A New Model For Reliability Centered Maintenance In Petroleum Refineries

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Abstract: - Refiners today operate their equipment for prolonged periods without shutdown. This is primarily due to the increased pressures of the market resulting in extended shutdown-to-shutdown intervals. This places extreme demands on the reliability of the plant equipment. The traditional methods of reliability assurance, like Preventive Maintenance, Predictive Maintenance and Condition Based Maintenance become inadequate in the face of such demands. The alternate approaches to reliability improvement, being adopted the world over are implementation of RCFA programs and Reliability Centered Maintenance. However refiners and process plants find it difficult to adopt this standardized methodology of RCM mainly due to the complexity and the large amount of analysis that needs to be done, resulting in a long drawn out implementation, requiring the services of a number of skilled people. These results in either an implementation restricted to only few equipment or alternately, one that is non-standard. The paper presents the current models in use, the core requirements of a standard RCM model, the alternatives to classical RCM, limitations in the existing model, classical RCM and available alternatives to RCM and will then go on to present an 'Accelerated' approach to RCM implementation, that, while ensuring close conformance to the standard, does not place a large burden on the implementers.

Index Terms: - Reliability, RCM, A-RCM, Accelerated Reliability Centered Maintenance, Petroleum Refining, Maintenance Management, Statistical Analysis

1. INTRODUCTION

The past few years have seen immense pressure on oil refineries in India, with margins often dropping below zero. This has forced Indian refiners to extend their shutdown periods and also look at running their units over rated capacity and Indian refineries contribute 5.4% of the worlds refining with only 4.5% of the capacity [1]. While operating margins are available in a few of the equipment, this mode of operation places tremendous strain on most equipment and also on the reliability assurance of these equipments. Additional pressure on operating costs is also being felt due to the spiraling costs of engineered components. This has forced refiners to look towards newer ways of reliability assurance of their equipment. The conventional response to an increased reliability need has been the implementation of Predictive Maintenance (PdM) or Condition Based Maintenance (CbM) programs. While this is adequate to ensure a certain degree of reliability, mere implementation of PdM or CbM has, while providing some degree of improvement in reliability has not ensured continuously improving reliability. In recent times, refineries have started to adopt strategies from outside the process industry like RCM, TPM and Six-Sigma to achieve improvement in reliability [2]. Of these, Reliability Centered Maintenance (RCM) has found some degree of popularity. This has mainly been due to its broad applicability and by the fact that the airline industry, which incidentally originated the idea of RCM, through the work of Nowlan and Heap [3], has shown remarkable improvement in reliability by the application of RCM. The RCM process was further refined into the RCM-II methods developed by Moubray [4]. This method, different in its form from the original Nowlan and Heap method (so called RCM-I), has found a high degree of acceptance. While many organizations have tried to carry out implementation based on this method, it has failed to produce the optimization or 'rationalization' of maintenance programs and consequently the increase in reliability. The complexity has mainly been due to the immense effort required to carry out identification of Failure Modes in equipment due to the fact that the methods were primarily aimed at the design phase of equipment rather than at mature, operating equipment. It was also recognized that these methods did not acknowledge the gains and inputs of a prevailing maintenance program but focused on building the entire structure from the start [5]. This has resulted in the development of alternate approached to reliability improvement primarily lead by consultants. Of these, methods developed by Shell and Steven Turner (The PMO approach described in Ref 5) have found some degree of acceptability [6]. The Ministry of Petroleum & Natural Gas in India has in fact appointed Shell as a consultant for a Refinery Business Improvement Program with Reliability Improvement as one of the core areas of focus, for Indian refineries [7]. Due to the consultant driven nature of the alternate reliability improvement programs, most of the work or models, due to commercial nature of the implementation, have remained unpublished as research works and hence unavailable for analysis [2]. The gains in reliability improvement witnessed by the airline industry, which proves the efficacy of the RCM model, coupled with the complexity in implementing the conventional RCM methodology and consultant driven alternates to RCM have prompted the authors to develop a new model of RCM implementation, which is described in this paper. The paper will describe the current models of maintenance in general and in Indian refineries in particular, the methodology of conventional RCM implementation, the limitations of both, the requirements from a new model for

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RCM, the development of the new model and the approach to implementing these models in refineries.

