THE DEVELOPMENT AND PROBLEMS EXPERIENCED WITH THE IMPLEMENTATION OF A RELIABILITY-CENTRED MAINTENANCE (RCM) PROGRAM AT A COAL FIRED POWER STATION (LETHABO POWER STATION).

Albert Heiberg Müller, B.Eng.

Thesis submitted in the Department of Economical Science of the Potchefstroomse Universiteit vir Christelike Hoër Onderwys in partial fulfilment of the requirements for the degree Masters in Business Administration.

Supervisor: Mr. J.J. Pieterse

POTCHEFSTROOM

1996

EXPRESSION OF THANKS.

* To my Creator for His bounteous Grace

* To my supervisor, Mr Koot Pieterse for his advice, guidance and contributions

* To my wife Louise, for motivation and support

* To my parents for the opportunities they have given me and their continued encouragement

* To everybody else who made this study possible and a success

* To Eskom for making this study possible

OPSOMMING

Die skripsie beskryf 'n breë bestuurs- en sisteemingenieurswese benaderingsmetode vir die optimisering van instandhouding beplanning vir 'n steenkool kragstasie. Die optimisering van instandhouding het 'n groot koste impak en invloed op die betroubaarheid en beskikbaarheid van 'n aanleg. Die betroubaarheid gesentreerde instandhoudingsmetode beklemtoon voorkomende instandhouding en fokus op die integrering van instandhoudingingenieurswese met betroubaarheid- en beskikbaarheidingenieurswese. Dit beskryf al die stappe nodig vir die opstel van 'n betroubaarheid gesentreerde instandhoudingstelsel vir die industrie.

Daar word van die standpunt uitgegaan dat 'n meer effektiewe en koste- effektiewe lewensiklus instandhoudingstelsel in plek gebring kan word, deur gebruik te maak van 'n gedissiplineerde betroubaarheid gesentreerde instandhoudings analise proses. Die proses identifiseer falings modes en die effek daarvan op die kritikaliteit van die aanlegproses waarby dit betrokke is. Die kritiese modes sal dan deur die "RCM logic tree" proses ge-evalueer word om die mees gepaste instandhoudingstaak toe te ken. Dus: 'n goedbeplande, betroubaarheid gesentreerde en veiligheidgedrewe instandhoudings program sal eenvoudig laer koste, laer risiko en meer effektiewe instandhoudingstake tot gevolg hê.

Met die implementering van bo-genoemde stelsel en die impak wat dit sal hê op die aanleg, sal daar noodwendig probleemareas wees

tydens die implementeringsproses. Die areas uitgewys is diè wat ondervind is tydens die implementering van die betroubaarheidgesentreerde instandhoudingsproses op 'n steenkool kragstasie. Dit sal egter ook van toepassing wees op ander industrieë aangesien die proses 'n logiese ingenieurswese analitiese metode volg om instandhouding te optimiseer.

CONTENT **PAGE NUMBER**

CONTENTS CONTINUE **PAGE NUMBER**

CONTENTS CONTINUE **PAGE NUMBER**

CONTENTS CONTINUE **PAGE NUMBER**

LIST OF ABBREVIATIONS

CM	-	Corrective maintenance.
FMECA	-	Failure modes effects criticality analysis.
HBS	-	Hardware breakdown structure.
MMIS	-	Maintenance management information system.
MSI	-	Maintenance significant items.
MTS	-	Maintenance technical specification.
NOSCAR	-	National occupational safety company accredited reward.
O&M	-	Operating and maintenance.
OEM	-	Original equipment manufacturer.
PERMAC	-	Plant engineering resources management and control.
P&ID	-	Plant identification diagram.
PM	-	Planned maintenance.
RCM	-	Reliability-centred maintenance.
TPM	-	Total productive maintenance.
TQM	-	Total quality management.

CHAPTER 1

PURPOSE AND SCOPE OF THIS STUDY

1.1. INTRODUCTION.

The running costs of a power station consist of fixed costs, comprising depreciation, fuel and decommissioning activities and manageable costs. Maintenance forms a large part of the manageable costs. Often of greater importance than the visible maintenance costs, are the hidden costs. These may include:

- Damage to equipment during maintenance.
- Loss of revenue due to breakdowns.
- Over maintaining of equipment.
- Under maintaining of equipment.

Furthermore, one must remember that the production plant constitutes most of the value of the fixed assets and hence the type of maintenance applied has a significant impact on the operating cost of the power station.

Maintenance is thus clearly one of the single most controllable running costs. To reduce maintenance costs one cannot simply perform less maintenance, as this will have a negative impact on plant reliability and long term plant integrity. A comprehensive analysis must be performed to gain an understanding of how each component can fail, in order to compile the most applicable and effective maintenance regime for that component.

The Reliability-Centred Maintenance (RCM) process is being used with success in many industries for optimising maintenance and reducing maintenance costs, while increasing the reliability of complex systems. The most important application of a failure statistics process is in the providing of information to engineers enabling them to determine system reliabilities, expected lives, optimal replacement or repair intervals, cost implications etc. with greater certainty.

1.2. PROBLEM STATEMENT.

The continuing economic pressure on the country and the enormous effect the price of electricity has on this, forced electricity utilities to optimise their costs. The current situation comprises of an increased demand for affordable electricity against high rise in the costs of material, labour, current unfavourable payment of electricity, the new open market system for electricity supply and an increase in fuel costs. The possibility of opening the electricity network to the north of our borders where cheap hydro supply of electricity for the future is in abundance, contributes to this situation.

Linking up to the above is the continuing pressure on the electricity supply utilities to minimise air pollution. In the future air pollution levels will be applied even more stringently. The demand on the water reserves of the country in the future will also have detrimental effects on power station costs.

Kuehn (1992:23) says that various factors will decrease the operating and maintenance costs of power stations, but that the main contributors will be increased capacity factors such as more reliable plant, less plant breakdowns and higher plant availability.

It is within this framework that Eskom generation, and for that matter Lethabo power station, has set out the following goals:

- 90% availability factor.
- 7% planned outage rate.
- 3% unplanned or forced outage rate.
- reducing the price of electricity by 15% up to the year 2000.
- Protecting the environment.

Thus the money spent on reliability-centred maintenance at the moment will have a good pay back in terms of the above in the future. The improved availability through effective plant maintenance is recognised as a key ingredient to plant operating cost efficiency. Avoiding forced outages and other operational transient is not only less expensive, it is safer as well. According to Kuehn (1992:24) there is also an indication that the economies realised that improved maintenance practices will continue to grow while maintenance expenses themselves will decline.

The above give the background against which this study was done.

1.3. PURPOSE OF THIS STUDY.

The main aim of this study is to, through means of literary research, set out a model so that coal fired power utilities in Eskom can implement a successful reliability-centred maintenance program.

The intention is to look at other utilities which successfully implemented RCM. Critical success factors will be drawn from literature and be evaluated for these utilities. The aim is to determine whether these factors had an influence in the development and implementation stages of the RCM philosophy..

Although the study was done on a specific power station, the objective is to lay down guidelines that can be used in any coal fired power utility.

1.4. SCOPE OF THIS STUDY.

1.4.1. General.

Reliability-centred maintenance is seen as a powerful tool in optimising the costs of utilities. Problems are generally experienced by managers implementing the program. This study is primarily aimed at the basic principles needed to develop and implement a successful program according to the experience gained and the model drawn-up by Lethabo power station.

1.4.2. Description of the company.

The power utility where the study was completed is a business unit within the Generation group of Eskom. The Generation group forms part of the ten groups within the company. The power station is one of 17 business units within the Generation group. The coal used for generating power at the station is of the lowest grade (average calorific value of 16 megajoules per kilogram) in the world with an ash content of up to 42%.

