APPLICATION OF RELIABILITY CENTERED MAINTENANCE (RCM) IN LEAD OXIDE PRODUCTION SYSTEM-A CASE STUDY

By

Md. Ahasan-Ul-Karim
ID: 0411082129 P

A thesis paper submitted to the Department of Industrial and Production Engineering (IPE), Bangladesh University of Engineering and Technology (BUET), Dhaka, in partial fulfillment of the requirements for the degree of Master of Engineering (M. Engg.) in Advanced Engineering Management (AEM).

Department of Industrial and Production Engineering

Bangladesh University of Engineering and Technology

Dhaka, Bangladesh

December 2015

CERTIFICATE OF APPROVAL

This thesis paper titled "APPLICATION OF RELIABILITY CENTERED MAINTENANCE (RCM) IN LEAD OXIDE PRODUCTION SYSTEM-A CASE STUDY" submitted by Md. Ahasan-Ul-Karim, Student ID- 0411082129 P of session April, 2011, has been accepted as satisfactory in partial fulfillment of the requirements for the award of the degree of Master of Engineering in Advanced Engineering Management on December 09,2015.

BOARD OF EXAMINERS

19.12.15

Dr. Nafis Ahmad — Chairman
Professor and Head
Department of Industrial and Production Engineering
Bangladesh University of Engineering and Technology (BUET), Dhaka

----

Dr. A. K. M. Masud — Member
Professor
Department of Industrial and Production Engineering
Bangladesh University of Engineering and Technology (BUET), Dhaka

Shuva Ghosh

Dr. Shuva Ghosh — Member
Assistant Professor
Department of Industrial and Production Engineering
Bangladesh University of Engineering and Technology (BUET), Dhaka

Department of Industrial and Production Engineering
Bangladesh University of Engineering and Technology, Dhaka- 1000

Declaration

I do hereby declare that this work has been done by me and neither this thesis nor any part of it has been submitted elsewhere for the award of any degree or diploma.

Md. Ahasan-Ul-Karim

Md. Ahasan-Ul-Karim

This dissertation is dedicated

To

My parents

Acknowledgement

I would like to convey my sincere gratitude to my honorable supervisor Professor Dr. Nafis Ahmad for his exceptional guidance and support during this work. He made me to do even better than best. Without his insightful supervision and invaluable advice it was really difficult to do it completely. I am grateful to all the personnel both production and maintenance of Rahimafrooz Batteries Limited, Bangladesh for their enormous support to get the maximum data and output in the stint of the work. Last but not the least; I am thankful to my parents and to my family for their patience, interest and encouragement during my studies.

Abstract

In this work a framework on application of Reliability Centered Maintenance (RCM) for Lead Oxide production process in the battery industry is developed. Reliability-Centered Maintenance (RCM) integrates Preventive Maintenance (PM), Predictive Testing and Inspection (PT&I), Repair (also called reactive maintenance), and Proactive Maintenance to increase the probability that a machine or component will function in the required manner over its design life-cycle with a minimum amount of maintenance and downtime. RCM method is used here through Failure Mode and Effect Analysis (FMEA) and decision making for maintenance criteria is established in view of Criticality and Logic Tree Analysis (LTA). Finally Task allocation of equipment is described based on the following strategies: condition based, interval based, failure finding and run to failure or redesign. Evaluation of this RCM frame work is performed based on standard evaluation criteria by society of automotive engineers inc. Challenges of the application which can influence the performance of the plan also described. The study is done for Lead Oxide production process- a critical system of battery industries. RCM method can shift the maintenance culture and thinking while maximizing equipment availability and enhancing plant reliability in this type of industries and other industries also.

Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Background of the study

Today industries are constantly being challenged to manage the operational excellence and maintenance efficiency while remaining competitive in the global market place. Reliability Centered Maintenance (RCM) is an industrial improvement approach that can manage the risk of equipment failure most effectively. RCM philosophy employs preventive maintenance (PM), Predictive Testing and Inspection (PT&I), run-to-failure and proactive maintenance techniques as an integrated manner to increase the probability that a machine or component will function in the required manner over its design life cycle with a minimum of maintenance and downtime while minimizing life-cycle costs. This integrated approach is applied to take advantage of their respective strengths in order to maximize facility and equipment reliability while minimizing life-cycle costs. Applying the RCM methodology demonstrated that the Mean Time Between Failures (MTBF) for the plant equipments improved and the probabilities of sudden equipment failures are decreased significantly. In this work a frame work will be developed for applying RCM methodology in lead oxide production system used in battery manufacturing industries. Currently break down maintenance, time based interval maintenance and corrective maintenance are generally practiced in these industries. Existing system is challenged frequently by sudden failures, manpower crisis, and unusual spares consumptions which directly affect the production capacity and operational expenditure. RCM can be the gateway to overcome this situation. The study will provide guidance for adopting RCM principles and implementing RCM in other industries also.

The first step in the RCM process is to define the functions of each asset in its operating context, together with the associated desired standards of performance. Then identify what failure can occur and defeat the functions. Once each functional failure has been identified, the next step is to try to identify the causes of failures, *i.e.*, all the events which are reasonably likely to cause each failure mode. These events are known as failure modes. The fourth step in the RCM process involves listing failure effects, which describe what happens when each failure mode occurs at the local and system level. Maintenance principle will be selected by analyzing the criticality of the failure effects.

The RCM was developed for the first time by United Airlines Company for the Defense American Department and was published in 1978. Currently The US Navy Air systems use Reliability-Centered Maintenance as the main tool in developing and implementing its integrated maintenance concept. It was also initiated in 1992 by the National Research Council (NRC) of Canada after examining the economic importance of diagnosing complex equipment problems correctly. Chemical Industries are constantly being challenged to manage the risks associated with the production and use of materials, while remaining competitive in the global market place. The Centre for Chemical Process Safety (CCPS) of the American Institute of Chemical Engineers (AIChE) has developed and operated an equipment reliability database to use RCM extensively.

1.2 Objectives of the study

The specific objectives of this project work are:

i. To develop a frame work for RCM for lead oxide production system used in battery manufacturing industries with component wise maintenance criteria selection process.
ii. To apply and evaluate proposed maintenance framework based on RCM techniques for lead oxide producing system.
iii. To find out the challenges to implement RCM in the existing system.

The possible outcome of the proposed work will be the guidelines and suggestions for implementation of RCM in a Lead Oxide producing system which will be helpful for the industries of this sector.

1.3 Organization of the thesis paper

After the introductory words reliability centered maintenance basics are elaborated in the chapter two. Here the principles of RCM approach, their major components overview and benefits of RCM described for literature base. Then in chapter three methodology of RCM described enormously with seven steps- system selection and information collection, system boundary definition, system description and functional block diagram, system function and functional failures, failure mode effects and criticality analysis (FMECA), logic tree analysis (LTA) and task selection. Following chapter four is on the case study of lead oxide production system based on the seven steps methodology in practical. Then the evaluation criteria of RCM analysis showed in chapter five. Challenges of implementation of RCM are described in chapter six. Finally concluding with the limitations, improvement and sustaining process of the study.

Chapter 2

Reliability Centered Maintenance (RCM)

2.1 Introduction to RCM approach

Reliability-Centered Maintenance (RCM) integrates Preventive Maintenance (PM), Predictive Testing and Inspection (PT&I), Repair (also called reactive maintenance), and Proactive Maintenance to increase the probability that a machine or component will function in the required manner over its design life-cycle with a minimum amount of maintenance and downtime. These principal maintenance strategies, rather than being applied independently, are optimally integrated to take advantage of their respective strengths, and maximize facility and equipment reliability while minimizing life-cycle costs. The goal of this approach is to reduce the Life-Cycle Cost (LCC) of a facility to a minimum while continuing to allow the facility to function as intended with required reliability and availability.

2.1.1 RCM principles

Reliability Centered Maintenance is a systematic approach to defining a planned maintenance program poised of cost-effective tasks while preserving critical plant functions. This is done in order to manage the risks of a system's functional failure in an economically effective manner, and is especially applicable to situations where there are low or constrained financial resources. An important aspect of this philosophy is to prioritize systems by assigning levels of criticality based on the consequences of failure.

RCM focuses on the following principles:

Function-Oriented: RCM seeks to preserve system or equipment function, not just operability for operability's sake. Redundancy of function through redundant equipment improves functional reliability but increases life-cycle cost in terms of procurement and operating costs.

System-Focused: RCM is more concerned with maintaining system function than individual component function.

Reliability-Centered: RCM treats failure statistics in an actuarial manner. The relationship between operating age and the failures experienced is important. RCM is not overly concerned with simple failure rate; it seeks to know the conditional probability of failure at specific ages (the probability that failure will occur in each given operating age bracket).

Acknowledges Design Limitations: The objective of RCM is to maintain the inherent reliability of the equipment design, recognizing that changes in inherent reliability are the province of design rather than maintenance. Maintenance can only achieve and maintain the level of reliability for equipment which is provided for by design. RCM recognizes that maintenance feedback can improve on the original design.

Safety, Security, and Economics: Safety and security must be ensured at any cost; life-cycle cost-effectiveness is a tertiary criterion.

Failure as Any Unsatisfactory Condition: Failure may be either a loss of function (operation ceases) or a loss of acceptable quality (operation continues).

Logic Tree to Screen Maintenance Tasks: This provides a consistent approach to the maintenance of all equipment.

Tasks Must Be Applicable: Tasks must address the failure mode and consider the failure mode characteristics.

Tasks Must Be Effective: Tasks must reduce the probability of failure and be cost-effective.

RCM is a living system: RCM collects information from the results achieved and feeds it back to improve design and future maintenance.

2.2 RCM Components

The four major components of RCM are shown in Fig. 2.1. These are: reactive maintenance, preventive maintenance, predictive testing and inspection (PT & I), and proactive maintenance. Each component is described below.

2.2.1 Reactive Maintenance

Reactive maintenance is also known as breakdown, fix-when-fail, run-to-failure, or repair maintenance. When using this maintenance approach, equipment repair, maintenance, or

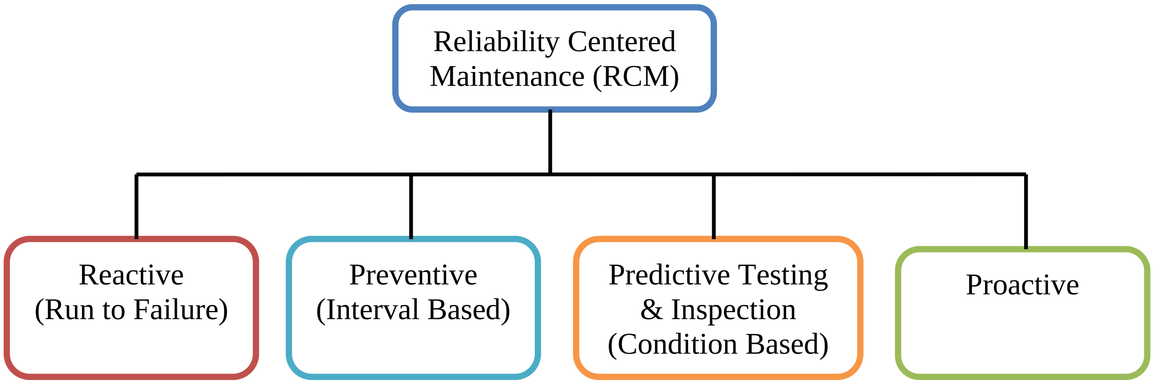

Fig 2.1: RCM program components

replacement takes place only when deterioration in the condition of an item/equipment results in a functional failure.

In this type of maintenance, it is assumed there is an equally likely chance for the occurrence of a failure in any part, component, or system. When reactive maintenance is practiced solely, a high replacement of part inventories, poor use of maintenance effort, and high percentage of unplanned maintenance activities are typical. Furthermore, an entirely reactive maintenance program overlooks opportunities to influence equipment/item survivability.

