must be based on a detailed Failure Modes and Effects Analysis (FMEA) and is used to determine appropriate maintenance tasks which identify each of the failure modes. The FMEA includes a detailed description of the asset function, the functional failures possible for that asset, the modes which likely cause each functional failure, and the consequence of each failure mode. Finally, an RCM method must have a decision logic which determines which of the maintenance tasks are both applicable and effective for an analyzed asset.

The USA RCM process encompasses this classical philosophy and these general principles and has been customized in accordance with SAE J1011 to optimally meet the needs of the maintenance program for aerospace and ground support system operations.

3. CLASSICAL RCM

The Classical RCM approach is applied to new or complicated systems or equipment. The FMEA is reviewed to determine if latent failure modes are present. If the equipment does not have an associated FMEA, the RCM team will generate one. A component level FMEA is created and failure mode mitigation tasks are identified. The FMEA prioritizes the tasks based on the consequences of failure identified by the Risk Priority Number and these tasks are then documented. Any existing maintenance documents are then compared to the results of the classical RCM and modified as required.

USA utilizes a commercial off the shelf software program called "RCM WorkSaver™" by JMS Software for performance of classical RCM and to capture the results of the analyses.

4. STREAMLINED RCM

Early in the RCM implementation phase, USA faced a unique RCM challenge: to analyze thousands of pieces of equipment with widely varying attributes. USA planned to analyze the maintenance procedures associated with over 30,000 items. The equipment varied greatly in cost, complexity, criticality, and age. This mix of challenges required an RCM analysis technique with seemingly dichotomous capabilities: to be fast and effective for simple and non-critical equipment, yet thorough and rigorous for complex, expensive, and critical equipment. A less intensive, more consistent approach than was offered by the Classical RCM methodology was determined to be essential for broad implementation of an RCM program.

The USA RCM Team developed a modified RCM approach: the Streamlined Process. The process includes a logic tree similar in intent to the traditional RCM decision logic, but with key differences to address the challenges previously mentioned, and it offers the efficiency and consistency to produce high quality analysis results.

As with Classical RCM, the input to the Streamlined Process is a failure mode and the output is a recommended maintenance tactic. A failure mode is a specific way in which a component might fail, including the material condition that led to the failure (*e.g.* a gear tooth might break due to excessive wear).

A difference from Classical RCM is the use of a "procedure-based approach" to identifying failure modes. With this approach, analysts examine maintenance procedures to determine what failure mode is being prevented. The analysts can do this with confidence when equipment has an established operational history and an existing FMEA which has been incorporated into the maintenance document. Any dominant failure modes not covered by existing maintenance can be deduced from the equipment's failure history or from the maintenance personnel's knowledge.

The Streamlined Process "Logic Tree" consists of two parts: a filter section and a tactic section. The filter is designed to quickly eliminate from consideration failure modes that do not benefit from maintenance. For failure modes not eliminated by the filter, the tactic section determines the optimal maintenance approach. This model forms an efficient yet effective process. Many failure modes can be eliminated from unnecessary tactical analysis while others receive the attention they deserve.

The filter section consists of considerations relating to risk, economics, and age degradation. If a failure mode presents an insignificant and negligible risk and economic consequence, then maintenance designed to prevent the failure is not worth the effort. If the failure mode exhibits no age degradation (*i.e.* the failure is random), then maintenance tactics based on age or usage are useless and they are eliminated from consideration. All the elements of the filter section increase the efficiency of the process by eliminating unnecessary tactical analyses. With some training, anyone with a technical background and knowledge of the equipment can assess the economic and age considerations consistently. The risk consideration, is, was prone to interpretation and error.

An early question in the Classical RCM decision logic is, "Could the failure have a direct, adverse effect on safety?" The answer is never simply "yes" or "no." Also, each RCM analysts might answer this question differently for the same situation since Classical RCM offers no standard by which to quantify the risk. The intent of the question is to avoid unnecessary analyses in situations where no safety risk exists. Additionally, risk is not limited to safety. Also important are risks to the schedule, supportability, and cost.

USA operates within a total risk management system, which encompasses both the traditional risk management efforts of the aerospace industry and innovative quantitative approaches for measuring and analyzing risk. A Risk Scorecard is utilized to quantify the magnitude of failure risk based on the likelihood and consequences relative to safety, mission success, supportability, schedule, and cost of recovery.

The more comprehensive and quantifiable the result of the risk consideration, the more optimal and efficient will be both the analysis and the results. USA RCM recognized the Risk Scorecard could address the remaining problem associated with the Classical RCM methodology. The tool brought clarity to the safety risk question, primarily through its clear definitions for severity and probability.

For this reason, USA inserted the Risk Scorecard (Figure 1) into the Streamlined Process. With this tool, the team can assess the severity and probability of the risk and therefore the magnitude. If the magnitude of the risk falls into either the red or the yellow zones, then the team is compelled to enter the tactical section of the analysis. Only if the risk is clearly in the green zone would the overall answer to the safety risk question be "no." The analyst can quickly answer the question "yes" or "no" and move on with the rest of the tactical section of the analysis thereby increasing efficiency.