2. EXISTING MODEL

The maintenance response to the need for preventing failures has been to have a Predictive Maintenance program that has both condition-based tasks and time-driven tasks [8]. Condition-based tasks are derived mainly from Vibration analysis [9]. Time-driven tasks typically arise out of equipment manufacturer recommendations and are conventionally referred to as PM Tasks or PM Plans. In addition to the PM Plans and the PdM plans, most organizations employ a Root Cause Failure Analysis program (RCFA). In the case of Indian refineries the Oil Industry Safety Directorate (OISD) has through its standards specified the type of maintenance strategies to be adopted by these refineries. These standards prescribe that as a minimum, the refineries have a PM Program [10], a PdM program [11] and an RCFA program [12]. This ensures that a preliminary level of reliability assurance is achieved in these plants. The author's refinery also uses categorized MTBF as a measure of the equipment reliability from early 2002 [13]. Considering these facts the present model of maintenance and reliability assurance practiced in general in Indian refineries is displayed in the figure 1.

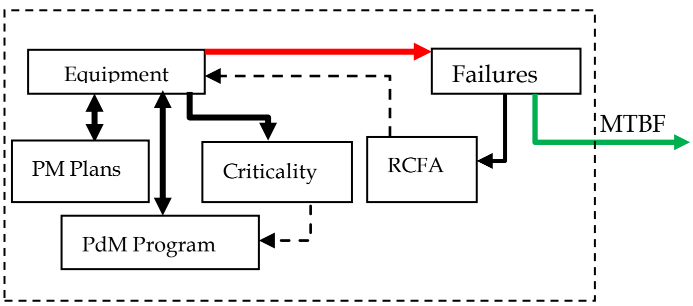

Figure 1- Existing Model

3. LIMITATIONS OF THE EXISTING MODEL

One of the primary issues relating to the existing model is that it is a static model. Once a PM or PdM program has been generated the actions do not change automatically based on the observed performance of the program. While an RCFA program does generate failure causes, this only results in the upgradation of the equipment or replacement of an inferior component by a superior component. This model does address core issues with reliability of equipment but has the following deficiencies:

- The model does not accept inputs from sources other than the equipment itself
- Equipment has to experience a failure before the corrective actions kick in
- Model treats all equipment as alike and decides on PM and PdM based on a onetime criticality analysis
- PM and PdM programs do not vary with time

These limitations result in a condition wherein, after some time of distinct reliability improvement, the organizations encounter insignificant of no improvement in reliability (as measured by the MTBF) [6]. For refineries that wish to proceed further, the conventional model is inadequate and this needs refinement.

4. CONVENTIONAL RCM PROCESS

As stated earlier, the classical or conventional RCM developed by Nowlan& Heap was developed into an approach that can be implemented in a broad spectrum of industries by Moubray and in the SAE standard. The conventional RCM implementation described in the guiding standard published by SAE [14] is through a 7-step process. The steps involved are briefly described below:

4.1 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. An example statement is "Pump ABC shall deliver flow of 200 m3/hr at 20 bar discharge pressure".

4.2 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.

4.3 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. 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.

4.4 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.

4.5 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.

4.6 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 to either 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.

4.7 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 to be selected only if the failure does not have any impact on the environment or safety.

5. LIMITATIONS OF CONVENTIONAL RCM
The conventional RCM approach has some major limitations that prevent the application in refineries.

5.1 Reasonable Likelihood:
Reasonable likelihood is often described as 'a likelihood that meets the test of reasonableness, when applied by trained and knowledgeable people' [15]. However, in reality this is difficult to achieve and can cause disputes between the implementers and the verifiers, mainly due to the lack of an objective measure of reasonability. This forces the implementers to default to carrying out a FMECA on the equipment. In fact one of the major criticisms from the classical school of RCM against any alternate approached has been the establishment of reasonable likelihood.

