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Title

RELIABILITY IMPROVEMENT OF THE BOILER-COAL PROCESSING PLANT IN ESKOM USING RELIABILITY CENTRED MAINTENANCE PRINCIPLES.

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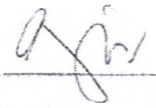
Professor Craig Law (University of the Witwatersrand)

A research report submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, in partial fulfilment of the requirements for the degree of Master of Science in Engineering in Mechanical Engineering by course work and research report.

25 October 2016

DECLARATION

I declare that this *research report* is my own unaided work. It is being submitted to the *Master of Science* to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.



.....

(Signature of Candidate)

...25th..... day of ...October....., ...2016.....

ABSTRACT

The objective of this report is to compare the existing maintenance methods in Eskom to RCM and then test the applicability of RCM in improving boiler reliability. Firstly, a comparative study was conducted on different RCM methods and the RCM method to apply selected and compared to the Eskom's initiatives. The RCM method is piloted to a sample system and the results are compared with those from the current Eskom's initiatives.

The biggest change due to the RCM analysis was the way to document the results of the RCM process as compared to the current practice. It was also found that intervals between maintenance tasks proposed by the RCM study are different from the intervals currently used. In conclusion, the report recommends that the RCM results be used as a guide for continuous improvement in order to fill in gaps that are crucial in determining reliability goals.

DEDICATION
For Goodness.

ACKNOWLEDGEMENTS

I would like to thank my Supervisor, Professor Craig Law, from the School of Mechanical Engineering at the University of the Witwatersrand for the guidance and coaching in the execution of this project. Special thanks also go to Eskom for allowing me to use its resources in the execution of this project especially to Anari van Gruening for all the support.

Thank you.

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LIST OF ACRYNOMS

AIA – Authorised Inspection Authority

BTF – Boiler Tube Failure

BTFR – Boiler Tube Failure Reduction

CHM – Critical, High Duty Cycle and Mild Environment

CHS – Critical, High Duty Cycle and Severe Environment

CLS – Critical, Low Duty Cycle and Severe Environment

CMMS – Computerised Maintenance Management System

CV – Calorific Value

ID – Induced Draft fan

EPRI – Electric Power Research Institute

FAE – Fly Ash Erosion

FLR – Forced Loss Rate

FMECA – Failure Mode Effect and Criticality Analysis

FSI – Functional Significant Item

GGCS – Generation Generic Component Strategy

GPSS – Generation Production Sales System

IRM – Integrated Risk Management

MCSI – Maintenance Cost Significant Items

MIMS – Manufacturing Information Management System

MSI – Maintenance Significant Item

MTBF – Mean time before failure

MTTF – Mean Time to Failure

MYPD3 – Third Multiyear Price Determination

NDT – Non Destructive Testing

NERSA – National Energy Regulator of South Africa

NOC – Normal-Operating Condition

OEM – Original Equipment Manufacturer

PM – Preventative maintenance

PSEP – Power Station Enhancement Program

PT – Pressure Transmitter

QA – Quality Assurance

RBI – Risk Based Inspection

RBO – Risk Based Optimisation

RIMAP – Risk Based Inspection and Maintenance

SAE – Society of Automotive Engineering

SAP – Systems Application Product

SP – Steam Pressure

SRCM – Streamlined Reliability Centred Maintenance

TLD –Thermo-Luminescent Dosimeter

UCLF – Unplanned Capability Loss Factor

UCF – Unit Capability Factor

NOMENCLATURE

Availability is the ability of an item (under combined aspects of its reliability, maintainability and maintenance support) to perform its required function at a stated instant of time or over a stated period of time (BS 4778).

Evident Failures is one that will eventually become evident to the operating crew under normal operating condition (NOC).

Hidden Failure is a failure that will not become evident to the operating crew under NOC if the failure mode occurs on its own.

Functions are what an asset is expected to perform but can also be anything an asset has to comply with, such as a colour or shape. It is possible to divide functions into two sub-categories, namely

- Primary functions describe the main purpose of the asset. These functions are the reason why the system/equipment exist
- Secondary functions describe additional features the asset should meet such as colour or safety aspects.

Functional block diagram is a graphical representation of the system operation.

Function failures is the inability of an item of equipment to meet a specified performance standard.

Failure is the termination of the ability of an item to perform a required function.

Failure modes are events that cause functional failures.

Failure effects are what happen when a failure mode occurs. The effect includes evidence of failures, safety and environmental hazards or production effects

Failure consequence the consequence of all failures can be classified as being either: Hidden, Safety, Environmental, Operational, or Non-Operational.

Maintainability is the ability of an item, under stated conditions of use, to be retained in, or restored to, a state in which it can perform its required functions, when maintenance is performed under stated conditions and using prescribed procedures and resources (BS 4778).

Maintenance (preventive, corrective, and inactive) is the action of performing tasks (time-directed, condition-directed, failure finding, servicing, and lubrication) at periodicities (periodic, situational, and unscheduled) to ensure the item's functions (active, passive, evident, and hidden) are available until the next scheduled maintenance period.

Potential failure is an identifiable physical condition that indicates a functional failure is imminent.

Quality is the totality of features and characteristics of a product or service that bear on its ability to satisfy stated or implied needs (ISO 8402).

Reliability is the ability of an item to perform a required function, under given environmental and operational conditions and for a stated period of time (ISO 8402). Quality denotes the conformity of the product to its specification as manufactured, while reliability denotes its ability to continue to comply with its specifications over its useful life. Reliability is therefore an extension of quality into the time domain.

Safety is the freedom from those conditions that can cause death, injury, occupational illness, or damage to or loss of equipment or property (MIL-STD-882D).

Chapter 1 BACKGROUND

1.1 INTRODUCTION

According to Wikipedia (2014), Eskom is a South African electricity public utility established in 1923. In the later months of 2007, South Africa started experiencing widespread rolling blackouts as supply fell behind demand threatening to destabilize the national grid (Wikipedia, 2014). Load shedding was introduced in the later months of 2014, due to poor equipment reliability of the old generating units with some of them over 40 years old (Wikipedia, 2014). While investment in new infrastructure is vital in the long term, the need to review current maintenance strategies is also critical to increasing equipment availability.

South Africa's energy demand surpassed available supply and coupled with most Eskom power stations lagging behind on maintenance, this has led to equipment operating costs substantially increasing over the years (Eskom, n.d.). In February 2013, The National Energy Regulator of South Africa (NERSA) announced that Eskom would be allowed to increase electricity tariffs at an average yearly rate of 8% between 2013 and 2018 – an increase that was half the 16% sought by the utility in its application for the Third Multiyear Price Determination (MYPD3) period. Operating units created budgets with the hope of getting a favourable ruling from NERSA, but with the 8% ruling Eskom had to reduce its operating costs by about 50% in order to be sustainable, hence the need to also look at the generation process efficiency.

Eskom has tried for years to improve on its ageing plant by applying many reliability improvement initiatives. In the last ten years, Eskom has initiated Reliability Based Optimisation (RBO), Power Station Enhancement Program (PSEP) and most recently Risk Based Inspection (RBI) initiatives. This research report investigates boiler system failures and identifies ways to improve on reliability using RCM principles at one of Eskom's facilities as an alternative to the above interventions.

The project focuses on the boiler system at one of Eskom coal fired Power Station, called the Utility in this project. The boiler is a critical system of the plant as its failure results in plant shutdown with statutory implications. There is no

redundancy on the boiler system hence unplanned failures are expensive compared to planned shutdowns on the same system.

1.2 RESEARCH PROBLEM

Reliability of a system is for a range of reasons including the following (British Standard 63208, 2006:9)

a) Setting targets and specifications,
b) Comparing options,
c) Identifying and prioritising problems,
d) Indicating fitness for purpose,
e) Optimizing support (e.g. spares),
f) To give input to other analysis (e.g. safety analysis) and,
g) To prioritise areas for improvement with the greatest cost-effectiveness improvement potential.

Reliability can quoted in a number of ways, including for example probability of survival, Availability, Mean time to failure (MTTF), Mean time before failures (MTBF). In Eskom, none of these measures is used. What is important in a power station is the amount of energy (in Megawatts) produced. Availability, for example, looks at the uptime and downtime without looking at how much the unit was generating when it was up. If a unit was operating at half load for the past 8hours, when using availability as a measure of reliability, it will be 100% available, but when using Unplanned Capability Loss Factor (UCLF) the value will reflect the 50% unavailable energy. This is what has made UCLF the measure of choice in Eskom. UCLF is the ratio of the unplanned energy losses over a given time period to the maximum amount of energy which could be produced over the same time period i.e.

$$\text{UCLF} = \frac{Unplannad\ losses}{Maximum\ Enegy} \qquad equation\ 1$$

Where:

Maximum Energy = ([190MW x 9] +185MW) x 24 x number of days in month.

Unplanned Losses = Capacity of unplanned losses (MW) x off time of load loss.

The Utility under study has 10 generating units. The 190MW stated above is the generating capacity of the nine units at the Utility while the 10^{th} unit produce 185MW.

Figure 1-1 shows UCLF target for the financial years 2008 to 2013. The Utility has never met the set out UCLF targets in this period with a rapid growth of around 5% in 2008 to just below 40% in 2013. This shows that reliability is a real problem within the power station.

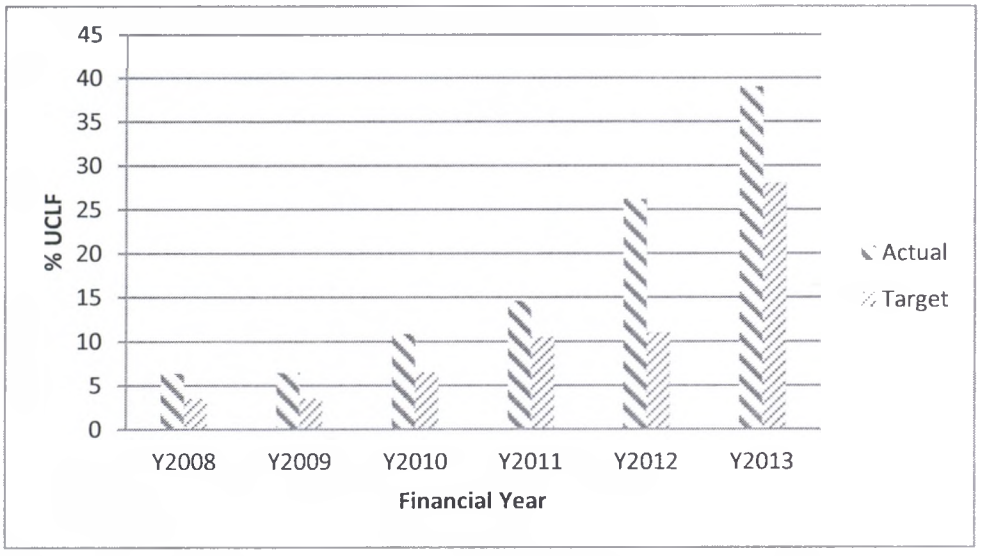


Figure 1-1 UCLF for the past 6 years. (Source: PSEP: 2013)

Eskom's Maintenance Strategy Determination Processes

For the past 10 years, Eskom has used the RBO, PSEP and RBI processes to determine the maintenance needs of equipment. These are discussed next.

a) Reliability Based Optimisation (RBO).

RBO is a systematic way of determining maintenance strategies (Chauke et al, 2013:5). Historically RCM application costs and data requirements are prohibitive in fossil plant environment. Perakis (2001:7) highlights that these problems have led to the development of a streamlined version of the method that reduces RCM analysis cost, cost for preventative maintenance (PM) task work plan development, and input into a plant's Computerized Maintenance Management System (CMMS). RBO is a streamlined RCM process developed by the Electric Power Research Institute (EPRI). The principal project objective was to enhance overall plant economic performance by:

- Defining technically correct levels and types of maintenance to be performed,
- Optimizing existing preventive maintenance tasks,
- Developing and documenting sound maintenance program strategy.

Eskom reliability based process identifies and protects critical plant assets from failure, by specifying and utilising the most cost-effective methods to manage their failure mechanisms (Chauke et al, 2013:7). The optimisation process includes

- Understanding of how equipment fails,
- Development of defence mechanisms to counteract these failures and,
- The application of technology to predict potential failures.

There is a need to find a balance between the amount of maintenance performed and the resulting reliability of the equipment.

b) Power Station Enhancement Programme (PSEP)

PSEP is an Eskom initiative (Msibi et al, 2013:14). The PSEP project aims at identifying initiates to improve the Power Station performance from a UCLF point of view within 3-4 years. The PSEP launch occurred in the last quarter of 2012 and completed beginning of 2013. Actions from the report were categorised as short term (to be implemented and closed within three months of the PSEP report), medium term (closed within 6 months) and long term actions (actions taking longer than 6 months to close). Currently the Utility is at various levels of implementation of the long-term action plans, all short term and medium term actions are complete.

The PSEP scope aims to address the following issues:

- Identify 5 areas causing high UCLF, investigate the causes, recommend corrective actions and implement recommendations,
- Identify other plant areas with a potential to cause load losses, conduct root cause analysis, recommend corrective actions and drive implementation, and
- Investigate human factors that can affect negatively on availability of plant, determine and implement strategies for mitigation of these factors.

The Utility identified the boiler plant, the draught plant, the ash plant, the milling plant and the turbine plant as the five systems that were contributing most to the high UCLF.

c) Risk Based Inspection (RBI)

The Risk Based Inspection and Maintenance (RIMAP) standard (2008:12) defines Risk Based Inspection (RBI) as an optimal maintenance business process used to examine equipment such as pressure vessels, heat exchangers and piping in industrial plants. In Europe, most power plants have now adopted the RBI method as part of their statutory obligation. In South Africa, the introduction of the Pressure Equipment Regulation (PER) allows for a statutory inspection that is carried out after every 36 months to be replaced with a RBI process which is verified by a certification body (OHSAct, 1993:148). The RBI process will determine the required inspection interval, based on the condition of the plant equipment. Eskom has taken a strategic decision to manage pressure equipment using the RBI process. To stop a boiler to do hydrostatic test every 3 years as currently required by the section of the PER of OHSAct is deemed costly to the organisation and can be avoided provided the risk is quantified and is demonstrated to be acceptable. This can result in Eskom actually carrying out the outage of the boiler at intervals greater than the required three years. Eskom will implement the RBI process on equipment operating at pressures above 50kPa; every other equipment will still be using the RBO process for its maintenance determination. The RBI process currently applied in Eskom is similar to the one in Figure 1-2, this is the based on the European Risk Based Inspection and Maintenance Programme. Although Eskom is not using RCM for the maintenance requirements determination, Figure 1-2 shows how RCM activities fit in the overall RBI process as adapted from the RIMAP (2008:20) procedure. Instead of using RCM activities, Eskom is applying the RBO process in the development of strategies.

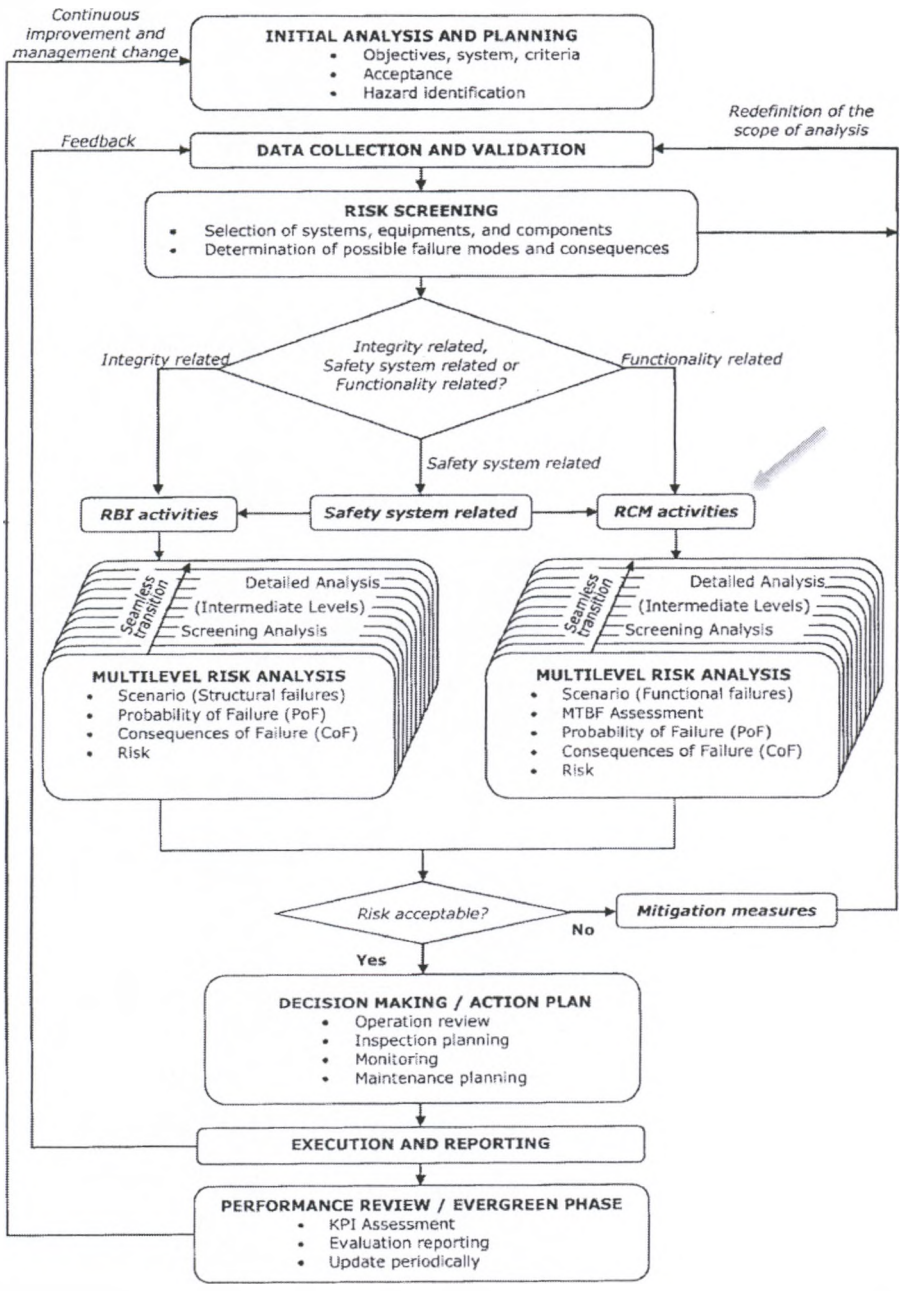


Figure 1-2 Framework of RIMAP procedure within the overall management system. (Source: CWA 15740, 2008:20)

By combining the RBI process and an RCM program, the organisation can limit the costs associated with RCM as these processes complement each other (RIMAP (2008:28)). In addition, in spite of the use of all these methods (RBO, PSEP) to improve on the maintenance strategies and reduce UCLF, Figure 1-1 reflects the opposite. The variance between actuals and targets seems to be

increasing rather than decreasing. Is the process use to determine the maintenance strategies the cause? Is the Utility executing the wrong strategies, Are some of the questions that this report seeks to address.

1.3 MOTIVATION

UCLF is defined in equation 1. The goal of this project is to reduce UCLF by minimising unplanned losses. Figure 1-1 shows an increase in UCLF above the set targets for the financial years from 2008 to 2013. Figure 1-3 is a fishbone diagram of potential causes of high UCLF (Msibi et al, 2013:227).

A variety of potential causes of high UCLF were identified in the PSEP report. However this report will concentrate on the potential cause due to wrong maintenance strategies by changing the processes currently applied. Other processes were identified within the organisation to deal with the other causes that were identified in this fishbone including for example, a project to identify the critical spares that are required within the organisation to deal with causes related to lack of spares.

The frequencies within which boilers are taken out for scheduled maintenance, termed outage frequencies, are more or less the same across the Eskom fleet of coal-fired boilers. The standards are Interim repairs happening every 18 months, Mini- general Overhauls (MGOs) happening every six years, and General Overhauls (GO) happening every 10 years (These are discussed in more detail in Section 3.8).