The electricity generated is directly supplied into a national transmission line network. Predetermined demand and supply figures are negotiated in a formal matter with a penalty system working both ways if these figures are not met.

Coal from another company is supplied on a predetermined demand via conveyor systems to the station. Ash generated from the process is conveyed back to the mine. Stackers dump ash back into the mined out open casting workings with top soiling and re-vegetation finishing off the rehabilitation of the land. Water is supplied from the Vaal River system via a pump house system. The water management system is designed specifically for the re-treatment and re-use of water and all the liquid effluents produced, including treated sewage and accumulated storm water.

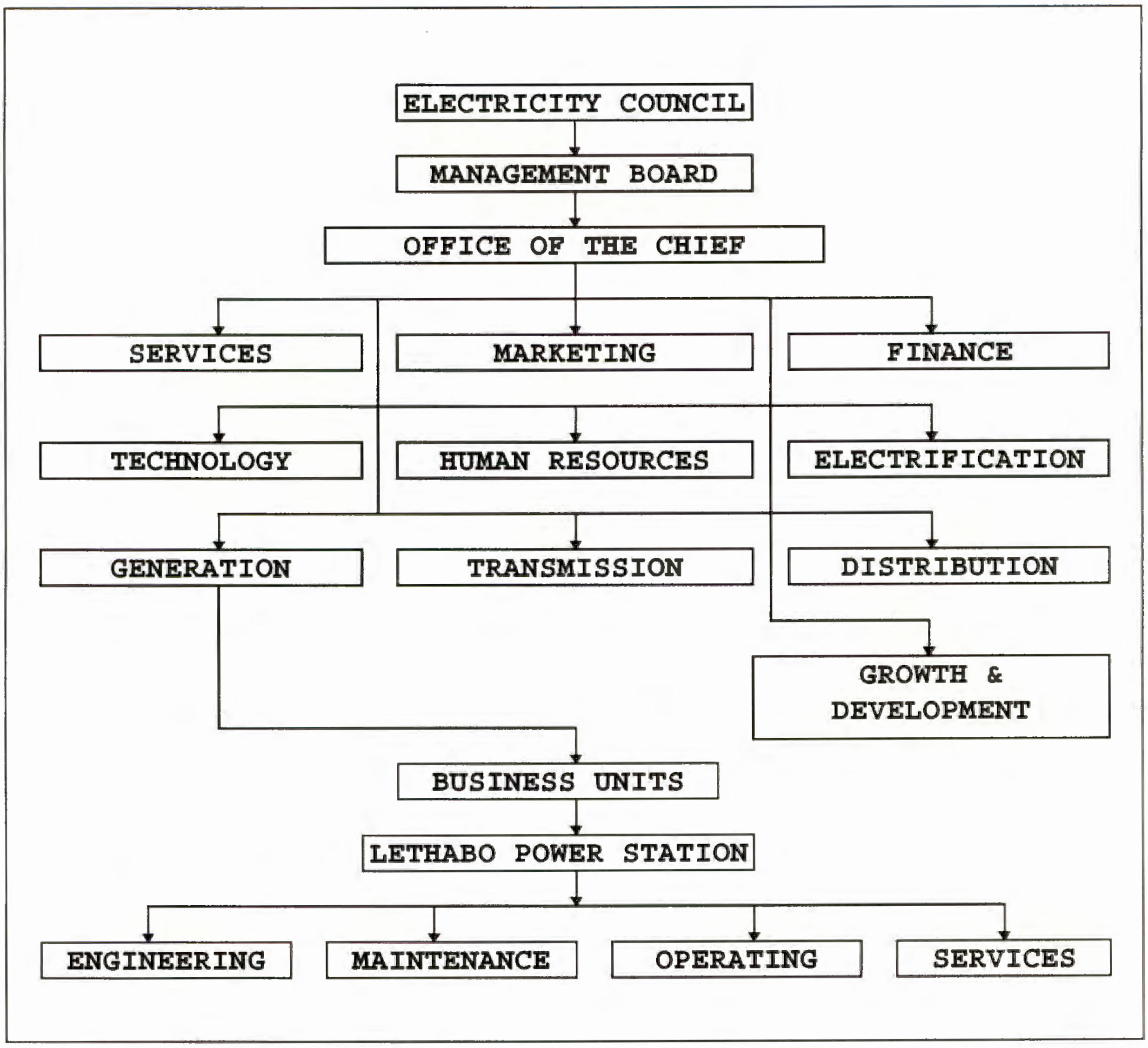

Figure 1.1. Simple organisational structure of the company.

An simple organisational structure of the company is shown in figure 1.1

Other information about the power station:

- About 1300 people work at the power station.

- Personnel and financial service is done via head office sections.

- It is the only NOSCAR safety graded Eskom power station in South Africa.

- The company is an equal opportunity company.

1.5. RESEARCH METHOD.

The study is based on literature investigation that looks at all aspects, principles and key success factors for the development and implementation of reliability-centred maintenance. The theoretical framework of reliability-centred maintenance is used as the basis for a model for developing practical reliability-centred maintenance implementation.

The practical experienced gained by the author during the developing and implementing stage of reliability-centred maintenance on the power station is also used to a large extent.

1.6. LAY-OUT OF THE PAPER.

In figure 1.2 is a lay-out of the paper. The lay-out will be briefly discussed:

In chapter 1 the purpose and scope of the study is discussed. The problem statement and purpose of the study as well as the research methods and discussions of the study are outlined.

In chapter 2 the reliability-centred maintenance methodology is explained.

In chapter 3 the literature study is brought into context with the maintenance optimisation process at the power station.

Chapter 4 deals with the development and implementation of a reliability-centred maintenance program in a electricity utility.

Chapter 5 looks at the critical success factors necessary for the implementation of a reliability-centred maintenance program.

