CBM, TPM, RCM and A-RCM - A Qualitative Comparison of Maintenance Management Strategies

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Abstract
Maintenance management strategies have been evolving over time and starting from the concept of Breakdown maintenance, varied strategies like Condition Based Maintenance, Total Productive Maintenance and Reliability Centered Maintenance are in practice. The authors had developed an alternate maintenance strategy – Accelerated Reliability Centered Maintenance specifically for use in process industries. Each of these strategies has distinct advantages as well as a few limitations. The authors develop a method of comparison of these strategies on the basis of established methods and drawing on the capability maturity method. This paper enumerates the salient features of CBM, TPM, RCM and A-RCM and presents a qualitative comparison of these strategies so as to provide implementers, primarily from the process industry, with a ready guide that will help in deciding on the adoption of one of these strategies.

Keywords
A-RCM, Capability-Maturity, CBM, Maintenance Strategy, RCM, TPM.

I. Introduction
Maintenance strategy had been evolving slowly over the past fifty years. The development of new maintenance strategies has been slow, mainly due to the relative lack of importance given to maintenance in the industries, with the greater focus being on production. However, in the past two decades, there has been a renewed focus on maintenance, mainly due to the pressures on operating margins and the need for continuously lowering down-times [1]. This focus has resulted in the adoption of different strategies like Condition Based Maintenance (CBM), Total Productive Maintenance (TPM) and Reliability Centered Maintenance (RCM)[2]. While these strategies are not new, RCM being first used as early as 1972 [3] and TPM evolving in the late 70s [4], the industrial absorption of these strategies has been slow and available surveys show TPM and RCM lagging behind other strategies [5]. In order to address the various issues that prevent the broad application of these strategies, the authors had developed a new strategy called Accelerated Reliability Centered Maintenance (A-RCM) that fuses approaches of these strategies and attempts to eliminate the limitations of these three strategies [6].

With four distinct strategies available for adoption, a detailed scan of the published literature suggests that, despite a large body of work existing in the respective areas, a comparative study of all these strategies do not exist, though some work exists in comparing TPM and RCM [7-11] and [12]. An attempt at comparison was also made using the Hales and Wheelwright four-stage framework for manufacturing effectiveness [13]. However, barring the paper by Paunovic, Popovic & Popovic [10] to a certain extent, no study provides implementers with a comparison with criteria that looks at these strategies from the point of view of implementation. This paper attempts to bridge that gap and presents a brief description of the four maintenance strategies namely CBM, TPM, RCM and A-RCM strategies and builds a qualitative comparison using a modified form of the Capability Maturity grid presented by Kunta & Shah [14], Fernandez et.al. [15] and Karner & Karni [16] and discusses these strategies with a view of adoption by process industries.

II. Condition Based Maintenance
This is the oldest of the four models being compared here. Condition based maintenance (CBM) is a management philosophy that posits repair or replacement decisions on the current or future condition of assets [17]. It recognizes that change in condition and/or performance of an asset is the main reason for executing maintenance [18]. Optimal time to perform maintenance is determined from actual monitoring of the asset, its subcomponent, or part. Condition assessment varies from simple visual inspections to elaborate automated inspections using variety of condition monitoring tools and techniques [18]. The objective of CBM is to minimize the total cost of inspection and repairs by collecting and interpreting intermittent or continuous data related to the operating condition of critical components of an asset [17].

Condition Based Maintenance has different forms, from the simple to the complex. However, the most common form adopted in most industries is as shown in Figure 1 where the focus is on data acquisition, prognosis and correction with varying degrees of automation. The starting point is to monitor a set of indicators representative of equipment condition over a period of time. When one or more of these indicators reach predetermined deterioration level, maintenance initiatives are undertaken to restore the equipment to desired condition. This means that equipment is taken out of service only when direct evidence exists that deterioration has taken place. Condition Based Maintenance is premised...
on the same principle as preventive maintenance although it employs a different criterion for determining the need for specific maintenance activities. The additional benefit comes from the need to perform maintenance only when the need is imminent, not after the passage of a specified period of time [19].