Reactive maintenance can be practiced effectively only if it is carried out as a conscious decision, based on the conclusions of an RCM analysis that compares risk and cost of failure with the cost of maintenance needed to mitigate that risk and failure cost.

Table 2.1: Reactive maintenance priority classifications

Priority Number	Priority Description	Criteria Based on System/Equipment Failure Consequences
1	Emergency	Safety of life or property threatened. Immediate serious impact on operation.
2	Urgent	Continuous facility operation threatened. Impending serious impact on operation.
3	Priority	Degrades quality of operation support. Significant and adverse effect on project.
4	Routine	Redundancy available. Impact on operation insignificant.
5	Discretionary	Impact on operation negligible. Resources available.
6	Deferred	Impact on operation negligible. Resources unavailable.

2.2.2 Preventive Maintenance

Preventive Maintenance (PM) consists of regularly scheduled inspection, adjustments, cleaning, lubrication, parts replacement, calibration, and repair of components and equipment. PM schedules periodic inspection and maintenance at pre-defined intervals (time, operating hours, or cycles) in an attempt to reduce equipment failure. It is performed regardless of equipment condition.

Depending on the intervals set, PM can result in a significant increase in inspections and routine maintenance. PM also reduces the frequency and seriousness of unplanned machine failures for components with defined, age-related wear patterns.

Traditional PM is keyed to failure rates and times between failures. Failure rate or its reciprocal, Mean Time between Failures (MTBF), is often used as a guide to establishing the interval at which the maintenance tasks should be performed. The major weakness in using these measurements to establish task periodicity is that failure rate data determines only the *average* (arithmetic mean) failure rate. Failures are equally likely to occur at random times and with a frequency unrelated to the average failure rate. Selecting a specific time to conduct periodic maintenance for a component with a random failure pattern is difficult. For some items with age-related failure, failure is not equally likely to occur throughout the life of the item. The majority of equipment is not subject to wear-out (sharply increasing conditional probability of failure at a specific operating age).

Timed maintenance can often result in unnecessary and in some cases harmful maintenance. PM can be costly and ineffective when it is the sole type of maintenance practiced.

2.2.2.1 Determining PM Task and Monitoring Periodicity

There are many ways to determine the correct periodicity of PM tasks; none are valid until the in-service age-reliability characteristics of the item affected by the desired tasks are known. Usually, this type of information is not available, but it must be obtained for new items/equipment. PT&I techniques should be used as an aid in determining the relationship between equipment condition and equipment age. Often, the parameter mean time between failures (MTBF) is used as the basis for determining the PM interval. This approach is considered wrong because it does not provide information about the effect of increasing age on item reliability. More specifically, the approach provides the average age at which failure occurs, but not the most likely age for the item under consideration. In the event of inadequate information on the effect of age on reliability, the most appropriate approach would be to monitor the item's condition.

2.2.2.2 Item/Equipment Monitoring

The main objectives in monitoring item/equipment condition are to determine item/equipment condition and to establish a trend to forecast future item/equipment condition. The following approaches are useful for setting initial periodicity:

Anticipating Failure from Experience: In some cases, failure history of equipment and personal experience can provide, to a certain degree, an intuitive feel as when to expect a failure.

Failure Distribution Statistics: The failure distribution and the probability of failure must be known when statistics are used to determine the basis for selecting periodicities.

Conservative approach: The common practice in the industrial sector is to monitor the equipment monthly/weekly when good monitoring methods and adequate information are unavailable. Often, this leads to excessive monitoring.

In situations when impending failure becomes apparent through the use of trending or other predictive analysis techniques, the monitoring interval can be shortened.

2.2.3 Predictive Testing and Inspection (PT&I)

PT&I, also known as predictive maintenance or condition monitoring, uses primarily nonintrusive testing techniques, visual inspection, and performance data to assess machinery condition. PT&I replaces arbitrarily timed maintenance tasks with maintenance that is scheduled only when warranted by equipment condition. Continuing analysis of equipment condition-monitoring data allows planning and scheduling of maintenance or repairs in advance of catastrophic and functional failure.

The collected PT&I data are used in one of the following ways to determine the condition of the equipment and identify the precursors of failure: trend analysis; pattern recognition; data comparison; tests against limits and ranges; correlation of multiple technologies; statistical process analysis.

PT&I does not lend itself to all types of equipment or possible failure modes and therefore should not be the sole type of maintenance practiced.

2.2.4 Proactive Maintenance

Proactive maintenance improves maintenance through better design, installation, maintenance procedures, workmanship, and scheduling. The characteristics of proactive maintenance are: Using feedback and communications to ensure that changes in design or procedures are rapidly made available to designers and managers; employing a life-cycle view of maintenance and supporting functions; ensuring that nothing affecting maintenance occurs in isolation; employing a continuous process of improvement; optimizing and tailoring maintenance techniques and technologies to each application; integrating functions that support maintenance into maintenance program planning; using root-cause failure analysis and predictive analysis to maximize maintenance effectiveness; adopting an ultimate goal of fixing the equipment permanently; periodic evaluation of the technical content and performance interval of maintenance tasks (PM and PT&I).

Proactive maintenance employs the following basic techniques to extend machinery life: specifications for new/rebuilt equipment; commissioning; precision rebuild and installation; failed-part analysis; root-cause failure analysis; reliability engineering; rebuild certification/verification; age Exploration (AE) and the relationship with Replacement of Obsolete Items (ROI); recurrence Control

2.3 Benefits of RCM

Some benefits of RCM include safety, security, cost, reliability, scheduling, and efficiency.

Safety: This ensures avoid loss of life, personal injury, illness, property loss, property damage, and environmental harm, and to ensure safe and healthful conditions for persons working at or visiting facilities. The RCM approach supports the analysis, monitoring, early and decisive action, and thorough documentation.

Security: An RCM approach provides improved reliability of physical barriers and emergency support by adding PT&I tasks.

Cost: Due to the initial investment required for obtaining the technological tools, training, and equipment condition baselines, a new RCM Program typically results in an increase in maintenance costs. This increase is relatively short-lived, averaging two to three years. The cost of repair decreases as failures are prevented and preventive maintenance tasks are replaced by condition monitoring. The net effect is a reduction of both repair and total maintenance costs. Often energy savings are also realized from the use of PT&I techniques.

Reliability: RCM places great emphasis on improving equipment reliability through the feedback of maintenance experience and equipment condition data to facility planners, designers, maintenance managers, craftsmen, and manufacturers. This information is instrumental for continually upgrading the equipment specifications for increased reliability. The increased reliability that comes from RCM leads to fewer equipment failures, greater availability for system support, and lower maintenance costs.

Scheduling: The ability of a condition-monitoring program to forecast maintenance provides time for planning, obtaining replacement parts, and arranging environmental and operating conditions before the maintenance is done. PT&I reduces the unnecessary maintenance performed by a time-scheduled maintenance program which are driven by the minimum “safe” intervals between maintenance tasks. A principal advantage of RCM is that it obtains the maximum use from equipment. With RCM, equipment replacement is based on actual equipment condition rather than a predetermined, generic length of life.

Efficiency/Productivity: Safety is the primary concern of RCM. The secondary concern of RCM is cost-effectiveness. Cost-effectiveness takes into consideration the priority or system criticality and then matches a level of cost appropriate to that priority. The flexibility of the RCM approach to maintenance ensures that the proper type of maintenance is performed on equipment when it is needed. Existing maintenance that is not cost-effective is identified and not performed.

Chapter 3

RCM Application Methodology

3.1 RCM basics

Reliability Centered Maintenance is applied as an optimum mix of Preventive Maintenance, Predictive Testing & Inspection, Repair (reactive maintenance) and Proactive Maintenance. This integrated approach is used to take advantages of their respective strengths and maximize facility and equipment reliability while minimizing lifecycle costs.

RCM identifies all the perspectives that a system function can fail and employs the appropriate maintenance approach for that failure. The methodology can be expressed entirely by the following four considerations:

1. Conservation of the system function
2. Finding out all the failure modes that can make the system nonfunctional
3. Determining the consequences of the failures and prioritize based on function criticality
4. Selection of effective actions those are only applicable to prevent that prioritize functional failure

These demonstrate RCM as to prioritize functional importance need to be maintained and focus resources on those maintenance works that promote system reliability.

As per SAE JA1011 (Society of Automotive Engineers Inc.) standard evaluation criteria of any RCM process as follows:

a. What are the functions and associated desired standards of performance of the asset in its present operating context (functions)?
b. In what ways can it fail to fulfill its functions (functional failures)?
c. What causes each functional failure (failure modes)?
d. What happens when each failure occurs (failure effects)?
e. In what way does each failure matter (failure consequences)?

f. What should be done to predict or prevent each failure (proactive tasks and task intervals)?

g. What should be done if a suitable proactive task cannot be found (default actions)?

3.2 Main Steps of RCM Methodology

To implement RCM following steps will be carried out.

1. System selection and information collection
2. System boundary definition
3. System description and functional block diagram
4. System function and functional failures
5. Failure mode effects and criticality analysis (FMECA)
6. Logic tree analysis (LTA)
7. Task selection.

3.2.1 System selection and data collection

This is the most important factor for RCM analysis. As many systems neither have the history of consistent failures nor incur excessive maintenance costs that would justify the whole effort. A system should be selected considering the following criteria

-More corrective maintenance done in recent times

-More preventive maintenance tasks

-Total maintenance cost is high

-Mean time between failures (MTBF) is low

-Mean time to repair (MTTR) is high

-Responsible for plant outages (full or partial) in recent times

-High safety concern

-High environmental concern

The next step, after selecting systems, is collecting information related to these systems. Some common documents are identified that may be required in a typical RCM study. Main data that need to be gathered are

-System schematic or block diagram
-Functional flow diagram
-Piping and instrumentation diagram
-Equipment design specification and operations manual
-Equipment failure and maintenance history
In absence of comprehensive data and records plant personnel (including maintenance and operations) interview can be conducted.

3.2.2 System boundary definition

Detailed and precise boundary identification is vital. Key reasons for this are:
1. An exact knowledge of what is included (conversely not included) in a system in order to make sure that any key system function or equipment is not neglected (conversely not overlapped from another equipment). This is especially important if two adjacent systems are selected.
2. Boundary definition also includes system interfaces (both IN and OUT interfaces) and interactions that establish inputs and outputs of a system. An accurate definitions of IN and OUT interfaces is a precondition to fulfill step 3 and 4.

There are no clear rules to define system boundaries; however as a general guideline a system has one or two main functions with a few supporting functions that would make up a logical grouping of equipment. However the boundary is identified, there must be clear documentation as part of a successful process.

3.2.3 System description and functional block diagram (FBD)

Description of each component is implied to establish a baseline status for function, performance specification, tolerance etc. These will make an indication for measuring ongoing performance or degradation. This baseline information also serves as a record that will assist in comparisons during modifications and upgrades in the design or operations. It also identifies key design and operational parameters that directly affect the performance of the system functions.

The Functional Block Diagram (FBD) is drawn showing the functional flow and functional interactions with in and out interfaces. It deals with the static and physical relationship that exists in a system. It does not illustrate the more significant characteristics of a system such as the behavioral response that happens with the changes in the system environment. This behavioral response depends on the function that a system can perform to such environmental inputs and constrictions. To model this functional behavior a FBD or functional block diagram is used. FBD elaborates functional flow in a system which is a top-level representation of the major function that a system performs. Arrows connecting blocks roughly represent interaction amongst functions and with the IN/OUT interfaces. IN interfaces exist within a system while OUT interfaces exist at the boundaries of the system, making themselves the principle objects to preserve system functions. A point to note is that the IN interfaces might be OUT interfaces in some other systems. If an interface is within a system boundary connecting to system environment it is called the Internal OUT interface.