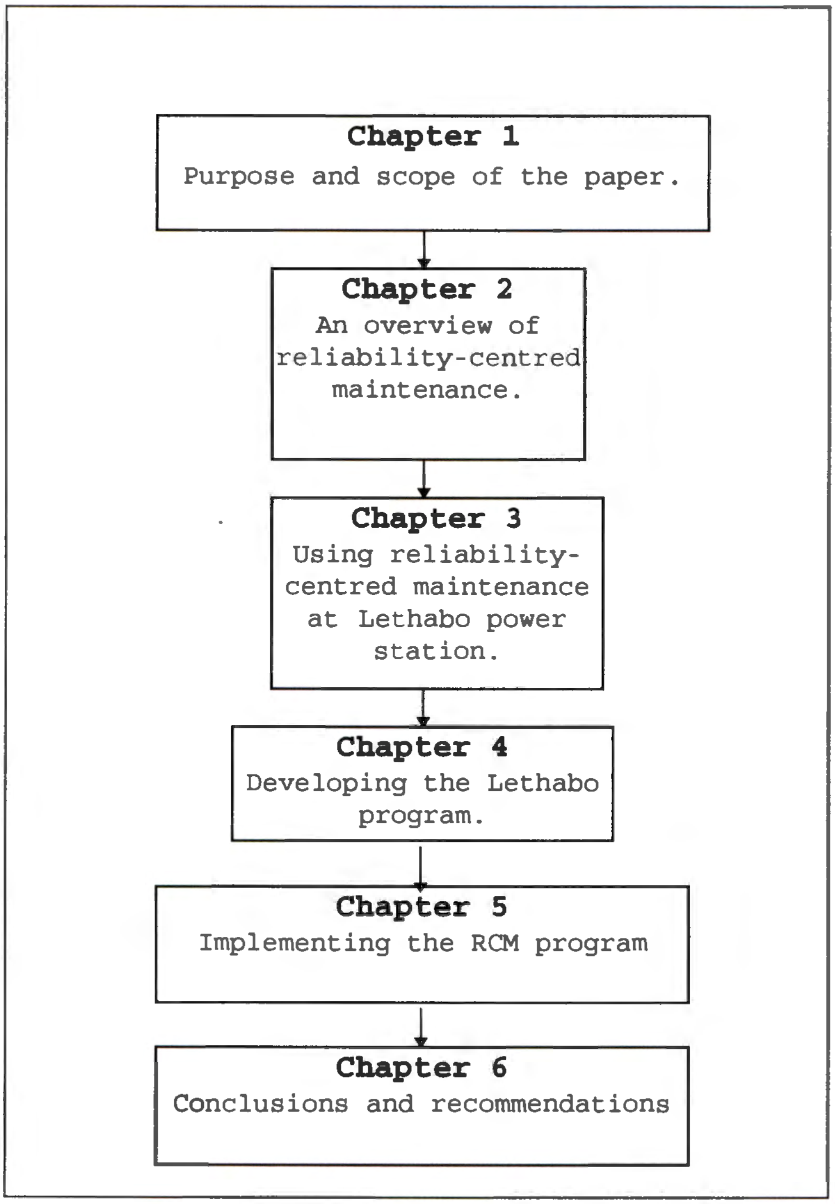

Figure 1.2. A lay-out of the paper.

In chapter 6 conclusions are drawn and recommendations are set out.

1.7. SUMMARY.

This paper deals with the development and implementation of a reliability-centred maintenance program. The purpose is to develop a practical reliability-centred maintenance model which can be used by other power utilities when implementing such a system. Problem areas to avoid with the implementation of such a program are further discussed.

CHAPTER 2

AN OVERVIEW OF RELIABILITY-CENTRED MAINTENANCE

2.1. INTRODUCTION.

Large utilities like power plants must be reliable and maintainable in order to render their operation both safe and cost effective and they must be supported by an efficient, responsive maintenance program. The attainment of reliable and maintainable systems requires the application of sound engineering effort, built-in high reliability and ease of maintenance features, and the implementation of well planned maintenance support tasks.

Maintainability and maintenance are distinct, yet related, disciplines covering the design, restoration and preservation of systems and components in their operational state (Anderson, 1990:1). Maintainability forms part of the RCM program that supports the development, production and operation of a life cycle maintenance program. Maintenance deals with the specific procedures, tasks, instructions, personnel qualifications, equipment and resources needed to satisfy the system maintainability requirement within an actual use environment.

A lot of overseas power utilities, especially the nuclear power station industry in the United States of America, implemented RCM on their plants. It is only in recent years that RCM has first been implemented on coal fired power stations. There is still much work to be done to determine the success of these programs in the South African power industry.

2.2. OTHER MAINTENANCE METHODOLOGIES.

The formulation of a maintenance strategy is not bound to a maintenance manager, but is rather determined by a set of circumstances existing in the production environment and governed by the mutual objectives set by the management, production and maintenance teams (Dreyer, 1995:7).

It is also not possible to lay down one strategy for maintenance of equipment in a factory or a plant. Each piece of equipment must be considered for the most applicable strategy for its maintenance in line with its function within the set objectives.

Total Productive Maintenance (TPM) is a philosophy that aims at optimising equipment effectiveness by the total elimination of failures and defects through full participation of the total workforce in maintenance activities (Nakajima, 1985:5). The objectives of TPM are: increased productivity and quality, employee ownership acceptance and optimised equipment life cycle cost.

A basic requirement of TPM is to eliminate the division that exists between departments and to get operator participation in maintenance. TPM is a company wide equipment maintenance system utilising all available skills in the company to support sophisticated production facilities. Its aim is to achieve zero breakdowns and zero defects. Elimination of breakdowns and defects results in improved equipment operation rates, reduced costs, minimal inventory and consequently improved productivity.

Following TPM "predictive" or "conditioned based maintenance" which uses modern monitoring and analysis techniques to diagnose the condition of equipment during operation. This way, signs of deterioration or imminent failures are identified. This techniques does not replace TPM but enhances the philosophy of zero failures.

Maintenance carried out in response to a significant deterioration in a unit as indicated by a change in monitored parameter of the unit condition or performance, is called conditioned based maintenance (Kelly, 1978:148).

However conditioned based maintenance cannot be employed in certain circumstances. First, not all causes of plant failure can be detected in advance. Second, condition monitoring is, by its very nature , costly in manpower, monitoring equipment or both. Only if the cost of condition monitoring is lower than the expected reduction in maintenance labour costs and unavailability costs, or where safety of personnel is relevant, is it worth applying conditioned based maintenance.

The above methodologies are both implemented and used to a fair degree at Lethabo power station. However the power station set out on a maintenance betterment project in the latter half of 1993. One of the important elements of the project was the optimisation of the maintenance function, in order for this to realise, it is necessary to scientifically determine the maintenance requirements of the plant. This it was felt could best be achieved through reliablity-centered maintenance.

2.3. DEFINITION OF RELIABILITY-CENTRED MAINTENANCE.

Reliability-centred maintenance (RCM) has been so named to emphasise the role that reliability theory and practice play in properly focusing preventive maintenance activities on the retention of the equipment's inherent design reliability (Smith, 1993:27).

According to Anderson (1990:12) the primary objective of the RCM process is therefore to determine that combination of maintenance tasks for a complex system or component item which will significantly reduce the major contributors to unreliability and maintenance costs.

RCM has often been called "organised common sense" (Kuehn, 1992:25). Maintenance programs are often designed and managed using many of the common sense principles embodied in RCM. However, the RCM methodology organises these common sense approaches into a structured program that can initially look unfamiliar. RCM is a different way of designing an effective maintenance program focusing in part on more cost effective maintenance resource allocation. However, the resultant goal is an appropriate and cost effective program that preserves important system functions and plant availability.

2.4. THE RELIABILITY-CENTRED MAINTENANCE METHODOLOGY.

The RCM process model, as explained in most literature, is basically a system analysis process that forms the basis of the program derived in this study.

For the purpose of this study the seven steps followed in the RCM model by Smith (1993:55) was found to be the most applicable to power utilities. The RCM model will be discussed in terms of the seven steps developed by Smith to systematically delineate the required information:

Step 1: System selection and information collection
Step 2: System boundary definition
Step 3: System description and functional block diagram
Step 4: System functions and functional failures
Step 5: Failure mode and effect analysis
Step 6: The RCM decision tree analysis
Step 7: Task analysis

The completion of these steps will provide a baseline definition of the preferred planned maintenance tasks on each system with a well documented record of how those tasks were selected and why they are considered to be the best selections amongst competing alternatives.

2.4.1. Step 1: System selection and information collection.

When a decision has been made to perform a RCM program two immediate questions arise (Smith, 1993:58):

1. At what level of assembly (component, system, plant) should the analysis process be conducted?

2. Should the entire plant receive the process and, if not, how is selection made?

Level of assembly: For the discussion here, the following definitions describe the levels of assembly:

- Part: the lowest level to which equipment can be disassembled, for example a pump impeller.

- Component: a grouping or collection of parts into some identifiable package that will perform at least one significant function as a stand alone item, for example a pump.

- System: a logical grouping of components that will perform a series of key functions that are required of a plant, for example the cooling water system on a power station that include components like pumps that include parts like impellers.

- Plant: logical grouping of systems that function together to provide an output, for example an output like electricity on a power station.

System selection: Having established that system is the best practical level of assembly, the question now arises which procedure can be used to select those systems with the highest potential for benefits from the RCM systems analysis process. The selection schemes include the following:

- Systems with a high content of PM tasks and /or cost.

- Systems with a large number of corrective maintenance (CM) actions over the past two years.

- A combination of item 1 and item 2.

- Systems with a high cost of CM action over the past two years.

