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High Pressure Feedwater Heaters Replacement Optimisation

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Year: 2016

UNIVERSITY OF PRETORIA

Submitted in partial fulfillment of the requirements for the degree:
Master of Engineering

Abstract

Title:	Feedwater Heaters Replacement Optimisation
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Department:	Mechanical and Aeronautical Engineering
Degree:	Master of Engineering (Mechanical Engineering)

Widespread uncertainty exists regarding the ideal replacement time of installed feedwater heaters in coal fired power plants. Eskom consequently identified the need for this research project to find the optimal age at which to replace high pressure (HP) feedwater heaters. Previous work has failed to quantify the unique financial risk of tube failures, which varies for individual heaters. Using life cycle cost (LCC) methodology, a framework is developed for the optimisation of the HP feedwater heater replacement age in Eskom coal fired power plants and integrated into existing software used in the organization. This entails identifying the most significant cost factors involved in the lifecycle of HP heaters and determining how they evolve over time by conducting a case study. Minimum life cycle cost for an actual HP heater is calculated in the case study based on failure data and cost information supplied by the power plant. This optimisation of replacement time can realise significant savings in annualised LCC compared to current practice.

Acknowledgements

The author especially acknowledges the contribution of Eskom Turbine Centre of Excellence for the opportunity to complete this degree as part of the Eskom Power Plant Engineering Institute (EPPEI). EPPEI is a truly unique endeavour and it has been a privilege being part of a select few to be fortunate enough to be admitted to the programme.

Also Professor Jasper Coetzee as Academic Supervisor, for his continued support and supervision, it has been an honour to engage with an individual with such a wealth of experience and extraordinary commitment to the maintenance engineering community. My appreciation for your time and inputs cannot be over emphasised.

Marthinus Bezuidenhoudt, Eskom Corporate Materials Specialist for topic inception & development. Your willingness to support this study has been unwavering throughout its duration. The difficult task of navigating through Eskom in search of the appropriate sources of information was significantly eased with your guidance.

In addition;

Sujen Balikisson – DPS FWH System Engineer for supply of tube plugging data

Wiets Roos – HPS FWH System Engineer for supply of tube plugging data

Carel Potgieter – Eskom C&I Senior Consultant for access to historical operating records

Jan Kiper – DPS FWH Senior Consultant for historical replacement and failure data

Gary De Klerk – Turbine Process Chief Engineer for guidance in the calculation of cycle efficiency contributions

Dr Francois du Preez – Eskom FWH Corporate Consultant for numerous meetings to affirm and critique data sources and input assumptions

Muhammad Rahiman – M-Tech Constulting Engineers for his intensely productive contributions towards the final submission of this research undertaking

Abbreviations

C&I - Control and Instrumentation

CPA - Contract Price Adjustment

CRF - Capital Recovery Factor

EPRI - Electric Power Research Institute

ERP - Enterprise Resource Planning

EUAC - Equivalent Uniform Annual Cost

FWH - Feedwater Heating

GPSS - Generation Power Sales System

GW - Gigawatt

Gx - Eskom Generation Division

HHV - High Heating Value

HP - High Pressure

HPP - Homogeneous Poisson Process

HR - Heat Rate

kJ - Kilojoule

K-S test - Kolmogorov-Smirnov Goodness-of-Fit Test

kWh - Kilowatt hour

LHV - Low Heating Value

MARR - Minimum Acceptable Rate of Return

MTBF - Mean Time Between Failure

NHPP - Non Homogeneous Poisson Process

O&M - Operations and Maintnenance

PDF - Probability Density Function

PV - Photovoltaic

ROCOF - Rate of Occurence of Failure

RUL - Remaining Useful Life

SEIFSA - Steel and Engineering Industries Federation of South Africa

TTFF - Time to First Failure

Contents

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1 Executive Summary

1.1 Introduction

Due to the uncertainty surrounding the ideal replacement time of HP heaters in Eskom an industry ready framework will aid plant leaders in their replacement decisions for HP heaters taking into account plant integrity and cost effectiveness.

HP feedwater heaters are one of the four most significant contributors to controllable losses in Eskom. This has significant cost implications for the business and highlights the importance of this study. Because LCC methodology encompasses all cost aspects of equipment life cycle, it is applied to quantify HP Heaters' increasing operational costs to determine a replacement age where LCC is a minimum.

1.2 Problem Statement

Eskom requires an improved understanding of the optimal age at which to replace HP feedwater heaters in coal fired power plants.

1.3 Research Purpose

The purpose of this research is to develop an industry ready framework to find the optimal replacement time of HP feedwater heaters in Eskom based on minimum lifecycle cost.

Data to perform this exploratory study is to be collected using existing reporting structures in the organization which is used to monitor the physical condition of feedwater heaters.

1.4 Research Questions

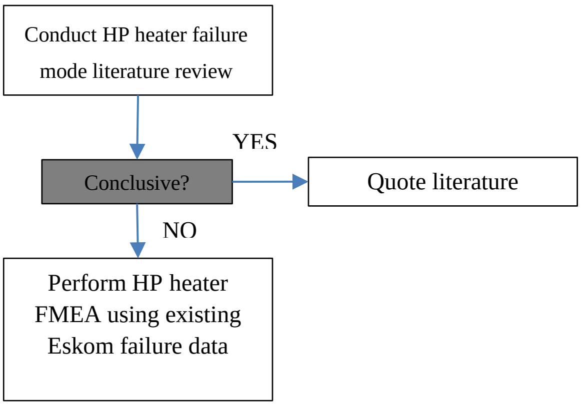
1. What are the most significant cost factors involved in the lifecycle of HP feedwater heaters and how do they evolve over time?
2. Can LCC methodology be applied to optimise HP feedwater heater replacement at Eskom?

1.5 Research Benefit

Approximately R25m was lost in final feedwater temperature in August 2015 alone in the Eskom coal fleet. If the timing of replacement of feedwater heaters can be estimated more accurately, an opportunity exists for significant savings.

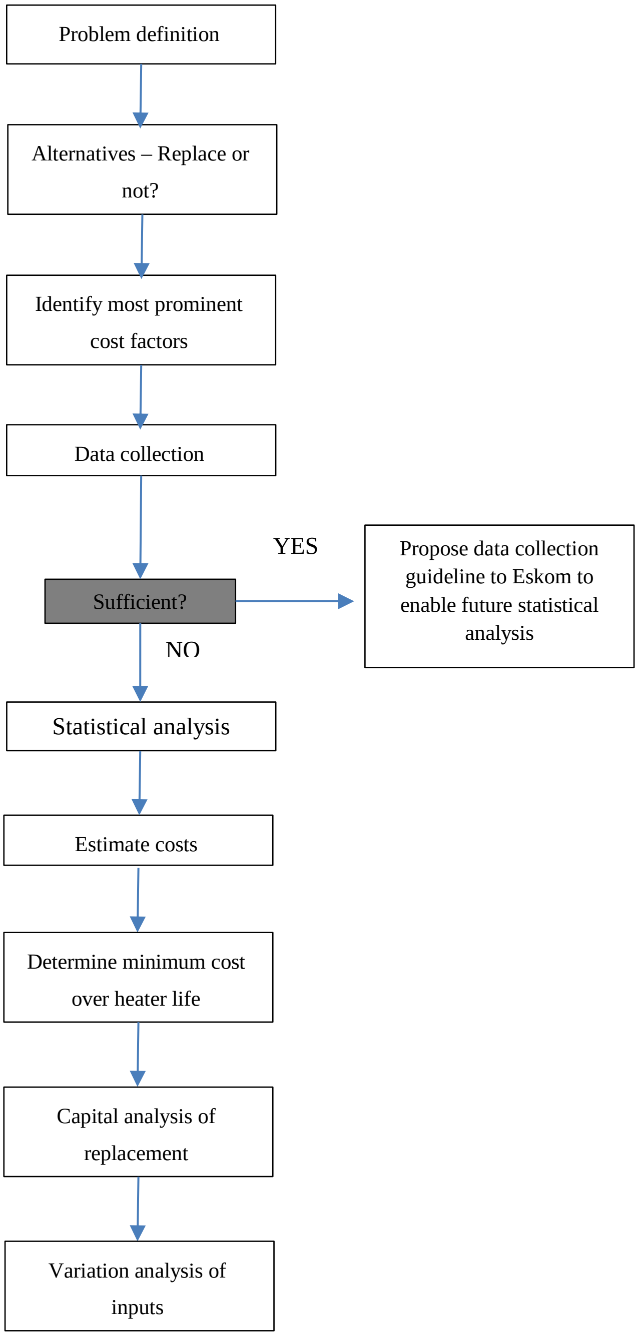
1.6 Methodology

A detailed literature review is to be conducted to conclude on the most prevalent failure modes in HP heaters. In the absence of this information, a Failure Mode and Effects Analysis (FMEA) must be performed using existing failure data in Eskom.



According to the result of research question 1, the appropriate data will be collected to conduct statistical analysis. An actual case study will be conducted using existing data in Eskom. From this it will be deduced if sufficient data exist in Eskom to apply LCC methodology to determine the optimal replacement time of HP heaters.

In the case where data is deemed inadequate, the appropriate method and format for data future data collection will be prescribed to enable future analysis for Eskom. The following scematic illustrates the methodology as adapted from Barringer (1995).



1.7 Scope & Limitations

The focus of this study is the replacement of HP feedwater heaters in South African coal fired power plants.

Because the marginal cost of HP heater downtime is unknown in nuclear power plants, this study is not applicable to nuclear power plants.

1.8 Structure

Herewith follows a layout of the most pertinent themes in this dissertation

Chapter 2 Literature Overview

Chapter 3 Background

Chapter 4 Research Strategy for Capital Replacement

Chapter 5 Probability of Heater Tube failures

Chapter 6 Consequence of Heater Tube failure

Chapter 7 Financial Risk exposure

Chapter 8 Case Study – DPS Unit 1 High Pressure Feedwater Heater 5B replacement

Chapter 9 Conclusion

1.9 Conclusion

Uncertainty exists concerning the ideal replacement time of HP heaters in Eskom and HP feedwater heaters are one of the four most significant contributors to controllable losses in the coal fleet. This has significant cost implications for the business and highlights the importance of this study. Because LCC methodology encompasses all cost aspects of equipment life cycle, it is applied to quantify HP Heaters' increasing operational costs to determine a replacement age where LCC is a minimum.

The purpose of this research is to develop an industry ready framework to find the optimal replacement time of HP feedwater heaters in Eskom. This may be achieved by addressing the following research questions:

> 1. *What are the most significant cost factors involved in the lifecycle of HP feedwater heaters and how do they evolve over time?*
>
> 2. *Can LCC methodology be applied to optimise HP feedwater heater replacement at Eskom?*

The benefit of the research was highlighted by citing the excessive costs of low feedwater temperatures in the Eskom coal fleet.