5.2 FMECA:
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 [4]. 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 MIL standard MIL-1629A [16] and in the IEC standard 60812 [17]. Considering that that there are 33failure 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, assuming that medium sized refineries have close to 2000 rotating machinery. This makes the task of carrying out FMECA highly time-consuming. It is now quite obvious that refiners with limited manpower are not in a position to carry out this analysis in a small time frame.

5.3 Sub-Optimality:
Due to the time consuming nature of the classical FMECA, in many places only critical equipment are analyzed [18]. These results in an implementation that does not take care of all equipment, which in turn results in an implementation that does not ensure consistent gains in reliability. Critical equipment, are better designed than other equipment and as it is would possess high reliability. Studies at the author's refinery [19] have shown that the in a 6 month period there were no failures of critical machinery whereas the non-critical machinery experienced large number of failures. By carrying out the FMECA in only critical equipment, the implementation becomes sub-optimal. Recognizing the limitations many alternate approaches to conventional RCM model have been proposed. Three popular models are also discussed in detail.

6. ALTERNATIVES TO RCM AND LIMITATIONS
Many alternatives to RCM have been proposed. These alternates can be best divided as research driven and consultant driven. Research driven approaches, where a large number of models with mathematical or probabilistic approached have been suggested [2] [20] [21], have not found many practical applications mainly due to the high levels of skill, often mathematical, required in handling these models. Quite a few consultant driven approaches have also been proposed – prominent among them being the Streamlined RCM (or SRCM) [18], the PM Optimization (PMO) from Turner [5] and TPM which in India is spearheaded by the Confederation of Indian Industries (CII).

6.1 SRCM:
Streamlined RCM or SRCM is an approach that has been put forth as simplifying the RCM implementation and was initially applied in the nuclear industry. This method consists of "identifying the failure mode that each existing maintenance task is supposed to be preventing and then work forward again through the last three steps of the RCM decision process to re-examine the consequences of each failure and to identify a more cost-effective failure management policy". Further this approach concentrates on analyzing critical equipment, critical failures and concentrating on the last 3 steps of the RCM process. SRCM has been criticized for being focused more on maintenance cost optimization rather than on reliability improvement [18].

6.2 PMO:
PM Optimization is another alternative to RCM. This process, which closely mirrors the classical RCM process, but with a difference in the order of the execution as in SRCM starts with review of existing tasks, and then carries out an analysis of the failure modes as a group rather than individually as done for RCM. The functional analysis which is mandatory in an RCM process is an optional step and the stated aim is to "generate a list of failure modes from the current maintenance program, an assessment of known failures and by scrutiny of technical documentation – primarily Piping and Instrumentation Diagrams (P&IDs)" [5]. This process too has been criticized for ignoring the function failures and for concentrating on the realization of an effective PM program rather than on overall reliability improvement [22].

6.3 TPM:
Total Productive Maintenance or TPM is used as an alternate to improve the effectiveness of equipment. The focus of TPM is more on involvement of people from various functions in the equipment operation and which thereby raises equipment effectiveness. TPM has been demonstrated as beneficial in reducing equipment breakdowns, minimizing idling and minor stops (indispensable in unmanned plants), lessening quality defects and claims, boosting productivity, trimming labour and costs, shrinking inventory, cutting accidents, and promoting employee involvement [23]. Review of published literature suggest that while TPM has found acceptance in manufacturing industries, in the process industries particularly in refineries the application has been limited. TPM has also been criticized for not being a unique process by itself, but rather seems to borrow aspects from many areas like Business Process Reengineering & Continual Improvement

[24] As can be seen from the alternate methods and their criticisms, there is a lack of convergence between the requirements and the benefits possible on a full-fledged conventional RCM implementation and the alternate methods currently in practice. This opens the need to develop an alternative approach to RCM that to a large extent, eases the complexity of implementation, allows for a high degree of accuracy and also considers the inputs of the prevalent maintenance program. It is also clear from the alternatives and their criticism, that, though the depth of analysis can be limited, the methodology needs to closely mirror the prescription of the standard methodology to accrue the true benefits of RCM.