- Systems with a large contribution to full or partial outages over the past two years.

- Systems with a high content of concern with respect to safety and environmental issues.

This whole process must be done as simply as possible, and without a large expenditure and of time and resources.

2.4.2. Step 2: System boundary definition (Smith, 1993:65).

The number of separately identifiable systems in a plant or facility can vary according to the plant complexity. In power generating plants these system boundaries are usually established in the normal course of the plant facility design, and these system definitions have already been used in step 1 as the base of the system selection. These system definitions serves quite well to define the precise boundaries that must be identified for the RCM analysis process.

These boundaries are important in that potentially important functions are not inadvertently neglected, and will determine what comes into and out of the system in terms of signals, heat flow etc.

2.4.3. Step 3: System description and functional block diagram.

In this step the essential details of the system are identified and documented in order to perform the remaining steps in a thorough and technically correct fashion.

System description: This explains what constitutes the system and how it operates (Smith, 1993:70).

Functional block diagram: The functional block diagram is a top-level representation of the major functions that the system performs (Smith, 1993:70). The block diagram is composed solely of functions.

The above three steps of the RCM model was combined into the first step of the RCM program developed for Lethabo in chapter 4.

2.4.4. Step 4: System functions and functional failures.

The previous steps have all been directed towards developing an orderly set of information that will provide the basis for now defining system functions. It is incumbent to define system functions since subsequent steps will deal with this listing ultimately defining planned maintenance tasks that will "preserve" them (Smith, 1993:78).

Once the system functions is defined, the analyst is ready to define the functional failures. That is, function preservation means avoidance of functional failures. We are now embarking on the step in the process of determining how functions might be defeated so that we can eventually ascertain the actions to prevent, mitigate, or detect onset of function loss.

2.4.5. Step 5: Failure mode, effects, and criticality analysis (FMECA) (Anderson, 1990:16).

Step 5 brings us to the question of which system equipments have the potential to defeat our principal objective to "preserve function". This is the point where the analyst will define the specific component failure modes and causes that can defeat the system functions, and it is at this level of detailed knowledge that we can finally determine if some appropriate PM task can prevent, mitigate, or detect the onset of that failure mode.

2.4.6. Step 6: The RCM decision tree analysis (Moubray, 1992:157).

The failure modes that are derived at in step 5 will now be further classified in a qualitative process known as the RCM II logic tree analysis. The purpose of this step is to further prioritise the emphasis and resources that should be devoted to each failure mode, recognising as we have earlier stated that all functions, functional failures and, hence, failure modes are not created equal.

Several ranking schemes could conceivably be used to achieve a priority listing of the failure modes, but the RCM process uses a simple decision structure that permits the analyst to place each failure mode quickly and accurately into a category.

2.4.7. Step 6: Task selection (Moubray, 1992:163).

The systems analyst efforts to this point have been directed to delineating those failure modes where a planned maintenance task will give us the biggest return for the investment to be made. Thus for each of these failure modes, a list of candidate tasks must be determined, and then select the most effective task from among the competing candidates.

If no applicable task exists, then the only option is to run the item to failure. Likewise, if the cost of an applicable planned maintenance task exceeds the cumulative cost associated with failure, then the effective task option will also be run to failure. The exception will be safety related items.

The above four steps of the RCM model was combined into the second step of the RCM program developed for Lethabo in chapter 4.

2.5. SUMMARY.

Reliability-centred maintenance process model is a simple yet thorough technique for improving an existing maintenance program. The RCM process identifies the important functions of each system in the plant being identified.

The RCM analyst establish his own unique criteria for which function at his facility are preserved. The resultant preventative maintenance program is then focused on those functional failures that are most likely to result in plant unavailability. Therefore each company will draw-up a unique preventative maintenance program best suited for their conditions.

Chapter 4 deals in depth with the RCM program itself and is discussed as such.

CHAPTER 3

USING RELIABILITY-CENTRED MAINTENANCE AT LETHABO POWER STATION

3.1. MAINTENANCE OPTIMISATION.

Preventative maintenance in large industrial plants is an expensive necessity. Repairing individual components after they fail (corrective maintenance) is costly. To keep damage, lost production, and other losses under control, periodic preventative maintenance tasks may be completed to decrease failure rates. Deciding among competing PM (planned maintenance) tasks and task frequencies depends on the relative consequences of the component's failure, its duty cycles and operating conditions, and the cost and availability of the technologies on which the PM tasks are based (Worledge, 1993:26).

Due to the reasons set out in 1.2 and the Lethabo vision to consistently produce quality electricity at the lowest cost, the power station enbarked on a process to optimise operating and maintenance costs. Various factors can contribute to a decrease in operating and maintenance (O&M) costs, but increased capacity factors and availability are the vanguard of such trends. Improved availability through effective plant maintenance is recognised as a key ingredient to plant operating cost efficiency. Avoiding forced outages and other operational transients are not only less expensive, it is safer as well. Thus we realise that improved maintenance practices will continue to grow while maintenance expenses themselves will decline.

This and the fact that most of our maintenance have been preventive, time-based and based on operating history were the main drive for optimising our maintenance at Lethabo power station.

3.2. REASONS FOR USING THE RELIABILITY-CENTRED MAINTENANCE PROCESS.

Like most power plants the Lethabo power station planned maintenance program had its origin in vendors conservative recommendations applied to components without considering real duty cycles, and with little systematic regard for the key system functions that these components support.

An organised practical approach to maintenance program development and improvement is the key. Reliability-centred maintenance is a proven technique for formulating a preventive maintenance program or improving an existing program. It is a complete maintenance philosophy based on maintenance engineering, a follow-up of manufacturer design activity and the best way to optimise planned maintenance.

According to Worledge (1993:26) RCM addresses both reliability and safety through a qualitative, top down process that preserves important system functions rather than equipment design specifications. When condition directed tasks are selected, RCM condition directed tasks take priority over time directed tasks, and provide a model for approach for integrating predictive maintenance technologies into the plant PM program.

As tasks are selected input it has to come from the maintenance community in terms of effective PM tasks and intervals that diminish, delay, or eliminate the causes of critical component failure modes. Most of the time this key part of the process breaks down because the traditional process of maintenance experience feedback does not always identify PM tasks that prevent failures. An ongoing PM process that is based on RCM must integrate PM task improvement via suitable information feedback mechanisms.

3.3. BENEFITS OF THE RELIABILITY-CENTRED MAINTENANCE PROCESS.

3.3.1. Cost benefits.

The primary benefit for using RCM is that it develops a PM strategy that adequately addresses system reliability, availability and safety without creating a totally impractical costs requirement (Smith, 1993:51)

The following points that have cost impacts are the reasons for Lethabo to go for this process:

- RCM emphasises predictive maintenance. The process replaces periodic maintenance tasks with predictive maintenance tasks that will lead to more planned maintenance activities (Kuehn, 1992:25).

  These emphasis helps reduce the traditional time directed tasks and increase reliance on condition directed tasks that are inherently more cost effective in most applications. This will also help to reduce use of corrective maintenance resources.

- Improved resource allocation: The combination of system analysis and maintenance task selection logic helps identify those components that warrant maintenance resources and then apply the most cost effective maintenance to address critical component failure modes (Kuehn, 1992:25).

  This is a cost saving that is easily identified by plant owners.

- Develop and document basis for the maintenance program. The analytical way for assigning component criticality ranking and selecting maintenance tasks is provided in the documentation associated with RCM analysis (Kuehn, 1992:25).

  The RCM process is a ideal method of developing and documenting bases for maintenance program elements. This documented bases can be used for future benefits with regulators, insurers and warranty contracts.

- Increase in plant reliability and availability. One of the most compelling reasons to use RCM as a method for maintenance program enhancement is improved system reliability and plant availability (Kuehn, 192:25).