III. Total Productive Maintenance

Total Productive Maintenance or TPM is a method in which the focus is on elimination of main factors of production loss. The elimination process starts from the plant reset, then the autonomous maintenance and the programming and planning of preventive maintenance. TPM is used to modify the preventive maintenance on the basis of the results obtained in the field rather than from the machine manufacturer [20]. Maintenance is subdivided into three parts – Independent Maintenance carried out by the operator, second level by the maintenance staff and third level by the manufacturer. The aim of TPM is to make the worker feel responsible for the first level works he is carrying out.

TPM is about communication. It mandates that operators, maintenance people and engineers collectively collaborate and understand each other’s language. TPM describes a synergistic relationship among all organizational functions, but particularly between production and maintenance, for the continuous improvement of product quality, operational efficiency, productivity and safety [2].

Nakajima [22] observed that TPM “establishes a maintenance plan for the entire life of equipment, by including maintenance prevention, preventive maintenance and maintainability improvement. All encompassing is the notion of autonomous maintenance by operators. TPM seeks to eliminate the ‘six big losses’: equipment failure, set-up and adjustment, idling and minor stoppages, reduced speed, process defects and reduced yield. Minor stoppages are reduced by lubrication, cleaning, performing adjustments and conducting inspections which are done by operators with maintenance staff performing periodic inspections and preventive repairs”.

The TPM methodology is described with the 12 step process described below [20]:

**Step 1:** Announcement of TPM - Top management needs to create an environment that will support the introduction of TPM. Without the support of management, scepticism and resistance will kill the initiative.

**Step 2:** Launch a formal education program. This program will inform and educate everyone in the organization about TPM activities, benefits, and the importance of contribution from everyone.

**Step 3:** Create an organizational support structure. This group will promote and sustain TPM activities once they begin. Team-based activities are essential to a TPM effort. This group needs to include members from every level of the organization from management to the shop floor. This structure will promote communication and will guarantee everyone is working toward the same goals.

**Step 4:** Establish basic TPM policies and quantifiable goals. Analyze the existing conditions and set goals that are SMART: Specific, Measurable, Attainable, Realistic, and Time-based.

**Step 5:** Outline a detailed master deployment plan. This plan will identify what resources will be needed and when for training, equipment restoration and improvements, maintenance management systems and new technologies.

**Step 6:** TPM kick-off. Implementation will begin at this stage.

**Step 7:** Improve effectiveness of each piece of equipment. Project Teams will analyse each piece of equipment and make the necessary improvements.

**Step 8:** Develop an autonomous maintenance program for operators. Operators routine cleaning and inspection will help stabilize conditions and stop accelerated deterioration.

**Step 9:** Develop a planned or preventive maintenance program. Create a schedule for preventive maintenance on each piece of equipment.

**Step 10:** Conduct training to improve operation and maintenance skills. Maintenance department will take on the role of teachers and guides to provide training, advice, and equipment information to the teams.

**Step 11:** Develop an early equipment management program. Apply preventive maintenance principles during the design process of equipment.

**Step 12:** Continuous Improvement - As in any Lean initiative the organization needs to develop a continuous improvement mindset.”

While TPM has gained popularity, its success has remained debatable. It has been reported in the literature that TPM implementation is not an easy task by any means. The number of companies that have successfully implemented a TPM program is considered relatively small. While there are several success stories and research on TPM, there are also documented cases of failure in the implementation of TPM programs in different situations. TPM demands not only commitments, but also structure and direction. Some of the prominent problems in TPM implementation include cultural resistance to change, partial implementation of TPM, overly optimistic expectations, lack of a well-defined routine for attaining the objectives of implementation (equipment effectiveness), lack of training and education, lack of organizational communication, and implementation of TPM to conform to societal norms rather than for its instrumentality to achieve world class manufacturing [23].

Woodhouse [24] posits that TPM, with its stimulation of ‘autonomous maintenance’ (getting the operators to do the obvious diagnosis and first-line maintenance actions), cleanliness and ‘right first time’, changes attitudes and delivers many of the ‘quick wins’ but falters on the specific tools needed to determine which tasks are worth doing in the first place, and in the consideration of risk and equipment life expectancy (short-term versus long-term horizons).