7. DEVELOPING THE NEW MODEL

As has been described earlier, RCM is a proven tool for continuous reliability improvement. However, there is a need for ensuring faster implementation as well as simplifying the process of implementation. Based on the criticism of the previous approaches to simplifying the process the following can be considered as minimum requirements for the new model:

- **i.** The process should consider the existing maintenance practices and outcomes
- **ii.** All failure modes that are reasonably likely to occur must be considered
- **iii.** Critical equipment need more intensive analysis
- **iv.** The model should provide results quickly
- **v.** The results should be measurable at a macro level
- **vi.** The new model should integrate with existing practices

These requirements are analysed in the following sections.

7.1 Consider existing maintenance practices:

Refineries in India have a reasonably robust maintenance program driven by the statutory requirements. These programs result in Preventive Maintenance (PM) schedules, Predictive Maintenance (PdM) and Failure Analysis records. The A-RCM model focuses on adding on to these PM & PdM programs and also extensively use the RCFA outputs to drive the program. The use of these failure analysis outcomes will greatly aid establishing likelihood of occurrence of Failure Modes.

7.2 Considering 'reasonably likely' Failure Modes

As described in section 5.2, the major factor that consumes time in a conventional RCM process, is carrying out the FMECA. The FMECA approach relies on a function-failure-failure mode-cause route so as arrive at a set of modes that meet the requirement of reasonably likelihood set out by the SAE standard. In any refinery that has been in operation for some time and which follows one of the basic strategies, namely Preventive Maintenance or Predictive Maintenance, a large number of failures and failure modes would be experienced. Analysis of failures of different components, which occurred in a period of 6 months in the author's refinery were analyzed. Analysis was carried out separately for the following categories -Turbomachinery failures, Motor Failures, Mechanical Seal failures in Process Pumps and Mechanical Equipment Bearings. The probability that the failure mode of any of the failures in the period under consideration had occurred sometime in the past long with the number of distinct failure modes is given below for each of the categories:

Table 1- Probability that a current failure mode has occurred in the past

Category	No. Failures	No. with a Repeating Mode	Prob. of repetition	No. of Modes
Turbom-achinery	Nil	Not quanti-fiable	0	Few Common Modes
Motors	40	40	1	6
Bearings	57	53	0.93	8
Seals	56	54	0.964	9

From the data in Table-1, it is clear for that all equipment except turbomachinery like Steam Turbines, Compressors etc, the probability that a failure mode has already occurred is extremely high. As larger data is analyzed a pattern emerges that the probability would increase with age of the plant. In fact, this relation can intuitively be arrived at by the fact that in the initial stages of commissioning, the failure patterns are quite varied and with time the unit experiences the majority of failure that 'could' have happened on the equipment. This effect, of a unit having experienced all 'probable' failures can be utilized in arriving at the failures that have a 'reasonable likelihood' of occurrence within the plant. It would be safe to assume, given the high probabilities of repetition of failures that, any failure that can happen in a particular unit, would be a subset of the failures that have already happened in the plant. This assumption is all the more valid when one considers that there is a strategy in place in any unit, aimed at preventing a particular subset of all failures, and the failures that have been occurring in the plant are in spite of the strategy. Hence for a given unit or plant, with a defined strategy of failure prevention in place, a robust mechanism for capturing failure data and standard maintenance practices, past failures in the particular category of equipment constitute a 'reasonably likely' failure mode. This means that the past failures in a particular category of equipment (say pumps) can be used, with a high degree of accuracy, as the failure modes that need to be analyzed while carrying out the RCM implementation. This high probability of repetition is used by the A-RCM model as an input.