A research methodology to address the research questions was proposed and represented schematically.

The scope was determined to be limited to the replacement of HP feedwater heaters in South African coal fired power plants and is not applicable to nuclear power plants.

The high level Structure of the dissertation was also presented.

2 Literature Overview

2.1 Introduction

As the purpose of this research is specifically to develop a framework for the optimisation for high pressure feedwater heaters the following databases were searched by using the search phrases *feedwater heater replacement* and *feedwater heater failure:*

- ASME Digital Collection
- IEEE
- Elsevier
- EPRI Member Center Search

Of the 130 results only 7 are pertinent to the purpose of this research and only 2 results are articles produced to specifically address the objective at hand. It must be mentioned however that, in both these cases, HP heaters are not specifically addressed but that the replacement of feedwater heaters in general is dealt with.

The content of this literature overview alludes to the following three aspects:

- Existing attempts to highlight the absence of effective feedwater heater replacement practices and also the deficiencies of previous attempts to optimise feedwater heater replacement.
- Statistical modelling techniques and their applicability to the research objective.
- Considerations regarding common practices applied to equipment replacement and their possible relevance to the research objective.

2.2 Background

Feedwater heaters are heat exchangers used in the regenerative cycle of the power generation process and have a history of chronic maintenance problems (EPRI, 2003).

Even though these chronic failures can be repaired, feedwater heaters do not have observed degradation signals. This limits the use of condition monitoring data to determine when a failure is imminent.

A statistical data driven approach may thus be appropriate. These methods construct estimation models by fitting existing failure data to a probabilistic model without relying on engineering principle (Si et al., 2011). These models indicate the expected change in failure arrival times over a specified time interval.

When the rate of occurrence of failures is a continuously increasing function of age, a specific replacement age exists which minimizes the expected cost per unit time over a finite time span or the expected long run cost per unit time (Sivazlian, 1973).

2.3 Feedwater Heating

Based on the data from a survey conducted by the Electric Power Research Institute (EPRI), originating from 44 power stations covering approximately 300 replacements concluded that no firm numerical figure emerged for the justification of replacement of feedwater heaters in power plants. This can naturally make the approval of funds for replacement difficult if there is no quantified value prescribing the replacement frequency or the impact of delaying replacement. If the cumulative monetary effect of downtime can be forecast over a given period of time, replacement times may be significantly optimized.

When considering regenerative feedwater heaters as independent components, there is one mode of failure which is most prominent, i.e. tube failures (EPRI, 2003). The tubes in a feedwater heater have the largest exposed surface area and are also of a thin walled design. This is done to maximize heat transfer and minimize cost. FWH failures involving tube damage far exceeds the damage from other causes according to a survey (EPRI GS-7417) conducted jointly by the Edison Electric Institute and EPRI specifically for fossil power generation plants in the US and Europe. The results indicate that in the US and Europe, 78% and 88% of damage incidents are tube related, respectively (EPRI, 2003).

Even though feedwater heaters used in power plants have a high variability of expected life and long delivery lead times, they are not subjected to detailed failure rate analysis (EPRI, 2009).

A straightforward approach to calculating the economical time for replacement of feedwater heaters is presented by Fehring and Gaggioli, but has not been applied by Eskom (Fehring and Gaggioli, 1977). Won and Park analyzed the tube plugging rate of a feedwater heater using the Weibull distribution function (Won and Park, 2010). This was also done by Pearce but only assuming an exponential plugging rate – he also added economic benefit analysis and additional technical detail regarding tube failure modes (Pearce, 1996). The reason for this assumption of exponential plugging rate is based on the ideas of Bell (1991) who also assumed that the growth of plugging rate for tubes in feedwater heaters would be exponential during their wearout phase (Bell et al., 1991). Vair on the other hand has attempted to determine the technical and economic practicality of adding feedwater heaters to the steam cycle (Viar et al., 1986). The economic aspect of decision support is ultimately as important as statistical modelling in determining replacement timing. Consequently the optimal replacement time of capital equipment cannot be determined without an economic study (Coetzee, 1997a).

2.4 Statistical modelling

Industrial systems are complex in their nature and costly to disrupt or manipulate (Blanchard and Fabrycky, 2011). When the direct manipulation of systems comes at significant cost or time, operational decisions are made through experimental investigation using models.

Many mathematical maintenance models are based on the application of component lifetime distribution to quantify the uncertainty of equipment ageing. The relevance of lifetime distributions is hampered by the fact that it can only describe the probability of survival and in order to represent ageing through lifetime distributions requires the use of a large population of components rather than a single component (van Noortwijk, 2009).

The assumption that the degradation processes of these separate components in a population are independent and identically distributed, has been adopted by many authors (Crowder and Lawless, 2007). However, even though these components may be manufactured to the same nominal specification, there always remains some random variation in their wear rates and thus the amount of wear experienced by individual components varies.

Jardine & Tsang (2013) present various concepts and techniques which can be used to optimize component replacement decisions which can improve the reliability of complex equipment. The preventive replacement of critical components within the system is addressed but little attention is given to the systems' reliability itself. The modelling of repairable systems is discussed extensively by Ascher & Feingold (1984) with detailed references to misconceptions and erroneous uses of reliability engineering techniques.

It is strongly iterated that failure processes occurring in repairable systems cannot be represented by distribution functions and far more attention is devoted to developing the fundamental properties of stochastic point processes appropriate to the modelling of repairable systems (Ascher and Feingold, 1984). In defining a simple stochastic process, reference is made to a time dependent function for which the average rate of deterioration is random per unit time (van Noortwijk, 2009).

A maintenance policy introduced by Barlow & Hunter (1960) aims to maximize the expected uptime as a fraction of the expected total age. It follows the premise that preventive maintenance be done on a system after an optimal amount of operating hours regardless of the number of intervening failures, allowing for the optimal amount of operating hours to be possibly infinite (Barlow and Hunter, 1960). This was the first presentation of a minimal repair model where a system, which has experienced functional failure, will function again following a repair but with the same rate of occurrence of failures and effective age as at the time of failure.

Earlier maintenance models, based on failure time distributions, usually assumed that a system can be restored to "good as new" and thus implying a perfect repair - this is not always realistic.

In reality most repairable systems deteriorate due to the accumulation of wear or degeneration of repairs (Wang and Christer, 2000). In the case of such a simple repairable system, it would be a rational assumption that the times between failures would become shorter and the durations of repair would become longer until it cannot run nor be repaired.

Lam (1988) first considered these occurrences by presenting a geometric process repair model for two different replacement policies. The one policy is based on the age T of the system and the other on the number of expected failures N.

The cost rate of the two scenarios were determined explicitly to find that, under certain conditions, that replacing the system at the optimal number of failures $N*$ is better than replacing the system at the optimal operating age $T*$ (Wang and Christer, 2000). However, in many research works for repairable systems the assumption is made that the system is repaired as soon as it fails which is not always the case in practice (Zhang and Wang, 2016). Also, many of the research works pertaining to the replacement of assets subject to deterioration over time base the modelling on either the working age of the system or the number of expected failures.

But the working age of equipment is the total accumulated operational time. This can obviously be very difficult to determine if the system is regularly in an out of operation, which calls the relevance and accuracy of the time based replacement models into question.

Data driven approaches, attempting to derive models from CM and event data, fall into categories of machine learning and statistics based approaches (Si et al., 2011).

Fusion approaches are a combination of these two model types and covariate-based models in reliability is such an approach. Here degradation models use indicators of physical degradation as covariates in statistical modelling. Covariate models can only be applied where degradation can adequately be described by such parameters and plant items have observed degradation signals.

Approaches pertaining to machine learning make use of observed data and simple statistical techniques, for instance least squares, but do not have a probabilistic orientation and hence no statistical functions of the remaining useful life is available (Si et al., 2011). For risk analysis and maintenance decision making, these statistical functions are essential (Wang and Christer, 2000).

Due to the practical challenges pertaining to the existing compendium of statistic techniques applied in the reliability engineering sphere, fundamental knowledge of a system is required before valid and robust models can be applied to the system (Si et al., 2011).

These challenges can be summarized into three distinct groups namely: data sufficiency, data fusion and external variables. Data sufficiency refers to the incompleteness of the data, especially in systems undergoing commissioning, where no failure data and condition monitoring data exists. Data fusion addresses two distinct problems, in that multidimensional condition monitoring data must be dealt with, and that multiple failure modes are observed for a single component. Both these problems complicate modelling capabilities due to the fact that life estimation is made failure mode dependent. Finally, external variables such as temperature or velocity influences remaining life but is not necessarily accounted for in the model which may reduce the robustness of the estimation (Si et al., 2011).

2.5 Equipment Replacement

Various considerations can motivate an equipment replacement decision. These include physical deficiency, obsolescence or external economic factors. The physical deficiencies of equipment due to aging or damage should not be the main motivation for the replacement of equipment as it may have several years of serviceable life remaining but not be economical to operate. Replacement decisions should then always be based on the economic life of an asset rather than its physical condition. Life cycle costs (LCC) are summations of all cost estimates of equipment from installation to retirement determined analytically as an estimate of total costs incurred during their entire life (Barringer and Weber, 1996).

When dealing with the replacement of equipment, ultimately one has to determine the economic life. Operating equipment too long results in high failure rates and unnecessary loss in revenue and profit. Replacing equipment too soon may negatively influence immediate cash flow due to large capital cost and also reduce the total benefit of the installed equipment. Clearly then there exists an optimal time to replace equipment to minimize the total cost to the owner by considering both the value of O&M expenses and the cost of replacement.

Equipment replacement problems can be solved by using either probabilistic or deterministic methods. Deterministic are assumed to be non-random in terms of consequence. Here a series of failures have already occurred and the consequences can be determined retrospectively. Probabilistic problems are random in nature and calculations are done based on historic events in order to make predictions of consequences of future events. The use of these mathematical models can be used to ease the tension between maintenance and operations (Jardine and Tsang, 2013).

Barlow and Hunter (1960) describe a case of minimal repair where the rate of occurrence of failure remains undisturbed by any repairs. With a given cost of repair and cost of replacement, they introduce a replacement policy where the incumbent equipment is replaced with new identical equipment. With the assumption of instantaneous repair and replacement the authors show that for a strictly increasing rate of occurrence of failure, a unique optimal replacement age exists which minimizes the total long run cost per unit time. This is identical to classical replacement problems found in economics and operations research. In its most basic form the modelling of equipment replacement assumes a fixed cost for replacement and operating. Operating costs can consist of repairs cost, operations costs or other services not affecting the equipment aging (Sivazlian, 1973).