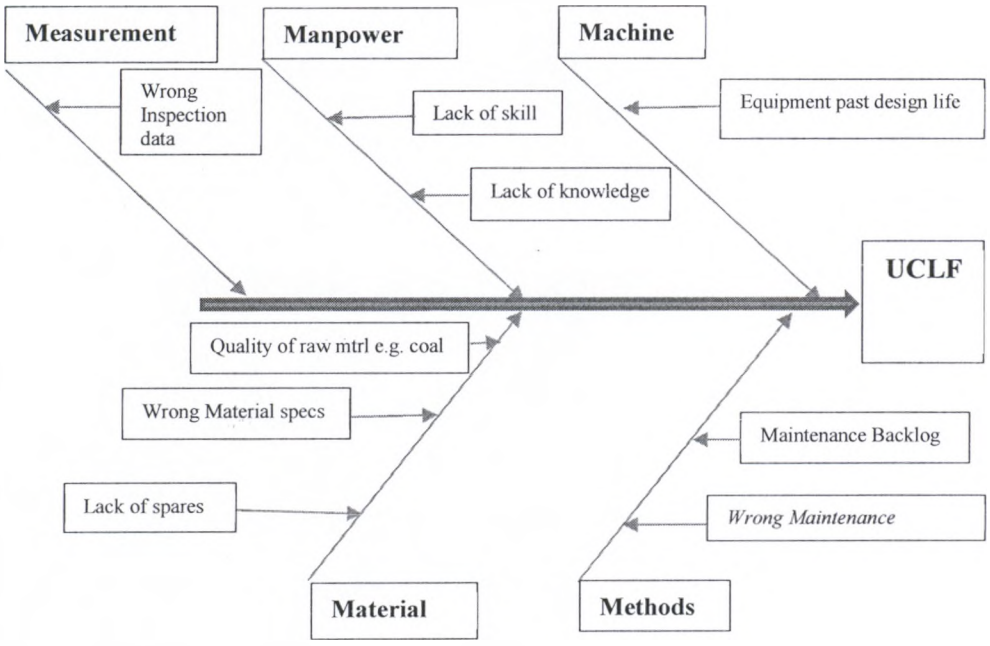


Figure 1-3 UCLF Fish bone diagram. **(Source: PSEP: 2013)**

UCLF reduction can be achieved by applying a different process. RCM was applied with success in many industries including aeroplane, nuclear and the military and will be used in this report to determine the maintenance requirements of the boiler plant subassemblies.

1.4 OBJECTIVES

The objective of this report is to compare the existing maintenance methods that in Eskom to RCM and then test the applicability of RCM in improving boiler reliability by carrying out an RCM analysis on a sample plant of the Coal fired power plant.

1.5 SCOPE

The scope of this reliability analysis will mainly focus on -

1) Defining of systems function for the boiler system and Super heater subsystem,
2) Functional failure analysis and critical item selection,
3) Selection of maintenance tasks and their frequencies.

Implementation and continuous improvement are the other basic steps of an RCM programme; however, they are not going to be considered in this report due to time constraints.

Figure 1-3 shows the causes of UCLF; this report will not look into causes that may be due to maintenance backlog, Machine, Material, Measurement and Manpower. This is also due to the limited time for the project as other initiatives were rolled out within Eskom to address these issues.

1.6 ETHICS CLEARANCE

Kimmel (1988) notes that regardless of the research design, social research should conform to four broad ethical principles namely voluntary participation, anonymity and confidentiality, no harm to participants, and informed consent. The University insists that all its research be conducted following the very highest ethical standards and as such, this project was awarded clearance number MIAEC 007/14 for its execution.

1.7 REPORT OVERVIEW

In Chapter 2, some of the literature on RCM is discussed. This chapter will conclude by selecting a method that will be applied in this project.

The RCM method is discussed in detail and how it was applied at Eskom in Chapter 3, and Chapter 4 is a presentation of the results in a similar format as the method described in chapter 3. Chapter 5 is a presentation of the conclusion and recommendations of the RCM analysis on the boiler system.

Chapter 2 LITERATURE REVIEW

2.1 INTRODUCTION

Eskom has embarked on a number of initiatives to come up with the correct maintenance strategies for its equipment. The initiatives are -

a) Streamlined Reliability Centred Maintenance (SRCM) -Reliability Based Optimisation (RBO; This initiative was started in 2008),
b) Power Station Enhancement Programme (PSEP; started in 2012), and more recently,
c) Risk Based Inspection (RBI; started in 2013).

The initiatives are directed at reducing the overall operating costs by improving equipment reliability; these initiatives are discussed in Section 1.2. Other manufacturing industries have also adopted Reliability Centred Maintenance (RCM) to increase their efficiencies as an alternative. This chapter discusses various RCM methods that were applied in other industries and the method to be adopted in this project.

2.2 RCM COMPARED TO ESKOM'S RELIABILITY IMPROVEMENT METHODS.

Figure 1-1 shows that the initiatives of RBO and PSEP have not reduced the UCLF figures to acceptable target levels. In this regard, the potential for RCM to better address current reliability issues needs to be explored. Below is a comparison of RCM and Eskom initiatives and why RCM is thought to better improve equipment reliability.

2.2.1 Difference between RBO and RCM

RBO differs from RCM in that: -

- RCM identified the failure modes (Rausand, 1998:2). There is no correlation of failure modes to preventive maintenance tasks when using the RBO process. With RCM, applicable failure modes are identified based on existing records (current operating context). Each is then managed based on the risk to the business. This allows the business to optimise by managing those risks that have a bigger impact to the organisation.

- If the functional importance, duty cycle and environment are the same, RBO suggests that the components should have similar maintenance strategies (Chauke et al, 2013:13). With RCM, above this, it also considers age and previous operating and maintenance history of the equipment. Similar equipment installed at different times will have the same strategy using RBO, but may have a different strategy when using the RCM process. Thus, accurate results are achieved using RCM than RBO. Eventually the organisation does not end up over-maintaining or under-maintaining assets.
- When using RCM, critical versus non-critical failures are clearly identified, a preventive maintenance regimen can be designed that focuses efforts on preventing and managing critical failures and monitoring failure thresholds, while eliminating unnecessary maintenance tasks. However, with the current RBO preventive maintenance strategy is unfocused at best. All components are analysed with the same effort.
- RCM analysis is done by initially defining the function of the component and how it fails (Koekermoer 2008:35). For example, the function of a pump is to deliver 1000l/minute of ash slurry at 6 bar to the ash dam, and its functional failures could be (1) it can fail completely to deliver the ash slurry or (2) it can partially fail where it is delivering at less volume and a lower pressure. RCM then analyse the failure modes associated with each respective function. However, RBO generalise the functional failure only of the equipment. For example, the same pump will be analysed in RBO as having a functional failure described as "loss of pumping" or "loss of flow" without specifying whether it is a complete or partial failure (P Phapo, 2012). This becomes a problem when defining equipment reliability goals in that for example, a partial failure may be acceptable to the organisation up to a certain extend. Hence, in RBO decision-making is subject to the person who carried out the initial analysis who will be

able to know whether he considered the worst-case scenario or not when defining failure.

- RCM is an exhaustive process; it analyses in detail the failure effects. RBO tries to summarise the failure effects. For example, RBO will classify a failure effect as either critical, non-critical or run to failure. However, RCM will analyse all applicable failure modes before analysis the failure effects. Moubray (1997:7) points out that one of the question that needs to be answered is "*What causes each functional failure* ". As will be explained in Section 3, this involves identifying the failure modes of the system. Knowing the failure modes is critical in that how the failure manifests itself can be better understood in order to better manage it so that it does not occur or to limit the probability of occurrence. The RBO process does not therefore capture all the failure modes that can be applicable to a piece of equipment.
- Because of the exhaustive nature of RCM, it can also be used as a knowledge transfer tool to new System Engineers.
- RBO is simple to apply and less time consuming compared to RCM, however because the templets used are adopted from EPRI they do not define Eskom's operating context.
- More resources (mainly personnel and time) are required in RCM compared to RBO. At the end all the resources required are quantified in terms of costs, hence the argument has always been that RCM is an expensive process. Since 2008 Eskom has employed Reliability Engineers, this resource could be used as the facilitator of the RCM process. This is the position that the author currently holds. Also with the introduction of RBI, Eskom is using teams as proposed in the RCM II method. The element of costs needs to be reviewed to see if it is still applicable to the organisation as resources are now readily available. The RBI analysis team on unit 10 executed this project (Section 3.1).

2.2.2 Difference between PSEP and RCM

RCM differs from PSEP in that: -

- PSEP is a tool in root-cause failure analysis. After implementation of an RCM program for example, PSEP evaluates the effectiveness of the maintenance strategies developed as a continuous improvement tool.
- PSEP is reactive; it manages a failure that has already occurred.
- PSEP does not evaluate the functional importance of the component

2.2.3 RCM investigations within Eskom.

There is no evidence to suggest of any previous RCM studies in. Cost is the feared factor in determining whether to apply RCM in many utilities (Perakis 2002:2). With the power problems experienced in South Africa and with more resources made available and the technological advancements in analysis that have occurred over the years, it would be ideal to re-look and evaluate if RCM methods can now be applied to power generating industries

2.3 EXISTING RCM METHODS

Moubray (1997:6) defines Reliability Centred Maintenance (RCM) as *a systematic consideration of system functions, the way functions can fail, and a priority-based consideration of safety and economics that identifies applicable and effective preventive maintenance (PM) tasks"".*

There are many variant methods of RCM from the initial one developed for the aeroplane industries to the more recent one focusing on cost (Quantified Reliability Centred Maintenance). Streamlined Reliability Centred Maintenance (SRCM) is a simplified version of RCM; Eskom has implemented a version of this called Reliability Based Optimisation (RBO). The streamlined versions lower the resources needed to perform RCM (Perakis et al, 2001:7). The various RCM methods implemented in various industries are in the next section.

2.3.1 Reliability Centred Maintenance

Nowlan et al (1978) at United Airlines, under the Department of Defence in the United States, established the concept of RCM in 1978.The principles of RCM arose from a rigorous examination of certain three questions as follows: -

1. How does a failure occur?
2. What are the consequences?

3. What good can preventive maintenance do?

Creating aircraft scheduled maintenance programs use the RCM process based on safety and operational risk control reasons for a maintenance activity. Nowlan et al continued this research and in 1983 started his collaboration with Moubray to adapt RCM to industry. This gave rise to RCM2 or RCM II. RCM II, devised by Moubray, is an innovative implementation and commercialization of Nowlan and Heap's RCM methodology.

Moubray's arguably major contribution to RCM is the "facilitated review group meeting" technique. The deficiency of facilitated group meetings in the original RCM method makes RCM II a good candidate for application in the execution of this project. When applying the RCM II method, subject matter experts, including experienced engineering, maintenance technicians and operators, participate in a series of structured meetings under the guidance of a RCM facilitator. The main advantage is to tap experience across a wide group, which help to improve the accuracy of the results (Moubray, 1997:266).

The output from the RCM II analysis is a concise data structure that thoroughly justifies and sets the maintenance plan. The maintenance plan will consist of timed preventive maintenance activities targeting and mitigating the consequences of each reasonably likely failure mode (Moubray, 1997:224). The activities are carried out at specified intervals.

2.3.2 Application Guide BS EN 60300-3-11:2009

According to the British Standard (BS EN 60300-3-11:2009:11), the basic steps of an RCM programme are as follows:

1) Initiation and planning
2) Functional failure analysis
3) Task selection
4) Implementation
5) Continuous improvement

The guide follows the same steps as the original RCM; however, its scope is very wide, as it is developed to apply to generally all industries. For example, as part of Task selection, when determining the task interval, the guide states that it is necessary to determine *the characteristics of the failure mode that suggest a cost-*

effective interval for task accomplishment. The guide contains detailed elaboration of the RCM steps and it will not be adopted due to time constraints, however it presents a good basis to follow should implementation of the RCM process is considered. Though the scope of the guide is too wide as it is intendent for all application fields, the report follows the basic steps as outlined in the guide (steps 1 to 5).

2.3.3 RCM II

The goal of RCM II is consequence mitigation rather than failure avoidance. RCM II is based on the following seven questions (Moubray, 1997:7).

1) *What are the functions and associated performance standards of the asset in its present operating context?*
2) *In what ways does it fail to fulfil its functions (failure mode)?*
3) *What causes each functional failure?*
4) *What happens when each functional failure occurs?*
5) *In what way does each failure matter?*
6) *What can be done to predict or prevent each failure?*
7) *What should be done if a suitable proactive task cannot be found?*

The RCM II method has a strong focus on environmental and safety issues. Eskom consider safety the number one priority above anything else. In this regard, RCM II is also a good candidate for use in the execution of this project.

2.3.4 Streamlined Reliability Centred Maintenance (SRCM)

The Electric Power Research Institute (EPRI) (Perakis et al, 2001) developed the version of streamlined RCM discussed here. EPRI conducts research on issues related to the electric power industry in USA. The Streamlined Reliability Centred Maintenance (Streamlined RCM) process evolved from RCM techniques currently used on nuclear plant safety systems. In early 1998, Reliant Energy and EPRI initiated a pilot project to demonstrate the feasibility of using the Streamlined RCM Process to aid in optimizing maintenance tasks at a fossil-fuelled power plant (Chambers, 2002:2). The pilot effort confirmed that it was beneficial to expand the process to other plants.

An EPRI database on maintenance task selection was developed and subsequently converted into templates in selection table format to facilitate customization of generic system analysis and maintenance templates. The main difference between RCM II and streamlined RCM is the use of predetermined maintenance templates. Eskom refers to this version of RCM Reliability Based Optimisation (RBO). The templates developed in Eskom are Generation Generic Component Strategies (GGCS). Appendix A is an example of the GGCS developed for Superheater 3. The GGCS defines the following three parameters: -

- Functional importance (The rating can either be critical, C, or non-critical, N),
- Duty cycle (high, H, or low, L) and,
- Environment (Severe, S, or mild, M).

The results of this classification can result in any one of the eight classifications listed on top of the table as CHS, CLS, and CHM etc. If the classification is a for example CHS, them the maintenance tasks together with the frequencies aligned to this column will be adopted for the Superheater 3. These become the maintenance strategy for the component.

Asset management software such SAP, COSWN, MIMS etc. document the results of the streamlined in most companies. They document, throughout the life of the equipment, important background and history information used in the decision-making process, which, for example, assists in determining why a task exits.

The SRCM is similar to the RBO process. Eskom templates are similar to those developed by EPRI whose research sample does not have the same operating context as Eskom. For example, as will be discussed in section 4.5 coal quality has a factor in determining the maintenance requirements of a system. In this case, the coal quality considered by EPRI is not the same quality that Eskom is currently using.

2.4 ADOPTED RCM METHOD

A variety of RCM methods are suggested by different industries including the standard JA1011 from the Society of Automotive Engineering (SAE), the United States Department of Defence's RCM standard MIL-STD-3034 etc. Cotaina et al (2000:12) states that *RCM can be applied to different industrial sectors and, depending on their problems and specificities; it can be adapted to more particular objectives*"". They analysed the various RCM methods that were

applied in aeronautical industries, nuclear industries, the chemical industries, Small and Medium Industries and others sectors. There is no applicable method mentioned specifically for a coal-fired power station. The basic steps according to Cotaina et al (2000:25), in undertaking an RCM analysis which were applied in the nuclear industry is: -

- Step 1: Study Preparation
- Step 2: Defining the system and/or subsystem boundaries,
- Step 3: Defining the functions of each system or subsystem,
- Step 4: Critical Item selection
- Step 5: Data collection and analysis
- Step 6: Failure Mode Effect and Criticality Analysis (FMECA)
- Step 7: Selection of maintenance action
- Step 8: Determination of maintenance intervals

This is the same method that is adopted in this report because of the close similarity between these two industries (nuclear and coal power generation). The next Chapter discuss the method in detail.

Chapter 3 RESEARCH DESIGN AND METHOD

This Chapter explains the research design and method.

3.1 RESEARCH DESIGN

This investigation is concerned with the evaluation of existing maintenance strategy determination processes currently applied in Eskom with Reliability Centred Maintenance (RCM). The objective is to test if RCM will improve the operational reliability of the subassemblies associated with heat generation in a coal-fired power plant using the method specified in Section 3.1.

According to PY Thomas (2010), "*colloquially a research design is an action plan for getting from here to there, where 'here' may be defined as the initial set of questions to be answered and 'there' is some set of (conclusions) answers*".

The research will seek to fulfil the above objective by using the approach shown in Figure 3-1 as the guide to the flow of the project.

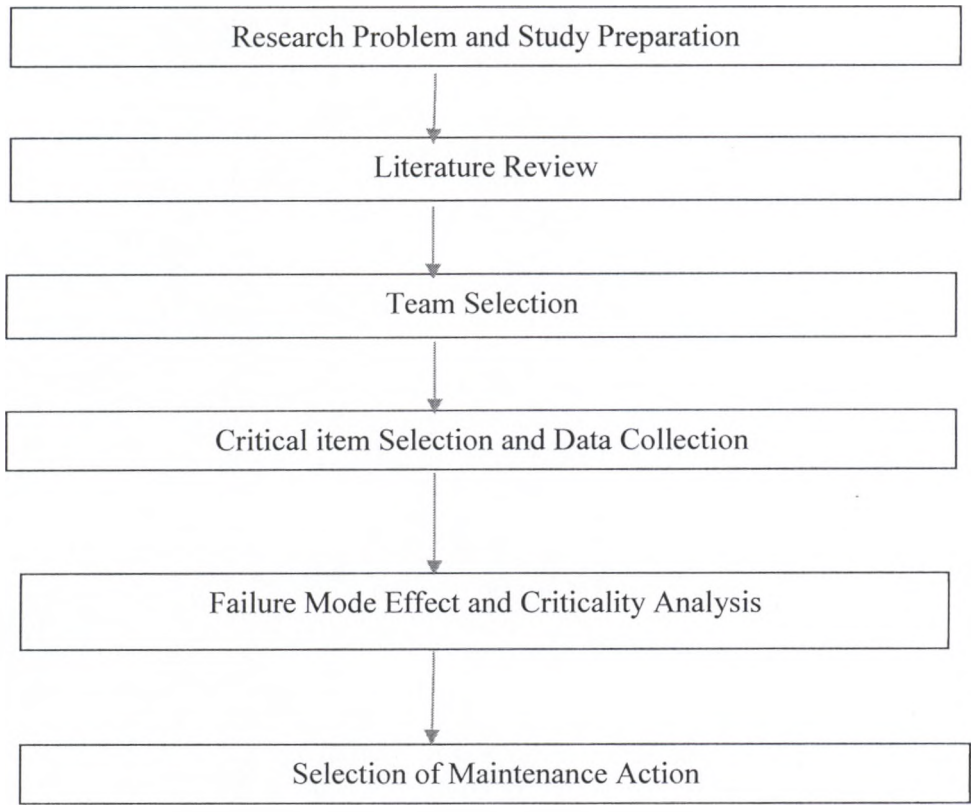


Figure 3-1 Research approach and design

The Research Problem is in Chapter 1; the other sections of the research design are in the next sections.

3.2 STUDY PREPARATION

The study preparation was in line with the recommendation of Rausand (n.d.), who says that study preparation involves -

- Forming of the RCM team,
- Defining and clarifying the objectives and scope of the work,
- Identifying requirements, policies and acceptance criteria,
- Providing drawings and process diagrams,
- Defining limitations for the analysis and,
- Format of questions.

Before an RCM analysis, Moubray (1987:267) suggest that a multi-disciplinary team consisting of maintenance and operating personnel to be set up. The multidisciplinary team selected to draft Unit 10 RBI strategy is the same team used in this RCM project. The team comprised personnel from Operations, Maintenance, Engineering and Risk Assurance (Discipline) departments. Each of the team members received an appointment letter for the duration of the analysis project signed by the Power Station Manager. RCM team members meeting time in dedicated boardrooms was from 9am to 3pm daily.

Table 3-1 lists the multi-disciplinary team members involved in the analysis together with their overall field experience. In the column "Name", the number represents the total number of personnel from that discipline.

Table 3-1 Multi-Disciplinary Team used in the RCM analysis.

Discipline	Name	Responsibility	Experience
Mechanical Engineering	Researcher	Team Leader	10 years
Operations Representative	1	Operation	30 years
Pressure Parts System Engineer	1	Engineering	5 years
High Energy Piping Engineer	1	Engineering	5 years
Carab Plant Care Engineer	1	Maintenance	5 years
Compliance Manager	1	Risk Assurance	30 years
Technical Specialist (BTFR)	1	Maintenance	20 years
Technical Specialist (Metallurgy)	2	Metallurgist	5 years
Maintenance Representative	1	Maintenance	10 years
IRM Representative	1	Risk Assurance	10 years
AIA Representative	1	Engineering	20 years
QA Representative	1	Quality Assurance	5 years
RBI Specialist Representative	1	Risk Assurance	20 years

The only criterion in selecting team members was experience in the field of practice is. The most experienced ones being the ones requested from each functional area. However, the experience is not at component level. For example, the Metallurgist involved in the analysis had individual experiences of over five years; however, their experience could be on other systems not necessary the boiler system that was analysed. This may affect the results of the analysis, especially if required to give specialised knowledge related to the current operating environment. The present operating context of the equipment is the one

considered in an RCM study; hence, it is also important that experience be from a group knowledgeable in that operating context (Moubray 1997:28). Future studies need to consider component level experience.

The team involved in the RCM analysis (from the RBI) was a large team, other authors like Smith AM, (1993:36) propose a team of maximum four core people. Core members are members from Operations, Engineering and Maintenance as recommended by Moubray (1987:267).

The RBI team members went through three modules of training in:-

- Module 1: Risk management,
- Module 2: Accident and consequent modelling,
- Module 3: Risk based inspection in power industries (this also covered training on the European Risk Based Inspection and Maintenance Procedure (RIMAP).

These modules covered most issues and tools that are required for an RCM analysis such as Probability of Failure, Consequence of failure, Failure cause, and Failure mechanism. Most literature does not refer to additional or formalised training on RCM principles for team members before a RCM analysis. With the only major requirement considered as experience in the components analysed. Members trained in the RCM process have the advantage that they approach the process with a common understanding, which saves time. The training is adequate to carry out the RCM analysis.