  In the electrical utilities these are the most important capacity factors that are taken in consideration for managing the plant.

Smith (1992:54) also list other operating and maintenance benefits that can be evaluated and that will add to the cost benefit picture, including the following:

- plant trip reductions.
- more accurate spare parts identification and stock holding.

- more efficient PM planning and scheduling.
- decrease in corrective maintenance costs.

3.3.2. Peripheral benefits from the RCM process.

As experience with the implementation process is developed, a series of peripheral technical and cost benefits accumulated that came about from the thoroughness of the RCM process (Smith, 1993:167).

These benefits are so significant that they alone make the systems analyses worthwhile.

- When doing the system analysis process, usage is made of the latest system component breakdown structure (HBS - hardware breakdown structure at Lethabo). By using this information the whole codification and plant breakdown at Lethabo was verified and checked against the drawings. This is almost like an audit of these systems.

- When doing the comparison of the RCM tasks against the current PM tasks, the whole current system is reviewed. This was also the case at Lethabo. In doing so all tasks on a component in terms of frequency and duplication between departments are eliminated.

- In many instances it was discovered that some components serve no useful role in the functions identified for the system. These components can usually be removed at the earliest convenience.

- The persons involved in the process also discovered plenty of design enhancements that can prevent failure modes, effects and PM tasks.

- RCM is done on all new plants. This offers a chance to correct deficiencies that have been overlooked during the commissioning phase.

- The RCM system analyses process is also a training ground, for all departments learn more about each others function and the relevant plant and processes involved.

3.4. SUMMARY.

In this chapter the reasons for needing to optimise the maintenance at the power station are discussed. These obviously led to a program being implemented in order to optimise maintenance. Why the RCM process was used at the power station is then discussed. The benefits for using RCM are outlined thereafter.

CHAPTER 4

DEVELOPING THE LETHABO PROGRAM

4.1. DEVELOPING THE PROGRAM.

Worledge (1993:25) state that each RCM program includes the following major steps: 1. select and prioritise systems; 2. perform the RCM evaluation on selected systems; 3. reconcile new recommendations with the existing program; and 4. plan the new tasks implementation process. At Lethabo we added a fifth step which is applying a sustaining engineering effort using actual hardware reliability-age analysis concepts to optimise the process.

4.1.1. Step 1: Select and prioritise systems.

At Lethabo the RCM model was conducted on systems level and the analysis done down to components level. The reason for this is that Lethabo and a power generating plant is already divided in logical major systems as they are used as building blocks in the design process, plant schematics, and piping and instrumentation diagrams. The Lethabo plant hardware breakdown structure is also coded according to plant systems which further strengthens this point, and clearly defines the system boundary definitions.

Smith (1993:59) state that when approaching PM planning from the function point of view, the most efficient and meaningful function list for RCM analysis is derived at the system level.

Having decided that the system is the best practical level of assembly at which to conduct the RCM analysis process, one must now focus on which systems to address and in what order. The decision at Lethabo was to treat all 26 plant systems. This is not, however, the view of the author because, and literature supports this (Smith, 1993:60), such a cause of action may not be cost effective in that some systems have neither a history of failures nor excessive maintenance costs that might warrant a special investigation to "make it better".

The above step in the program represents basically the first three steps in the RCM model covered in chapter 2.

4.1.2. Step 2: Perform the RCM evaluation.

The process from this point forward is done on a computerised software program at Lethabo. The program basically follows the RCM model steps 4 to 7 as outlined in chapter 2. It starts with component functions and moves directly on towards failure modes effects and criticality analysis (FMECA), and identifying maintenance significant items (MSI). Lastly the program moves over to RCM decision tree analysis and task selection.

Component functions: The objectives of maintenance with respect to any asset are defined by the functions of the asset and its associated desired standards of performance (Moubray, 1992:8). For this reason, the RCM process starts by defining functions and performance standards of each component in its operating context.

Failure mode effects and criticality analysis (FMECA): FMECA is done in order to identify the critical items in a particular end-item. This period not only constitutes the end-item environment, but is also the time frame in which some of the most vital RCM data and information are generated and collected. It provides information on the occurrence of specific failures, required removals, repair costs, spares requirements, and much of the economic data needed for the refinement of the initial RCM derived maintenance program (Anderson, 1990:6).

In the above analysis criticality was added to step five, failure modes effect analysis, of the RCM model in chapter 2. This is a simple way of outlining the failure effect some components can have on your performance parameters.

Maintenance significant items (MSI): This step is done before RCM decision tree- and task analysis, in order to prevent doing these analyses on items that will, because of there failure modes and effects, not need planned maintenance. Every time a failure mode occurs, the plant is affected in some way. These affects can be one of the following: safety, environment, lead to loss in production or high repair costs. Still others may appear to have no effect at all if they occur on their own, but may expose the plant to the risk of much more serious failures. If any of these failures are not prevented, time and effort need to be spent correcting them.

On the other hand, if the consequences of the failure are trivial, it is possible that we may decide to take no preventive action and simply take appropriate corrective action when the failure does occur.

Thus the need arises to determine whether an item or component is maintenance significant in terms of the above or not.

RCM II logic analysis: This logic process is applied to each critical item in order to select the optimum combination of maintenance task requirements or to determine if redesign is needed (Anderson, 1990:4). The logic process is applied to each critical item and judgements are made as to the necessity of various maintenance tasks.

Task selection: From the decision tree tasks arrived at, one now selects the tasks deemed to be necessary. This, together with the intervals determined to be appropriate, form the total scheduled maintenance program.

4.1.3. Step 3: Reconcile RCM tasks with existing PM's.

Normally when RCM is done on existing plants, there is a PM program of one sort or other already in place. One now needs to upgrade this existing program. In doing so one wants to know how the RCM-based PM tasks stack up against the current PM tasks. How different is the RCM program, and what is the nature of those differences? It is always important to compare the original equipment manufacturer (OEM) recommendations to the RCM-based PM tasks. The following categories of comparison were used at Lethabo power station:

- RCM-based and current PM tasks that are identical

- Current PM tasks exist, but must be modified to meet the RCM-based tasks.

- RCM based PM tasks are recommended where no current tasks exist.

- Current PM tasks exist where no RCM-based tasks are recommended, and are therefore candidates for deletion.

4.1.4. Step 4: Plan the implementation process.

Maximum benefits from RCM can only be obtained if the recommendations for PM change are implemented fully and effectively, thus ensuring that maintenance tasks are improving over a period of time.

The Lethabo power station maintenance management information system had to be correlated with the RCM-based tasks in terms of disciplines skill level, task frequencies and current scheduled intervals in order to ensure that no current scheduled maintenance was neglected. This process includes the following major steps:

- Verification of old detail with RCM results.

- Approval of the new PM schedules.

- Allocate new planned maintenance management information numbers to these schedules.

- Correlate the phasing in of the new task implementations.

- Load the information into the maintenance management information system.

Tasks that can only be done on plant outages must be loaded to these work packages along the line of the above steps.

4.1.5. Step 5: Reliability analysis concepts.

During the RCM system analysis process at Lethabo no quantitative reliability data were used, and in particular no quantitative failure rate. The reasons were the following:

1. No quantitative data is collected at the failure mode level; all data is collected at the component level.

2. There is no pressing need for such data in the RCM system analysis process. Realistic evaluations and decisions are made from the qualitative engineering and logic tree information that is

systematically developed in the system analysis process.

However, when the initial RCM program is implemented and operational experience begins to accrue, the documentation and reporting system serves as a major source of RCM information for program revision and improvement. Activities will focus on:

- Determining actual reliability-age characteristics and re-applying the RCM decision tree logic to respond to failures anticipated during development.

- Assessing the desirability or additional maintenance tasks.