3.2.4 System function and functional failures

This step identifies the functions that are needed to be preserved by the system (at the OUT interfaces). An important point to note is that these statements are for defining system functions and not the equipment. With the definition of system functions, come the functional failures. In fact, failing to preserve a system function constitutes what is called a functional failure. This leads to the step of how a process function can be defeated. This requires two things; keeping the focus on the loss of function and not the equipment and that the functional failures are more than just a single statement of loss of function. The loss conditions may be two or more (*e.g.,* complete paralysis of the plant or major or minor deprivation of functionality. This distinction is important and will lead to the proper ranking of functions and functional failures.

It is important that all functions be identified. Failure to identify all functions can result in important failures being overlooked. To ensure that all functions are identified and completely defined, it is important that functions be stated in terms of what the functional group must do/provide for the operation of the system, and not how individual equipment items operate.

Each function should be documented as a function statement that contains a verb, an object and a performance standard. The performance standard is to describe the minimum acceptable requirement rather than the design capability. Performance standards must be clearly defined or quantified. They are used to define failure, which forms the basis of the maintenance decision-making process.

Functions are to be categorized as follows:

Primary function: These functions are the reasons why the system/equipment exists. For example, the primary functions of a diesel engine are to provide power to drive the propeller from 0 to 91 RPM with output from 0 to 16,860 kW. The minimum acceptable output is 9,000 kW to maintain a minimum vessel speed of 7 knots.

Secondary function: Most systems/equipment will have secondary functions that will generally be less obvious than the primary functions, although their failure may sometimes have worse consequences. For example, some of the secondary functions of a diesel engine are to have acceptable engine emissions in accordance with some standard, to have a vibration level that will not affect structural integrity, etc.

3.2.4.1 Identifying Functional Failures

For each function in the functional group, a series of functional failures must be identified. In general, each function will have at least two functional failures. A functional failure can be a complete loss of function or partial loss of function. The partial loss of function is usually represented by deviations in the performance standard. Functional failures can be identified from functions by applying the following guides to each function:

- No or none of the function
- Less of each performance standard parameter
- More of each performance parameter
- Premature operation of the function
- Failure to cease operation of the function (e.g., function operates too long)
- Intermittent operation of the function
- Other functional failures appropriate for the functional group

Each functional failure should be documented in a functional failure statement that contains a verb, an object and the functional deviation.

3.2.5 Failure mode effects and criticality analysis (FMECA)

Once potential functional failures have been identified, the next step in the RCM analysis is to conduct an FMECA. The purpose of this step is to establish the cause-and-effect relationship among potential equipment failures, functional failures and the end effect of the functional failures, and to evaluate the criticality of the postulated failure mode.

There are two basic approaches for conducting an FMECA: a bottom-up approach and a top-down approach. For the analysis here bottom-up approach will be performed. The bottom-up approach determines whether the equipment failure mode results in a local effect that causes a functional failure that causes an end effect of interest. Following are the steps for performing a bottom-up FMECA:

1. Select an equipment item for analysis
2. Identify the potential failure modes for the equipment item
3. Select a failure mode for evaluation
4. Determine the local, next higher level and end effects for the postulated failure mode
5. If the end effect results in a consequence of interest, determine the causes of the failure mode
6. Determine the criticality of the failure mode using the risk decision tool
7. Repeat steps as necessary until all equipment items and associated failure modes have been evaluated

For the step six here using data and knowledge of the process or equipment, each potential failure mode and effect is rated in each of the following three factors:
Severity – the consequence of the failure when it happens;
Occurrence – the probability or frequency of the failure occurring; and
Detection – the probability of the failure being detected before the impact of the effect is realized.

Then these three factors are combined in one number called the risk priority number (RPN) to reflect the priority of the failure modes identified. The risk priority number (RPN) is simply calculated by multiplying the severity rating, times the occurrence probability rating, times the detection probability rating.

Further prioritization will be conducted in the next step using logic tree analysis.

For each component, the failure modes are listed, their causes are identified, and their effects are determined. Standardized form of FMEA is shown in the **fig.3.1.** This initial screening of the failure modes help to prioritize them.

No.	**Description of the equipment**				
Item	**Failure Mode**	**Causes**	**Local Effects**	**Functional failures**	**End Effects**

Fig. 3.1: Standardized form for FMEA

3.2.5.1 Considerations in Identifying Failure Modes and Failure Effects

The FMECA must identify the equipment failures that cause functional failures, which will result in end effects of interest so that proper failure management strategies can be determined. To ensure that the FMECA accomplishes this purpose, the following issues must be considered.

To identify Failure Modes:

i) Failures that have previously occurred on similar equipment

ii) Any other failure modes that have not yet occurred but are considered probable, including those being suppressed by the current preventative maintenance program

iii) Failure modes that are possible but considered unlikely

To Identify Failure Effects:

Failure effects should be identified at three levels:

i) Local effects to the system/equipment are being analyzed

ii) Next higher effects are effects on the larger system to which the system/equipment forms a part and should include the following: Potential physical damage to the system/equipment, potential secondary damage to either other equipment in the system or unrelated equipment in the surrounding area

iii) End effects are effects on the system and should include the following: Threats to safety and the environment or operational effectiveness of the system or downtime needed to repair the damage

3.2.5.2 Assessing the Criticality of Failure Modes and Effects

The purpose of the criticality analysis is to rank, based on the best available data, each potential failure mode identified during the FMECA according to the combined influence of severity classification and its probability of occurrence and failure detection. This allows the comparison of each failure mode to all other failure modes with respect to risk. The process highlights the risk associated with each failure mode.

Evaluation of criticality of the failure modes is done considering three factors severity, occurrence and detection. Then the prioritizing of the failure modes is conducted based on risk priority number (RPN) - product of *severity, occurrence and detection*. Here,

Severity- is an index that denotes the gravity of the consequences.

Occurrence- is an index defined in terms of number of failure occurrences in a time frame; this is a dynamic index and need to be reevaluated every year.

Detection- is an index based on probability estimative that a failure can be detected.

Therefore, the FMECA analysis is dynamic and its values should be annually modified.

3.2.6 Logic tree analysis (LTA)

To preserve the system, selection of the most appropriate failure management strategy of the Failure modes (for which FMEA has been conducted) are performed based on three issues - safety, operational and economical vital factors.

This is done since each failure mode and its impact on the whole plant is not the same. This process structured in simple and intuitive question logic of decisions that enables a user with minimal effort to find the appropriate management strategy.

Each question is answered yes or no only.

RCM logic tree helps to determine the type of maintenance appropriate for any given sub-system or equipment item. The result of this analysis indicates whether a particular piece of equipment will be maintained reactively (Run to Fail), through a preventive maintenance approach (Define PM task and schedule), monitor and take maintenance action based on predictions of imminent failure (Define PT&I task and schedule) or redesign proactively rather accept risk of failure.

3.2.7 Task selection

Finally allocation of tasks in an applicable and cost effective way is justified. Application of tasks is to be qualified as interval based, condition based or redesign system. If no suitable task is found ‘run equipment to failure’ will be decided.

The task selection requires that each task is applicable and effective. Here, applicable means that the task should be able to prevent failures, detect failures, or unearth hidden failures, while effective is related to the cost effectiveness of the alternative PM strategies. This activity requires contribution from the maintenance personnel as their experience is invaluable in the right selection of the PM task.

It is necessary to assign a maintenance activity to every failure mode. That activity should prevent the occurrence of the failure mode in the most efficient way. Every selected type of activity should have its description and details about its periodic repetitions.

3.2.7.1 Considerations for task selection

There are some criteria to be considered prior to deciding the type of task to select for a piece of equipment (condition directed, time based, failure finding).

When determining the applicability and effectiveness, the following should be considered:

1. Must be practicable to implement (e.g., the required maintenance task interval and accessibility for carrying out the task are operationally feasible)
2. Must have a high degree of success in detecting the failure mode
3. Must be cost-effective. The cost of undertaking a task over a period of time should be less than the total cost of the consequences of failure. The costs should include man-hours, spares, tools and facilities, and should be assessed on the basis of through-life costs.

Condition Directed Tasks: For a condition-monitoring task to be selected, it must first be applicable and effective. The task must be able to detect the potential failure condition and there must be a reasonable, consistent amount of time between the first indication of potential failure and the actual failure. The task frequency must be determined from the following sources listed in ascending order of priority and documented: Generic P-F interval data, manufacturers' recommendations, current task intervals, team experience

More specifically, however, when determining the frequency for condition monitoring tasks, the frequency should be consistent with the time interval between the first indication of potential failure (a "threshold value") and the actual time of failure to allow a condition directed task to be carried out.

Time Based Tasks: For time based overhaul tasks to be applicable there must be an identifiable age at which the component displays a rapid increase in the conditional probability of failure. A large proportion of the same equipment type must survive to that age, and it must be possible to restore the original failure resistance to the component through rebuild or overhaul (or else the component must be replaced periodically).

Next, the team must evaluate the potential risk reduction resulting from implementing the planned-maintenance task just as in the condition-monitoring task.

The task frequency must be determined from the following sources listed in ascending order of priority and documented: Generic failure data, manufacturers' recommendations or failure data, Current task intervals, team experience

Failure Finding Tasks: For failure finding tasks to be applicable, the component must be subject to a failure mechanism that is not evident to personnel during normal operation of the equipment and there is no other applicable and effective type of task to prevent the failure from occurring.

Functional tests are useful failure finding tasks for protective features and interlocks.

However, it must be assured that the test fully verifies the feature. If a device is supposed to block operation of a valve or pump start, make sure this function is tested, not just that the input works properly.

When determining frequency for failure finding tasks, consideration should be given to the expected frequency of demand, failure rate and tolerability of failure. Therefore, the task frequency must be determined from the following sources listed in ascending order of priority and documented: Generic failure data, manufacturers' recommendations or failure data, current task intervals, team experience. For failure-finding tasks, availability and reliability information, where possible, is to be used to set failure-finding intervals

Non Critical Components task: For non-critical components, maintenance tasks should only be selected if they are cost effective to perform. If no cost effective maintenance can be defined the components should be run-to-failure. This does not mean that the component is to be run to destruction or other significant effect – the component would have had routine maintenance recommended to prevent that. It means that there is no applicable, cost-effective maintenance that should be done to it, the consequences of run-to-failure are tolerable, and the failure is obvious to operators or maintenance personnel. It is to be noted that run-to-failure may imply that spare parts should be on hand, or easily obtainable, to repair or replace the component upon “failure.”

Chapter 4

RCM in Lead Oxide Production System

From the points of view described in section 3.1 lead oxide producing facility is selected for RCM analysis. This system delivers PbO to the pasted plate making facility which is a vital and compulsory part for battery production process.

In a battery production system there are mainly three divisions: Plate preparation, plastic container and cover molding and finally assembly of the battery with all the components. Among these parts plate preparation is the most important part where the finished plates for battery assembly produced in different steps of processes. Following are the steps to make finished plates from the lead ingots showed in **fig. 4.1.**

Production system follows process lay out in the plate preparation department. Here most of the chemical processes are performed for the making of finished (flat) plates required for battery assembly. In this lay out lead oxide production system has significant impact on battery production capacity which is selected for RCM analysis.