The roles of the Researcher are -

- Development of the scope of work for the analysis: This scope is in line with the initial boundary set up for the RBI analysis for the same unit. Setting up scope involved defining the boundaries of the analysis. Only Superheater 3 used the RCM process, with the rest of the components analysed using the RBO process. Section 3.3 elaborates this further.
- Gathering of all relevant technical information pertaining to the analysis: This information included information related to the component that is being analysed as per the data collection process in section 3.6.

- Provide engineering technical input on the system under analysis and ensuring the right level of RCM analysis.
- Provide the risk assessment team with the plant system strategy for the components.
- Lead the analysis process.
- Complete the FMECA spreadsheet and report.
- Update the RBO Plant System strategy based on the analysis outcomes.

Table 3-2 is a summary of the roles of the team members, the detailed roles of the team members are in the report "Unit 10 RBI Analysis" (Nelwamondo, 2014:18). The first meeting clarified the roles and responsibility of the team members. For example, the Authorised Inspection Authority was responsible for mainly advising on the components statutory obligations, how the component is categorised in the South African National Standard (SANS) 347. He also provided technical input during the analysis sessions.

Table 3-2 Function of RCM team members

Discipline	Function
AIA Representative	Component Statutory requirements, Technical input and Sans 347 categorisation.
Plant System Engineer	Technical content and responsibility for implementation of results.
GMR 2.1	Statutory requirements and framework of approval for Certification.
In-service Inspector	Component History and fitness for service requirements.
Integrated Risk Management	Risk Management Policy, Standard and Framework for Risk Register integration
Maintenance Representative	Maintenance experience on the components
Management Representative	Provides Management Support and communication
Operating Representative	Operating parameters, specifications and content
Quality Assurance	ISO 9001:2008 Framework, content and principle
Team Leader	Process methodology and Report compilation
Senior Metallurgist	Materials Expert on Equipment Material
Technical Specialist	Subject Matter Expert (SME) for Plant System

Semi-structured interviews, according to Saunders et al (2007:74), are best used when you will not get more than one chance to interview someone and when you will be sending several interviewers out into the field to collect data. While a structured interview has rigorous set of questions that do not allow one to divert, a semi-structured interview is open allowing new ideas to be brought up during the interview because of the interviewee response (Nigel Newton, 2010). Semi-structures interviews were applied during the execution of the project. The standard questions included operating and design data as will be presented in the FMCA spreadsheet in Appendix E.

The questions that were used to populate the data collection templates ensured that they answered the questions set out below. These questions are divided into two groups with the first group addressing the functional failure, and the second group addressing issues to do with failure mode.

The following questions addressed the loss of function of the boiler: -

- What is the Primary and secondary functions of the boiler? This is also explained further in Section 3.1.
- How are boiler failures defined?
- What is the probability of the identified failures occurring?
- What are the consequences of the identified failures occurring?

The following questions were used to populate the Superheater FMECA: -

- Which is the maintenance cost significant items (MCSI) for the Superheater?
- What is the primary function of each MCSI?
- What are the known failure modes of each MCSI?
- What are the effects of failures at the three levels (discussed in Section 2.4)?

The answers to these questions were used to populate the RCM worksheet in Appendix E.

3.3 DEFINING THE SYSTEM AND/OR SUBSYSTEM BOUNDARIES

Hoch R, (1990:3) states that before an RCM analysis is undertaken, the following 2 questions must be considered:

1. To which system is an RCM analysis beneficial compared with more traditional maintenance planning?
2. At what level of assembly (plant, system, and subsystem) should the analysis be conducted?

In order to answer these questions, the system must be defined. According to Rausand et al (1998:5), a system is a logical grouping of subsystems that will perform a series of key functions, which often can be summarized as one main function that is required from the plant. The following system hierarchy levels are proposed by Rausand et al (1998:5),

1. Plant (e.g., process plant)

2. System (e.g., gas compression system)
3. Subsystem (e.g., one gas compressor)
4. Maintainable item (e.g., pumps, valves, electric motors), in this case he defines a maintainable item as an item that is able to perform at least one significant function as a stand-alone item.

The objectives of defining the system is to identify the input interface required for the system to operate and describe the system's required functions and performance criteria Moubray (1997:80). Moubray further recommends that failures be identified at system level.

Eskom's power plant is divided into 26 systems (coal plant, boiler plant, draught group etc.) (Begg, 1998:9). In determining which system to focus on, benefits are measured in UCLF terms. System selected for RCM analysis based on the two questions above are addressed in detail in Section 4.1 under system boundary.

3.4 DEFINING THE FUNCTIONS OF EACH SYSTEM OR SUBSYSTEM

A function is what the item or process is intended to do, usually to a given standard of performance or requirement. According to Moubray (1997:28), functions must be defined in the asset's present operating context. Lindley R et al (2008:18) states that *all the functions of the asset or system shall be identified (all primary and secondary functions, including the functions of all protective devices)*". This is because the RCM process tries to preserve function and hence all functions should be clearly defined.

The objectives for defining the functions can be summarised as:

(i) *To identify and describe the systems required function,*

Functions can be categorised as follows (Moubray, 1997:22): -

- *Primary functions*, which summarise why the asset was acquired in the first place. This category of functions covers issues such as speed, output, carrying or storage capacity, product quality and customer service.
- *Secondary functions*, which recognise that every asset is expected to do more than simply fulfil its primary functions. Users also have expectations in areas such as safety, control, containment, comfort,

structural integrity, economy, protection, efficiency of operation, compliance with environmental regulations, and even the appearance of the asset.

According to the Society of Automotive Engineers (SAE) standard SAE JA1012 (2009:20) all functions of the system/asset must be identified. Nowlan et al (1978:41) states "*In listing the functions of the item it is important to describe both its basic function and each of its secondary functions clearly and accurately.* SAE JA1012 standards further states that in order to create a systematic and standard approach, all function statement shall contain a verb, an object, and a performance standard (quantified in every case where this can be done).

In this report, the functions were drawn from operational data and original equipment manufacturing (OEM) data in consultation with the Operations department.

(ii) To describe the input interface required for system to operate,

The various system functions may be represented by functional block diagrams to illustrate the input interfaces to a function In some cases, Smith (1993:74) suggests we split system functions into sub functions on an increasing level of detail, down to functions of maintainable items. This may be accomplished by functional block diagrams (FBD) or reliability block diagrams. In this report FBD are used due to missing equipment reliability data as will be discussed in step 5. Functional Block diagrams are not usually required for all system function. The diagrams are, however recommended for RCM. A detailed description of this type of diagram as used here is given in the RCM guide USACERL TR 99/41 (1999:18).

In order to identify the functions, the criteria suggested by Rausand et al (1998:22), was used. He proposed that the following questions when identifying functions for a system or design Failure Mode Effect Analysis: -

- What are the primary purposes of this item?
- What is the item supposed to do?
- What must the item not do?
- What is the standard of performance?
- What functions occur at the interfaces?

- What safety-related functions are important for this item?

Furthermore, the proposal by Moubray (2001:36) was also used to guide the group in coming up with a list of all the functions. The checklist includes: -

- Basic functions (the primary purpose of a product, obtained mainly from OEM documents),
- Safety functions (during manufacture or use),
- Reliability functions (life of the product),
- Product-appeal functions,
- Ergonomic functions,
- Human-interaction functions,
- Legal and regulatory functions,
- Functions relating to equipment installation,
- Fluid-retention functions,
- Service functions,
- Storage functions and
- Design for manufacturing or assembly function.

Once the interface between sub-systems is established, the functional degradation/failures for each function are identified and ranked during critical item selection in the next step.

3.5 CRITICAL ITEM SELECTION

The objective of this task is to prioritize functional failures based on how often they occur and the impacts to safety, availability and environment (risk). This step will identify maintainable items that are potentially critical with respect to the functional failures identified in Step 3.4. These maintainable items are denoted *functional significant items* (FSI). In order to rank functional failures a risk matrix is applied. Koekermoer (2008:3) highlights the importance of selecting critical items using risk. Risk is a product of Consequence of Failure (CoF) and Probability of Failure (PoF).

Determination of Consequence of failure (CoF)

The health, safety, environmental and business consequences of failure (CoF) are assessed for the relevant functional failure. Table 3-3 is the consequence matrix used in this analysis as extracted from the RBI procedure (S Singh, 2013:14). The matrix rates consequences from A to E, with A being the least and E the worst case. Consequences to economic values were determined using data from previous investigation were the losses are quantified in Rands.

Table 3-3 Consequence of Failure (CoF) Rating.

	A	B	C	D	E
Health (Long-term visibility).	Warning issued, no effect.	Warning issued, possible impact.	Temporary health problems, curable.	Limited impact on public health, threat of chronic illness.	Serious impact on public health, life-threatening illness.
Safety (Instant visibility).	No aid needed, work disruption.	First aid needed, no work disability.	Temporary work disability.	Permanent work disability.	Fatality (ies).
Environment.	Negligible impact.	Impact contained.	Major impact.	On-site damage.	Off-site damage, long-term effect.
Economic.	<R20K.	>R20K < R500K.	>R500K <R1m.	>R1m <20m.	More than R20m production delay and/or damage.

The effects of failure are described in terms of the "worst case" outcome with respect to Health, Safety, Environment and Economic. For tube leak failure for example, CoF is rated as AAAD, this means that for Health the impact is a "warning issued, no effect" (the first A) while the last letter is for Economic, with an impact within 1 to 20m Rands (the last D). The higher alphabetical score, in this case ***D***, is the worst case and becomes the CoF score that would be used for the risk scoring.

Determination of Probability of Failure (PoF)

The probability of failure is also rated using the worst-case scenario as in the consequence matrix. Numerical or descriptive measures of probability can be used (Jacobson, 2007:27). The PoF is determined using Table 3-4 (S Singh, 2013:15). Descriptive measures of very probable to very unlikely were used due to absence of reliability data on Mean Time Before Failures (MTBF). In future if values of MTBF become available the table could still be applied for the same process.

In applying Table 3-4 for tube leak failures for example, the data analysed showed that they occurred between a ranges of 1 to 5 years. The team would agree to either use the descriptive scoring Probable or the MTBF period (1-5years) and rate the PoF as four.

Table 3-4 Probability of Failure (PoF) Rating.

Very Probable	year<1	$>1x10^{-1}$	**5**
Probable	1-5 years	$1x10^{-1}$ to $1x10^{-2}$	**4**
Possible	5-10 years	$1x10^{-2}$ to $1x10^{-3}$	**3**
Unlikely	10-50 years	$1x10^{-3}$ to $1x10^{-4}$	**2**
Very unlikely	>100 years	$1x10^{-4}$	**1**
Descriptive	**MTBF**	**Probability**	**Rating**

Determination of Risk

The risk level is the product of the sum of weighting factors (or scoring points) of each of the probability of failure and consequences, this is the point of intersection of the PoF and CoF in Table 3-5 (S Singh, 2013:15). The four colours in the table represents red zone for high risk areas, yellow zone for medium risk, green zone for low risk and the white zone for very low negligible risk. The focus is to manage all risks in the red zone until they become tolerable and fall in either the green or white zone.

If the CoF score is D and that of PoF is four, using Table 3-5, they intersect at point 5 which is the red zone labelled as a *high-risk zone*.

Table 3-5 Risk Matrix.

PoF						
	5	15	10	6	3	1. Very high risk
	4	19	14	9	5. High risk	2
	3	22	18	13. Medium risk	8	4
	2	24	21. Low risk	17	12	7
	1	25. (Very low, negligible risk)	23	20	16	11
		A	*B*	*C*	*D*	*E*
				CoF		

Failure modes in the high-risk zones are the ones that this report focused on. Other failure modes, which fall into the low to medium risks zones may need to be, analysed further depending on the priorities of the organisation.

3.6 DATA COLLECTION AND ANALYSIS

The preparatory data required for RBI was the same data that was used for the RCM analysis. The data was collected as per the roles and responsibilities

outlined in section 3.2, and grouped according to Smith AM (1993:78) in the boardroom where the analysis took place.

3.6.1 Data Collection Method

Data was grouped according to Smith AM (1993:78) as; *design, operational* and *statistical data.*

Design data include: -

- Technical description of each sub-system
- Required performance standards
- OEM manuals and Carab Drawings

Operational data & failure data include: -

- Performance requirements
- Outage scope of work
- Outage reports
- Failure Reports and associated inspection results
- Maintenance strategy for each subsystem
- Certificate of Compliances
- Wall thickness test reports
- Visual inspection reports
- Metallurgical survey reports
- Plant Equipment Risk Management Procedure
- Systems Application Product Planned Maintenance (SAP-PM)

Reliability data. This is data that is derived from operational data by statistical analysis, it was not readily available.

3.6.2 Data Collection Techniques

The main data collection techniques used in this research study are the literature reviews and focus group discussion. These tools were considered adequate for the purpose of this report. Literature reviews is discussed in detail in Chapter 2. Nowlan et al (1978:18) propose a team approach to RCM analysis with functional groups from Operations and Maintenance. In this regard, Focus groups discussions were deemed appropriate for the execution of this project. The current RBI analysis was also being conducted by the same focus group that was used for this project. The use and advantages of focus groups is discussed by Lia

(2003:19), with the main disadvantage of focus groups cited as the tendency to be influenced by one or two dominant people in the session thus making the output very biased. The influence of bias is not ruled out in this project, however this was minimised by documenting source data and not giving opinion during moderation.

3.6.3 Data Analysis

According to Smith AM, (1993:78), this step primarily serves to establish a basis for qualitative analysis (of the relevant failure modes and causes), or quantitative analysis (reliability parameter such as MTTF, P-F intervals, and so on).

Saunders et al (2007:19) argues that the decision to use quantitative or qualitative approach is ultimately a philosophical question. The method to use depends on the nature of the project, the context of the study and the availability of resources (tools, time and human).

Dawn Lacobucci et al (2007) break down key features of qualitative compared to quantitative research methods as shown in Table 3-6.

Table 3-6 Key features of Qualitative and Quantitative research methods.

	Quantitative	Qualitative
Aim	The aim is to count things in an attempt to explain what is observed.	The aim is a complete, detailed description of what is observed.
Purpose	Generalisability, prediction, causal explanations	Contextualisation, interpretation, understanding perspectives
Tools	Researcher uses tools, such as surveys, to collect numerical data.	Researcher is the data-gathering instrument.
Data collection	Structured	Unstructured
Output	Data is in the form of numbers and statistics.	Data is in the form of words, pictures or objects.
Sample	Usually a large number of cases representing the population of interest. Randomly selected respondents	Usually a small number of non-representative cases. Respondents selected on their experience.
Objective/ Subjective	Objective – seeks precise measurement & analysis	Subjective - individuals' interpretation of events is important
Researcher role	Researcher tends to remain objectively separated from the subject matter.	Researcher tends to become subjectively immersed in the subject matter.
Analysis	Statistical	Interpretive

In the absence of reliability data, qualitative analysis is applied to the relevant failure modes. Qualitative approach is used in this report because the necessary data and the tools to carry out a statistical analysis in the available time of this project (Reliability Data) were not available. The research adopts a qualitative

approach to data analysis. However, it is ideal to use quantitative analysis due to the objective nature of this method (Saunders et al, 2007:18). Saunders et al urges that applying qualitative analysis can results in subjective results based on what the individual has experienced in his experience that may not necessarily be applicable to the present operating context. However, applying qualitative analysis will still give acceptable results that can form a basis for continuous improvement going forward.

Dawn Lacobucci et al (2007) highlight that the researcher is the data gathering instrument in a qualitative research, the data collecting techniques are unstructured. However, the data collecting technique adopted is explained in section 3.6.1.

3.6.4 Data Quality

Saunders et al, 2007:18 states the subjectively of qualitative methods, however qualitative methods are still adopted in many industries. The MIL-STD-1629AMIL-STD-1629A (1980) recommends the use of qualitative criticality analysis method to evaluate risk and prioritize corrective actions. The reliability improvements methods discussed in section 2.2 used qualitative methods to come to conclusion on the maintenance strategies. Will the use of the same qualitative methods yield different results when the Nowlan's (1978) RCM process was done using quantitative methods? This can only be answered when the results are implemented. To improve on the quality of data, it is recommended that statistical information on equipment as in the original RCM analysis of Nowlan (1978), such as Mean Time to Failure, be tracked so that the RCM process is applied in its entirety. In the meantime, the results of the RCM analysis using qualitative methods will be used to evaluate the objective of the project. Since the current processes are also using qualitative measures, the results are assumed acceptable. The study is carried out on a single unit at a power station with ten units operational. Some of the failure history records on the unit under analysis were not obtained (This is discussed in Section 4.4) which could compromise the results of the FMECA analysis. To improve on the quality of results, the sample size could be increased to include other units from the same power station and other business unit within Eskom.

3.7 FMECA

Identification of failure modes is an important step for failure analysis mainly because it allows the organisation to efficiently focus its resources in managing those failures that affects its core objectives (UCLF reduction).

Standard IEC 60050:191 (2006:8) defines failure as *the termination of the ability to perform a required function"*. A failure mode is defined in British Standard (BS 5760:2006:8), as *the effects by which a failure is observed on failed item""*. The failure mode (event leading to a functional failure) is a combination of a (failure mode) *cause* and a (failure mode) *mechanism*. A (failure mode) cause is the direct cause of a functional failure. A (failure mode) mechanism is the process that results in the cause. The FMECA analysis sheet used in this project will treat a failure mode as a combination of failure cause and a mechanism.

SAE JA1011(2002:17) indicates that the failure modes to be considered in an analysis are:

- Failures that have previously occurred on the equipment or similar machines. Failure modes that have previously occurred information comes from failure history data that is contained in the Eskom data base such as root cause reports and the PSEP report (Msibi et al, 2013:14),
- Possible failures that have not occurred before, but could have serious consequences. This information came from available literature, and is discussed in detail in section 4.5,
- Failure modes for which preventive maintenance was undertaken in order to prevent failure. This information was obtained using the design and operational data that was obtained in the data collection process. Maintenance reports and outage reports (reports of work done during scheduled outages) were analysed to identify failure modes for which preventative maintenance has occurred. Section 4.5 discuss the failure modes that were identified.

SAE JA1012 (2002:21) states that *the failure mode shall be identified at a level of causation that makes it possible to identify an appropriate failure management policy""*. This implies that when a failure mode is identified for a system, it must

be at a level of detail that will allow us to understand the technical characteristics of the failure mode. The technical characteristics will form the basis from which a maintenance program to manage or contain the failure mode is built. These are discussed in the next step under the RCM rules for proactive tasks.
Table 4-4 is a sample FMECA sheet for systems failure mode. This is in section 4.5. For each system function, the relevant system failure modes are recorded in this table.
Nowlan et al (1978:163) states that "*Failure effects refer to all the immediate results of failure*". The failure effects describe what happens if no specific tasks are done to anticipate, prevent or detect the failure. In this report, Failure effects descriptions are divided according to the proposal of SAE JA1011 (1999:32) as:

- ***Local Effect***. The local effect is the effect that the failure mode will have on the component on which the failure mode occurs.
- ***Next Higher Level Effect***. Next higher-level effect is a description of the physical effect the failure mode will have on the system of which the component is a part. This is the level on which the RCM analysis will be performed.
- ***End Effect***. The end effect is a description of the physical effect that the failure mode will have on production or operational capability as well as any effects that the failure mode could have on operational safety or the environment. Eskom strategies are being formulated at this level.

These are the level of analysis that are applied in the project.

3.8 SELECTION OF MAINTENANCE ACTION & INTERVAL

3.8.1 Maintenance Action

Moubray (1997:196) propose that RCM uses a logic tree to screen maintenance tasks. For each failure mode a decision must be taken on whether a PM task is applicable and effective or it will be best to let the item deliberately run to failure. A variety of different RCM decision logic diagrams are used in the main RCM references. Some of these are rather complex depending on the industry in which it is applied. RCM diagrams generally provide the following basic information about each failure: -

- Whether the failure will be evident, and therefore reported for correction,
- Whether its consequences include a possible safety hazard for the equipment or its operators,
- Whether its consequences have a direct effect on operational capability,
- The objective of preventive maintenance in each case, and hence the criterion for evaluating task effectiveness.

The decision logic diagram shown in Appendix D is the one used in RCM II and used for this project; this is according to Moubray (1997:196). Figure 3-2 is a sample of the Logic tree.