Capital equipment forms part of an organization’s core business and requires a significant outlay and planning to replace. Rather than operating weeks or months before replacement, capital equipment can operate for decades before replacement is contemplated. The time required for the manufacture of bespoke capital equipment can also extend over several years. From the contract placement to delivery of HP heaters can take up to 4 years. Over such long periods the time value of money must be considered by a discounted cash flow analysis (Campbell et al., 2011). A discounted cash flow analysis express historic and future costs in present value by discounting using a specified discount rate (Shamir and Howard, 1979).

It can be difficult to specify the discount rate in practice. If money is borrowed from an external source to fund replacement, the discount rate would be the interest rate paid on borrowed money. If the replacement is funded by sources internal to the business, then the discount rate is correlated to the interest rate gained from investments within the corporation. A survey conducted in the US regarding the way discount rates are calculated in companies found that “31% of firms used the rate of return on new investments, 26% used the weighted average of market yields on debt and equity securities, 18% used the cost of additional borrowing and 6% used the rate which keeps the market price of a common stock of the firm from falling” (Jardine and Tsang, 2013).

Representing the economic life of an asset by means of a cost function per unit time ensures tractability for several unique situations. However, in industry, expenditures are normally monitored by means of annual budgets where money is allocated for capital expenditures such as the replacement of equipment. When the optimal replacement time of equipment approaches it is prudent to validate such a result with a capital analysis. This capital analysis can support the decision to immediately replace equipment or continue to operate it for additional years. A replacement problem can be reanalyzed in future when lower costs or better performance emerges.

The adversarial relationship between the incumbent equipment and its replacement has given rise to the terms defender and challenger, respectively. If it is known that the operating and maintenance costs, or marginal costs, are increasing the defenders’ next year’s marginal cost is compared to the challenger’s minimum equivalent annual cost (EUAC). Initially the EUAC for new equipment is high but decreases to a minimum before increasing due to higher marginal cost (Newnan et al., 2009).

Quantifying the marginal costs for HP heaters can be troublesome as the monetary value of failure is concealed in the reduction of net plant efficiency. In conjunction to this, data for the main cause of HP heater downtime, tube failure, is only kept by plant owners and operators. Consequently the manufacturers of HP heaters cannot comment on the rate of occurrence of tube failures after their warranty expires. As a result the commonly accepted rate of occurrence of tube failures in HP heaters is exponential (Bell et al., 1991). This is contradicted in other sources where the estimation of remaining life is given by

$$RL = \frac{(PL - PT)}{GR}$$

Where RL=Remaining Life in months
PL=Number of plugged tubes before performance is affected
PT=Number of plugged tubes to date
GR=Growth rate of tube failures in number of failures per month
(EPRI, 2002)

In the formula above the rate of tube failures are bluntly assumed to be linear, contradicting common assumptions of exponential tube failure growth.

Regardless, the estimation of the rate of occurrence of failure of equipment is not an exact science. When referring specifically to feedwater heaters, the term failure can adopt different meanings among different utilities. Unlike electronic components which are replaced upon failure, feedwater heaters can be repaired. Naturally a breach of the shell would be considered a failure but the plugging of a single tube can be interpreted as proper maintenance (EPRI, 2003).

Replacement of feedwater heaters are seen as a last resort after all other options have been exhausted. It is generally accepted that a feedwater heater is approaching replacement when approximately 10% of tubes have been plugged as mentioned by EPRI (2003). With the replacement of an entire feedwater heater being an ambitious endeavor, variations of replacement exist. Replacement options include retubing, rebundling and complete replacement. During retubing, only the tubes are replaced whereas during rebundling the tube, tube sheets, support and baffle plates are replaced in an existing shell. A complete replacement includes a new shell and internals. Retubing is normally the lowest cost option but only suited for low pressure straight type heaters (EPRI, 2002).

Quantitative failure data is available for feedwater heaters and their components from generic industry databases but do not contain all component failures. Mostly functional failures rather than chronic failures related to degradation are included (EPRI, 2003). This is a questionable source of failure data for quantitative analysis considering that the primary focus of maintenance activities is the prevention of chronic failure.

2.6 Conclusion

HP feedwater failures are not extensively modelled by statistical techniques. Where statistical analysis is employed, inappropriate techniques are applied or dubious assumptions are made.

Feedwater heater failures are recorded but not used for inference and universal rates of occurrence of failures are assumed for all feedwater heaters. Consequently a generalised replacement recommendation at a plugging ratio of 10% is also applied to feedwater heaters by and large (EPRI, 2003).

3 Background

3.1 Introduction

Regenerative feedwater heating is applied widely by steam driven power plants around the world. This is accomplished by the use of feedwater heaters which improve the efficiency of the thermal cycle. Steam is extracted from various stages of the turbine and conveyed to the feedwater heaters. Condensed steam from the turbine exhaust is then pumped through the feedwater heaters where its temperature is increased by the bled steam (EPRI, 2002).

Disruptive changes in the electric industry requires Eskom to have a better understanding of the life cycle cost of feedwater heaters in order to make more informed replacement decisions.

3.2 HP Feedwater Heaters

Two classifications of feedwater heaters exist, namely direct contact and shell and tube heaters. Direct contact feedwater heaters bring feedwater in direct contact with heating steam without a tube wall interface. The result is a mixture of water and steam and this class of feedwater heater is commonly referred to as a deaerator. Shell and tube heaters are designed to heat feedwater passing through a tube bundle by steam on the shell side. Only shell and tube heaters will be considered in this study.

Feedwater always remains inside the tubes and steam always flows outside the tubes implying that no contact is made between the two fluids under normal operation. The feedwater flows into the shell via the inlet and is distributed, via the tubes, throughout the steam space and exits the shell through the outlet.

Three zones usually make up the heater internals:

The desuperheating zone is an enclosed portion at the outlet of the tube bundle and requires an impingement plate to prevent impact damage and corrosion to the tubes from superheated incoming steam (EPRI, 2010).

The condensing zone makes up the largest part of the internal area of the heater and is responsible for 90% of heat transfer.

The drains cooler is an enclosed section at the inlet of the tube bundle where tubes are subjected to potential flashing and erosion (EPRI, 2010).

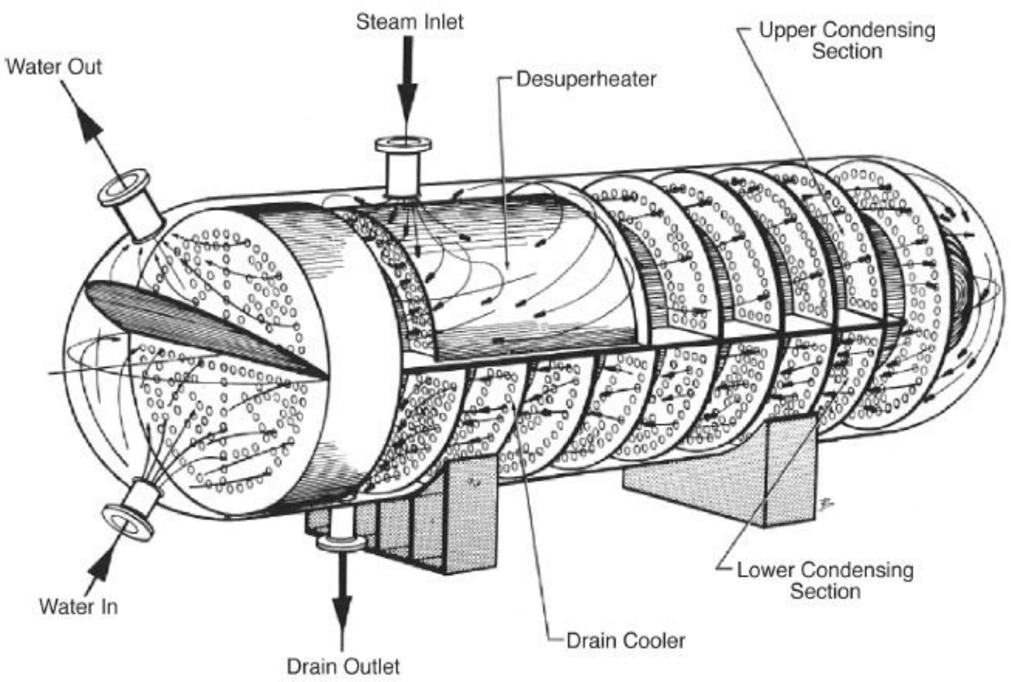


Figure 1 – Tubeplate type HP Feedwater Heater (EPRI, 2010)

Within the class of shell and tube feedwater heaters there can also be differentiated between tubesheet type (or channel type) and header type heaters. Tubesheet type heaters consist of a tubesheet which holds the straight or u-shaped tubes in a shell as in Figure 2.

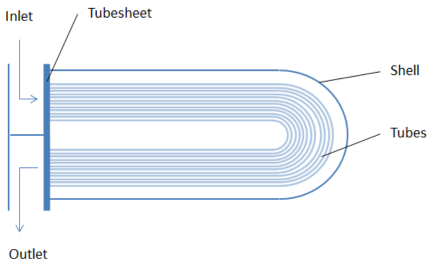


Figure 2 - Tubesheet type feedwater heater

This configuration is not commonly used in large capacity Eskom power plants where header type heaters are more common. Header type heaters present higher flexibility in terms of operating fluctuations mainly because of smaller material cross sections but does not allow for the application of non-destructive inspection techniques to determine tube wall thicknesses. Every main pressure retaining element of a header type heater is composed of tubular components with optimal stress configurations reducing the risk of failure during cycling conditions (EPRI, 1991).

Header type heaters' construction mimics boiler header applications where the feedwater inlet and outlet headers have tubes and nipples attached to each header as in Figure 3. This design has been used successfully in South Africa for many years. Header heaters are much larger, more expensive and more difficult to maintain than the tubesheet type heaters but have an advantage of being much more resilient under conditions of thermal cycling.

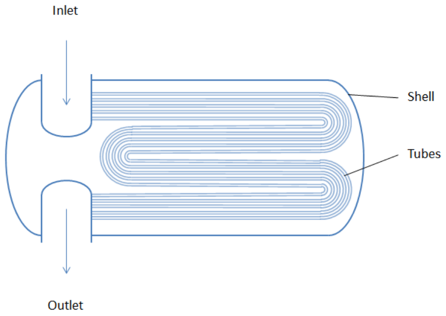


Figure 3 - Header type feedwater heater

In Eskom, fleet wide reporting is done on the controllable losses experienced by coal fired power stations. Costs are incurred when the plant operates outside of design parameters and the most prominent of these are displayed in Figure 4. Here it can be seen that final feedwater temperature loss is among the top four controllable losses in the Gx coal fleet.