- Adjusting maintenance task intervals.

- Eliminating the cost of unnecessary and over intensive maintenance resulting from the use of default answers in the initial RCM logic analysis.

The above optimisation will in future be done with the use of reliability analysis concepts. This end result data will ten truly reflect the optimised maintenance planning system.

4.2. LAY-OUT OF THE LETHABO RCM PROGRAM.

This section is included to give the reader a view of what the Lethabo RCM program, or the RCM program for other plant utilities for that matter may look like when going through the above five major program steps.

The initial step in the program (Figure 4.1) was to break the plant down as per the hardware breakdown structure (HBS) system currently in place at Lethabo. Work started on critical plant areas which impact on safety, availability and costs.

Before starting the second step one needs to compile data for the relevant plant area. This information comprises the maintenance manuals, design specifications, drawings, physical inspections and running regime.

A software program is from here on used to identify dominant failure modes, their effect and a criticality analysis (FMECA). The software program then moves on to maintenance significant items (MSI). The above analysis process can be done per component or, for example, functions and failure modes can be done per system and then the MSI's, etc., to speed up the process.

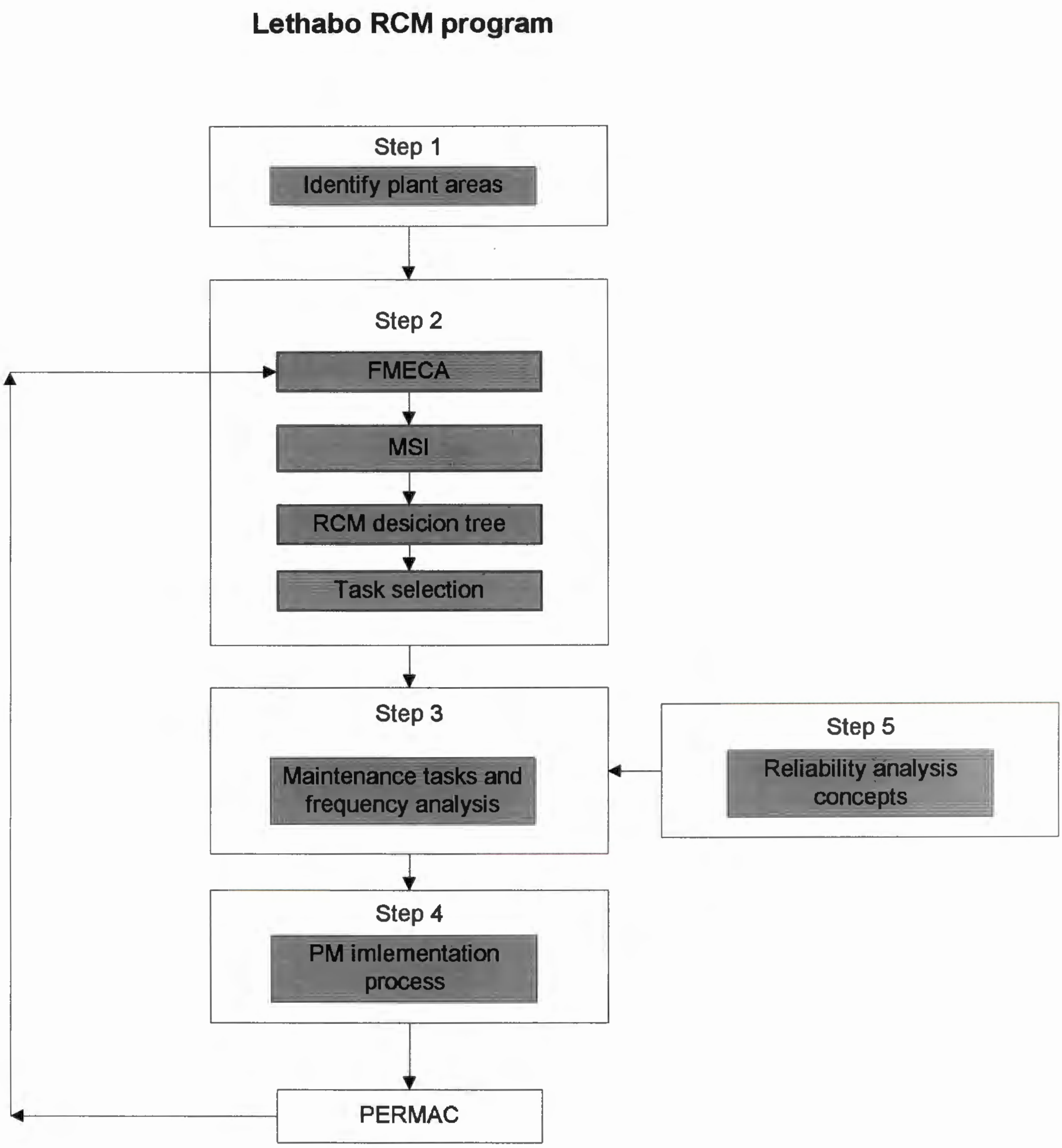

Figure 4.1. Lethabo RCM program

Next each identified maintenance significant item is processed through the RCM II algorithm. This will ensure that a maintenance task, which is both applicable and effective in preventing or identifying a potential failure condition, is developed and compiled for each failure mode. For each of these identified items a task is then developed along the RCM decision tree guide lines.

The third step is to determine the optimum frequency for each identified task. In order to develop and compile the first iteration engineering judgement of people attending RCM work groups is used to determine failure intervals. The actual task frequency will then be set to ensure sufficient reaction time to any potential failure condition. In future for second iterations and so forth this step will be replaced with step 5 in order to optimise the relevant data in the program. Smith (1993:188) talks of a living RCM program, which is basically the continuation of some RCM activities in order to continuously optimise the program data.

The fourth step is then to compile a service notification for each routine maintenance and monitoring activity. On this service notification, which will be drawn up by maintenance personnel, the information required to perform the activity is a detailed task writing process done by the maintenance department.

The last step would be to load the service notifications information into the maintenance management information system (called PERMAC at Lethabo) which will schedule all the activities.

4.3. SUMMARY.

In this chapter a model was constructed for the development and implementation of a reliability-centred maintenance program on a coal fired power utility. All aspects of reliability-centred maintenance as identified in the literature were integrated in developing the model for the power station that covers all the key factors of RCM.

The model shows all the elements of the process, as well as the steps to follow when developing and implementing the process.

CHAPTER 5

IMPLEMENTATION OF THE RELIABILITY-CENTRED MAINTENANCE PROGRAM

5.1. PROBLEM AREAS TO LOOK OUT FOR WHEN IMPLEMENTING THE RCM PROGRAM (Worledge, 1993:26 and Smith, 1993:173).

This is probably the most important phase of the whole process, since this can determine the failure or success of the program.

5.1.1. Upper management support.

This almost speak for itself. There must be a clear and visible support for the RCM program from management (Worledge, 1993:26). Without this the program is dead before it has started. Nobody else will buy-in into the process if it is not supported from the top. From the outset the management at Lethabo gave their endorsement for the program which in the end made the implementation process a success.

5.1.2. Remain up to date with company and business unit vision, progress and future action (Smith, 1993:177).

Eskom is committed to being an efficient and effective organisation. It is also making electricity available at the lowest possible price to all in South Africa who want it.

The company vision is: To supply the world's lowest-cost electricity for growth and prosperity.

The Lethabo vision is: To consistently produce quality electricity at the lowest cost.

The Lethabo Maintenance Department mission is: To safely maintain the Lethabo power station at optimal maintenance cost for its life cycle by providing quality service to ensure that the production goals are achieved.

From the above one can see that RCM addresses the core issues of the company. It was therefore not difficult to motivate the implementation of the RCM at the power station based on cost reductions achieved at overseas stations. Eskom is at the moment implementing RCM at most of its coal fired power stations.