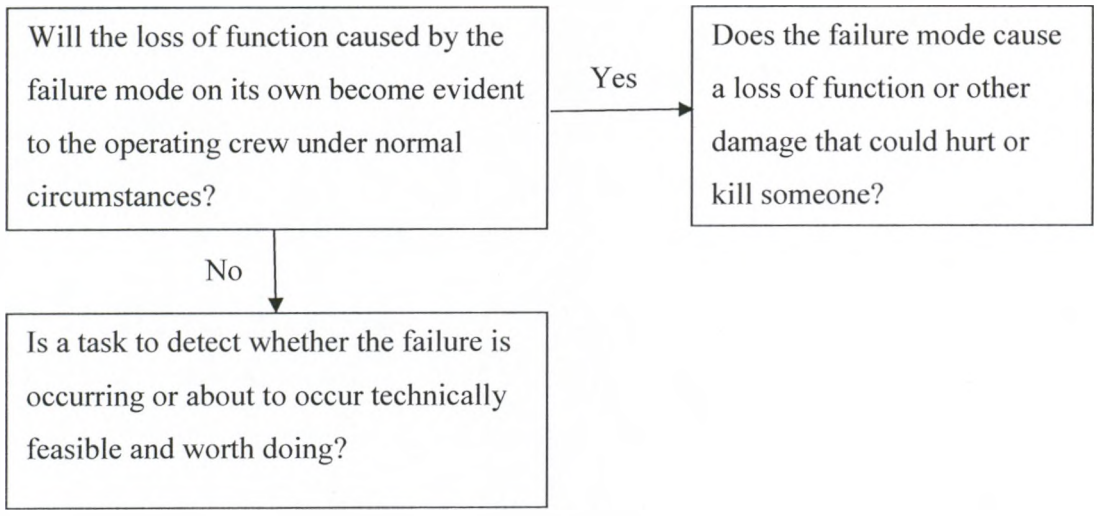


Figure 3-2 Sample of decision Logic Tree diagram for RCM II.

By answering the questions from the initial "Will the loss of function caused by the failure mode on its own become evident to the operating crew under normal circumstances?" the logic tree will lead to a proactive task type required to mitigate against the failure mode.

According to the British Standard (60300-3-11:2009:26) RCM divides proactive tasks into three categories as follows:

- Scheduled restoration tasks
- Scheduled failure-finding tasks
- Scheduled on-condition tasks

The following rules are generally applicable to these three categories of task (Naval Sea Systems, 2007:4-3): -

Rules for Scheduled restoration tasks

1. The conditional probability of failure increases at a specific age (evidence of "wear out").
2. A large proportion of the population must survive to the point of "wear out".
3. There must be no condition that predicts early failure.

Rules for Scheduled Failure-finding task

1. The functional failure must not be evident to the operating crew during routine operations.
2. The failure-finding task determines whether or not the intended function is available.
3. No appropriate condition-directed or time-directed life-renewal task can be devised to prevent failure.

Rules for Scheduled on-condition tasks

1. An equipment characteristic corresponding to the specific failure mode can be identified.
2. That characteristic can be measured accurately and with consistency.
3. Sufficient time exists between the identification of potential failure and actual failure to take corrective action to prevent failure.

If none of the above applies, then the component is run to failure. *Run to failure* is a deliberate decision to run to failure because the other tasks are not possible or the economic costs are less favourable and safety is not an issue.

The maintenance strategy selected must manage the failure mode it is trying to address.

3.8.2 Determination of maintenance intervals

When planning for maintenance, a crucial decision that must be made is the intervals between preventive maintenance tasks. The choice of intervals has a direct influence on the cost of maintenance. Reliability is affected by the length of time between which maintenance tasks are performed. Ultimately, the purpose of a maintenance tasks is to avoid or postpone failures.

Most failure modes identified during the analysis, will through some inspection method be urged that they give a warning that they are in the process of failing/occurring. For example, by carrying out regular thickness surveys, a trend can be used to calculate the rate of wear. If evidence can be found that something is in the final stages of failure, it may be possible to take action to prevent it from failing completely and/or to avoid the consequences. The warning period during which condition-monitoring tasks can be used to detect the onset of failure is known as the P-F interval (Rausand, 1998:20). There is wide literature available on P-F curves.

Condition monitoring maintenance task intervals must be determined based on expected P-F intervals. The following sources may be referred to as an aid to determine the P-F interval: -

- Expert opinion and judgement.
- Published information about condition monitoring tasks.
- Historical data (e.g. condition monitoring task intervals).

To determine the optimal interval requires information based on the failure rate function, the likely consequences of the failure, the cost of failure the PM task is supposed to prevent, and the cost and risk of the PM task. Usually formalised methods for optimisation of maintenance intervals are not part of the RCM but can help in the decision making process. A wide range of general models and methods for maintenance optimisation have been proposed e.g. see Valdez et al (1989).

Determination of maintenance intervals in this report was done using opinions from the team members assembled. Reliance was mainly based on original equipment manufacturer recommendations because not enough data was gathered/analysed to carry out statistical analysis and challenge otherwise. As was urged in 3.6.2, qualitative analysis is a subjective opinion; it cannot be guaranteed that a different group of experts will come with the same results.

3.9 VALIDITY OF RESEARCH AND RESEARCH LIMITATIONS

3.9.1 Validity and Reliability of Method

Long et al (2000: 30) defines validity as referring to the integrity and application of the methods undertaken and the precision in which the findings accurately

reflect the data, while reliability describes the consistency within the employed analytical procedures. Sandelowski (1993) propose use of alternative frameworks for establishing rigour due to the inherent difference in philosophical positions and purpose of qualitative and quantitative research methods. . Lincoln and Guba (1985) offer alternative criteria for demonstrating rigour within qualitative research namely truth-value, consistency and neutrality and applicability. There are various approaches that can be used in qualitative studies to address validity (quality/rigor/ trustworthiness) and reliability (dependability). According to Young (1998) one such method is 'triangulation' which refers to a process by which a researcher wants to verify findings by showing that independent measures of it agree with or, at least, do not contradict it. This project applies triangulation of information among different sources of methods, receiving feedback from team members and expert assembled for the RBI analysis. This involves verifying information (such as failure modes and mechanism) in the analysis sessions with the team members and allowing the stakeholders the chance to correct errors of facts or errors of interpretation that may arise. The RCM results will be compared with the results on similar components analysed using the RBI and RBO (Streamlined RCM) processes.

3.9.2 Research Limitations and Continuous improvement

Reliability is a statistical measure. The research was limited in the availability of reliability data. Though this is an academic research, the impact will be minimal as the results will not be implemented. Unavailability of statistical data means that information to do with failure MTBF, for example had to be decided based on experience of the team members.

Time was also a limiting factor that resulted in some parts of the methods being streamlined. For example, instead of analysing the whole boiler, only the subassembly is analysed. This will not affect the quality results because the objective is to test if RCM can be applied to the boiler subcomponents.

RCM is a living process; defined in SAEJA 1011 as a "*process used to determine what must be done to ensure that any physical asset continues to do what its users want it to do in its present operating context...*". The present operating context ensures that the RCM program stays relevant to the physical asset. Therefore, the

maintenance practices will need to be continuously reviewed and the RCM process continuously applied. RCM is a continuous improvement framework for defining and optimising the maintenance requirements for physical assets (Gilberto F et al 2012:190). Mechanisms to accurately monitor and evaluate the effectiveness of measures taken (PM reviews) must be established as part of the exercise together with the means to review and revise maintenance programmes based on the data gathered (IAEA-TECDOC-1590, 2007:24). Continuous improvement implies that the analysis gradually moves from qualitative to a quantitative nature based on reliability data.

Chapter 4 RESULTS PRESENTATION AND DATA ANALYSIS

The results of the RCM analysis are presented in this chapter. Most of the information was gathered during the analysis session with the team members. During the analysis, team members will bring to the analysis boardrooms manuals and any relevant information as per the roles in their appointments letters. The set-up of the team was discussed earlier.

4.1 SYSTEM BOUNDARIES

4.1.1 System Selection

Power plants generate electrical power by using fuels like coal, oil or natural gas. A simple power plant consists of a boiler, turbine, condenser and a generator as shown in Figure 4-1, this is similar to the configuration on unit number 10 analysed.

In order to manage the plants effectively, Eskom's power plants are divided into 26 systems (namely coal plant, boiler plant, draught group etc.) (Begg, 1998:9).

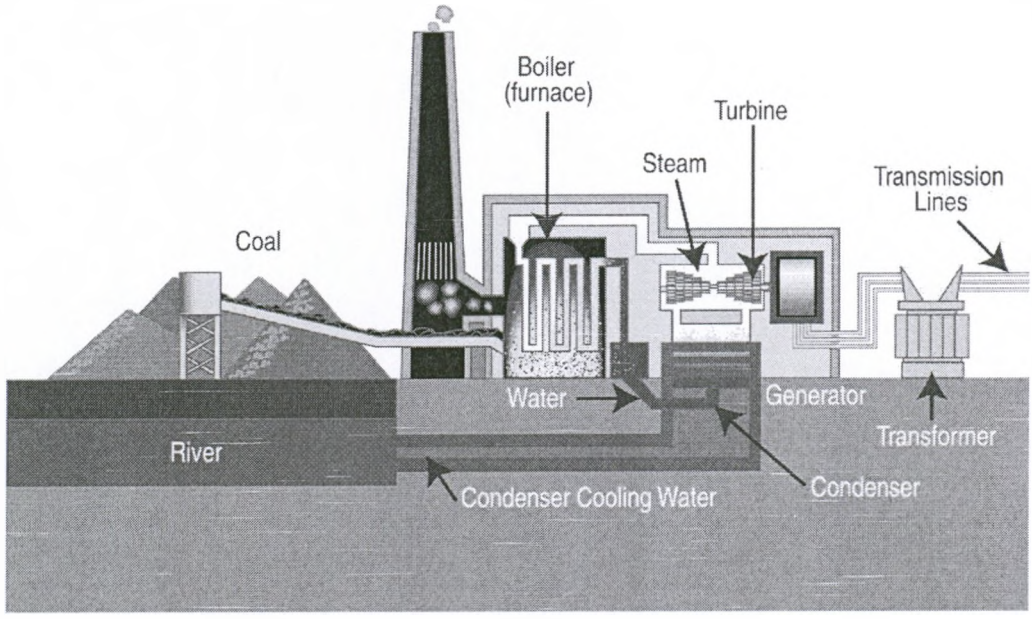


Figure 4-1 Fossil Fuel Power Plant

In power plants, many measures measure reliability including Unit Capability Factor, Unplanned Capability Loss Factor (UCLF), Forced Loss Rate (FLR), and Unplanned Automatic Grid Separations (UAGS). However, the measure used to set targets in Eskom is UCLF.

UCLF is the ratio of the unplanned energy losses over a given time period to the maximum amount of energy which could be produced over the same period. Low UCLF value indicates reliable plant equipment.

In comparison Unit Capability Factor (UCF), is the ratio of the available energy over a given time period to the maximum amount of energy which could be produced over the same period. A high unit capability factor indicates effective plant programmes and practices to minimise unplanned energy losses and to optimise planned outages. Equation 2 is the formula for UCF.

$$UCF = \frac{Maximum\ Energy - (Unplannad\ losses + Planned\ Losses)}{Maximum\ Enegy} \qquad equation\ 2$$

Where:

Maximum Energy = *190 x 10 x 24 x number of days in month*

Unplanned Losses = *Mw Capacity of unplanned losses x Off-time of load loss*

Planned Losses = *Mw Capacity of planned losses x Off-time of load loss*

The difference between UCLF and UCF is that UCF considers planned losses. UCF is a better measure to use because it indicates the effectiveness of the maintenance programme. Planned losses improve asset reliability, incorporating them in a reliability measure will be more effective to Eskom due to the high costs of outages. In this report, UCLF is the measure of choice of Reliability due to reasons outlined in section 1.2 and because it is the current measure used within Eskom.

The Power Station Enhancement Programme (PSEP) programme started at the Utility in 2012. Its aim was to identify the top five systems that contributed the most UCLF in the past five years. The following plants were identified (Msibi et al, 2013:20): -

- Boiler plant (3.36%),
- Turbine plant (1.55%),
- Milling plant (0.37%),
- Draught plant (0.61%), and
- Ash and dust plant (0.31%).

Figure 4-2 (extracted from the PSEP report) shows the contribution of each system over a period of five years. Each graph represents the total UCLF for the year for that particular system. The graph shows that the boiler plant is the most problematic in terms of reliability for all these years. It is thus, more beneficial to carry out the RCM process on the boiler plant components.

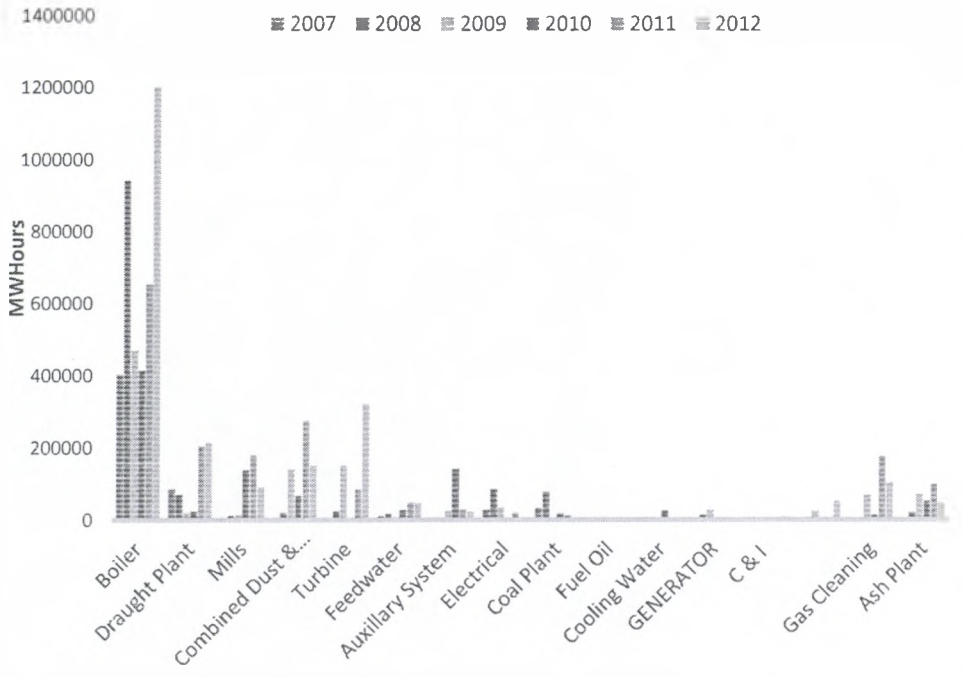


Figure 4-2 UCLF per plant systems. (Source: PSEP report)

The information from the graph comes from the Generation Production and Sales System (GPSS). The GPSS is a system that log faults as they happen in the plant before any investigations. The GPSS is not completely accurate in that it apportions UCLF losses to a particular plant before conclusion of root-cause investigation. If for example, a boiler trips and the operator suspects that it is due to a clinker in the boiler, the operator will log the information in the GPSS as failure due to clinker in the boiler even though the investigation might find a different cause later on. In order to correct the information in the GPSS to reflect the correct cause of a failure, investigations closure must be within the seven-day window. The tight period is difficult to meet as a result; most faults in the GPSS system are as the operators in the log them GPSS. This has an effect of over exaggerating the total losses per plant area, especially those due to the boiler. This will have an effect were prioritisation of analysis is based on reliability measures,

in the case because this is an academic project there will be no impact on the results of the analysis.

4.1.2 Level of Analysis

Appendix B is the layout of the boiler under study; it consists of the Economiser, the Superheaters, and the Furnace among other components. According to USACERL TR 99/41 (1999:27), the RCM analysis must be performed on a grouping or collection of components that together form some identifiable package that will perform at least one significant function as a standalone item. Correctly defining the level ensures that the project is manageable and controllable. In the RBI process, the boiler sub-systems are as shown in Figure 4-3.

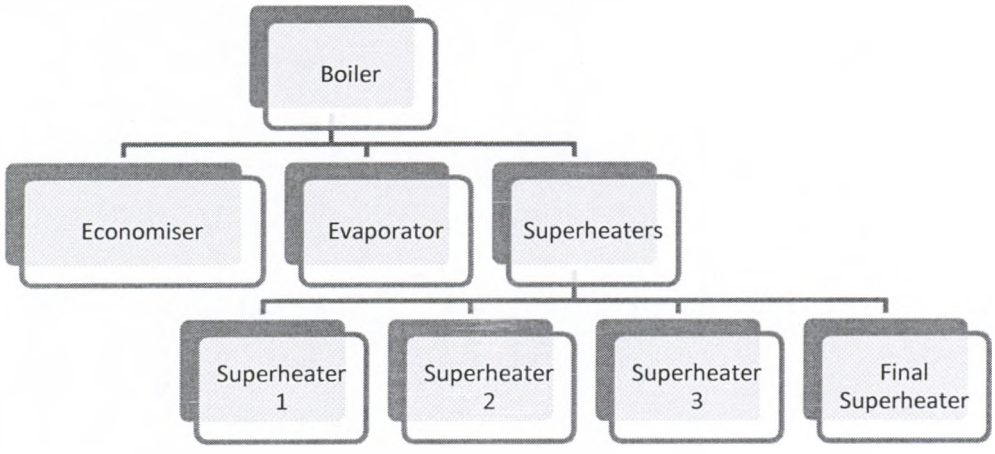


Figure 4-3 Unit 10 Boiler subsystems.

In Eskom, Maintenance history is at the subsystems (Economiser, Evaporator, Superheater 1, 2, 3) level. These are the levels at which the RBI process is carried out. This is the level at which RCM is performed. This will allow for a direct comparison with the results of the other maintenance interventions that Eskom has employed on the other subsystems.

The next higher level (boiler) has many components and hence functions. This will see the project being unmanageable. Considering that for every function there could be more than one functional failure there could be multiple failure modes and causes. This results in the analysis taking long to complete.

On the other hand, analysis at the next lower level could lead to isolating equipment and even components from the overall operating context due to the enclosed nature of the boiler structure. For example, the next lower level will include analysing valves as systems, which will make the analysis cumbersome and difficult in terms of identifying one significant function associated with the valve as a stand-alone. This can result in a misinterpretation of the risk that the failure modes and causes represent in the overall business context resulting in over or under maintaining equipment. This is the level at which RBO is executed in Eskom.

There is no specific rule regarding the level of analysis. Normally the complexity of the system will determine the level of analysis. The RBI analysis is done at the subsystem level; this is the same level that the RCM analysis will be performed. Moubray (1997:80) states that the objective of defining the system is to identify the input interface required for the system to operate and describe the system's required functions and performance criteria. The project applies the RCM process to boiler plant system (with subsystems components shown Figure 4-3) which according to Figure 4-2 is the least reliable. RCM is being applied to reduce UCLF. At this level, the requirements for defining a system for an RCM analysis as contemplated by Hoch (1990:3) in section 3.3 are met.

4.2 BOILER FUNCTIONS

4.2.1 Boiler operating context

Rausand et al (1998: 6) define the operating context as the current condition and environment in which the equipment operates. The operating context affects functions and performance standards. Technically identical equipment will perform differently if the operating context is different. The RBO uses templates developed by EPRI based on a study on power stations operating on a different environment as Eskom. This means that the operating context for which those templates may be different to the Eskom environment.

The following operating contexts for the boiler plant use the recommendations of Lucky (2013) and the PSEP report.

- *Constrained national grid resulting in deferred outages (Maintenance backlog):* This occurs when the unit is due for planned maintenance outage but is kept running due to system constraints (In this case, demand on the national grid is greater than the generated capacity due to equipment breakdowns from other Eskom plants). The decision to take a unit out for planned maintenance considers the total demand and supply at that period on the national grid. If the grid is strained the outage is usually postponed indefinitely. This decision is beyond the control of the local business unit. For example, if the national grid is short of 3000MW, the decision may be to postpone all planned outages while managing the grid. The unit may suffer a random failure during this period. Random failures are costlier, for example, the failure may occur over the weekend when costs of labour are high due to overtime. Due to less time available, to plan for the repairs during random failures compromise quality, and subsequently more costs. The focus during random failures is on returning the unit back on line without necessarily inspecting other areas that could potentially fail the same way.
- *High number of outage slips*: Every outage that occurs is planned based on time to complete the work. An outage slip occurs if the outage is not completed within the budgeted period. Many reasons exist for outage slips but the common ones are unavailability of spares to complete tasks, and additional scope that is discovered when the unit is taken off-load resulting in additional unplanned work. The RCM study will not look at the outage slips as it is deemed to have no direct effect on the choice of maintenance tasks and hence the RCM results. However, it must be noted that in some cases the outage slip can also result in system constraints, as units are not brought back on line on the planned periods.
- *High frequency of boiler loss of fire:* Boiler loss of fires is the name of the failure alarm that activates when there are no fires in the boiler (Flame monitors). Loss of boiler fires is mainly due to boiler tube

leaks. Boiler tube leaks results in the unit shutting down resulting in lack of generating capacity. It is then not surprising to see that a higher number of boiler loss of fires are reported as the alarm reports both losses due to water leak and due to flame disturbances within the boiler.

- *Poor coal quality.* The quality of coal has deteriorated over the years. Poor coal quality affects boiler reliability. Poor quality results in more coal usage to compensate for the loss of calorific value. The report discussed the effect coal in section 4.5.
- *Equipment is governed by OHSAct.* The requirements of the Pressure Equipment Regulation (OHSAct, 1993: 148) requires that steam generators or pressure vessels be inspected after every 36 months. Depending on age (whether new or old) or reliability the boiler will still need to be taken down for statutory inspections after every 36 months. Eskom is moving towards RBI as discussed in section 1.2, in order to delay the inspection frequency based on a formalised risk assessment of components.
- *There is no standby or redundancy.* The boiler operates continuously without a standby or redundancy. This makes it a critical component in the electrical generation process because failure of the unit will automatically affect production. Eventually the reliability of the boiler is affected due to continuous use. Availability is crucial to the boiler because its failure will affect the whole electricity generating system.
- *Operational Mode,* the Boiler is required to operates 24hours a day. Continuous use of the boiler means that the components are continuously stressed.