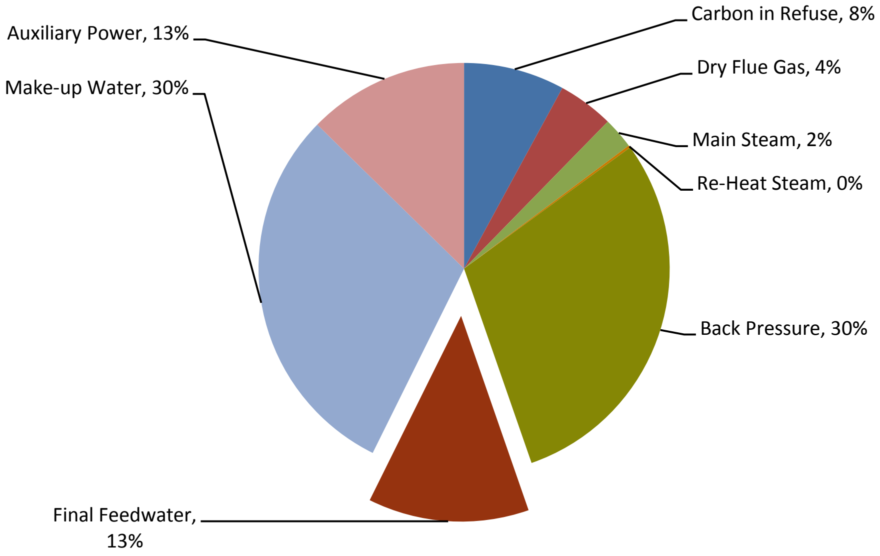


Figure 4 - Gx Controllable losses

In a detailed survey sponsored by EPRI, data was gathered through literature, visits to industry and a questionnaire distributed to utilities with fossil units over 500 MW. The major known causes of failure were tube vibration, flashing in the subcooler zone (caused by inadequate level control), tube inlet corrosion, steam impingement and difficulty in plugging tubes (EPRI, 1981). The results of the survey is summarised in Table 1.

Steam impingement refers to erosive damage on the shell side of tubes caused by water droplets in high velocity extraction steam.

Tube inlet erosion is the gradual deterioration of the tube from the inside at the feedwater inlet due to erosive turbulence.

Because the pressure inside the drains cooling zone is lower than outside the zone, steam flashing occurs when the correct liquid levels are not maintained during operation. This causes cavitation type erosion resulting in deformation and pitting of the tube surface and are one of the leading causes of feedwater heater tube failures.

Tube vibration is the inevitable result of putting steam and water into the shell side of a feedwater heater. When vibrations are sufficient enough it can cause failure due to fatigue or wear in tube supports.

The plugging of feedwater heater tubes is the most common and one of the most crucial reactive maintenance interventions but can reoccur due to inadequate procedures or improper weld preparations (EPRI, 2010).

Tube connection issues, foreign object impact and manufacturing defects are some of the miscellaneous failures reported in the survey. Only head or shell leaks and failure of other internal components (than tubes) were failures not resulting in tube failure (EPRI, 1981).

Problem Types:	**HP**	**LP**	**IP**
Steam impingement	21	25	6
Tube inlet erosion-corrosion	25	4	0
Level control and/or drains cooler zone problems	62	40	5
Tube vibration	17	9	15
Tube plugging	26	4	8
Tube corrosion	30	13	6
Inadequate tube-tubesheet weld or expansion	27	1	0
Foreign material impingement	1	2	0
Tube manufacturing defect	1	0	0
Head or shell leak	28	8	0
Failure of internal component (other than tube or impingement plate)	16	0	0

Table 1 - Summary of EPRI FWH failure survey

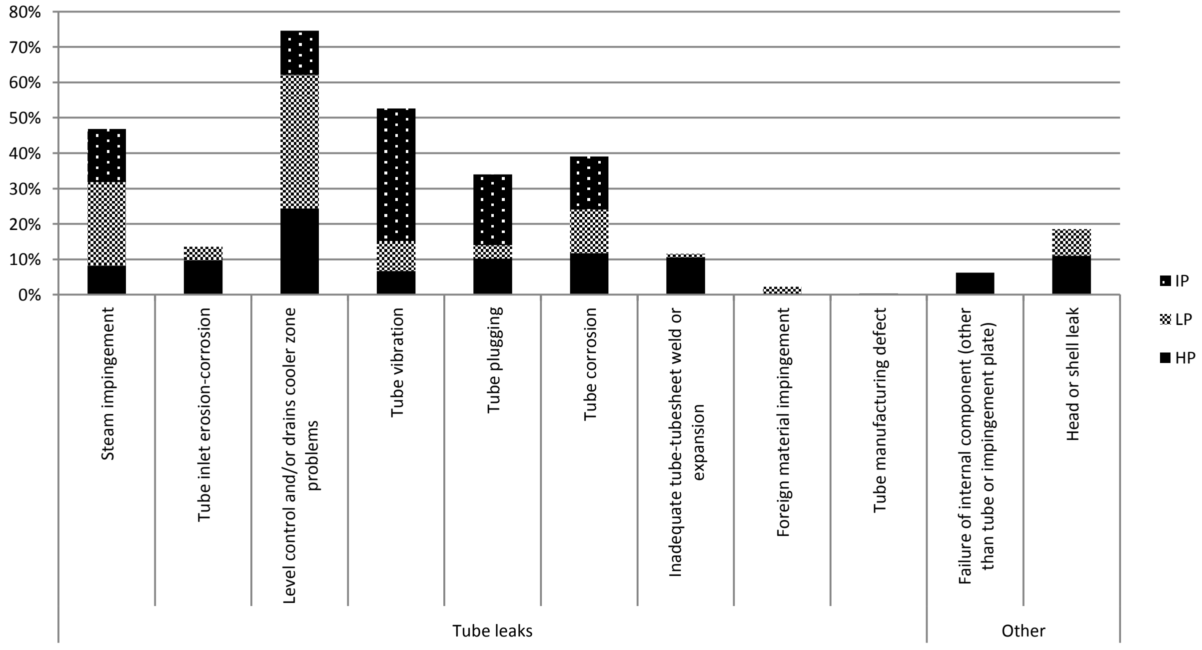


Figure 5 - Summary of EPRI FWH failure survey

In Figure 5 it is clear that FWH failures involving tube damage far exceeds the damage from other causes. This is confirmed by another survey (EPRI GS-7417) conducted jointly by the Edison Electric Institute and EPRI specifically for fossil power generation plants in the US and Europe. The results indicate that in the US and Europe, 78% and 88% of damage incidents are tube related, respectively (EPRI, 2003).

When only considering the results for HP heaters in Figure 5, 83% of failure causes are tube related and 17% from other causes. These other causes consist of 11% shell failures and 6% failure of internal components other than tubes or impingement plates.

Tube failures in a feedwater heater force power plant operators to take immediate action to prevent consequential damage to adjacent tubes and other areas of plant (Bell et al., 1991). Adjacent tubes can experience damage due to the cutting effect of the resulting water jet at full feedwater pressure escaping through the small area created by a crack or pinhole.

Each of these tube failures usually result in a complete bypass of the heater up until an opportune time for repair. This has significant implications for the utility in terms of primary energy cost as the reduction in final feedwater temperature reduces the steam cycle efficiency.

When there is an opportunity to isolate the heater completely from the steam cycle the leaking tubes are plugged, never to function again. The periodic plugging of tubes will thus progressively impact on effectiveness of the heaters. Tube failures within feedwater heaters occur without warning. Each heater contains hundreds of tubes in which there flows feedwater at velocities in excess of 2 m/s. These tubes are surrounded by steam which heats the feedwater to temperatures up to and over 200^{o}C. The wall thicknesses of these tubes are not monitored on a continuous basis in Eskom and it is therefore impossible to predict which tube will fail next.

Fast wall examinations by electromagnetic non-destructive techniques are sometimes used from inside the tubes to test and maintain the structural integrity of installed tubing (EPRI, 2001). These techniques can readily be applied to tube plate type heaters where the tube ends are easily accessible when the feedwater inlet/outlet is removed but this practice does not form part of the normal feedwater maintenance regime in Eskom.

3.3 Power Sector Challenges

Many of the 14 coal fired power stations currently in operation in Eskom are nearing the end of their design lives (Cohen, 2013). Consequently power station equipment must be monitored and assessed to determine the optimal replacement time, if replacement is feasible. The justification of capital expenses becomes increasingly difficult as the profit generated from the sale of electricity generated by thermal plants in South Africa deteriorates (Eskom, 2015). This may be occurring amid an energy sector transition which has already gained traction on a global scale. Various legislative and commercial commitments to support this transition are increasingly being adopted by most of the developed world and subsequently these cooperative policies has led to the installation of significant amounts of renewable generating capacity in the power sector in recent years. This has resulted in renewable energy attaining its position globally as the second-largest source of electricity, only behind coal (IEA, 2015).

Approximately 40 GW of thermal electricity generation plants have been decommissioned in western Europe before reaching the end of their lifetime (Willemot and Crooks, 2016).

In Germany, the mainstay of many power plant technologies used in South Africa, the levelised cost of electricity (LCOE) from alternative sources were assessed for parity against brown coal, hard coal and combined cycle gas turbines. Consolidating the costs to account for scale and technology the conclusion is that by 2030 even small rooftop solar photovoltaic (PV) systems will have a LCOE comparable to that of hard coal as seen in Figure 6. But by 2030, the average LCOE of any fossil fuel power generation will be higher than utility scale PV power plants in Southern Germany (ISE, 2013).