IV. Reliability Centered Maintenance

RCM is defined as a structured, logical process for developing or optimizing the maintenance requirements of a physical resource in its operating context to realize its ‘inherent reliability’, where ‘inherent reliability’ is the level of reliability which can be achieved with an effective maintenance program” [23]. RCM is further defined as a process used to determine what must be done to ensure that any physical component continues to do whatever it was designed to do under the existing circumstances [25]. It entails asking questions about the asset under review, namely:-

1. What are the functions and associated performance standards required of the component?
2. In what ways does the component fail to fulfill its functions?
3. What causes the functional failure?
4. In what way does each failure matter?
5. What can be done to predict or prevent each failure?
6. What happens if a suitable proactive remedial procedure cannot be found?”

The SAE standard [26] further elaborates the questions as below:

Function: The first step is defining the function of the equipment.
The function definition needs to be clear and needs to contain ‘a verb, object and a performance standard’. The performance standard as defined in this statement needs to be what is desired by the organization.

Functional Failures: All failure states that can happen to the equipment need to be defined. This can be in the form of deviation or absence of performance. Low Flow, No Flow, Low pressure are examples of functional failures.

Failure Modes: Once failures have been defined, the failure modes need to be defined. The requirement is that modes that are ‘reasonably likely’ to cause each failure needs to be identified (Reasonable likelihood is described as ‘a likelihood that meets the test of reasonableness, when applied by trained and knowledgeable people’ [27]). The responsibility of what constitutes a likely failure is again what is required for the organization. Normal modes like deterioration, design defects, human error needs to be identified in this step. The only way to remove the ambiguity in assuring reasonableness would be to carry out Failure, Mode, Effects and Criticality Analysis (FMEA or FMECA) on their equipment as suggested in the process developed by Moubray [28]. The normal approach to carrying out FMECA is by evaluating the equipment from the design angle and this result in an implementation that involves evaluating large number of failure modes per equipment. The method of FMECA was standardized in the US MIL standard MIL-1629A [29] and in the IEC standard 60812 [30]. Considering that that there are 33 failure modes prescribed in IEC812 which need to be evaluated, the total number of analyses for a medium size refinery would be to the order of nearly 50000.

Failure Effects: After identification of the failure modes the effects of the failures needs to be identified in case specific action is not adopted in order to prevent the failure. Failure effects need to contain the information needed to support the evaluation of the consequences. Some examples of failure effects would be — Leakage, Fire etc.

Failure Consequences: Failure effects lead to certain consequences. The consequences need to be highlighted for each failure effect and the needs to be further categorized as hidden and evident. Additionally the consequences also need to be categorized as pure economic or as affecting environment and safety. The consequences are evaluated assuming that there is no specific method to anticipate, prevent or detect the failure, unlike the failure effects, which are evaluated considering the presence of an anticipation/ prevention/ detection mechanism.

Failure Management Policy Selection: Once consequences are identified for each failure, the organization needs to choose what policy it will follow for each of these failures. Broadly, the policy needs to be either to prevent the failure from occurring or to predict the failure as it happens (called proactive tasks). When any one of these policies is adopted, the organization needs to have in place the required preventive maintenance programs or a predictive maintenance program in place.

Default Actions: In case the organization is unable to find a suitable proactive task to be applied to a failure, a policy of run to failure or a one-time change may be adopted. The run to failure task can be selected only if the failure does not have any impact on the environment or safety.

**The typical questions asked of an RCM implementation is as follows:** “Craft workers know maintenance performance, but do they know the right maintenance? Do they know when to do it? Can they show why certain maintenance is correct? Can they discover when it is wrong? Over time, can they incorporate learning? Do they know when they have reached maintenance limits and what the equipment can achieve under optimum maintenance? Does maintenance complement operations?” [31]

It is reported that while RCM is an excellent methodology for analyzing the maintenance needs, it seems to lack a defined approach for implementation and while RCM as a maintenance methodology may be considered by some to be difficult to implement, as a philosophy its salient points can easily be used to make their maintenance plans or decisions [32]. It is also reported that the primary concern for industrial organizations adopting RCM is whether they can implement RCM without excessive costs [31]. Pilot studies in various industries show recognition for RCM benefits but concern over resulting analysis cost and its implementation. August, Ramey & Vasudevan [33] report an extreme case where the RCM analysis of nuclear plant with 80 systems resulted in analysis that filled 40 boxes with close to hundred thousand pages of analysis with the result that it made it easier to ignore the results of the analysis.