The above operating contexts will affect both the maintenance programme and/or the reliability of the boiler.

There are two important factors not considered in the operating context, which are crucial and affect the reliability of the equipment. These are the asset condition and the level of skill. The asset condition will determine the reliability goals, as for example, unit 10 is the oldest at the station. As equipment gets older, the

bathtub curve shows that failures will increase exponentially (Nowlan1978:45). Though this may not necessarily apply to the boiler, there is a need to be exploring it further. The result is setting reliability goals for individual units instead of the current scenario where reliability goals (in terms of UCLF) are set for the whole station.

The skills level is also an important factor to consider as shown in Figure 1-3. The skills level includes the experience of plant operators and their qualifications. Five of the units operated at the Utility are of the same configuration but their reliability figures are not the same as highlighted in the PSEP report. This report will not look at the labour qualifications issues due to the limited time.

4.2.2 Boiler Functions

Primary Function

The boiler is required to produce a continuous output, known as boiler Maximum Continuous Rating (MCR) of 214.2kg/sec of superheated steam at a pressure of 11.0MPa and a temperature of 543°C using feed water at a temperature of approximately 218°C. The primary function is defined using literature from the OEM. The assumption is that no changes have occurred in that period.

Secondary Functions.

Below is a lists of the functions for the boiler systems; this is according to Moubray (2001:36) who identifies secondary functions as functions which support compliance, safety, efficiency of operation, control, containment, structural integrity, economy, protection: -

- *Compliance*: To comply with the Pressure Equipment Regulation (PER) with regard to its safe use.
- *Safety*: To produce steam in a safe manner without over pressurising the boiler (above 11 MPa).
- *Efficiency of operation*: To provide the operator with accurate inlet and outlet readings of operating parameters.
- *Control*: To be able to notify clearly the operator if operating limits are about to be exceeded.
- *Protection*: To be able to relief pressure if it exceeds 11MPa.

- *Economy*: To provide the operator with an easy access to monitor operating parameters.
- *Containment*: To be able to contain inputs and outputs of combustion (air, coal and steam, coarse and fly ash).

Due to unavailability of design data, performance standards at a level of performance desired by RCM were not clearly defined (Rausand et al, 1998:22). This is important because it, for example, allows the analysis to define what constitute a partial failure or a complete failure (Lindley R et al, 2008:4). Partial failures and complete failures are not desirable within Eskom due to current grid demand exceeding generating supply. This RCM analysis is, thus done at design capacity (100% Capacity).

Functional block diagrams

Table 4-1 represents the process of steam generation model with the inputs, processes and the outputs (IPO). A mixture of coal and air meet in the furnace where combustion takes place. Steam generation takes place within the boiler. As the flue gases escape upward of the furnace, they lose heat through heat exchange to the incoming feed water in the Economiser and the Superheaters; these are the heat transfer surfaces referred in Table 4-1. Superheated steam then flows to the turbine to supply mechanical energy required for electrical generation. Course ash and fly ash are the other outputs of the combustion process. Course ash collects at the bottom of the boiler while fly ash is exit using the Induced Draft (ID) fan through the smoke stacks.

Table 4-1 Basic Boiler System.

INPUTS	PROCESS			OUTPUTS
Boiler Feed water	Steam Generation			Steam blowdown
Coal	Mixing of coal and air	Furnace	Heat Transfer surface	Flue Gas
Air				Ash

The IPO model is shown as a simplified functional block diagram in

Figure 4-4. This model shows how the various functions can be apportioned to the subsystem (e.g. Sootblowers) which will support the overall boiler system function. The blue lines are the inputs, the green lines show the boiler controls while the red lines represent the outputs from the boiler.

Figure 4-4 was used to ensure that the team determine all of the functions provided by the system and within the system so that functional failures could be determined and analysed. This is discussed in the next section.

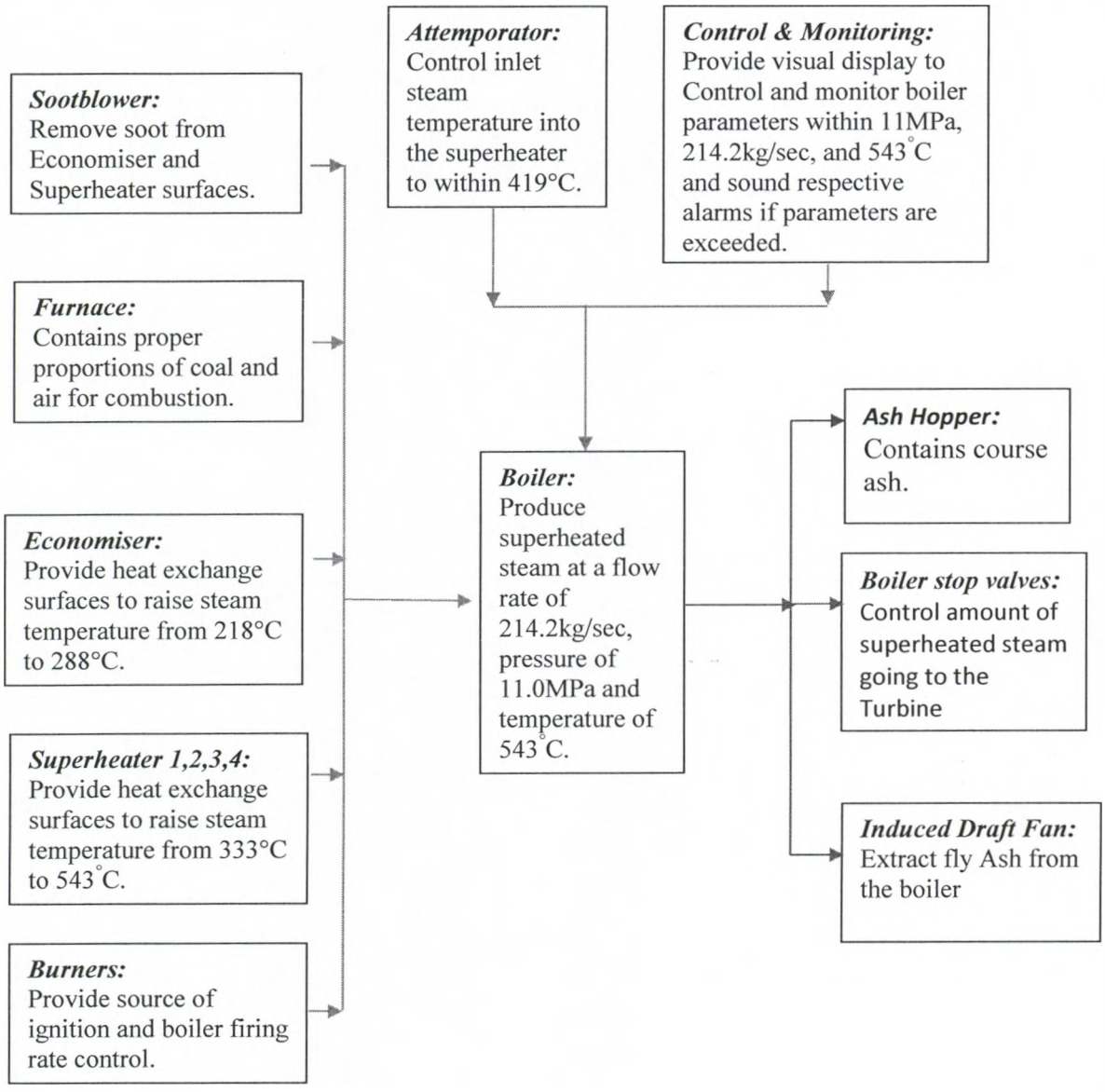


Figure 4-4 Boiler System Functional Block diagram.

4.2.3 Functional failure identification

The functional failure defines ways in which the boiler will fail to fulfil the functions listed in

Figure 4-4.The Functional failures were derived from the Functional Block diagram in Figure 4-4 and Figure 4-5. Figure 4-5 shows the recorded failures that operators log into the GPSS system. This graph, obtained from the PSEP report shows the failures listed below as associated with the primary function of the boiler: -

- Boiler leaks
- Boiler loses fires
- Clinkers develop in boiler etc.

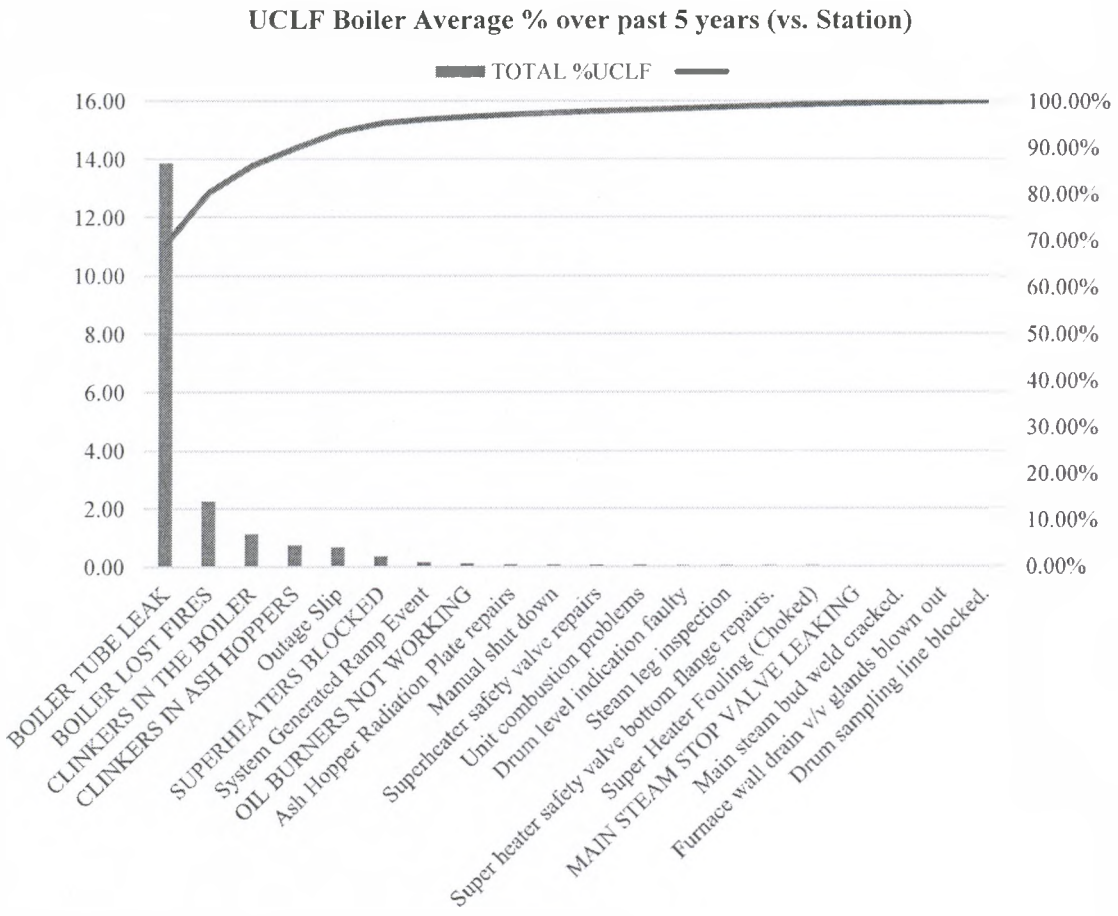


Figure 4-5 Failures as logged in GPSS. (Source: PSEP: 2013)

From Figure 4-5, boiler tube leaks and boiler lost fires contributed 80% towards the UCLF values for the five years that were analysed. The PSEP report treats boiler lost fires and boiler tube leaks as similar failures. This is because boiler tube leaks will lead to loss of boiler fires. In the boiler, Pyrometers are used to monitor the flame intensity, if they pick up a failure it is recorded in the GPSS by operators as boiler loss of fire. Acoustic tube leak detectors monitor the presence of a tube leak within the boiler. The two systems complement each other. This report will also incorporate boiler loss of fires as forming part of boiler tube leaks. At the international boiler tube failure conference held in 1991, it was also noted that Boiler Tube Failure (BTF) ranked as the number one equipment problem in fossil plants and had remained there for the previous 28 years (Palo, 1992:37). It is a fact therefore that analysing boiler tube leak failures will have a big impact in reducing the UCLF values.

The functional failure analysis is done by completing the functional failure analysis (FFA) sheet shown in Table 4-2. All the failures identified are partial failures. A partial failure means that after experiencing the failure, performance of the boiler is still possible but not at the maximum rating of 200MW output. Low loading the boiler is acceptable to some level but in the end the fault has to be addressed otherwise, a complete failure occurs. The current practice requires that a risk assessment be carried out after each failure before the unit is switched off. When implementing RCM, both the partial failures and the complete failures should be considered.

Table 4-2 Boiler Functional Failure Analysis

Operational Mode	Function *Primary Function (Steam conditions)*	Functional Failure	*CoF*	*PoF*	*Risk*
100 % Load	Steam Flow at 214.2 Kg/s	Boiler Leaks (Drum low level trip -220 mm and high level trip +220mm)	D (economic)	5	High
	Steam Temperature at 543°C,	Steam Temperatures below requirements (trip at steam temperature 560°C or flame less than 600°C)	C (economic)	3	Medium
	Steam Pressure at 11MPa	Boiler Loses Pressure (trip occurs when furnace pressure falls to -250Pa or rise to +250Pa)	C (economic)	3	Medium
	Secondary Functions				
	Operable within set parameters (Pressure, Temperature, Flow)	Boiler fails to control parameters	E(economic)	1	Medium
	Exhaust Coarse ash	Boiler fails to exhaust coarse ash	C (economic)	4	Medium
	Exhaust fly ash	Boiler fails to exhaust fly ash	C (economic)	3	Medium
	Contain raw materials	Boiler fails to contain inputs/outputs	C (economic)	4	Medium
	Raise alarm from set parameters	Fails to raise alarm when limits are exceeded	E(economic)	1	Medium

The FFA sheet above is based on the following definitions of the headings: -

The operational mode denotes the various operation modes of the boiler. For example, the boiler can be in full operational mode (Where it is generating at 100% capacity) or half load, or completely off. In this report, because of the large demand of electricity and the project time scales, only the full operational mode is the one that is analysed.

Functions. Contain the primary and secondary functions of the boiler system.

Functional Failure: The column contains all the functional failures associated with the function under analysis.

Consequence of failure (CoF) is the CoF value of the functional failure rated across Safety, Health, Environment and Economic as discussed earlier (Table 3-3).

Probability of failure (PoF) is obtained by using Table 3-4 and represents the Frequency or probability of occurrence of the functional failure under analysis.

Risk is the product of the CoF and PoF and is used to identify the critical items. It is up to the organisation to determine which risk levels are acceptable for analysis. Analysing medium risk for example, may widen the scope and but increase the reliability. The time required to complete the analysis and cost will also increase hence the need for the organisation to make a decision. In this project, only functional failures with a high risk rating (falling in red region of the risk matrix in Table 3-5) are the ones that were selected to go for the next process of critical item selection as discussed in the next section.

Section 3.4 mention the objectives of defining boiler functions as to identify primary and secondary functions and to describe the input interface for the system to operate. In this project, only primary functions are considered. RCM requires that all functional failures be defined. If functions are not exhaustively defined, then not all functional failures are considered and subsequently it may result in some of the failure modes been excluded in the final analysis. The effect of the omission of the other boiler functions will not have a major impact on the objective of the project. This is because the RCM results will be compared for the same loss of function, for example, failure modes that have been identified to affect the primary function in the RBI or RBO process will be compared with

those that come from the RCM analysis. However, during RCM implementation all functions need to be defined.

4.3 CRITICAL ITEM SELECTION

This steps aims to identify items that are critical with respect to the functions identified previously. From the FFA analysis sheet, Functional failures (boiler tube leaks) resulting in a higher risk to the plant were analysed further. Boiler tube leak failure reports on Unit 10 between the years 2000 to 2011 were analysed. While analysing the failure reports two issues were primarily looked at which are number of failures and the failure location in accordance with the system levels. The results that are presented in Figure 4-6 were used to identify the critical items for further analysing. Superheater 3, 4 and the furnace wall had the most number of tube leaks, contributing 80% of the total failures in the last eleven years analysed. These items are critical with respect to the boiler leak failure and are denoted functional significant items (FSI). As discussed Rausand et al (1998: 11) failure rate can also be used as a measure for selecting critical items.

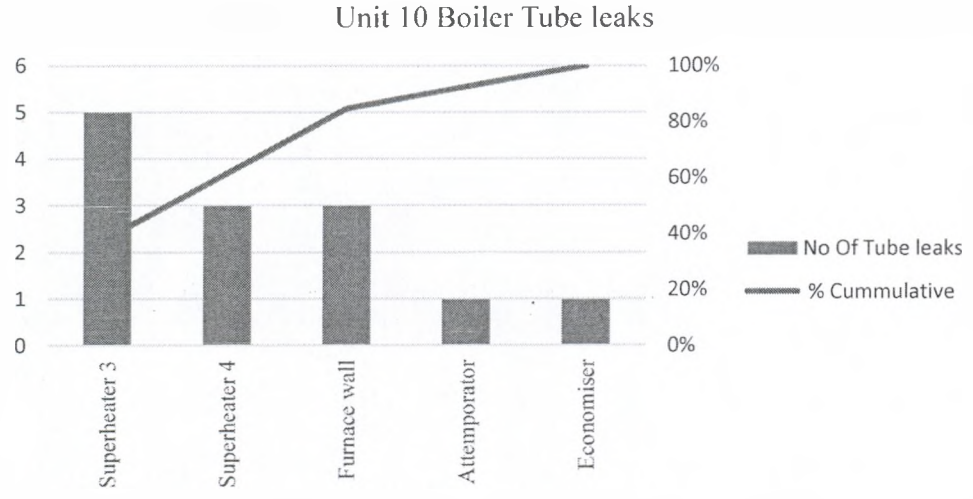


Figure 4-6 Unit 10 Boiler Tube failures per FSI

Because of the academic nature of this project and time limitations, the RCM process was applied only on Superheater 3. This will not affect the results of the process; the other components were analysed using the RBI process. The result of the RCM analysis on Superheater 3 cannot be applied on the other FSI due to the

different operating context. The method as demonstrated on Superheater 3 however can be applied on the other FSIs.

4.4 SUPERHEATER 3 DATA COLLECTION & ANALYSIS.

Superheater 3 data was collected and grouped in accordance with the proposals of Smith AM (1993:78) i.e. design, operational & failure data and reliability data. Superheater 3 design data was readily available from the local library. The design data was used to define both the system boundaries and the subsystem of the superheater 3.

Superheater 3 failure history data between 2000 and 2011 was used to identify failure causes and mechanisms that were experienced, the maintenance actions taken, downtime costs, and the failure locations. The Failure history data is shown in Appendix C. The information was obtained from the electronic failure management system that the plant is using to manage its failure records and reporting. When a failure occurs and results in a reduced load or if the unit is switched off, the nature of the failure is recorded and given a unique incident number. Records are then stored based on this unique number. When trying to retrieve some of this history it was discovered that some of the failure records were not readily available. Failure records are crucial in the determination of reliability requirements for example; the history is used to identify dominant failures. One of the reasons for the missing information is that investigations are linked to previous investigations if they are similar. Records are then referenced to the previous or original investigation. Appendix C shows some of the incidents where no records were found and how they are linked.

Maintenance intervals are not optimised mainly due to the requirements of the OHSAct (1993:148) which requires that the boiler be inspected every three years. With the introduction of RBI in Eskom, tracking of these parameters in future will help to optimise the maintenance intervals. This lack of reliability data leads the RCM analysis to be carried out qualitatively.

Some of the maintenance data could not be found due to the maintenance being carried out by contractors. This may affect the quality of the results because the missing information held by contractors may not be included in the decision-

making. In order to manage this, one of the contracting partners (Form Carab Plant Care) was also invited to be part of the analysis team.
The next sections will describe how the data was analysed to come up with the Superheater failure modes.