7.3 Critical Equipment to be treated separately

The analysis in section 7.2 indicates that, due to nature of the construction of the equipment and the maintenance procedures adopted for critical equipment (mainly turbomachinery), large numbers of failure modes are eliminated or occur at very low frequencies. This prevents using data from the previous failures to generate a reasonably likely set of failure modes and hence for such equipment mainly large turbomachinery, the only option is to carry out the FMECA as per the classical approach. However due to the limited number of turbomachinery, this analysis may not be as time consuming as would have been if all rotating machinery were to be analysed.

7.4 Quick Results

One of the issues with the conventional RCM process is that the analysis takes time and consequently, the results of the program accrue after a substantial period of time. The new model should eliminate the time lag and allow for quicker realisation of benefits. Towards this end, along with the model developed here, an approach to the physical implementation also needs to be developed.

7.5 Measurable at Macro Level

The program should have a measurable parameter/s that demonstrates the performance of the program adequately. As the purpose of maintenance programs in refineries is to primarily ensure availability of equipment, and availability is directly connected to MTBF, this can be the primary parameter. Failure data of rotating machinery can be considered as a reliability model with repairs and equal probability of failure of all equipment at the same time. In this case the failure time of individual equipment can be approximated to a two parameter Weibull distribution the CDF of which is given by [13] [25] [26]

$$F(x) = 1 - exp((-t/\alpha)\hat{}\beta)$$

Based on standard methods of analysis [26], the MTBF can be calculated from the regression of the failure data with a median rank (MR). Though Maximum Likelihood (ML) has been suggested as a better alternative to MR [27], due to the ease of calculation, the authors propose to use MR calculated by Bernard's approximation as for the regression since the calculation will need to be done by users without sophisticated knowledge of statistics and advanced computing tools at their disposal. The method is proposed was developed and demonstrated by the author in 2002 [13]

Based on this the model calculates the MTBF as:

$$\tau = a.\Gamma(1/\beta + 1)$$

Where 'α' is the shape factor and 'β' is the scale factor. The parameter β is a good indicator of the maturity of the system [27]. A study of the parameter indicates that above a value of 2, the CDF tends to concentrate around a mean value. Hence along with the measurement of MTBF, the model also should include the tracking of this parameter as a measure of the effectiveness. Interpretation of the parameter β can provide important clues on the type of failures taking place. If MTBF increases with the b values lower that 2 indicates that failures are still occurring before maturity and there exists a scope for improvement, whereas a value higher than 2 indicates a maturity of the failures.

7.6 Integration

Any new process or model needs acceptance of the users. The human factor has been cited as a major hurdle in the acceptance of newer processes. In Indian refineries where there is a mix of skills, this resistance is expected to be all the more prevalent. Hence the new model should be tightly integrated with the existing processes and the additional actions generated out of the new model should be adding on the existing PM and PdM program rather than creating a separate set of processes for implementation. Since the primary outcome of such a process would be the speeding up of the RCM process, the authors propose that the process described here be called as the Accelerated RCM or the A-RCM model. Considering these factors, the new model for the RCM implementation in process industries, with specific application to Indian refineries has been developed and is described in the succeeding sections.

8. THE A-RCM MODEL

In the preceding section, the core requirements of a new model were developed. These requirements can be translated as Inputs, Desired Outputs and Parameters for measurement.

8.1 The Model Definition

8.1.1 Inputs to the Model

The key inputs that the new model requires are:

- Equipment Criticality
- Equipment History of the population
- Failure modes of previous failures
- Existing Preventive & Predictive Programs

8.1.2 Desired Outputs

The model should ideally provide the following:

- Preventive Maintenance Schedules
- Predictive Maintenance recommendations
- Design Changes

8.1.3 Parameters for measuring effectiveness

As stated earlier the parameters for measuring the effectiveness of the new model are:

- MTBF
- Scale parameter 'β' (described in later sections)

8.2 The Model

The new model is sown in Figure 2.