Woodhouse [24] states that “RCM gives us some logic ‘rules’ for determining what type of maintenance is appropriate, based on failure mechanisms and consequences and is suited to complex plant where there are lots of failure modes. He further states that while RCM provides a consistent navigation path with logical ‘pigeon holes’ for predictive, preventive, detective (failure-finding) and mitigation actions it treats each failure mode individually and may miss some important combinational effects. Woodhouse further reports that “the majority of RCM pilot studies during the ’80-90’s were not fully implemented or sustained, probably due to the temporary enthusiasm and that they lost impetus, became unfocussed/unwieldy/’ too expensive’ or were ‘displaced by other priorities’ and concludes that RCM programs need some aspects of TPM to survive and deliver their full potential”.

**V. Accelerated Reliability Centered Maintenance**

This method, a modification to the RCM process to take care of limitations in the implementation process, while retaining the core philosophy of RCM, introduced in 2007 [34] was developed by the authors in 2013 [6]. The model for A-RCM is shown in fig. 2.

The process developed by the authors in [6] can be stated briefly as below:

**Step 1:** Carry out reliability audits and list equipment wised failure modes
**Step 2:** Apply RCFA actions of failed equipment to its standby
**Step 3:** Identify activities that occurred the most frequently and address these immediately
**Step 4:** Identify the bad actors on the basis of highest number of failures and further analyze these first
**Step 5:** Stratify the equipment on basis of make & model and on the basis of service
**Step 6:** List all failure modes / causes encountered by all
equipment in a particular group

**Step 7:** Extend the failure modes & causes for each group, as potential failures for all equipment of the group

**Step 8:** Apply the default actions (preventive, predictive or design changes) that prevent these failure modes from occurring to all the equipment

**Step 9:** Carry out FMECA on Critical equipment and those without any history of failures.

We have argued that the objective of this method is to provide immediate improvement in reliability and this method provides for improvement as soon as or even concurrently as the failure modes are identified, which takes care of one of the causes of failure of the conventional RCM process that of excessive delay in implementation of actions.

![Diagram of the A-RCM Model](image-url)

**Fig. 2:** The A-RCM Model

This method in effect provides an amalgamation of the various methods and collates the key features of CBM, TPM and RCM into one target, that of failure prevention. However this method is not without its limitations and the most obvious one is the fact that establishing reasonable likelihood is dependent on a sequential process and this may result in all potential failure modes not being apparent at the initial stages of the implementation. Further this also relies on a continual system of adding on failure modes and can result in missing certain key modes, in the event there is a lapse in reporting and analysing a failure.
VI. Summary of Salient Features

The below sections described each of the strategies in detail. Before we undertake a comparison, the salient features of these strategies are summarized and tabulated in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CBM</th>
<th>TPM</th>
<th>RCM</th>
<th>A-RCM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core Intent</td>
<td>Detection of Failure</td>
<td>Cultural Change</td>
<td>Failure Prevention</td>
<td>Failure Prevention</td>
</tr>
<tr>
<td>Focus of Implementation</td>
<td>Monitoring</td>
<td>Planning for different conditions</td>
<td>Coverage of all possible failure modes</td>
<td>Quick gains initially, scaling up</td>
</tr>
<tr>
<td>Program Initiation</td>
<td>Deciding on parameters, procurement of equipment</td>
<td>Top management announcement, launch training program</td>
<td>Assembling team, Training</td>
<td>Assembling team, collection of failure history</td>
</tr>
<tr>
<td>Program support</td>
<td>Separate section for monitoring and recommending actions</td>
<td>Creation of organizational support structure, Policies</td>
<td>Post training implementation can begin immediately</td>
<td>Implementation happens concurrently</td>
</tr>
<tr>
<td>Presumed existing systems</td>
<td>PM</td>
<td>PM</td>
<td>PM, RCFA</td>
<td>PdM, RCFA</td>
</tr>
<tr>
<td>Process Changes</td>
<td>CBM section becomes initiator of maintenance jobs.</td>
<td>Autonomous maintenance by operators</td>
<td>No changes to maintenance process. PM/ PdM Plan generation based on RCM outcome</td>
<td>No changes to maintenance process. PM/ PdM Plan generation based on RCM outcome</td>
</tr>
<tr>
<td>Major Maintenance Activity</td>
<td>Predictive Maintenance. PM largely stopped</td>
<td>Preventive Maintenance. Operator level monitoring</td>
<td>Predictive. Preventive where Predictive does not work and Design change where both fail</td>
<td>Predictive. No manufacturer recommended PM. PM only where Predictive does not work. Design change where both fail</td>
</tr>
<tr>
<td>Measures of Effectiveness</td>
<td>Number of Failures without notice</td>
<td>Equipment effectiveness</td>
<td>MTBF</td>
<td>MTBF, beta (Weibull)</td>
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</table>