4.5 SUPERHEATER 3 FAILURE MODE ANALYSIS

4.5.1 Failure Mode (Cause and Mechanisms)

Previous Mechanisms

Previous Failure mechanisms on Superheater 3 were obtained from previous root cause analysis incidents. These incidents are listed in Appendix C, and an example is presented in Table 4-3

Table 4-3 Sample Incident Records

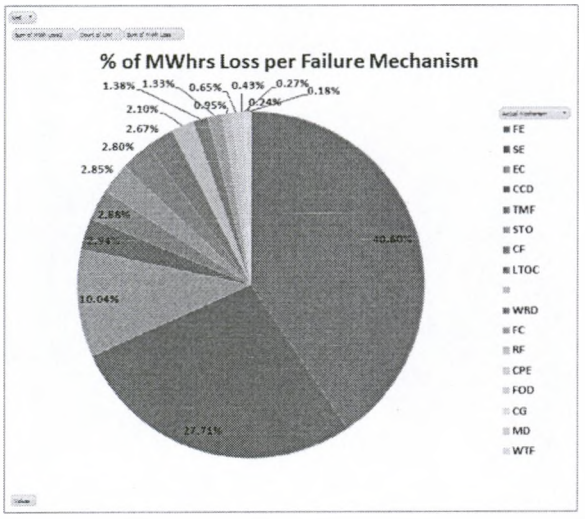
Year	Incident No.	Incident Description	Failure Location	Mechanism	Root Cause
2000	00/037	Boiler tube leak (linked to 99/111 & 97/041)	Economiser	Soot blower Erosion	FAE, Soot blower erosion, Ageing

Table 4-3 shows incident number 00/037 that occurred in the year 2000. This incident was recorded in the GPSS as a Boiler tube leak. There are other incidents of a similar nature that have occurred on the same unit, these are incident number 99/111 and 97/041. The Failure location was determined to be on the Economiser and the root cause was due to a combination of Fly Ash Erosion (FAE), Sootblower Erosion and Ageing.
The Information was extracted from the Eskom Incident management centre. The process of incident investigation in Eskom generally starts with the setting up of an investigating team, which will present their findings to a team of engineers. Acceptance of the findings will then result in the closure of the investigation. All findings are recorded under the incident number in this case, 00/037.
Only incidents occurring on Unit 10 were analysed. The accuracy of the analysis results can be increased by considering failure history on other units with similar

designs within the plant, however due to the limited time scale of the project this could not be achieved.

Other Mechanisms

These are the failure mechanisms that are likely to have serious consequences when they occur and where preventative maintenance is already occurring. This identification was based on literature, RBI information, outage reports and the PSEP report. Figure 4-7 is an extract from the PSEP report showings the damage mechanisms that were experienced at the station (for all the 10 Units). Fly ash erosion (FE) 40.60% and Sootblower erosion (SE) 27.71% are the most dominant failure mechanisms experienced at the Utility.



Long Description	Actual Mechanism
Fly Ash Erosion	FE
Sootblower Erosion	SE
External Corosion	EC
Chemical Cleaning Damage	CCD
Thermal Mechanical Fatigue	TMF
Short Term Overheating	STO
Corrosion Fatigue	CF
Long Term Overheating	LTOC
Welding Related defect	WRD
Fireside corrosion	FC
Rubbing Fretting	RF
Coal Partical Erosion	CPE
Falling Object Dammage	FOD
Caustic Gauging	CG
Mechanical dammage	MD
Water Blower Thermal Fatigue	WTF

Figure 4-7 Production loss per failure mechanism at the Power Station. (Source: PSEP Report)

Eskom's E2-R04b *Risk based Inspection in Power Industries"* identifies the following common mechanisms as dominant within the boiler Superheater systems

- Creep,
- Long-term overheating,
- Corrosion under deposit
- Pitting,
- Fly ash erosion,
- Thermal-mechanical fatigue,
- Fireside corrosion,

- Sootblower erosion,
- Stress corrosion cracking and,
- Chemical cleaning damage

Due to time limitations not all these mechanisms will be looked at in detail, focus will only be on Sootblower erosion and Fly ash erosion as these are the two dominant failure mechanisms on Unit 10 Superheater 3. The two failure modes are analysed and the results of the failure mode analysis are presented in a Failure Mode Effect and Criticality Analysis (FMECA) sheet in Appendix E however, a sample of the sheet is presented in Table 4-4. This is the same FMECA sheet that is recommended by Lindley R et al, (2008:49). The various columns in this FMECA form are discussed below.

- *Maintenance cost significant item (MSI):* - These are items with high failure rate, high repair costs, low maintainability, long lead-times for spare parts, or items requiring external maintenance personnel, these are the analysis items.
- *Operational mode:* The operational mode identified in this report is the running mode. Other operational modes could be standby, idling etc. Due to the electricity demand and the system constraints, Eskom requires that all units to be running at full capacity at all times. The MSIs are not required to be, for example, on standby as there is no redundancy.
- *Function:* The functions of the MSI
- *Failure mode "cause":* Direct cause of a functional failure
- *Failure mode "mechanism":* Process that results in the manifestation of a cause
- *Effect of failure (CoF):* worst-case consequences on health, safety, environmental and business of failure with current context.
- *Effect of failure (PoF):* Worst-case probability using descriptive measures in current operating context.
- *Criticality (Risk):* Product of CoF and PoF

- *Strategy action:* This failure management strategy may include any preventive maintenance task or even run to failure for non-critical components.
- *Recommended interval*: The time between maintenance task interventions.

Table 4-4 Failure Mode Analysis Sheet

MCSI		Function	FAILURE MODE		FAILURE EFFECTS		
			Cause	Damage Mechanism	Local Effect	Effect on Subsystem	Final effect
Piping	Connecting pipes from distribution header to SH3 header inlet (64)	Convey steam to headers	Deposition/ Scale	Thermal Mechanical Fatigue	Scale build up	Reduced steam outlet temperatures. High exhaust flue gas temperatures	Boiler loss of fires
					Stress concentration resulting in Fatigue cracks	Decreased steam flow and outlet steam temperature.	Boiler loss of fires
			Cyclic Temperature Increase	Thermal Mechanical Fatigue	Stress concentration resulting in Fatigue cracks	Decreased steam flow and outlet steam temperature.	Boiler loss of fires
			Combustion disturbance	Thermal Mechanical Fatigue	Stress concentration resulting in Fatigue cracks	Decreased steam flow and outlet steam temperature.	Boiler loss of fires

From the design data, the components of the superheater 3 were identified and listed in the FMECA spreadsheet as maintenance cost significant items (MCSI). Maintenance cost significant items are those that have high failure rate, high repair costs, low maintainability, long lead-time for spare parts, or items requiring external maintenance personnel. This data was readily available from the maintenance history data books and OEM manuals. The failure modes were then identified at this level (MCSI level). If the failure can be prevented at this level, then the reliability of the overall system will improve.

The following MCSI were identified using Stein Muller drawing number 06538176066001:

- Superheater Piping (These include the connecting pipes from distribution header to header inlet headers)
- Superheater Headers (Include the inlet and outlet header)
- Superheater connecting tubes (superheater convection coil and 180° bends)

The example in Table 4-4 identify piping as one of the MCS Item. These are the pipes that connect the distribution header to inlet header; they are numbered 64 in the OEM Manual (Stein Muller drawing number 06538176066001). Their primary function is to carry steam to the headers. In the table, the failure mode causes are the direct cause of failure that will result in steam not delivered to the headers at maximum boiler operating capacity. The physical effect that the failure mode will have on production or operation is an eventual boiler loss of fire (this will be picked up by the flame monitors or by the tube leak detectors depending on the extend of the failure). Depending on the extend of the failure and the national grid constraints, the unit may be allowed to continue operating at reduced load after a comprehensive risk assessment or be shut down. However, the energy required to raise steam temperatures (if allowed to continue operating) to the desired levels need to be increased which is costly to the organisation. This shows how expensive failures can be to the organisation and the need to avoid them.

Failure analysis can determine the damage mechanisms; in Eskom, this is mainly done through material grain structure analysis. During the RCM analysis process, the metallurgist using previous inspection reports verified the data on material

failure characteristics. This information was combined with information coming from the RIMAP procedure that was applied in the RBI process to come up with the failure mechanisms in the FMECA spreadsheet. Part of this information is shown in Table 4-5.

Table 4-5 Possible causes of damage mechanism

		Possible causes											
		Inadequate water quality	Deposit/scale	Increased static load	Dynamic load	Temperature increase	Irregularity in hydrodynamics	Fuel quality	Combustion disturbances	Inadequate material quality	Process quality	Chemical cleaning	Other
Damage mechanisms	Creep		√	√		√				√			
	Oxidation					√				√			
	Overheating		√			√			√				
	Thermal fatigue		√		√	√	√		√				
	Corrosion fatigue	√			√		√			√			√
	Stress corrosion cracking	√		√			√			√	√		√
	Fatigue (vibration and mechanical)				√						√		√
	Under deposit corrosion/ Pitting	√	√				√			√		√	√
	Acid corrosion	√	√				√			√		√	√
	Caustic corrosion	√	√				√			√		√	√
	Hydrogen damage	√	√				√			√	√	√	√
	Fly ash erosion							√					
	Gas corrosion							√	√	√			√
	Corrosion (outages)		√										√

Table 4-5 is an extract from the RIMAP (2008:39) procedure showing possible causes to some of the damage mechanism. These causes were applied in the analysis. Of the above mechanisms, Fly Ash Erosion caused by fuel quality (Coal quality) will be considered together with Sootblower erosion as these are the most dominant mechanisms that were experienced on the Units (see Figure 4-7 and Appendix C).

4.5.2 Soot blower erosion

In a coal fire boiler, slag from ash builds up on the walls of the furnace. If left unattended, the deposits can become unmanageable in size and require an expensive outage to remove. The deposits also reduce the amount of heat transfer, resulting in increased gas temperatures leaving the furnace, which is not desirable as this is energy wasted. The main purpose of soot blowing is to maintain boiler efficiency by maintaining clean heat transfer surfaces throughout the boiler (the desired final steam temperatures and subsequently the final flue gas temperatures are achieved).

Lance type blowers are used for Super heater tube cleaning. The lance slowly rotates and travels into and then out of the tube nest gas pass, blasting steam over the tube surfaces and cleaning them in the process. The process of soot blowing causes transient temperature fluctuations within the boiler. This has the effect of causing thermal fatigue on the pipes. In order to compensate for these fluctuations a Sootblower procedure is developed to guide operators in the soot blowing process. For example, just before soot blowing, temperatures are lowered by about 5°C depending on the operating temperature so that the pipes are not stressed. The super heater blowing time is approximately 90 seconds.

The failure history in Appendix C shows that Soot blower erosion is the most dominant mechanism on unit 10. Damage occurs near or in the direct path of Soot blower discharge. The incidents analysed show that the common damage locations include tubes along the path of retractable Soot blowers, particularly those tubes nearest wall entrance.

A misdirected blower allows a high-velocity jet of steam carrying condensed water droplets to impinge directly upon tube surfaces, rather than to be directed between tubes (Palo Alto, 1996:42). Physical abrasion and accelerated oxidation

cause metal loss. Damage can be accelerated by fly ash entrained in the velocity jet stream directed against the tube surface. Erosive thinning often results in tube ruptures.

The analysis team did a root cause analysis on the causes of Soot blower erosion. The causes were identified using the 5M method proposed by Ishikawa (1968). The causes were grouped into those that can be attributed to Measurement, Manpower etc. The fishbone diagram produced is shown in Figure 4-8.

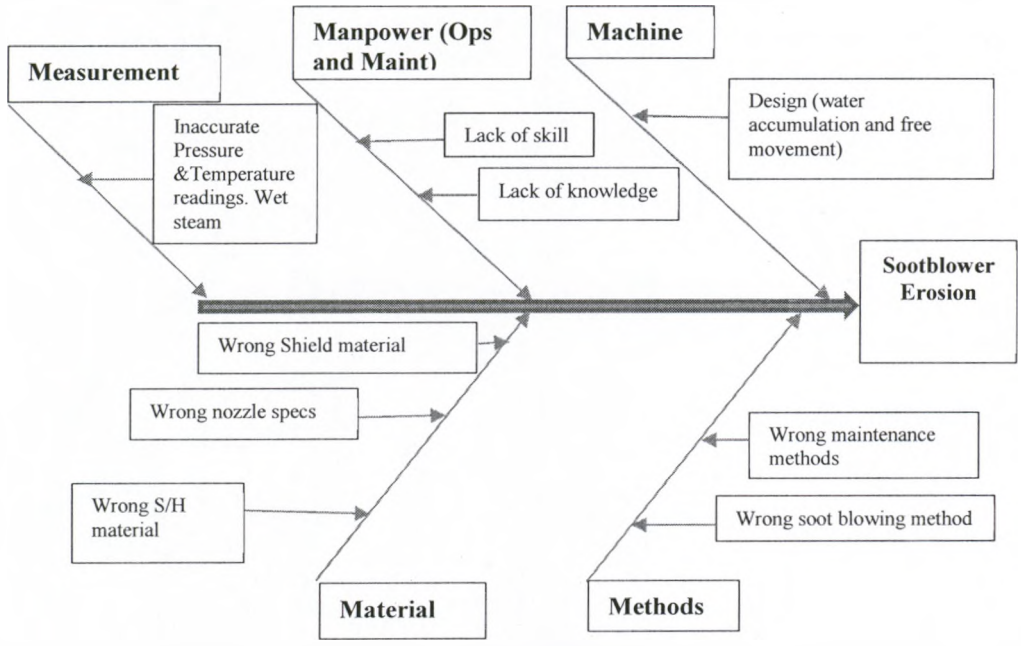


Figure 4-8 Soot blower Erosion Fish bone diagram.

The causes identified in the fishbone were used to populate the causes on the FMECA spreadsheet.

The failure reports analysed cite poor maintenance as the main reason for soot blower failures. For all the four incidents recorded from 14 April 2006 to 13 June 2009, all tube leak failures happening on the Soot blowers had the following similar actions: -

a) *Review maintenance philosophy to include elevation surveys and repairs on the Soot blower pipework.*

b) *Soot blower nozzles must be inspected to ensure it is according to specification and not worn out.*

c) *Operator to submit notification of stuck Soot blowers.*

d) *Review maintenance philosophy to include the replacement and testing of damaged tubes on the unit primary and secondary inlet and outlet Super heaters.*

Based on the same actions proposed over three years, the team felt that the effectiveness of both the investigation method and the actions need to be ascertained as to whether they were really addressing the root cause.

The causes identified in Figure 4-8 were used as the basis to populate the FMECA in Appendix C. The effect of each failure mode was agreed to by the team at the system level. For example, the following effects in Table 4-4 were identified: -

Local Effect. Pipes on which soot blowing is done will gradually erode (wear) the material off. Depending on the material thickness, this wear off will occur until the pipe raptures/ leaks.

Next Higher Level Effect. The ultrasonic sound detectors will pick the failure as a tube leak to due changes in the sound signatures received by the tube leak detectors.

End Effect. The unit has to be switched off to attend to the tube leaks. This will thus result in production loss.

The following shortcomings were observed as compared to the FMECA process suggested by Smith AM (1993): -

The following failure modes were not looked at in detail

- Failure to operate when required.
- Erroneous output (given the current condition).
- Invalid output (for any condition).

These failure modes can affect the results of the analysis by introducing additional maintenance tasks. For example, an error in the pressure or temperature reading of the superheated steam used for soot blowing may result in undesirable consequences even if the operator is following the correct soot blowing procedure. By looking at Sootblower erosion, the team was more inclined to look at the failure causes that were experienced instead of also looking at potential culprits.

In future, it is recommended that information from similar designs within the Eskom fleet of equipment be used to generate the failure causes.

Although Skills are not explored in this report, it is important in future to look at the level of skills of personnel that are carrying out both the soot blowing process and maintenance. If for example wet steam is used for soot blowing, the failure will manifest itself as soot blower erosion. All the failure analysis processes done on the unit have never looked at whether the people carrying out the soot blowing process are correctly trained.

4.5.3 Fly Ash Erosion (FAE)

Fly ash erosion was experienced 40% of the time (Figure 4-7). This type of erosion occurs when hard fly ash particles damage the boiler gas side. The rate and extent of erosive processes are affected by particle velocity, angle of impact, particle composition and shape, abrasive index of coal, and erosive resistance of the tube surface including compositional and temperature variations (Barry D, et al, 2000:197). Since 1999, the quality of coal is deteriorating as shown in Table 4-6. The energy (Calorific Value- CV) in coal compared to average ash and abrasive index is gradually decreasing. This means that more coal is now burnt for the same energy output in 2012 compared to 1999.

Table 4-6: Variation of coal characteristics as received at the coalbunkers.

Year	Average of CV	Average of Ash	Average of Volatile Matter	Average of Total Moisture	Average of Abrasiveness
1999	22.39	23.60	22.34	7.78	360.55
2000	22.09	23.99	21.87	8.10	422.29
2001	22.20	24.55	21.96	7.35	392.52
2002	21.77	25.04	21.43	7.78	444.76
2003	22.39	23.68	22.17	7.36	394.00
2004	21.99	23.93	22.37	7.90	413.59
2005	21.51	24.80	21.51	8.35	517.56
2006	21.53	25.32	21.45	9.22	576.11
2007	21.32	25.92	21.45	8.30	570.72
2008	21.23	25.42	20.57	6.94	586.42
2009	21.58	26.09	22.14	6.56	540.01
2010	21.74	27.06	22.09	5.82	555.79
2011	21.81	26.99	22.46	6.43	649.75
2012	21.48	26.55	22.29	6.65	659.80

The effect is that the Superheater can fail due to Fly ash erosion mechanism. Although it was not experienced specifically on unit 10, Figure 4-7 shows that Fly ash erosion is the overall dominant mechanism across the Utility.

Due to the deteriorating coal quality, Eskom is negotiating with coal suppliers for improved quality. The effect of deteriorating coal quality results in a change in the boiler-operating context compared to the first operating years.

In section 3.9, continuous improvement was highlighted as a backbone of an RCM program. Once a strategy is determined, it needs to be continuously evaluated for validity and relevant. With the quality of coal deteriorating it means that maintenance strategies need to be continuously reviewed. This will mean that in future Eskom need to track the wear rate of the boiler tubes based on each inspection. The current scenario involves maintenance personnel going to the plant, measuring the remaining wall thickness, and recommending replacement once the measured thickness is 75% of the original thickness. This is based on the long lead times that are required for the procurement of spares. These recommendations will not necessarily change once an RCM analysis is concluded, as the process does not look at the long lead times for spares.

The RCM analysis process only looked at the deteriorating coal conditions as the major factor in soot blower erosion. FAE in boiler pressure parts is also the result of the combined effect of local ash loading and gas velocity (Palo Alto, 1992:58). These parameters were not reviewed in the RCM analysis. Possibly, for example, by reviewing these parameters design issues could be unearthed as also playing a primary role in the failure process. These will need to be investigated further in future.

Data collection was done in accordance to the requirements of Smith AM (1993:78) however in section 4.4 the lack of reliability data (such as MTTR and the P-F intervals) derived from operational data by statistical analysis was discussed. This information is not currently tracked at the power station. The lack of reliability data affects the validity of the results as it limits the study to a qualitative analysis of the available data. Saunders et al (2007:18) urges that applying qualitative analysis can results in subjective results based on what the individual has experienced which may not necessarily be applicable to the present

operating context. In this case the failure mode frequency and hence the inspection frequency will not be based on any verifiable literature in the present operating context. One of the question that can be asked is "*is the frequency not*? By addressing the subjectivity, the validity of the results can be assured; This is discussed next.

4.6 MAINTENANCE ACTIONS AND FREQUENCY

4.6.1 Selection maintenance tasks

The RCM decision logic tree in Appendix D is used to select the maintenance tasks type that is applicable to each failure mode. The tree will result in the selection of proactive tasks, which are categorised as -

- Scheduled restoration tasks,
- Scheduled failure-finding tasks or,
- Scheduled on-condition tasks

If none of the above applies, then the component is run until either it fails or a redesign is considered.

Part of the logic tree used is shown in Figure 4-9. When applying the logic tree to thermal fatigue caused by deposit or scale build up in Table 4-4 for example, the loss of function caused by the failure mode occurring on its own will become evident to the operating crew. This entails going along the "Yes" route.

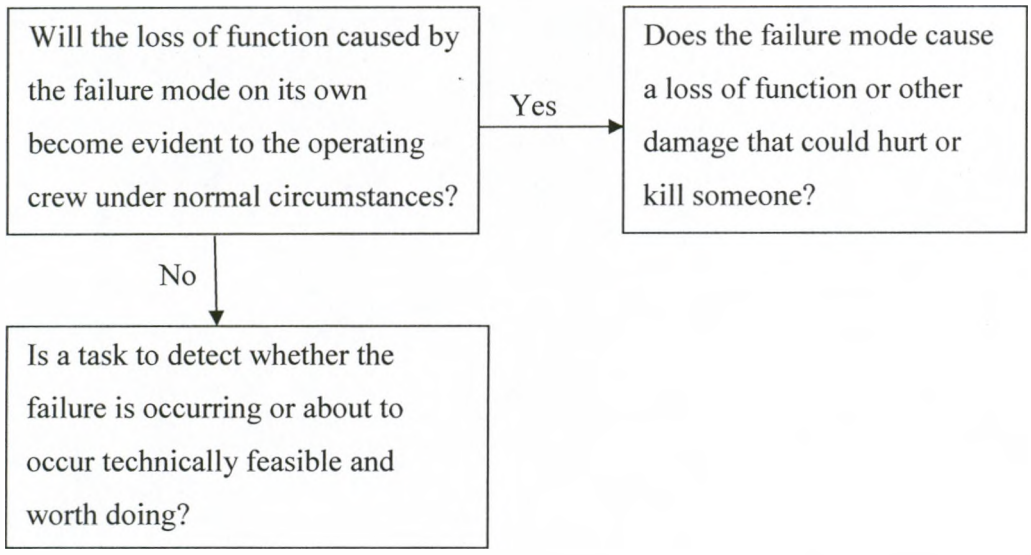


Figure 4-9 Sample RCM Logic tree

This process is repeated until a decision on the type of maintenance task decision is reached. The results are shown on the FMECA in Appendix E. The majority of the tasks selected were scheduled on-condition tasks. On-condition maintenance tasks include predictive maintenance, condition-based maintenance and condition monitoring tasks. The rules of these proactive tasks are discussed in section 3.8. The frequency of monitoring is governed by the time it takes from when the time a warning of an imminent failure is identified to the point at which the failure occurs. This is illustrated in Figure 4-10: the warning is shown at point P (Potential failure) and the full failure occurs at point F (Functional failure). In RCM analysis, the monitoring task should be carried out at an interval that is less than the time between the P-F intervals.