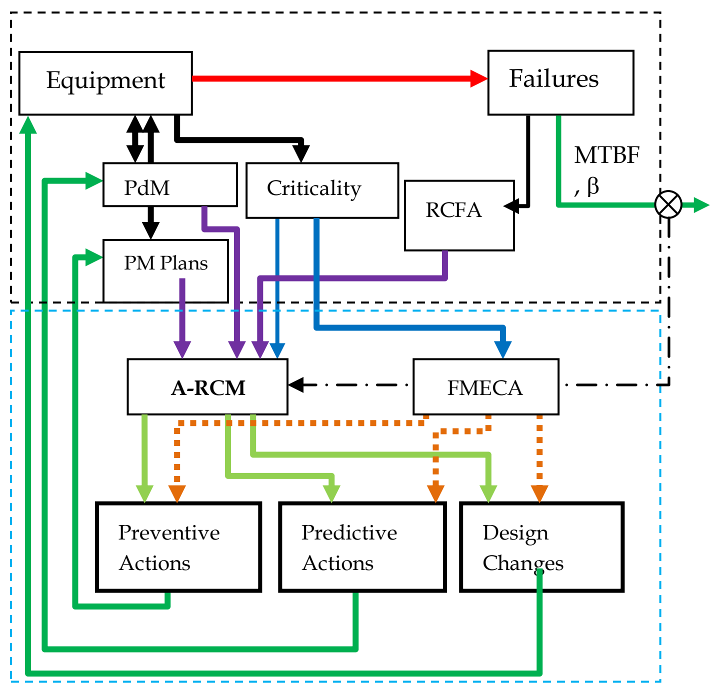

Figure 2- The A-RCM Model

8.3 The A-RCM Process

The development of a model does not guarantee effective implementation. It is imperative that, the model developed is also accompanied by a detailing of how the model should be deployed. This is the key to success and practical application of the model. Additionally, the stated objectives of this work were to create a model that can be easily implemented and also one that provides immediate improvement in reliability for the users. This section then describes the process of implementation of A-RCM. During the model development we had stated that one of the key inputs to the model is the prevalent failure modes of the plant or location from the equipment history or the output of the existing RCFA program. The process of collecting past failure modes can be utilized to effectively accelerate the reliability improvement, before the formal completion of the A-RCM implementation. A four-stage methodology of implementation for ensuring that the new model of RCM implementation results in truly 'Accelerated' reliability improvement, is detailed below.

Stage 1 – Reliability Audits and Analysis:
The first step in implementing A-RCM is to carry out reliability audits. This step involves collecting information from history files and/or the ERP/ CMMS system regarding past failures of all equipment. The information collected needs to be organized in the form of Reliability Audit sheets. Here the numbers of particular kind of failure that has been experienced in the equipment is detailed. This information, along with a brief note on the type of failures that have been faced, forms the Reliability Audit Sheet. Such sheets need to be generated for all equipment under consideration. While individual organizations can choose to select particular classes of equipment for analysis, this method will be more beneficial if all equipment that have an impact on the operation of the plant are considered for analysis. Typically, majority of rotating machinery have standby equipment. While carrying out the reliability audit, the first step in acceleration would be to immediately carry out the RCFA recommendations of the failed equipment, on all its standby equipment, even if the failure has not been experienced by the standby. This immediately prevents one potential failure mode from recurring. The second step while carrying out the audit is to identify the failure modes that have occurred most frequently in each of the equipment. These failure modes need to be flagged as critical failure modes. Here it needs to be noted that there may be persistent minor issues that, though not considered as a failure, may be contributing to the poor MTBF of the equipment in the long run. A very representative sample was observed by the author while carrying out the reliability audit at his refinery. In this pump, the mechanical seal had an MTBF of around 24 months which was high enough to get exclude the equipment from the 'bad actors'. However on closer examination of the equipment history, it was observed that the seal flush lines used to get de-choked once every 8 months. Flush is an important aspect of seal performance and though maintenance was being carried out, these were post the chokage, resulting in the seal running in less optimal operating conditions for some time. The cleaning of flush line was moved to a 6 month preventive task and the seal MTBF has thence more than doubled. The third step in this is to identify the top 10% equipment that has had the largest number of failures. These are to be considered as the 'bad actors'. These equipment need to be analyzed first. This step too results in a quicker accrual of the benefits.