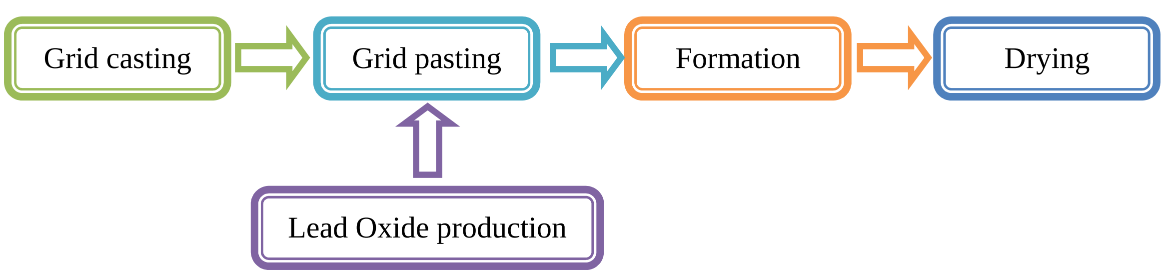

Fig. 4.1: Plate preparation process

4.1 Information Collection

Required documents are collected from the maintenance and operation departments of the factory. Machine failure history is collected from maintenance log book and Preventive maintenance records are collected from the maintenance officers. Functional data and specifications are gathered from process instruction (PI) manual. The original equipment manufacturers manual is collected from the maintenance department for technical information. Field supervision and interviewing the maintenance and operation personnel make a base for this study. But the unavailability of automated or accumulated data storage device tends the study slower.

Following are the failure modes and their frequencies found from the failure records in the last one year:

Table 4.1: Failure records summary of oxide production system

S/N.	Failure modes	Frequency
1.	Cylinder silo gate valve open/close failure	3
2.	Cylinder conveyor belt operational breakdown	4
3.	Cylinder conveyor belt torn out	1
4.	Oxide ball mill stops while running	25
5.	Ball mill running in less than required rpm	4
6.	Cooling spray mechanism failure	6
7.	Dust recovery auger stops	2
8.	Filter bag clogged	4
9.	Filter bag cleaning air distributor failure	20
10.	Filter bags torn out	2
11.	Absolute filter clogged	10
12.	Oxide extraction auger failure	6
13	Main fan motor stops	4
14	Air register operation failure	12
15	Oxide delivery auger stops	7
16	Bucket elevator failure	8
17	Oxide storage silo auger stops	5

4.2 System boundary Overview

The major facilities included in the selected process-

1. Cylinder storage silo
2. Oxide ball mill
3. Oxide filtering system
4. Air depression making mechanism
5. Oxide storage system

Electric power is the basic requirement for the subsystems. The functional connections are defined as below-

1. Lead cylinder enters to ball mill by a belt conveyor
2. Oxide mill cooled by water spray line while running
3. Produced oxide transferred to filter house through recovery auger from ball mill
4. Filter bag cleaning mechanism cleans the bags for fine oxide powder
5. Air depression made by main fan motor and controlled by air register connected to the filter bag out air pipe

Fig. 4.2: Main functional machines for lead oxide production system

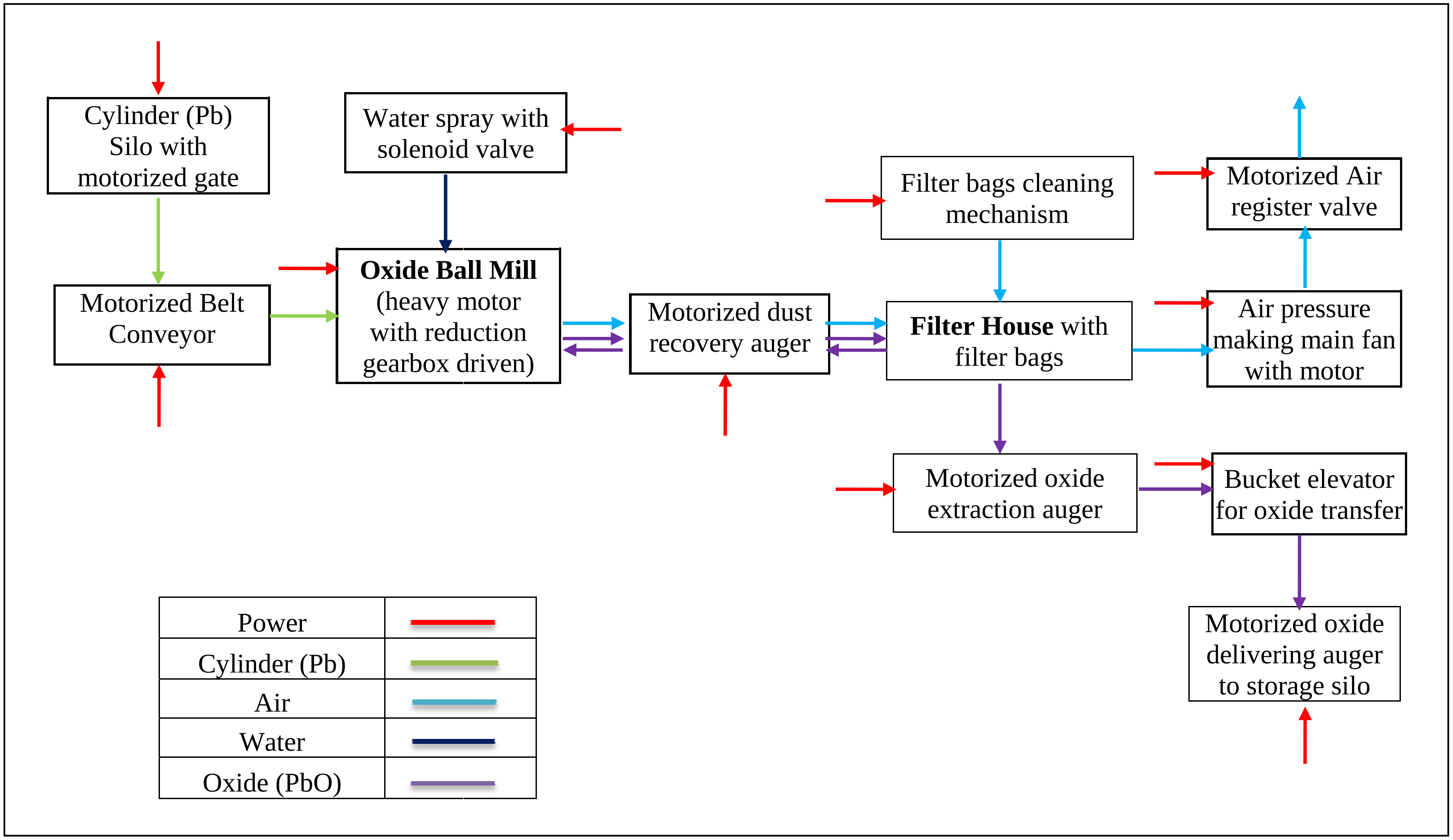

Fig. 4.3: Lead Oxide Production System Functional Block Diagram

6. Desired oxide passed to bucket elevator by extraction auger and delivering auger put that to oxide storage silo.

4.3 Description of Lead Oxide Production system

To produce lead oxide a chemical reaction is created between lead cylinder and oxygen of air with presence of heat energy - generated by the rotation inside the ball mill. Required air depression in the ball mill facilitated by a fan motor. The produced oxide has to maintain the free lead content (FLC) at 28±4%. To sustain this quality specification three criteria have to be preserved.

1) The weight of the filled ball mill should between 3500-4000Kgs which is controlled by the weigh cell and a controller- manage the cylinder entrance in the mill by the silo motorized gate valve.
2) Temperature of the ball mill on 120±10°C maintained by sensor (thermocouple) and a controller to let the water spray on the ball mill switch on or switch off.
3) Inlet depression of the ball mill in the range of 123-160mm of H_2O checked by a pressure sensor and maintained by a motorized air register assembly.

The produced oxide dust is transferred to filter house in the filter bags by the main air depression through dust recovery auger. Filter bags are kept clean by a washing fan motor. The washing air pressure made opposite of oxide flow by a washing distributor header and locking a specific part of filter bags by an air pulse rotating system.

Consequently the remaining oxides after filtration return back to the mill. Then the filtered oxides go through an absolute filter to ensure the desired particle size. After the absolute filter main air depression motor is connected with the air register control assembly and piping out to exhaust air line. The filter clogging is measured by the output air depression if greater than 500mm of H_2O. The yielded oxide of the filter house is extracted by an auger to the bucket elevator which is further delivered to top of the oxide storage silo by another auger. The whole system is air leak proof to maintain the quality.

4.4 Functions and identifying functional failures

The whole oxide production system is consists of the main two sub functional systems. For stating the system function and their failure lead oxide ball mill and filter house functional groups are analyzed. The functions are identified based on the operating context of the functional group. To ensure that all functions are identified and completely defined, functions are stated for oxide ball mill and filter house operation. Any of their functional failure may hamper the whole production system function. Each function is documented as a function statement that contains a verb, an object and a performance standard. The performance standard is the minimum acceptable requirement rather than the design capability. Whether the function is primary or secondary also mentioned. For each function in the functional group functional failures (at least two) are identified. A functional failure represented as complete loss of function or partial loss of function. The partial loss of function is represented by deviations in the performance standard. In **Table 4.2** and **Table 4.3** equipments functional parameters and specifications are displayed, deviation of these specifications can make system outage or partial outage.

4.5 Failure modes effects and criticality analysis (FMECA)

After knowing the system functional failures more specific component wise failure modes are detected, their causes are indentified and their effects are determined both locally and on whole system. The systematic approach of FMEA analysis is presented in **Table4.4a** to **Table4.4j**.

Here all the equipment items are selected one by one for analysis. Potential failure modes for each equipment item are detected from the past failure history from the maintenance records and by consulting operation and maintenance personnel. Then every failure modes are evaluated by detecting their causes of failure and failure effects at the local and system level or end effects. The whole process is repeated as necessary until all equipment items and associated failure modes have been evaluated.

Table 4.2: Functions and functional failures of oxide ball mill

Equipment item: Oxide ball mill				
Function			**Functional Failure**	
Item No.	Function Statement	Function Type	Item No.	Functional Failure Statement
1	Producing lead oxide (PbO) with free lead content (FLC) 28±4%, maintaining temperature 120±10°C and weight 3500-4000Kg while inlet depression is 123-160mm of H_2O	Primary	1.1	No lead oxide production
			1.2	FLC in PbO is less than 24%
			1.3	FLC in PbO is more than 34%
			1.4	Temperature is less than 110°C
			1.5	Temperature is more than130°C
			1.6	Ball mill weight is less than 3500Kg
			1.7	Ball mill weight is more than 4000Kg
			1.8	Inlet depression is less than 123mm of H_2O
			1.9	Inlet depression is more than 160mm of H_2O

Table 4.3: Functions and functional failures of oxide filter house

Equipment item: Filter house				
Function			**Functional Failure**	
Item No.	Function Statement	Function Type	Item No.	Functional Failure Statement
1	Filtering of lead oxide (PbO) with 85mesh (or 180micron) with 5% retention	Primary	1.1	Filtered lead oxide particle size less than 85mesh (or 180 micron) with less than 5% retention
			1.2	Filtered lead oxide particle size more than 85mesh (or 180 micron) with more than 5% retention
2	After filtering filter house air outlet depression should maintain 100-500mm of H_2O	Secondary	1.1	Air outlet depression less than 100mm of H_2O
			1.2	Air outlet depression more than 500mm of H_2O

Table 4.4a: FMEA for cylinder silo gate valve

No.1	**Description: Cylinder silo motor driven gate valve**				
Item	**Failure Mode**	**Causes**	**Local Effects**	**Functional failures**	**End Effects**
1.1	Gate valve fails to open	• Driver motor failure • Motor gate coupling worn out • Motor control failure	No supply of lead cylinder to the feeding conveyor	Cylinder feeding of oxide ball mill stops	Oxide ball mill weight reduction, if it crosses the lower limit oxide mill stops
1.2	Gate valve fails to close	• Driver motor failure • Motor gate coupling worn out • Motor control failure	Excess supply of lead cylinder to the feeding conveyor	Cylinder feeding conveyor jamming and cylinder wastage	Conveyor motor trips consequently ball mill stops

Table 4.4b: FMEA for belt conveyor

No.2	**Description: Motorized belt conveyor**				
Item	**Failure Mode**	**Causes**	**Local Effects**	**Functional failures**	**End Effects**
2.1	Belt conveyor fails to feed cylinder	• Driver motor failure • Motor coupling worn out • Motor control failure • Conveyor roller worn out • Conveyor roller bearing seized	No supply of lead cylinder to the ball mill	Cylinder feeding of oxide ball mill stops	Weight of the ball mill becomes reduced, after the least value shut down mechanism starts.
2.2	Belt conveyor torn out	• Excess cylinder jamming on the conveyor • Too much tight installation • Wear out due to usage	No supply of lead cylinder to the ball mill	Cylinder feeding of oxide ball mill stops	Ball mill weight goes lower and stops after passing the smaller limiting value.