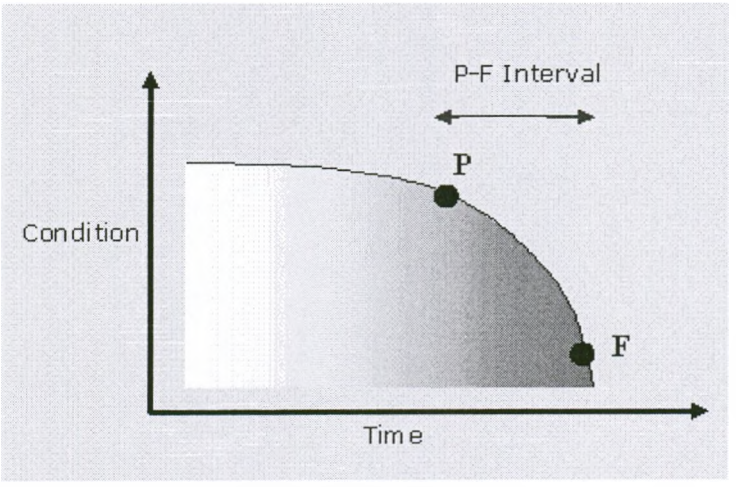


Figure 4-10 P-F curve.

The time between P and F is currently not tracked within Eskom for any of the MCSIs. The result is that there is no rule of thumb when determining the frequencies. The only rule is to abide by the requirements of the OHSAct (1993:148) which requires pressure vessels to be inspected after every three years. In the RCM analysis process, a 6-year inspection frequency was recommended for all the task. In the absence of objective data (reliability data), this time frame cannot be supported as the optimum frequency. Most Eskom units at the station have exemption letter from the government inspector for the three-year inspection to be done every 6 years. This could be the basis on which the experience of the panel was based on when making their decision on frequency. With the

introduction of RBI, this period can now be changed to reflect the actual time when inspection should be carried out based on a calculated risk at those operating conditions (operating context). However, in order to optimise the period, Eskom need to start monitoring the reliability parameters such as MTBF, MTTF etc.
The RCM task selection process is different from the task selection process applied in the RBO process. The RBO process use Generation Generic Component Strategy (GGCS) shown in appendix A following the process explained in Section 2.2.1.
The RCM process can be used to support the RBI process that Eskom is currently embarking on. The advantage is that the failure mechanisms are identified at the MSCI level thus allowing the risk of failure to be addressed at a much lower level of the equipment hierarchy as compared to the RBO process.

4.6.2 RCM inspection strategies

In order to determine the applicable inspection method, the failure mode mechanism and effects were compared based on available literature. The general characteristics of each method are listed in Table 4-7. Currently all the methods mentioned in the table were successfully applied in Eskom. The team used the table as a cross reference to see if the method could detect the failure mode. For example, fatigue cracks at known areas of stress concentration can be detected by non-destructive examination techniques such as magnetic particles testing, liquid penetrant and visual optical from the table. In order to select the appropriate method, Table 4-8 was then applied. This table allowed the team to make a decision it terms of the important parameters such as the skills of contractors that will carry out the inspection during the outage. The limitation in choosing the inspection method is that most Eskom contracts are already agreed for the next five years as to who should be carrying out maintenance. It is therefore suggested that the inspection methods be relooked at once the contracts expire in order to optimise on both cost and applicability. The results of the agreements are contained in the RCM analysis sheet in appendix E; however, a sample of these results is shown in Table 4-9.

Table 4-7 Comparison of various NDT methods

Method	Characteristics detected	Advantages	Limitations
Ultrasonic Testing (UT)	Changes in acoustic impedance, caused by cracks, inclusions, or interfaces	Can penetrate thick materials; excellent for crack detection; can be automated	Normally requires coupling to material either by contact to surface or immersion in a fluid such as water. Surface needs to be smooth.
Radiography	Changes in density from voids, inclusions, material variations; placement of internal parts	Can be used to inspect wide range of materials and thicknesses; versatile; film provides record of inspection	Radiation safety requires precautions; expensive; detection of cracks can be difficult unless perpendicular to x-ray film.
Visual optical (VO)	Surface characteristics such as finish, scratches, cracks or colour; corrosion	Often convenient; can be automated	Can be applied only to surfaces, through surface openings, or to transparent material
Eddy current (EC)	Changes in electrical conductivity caused by material variations, cracks, voids, or inclusions	Readily automated; moderate cost	Limited to electrically conducting materials; limited penetration depth
Liquid penetrant (PT)	Surface openings due to cracks, porosity, seams, or folds	Inexpensive, easy to use, readily portable, sensitive to small surface flaws	Flaw must be open to surface. Not useful on porous materials or rough surfaces
Magnetic particles (MT)	Leakage magnetic flux caused by surface or near-surface cracks, voids, inclusions, or material or geometry changes	Inexpensive or moderate cost, sensitive both to surface and near- surface flaws	Limited to ferromagnetic material; surface preparation and post-inspection demagnetization may be required.

Table 4-8 Relative cost and other characteristics of various NDT methods

	Test method				
Important consideration	***Ultrasonic***	***X-ray***	***Eddy current***	***Magnetic particle***	***Liquid penetrant***
Time of results	Immediate	Delayed	Immediate	Short delay	Short delay
Effect of geometry	Important	Important	Important	Not too important	Not too important
Access problems	Important	Important	Important	Important	Important
Type of defect	Internal	Most	External	External	Surface breaking
Relative sensitivity	High	Medium	High	Low	Low
Operator skill	High	High	Medium	Low	Low
Operator training	Important	Important	Important	Important	
Training needs	High	High	Medium	Low	Low
Portability of equipment	High	Low	High to Medium	High to Medium	High
Dependent on material composition	Very	Quite	Very	Magnetic only	Little
Capabilities	Thickness gaging: some composition testing	Thickness gaging	Thickness gaging: grade sorting	Defects only	Defects only

Table 4-9 Sample of FMECA task and frequency results

MCSI		Function	FAILURE MODE			
			Cause	Damage Mechanism	Task	Frequency
Piping	Connecting pipes from distribution header to SH3 header inlet (64)	Convey steam to headers	Deposition/ Scale	Thermal Mechanical Fatigue	NDE techniques such as PT, MT can be used to detect fatigue cracks at known areas of stress concentration.	72 months
					Controlled rates of heating and cooling during start-up and shutdown of equipment.	72 months
			Cyclic Temperature Increase	Thermal Mechanical Fatigue	Controlled rates of heating and cooling during start-up and shutdown of equipment.	72 months

In Table 4-9 a combination of tasks was suggested for some of the failure modes. This is due to the current contracts within Eskom and external contractors carrying out the work. The results of the analysis can be used in future when the contracts are renegotiated as a source of data, Eskom will be in a position to guide contractors as to the preferred optimised methods. Other differences between the RCM process findings and the maintenance initiatives in Eskom are discussed in the next section.

In this project, frequency determination is not based on objective reliability data such as P-F intervals rather it is based on the experience of the team members. Most RCM literature requests that the frequency be based on the P-F interval as discussed above. Thus RCM should be quantitatively analysed not qualitatively. In future, the organisation should start tracking statistical failure data as a basis to improve on the accuracy of the results and future analysis. Currently, the RBO and RBI initiatives are also applying qualitative methods to determine the

inspection levels. The inspection frequencies need to be optimised as this may result in over maintaining (where maintenance is been done too often). As explained in section 3.2, the use of a qualitative approach at first to the data analysis can however be relied on to produce acceptable results.

4.7 DISCUSSION

Section 2.4 presents the overall RCM method adopted in this project as similar to the RCM method that has been applied in the nuclear industry (Cotaina et al 2000:25). However, data analysis was done qualitatively due to limited availability of quantitative data. Qualitative research is frequently criticised for lacking scientific rigour with poor justification of the methods adopted, lack of transparency in the analytical procedures and the findings being merely a collection of personal opinions subject to researcher bias (Rolfe 2006: 53). As explained in section 3.2, the use of qualitative approach to data analysis was confirmed to produce acceptable results.

The discussion below centres mainly on the benefits and recommendations of the current maintenance determination processes and how they differ with the results of the RCM study.

4.7.1 RBO Boiler strategy

Maintenance intervals on the boiler plant is planned mainly to align all activities with the 36 months (3 years) boiler statutory inspections and pressure testing. The scope of maintenance during the 3 year-outages is determined by prescribed routine maintenance activities, such as plant refurbishment and actions identified during previous inspections. The current inspection and repair cycles are shown in Table 4-10. The decision to have these repair cycles is done centrally (from Eskom head office) and is not within the control of the local plant. This presents a disadvantage if the same approach of managing maintenance frequencies is done centrally and goes against the principles of RCM where maintenance decisions should be based on the operating context.

Boiler internal tube inspections and critical repairs is conducted after 18 months to prevent boiler tube failures, with more comprehensive inspection and repairs done on 6 yearly intervals. A detailed scope of work showing the areas that need to be

inspected is issued out but generally, the scope is as summarised in Table 4-10, this is the standard scope across all Eskom Plants.

Table 4-10 Current Inspection and Repair cycles.

Plant	Interim Repair	Mid-term repairs	Interim Repair	MINI-GO	Unit GO
Interval	18 Months	36 months	54 Months	72 Months	120 Months
Duration	14 days	21 days	14 days	40 days	92 days
SCOPE	Carry out dirty and clean visual inspection. Carry out comprehensive wall thickness tests on all suspected areas based on duration. Do life estimates & repairs. Carry out inspections based on Tube inspection recovery plan	Carry out complete scope as per 18-month outage. Cut water touched samples and evaluate for oxide thickness	Carry out complete scope as per 18-month outage. Implement actions forthcoming from previous outage	Boiler statutory inspection and hydraulic pressure testing at 160 Bar. Chemical cleaning based on 45-month sample analysis.	Boiler general overhaul. Boiler statutory inspection and hydraulic pressure testing at 160 Bar. Chemical cleaning based on 105-month sample analysis.

The discussion surrounding how the 18 monthly schedules came to be is not documented within Eskom. The results of the RCM study do not recommend any 18 monthly inspections, only 72 monthly inspections were recommended as shown in Appendix E. This will result in less frequent shutdowns of the boiler and ultimately costs associated with these inspections.

The 36 monthly inspections recommended from the RBI analysis are assumed to have arisen form the Occupational health and safety Act which requires that all pressure vessels be inspection after every 36 months and be pressure tested at 1.5 times the operating pressure. Eskom has always requested exemption to actually do the statutory inspections after every 72 months. However, they still maintained that they would shut down the boiler after every 36 months. With the introduction of RBI, the statutory frequency of 36 monthly can now be moved to any frequency based on a calculated risk, which mean that Eskom can now apply to align the inspection with the frequency identified in the RCM analysis.

The current RBO inspection program can be urged that it result in less scope when the boiler is ultimately switched off for the hydro-test after 72 months because other inspections are done at 18, 36 months. By the time you switch off to do the 72 monthly inspections, some of the plant problems will be addressed then. This could not be proven as the scope based on Table 4-10 does not clearly define what needs to be executed on the Superheater as it does on the RCM results.

Previous outages on the boiler were not done as per the recommended durations with all the outages usually lasting longer (Section 4.2.1). The outage slips were identified also in the PSEP report and recommendations adopted to set up outage planning and scoping teams. The teams look at both the task that are done as part of preventative maintenance and also tasks that arise during the operation of the boiler but could not be addressed because the boiler needs to be switched off (corrective maintenance tasks). The scope arising from the RCM analysis will need to be compared with the scopes in Table 4-10 because more resources may be required to complete the RCM tasks as compared for example, with the 18 monthly schedules listed. However, at the face value of it, the UCLF targets in Figure 4-2 were not met which mean that if there is no change in how

maintenance is carried out, then the same undesirable results might still be obtained.

4.7.2 Team approach to RCM strategy

The results of this RCM process differ to the RBO in that the 18, 36 and 54 monthly frequencies were replaced by a 72 monthly frequency. This resulted in a change in the overall maintenance scope as compared to the scope in Table 4-10. The scope of the outages in Table 4-10 is determined by the system engineer, but in the RCM analysis a multi-disciplinary team is used to determine the scope based on the failure modes. A multi-disciplinary team will result in a better analysis than if done by a single person. For example, the System Engineer for the boiler plant has a mechanical background however, Table 3-2 shows the background of each team member who was involved in the RCM process and how other team members helped support the System Engineer come up with maintenance strategies for the plant.

4.7.3 Proposals from RBI

The RCM process can be compared to the results of the RBI process that was currently running on unit10. The RBI information was recorded on an excel spreadsheet almost similar to the RCM, a sample is shown in Table 4-11.

Table 4-11 RBI analysis sheet

System	Equipment	Component	Functional Importance (C/NC/RTF)	CoF	PoF	Risk Rating	Damage Mechanism (Type of Damage)	RBI IMT Strategy
Superheater 3	Piping	Connecting pipes from distribution header to SH3 header inlet.	C	ABA	3	III	11D: Thermal Mechanical Fatigue	MPI

The main difference is that the RBI process identified the functional importance as either critical (C) if it satisfies a certain predetermined criterion, or non-critical

(NC) and/ or run to failure (RTF). This process is explained in section 2.3. For example, if failure results in any of the scenarios listed below, the component is classified as critical:

- If failure result in a load loss greater than 20MW.
- If failure results in environmental or statutory violations.
- If failure results in damage worth more than R10million

By just looking at the information in Table 4-11 an inexperienced person may not be able to understand which criterion resulted in the piping classified as critical (C). So the functional important does not really communicate much information to the reader save for the fact that the component is critical. In the RCM process however, the effects of failure are described at three levels as discussed earlier. These are the effects of failure that are listed in Table 4-4. The effects of failure will influence the value of the CoF in Table 3-3, RIMAP (2008:28).

The RBI process calculates the risk of failure (Combination of PoF and CoF) for the failure modes. However, in the RCM analysis this is done to determine the probability of losing a function. It can thus be urged that RCM primarily focus on preserving function whereas RBI focuses on preventing failure modes that have a higher chance of occurring. In RBI, the focus could be on failure modes, which do not really affect, for example, the primary function. This can result in wasting effort on failure modes, which do not really have much impact on the organisation.

In spite of these differences, the damage mechanisms that were identified by both processes are the same regardless of the process used.

4.7.4 Other differences

The other differences observed between the current practices on the superheater and the RCM analyses are -

- The use of the fishbone technique was widely adopted in this report to identify causes of failure (Figure 4-8), this approach can also be adopted though many other failure cause analysis methods exist such the 5Whys etc., this will allow for consistence in the way causes of failures are arrived at. There is no structured method that is employed in identifying causes in both the RBO and RBI processes. Section 4.5.2

explains how the team argued on the effectiveness of the current investigation method given the same actions were recommended for incidents happening over a three-year window.

- RCM links the inspection strategy to the failure mode in the FMECA sheet however, Table 4-10 generalise the inspections without reference to failure modes. When the outage is executed, the maintenance personnel may miss the failure mode, which the inspection strategy wishes to address. For example, the current 18 monthly schedule requires that maintenance carry out a dirty and clean visual inspection. Why this task is carried out or on which sections this needs to be done is not stated in Table 4-10. The assumption could be that the inspections will be done by someone who is very competent and will know why they are doing the visual inspection, moreover what they are inspecting/looking for. The RCM results however link the inspection strategy to the failure modes and failure location. Maintenance personnel are aware of the damage mechanism that they need to inspect for before they even go on to carry out the actual inspection. This allow for better planning in terms of resources and time.
- The main objective of RCM is to preserve the equipment function (Section 2.3). This functionality must be defined before preservation methods can be suggested. The RBO strategies define Equipment function as either critical, non-critical and or run to failure. The question becomes which is then the best way of defining the equipment function, and how important it is to define the equipment function when defining maintenance strategies (even if the strategy is going to come up similar), this is discussed in section 4.2.2. The FMECA spreadsheet contains more information compared to the RBO spreadsheet, especially the presence of failure effects on the FMECA spreadsheet. Knowing the failure effects allows maintenance personnel to be able to understand the effects of their maintenance actions on the overall operation of the equipment and hence they can better advice especially where inspection of critical areas is concerned.

In consideration of the above, the advantages of RCM can be summarised as

4.7.5 Benefits of the RCM process

Multi-functional team experience utilised. The usual RBO strategy is drawn using smaller team, and in some cases, only the system engineer is involved in drawing up their maintenance strategy. However, the RCM process used a cross functional team with a lot of experience to draw the maintenance strategy shown and explained in section 3.2. This ensures that the RCM strategy decision is reached by taking into consideration many factors including operational experience, which the engineer may overlook when using the RBO process.

RCM knowledge tools. RCM help to identify some of the critical data missing from existing maintenance strategies. This is mainly due to the structured nature of the RCM process shown in section 2.4. For example, functions must be defined in measurable terms where possible, this is not the case with RBO (also explained in section 2.2). Knowing that what gets measured can be controlled, it then is an advantage to use RCM because failures can be defined clearly based on the measurable functions.

Interrelationship of System. The Functional block diagram in section 3.4 helps show the relationships and function of the boiler system. This allows the process to focus on the functions that are critical to preserve function thereby saving both time and resources; however, the RBO process does not define the functions that the strategy is trying to preserve. This is critical where there are limited resources.

4.7.6 Time and Cost Savings

The overall costs savings as a result of this project are not quantified. At the Utility, outage work is carried out by contractors who have the cost structures of each task; these could not be obtained during the execution of this project. In order to correctly optimize the maintenance methods, it is suggested that costs of material and labour used be considered in future.

However, a general comparison of the RCM and the other methods can be qualitatively made by dividing the costs into cost of executing the RCM project and Cost savings that resulted due to the implementation of the results.

Cost of executing the RCM project. These include costs of human resource requirements to carry out the project, venues, materials etc. The same team that

was carrying out the RBI analysis on unit 10 is the same team that was used in the RCM project. No additional costs were incurred above those allocated for the RBI initiative. In this regard, the costs of the RCM analysis process can be described as at most equal to the costs of the RBI analysis.

Costs savings due to the implementation of the project are not considered here due to the academic nature of the project and time to implement. However, one can argue that based on the increase in the duration to take out the unit, cost savings will be achieved. The current regime requires that the unit be taken out for one form of maintenance or the other as discussed in 4.7.1 after every 18 months. With the RCM results propose every 72 months. A saving of three outages. However, because the results were not tested, this can only be assumed.

The analysis was done within the three weeks' period; this was well within the time budgeted for analysis i.e. excluding time for data gathering and compiling as this was done concurrently with the RBI project on Unit 10.

Chapter 5 CONCLUSION AND FUTURE WORK

5.1 CONCLUSION

The RCM results obtained were not implemented to see if an improvement in the UCLF would be achieved. The results of the RCM process and existing maintenance practices were discussed in section 4.7. However, the major difference in the results obtained with the current practice is an increased duration between which the equipment should be taken out for preventative inspection. This will result in additional time that the unit is available for production compared to current reliability methods. RCM was also shown to be a structured process that is capable of improving the operational reliability of the boiler subassemblies in a coal fired power station due to the level of equipment detail that it requires to be captured. No additional costs were incurred in the application of this RCM method, it will be beneficial to the organisation if the RCM method and results were implemented in conjunction with the RBI process to test if the results can improve on UCLF.

5.2 AREAS REQUIRING IMPROVEMENTS

Lack of reliable data. The RCM method identified by Cotaina et al (2000:25) differs to the one applied in this project in the use of quantitative methods to determine the mean time to failure as opposed to qualitative methods that were adopted in this report. The accuracy of a RCM analysis depends on the available data. The Failure history of incidents analysed in Appendix C does not properly address the cause, and failure location. Section 3.7.2 explains how actions are then generalised due to the non-specific nature of the root cause of the failures that is identified. In future failure mechanisms need to be linked to a failure cause to reduce the inconsistences in the way incidents are captured hence the difficulty to determine the basic parameters such as MTTF as applied in the RCM method.

Effectiveness of root cause analysis. The success of any maintenance programme does not only depend on the maintenance programme applied but also the process of continuous improvement process including the root cause analysis process. The incidents 07/175 and 07/178 Appendix C, though occurring months apart identified the root cause as due to poor maintenance on the Sootblower pipework. There is no mention of the structured ways of identifying causes when carrying out root cause analysis as per occurrence management procedure (HSPPA033-R9 Occurrence Management Procedure). There are many structured methods that can be used for root cause analysis with the common ones the Fish-borne analysis and the 5-why methods. Further training is required to ensure that solutions identified in the root cause process are effective in addressing the problems.