5.1.3. Buy-in into the process.

This is the process whereby an individual or a group, responsible for carrying out some action, has been a party to the development and planning for that action (Smith, 1993:175). When this process is successful, the people involved have made a direct contribution to the action plan, and have accepted the plan as well as assumed some level of ownership in the plan. Without acceptance and ownership, it is highly improbable that plant staff will feel motivated and compelled to implement anything. This especially includes the recommended PM tasks from the RCM program.

Buy-in must come from the top down in the organisation. If top management supports the process then the plant staff will more readily buy-in to the process. However the sales and education processes are not one-stop jobs, but will continue over a long period of time before capturing everyones attention on the success of implementing RCM.(Smith,1993:176).

The best way of getting plant staff to buy-in into the process is involvement in the systems analysis process. This level of plant involvement injects valuable technical experience into the process, and ultimately becomes the primary mechanism whereby ownership is instilled.

5.1.4. Define the statement of work and provide an early project plan (Worledge, 1993:26).

This almost speaks for itself. Any project of this size needs a well defined project plan. The program must be very clear on start and end dates for each process in the program. In the case of a power station and the way our task groups are set up at Lethabo, one needs to take planned outages and staff considerations of certain sections into account. As one moves along the project plan must be kept up to date, and be adapted where necessary. At all times everybody concerned and involved in the project must agree on the project plan.

The statement of the work to be carried out must underline the importance of the project in order to optimise maintenance on the plant. It must further explain what amount of work needs to be carried out, in terms of manpower , skills and commitment in order to meet the project plan.

5.1.5. Organisational considerations.

There is an old saying that it is the disposition, personalities and motivation of the people, not the structure of the organisation in which they work, which ultimately determine project success or failure (Smith, 1993:177). But, experience also says that the particular version of organisational structure that is employed can be a significant factor in making success easy or difficult to achieve. The following important issues interplay with these organisation structures:

1. Buy-in: The first essential step has been identified as endorsement by the RCM program upper management (Smith, 1993:180).

   Given this endorsement, the really crucial buy-in actions must focus on the plant organisation. What is important here, is to sell to engineering and operational personnel as thoroughly as the need to sell to the maintenance personnel. The reasons for this are embedded in the RCM process itself, where the condition directed and failure finding tasks takes on equal importance to the traditional time directed tasks. The engineering and operating staff own a share of the condition directed and failure finding tasks. It is thus important that they buy-in into the process as well.

2. Resource allocation: This is the biggest delaying factor of the whole process at Lethabo. The first and still the best in the author's view is to staff and conduct the RCM program from the plant itself. Being a fossil plant, staffing and particular subject matter experts are "lean and mean". This fact and the frequency of plant

outages were the main contributors to the delays in the implementation process.

Smith (1993:181) discuss the following possible solutions to overcome the staffing issue:

- Assign appropriate on site personnel to the RCM program by giving it priority over other activities. The problem is as discussed above that the priority assignment goes by the wayside every time there is a hiccup in the plant availability status. The net effect is that a smooth and continuos RCM program never really occurs. If there is a consultant involved, in the beginning, as in Lethabo's case, to smooth out the process it just worsens the case in terms of costs. In the end everybody gets frustrated with the process and the program can be extended far beyond the original target dates.

- A second option is to authorise an increase in plant staffing to accomplish the RCM program. With this approach, one or two key personnel from the exiting staff can be placed in lead positions to help orient and integrate the new personnel. Experience has shown that this method ultimately deliver some of the best implementation results.

- A third option is to staff and conduct the RCM program through the engineering support group at headquarters. This is a good solution in terms of staffing point of view, but poor in terms of the buy-in at the plant. To overcome the latter problem corporate staff need to play a continuing and highly visible role with involvement from and integration with the plant personnel.

- The last option would be to bring in an outside contractor to execute the whole program. This will result in the plant staff playing a minute role. The effect would be a huge buy-in problem at the plant and may create technical deficiencies in the system analysis process, since the contractor personnel may not have the in-depth system knowledge required to thoroughly do the analysis. This approach is the most expensive and has the lowest probability of yielding completely satisfactory results.

The route at Lethabo was to use a single consultant in combination with point one in the RCM groups until the teams become RCM process experts in their own right, and can then use in-house personnel exclusively to complete the program. In the end one wants high plant support rather than contractor support.

5.1.6. **Maintenance management information system (MMIS) integration.**

If there is already a MMIS present, then the MMIS requirements in the RCM program is a minor issue. If the opposite is true, there may be a stumbling block. MMIS facilitates the efficient conduct of a PM program (Smith, 1993:176).

With a RCM program the efficient monitoring of task parameters is essential for the compilation of PM and CM cost data, for benefits analysis. This is also necessary for processes further down the line like age exploration programs, component histories for statistical analysis and other related program measurements. The MMIS system at Lethabo is in the process of upgrading and will specifically also cater for RCM requirements. This requirement should never become a reason for not doing an RCM program.

5.1.7. **PM task procedures.**

The RCM process leads to PM tasks, which might be new or modified and thus require the generation or change of procedures before the tasks can be performed on the floor. The degree of formality and detail required of these procedures will vary from plant to plant. The problem is to determine who is responsible to prepare these procedures. It is better not to wait until the last minute, and just jump on some unsuspecting group or individual (Smith, 1993:174).

The best is, as in Lethabo's case, to have an identified group whose job is procedure upkeep in the organisation. It is even better to have this for plant groups (example electrical, mechanical, etc.). If this is not possible then using a system analyst is the next best course of action.

5.1.8. Defined goals are understood and accepted by plant groups (Worledge, 1993:26).

Make sure that defined goals are understood and accepted by plant groups (e.g. maintenance and operation) and management. Everyone must realise that a fundamental change in maintenance philosophy is taking place and that it is a plant goal to reformulate the PM program. Identify, early on, the degree of conservatism or aggressiveness that can be used to incorporate predictive maintenance, and the tolerable degree of challenge to the existing PM program. Nothing should be sacrosanct. Everyone should be aware that a major plant program is underway and it is no longer a trial project.

5.1.9. Program measurement.

Even if the baseline definition never changes, at a minimum one should measure the benefits derived from the RCM program as part of the routine operating reports to management (Smith, 1993:191). The following are the minimum performance measurements at Lethabo, against which the program is measured:

- Corrective maintenance: This measurement is obviously valuable in fine tuning the PM baseline definition for each system. Over time, the occurrence of corrective maintenance should approach zero. The immediate goal Lethabo will set out for is a PM:CM ratio of 80:20.

- Plant availability: At power utilities this represents a very important indicator of plant performance. As plant availability increase, cost avoidance accruals are a major bottom-line benefit.

- PM + CM costs: The total figure, tracked over time, gives a very good measure of how the RCM program is affecting maintenance expenses.

5.1.10. Find a comfortable level of detail and documentation to suit all users.

Considerable time and effort can be saved by deciding from the outset what system documents and information will be needed during the analysis process (Worledge, 1993:27). A list of documents and information typically used for each system by the RCM analysts at Lethabo are as follows:

- System piping and instrumentation diagram (P&ID)

- System schematic and or block diagram if available. Usually one only gets a drawing of components, which will also help.

- Individual original equipment manufacturer manuals for the equipment in the system which will contain potentially valuable information on the design and operation of the equipment.

- Equipment history data. These may be modifications done, actual history on failures or corrective action taking.

- System operation manuals which provides valuable detail on how the system is intended to function, how it relates to other systems and what operational limits and ground rules are employed.

- System design specifications and descriptive data which will support the proceeding.

- Printout of the current PM program employed on the plant.