Table 4.4c: FMEA for oxide ball mill

No.3		**Description: Oxide ball mill**			
Item	**Failure Mode**	**Causes**	**Local Effects**	**Functional failures**	**End Effects**
3.1	Oxide ball mill stops while running	• Driver motor failure • Motor V-belt torn out • Motor control failure • Motor and gearbox hydraulic coupling failure • Gear box bearing seized and motor trips • Gear worn out and motor trips • Temperature increased higher than 130°C and uncontrolled • Weight increased higher than 4000kg and uncontrolled • Inlet depression lower than 123mm of H_2O • Filter cleaning fan motor failure • Filter air distributor header motor failure	No oxide supply to filter house Oxide may burn out for over temperature	Oxide production stops	Oxide production system trips by the interlock system
3.2	Ball mill running less than 28 rpm	• Hydraulic oil of the coupling reduced • Gear box gear worn out • V-belt of the motor and coupling loosened	Oxide production may be stopped and may fail to achieve minimum temperature	Oxide free lead content more than 34%	Production of oxide could not meet the quality specifications

Table 4.4d: FMEA for cooling water spray system

No.4	Description: Cooling water spray system				
Item	**Failure Mode**	**Causes**	**Local Effects**	**Functional failures**	**End Effects**
4.1	Cooling spray could not be operated while it is desired to start	• Water solenoid valve failure • Water supply failure • Valve operating control signal failed • Thermocouple faulty	Cooling system stops	Temperature goes higher than 130°C	Lead oxide may burn out and system over temperature lock trips the oxide mill.
4.2	Cooling spray running while it is desired to stop	• Water solenoid valve failure • Thermocouple faulty	Temperature cannot be controlled	Temperature goes below 110°C	FLC may increase more than 34%

Table 4.4e: FMEA for dust recovery auger

No.5	Description: Motorized dust recovery auger				
Item	**Failure Mode**	**Causes**	**Local Effects**	**Functional failures**	**End Effects**
5.1	Dust recovery auger stops	• Driver motor failure • Motor coupling worn out • Motor control failure • Bearing seized • Auger seized with the casing	Lead chips may fill the filter bags	Filter outlet depression goes higher than 500mm H_2O	Filter clogged and eventually lower the oxide production

Table 4.4f: FMEA for filter bag cleaning mechanism

No.6	Description: Filter bag cleaning mechanism				
Item	**Failure Mode**	**Causes**	**Local Effects**	**Functional failures**	**End Effects**
6.1	Filter bag clogged	• Filter bag cleaning fan motor failure • Fan Motor control failure • Dust recovery auger failure • Filter bags air distributor header motor failure	Reduction of oxide flow to the oxide extractor	Outlet depression goes higher than 500mm of H_2O	Oxide production reduced and may trips the oxide mill due to higher inlet depression more than 160mm of H_2O
6.2	Filter air distributor chain coupling failure	• Filter bags air distributor header motor failure • Motor control failure • Torn out chain coupling system • Upper limit and lower limit controls failure	Filter bag clogging and air distributor system failure	Outlet depression goes higher than 500mm of H_2O	Oxide production reduced and Trip the oxide mill due to higher inlet depression more than 160mm of H_2O

Table 4.4g: FMEA for filter bags and filter house

No.7	Description: Filter bags and filter house				
Item	**Failure Mode**	**Causes**	**Local Effects**	**Functional failures**	**End Effects**
7.1	Filter bags torn out	• Filter cleaning mechanism failure • Dust recovery auger failure • Life cycle failure	Absolute filter clogged frequently	Outlet depression goes higher than 500mm of H_2O	Oxide production reduced and Trip the oxide mill due to higher inlet depression more than 160mm of H_2O
7.2	Absolute filter clogged	• Filter bags torn out • Filter cleaning mechanism failure	Oxide extraction reduced	Outlet depression goes higher than 500mm of H_2O	Oxide production reduced and Trip the oxide mill due to higher inlet depression more than 160mm of H_2O

Table 4.4h: FMEA for oxide extraction auger

No.8	Description: Oxide extraction auger from filter house				
Item	**Failure Mode**	**Causes**	**Local Effects**	**Functional failures**	**End Effects**
8.1	Oxide extraction auger stops	• Driver motor failure • Motor coupling worn out • Motor control failure • Bearing seized • Auger seized with the casing	Outlet depression goes higher than 500mm of H_2O	Oxide delivery failure to the silo	Trips the oxide mill due to higher inlet depression more than 160mm of H_2O

Table 4.4i: FMEA for main fan and air register system

No.9	Description: Air pressure making main fan and air register system				
Item	**Failure Mode**	**Causes**	**Local Effects**	**Functional failures**	**End Effects**
9.1	Fan motor stops	• Driver motor failure • Motor control failure	Inlet depression goes zero	Oxide production stops	Oxide ball mill stops
9.2	Air register not in operation	• Driver motor failure • Motor gate coupling worn out • Motor control failure	Uncontrolled air depression at the inlet	Oxide production stops	Oxide ball mill stops
9.3	Air register is open when it is desired to be closed and air register closed when it is desired to be opened	• In let depression signal error • Controller error • Connection faulty	Uncontrolled air depression at the inlet	Un controlled FLC of the produced Oxide	lead oxide free lead content (FLC) 28±4% cannot be maintained

Table 4.4j: FMEA for Oxide storage mechanism

No.10	**Description: Oxide storage mechanism (delivering auger, bucket elevator, silo auger)**				
Item	**Failure Mode**	**Causes**	**Local Effects**	**Functional failures**	**End Effects**
10.1	Oxide delivering auger stops	• Driver motor failure • Motor coupling worn out • Motor control failure • Bearing seized • Auger seized with the casing	No supply of lead oxide to the elevator	Inlet depression goes higher than 160mm of H_2O	Ball mill and oxide production stops
10.2	Bucket elevator stops	• Driver motor failure • Motor coupling worn out • Motor control failure • Bearing seized • Elevator belt torn out • Bucket jammed due to vibrator stopping	No supply of lead oxide to the silo auger	Inlet depression goes higher than 160mm of H_2O	Ball mill and oxide production stops
10.3	Silo delivery auger stops	• Driver motor failure • Motor coupling worn out • Motor control failure • Bearing seized • Auger seized with the casing	No supply of lead oxide to the silo	Inlet depression goes higher than 160mm of H_2O	Ball mill and oxide production stops

In the above FMEA each failure mode is sequentially numbered. Counting of the modes is restarted for each new component. This number is used as failure mode pointer for the evaluation of the criticality or risk priority of that particular failure- influenced by severity, occurrence and detection. Where, severity is an index that reflects the gravity of the failure consequences, occurrence is an index defined in function of the number of failure occurrences registered, detection is an index constructed based on the probability estimative that a failure can be detected, assuming that it has occurred. The occurrence index is dynamic and must be reevaluated annually. Therefore, the FMEA analysis is dynamic and has its values annually modified. These parameters are measured in a scale of 1 to 10 where 1 indicates the lowest importance and 10 indicates the highest importance as per failure characteristics. **Table 4.5** (a, b, c) shows the classification criteria for each of these parameters. From these factors risk priority number is calculated in **Table 4.6.** The RPN is the value calculated by the product of the three previous indices (*Severity x Occurrence x Detection*). It is used for action taking prioritization. It is a practical way to prioritize certain failures and to evaluate which steps they must be taken first.

Table 4.5a: Criteria for failure mode assessment

	Severity
1	Very insignificant effect, corrected immediately by the operation team
2	Insignificant effect, corrected immediately by the maintenance
3	Minor effect, the component suffers to a gradual degradation case is not repaired
4	Moderate effect, the component does not execute its function, but the failure does not provoke stopping production its maintenance does not demand stop of machine
5	Moderate effect, which does not provoke stopping but whose maintenance demands stop of machine
6	Moderate effect, which does not provoke stopping but whose maintenance demands stop of machine for one day or less
7	Critical effect that provokes stopping production and whose maintenance demands stop of machine for more than one day
8	Very critical effect that provokes stopping production and instantly interrupts the system functions
9	Very critical effect that provokes stopping production and collapse the whole system
10	Catastrophic effect that can cause damages to properties or people

Table 4.5b: Criteria for failure mode assessment

	Occurrence
1	Without failure registry in the last 2 years.
2	1 failure in the last 1 year
3	2 failure in the last 1 year
4	3 failure in the last 1 year
5	4 or 5 failure in the last 1 year
6	6 failure in the last 1 year
7	7 failure in the last 1 year
8	8 failure in the last 1 year
9	9 failure in the last 1 year
10	10 or more failure in the last 1 year

Table 4.5c: Criteria for failure mode assessment

	Detection
1	Failure indicated directly by the instrumentation
3	Failure identified by the team operation daily inspections
5	Failure identified for abnormal noises, or indirectly by the instrumentation
7	Occult failure, impossible to be identified by the operator

Table 4.6: RPN calculation and criticality indication

	Factors for failure mode evaluation			
Failure ID	**Severity**	**Occurrence**	**Detection**	**General evaluation by RPN**
1.1	4	3	3	36
1.2	4	2	3	24
2.1	3	2	3	18
2.2	3	1	3	9
3.1	5	10	3	150
3.2	5	3	5	75
4.1	8	9	3	216
4.2	8	8	3	192
5.1	3	3	5	45
6.1	7	5	3	105
6.2	7	5	3	105
7.1	3	2	3	18
7.2	3	2	3	18
8.1	5	5	1	25
9.1	5	8	1	40
9.1	5	8	1	40
9.3	5	8	1	40
10.1	4	9	1	36
10.2	4	9	1	36
10.3	4	9	1	36