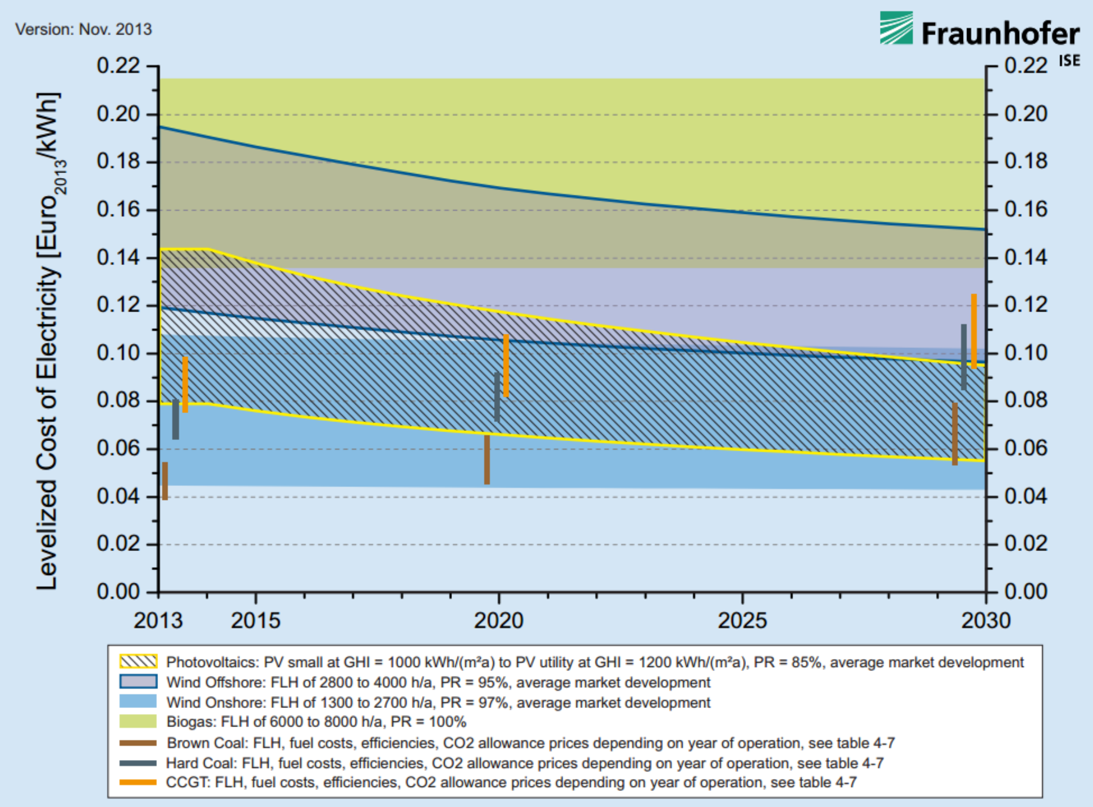


Figure 6 - Predicted LCOE of power generation technologies (ISE, 2013)

This raises concern regarding the fiscal sustainability of large electric utilities in South Africa and if they will be able to avoid a dreaded “death spiral”. In the period from the year 2000 to 2014 a total of approximately 63 GW of thermal (coal, fuel oil & nuclear) power generating capacity was decommissioned across the European Union (including the United Kingdom) (EWEA, 2015).

Electric utilities may face trying times in preserving their financial sustainability. Dormant revenues and increasing expenses are at the order of the day which depicts a potentially unpleasant future. Fortunately death-spiral threats seem to be more prevalent in competitive environments where high fixed costs and the absence of governmental protections are common place (Costello and Hemphill, 2014).

The economic viability is however not the only risk posed to the utility industry in the medium to long term. In South-Africa, the state owned utility Eskom provides approximately 95% of the country’s electricity demand with a total generation capacity in excess of 40GW. The majority of this electricity is generated from coal.

Eskom also owns and operates the national transmission and distribution networks. Thus the core business of electricity generation in Eskom is supported by the transmission and distribution divisions.

The national grid control center which dispatches electricity to different areas of the country and ensures that the electricity is of a required quality for customers, is also part of the Eskom business. National Grid control is the most crucial part of the distribution system and controls the inputs and outputs of the entire electricity grid.

With the advent of an increasing wave of renewable energy resource exploitation, the distribution of electricity also changes. Because the availability of renewable generation is intermittent and its variable cost very low, penetration levels of renewable energy is very high. This means that whenever renewable capacity is generating it should be dispatched, implying that national grid control requires added flexibility from other sources to maintain stability. This flexibility comes in the form of either cycling operation or 2-shifting.

Cycling operation refers to the range of operations in which a plant’s output changes and can include starting up and shutting down or ramping up and down or running at part-load. Operational flexibility can also come in the form of 2-shifting which refers to the sequence whereby a generating unit is started up and shut down more than once in a 24-hour period to meet various peaks in demand (Cochran et al., 2013).

Most coal fired power plants in South Africa were not designed for flexibility but rather to operate at full load for extended periods of time with minimal cold starts. Requirements of exceeding flexibility imposed on more mature power plants can have serious technical consequences which will hamper reliability if pre-emptive steps are not taken.

The increased number of cold starts over the lifetime of a power plant exacerbates the overarching impact of thermal fatigue, where large variations in temperature create fluctuating thermal stresses in various critical components on the plant. These stresses are not limited only to individual components but also to piping connections, especially where dissimilar metals conduct heat at different rates but are joined by the same weld.

The greatest impact of cycling operation in a power plant will typically be felt by the most crucial components, for instance the feedwater heaters. Excessive start up and shut down cycles also increases the risk of air ingress which promotes corrosion, one of the main causes of feedwater tube failure. Subsequently the damage caused by cycling operation will not manifest immediately but time between component failures may start to decrease together with availability. These intermittent equipment failures lead to increases in outage rates, increased operations & maintenance (O&M) costs and more extensive inspection and evaluation regimes (EPRI, 2001).

This implies that plant leaders will require continuously increasing amounts of decision support to prioritise the allocation of maintenance budgets. The impact of potential load cycling and reduced profits underscores the need for an improved understanding of the optimal replacement time of critical power plant components such as HP feedwater heaters.

3.4 Conclusion

From the construction of feedwater heaters it can be seen that the tubes are the most vulnerable components of the system. This notion is confirmed by results from multiple surveys indicating that the overwhelming majority of feedwater heater failures are tube related.

The power generating industry faces significant challenges which will require intensified focus on economic sustainability and financial prudence as consumers contemplate alternatives to utility scale coal fired power stations.

4 Research Strategy for Capital Replacement

4.1 Introduction

This chapter serves as an preparatory overview for chapters 5 to 8 by stipulating the manner in which the research objective will be achieved.

Strategies for capital replacement can take on various forms to satisfy the needs of the plant owner. In general, two possibilities exist which is either minimising downtime or minimising cost. For state owned utilities where the mandate is not necessarily to make profit but rather to stimulate the economy, therefore minimising downtime seems like the most probable option. However, utilities also operate equipment for extended periods of time which requires large amounts of resources such as coal, gas and oil. The efficient consumption of these primary energy resources adds to the financial sustainability of utilities. This implies that reducing the downtime of equipment in a power plant will improve the efficiency of primary energy consumption. Unfortunately the improvement in cycle efficiency does not directly translate into expendable income and is thus difficult to perceive as an incentive for replacement. Actual cost is less abstract than downtime or cycle efficiency and it is easier for plant leaders to relate cost with downside risk.

The approach used throughout this dissertation to develop a costing optimisation model is similar to quantifying risk. Risk is widely defined as a function of probability and consequence. Regenerative feedwater heaters are closed vessels and cannot be easily inspected. With hundreds of tubes inside every vessel it is impossible to predict which tube will fail next. Thus, probabilistic modelling is very much suited to the prediction of the number of expected tube failures, within a defined time window, due to their random nature of occurrence. Therefore the main deliverable of this research would be to develop a generalised industry ready methodology which will aid plant leaders in their replacement decisions for HP heaters taking into account plant integrity and cost effectiveness.

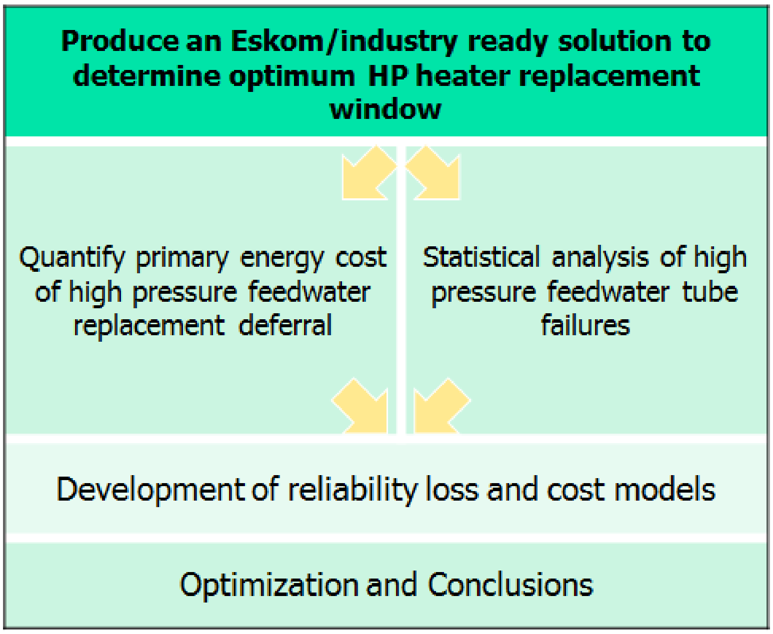


Figure 7 - Research Approach

Because it is important to collect data in an accurate but economical way, the main sources of data considered are sources which already exist within the Eskom business. The intention is to use failure data of a specific heater from installation to its current life to demonstrate the ability of the methodology[1].

4.2 Ethical considerations

Due to corporate constraints no names of power plants will be disclosed in this dissertation.

Microsoft® is a registered trademark of the Microsoft Corporation.

Steam Master 24.0 and Steam PRO 24 are simulation products supplied and developed by Thermoflow Inc.

This research is not sponsored or affiliated with either the Microsoft Corporation or Thermoflow Inc.

All software utilised to process data or generate results are licensed for use by Eskom SOC Ltd.

4.3 Content Stucture

Consistent with common practice in failure data analysis, trend testing is discussed and serves to initiate the analysis process. The results arising from trend tests are the foundation for determining which analysis technique to apply. Results are compared under synchronous and asynchronous

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[1] Applying the methodology to a single heater successfully must initiate stepwise fleetwide application to eventually form part of the formal capital replacement evaluation process for HP heaters.

sampling of the tube failure process affirming the use of different modelling techniques for different life stages.

Isolating HP heaters from the rest of a thermal plant and considering only the most prevalent failure mode focusses the analysis of failure data on a single heater as a unit. This disregards the interruptions in operations caused by external factors and only takes into account the failures of the heater itself and the statistical representation thereof. A Weibull failure distribution function is used to quantify the probability of the time to first failure (TTFF) for a group high pressure feedwater heaters in a coal fired South African power plant.

The tube failure process in HP feedwater heaters is clarified. Feedwater heater tubes often fail in groups due to the consequential damage of a feedwater leak. The effect of this is considered in the statistical analysis of the failure process and also on heater performance.

Feedwater heaters are expected to operate continuously in excess of 20 years and, following a tube leak, are repairable. However, even though the heater can be returned to service, the offending tube cannot. The tube is plugged permanently and thus reduces the heat transfer area inside the heater. The effect of this reduction in heat transfer area is explored. Imperfect repair does in this context not refer to the quality of the executed repair but rather to the reduced performance of the heater following the repair.

The interdependence of heater tube failures requires special consideration due to the fact that the failure of a single tube will cause the entire heater bank to be taken out of service. The non-homogeneous Poisson Process Power Law is thus applied to model the tube failure process.

Quantifying the uncertainty, characteristic to probabilistic modelling, is done by determining the goodness of fit for both IID data for TTFF’s of a group of heaters and point process data for a single heater modeled by the NHPP. The Weibull fit to IID data was tested using the Kolmogorov-Smirnoff goodness of fit test and the power law point process fit was tested using the Chi-square test. Confidence intervals were also produced for Weibull and NHPP models by applying non-parametric methods.