5.1.11. Reduction in plant staff (Smith, 1993:177).

Labour adjustments deal not only with the issue of skill and training needs, but also with the question of workforce reductions at the plant. The reasoning goes along the line that if the RCM program is capable of reducing or improving PM's and or PM costs, then this must equate to a loss of jobs. Evidence in industry indicates that such reductions do not occur.

There are several reasons for this, but two factors seem to dominate. Firstly, a major faction of the PM savings that may be realised develops from either the extension or elimination of complex overhaul tasks which are usually performed by vendors or contractors and does not directly affect plant staff. Secondly, the RCM program is aimed at obtaining the best possible productivity and availability for the cost incurred, not the reduction in plant staff required to achieve this. What might happen is that new skills may be needed and current plant staff may need to learn these skills.

5.2 SUMMARY.

This chapter dealt with the key success conditions for the development and implementation of the RCM process. These conditions are essential for getting RCM up from ground level to full implementation. Many RCM programs are stillborn and these are conditions to improve the chance of developing a successful program.

CHAPTER 6

CONCLUSIONS, RECOMMENDATIONS AND CLOSURE.

6.1 INTRODUCTION

The theory concerning the aspects of developing and implementing RCM was investigated in the literature. With this theory and practical experience a program for RCM design implementation on a coal fired power station was developed.

The main aim of the paper was to set forward a practical and applicable RCM program for a coal fired power station. Other aims that were also achieved, were to explain the principles of RCM and factors that can influence the implementation of a RCM program.

6.2 CONCLUSIONS.

The maximum benefits from RCM can only be obtained if the recommendations put forward for preventative maintenance are implemented fully and effectively. Lethabo power station will develop the existing PM program by incorporating RCM implementation as it is completed. The two major goals of the RCM project is to ensure that the power station is safely maintained at optimal maintenance costs and show how preventative maintenance tasks can steadily be improved over time.

As the RCM process gathers momentum the popularity amongst participants increases as well. This is due to the way it helps the task group members to gather and sort information so they can understand the way components function in a given system, how and when they break, and how they can be maintained cost effectively. RCM analysis, however, does not actually supply this data. Maintenance and operating histories and other existing operational data are analysed to find out what is the optimum maintenance practice. This process thus leaves a feeling of empowerment amongst the people responsible for doing maintenance on the plant, as they can now for the first time use their knowledge and experience to optimise maintenance in their area.

Successful implementation means that we recognise the type of impediments that can occur, as well as the technical and programmatic issues that will arise, and deal with them in a timely fashion. This includes making them visible to all parties with a vested interest in such issues, and assuring that a stumbling block on only one or two points will not stop the entire program. At Lethabo the difficulties and impediments were overcome, and successful implementation is on its way. However, the future plant conditions in terms of availability, reliability and cost trends will finally determine the success of the project.

6.3. RECOMMENDATIONS

Reliability centred maintenance can only be applied if everybody and all activities and personnel in the power station are integrated into the process. The conditions for a successful program have already been discussed in detail in section 5.1. These conditions were not necessarily followed during the initial stages of the process at the power station. The mistakes made and the corrective actions that were taken to keep the program on the right track were as follows:

MISTAKES OF THE PAST	(CORRECTIVE) ACTIONS
1. No proper implementation plan.	1. Develop implementation plan.
2. Project to long.	2. Prioritise project plan.
3. Do the whole plant.	3. Prioritise plant areas.
4. Management not involved.	4. Awareness: Presentation each year.
5. No ROI calculations.	5. PM:CM ratios, total cost picture and effects.
6. Lack of RCM knowledge.	6. RCM training.
7. Lack of management understanding.	7. Selling of concepts.
8. No group concept.	8. Facilitators concept.

9. Too long for results to realise.	9. Implementation as soon as possible.
10. Paper exercise.	10. Show results as soon as possible.
11. Reduce PM's as driver.	11. Sell idea of optimised PM's and maintenance activities.
12. Responsibilities not allocated.	12. Project team leader and groups.
13. Seen as "magic stick".	13. Sell realities.
14. Project participation low.	14. Link project results to performance contracts.
15. Minimise consultants involvement.	15. Minimise effect of consultants participation on program duration.
16. Lack of RCM motivation.	16. "Bigger picture" understanding.

It is suggested that other coal fired power stations thinking of implementing RCM on their plant should look thoroughly at the program, identify problem areas and get them in line with the company goals. The program can be modified to accommodate any changing needs.

RCM is a continued maintenance optimisation process. The continuation of the process must be built into the current maintenance management information system. This will force the continued involvement of management and personnel in the process and the subsequent optimisation of preventative maintenance.

6.4 CLOSURE.

The impetus that ushered in the predictive, reliability-driven maintenance programs represents a cultural shift in the attitudes of power station maintenance managers. Maintenance practice, more often than not, was (and continues to be) based on fixing components after they had broken and relying on vendor-supplied maintenance schedules rather than scientific, analytical methods (Kuehn, 1992:24).

Through the usage of the structured process of planning, changing, redesigning, measuring, evaluating, communication and team work, reliability centred maintenance lies within the reach of every company.

REFERENCES

ANDERSON, R.T. & NERI, L. 1990. Reliability-centred Maintenance: Management and Engineering Methods. Essex : Elsevier Science Inc.

DREYER, H.N. 1995. Maintenance processes and management techniques. (Lecture given on 24 June 1995 as part of course in Maintenance Practice.) University Pretoria. 7p. (Unpublished.)

FITCH, E.C. 1992. Proactive maintenance for Mechanical systems. Stillwater : FES Inc.

GRADIN, L.P. CARTWRIGHT, W.B. & BURSTEIN, N.M. 1994. Test method improves motor bearing wear assessment at Calvert Cliffs. *Power engineering*, 98(6): 32-33, Jun.

JARDINE, A.K.S. 1973. Maintenance, Replacement and Reliability. London : Pitman.

JONES, R. 1987. Reliability-centred Maintenance. New York : Gulf publishing company.

KELLY, A. & HARRIS, M.J. 1978. Management of Industrial Maintenance. London : Butterworth.

KUEHN, S.E. 1992. Reliability-Centred Maintenance trims nuclear plant costs. *Power engineering*, 96(8): 23-28, Aug.

KUEHN, S.E. 1992. Reliability-centred maintenance trims nuclear plant costs (Part II). *Power engineering*, 96(11): 30-32, Nov.

MOUBRAY, J. 1992. Reliability-centred maintenance. Oxford : Butterworth-Heinemann.

MOUBRAY, J.M. 1988. Developments in Reliability-centred Maintenance. *The Factory Efficiency & Maintenance Show and Conference*, NEC, Birmingham, UK: 27-30 Sept.

MOUBRAY, J.M. 1987. Reliability-centred Maintenance. A conference on Condition monitoring, Gol, Norway: 2-4 Nov.

NAKAJIMA, S. 1988. Introduction to TPM: Total Productive Maintenance. Cambridge : Productivity Press.

NOWLAN, F.S. & HOWARD, F.H. 1978. Reliability-centred Maintenance. San Francisco, Calif. : United Airlines.

SANDTORV, H. 1991. "RCM - Closing the loop between design reliability and operational reliability". Maintenance, 6(1): 13-21, Jan.

SMITH, A.M. 1993. Reliability-centred Maintenance. New York : McGraw-Hill.

SMITH, A.M. & HINCHCLIFFE, G.R. 1991. Using reliability-centred maintenance to support corporate TQM objectives. Annual reliability and maintainability symposium, pp 101-107.

SMOCK, R.W. 1993. A comprehensive look at reliability-centred maintenance. *Power engineering*, 97(10): 12, Oct.

WORLEDGE, D.H. 1993. Nuclear industry embraces reliability - centred maintenance. *Power engineering, 97(7)*: 25-28, July.