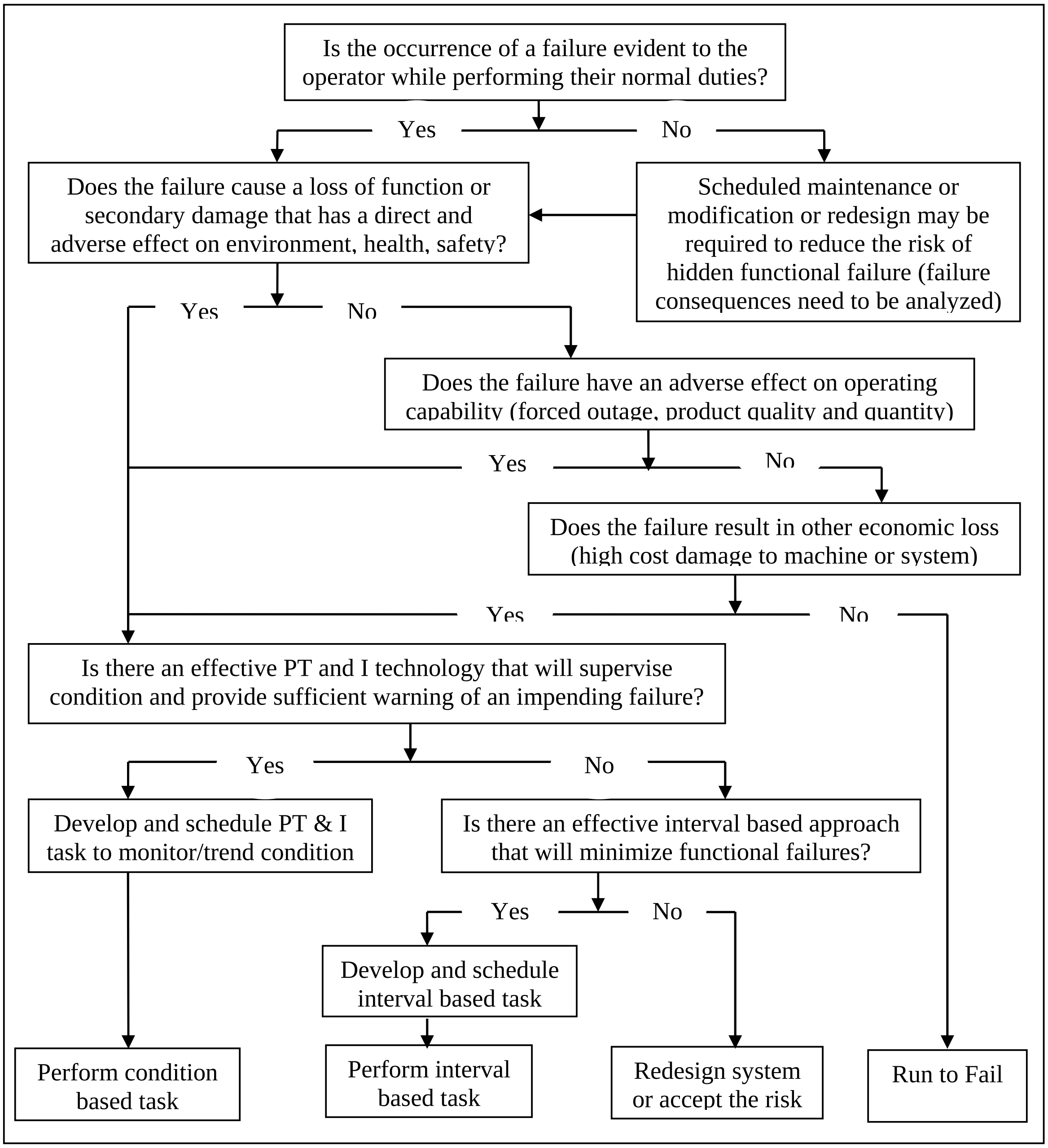

Fig. 4.4: Logic Tree Analysis for every failure mode (from FMEA)

4.6 Logic Tree Analysis (LTA)

To preserve the system function each of the failure modes from the FMEA decision tree is used for finding the appropriate failure management strategy as shown in **Figure 4.4**.

Here the first logic is to know if the failure is hidden or not in normal operating context. Each failure mode is entered into the top box of the tree, where the first question is to detect if the failure evident for the operator in normal operating condition.

Then safety and environmental, forced outage and quality related, economical aspects are checked sequentially. Each question is answered yes or no only.

For every failure mode appropriate failure management strategy- condition based or interval based or run to fail or to redesign system is decided from this simple but effective approach.

4.7 Task Allocation

After selection of failure management strategy maintenance tasks are allocated with them to preserve the function. Tasks are selected taking technical and economical feasibility in mind. In the **Table 4.7a to 4.7i** task selection with their frequency is illustrated. Here strategies are mentioned in abbreviated form as IB (Interval Based), CB (Condition Based), FF (Failure Finding), RD (Redesign) and RTF (Run to Fail).

Every task is selected that can be practically implemented, failure finding capability is high and cost of the task must be lower than the consequences of the failure.

Every selected type of activity has its description and details about its frequency. For condition based task a reasonable time left after the detection method till the failure happens so that the task can be carried out. For interval based task age of deterioration is identified and the task takes place before that period or simply replaced where applicable. Planned maintenance induced failure condition is also taken into mind for selection of task. For the failure finding tasks functional tests are done for protective features and interlocks. For non critical item if no suitable task is found then set to run to fail which evident to the operator.

Task frequency is determined based on generic failure data, manufacturers' recommendations, current task intervals and invaluable team experience.

Table 4.7a: Task allocation

Equipment	Failure Mode	Causes	Strategy	Description	Frequency
Cylinder silo gate valve	Gate valve fails to open or close	Driver motor failure	IB	•Check the motor current •Check the vibration of the motor	Monthly
		Motor control failure	FF	•Check the control wire •Check the thermal overload controller	Six Monthly
			CB	•Check the magnetic contactor contacts separately	Yearly
		Motor gate coupling worn out	IB	•Check the vibration of the motor	Monthly
			CB	•Check the coupling physical condition for replacement need	Monthly

Table 4.7b: Task allocation

Equipment	Failure Mode	Causes	Strategy	Description	Frequency
Belt conveyor	Belt conveyor fails to feed cylinder	Driver motor failure	IB	•Check the motor current •Check the vibration of the motor	Monthly
		Motor control failure	FF	•Check the control wire •Check the thermal overload controller	Six Monthly
			CB	•Check the magnetic contactor contacts separately	Yearly
		Motor coupling worn out	IB	•Check the vibration of the motor	Monthly
			CB	•Check the coupling physical condition for replacement need	Monthly
		Conveyor roller worn out	CB	•Check the roller physical condition if the belt loosened need fabrication	Six Monthly
		Conveyor roller bearing seized	CB	•Check the vibration, and noise of roller for replacement of bearing	Monthly
			IB	•Lubricate the roller bearing optimally	Weekly
	Belt conveyor torn out	Cylinder jamming on the conveyor	FF	•Check the gate valve operation	Monthly
		Extra tight installation	FF	•Check the tension with the weight of the cylinder	Yearly
		Wear out due to usage	IB	•Replace the belt after checking condition	Six Monthly
			CB	•Check the physical condition	Monthly

Table 4.7c: Task allocation

Equipment	Failure Mode	Causes	Strategy	Description	Frequency
Oxide ball mill	Oxide ball mill stops while running	Driver motor failure	IB	•Check the motor current •Check the vibration of the motor	Monthly
		Motor control failure	FF	•Check the control wire •Check the thermal overload controller	Six Monthly
			CB	•Check the magnetic contactor contacts separately	Yearly
		Motor V-belt torn out	CB	•Check the tension of the v-belts	Monthly
			IB	•Check the V-belt physical condition for replacement need	Six Monthly
		Motor and gearbox hydraulic coupling failure	IB	•Check the hydraulic oil level and refill if necessary	Monthly
			CB	•Check the leakage of the reservoir	Weekly
		Gear box bearing seized or gear worn out and motor trips	CB	•Check the vibration, and noise of gear box for replacement of bearing or gear	Monthly
			IB	•Check the oil level of the gear box and refill if necessary	Weekly
		Temperature increased higher than 130°C and uncontrolled	FF	•Check the thermocouple and the controller if faulty replace	Monthly
			IB	•Calibrate the controller for actual reading	Yearly
		Weight increased higher than 4000kg and uncontrolled	FF	•Check the weight cell and the controller if faulty replace •Check the gate valve operation	Monthly
			IB	•Calibrate the controller for actual reading	Yearly
		Inlet depression lower than 123mm of H_2O	FF	•Check the main fan motor operation •Check the operation of air register •Check the filter bag cleaning mechanism operation	Monthly

		Filter cleaning fan motor failure	FF	•Check the motor controller circuit	Monthly
		Filter air distributor header motor failure	FF	•Check the motor controller circuit	Monthly
	Ball mill running less than 28 rpm	Hydraulic oil of the coupling reduced	IB	•Check level of hydraulic oil refill if necessary	Weekly
		V-belt of the motor and coupling loosened	IB	•Check the tension of the v-belts	Monthly
			CB	•Check the V-belt physical condition for replacement need	Six Monthly

Table 4.7d: Task allocation

Equipment	Failure Mode	Causes	Strategy	Description	Frequency
Cooling water spray system	Cooling spray could not be operated while it is desired to start	Water solenoid valve failure	CB	•Check the solenoid valve operation manually •Check the baffle condition	Six Monthly
		Water supply failure	FF	•Check the water supply main valve •Check the water supply motor and pump	Monthly
		Valve operating control signal failed	FF	•Check the temperature controller •Check the control wire	Six Monthly
		Thermocouple or controller faulty	CB	•Check the thermocouple condition	Six Monthly
			IB	•Calibrate the controller for actual reading	Yearly
	Cooling spray running while it is desired to stop	Water solenoid valve failure	CB	•Check the solenoid valve operation manually •Check the baffle condition	Six Monthly
		Thermocouple or controller faulty	FF	•Check the tension with the weight of the cylinder	Yearly
			IB	•Calibrate the controller for actual reading	Yearly

Table 4.7e: Task allocation

Equipment	Failure Mode	Causes	Strategy	Description	Frequency
dust recovery auger, Oxide extraction auger, Delivery auger and Silo auger	Dust recovery auger stops	Driver motor failure	IB	•Check the motor current •Check the vibration of the motor	Monthly
		Motor control failure	FF	•Check the control wire •Check the thermal overload controller	Six Monthly
			CB	•Check the magnetic contactor	Yearly
		Motor coupling worn out	IB	•Check the vibration of the motor	Monthly
			CB	•Check the coupling physical condition for replacement need	Monthly
		Bearing seized	CB	•Check the vibration, and noise of the auger for replacement of bearing	Monthly
		Auger seized with the casing	CB	•Check the vibration, and noise of the auger and check the alignment with the casing	Six Monthly

Table 4.7f: Task allocation

Equipment	Failure Mode	Causes	Strategy	Description	Frequency
Filter bag cleaning mechanism	Filter bag clogged	Filter bag cleaning fan motor failure	IB	•Check the motor current •Check the vibration of the motor	Monthly
		Fan Motor control failure	FF	•Check the control wire •Check the thermal overload controller	Six Monthly
			CB	•Check the magnetic contactor	Yearly
		Dust recovery auger failure	IB	•Check the motor current •Check the vibration of auger	Monthly
			CB	•Check the clearance of the auger to cover wall	Six Monthly
		Filter bags air distributor header motor failure	IB	•Check the motor current •Check the vibration of the motor	Monthly
			CB	•Check the distributor mechanism	Six Monthly
	Filter air distributor chain coupling failure	Filter bags air distributor header motor failure	IB	•Check the motor current •Check the vibration of the motor	Monthly
			CB	•Check the distributor mechanism	Six Monthly
		Motor control failure	FF	•Check the control wire •Check the thermal overload controller	Six Monthly
			CB	•Check the magnetic contactor	Yearly
		Torn out chain coupling system	IB	•Lubricate the chain optimally	Monthly
			CB	•Check the chain condition	Monthly
		Upper limit and lower limit controls failure	CB	•Check the limit proximity sensor •Check the control wire	Monthly

Table 4.7g: Task allocation

Equipment	Failure Mode	Causes	Strategy	Description	Frequency
filter house	Filter bags torn out	Filter cleaning mechanism failure	CB	•Check the Filter cleaning mechanism	Monthly
		Dust recovery auger failure	CB	•Check the dust recovery auger assembly	Six Monthly
		Life cycle failure	CB	•Check the condition of filter bags	Monthly
			IB	•Replace the filter bags after checking condition	Six Monthly
	Absolute filter clogged	Filter bags torn out	CB	•Check the condition of filter bags	Monthly
			IB	•Replace the filter bags after checking condition	Six Monthly
		Filter cleaning mechanism failure	FF	•Check the mechanism manually	Monthly
			IB	•Check the filter condition and clean manually	Monthly