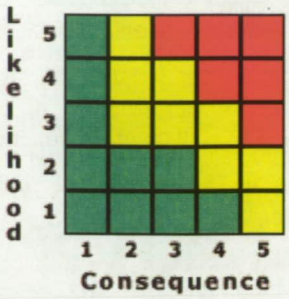

Figure 1 - Risk Scorecard

The purpose of the tactical section of the Streamlined Process is to select the optimal maintenance tactic for a given failure mode. If the risk falls into either the red or yellow zone, then the goal of the maintenance strategy would be to reduce the risk to green. The purpose of predictive, preventive, and failure-finding maintenance strategies is to reduce the likelihood of a risk and thus its overall magnitude. These tactics cannot affect the severity of a failure mode. Only its probability of occurrence is affected. For example, a solenoid valve might stick due to the accumulation of contamination, causing a failure. Without preventive maintenance, this failure will have a higher likelihood of occurrence. Preventive maintenance, such as periodic cleaning and lubrication, will reduce this probability of failure, thus reducing the overall risk of failure. However, the consequence of failure will remain the same. Only redesign of the equipment can reduce the severity of a failure mode. In the case of a failure mode with a medium or high risk, the selected maintenance tactic(s) will hopefully reduce the risk to an acceptable level and eliminate the need for redesign.

The USA RCM team uses the "USA Streamlined RCM Database" which consists of an SQL database with a Cold Fusion web interface to capture the analysis results.

5. LEAN SIX SIGMA TOOLS

United Space Alliance is a proponent of the Lean Six Sigma (L6S) approach to process improvement. The tools utilized in the Measure, Analyze, and Improve phases of a Lean Six Sigma project lend themselves to application in the RCM process. USA RCM has integrated many of the L6S tools into both RCM methodologies. This tool capitalizes on the existence of data and uses statistical processes to optimize maintenance protocols for maximum operation with minimum downtime.

Often solutions to maintenance problems may not be evident or readily understood. By beginning an RCM project with a process map, the steps of a process, their inputs and outputs, and decision points are identified and provide insight into process disconnects and the value of

each step. L6S tools make RCM a "data-driven approach" to identifying failure modes and selecting maintenance tasks and can be used as a supplement to both the Classical and Streamlined RCM methodologies. The process map helps guide the analyst in determining what data are needed. With this approach, analysts examine operational history to determine predominant contributors to unplanned maintenance or operational time lost for non-value-added maintenance. Collected data are statistically analyzed to determine the biggest contributors, degrees of variation, and maintenance process capability. The analyst uses the data to answer a series of questions about a particular failure mode which, via the scorecard, leads to a tactic for dealing with a failure mode.

The statistical tools used can vary depending on the nature of data available and the scope of the equipment maintenance problem. An analysis may incorporate control charts to aid in the identification of variations and their sources. Stratified data charts and Pareto charts provide pattern recognition tools which enable the analyst to target root causes and/or major contributors. Regression Analysis may be used to determine the benefits of a tactic by producing a prediction equation. Correlation tables and analysis of variance (ANOVA) may be used to determine the best tactic by evaluating the relationship between the inputs and outputs. The Weibull distribution may also be used to characterize failure modes and forecast time-to-failure.

6. RCM AT USA

The goal of USA RCM is to preserve system functionality while optimizing maintenance requirements and resources. To achieve this goal, applicable RCM methodologies are used to select the type of maintenance to be performed, extend maintenance periodicity, select alternative tasks such as condition-based maintenance, and/or eliminate unnecessary scheduled maintenance.

The USA RCM Toolbox – which includes the USA Streamlined RCM methodology, Classical RCM methodology, and Lean Six Sigma Tools – has proven to be very beneficial to USA's outstanding performance in the SPOC. USA strives to capitalize on its superior work force, drawing on their collective system knowledge. Analysis teams are formed and lead by an RCM Mentor for facilitation of the RCM analysis. The USA RCM process places strong emphasis on high quality training and mentoring for system engineers, technicians, analysts, and technical support personnel. Mentoring of RCM Teams and the subsequent harnessing the work force operational knowledge base has proven to be the key to the successful application of these tools and the institutionalization of RCM.

Additionally, the Reliability-Centered Maintenance and Predictive Maintenance Engineering Lab (PMEL) groups are joined in the same organization to promote the interaction of their functionalities. The predictive technologies utilized by the PMEL are then integrated into current maintenance processes where applicable. These technologies consist of:

- Laser Shaft Alignment & Dynamic Balancing
- Motor Circuit Evaluation
- Oil Analysis:
  - Ferrography
  - Spectral Analysis
  - Elemental Analysis
  - Particle Count
  - Viscosity
- Thermography
- Ultrasonic Noise Detection
- Vibration Analysis

The RCM methodology coupled with a mentor and team approach maximizes the benefits derived from the USA RCM process. Each method is supported by software and a database to capture results including cost and savings, risk reduction, and schedule adherence. The RCM methodology becomes a Living Process with analysis results being implemented and tracked for verification of benefits and for continuous improvement.

USA has a robust foundation in the development of implementation plans, expertise maturation and consolidation, and wide-ranging training of personnel. USA also has a proven infrastructure for applying and continuously improving Reliability Centered Maintenance in all of its maintenance activities.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

Journal article about RCM methodologies used by United Space Alliance, LLC (USA) in support of the Space Shuttle Program at Kennedy Space Center. The USA Reliability Centered Maintenance program differs from traditional RCM programs because various methodologies are utilized to take advantage of their respective strengths for each application. Based on operational experience, USA has customized the traditional RCM methodology into a streamlined lean logic path and has implemented the use of statistical tools to drive the process. USA RCM has integrated many of the L6S tools into both RCM methodologies. The tools utilized in the Measure, Analyze, and Improve phases of a Lean Six Sigma project lend themselves to application in the RCM process. All USA RCM methodologies meet the requirements defined in SAE JA1011, Evaluation Criteria for Reliability-Centered Maintenance (RCM) Processes. The proposed article explores these methodologies.

15. SUBJECT TERMS

Reliability Centered Maintenance, RCM, Lean Six Sigma, JA1011

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