VII. Methodology of Comparison

As mentioned in the introduction, though these maintenance strategies described above have been coexisting in the industry, there have not been many attempts at comparing these on a common base. As mentioned earlier, though some work has been done by Hipkin & DeCock [7], Kennedy [8], Legutko [9] & Paunovic et.al [10], in building some comparisons between RCM & TPM, and Sherwin [11] and Fraser et.al [12] have attempted a review of the maintenance models, an even comparison based on how these strategies are implemented and the management of the change in industries have not been done. Studies have been done on factors affecting implementation of TPM [35-36] and RCM [37-38] but have stopped short of providing an unambiguous case for implementation of either strategy.

Any strategy implementation is also a simultaneous management of change. Change impacts people and processes. In selecting a particular strategy for implementation, the user must be aware of what are the various levels of maturity of the strategy and the various factors that are present in each stage that decides the success of the strategy. In order to provide a direction to those wishing to carry out the implementation of these strategies, the authors have taken two approaches. The first draws on the work done by Paunovic [10] and develops the criteria used by them and further draws upon the Capability Maturity model (CMM) used for software development (E.g. Kumta & Shah[14]) in order to compare how each strategy handles maturity.

Paunovic et.al. [10] used the criteria of Methods, Goals, Advantages, Shortcomings and Approach to Employees for comparison. Kumta & Shah [14] suggests five stages of maturity as (1) Initial Level (2) Repeatable Level (3) Defined Level (4) Managed Level and (5) Optimising Level. They further elaborate the issues at each level as follows:

**Level 1**: Displacement of Responsibility, Ritualistic Practices & Emotional Detachment
**Level 2**: Work Over Load, Unclear performance standards, Lack of knowledge, Poor Communication, Lack of Organizational Focus
**Level 3**: Inconsistency in Processes, Continual Improvement, Focus on Individual rather than the activity
**Level 4**: Establishing realistic goals/ expectations, proper baselines
**Level 5**: Involvement of everyone, sustaining enthusiasm

While the model by Paunovic uses very generic criteria for comparison, and the CMM is focused on the management of change process, the authors propose the following criteria that merge the intent of both these methods and create a set of criteria that are more specific. The following are being used for the comparison:

**A. Methods**
1. Simplicity of Method
2. Scalability of Method
3. Prioritisation of Effort
4. Standardization of Method
5. Degree of Change from existing processes
6. Effort required
7. Built-in Continual Improvement

**B. Goals**
1. Goal Complexity
2. Measurable Goals
3. Goal Realization Timeframe
The final comparison is based on the above 15 criteria. Cost of implementation has not been considered as this will be highly dependent on the implementing organization and the extant state of maintenance maturity.

**VIII. Comparing the Strategies**

Based on the criteria developed, a qualitative comparison of the strategies is carried. This uses the base as developed in section VI and presents the analysis of each of the factors in a concise form.

The comparison is shown in the following table (Table 2).

<table>
<thead>
<tr>
<th>Table 2 – Comparison of Strategies</th>
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<tbody>
<tr>
<td><strong>A. Methods</strong></td>
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<tr>
<td>Criteria</td>
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<tr>
<td>Simplicity</td>
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<td>Scalability</td>
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<td>Effort Prioritization</td>
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<td>Standardization</td>
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<td>Degree of Change</td>
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<td>Built-in continual improvement</td>
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<td><strong>B. Goals</strong></td>
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<tr>
<td>Goal Complexity</td>
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<tr>
<td>Measurable Goals</td>
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<tr>
<td>Timeframe</td>
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<td><strong>C. Employee</strong></td>
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<tr>
<td>Skill Required</td>
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<tr>
<td>Employee Participation</td>
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<tr>
<td>Individual Focus</td>
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<tr>
<td>Training Requirement</td>
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<tr>
<td>Sustainability</td>
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</table>
IX. Discussion on Comparison With Respect to Process Industries
Process industries are characterised by low manpower and concentration of skills. Maintenance is typically an outsourced activity in these industries, or at best performed by low skill employees, unlike in the case of a manufacturing or automotive industry where maintenance is a part of the core business process. Further, process industries are also characterised by a large number of equipment. Typically the number of machinery even in a mid sized process plant runs into the thousands. This large equipment count coupled with low skill of execution and higher skill concentration, creates a unique problem for process industries in as to which of these strategies needs to be adopted which will ensure increase in reliability, but without intense effort and continuous monitoring of the implementation.