Table 4.7h: Task allocation

Equipment	Failure Mode	Causes	Strategy	Description	Frequency
main fan and air register system	Fan motor stops	Driver motor failure	IB	•Check the motor current •Check the vibration of the motor	Monthly
		Motor control failure	FF	•Check the control wire •Check the thermal overload controller	Six Monthly
			CB	•Check the magnetic contactor contacts separately	Yearly
			IB	•Lubricate the roller bearing optimally	Weekly
	Air register not in operation	Driver motor failure	IB	•Check the motor current •Check the vibration of the motor	Monthly
		Motor control failure	FF	•Check the control wire •Check the thermal overload controller	Six Monthly
		Motor coupling worn out	IB	•Check the vibration of the motor	Monthly
			CB	•Check the coupling physical condition for replacement need	Monthly
	Air register is open when it is desired to be closed and air register closed when it is desired to be opened	In let depression signal error	FF	•Check the pressure sensor •Check the control wire	Six Monthly
		Controller error	FF	•Check the controller function	Six Monthly
			IB	•Clean the controller with a mild air	Monthly
		Connection faulty	FF	•Check the connection of sensor with the controller	Six Monthly

Table 4.7i: Task allocation

Equipment	Failure Mode	Causes	Strategy	Description	Frequency
Oxide storage mechanism	Bucket elevator stops	Driver motor failure	IB	•Check the motor current •Check the vibration of the motor	Monthly
		Motor control failure	FF	•Check the control wire •Check the thermal overload controller	Six Monthly
			CB	•Check the magnetic contactor contacts separately	Yearly
		Motor coupling worn out	IB	•Check the vibration of the motor	Monthly
			CB	•Check the coupling physical condition for replacement need	Monthly
		Bearing of the elevator roller seized	CB	•Check the vibration, and noise of roller for replacement of bearing	Monthly
			IB	•Lubricate the roller bearing optimally	Weekly
		Elevator belt torn out	CB	•Check the condition of the belt and alignment	Monthly
			IB	•Tighten the bucket fixing points	Monthly
		Bucket jammed due to vibrator stopping	FF	•Check the vibrator overload	Monthly
			IB	•Check the vibrator current	Monthly

4.8 Proactive Maintenance practices

Proactive maintenance technique improves plant reliability with better design, change in maintenance procedure, prevention of recurrence of failure etc. from the table 4.1 the highest failure occurrence mode is noticed that is *the ball mill stopped while it is running*.

This type of maintenance methodology is very new to the factory management. But they are trying to implement it step by step. To reduce failure in fix forever mindset, Root Cause Failure Analysis (RCFA) is selected.

4.8.1 Root Cause Failure Analysis

Root-Cause Failure Analysis (RCFA) proactively seeks the fundamental causes that lead to facility and equipment failure. Its goals are to:

-Find the cause of a problem quickly, efficiently, and economically.

-Correct the cause of the problem, not just its effect.

-Provide information that can help prevent the problem from recurring.

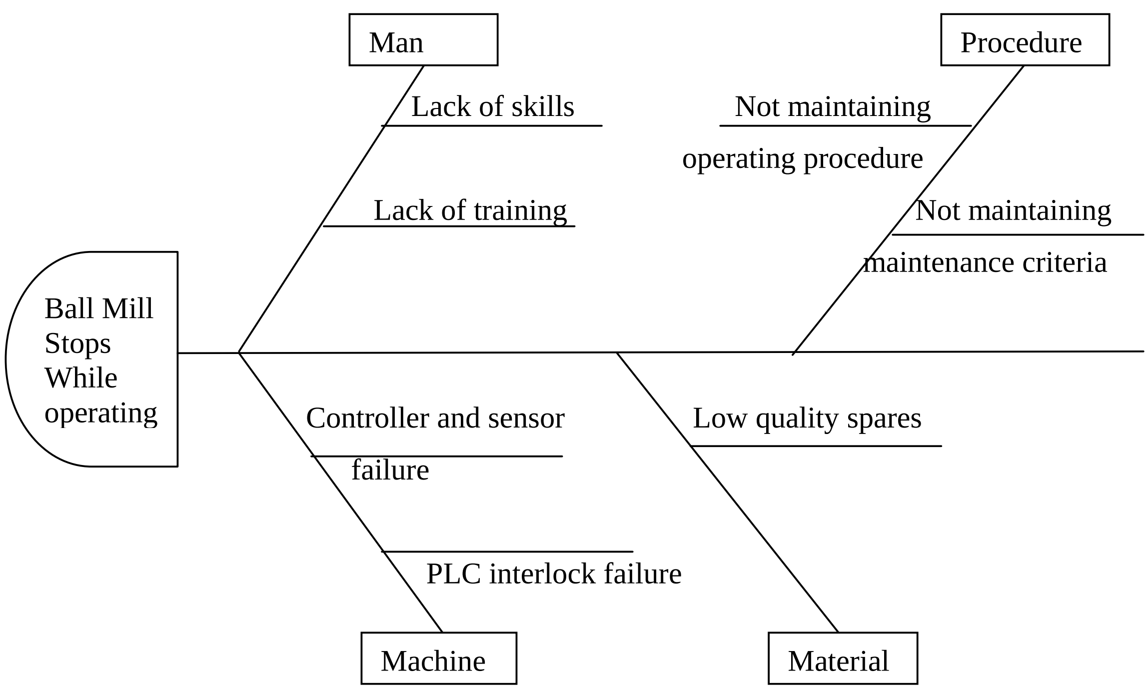

Fig 4.5: Cause and Effect diagram (Fish-Bone diagram)

First of all a team of five member is formed including maintenance and operation personnel to implement the analysis. Required data are gathered by brain storming, consultation with the experts, failure history etc. Here the ball mill failure analysis will be accomplished by a cause and effect diagram which is also known as fish bone diagram. This is very useful for finding cross functional influences.

As seen in **fig. 4.5** the head of the fish is the problem to be investigated and each of the main branches (bones) represents a specific functional area. To complete the diagram the investigation team continues to list all the possible connections each functional area might have with the failure. This format allows the team to see the overall picture and begin to focus the investigation as each of the functional branches is evaluated.

Each member put their rating regarding data collections and idea about every type of branches of failure causes. Here four types of criteria are evaluated: man, machine, material and procedure. Most of the cases data trend could not be found so experienced team mates express their valuable data ratings through past failure experiences shown in **Table 4.8**.
Then the failure root causes are streamlined by their rating formulations and gathered in a descending order in **Table 4.9**. From these data a Pareto diagram (**fig. 4.6**) is formed to depict the main cause to be solved. It is to be noted that rating impact factor defined from 0 to 5.

Table 4.8: Data formulation from the RCM team members

Causes	M-1	M-2	M-3	M-4	M-5	No. of formulation
Lack of skills	2	3	2	1	1	9
Lack of training	3	3	1	2	2	11
Controller and sensor failure	4	5	3	2	4	18
PLC interlock failure	5	5	3	5	5	23
Low quality spares	4	3	3	2	2	14
Not maintaining operating procedure	2	2	1	1	1	7
Not maintaining maintenance criteria	3	3	1	2	1	10

Table 4.9: Data formulation for Pareto diagram

Cause	No. of Formulations	Cumulative No. of formulations	% of Cumulative No. of formulations
PLC interlock failure	23	23	25.00%
Controller and sensor failure	18	41	44.57%
Low quality spares	14	55	59.78%
Lack of training	11	66	71.74%
Not maintaining maintenance criteria	10	76	82.61%
Lack of skills	9	85	92.39%
Not maintaining operating procedure	7	92	100.00%

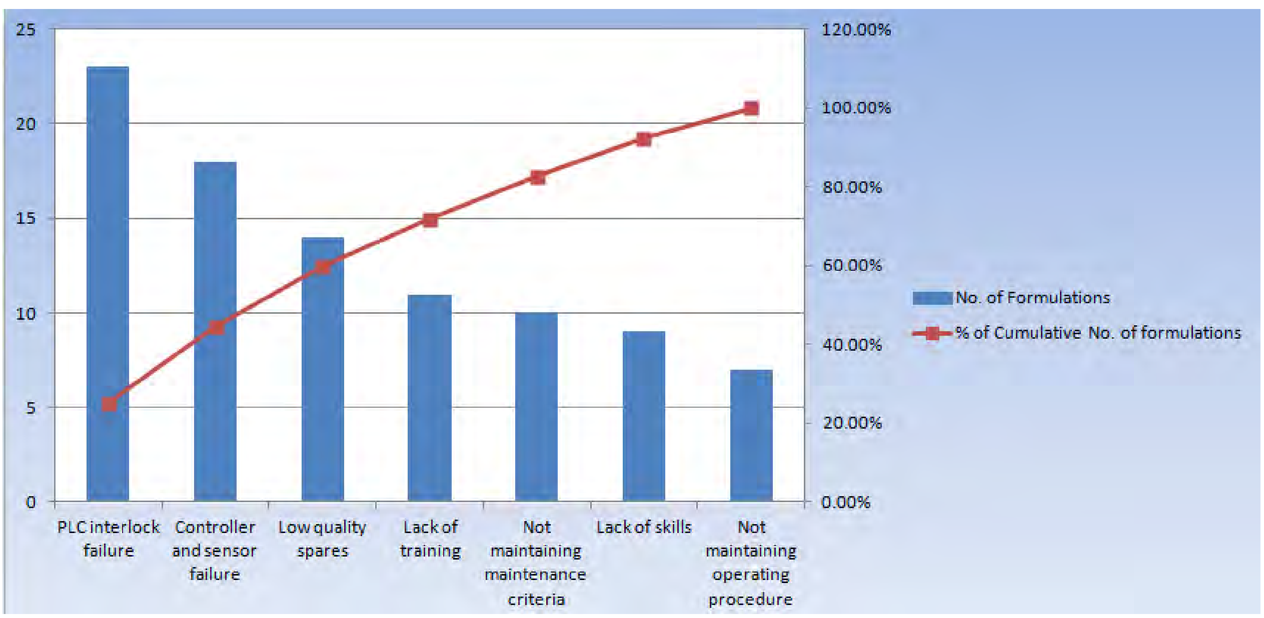

Fig. 4.6: Pareto diagram

From the Pareto diagram most significant root cause is identified as the PLC interlocks system not working properly. To solve this issue 'why-why' questions are used.

Table4.10: Why Chart

S/N	Why?	Reason
1	The PLC interlocks is not working properly	I/O module is not working properly
2	The I/O module is not working properly	Processor card malfunctioning
3	The processor card malfunctioning	Life cycle break down and out dated

So, no replacement or support can be found from the manufactures. To solve this problem the PLC need to be updated with a newer version and program.

The top management of the factory along with business head decided together to update the PLC with program also rechecks the sensors for reducing breakdowns.

Maintenance and operation team make it happen with the help of a vendor to supply and installation. It takes some time to realize the outcome from these new changes.

RCM is a continuous process to develop and recheck and rebuild to new improved benchmarks. The efforts are never ending.

Chapter 5

Evaluation of RCM frame work

5.1 RCM evaluation process

The evaluation process is designed here based on standard evaluation criteria of any RCM program published by Society of Automotive Engineers Inc. in the standard SAE JA1011. This is also described in section 3.1.

Plant reliability was struggling a lot due to proper system of maintenance management. Now the RCM method is implemented phase by phase together with maintenance and operation team. For the complete implementation process it will take minimum one year time: for training and system development in the root level. But the experienced operation and maintenance personnel can provide their valuable opinion about frame works of the implementation of RCM method in comparison to the present maintenance management system. In this context a set of evaluation questionnaires are formed based on SAE JA1011 to get the most experienced personnel opinions. Here five operation and five maintenance personnel are employed to make the evaluation data.

Answers of the questionnaires are rated as follows:

Excellent	5
Improved	4
Unchanged	3
Degraded	2
Poor	1

Now let's have a look of the questionnaires that have been formed sequentially:

Please put tick (√) to select one answer from the given options for each of the questions

1. Which is the level that the functions of the functional equipments are defined specifically with the desired standards of operation?

Answer: ○ Excellent ○ Improved ○ Unchanged ○ Degraded ○Poor

2. How do the functional failures are described in terms of their functional standards, degradation of quality of product or plant outage separately?