Maintenance History and Data. Most of the maintenance history could not be accessed because contractors (Section 3.6) hold it. Some modifications done to the plant were not documented. During analysis, the team found out that there were modifications that were done but not properly documented. The change process needs to be reviewed to ensure that the documentations available (such as Process and Instrumentation diagrams) reflect exactly what is in the plant.

Skills of people carrying out maintenance. Correct maintenance strategies require implementation by the correct skilled personnel. The levels of skill of people carrying out maintenance together with qualification were not explored in this report as highlighted in section 3.7.2. Though mentioned in the root cause analysis as an issue, training should be highly emphasised and recommended.

Clearing of maintenance backlog. Current maintenance tasks are not carried out in some cases when they are due because of various reasons with the main one the electricity demands and system constraints. Maintenance task should be carried out when they are due. Cost of delaying maintenance should be evaluated with cost of carrying out maintenance should a decision to postpone maintenance be mooted. The issue of constrained national grid resulting in deferred outages is discussed in section 3.3.1.

5.3 FUTURE WORK

The following future work is recommended: -

Use of quantitative methods to determine inspection frequencies. The RCM method that was applied in this document is similar in method to the one that were applied in the nuclear industries (Cotaina et al, 2000:12). In order to ensure that the method was correctly applied, the results were structured in the same way that the method is structured. The major difference in the method applied in this project as compared to the recommendations of Cotaina et al is the use of quantitative method in the determination of maintenance actions and strategy as presented in section 3.8. Kvale (1989: 62) says that qualitative studies were rejected as subjective, unreliable and invalid. RCM does not tie the user to a specific method of determining the frequency. The use of software such as Minitab to do the reliability calculations to generate MTTF reports could have removed some subjectivity from the analysis. For example, a common curve that illustrates the behaviour of equipment as it approaches failure is the P-F curve (Figure 4-10). The curve shows that as a failure starts manifesting, the equipment deteriorates to the point at which it can possibly be detected (P). If the failure is not detected and mitigated, it continues until a "hard" failure occurs (F). According to William (2010,20), the time range between P and F, commonly called the P-F interval, is the window of opportunity during which an inspection can possibly detect the imminent failure and address it; this is discussed in detail section 3.8. Determination of these parameters could guide analysts into accurately determining the frequency of maintenance.

Increase analysis sample. In this report only boiler 10 superheater 3 is analysed, if the process is carried over to include all the boilers within the Eskom fleet then more data can be analysed. Increasing analysis to include more boilers mean that statistically the sample size is bigger and the results become more accurate. More information can also be gathered including relationships between failures, effects of operator and maintenance training etc.

Costs of maintenance. RCM requires more skill and man-hours when introduced in a company. It is however documented by many organisations that the long-term benefits far outweigh the initial extra costs. The benefits are also realised when you consider that Eskom has in the past five years introduced a post of Reliability Engineers across stations that can be used for analysis.

Skill Gap. Lack of skill and knowledge was identified as contributing to Sootblower erosion (Section 3.7.2). Previous maintenance strategies do not consider the skills, however after analysing previous failure history it was actually realised that between 2006 and 2009 four incidents attributed to poor maintenance occurred on the Superheater. As a result, the company lost R9.2million. In addition, in each of the four cases, the same action plans were drawn up. This report and the RCM methodology assume that the right people are entrusted to both carry out maintenance and/or operate the machine. It is recommended that skills level of operators and maintenance personnel be analysed to identify the training matrix that is required to correct the skills gaps that may be identified.

The results obtained in this analysis can be used as a basis for continuous improvement on the equipment reliability by also applying a quantitative approach to the reliability data.

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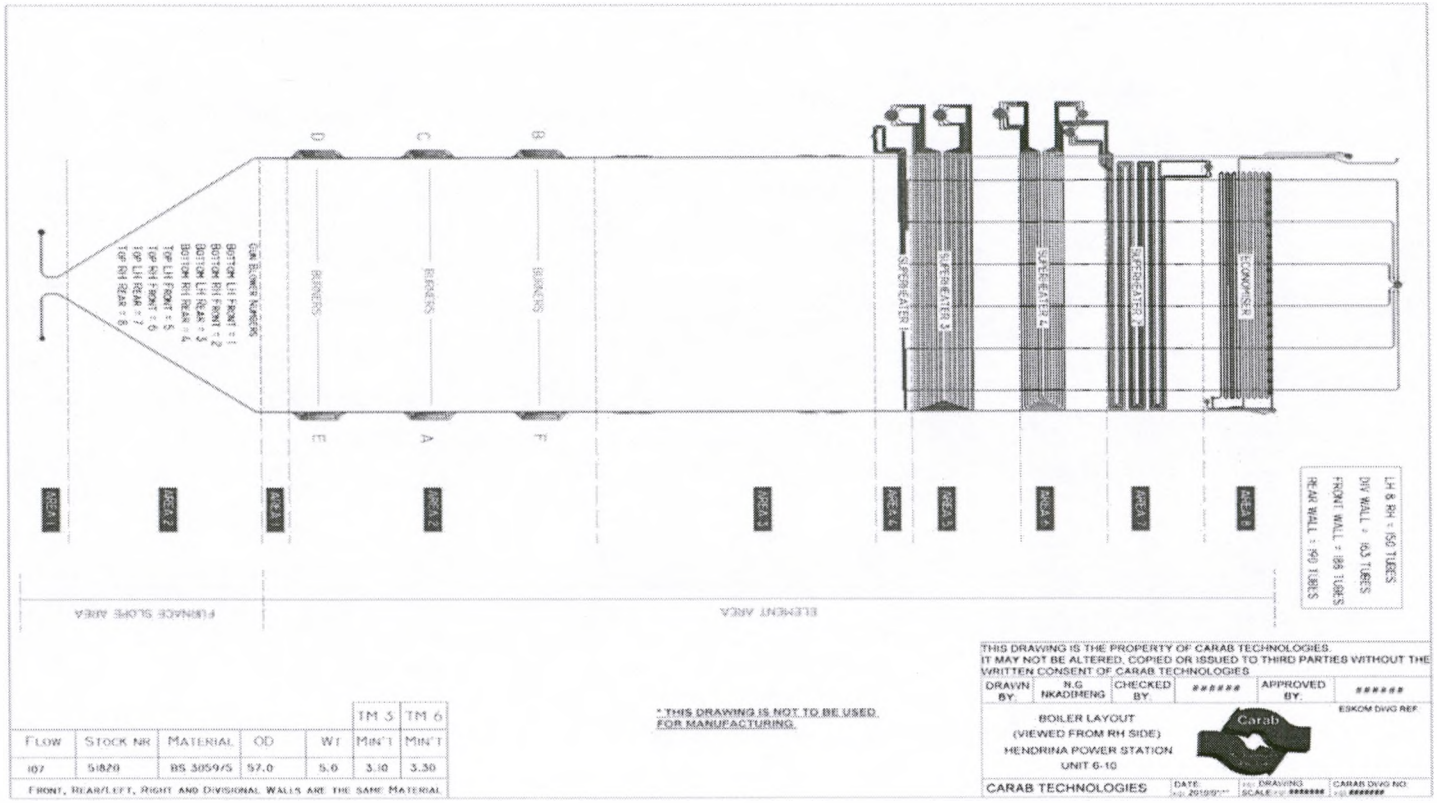
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APPENDICES

(A) Superheater 3 GGCS

1142 Mechanical - Superheater 3 System									
			CHS	CLS	CHM	CLM	NHS	NLS	NHM	NLM
Eskom Generation	Functional Importance	Critical	X	X	X	X				
		Non-Critical					X	X	X	X
	Duty Cycle	High	X		X		X		X	
		Low		X		X		X		X
	Environment	Severe	X	X			X	X		
		Mild			X	X			X	X
PM Task:	**Failure Mode Addressed:**		**Frequency:**							
Condition Monitoring										
Performance Monitoring			1M	1M	1M	1M	1M	1M	1M	1M
Temperature Monitoring			1S	1S	1S	1S	1S	1S	1S	1S
Chemical Monitoring			1D	1D	1D	1D	1D	1D	1D	1D
Time Directed										
Corrosion/Erosion Monitoring			2Y	2Y	2Y	2Y	2Y	2Y	2Y	2Y
Major Inspection and Repair	2,3,5,7,9,13,14,16,18,20,22,		6Y	6Y	6Y	6Y	6Y	6Y	6Y	6Y
Thickness tests, NDE	6,17		2Y	2Y	2Y	2Y	2Y	2Y	2Y	2Y
Metallurgical Survey	1,4,6,8,10,11,12,15,17,19,21,		6Y	6Y	6Y	6Y	6Y	6Y	6Y	6Y
Failure Finding	None									
Surveillance Tasks										
Operator walk down			1S	1S	1S	1S	1D	1D	1D	1D
Maintenance walk down			1W	1W	1W	1W	1M	1M	1M	1M
System Engineer walk down			1M	1M	1M	1M	1M	1M	1M	1M

(B) Stein Müller Boiler General layout



					TM 3	TM 6
FLOW	STOCK NR	MATERIAL	OD	WT	MIN'T	MIN'T
107	51820	BS 3059/S	57.0	5.6	3.10	3.30

FRONT, REAR/LEFT, RIGHT AND DIVISIONAL WALLS ARE THE SAME MATERIAL

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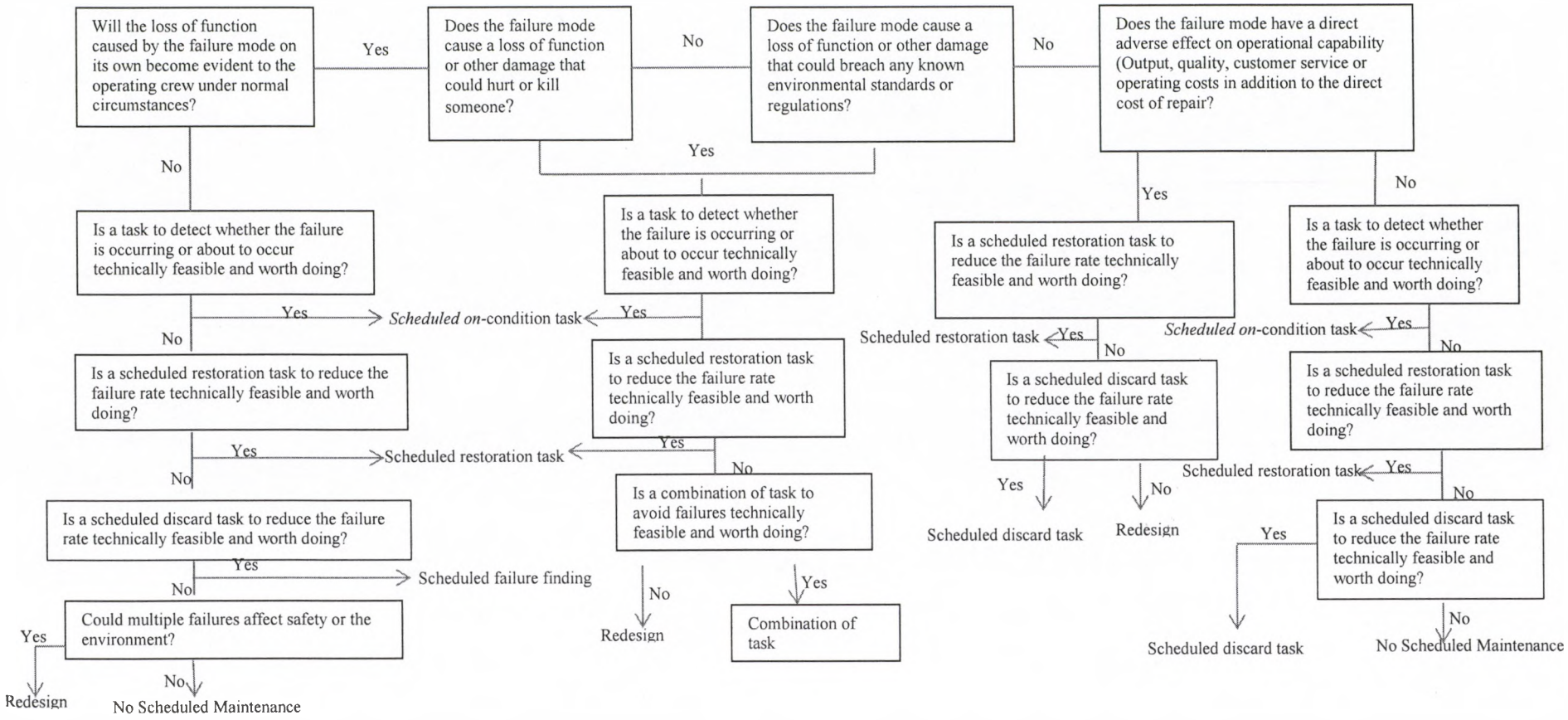
BOILER LAYOUT
(VIEWED FROM RH SIDE)
HENDRINA POWER STATION
UNIT 6-10

CARAB TECHNOLOGIES | DATE: 2019/**/** | DRAWING SCALE: ###### | CARAB DWG NO: #######

(C) Unit 10 Failure History

Year	Incident No.	Incident Description	Failure Location	Mechanism	Root Cause
2000	00/037	Boiler tube leak (linked to 99/111 & 97/041)	Economiser	Soot blower Erosion	FAE, Soot blower erosion, Ageing
2000	00/045	Ctl V/V Bypass V/V gland blowing	Attemporator	Unknown	Sample VKS II valve is not fit for control purposes
2004	04/068	Boiler Tube Leak (Linked 03/208, 06/113)	Furnace Wall	Human Factors	Poor workmanship
2004	04/072	Tube leak - LH side of economiser (Linked 03/202)	Economiser	Unknown	Lack of maintenance
2004	04/181	Boiler ignition lost - tube leak super heater No 3 (Linked 04/016)	Super heater 3	Unknown	Incorrect application of soot blowing system.
2006	06/060	Boiler Tube Leak [Linked to 06/240]	Super heater 3	Soot blower Erosion	Poor Maintenance
2006	06/113	Boiler tube leak (Linked 04/068)	Furnace Wall	Human Factors	Mill C motor overload
2006	06/256	Boiler tube leak [Linked 06/240]	Super heater 3	Soot blower Erosion	Poor Maintenance
2007	07/013	Boiler tube leak [Linked 06/240]	Super heater 3	Soot blower Erosion	Poor Maintenance
2007	07/073	Boiler tube leak [Linked 06/193]	Furnace Wall	Welding Defect	Poor workmanship
2007	07/075	Boiler tube leak [Linked 06/240]	Super heater 4	Soot blower Erosion	Poor Maintenance
2007	07/178	Boiler tube leak [Linked 06/240]	Super heater 4	Soot blower Erosion	Poor Maintenance
2009	09/162	UCLF - Boiler tube leak [Linked 06/240]	Super heater 3	Soot blower Erosion	Poor Maintenance
2011	11/266	Boiler tube leak - RH Super Heater No 4 [Linked 10/166]	Super heater 4	Soot blower Erosion	Poor Soot Blower Maintenance
2011	11/344	Boiler tube leak on LH economiser element 28 & 29 E row [Linked 07/029]	Economiser	Unknown	Higher rate of FAE and load factors prevented components from reaching planned outages

(D) Extract of the RCM Logic tree (Decision Logic Tree diagram for RCM II. (Source: Moubray (1997:198))



(E) FMECA Analysis Sheet

Superheater 3 Failure

MCSI		Function	FAILURE MODE		Local Effect	Effect on Subsystem	Final effect on Production/Safety/ Health	Task Type	Task	Frequency (months)
			Cause	Damage Mechanism						
Piping	Connecting pipes from distribution header to SH3 header inlet (64)	Convey steam to headers	Deposition/Scale	Thermal Mechanical Fatigue	Scale build up	Reduced steam outlet temperatures. High exhaust flue gas temperatures	Boiler loss of fires	Scheduled on Condition Task	NDE techniques such as PT, MT and SWUT can be used to detect fatigue cracks at known areas of stress concentration.	72
					Stress concentration resulting in Fatigue cracks	Decreased steam flow and outlet steam temperature.	Boiler loss of fires	Scheduled on Condition Task	Controlled rates of heating and cooling during start-up and shutdown of equipment.	72
			Cyclic Temperature Increase	Thermal Mechanical Fatigue	Stress concentration resulting in Fatigue cracks	Decreased steam flow and outlet steam temperature.	Boiler loss of fires	Scheduled on Condition Task	Controlled rates of heating and cooling during start-up and shutdown of equipment.	72

			Combustion disturbances	Thermal Mechanical Fatigue	Stress concentration resulting in Fatigue cracks	Decreased steam flow and outlet steam temperature.	Boiler loss of fires	Scheduled on Condition Task	Drain lines should be provided on soot-blowers to prevent condensate in the first portion of the soot blowing cycle.	72
Header	Inlet header (65)	Distributes steam to convection coil	Deposition/Scale	Creep (Long term overheating)	Localized deformation appearing in the form of cavities, dependent on material and load.	Reduced steam outlet temperatures. High exhaust flue gas temperatures	Reduced boiler efficiency	Scheduled on Condition Task	MPI, Ultrasonic testing, dimensions, hardness, replication	72
			Temperature Increase (above 400-500°C)	Creep (Long term overheating)	Creep cracking	Decreased steam flow and outlet steam temperature.	Boiler loss of fires	Scheduled on Condition Task	IR monitoring of tubes and tube skin thermocouples are used to monitor temperatures	72
			Increased static load on supports.	Creep (Long term overheating)	Creep cracking	Mechanical rapture of tubes.	Boiler loss of fires	Scheduled on Condition Task	Since cracking is usually surface connected, visual examination, MT and PT are effective methods of	72

									inspection	
			As identified in Piping above	Thermal Mechanical Fatigue	as above	as above	as above	as above	MPI	72
Tubes	3rd stage superheater convection coil (66)	Provides surface area for heat exchange and conveyance of steam to header.	As identified in the header	Creep (Long term overheating)	as above	as above	as above	as above	Tube SOLO	72
			Soot blowing with wet steam.	Erosion (Sootblower)	Wear (Volumetric loss of material on surface)	Tube leak	Boiler loss of fires	Scheduled on Condition Task	Ultrasonic wall thickness testing	72
			Wrong Superheater material					Scheduled on Condition Task		72
			Incorrect nozzle specifications					Scheduled on Condition Task		72
			Lack of skill/Knowledge					Scheduled on Condition Task		72

			Wrong shield material					Scheduled on Condition Task		72
			Fuel quality	Erosion (Fly ash)	Wear (Volumetric loss of material on surface)	Tube leak	Boiler loss of fires	Scheduled on Condition Task	Ultrasonic wall thickness testing	72
			Mechanical Vibrations	Sliding wear (Rubbing and Fretting)	Wear (Volumetric loss of material on surface)	Tube leak	Boiler loss of fires	Scheduled on Condition Task	Visual inspection and wall thickness surveys	72
	3rd stage superheater convection coil (67)	Provides surface area for heat exchange and conveyance of steam to header.	As identified in the header	Creep (Long term overheating)	as above	as above	as above	as above	Tube SOLO	72
			same as above	Erosion (Sootblower)	as above	as above	as above	as above	Ultrasonic wall thickness testing	72
			same as above	Erosion (Fly ash)	as above	as above	as above	as above	Visual inspection is usually sufficient to detect hot ash corrosion	72
			same as above	Sliding wear (Rubbing and Fretting)	as above	as above	as above	as above	Visual inspection and wall thickness surveys	72

	Inlet 180° Bends (67)	The bends redirect flow path of steam.	As identified in the header	Creep (Long term overheating)	as above	as above	as above	as above	Tube SOLO	72
			same as above	Erosion (Fly ash)	as above	as above	as above	as above	Visual examination of suspected or troublesome areas, as well as UT checks or RT can be used to detect the extent of metal loss	72
			same as above	Sliding wear (Rubbing and Fretting)	as above	as above	as above	as above	Visual inspection and wall thickness surveys	72
			same as above	Sliding wear (Rubbing and Fretting)	as above	as above	as above	as above	Visual inspection and wall thickness surveys	72
	3rd stage superheater convection coil (68)	Provides surface area for heat exchange and conveyance	As identified in the header	Creep (Long term overheating)	as above	as above	as above	as above	Tube SOLO	72
			same as above	Erosion (Sootblower and Fly ash)	as above	as above	as above	as above	Ultrasonic wall thickness testing	72

		of steam to header.	same as above	Sliding wear (Rubbing and Fretting)	as above	as above	as above	as above	Visual inspection and wall thickness surveys	72
Header	Outlet Header (70)	Distributes steam to steam users	As identified in the header	Creep (Long term overheating)	as above	as above	as above	as above	MPI, Ultrasonic testing, dimensions, hardness, replication	72
			same as above	Thermal Mechanical Fatigue	as above	as above	as above	as above	MPI	72
Piping	S/H Drains	Remove wet steam.	Steam	Erosion (Steam erosion)	as above	as above	as above	as above	Ultrasonic Wall thickness testing	72