The consequence of heater tube failures is calculated by considering the primary energy cost consequential to HP heater downtime. Simulated net plant heat rates are compared for heaters in service and during down times following tube failures. Operational data is also consolidated to determine the expected downtime during tube failures only to subsequently determine the variable cost of failure incurred during heater downtime.

The replacement of feedwater heaters is not a common occurrence in Eskom and the estimation of replacement cost is done using a combination of segmenting and cost index models.

The matter to be addressed by the development of a costing optimisation model is the modelling of life cycle cost (LCC). Here the goal is to find the replacement age of equipment where the total cost per unit time is a minimum. Operating & Maintenance (O&M) cost increase over equipment life but specific replacement cost decreases. As the proposed replacement age of equipment increase their expected operational cost also increases per unit time whereas the replacement cost decreases per unit time. These two options, repair or replace, are compared in inflation free cost terms at fixed intervals of unit time in order to determine a minimum cost per unit time over the entire operational life of the heater.

An industry relevant case study is developed to determine the optimal replacement time for an HP heater at DPS power station. The case study is based on data supplied by the plant personnel with costs in actual current values.

4.4 Conclusion

The content of this dissertation is grouped into three distinct sections namely probability, consequence and risk.

In the probability portion, chapter 5 addresses a sequential approach to the analysis of failure data both through the application of renewal theory and repairable systems reliability. This entails the use of Weibull analysis and stochastic point process techniques respectively. Goodness-of-Fit tests and confidence intervals are also discussed briefly for the quantification of probabilistic uncertainty inherent in stochastic techniques.

Chapter 6, the portion concerning consequence, addresses the cost implication of tube failures in feedwater heaters. This includes a short overview of the role of HP heaters in the context of power generation. Consequently a discussion follows of the cost of failure, imperfect repair and replacement.

Throughout chapter 7, pertaining risk, the combination of probability and consequence is discussed and a model is constructed to project life cycle cost per unit time.

Finally, in chapter 8, a practical case study is performed to compare the calculated optimal replacement time of a high pressure feedwater heater at a South African power plant with the actual replacement time. Here a function to minimize the exposure of equipment to financial risk at defined fixed increments of calendar time is developed. The integration of the modelling workbook into the existing online work sharing system of Eskom is also briefly explained.

This content summary can also be represented visually by a structured functional breakdown to ease the interpretation of the logic.

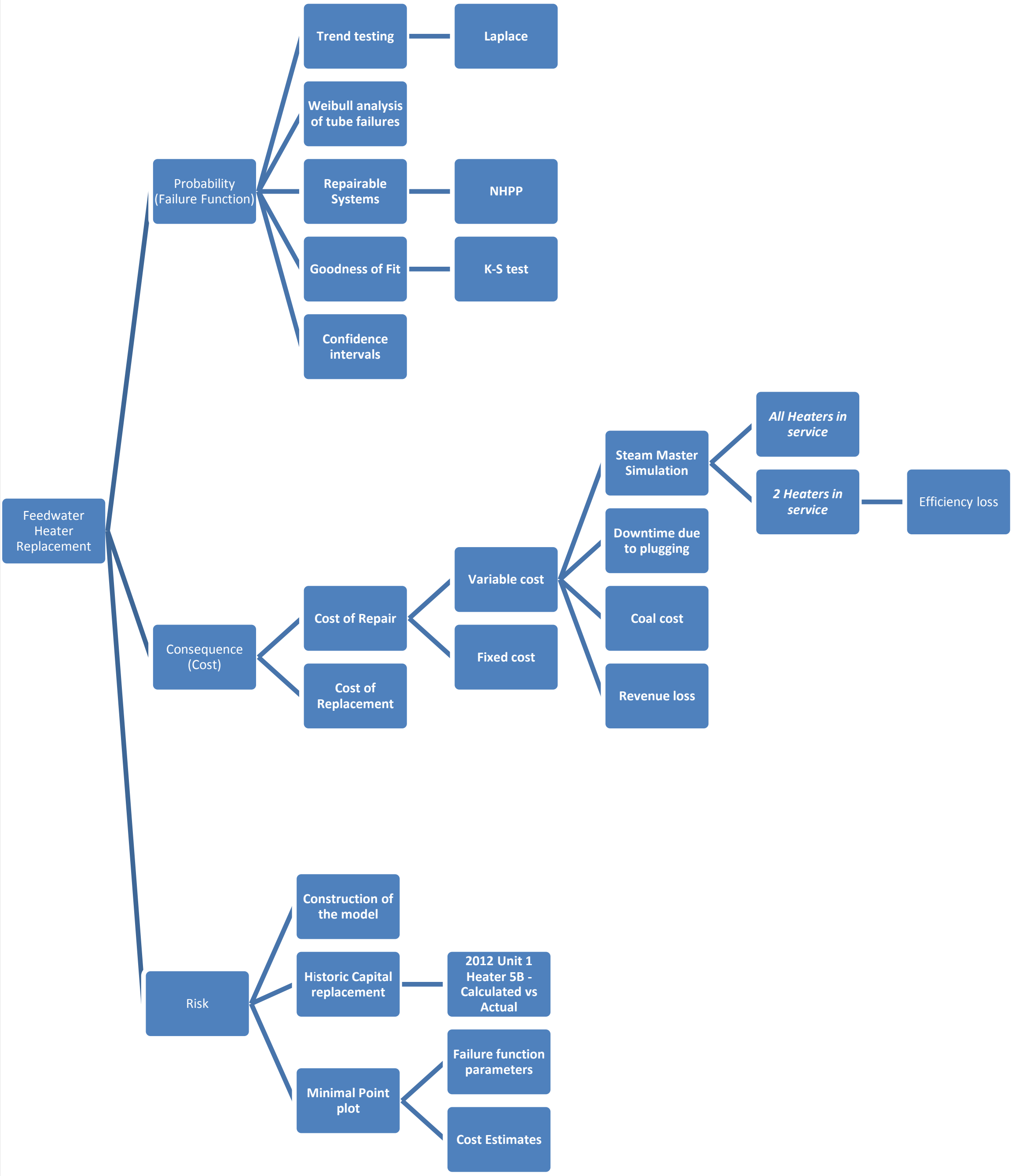


Figure 8 - Content Structure

5 Probability of Heater Tube failures

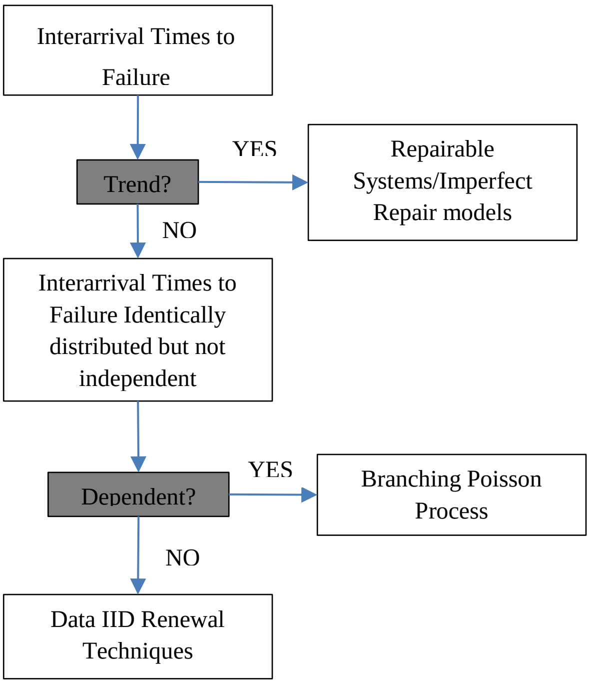
5.1 Introduction

Maintenance actions consist broadly of corrective and preventive strategies which both aim to keep equipment in a functional state. Corrective maintenance actions aims to restore equipment from a non-available state of operation to an functional state of operation following failure, and preventive maintenance aims to avert breakdowns through early interventions (Pintelon et al., 2000). The amount of corrective maintenance to be done to equipment is determined by its reliability. The aim of these probabilistic calculations is to quantify the uncertainty of randomly occurring failures by using the knowledge gained from historic events. In this way history is utilized to construct the optimal maintenance or replacement strategy for equipment which experience failure. Pure reliability calculations only use statistical data as basis and must be used with circumspection in maintenance. Commonly applied statistical methods have the luxury of a multitude of data and narrow distributions where the focus is on the majority of the population. In maintenance reliability studies it is necessary to augment the use of statistical analysis by considering external factors to produce acceptable results.

For electric utilities the modelling of the rate of occurrence of failure (ROCOF) of systems is becoming more important as equipment reaches the end of their design life and the mean time between failures (MTBF) begins to decrease. After the end of a component’s design life, the MTBF usually reduces and the interval between failures is shortened. If the rate at which failures increase is known, the probability of the next failure within a known period can be inferred.

According to the Eskom Feedheating Healthcare Standard, all tube failures occurring in feedwater heaters must be recorded and kept in an In-service Maintenance Data book of which 3 copies should exist for various stakeholders. Tube failures must also form part of a Statutory Vessel Inspection Data Book. Unfortunately, the data is traditionally not subjected to any sort of statistical failure modelling which presents an opportunity for improved periodic maintenance and replacement planning.

Ascher and Feingold (1984) suggests a specific order in which the successive interarrival times of failure of a single system should be analysed and a more generalised version of this process is also adopted by Coetzee (1997). The method is represented schematically in Figure 9 and describes a road map to the selection of the most appropriate analysis method to represent the failure data without explanatory variables (Vlok and Fourie, 2010).



(Coetzee, 1997b)

Figure 9 - Failure data analysis process

5.2 Trend testing

Failure data consisting of successive interarrival times for a single system like an HP heater should firstly be tested for a trend before any statistical analysis. If these successive $X_i's, i = 1,2,...,m,$ exhibit a trend, the rate of occurrence of interarrival times to failure changes during the operating life and these interarrival times can then not be described by the same statistical distribution. It is therefore meaningless to investigate a non-existent common distribution of interarrival times before trend testing. Testing for a trend in the failure data determines how to proceed with the statistical analysis of the data.

Renewal analysis in general and more specifically Weibull analysis involves fitting a statistical distribution to a set of failure data, assuming that the process causing the failures is stable and that the failures are independent of each other (Jardine and Tsang, 2013). Attempting to construct a function to describe the probability of failure using renewal techniques while there does indeed exist a trend in the failure sequence is inappropriate as the statistical distribution may vary between failures. To eliminate the possibility of varying distributions between failures, the existence of a trend within the consecutive failure times must be disproven.