Activities in this stage:
1. Carry out reliability audits and list equipment wised failure modes
2. Apply RCFA actions of failed equipment to its standby
3. Identify activities that occurred the most frequently and address these immediately
4. Identify the bad actors on the basis of highest number of failures and further analyze these first

Outcome of this stage:
1. List of equipment wise failure modes
2. Action on standby equipment of failed equipment
3. Identification of 'bad actors'

The net result of this stage is that a list of failure modes applicable is now available for all equipment. This stage also results in actual implementation of some reliability improvement programs.

Stage 2 – Identifying Likely Failure Modes
Once the list of failure modes, which have already occurred in the location or plant, is available from Step1 of the process the step 2 of the process, namely, identification of likely failure modes need to be carried out. The Step 1 of the ARCM process will result in the identification of a large number of failure modes and causes. In order to identify only those failures that have a reasonable likelihood of occurrence in particular equipment, this failure data needs to be stratified. Analysis of the failure data from the author's refinery gives commonality of failure modes of the following groups:

- Make & Model for the drive part of the equipment (Bearings, couplings etc)
- Process Fluid for wetted parts of the equipment (Impellers, Seals, Corrosion etc)

Considering the commonality of failure modes across models and services, the equipment can be grouped into two major strata.

Group1 – Make & Model: The first grouping needs to be on the basis of Make and Model. It is a recognized fact that the behavior of the same type of equipment varies with manufacturer. There is also a high probability that the particular model exhibits the same behavior irrespective of the unit or service it is installed in. Grouping along the lines of the Make and Model of the equipment provides the failure modes that are inherent to that particular model of equipment and help in faster roll out of the actions to prevent failure.

Group2 – Service: The second grouping that needs to be done is in terms of the service. In this equipment, though belonging to different loops, but handling similar service can be clubbed together for analysis. This grouping gives the advantage of being able to map failures due to service, irrespective of the location of the equipment. An example of such stratification can be – "LPG Pumps", "HGO Pumps >300 degrees Temperature" etc. Once the groupings of all the equipments have been done as above, then all the failure modes that equipments in the particular group have experienced, are treated as potential failures for all equipment in that particular group. There will be two distinct sets of failure modes & causes – for the drive side and for the wetted side, which emerges out of this stage. However, as we had stated earlier, the objective of this method is to provide immediate improvement in reliability. Therefore, as soon or even concurrently as the failure modes are identified for the group, the equipments need to be evaluated for the cause of the failure and a proactive method with which this failure can be prevented must be identified. This prevention needs to be applied for all equipments belonging to the particular group. For example a common failure cause that was observed for a particular make-model of pumps was the 'water entry into the bearing housing'. The solution that was applied to all the pumps of this make-model was the installation of bearing isolators which all but eliminated the failure mode completely. On completion of this stage, it is likely that there will be a large number of Preventive and Predictive actions emerging. In mature plants, where robust PM/ PdM efforts are already in place, the design change actions will be high. The prioritization of the actions for implementation now becomes important. For this the criticality of the equipment to the process is used as an input and equipment that have the higher impact on the process and safety are taken up first. This stage may also result in groups that have had no previous failures. For these groups, there is no option but to carry out the FMECA in Stage-3 of the implementation.

Activities in this stage:

1. Stratify the equipment on basis of make & model and on the basis of service
2. List all failure modes / causes encountered by all equipment in a particular group
3. Extend the failure modes & causes for each group, as potential failures for all equipment of the group
4. Apply the default actions (preventive, predictive or design changes) that prevent these failure modes from occurring to all the equipment

Outcome of this stage:

1. Grouped failure modes & causes
2. Preventive & Predictive actions for all equipment in the group
3. Design changes required
4. Groups where there have been no failures

This stage provides the quick identification of a large number of 'highly probable' failure modes and causes as well as the actions required to prevent these modes from occurring. The second stage leads to the highest gains in reliability for the unit.