Answer: ○ Excellent ○ Improved ○ Unchanged ○Degraded ○Poor

3. In what extent the failure modes are analyzed with specific causes of functional failures?

Answer: ○ Excellent ○ Improved ○ Unchanged ○Degraded ○Poor

4. In what extent the failure effects of the each failure modes are analyzed?

Answer: ○ Excellent ○ Improved ○ Unchanged ○Degraded ○Poor

5. How do the failure consequences are categorized systematically in terms of critical impact on lead oxide production system and failure management strategy employed?

Answer: ○ Excellent ○ Improved ○ Unchanged ○Degraded ○Poor

6. What level the failure management tasks and their frequencies are specified?

Answer: ○ Excellent ○ Improved ○ Unchanged ○Degraded ○Poor

7. How do the non critical impact failures managed?

Answer: ○ Excellent ○ Improved ○ Unchanged ○Degraded ○Poor

8. What extent the plant availability improved compared to previous condition?

Answer: ○ Excellent ○ Improved ○ Unchanged ○Degraded ○Poor

9. Which level maintenance overtime reduced?

Answer: ○ Excellent ○ Improved ○ Unchanged ○Degraded ○Poor

10. What extent the emergency maintenance works reduced?

Answer: ○ Excellent ○ Improved ○ Unchanged ○Degraded ○Poor

The opinions of the experienced personnel are summed up as per declared ratings individually. Then the arithmetic mean of the total ten people is calculated. This value evaluates the RCM frame works.

The evaluation rating is categorized as below:

Range	Remarks
10-20	Frame works must be redesigned
21-30	Critical improvement
31-40	Improvement
41-50	Plant reliability increased, continuous rechecking for greater reliability

The score cards of the ten people are shown below:

Table 5.1: Score card for the ratings of evaluation

ID	Q1	Q2	Q3	Q3	Q5	Q6	Q7	Q8	Q9	Q10	Total Ratings
Person-1	4	4	4	5	4	5	5	5	4	5	45
Person-2	4	5	4	4	3	5	5	4	4	5	43
Person-3	5	4	4	4	4	4	5	4	5	5	44
Person-4	5	4	5	4	4	5	5	4	4	4	44
Person-5	5	5	5	5	3	5	5	5	4	5	47
Person-6	4	5	5	5	5	5	5	4	4	5	47
Person-7	5	5	4	4	4	4	5	4	5	4	44
Person-8	5	5	5	5	5	4	5	4	5	5	48
Person-9	5	4	5	4	4	5	5	4	4	5	45
Person-10	4	5	4	5	3	5	5	5	4	5	45

Now, from the score card, the arithmetic mean of ratings = $\frac{\text{Total Rating}}{\text{Total person}}$

≈ 45

It is in the range of 41-50 Therefore, it is clear from the evaluation value the plant reliability is increased from the previous condition.

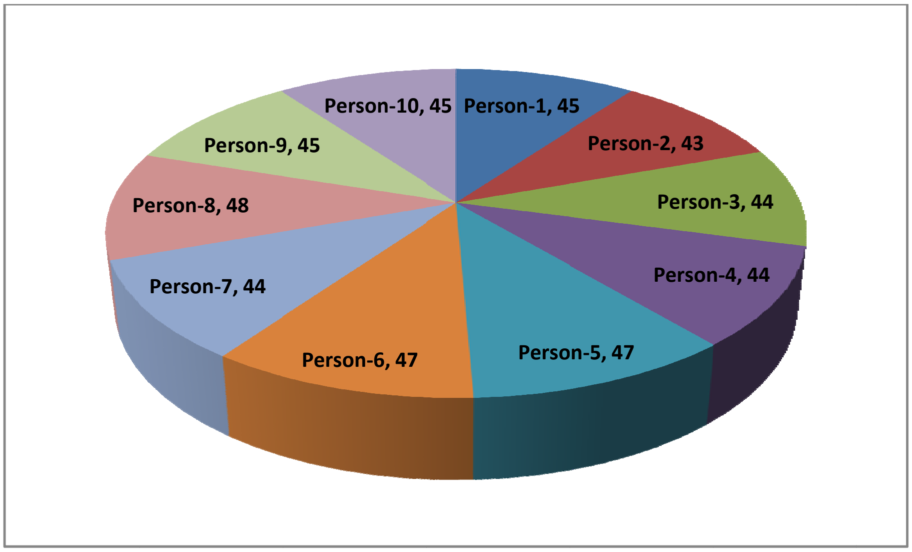

Fig. 5.1: Pie chart of individual ratings for evaluation

5.2 RCM effectiveness metrics (future study)

To measure the RCM effectiveness of a program some metrics are developed. For the improvement study of lead oxide production system following indicators are measured in the present operating context. For each metric a benchmark in a numerical expression is set to form a goal found from the analysis of fifty different industries after implementation of RCM. Some are presented below along with suggested benchmarks. The described metrics are applicable after attaining RCM for a time period of one year. However it can be measured in six months range also.

a) Equipment Availability

$$EA = \frac{Hea}{THrp}$$

Where,

EA = Equipment availability %

Hea = Hours system/equipment is available to run at capacity

$THrp$ = Total hours during the reporting time period

The benchmark figure for this metric is **96%.**

Presently for oxide production system availability in a month on average (6 months),

EA = $\frac{600}{720}$ = 83.33%

RCM program can make the availability more than 96%.

b) Maintenance Overtime Percentage Index

$Pmo = \frac{TMOH}{TRMH}$

Where,

Pmo = Maintenance overtime percentage

$TMOH$ = Total maintenance overtime hours during period

$TRMH$ = Total regular maintenance hours during period

The benchmark figure is **5% or less**.

Present overtime percentage for the maintenance on average (6 months),

$Pmo = \frac{200}{680}$ = 29.41 %

The new model able to reduce it to 10% as the factory is in shortages of potent manpower.

c) Emergency percentage index

EP = $\frac{Hej}{THw}$

Where,

EP = Emergency percentage

Hej = Total hours of emergency works

THw = Total hours of maintenance works

The benchmark figure for this indicator **10% or less**.

At present the factory is fire fighting for emergency maintenance on this system frequently. The emergency percentage index on average (6 months),

EP = $\frac{48}{128}$ = 37.5%

RCM can reduce it to 15% as the factory need to change the on line condition monitoring system.

d) PM/PTI-Reactive maintenance index

This index is divided into two areas: PM/PTI and reactive maintenance.

The PM/PTI related index is expressed as

Ppp = $\frac{\text{MHPP}}{\text{MHR} + \text{MHPP}}$

Where,

Ppp = PM/PTI work percentage

MHPP = Total man hours of PM/PTI work

MHR = Total man hours of reactive maintenance work

The benchmark figure for this metric is 70%.

For PbO production system on average (6 months) Ppp $= \frac{144}{256 + 144}$ = 36%

RCM program should make it 65% considering manpower shortage.

The reactive maintenance related index is defined as

$$\text{Prm} = \frac{\text{MHR}}{\text{MHR} + \text{MHPP}}$$

Where,

Prm = Reactive maintenance work percentage

The benchmark figure for this metric is 30%.

At present the system is facing breakdowns frequently. On average (6months),

$$\text{Prm} = \frac{256}{256 + 144} = 64\%$$

New RCM model should make it 35% considering environmental issues like climate control.

The sum of the PM/PTI and Reactive maintenance index are equal to unity or 100%.

Here in the above discussion we make an assumption of performance improvement of the present condition after the complete implementation of RCM method.

Chapter 6

Challenges to implement RCM

RCM benefits are derived over a medium to long term period therefore, gains in cost or performance right away could not be experienced.

The RCM process involve both significant changes to the work practices and the inter relationships between the maintenance practitioners and the operators. This adjustment is a great challenge.

Data collection for the lead oxide production system is vital part for this analysis. Some equipment failure data could not be found from the maintenance records. Machine wise failure data history is highly important for this study which was not recorded by the maintenance team as a result failure trend could not be found. So, break down log book was the only written records. Mostly the history was collected from the maintenance and operation personnel.

PF interval data was unavailable for conducting the condition based tasks. So the original equipment manufacturers' recommendation and log book was the main base for consideration of frequency of maintenance.

Organizational factors play an important part as they define responsibilities and authorities, and establish communication channels essential for successful RCM implementation. The management, both at the top and at plant level alignment about the concept of RCM is a big factor for the success that yet to be solved. This becomes even more essential as such initiative demands a change in a company's cultural and major operational methodologies, which resulting internal resistances and lack of employee commitment and motivation.

Total financial commitments are on process while unforeseen costs may appear. Major cost factors include training, consultation fees, software support, project facilitation cost, etc.

Availability of experienced personnel and on-site plant staff with the present work load are some of the issues to handle, especially for keeping the whole operation alive.

Assigning appropriate on site personnel to the RCM team by giving it top priority over other activities or increase in plant staffing or outsourcing, mad the RCM process harder initially.

Training is required with a firm grip on RCM philosophy, seven step methodologies and; a good knowledge of practical issues in the root level of operators and maintenance technicians which requires a long time to align with the new frame work.

Chapter 7

Conclusion

The RCM program definitely can improve the system availability and reduce unwanted breakdown while minimize spare consumption and man-hour requirements in a cost effective manner. The RCM goals are to identify for each system and equipment the failure modes and their consequences and to determine the most cost-effective and applicable maintenance technique to minimize the risk and impact of failure. This allows system and equipment functionality to be maintained in the most economical manner.

By means of a correct implementation of the RCM, it will be: Ensured realization of the inherent safety and reliability levels of the equipment; restored the equipment to these inherent levels when deterioration occurs; obtained the information necessary for design improvement of those items where their inherent reliability proves to be inadequate; accomplished these goals at a minimum total cost, including maintenance costs, support costs, and economic consequences of operational failures.

Continuous improvement of this program is essential for sustaining this program. So, RCM program is very dynamic especially in the implementation level. It can be done by feedback control system. For a sustainable RCM program following points to can be examined:

• Continually monitor and optimize the current maintenance program

• Delete unnecessary requirements

• Identify adverse failure trends

• Address new failure modes

• Improve overall efficiency and effectiveness of the maintenance programs

Sustainment efforts should be organized such that the results can be effectively used to support the RCM analysis updates. For RCM sustainment processes like trend analysis, maintenance documents review, task allocation review, age exploration, and failure mode review can be used.

For collection of in-service data throughout the operating life the operator of the machine can be prepared. It is highly important to analyze, review and respond to necessity of continual refinement of the maintenance program.

Presently average downtime of the functional group of oxide ball mill and filter house is 864 hrs per year and expected downtime is 600 hrs per year initially which is 30% reduction of the existing scenario.

In the future we can use RCM analysis by dynamic software which will make the outcome faster and accurate. Introducing artificial intelligence in this era will be another interesting study in this section.

This program can help to improve the plant reliability and make the business more competitive and efficient in the global market place.

Bibliography

[1] "Reliability Centred Maintenance (RCM)", http://www.ebme.co.uk/articles/management/327-reliability-centred-maintenance-rcm, last accessed 8:00PM, May 20, 2015.

[2] NASA *Reliability-Centered Maintenance Guide for Facilities and Collateral Equipment 2008*. National Aeronautics and Space Administration, Washington D.C., September 2008.

[3] Igba, J., Alemzadeh, K., Ebo, I. A., Gibbons, P., Friis, J., "A Systems Approach towards Reliability-Centered Maintenance (RCM) of Wind Turbines", Trans. of the Elsevier, *Procedia Computer Science*, Vol. 16, pp. 814 – 823, 2013.

[4] Kammerer, C. C., "Reliability Centered Maintenance – Methodologies" NASA Kennedy Space Center, Florida, Tech. Rep. KSC-2009-210, January 2009.

[5] Afefy, H. I., "Reliability-Centered Maintenance Methodology and Application: A Case Study", Trans. of the Scientific Research, Engineering, Vol. 2, pp 863-873, 2010.

[6] ABS *Guidance Notes on Reliability Centered Maintenance 2004*. American Bureau of Shipping, Houston, Texas, July 2004.