The Laplace variate is a simple measure of the existence of a trend within a data set and is an adequate test for trends in many failure analysis situations. The Laplace variate U is given by equation 5-1 (Coetzee, 1997a)

$$U = \frac{\frac{1}{n-1}\sum_{i=1}^{n-1} T_i - \frac{T_n}{2}}{T_n\sqrt{\left[\frac{1}{12(n-1)}\right]}} \qquad \textbf{5-1}$$

Here the term T_i represents the time of the *i*th failure and *i*=1, 2… *n*, where *n* is the total number of failure instances and T_n the time to the *n*th failure. If *U* is significantly small (large) then the failures cannot be described by a common distribution due to the indication of reliability growth (deterioration). Hence if *U* is close enough to zero, the failures are identically distributed and may be described by a common distribution such as Weibull. But how close is close enough? If failure times are independently distributed then *U* is normally distributed with mean μ=0 and standard deviation σ=1 (Jardine and Tsang, 2013). If evaluated at a 5% significance level, α, then U_{crit} will be the value of the standard normal variate, *z*, if the value of the standardized normally distributed probability $\Phi(z)$ is equal to 0.025. Thus if *U* falls within the interval (-1.96, 1.96) one can only assume with 11.6% confidence that the failures are identically distributed. As this interval shrinks to zero the probability of identically distributed failures improves.

The Laplace statistic is able to provide evidence of the assumption of an Homogeneous Poisson process (HPP) (Calabria and Pulcini, 2000) for parts and has also been shown by Cox & Lewis (1966) to be optimum for the Non Homogeneous Poisson process (NHPP) model $\rho_1(t) = e^{\alpha_0+\alpha_1 t}$ (Ascher and Feingold, 1984) which will be discussed in section 5.4.

From Figure 9 it can be seen that if no trend exists, it can only be assumed that the times between failures are identically distributed but not necessarily independent. Cox & Lewis (1966) have found that testing for dependence of failure times can only be performed with certainty with roughly 30 or more observations (Vlok and Fourie, 2010). Even though more than 30 tubes can be expected to be plugged during the life of the heater, this is likely to occur long before 30 observations of failure due to the simultaneous failure of several tubes during a failure cycle. Nonetheless, data independence is normally assumed in practice (Coetzee, 1997a).

For some contextual background it is important to understand the objective of the study, which is the optimal the replacement of HP heaters, considering the correct application of probabilistic modelling of repairable systems. The conclusion of a study for the optimal replacement of capital equipment (HP heaters) entails the consideration of various probabilistic elements in order to emulate reality. Trend testing is only a hint as to which direction to explore in order to find a body of techniques which should then also be applied with the proper discretion. Thus the origin of the data under question must be considered together with the outcome of the trend test. To illustrate this point, it is fitting to consider synchronous and asynchronous sampling. Synchronous sampling occurs where the observations are started by the occurrence of a specific event (Ascher and Feingold, 1984). Asynchronous sampling occurs where observation begins without any knowledge of prior events (Ascher and Feingold, 1984). If we consider a typical dataset where the tube failure interarrival times are given by:

117, 170, 98, 280, 91, 77, 319, 132, 9, 18, 290, 82, 378

These are the interarrival times to tube failures of an HP heater from the second tube failure onwards, that is $t_2, t_3 ..... t_{14}$. Under this asynchronous sampling, the Laplace variate is calculated as -0.48, which falls between $-\sigma$ and σ and thus yields a 71.1% probability of being identically distributed as read from a standardized normal distribution tables.

However, when considering the failure data

7004, 117, 170, 98, 280, 91, 77, 319, 132, 9, 18, 290, 82, 378

from the same HP heater but including t_1, under synchronous sampling the Laplace variate is 4.6 and has less than 0.00002% probability of being identically distributed.

From these results it can be seen that even though a series of tube failures may be described by the same distribution, the time to the initial failure is from a different failure dispensation. This implies that even though tube failure data can be subjected to trend testing to determine the avenue to be explored to commence analysis, an underlying understanding of the failure dispensations must also be applied. Thus, if there are only a relatively small number of failures, as with HP heaters, the choice of time origin has a significant effect (Ascher and Feingold, 1984).

5.3 Unit Analysis

Because the tubes inside a feedwater heater are subjected to similar conditions, one would expect the majority of tubes in a heater to fail at similar operating times. A small number of tubes will fail earlier than their peers and a small number of tubes will fail later than their peers. Even though tubes are manufactured to the same nominal specification, there always remains some random variation in their wear rates (Crowder and Lawless, 2007).

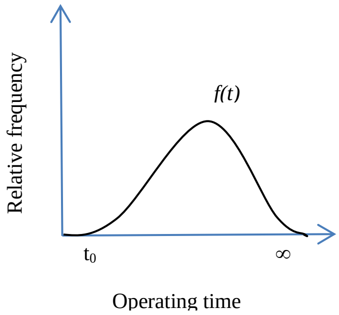


Figure 10 - Probability Density Function

Consequently, individual, time dependent failures of similar components should occur at similar time intervals. The distribution of these failures is given by a *probability density function (PDF)* (see Figure 10), $f(t)$ which describes the relative frequency of failures at a specified operating time.

The area underneath the PDF curve is the probability of a failure occurring between t_0 and ∞, and is given by $\int_{t_0}^{\infty} f(t)dt = 1$ (Jardine and Tsang, 2013)

The trend of failures and repairs may differ significantly for different designs and manufacturers. Therefore the tube failure data should be analyzed statistically to determine the reliability.

Reliability given by $R(t)$ is the probability that a component will still function at an age t. Cumulative probability of failure is given by $F(t)$ and is the distribution of probability of failure before or at time t for a part. Initially, the probability of failure would be low for a new component and would increase over time whereas the probability of survival would initially be high and deteriorate over time. The sum of $R(t)$ and $F(t)$ at the same time t is 1 and the two functions are defined as

$$R(t) = \int_{t}^{\infty} f(t)dt,\ 0 \le R(t) \le 1$$

$$F(t) = \int_{t_0}^{t} f(t)dt,\ 0 \le F(t) \le 1$$

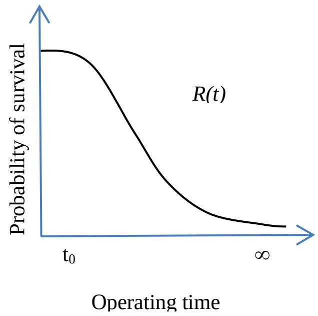


Figure 11 - Survival function

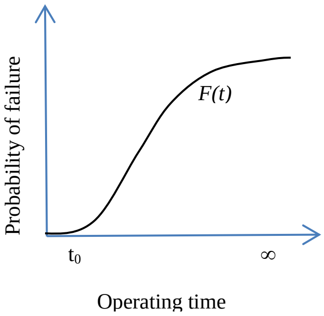


Figure 12 - Cumulative distribution function

From the parameters $f(t)$, $R(t)$ and $F(t)$ we find

$$h(t) = \frac{f(t)}{R(t)} = \frac{f(t)}{1 - R(t)} \qquad \textbf{5-2}$$

The *hazard rate* function $h(t)$ is the conditional probability of failure at time t. This is the probability of failure at time t given that it survived up to time t.

Even though lifetime distributions in general and hazard rate functions specifically are very useful to interpret failure phenomena, they cannot be physically observed or measured for a particular component but are derived from measurable data.

The four functions $f(t)$, $F(t)$, $R(t)$ and $h(t)$ are used to represent as accurately as possible the reliability behavior of the component. Due to the acceleration of the rate at which tube failures occur towards the end of the tube design lives, the rate of tube plugging also increases. As tubes are plugged the effective area of heat exchange decreases and consequently the flow increases. This supposedly accelerates the rate of degradation of the tubes. The result of this is an exponential increase in the rate of tube failures (Bell et al., 1991).

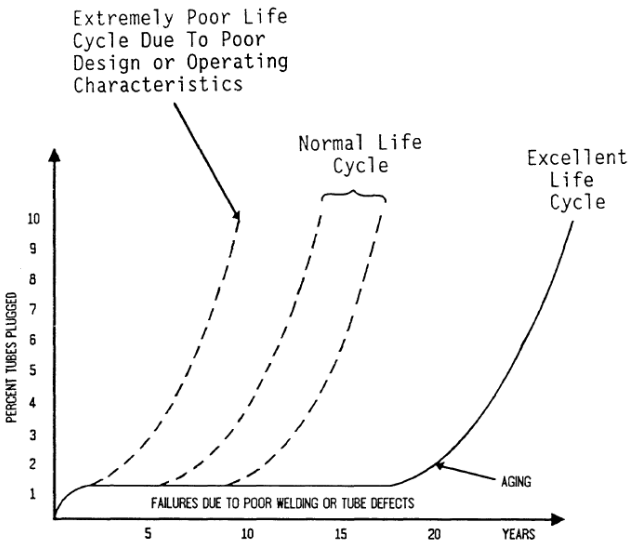


Figure 13 - Steel tube HP heater tube failure curves (Bell et al., 1991)

5.3.1 Renewal Techniques

It is important at this stage to distinguish between the analyses of failures of parts as opposed to the analyses of failures in systems. A part can be considered an item which is not repairable and is discarded at first failure, and a system being a collection of one or more parts, interconnected to perform a specific function (Ascher and Feingold, 1984). In the case of feedwater heaters the individual tubes are considered parts but the entire heater is considered a system. During the greatest part of the life of the heater, the rate of occurrence of failures remains constant – this changes at some significant age where most of the tubes start to experience failures in a successive fashion.

This presumed presence of a trend in the plugging rate necessitates the use of repairable systems theory. Based mainly on the application of stochastic point processes, such as the Non-Homogeneous Poisson Process (NHPP), these techniques are more suited to systems where the sequence of failures remain an important indicator of the mode which causes said failures to occur. Thus the default use of renewal theory to a sequence of tube failures would be incorrectly applied as there is a clear trend in the rate at which failures occur over the total life of the heater. Generally it is also more appropriate to base a model on failure mechanisms within engineering equipment and their operating environments, thus representing deterioration in terms of a time dependent stochastic process (van Noortwijk, 2009).

However, if it is assumed that a power station operates a known number of p nominally identical HP heaters under nominally identical conditions so that the time to the first tube failure of a HP heater is not affected by the failure of the first tube of another HP heater, the time to the first tube failure of p HP heaters are independent samples of the same distribution $F(t)$ (Ascher and Feingold, 1984). Essentially, the times to first failure (TTFF) of HP heaters are independent and identically distributed

(IID). By estimating the distribution function $F(t)$ we are essentially estimating the probability of the occurrence of the first failure by time t (Ascher and Feingold, 1984).