Stage-3 FMECA on Critical Equipment

The previous stages helped identify failures with reasonable likelihood of occurrence. These stages also ensure that some action is implemented concurrently in order to prevent/ predict the potential failures. The next stage is carrying out the FMECA on the Critical Equipment. It is to be noted that the process suggested here varies from all other processes in that it only by Stage-3 that FMECA is taken up. (This activity, for the critical equipment, is purposely delayed due to the fact that critical equipments in process industries, especially refineries, are built following stringent standards like API 612, API610 etc and hence have very high inherent reliability). The methodology suggested by the MIL1629A standard as well as the SAEJA1012 is adopted. To categorize the consequences, the Risk Priority Number (RPN) method as detailed in API RP 580 [28] is used. Alternate methods that can quantify the consequences in terms of indices can also be used. Based on the FMECA, the Preventive, Predictive of Design Change actions are identified for the Critical Equipment. Once analysis of critical equipments has been completed, then the groups where no failures were observed (identified in stage 2) are taken up for FMECA and potential failure modes and causes are identified along with the actions necessary to prevent these from occurring. This stage provides the final set of actions for implementation. In practice the FMECA on critical equipment will yield very few actions and the few actions that do get identified will require significant investment of cost and effort to implement.

Stage 4 – Sustaining the Program

While the above three stages were based on the past data of the equipment, the implementation becomes a 'living' program only when it also contains steps to sustain the implementation. There are two important steps to sustenance – feedback and measurement.

Feedback: Subsequent to the rollout of the program, in the event of any failure, RCFA as well as the A-RCM Stage1 & Stage2 needs to be carried out immediately, but only for the group in which the equipment belongs. In case of a failure whose cause was already identified, then it can be concluded that the action that was being followed was incapable of preventing the failure and a new action needs to be finalized. This action now needs to be deployed across all the equipment in the group. In case the failure mode / cause is new, then the new action identified by the RCFA needs to be deployed across all equipment in the group. This will ensure that the model continuously 'learns' and updates itself and errors become lesser as time progresses.

Measurement: As detailed in section 7.5, the MTBF & β, calculated using the two-parameter Weibull Distribution is the ideal measure for the performance of the program. These two factors can indicate whether the program is successful and also the next steps in the program. While individual organizations can take calls based on their experience, an assessment table is given in Table-2.

Table 2 - Decision tree based on MTBF and β

		MTBF	
		Stagnant	Increasing
β	≤ 1.5	Infant Mortality. Increase PM & PdM Efforts	Program sub-optimal. Identify 'bad-actors' for FMECA
	>1.5 ≤ 2	Mature Failures. Concentrate of Design Changes	Program Working. Continue as is.
	>2	Maximum life of equipment reached. Replace or Repair decision	Continue with Program. Move more equipment to FMECA

By including these two key factors, the model becomes self-sustaining as well as provides an indication when its usefulness is decreasing.

9. FURTHER WORK

This paper identified the new model and the process for carrying out accelerated RCM. The model has been deployed at the author's refinery. The authors propose to carry out further work by assessing the impact of the implementation of the model, applied to the large and complex refinery. The outcome of the implementation will further be used to fine tune both the model and the process. The authors also propose to use the implementation to fine tune the methodology of measurement as well as the decision tree based on the measurement.

10. CONCLUSION

Petroleum refineries require extremely high levels of equipment reliability. The reliability assurance in such industries is marred by the large number of equipment, the complexity of the system, the paucity of staff to carry out dedicated reliability programs and a need for quick gains in reliability. Considering these factors it is imperative that a process that allows for refiners to obtain quick gains in reliability is the need. The A-RCM model and process provides refineries with a comprehensive tool for accelerated improvement in reliability.

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