Condition Based Maintenance, with its simplicity of methods and goals may appear as the ideal strategy. However due to the static nature of the strategy, continual improvement is not possible. Further, the strategy limits itself to monitoring and correcting the issues causing failures, but does not extend to the preventing these from occurring in future. Even with a Root Cause Failure Analysis (RCFA) program, this strategy fails to address the need for across the board reliability improvement due to its inability to address potential and hidden failures.

TPM is a strategy that aims to empower individuals. This approach is best suited where there is typically one employee for a small group of machines. In process industries, the typical operator to machine ratios run to 100+ and this makes it impossible for the concept of autonomous maintenance to be effective. Further, TPM requires that the organizational culture changes as a whole. The strategy depends on this cultural change to provide the benefits in terms of increased reliability. Training requirements are higher and this strategy is directed towards building a minimum level of competency across all employees. The goals are also complicated and in varied areas, resulting in a greater degree of effort required and higher amount of monitoring and control. These are difficult to achieve in process industries due to the nature of the production process, need for specialization and a very narrow focus on core production activities. On the positive side, the strategy results in increased skill of all employees, greater participation and hence improved morale. However the complexity and ‘vagueness’ of goals can cause the program to falter after some time.

RCM is a very systematic strategy with clear goals. It demands high skill from only a few people and hence can be quickly started. However since the focus is on uncovering all potential modes of failures and addressing these though the three actions of preventive, predictive and default actions, the process requires the extensive analysis, through an FMEA of all equipment and is time consuming. The number of analyses required for completing this study exhaustively for a mid sized process plant will run to the order of 10000s and becomes a time consuming activity. The major issue with a conventional RCM process is that in the period of the study, there will be no benefit accrued and at times this can lead to loss of management support. With such large volume of analyses, it also becomes easy to miss crucial recommendations. In addition to this, conventional RCM is a large one-time effort. To build in continual improvement this process will need to be done periodically. Despite these issues, RCM has its advantages. The goals are simple and measurable, the entire process is system driven and training requirements are minimal. Further an international standard (SAE J1012 [26]) is available to benchmark the implementation. The process is also fully scalable and can be applied one plant after the other, in order lower timeframe of benefit accrual.

A-RCM is a process that largely follows the RCM process. It differs from RCM in the methodology of identifying potential failures, wherein, instead of an FMEA, this process uses a history of past failures for providing the first round of predictive, preventive & default actions. This allows quick realization of reliability improvement in comparison with RCM. This process is, like RCM, benchmarked through the SAE standard with the exception of the demand for meeting ‘reasonable likelihood’ where this process may not immediately meet the requirements of the standard. Further the system allows for prioritisation of effort based on the criticality of the equipment in consideration. The skill required is comparable or lower than that required for RCM. The system builds in continual improvement. The disadvantages of the system are that unlike RCM, this cannot be applied plant by plant and needs to be implemented across all the plants in one location so as to ensure that adequate history of failures are available. This also has a limitation in that the method is not strictly as prescribed by the standard. However for process industries, especially those with poor reliability, this method provides the quick improvement in reliability that provides for the immediate gains.

X. Conclusion
Selecting a maintenance strategy for implementation requires care and a clear understanding of the organization’s goals, its capabilities, the organisation culture and the effort it can put in for implementing the strategy. The selection of a particular strategy needs to be done with care, since the results will be apparent only after a few years by which time the organisation would have put in considerable effort into the implementation. Considering the risks, a ready comparison, from the point of view of the implementer was needed. This paper provided such a comparison that can be used as a first guide for selection of a particular maintenance strategy.

References