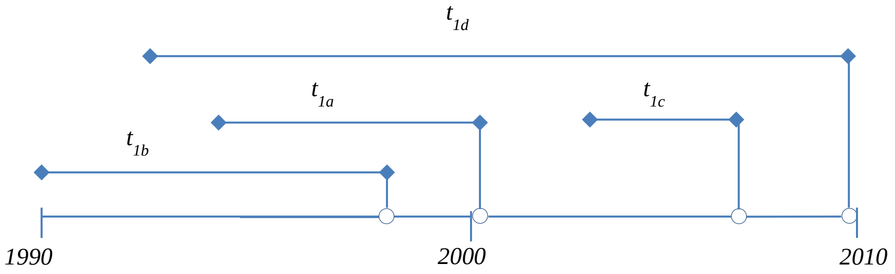


Figure 14 - IID times to first failure of HP heaters

In all cases observed the tube failure data following the TTFF of HP heaters follow a trend, however, this trend only follows after a prolonged period of failure free operation (i.e. after the TTFF). Thus the TTFF's of these heaters can be represented by a common distribution function $F(t)$ due to the IID nature of TTFF's. Figure 14 represents the typical random nature of time to first failures of parts from a common distribution function and is completely appropriate for HP heaters.

Weibull distribution

The Weibull distribution function was developed specifically for the modelling of failures (Coetzee, 1997a). It may be used to model both increasing, constant and decreasing hazard rates and is therefore one of the most useful probability distributions to characterize failure data (Ebeling, 2010).

When considering the TTFF's of a sample of 12 HP heaters in Table 2 through Weibull analysis the parameters of the distribution are $\beta_d = 2.66$ and $\eta_d = 6787$ calendar days. From this, one can expect the characteristic TTFF of 63.2% of similar HP heaters to before or at the characteristic life η_d =6787 calendar days.

The expected TTFF of the sample is given by the arithmetic mean μ as determined in equation 5-3 where Γ represents the Gamma function.

$$\begin{aligned}\mu &= \eta\Gamma\left(1+\frac{1}{\beta}\right)+\gamma \\ &= 6787\,\Gamma(1.376)+0 \\ &= 6787(0.8885) \\ &= 6030\ days\end{aligned} \quad \text{5-3}$$

This renewal technique is applied to the TTFF's only due to the fact that the arrival times of the first failure for HP heaters is not at all distributed identically to that of the following interarrival times as discussed in section 5.2.

In Table 2 the TTFF data is presented for a group of HP heaters of identical design and manufacturer, all operating under similar conditions but installed at different calendar times.

Subjected to a Laplace trend test as described in section 5.2, the Laplace variate is calculated as -0.13, and thus yields a 79.1% probability of being identically distributed as read from a standardized normal distribution tables.

Install date	Heater	Time to First Failure	Total Time to First Failure
Oct-83	U1B	7004	7004
Nov-83	U2A	2061	9065
Nov-83	U2B	5624	14689
Jan-84	U4A	9118	23807
Jan-84	U5A	8245	32052
Jan-84	U6A	4862	36914
Jan-84	U4B	5780	42694
Jan-84	U5B	2298	44992
Jan-84	U6B	5249	50241
Feb-84	U1A	7896	58137
May-84	U3A	10336	68473
May-84	U3B	3785	72258

Table 2 - HP heaters TTFF's

Apart from the Weibull distribution's exceptional statistical tractability and prevalence, its relevance will become more clear in section 5.4 where the application of repairable systems theory is presented. Two versions of the Non Homogeneous Poisson Process (NHPP) is explored and one in particular enjoys specific attention.

The Power Law process is a unique stochastic point process which is often also referred to as the "Weibull Process". This is based on the fact that the peril rate of the Power Law process is of the same functional form as the hazard rate of the Weibull distribution. The results of this relationship is that the arrival of the time to first failure (TTFF) under the Power Law process is Weibull distributed (Ascher and Feingold, 1984).

5.3.2 Grouped failure data

When abundant failure data is available, the data can be grouped into separate classes to ease processing (Jardine and Tsang, 2013).

Jardine & Tsang (2013) proposes an analysis of grouped failure data with multiple suspensions by estimating the hazard rate $h(t)$ at the center of each unit time interval. Even though the nature of tube failures tend to cause the failure of HP heater tubes in groups, the size of these groups have been found to be random in the failure data (making a strong case for independence) with no observable trend.

Considering that the independence of failure increments are determined by their influence on one another, the randomness of the number of failed tubes following a failure may be a strong indication of independence. Considering also, that the failure of a tube causes consequential damage to neighboring tubes, there is a strong case for dependence of the failures within these groups.

Despite the strong case for the grouping of data one must consider the causes of failure within each group. The failure of an entire group may be caused by the failure of only one in close proximity of the others.

Due to the high variable cost of a failure cycle, mainly driven by primary fuel cost, the consequential failure of adjacent tubes is not the primary focus. The failure of a single tube will cause a heater to be taken out of service and thus the rate of occurrence of failure of tube failures is the main concern.

However, the random nature of consequential tube failures, caused by the initial failure, presents a strong case for IID data and means that the expected number of failures in each failure cycle can also be described by a common distribution function.

In Table 3 the failure data is presented for a single HP heater of which the number of tubes plugged per failure cycle is tabulated according to calendar time.

Also subjected to a Laplace trend test, the Laplace variate is calculated as -0.35, and thus yields a 75% probability of being identically distributed as read from a standardized normal distribution tables. This implies that the sizes of these groups are uniformly distributed and every failure cycle is expected to affect the rate of tube failures equally.

Date	Number of Tubes Plugged	Total Number of Tubes Plugged
12/2002	4	4
04/2003	1	5
09/2003	3	8
12/2003	4	12
09/2004	3	15
12/2004	4	19
03/2005	4	23
01/2006	2	25
06/2006	3	28
06/2006	2	30
07/2006	3	33
04/2007	2	35
07/2007	4	39
07/2008	6	45

Table 3 - Number of tubes failed per failure cycle for an HP heater

The histogram in Figure 15 represents the relative frequency (proportion) of failed tubes per failure cycle for a sample of 23 HP heaters. Even though this is only an approximation of the probability density function for the population of tube failures, the data is displayed in such a way as to deduct important facts about the underlying probabilities. Because of the discrete nature of the variables it can easily be seen from the histogram that the cumulative probability of more than 4 tubes failing per failure cycle in an HP heater is less than 10%.

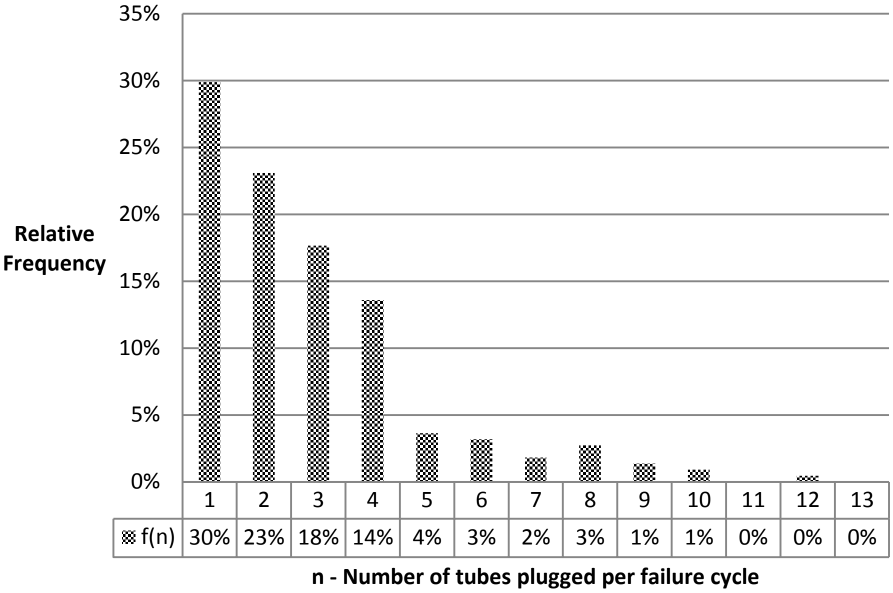


Figure 15 - Number of failed tubes per failure cycle

5.4 Repairable systems

Early maintenance models based on failure time distributions usually assumed that a system can be restored to “as good as new”, and thus implying a perfect repair but this is not always realistic. In reality most repairable systems deteriorate due to the accumulation of wear or degeneration of repairs (Wang and Christer, 2000).

In Figure 16 the successive tube plugging events of a single heater is represented schematically. This is asuming (1) that the system is operated whenever possible and (2) that repair times are negligible. If the heater is sometimes taken out of service and such downtimes are accounted for, the direct connection to calender time immediately disappears but the successive plugging events still remain calender time ordered. It should be noted that the major difference between the times to failure of parts and the times between successive failures of systems is that system failures occur in a specific sequence called a stochastic point process. In the application of failure analysis, a point process is a mathematical model for a physical phenomenon characterized by failures distributed randomly in time (Ascher and Feingold, 1984).

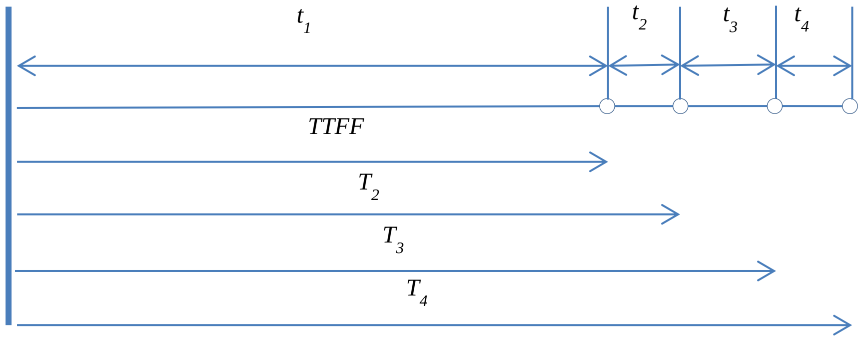


Figure 16 - Failure process of HP heater tubes

The modelling of failures of repairable systems relies heavily on the application of the Non-Homogeneous Poisson process (NHPP) which is a generalisation of the Homogeneous Poisson Process (HPP) stochastic point process model. Some functions describing this process have gained general acceptance and one of them, the Power Law, features prominently in point process applications. Another, much less prominent, model developed by Cox & Lewis in 1966, describes the peril rate ρ_1 as a function of two constant parameters α_0 and α_1 in the form

$$\rho_1(T) = e^{\alpha_0 + \alpha_1 T} , \qquad \textbf{5-4}$$

(Ascher and Feingold, 1984)

where T is the cumulative time to failure.

The Power Law function describes the failure intensity ρ_2 as a function of two constant parameters β and λ in the form

$$\rho_2(T) = \lambda \beta T^{\beta - 1}, \qquad \textbf{5-5}$$

(Coetzee, 1997a)

where T is the cumulative time to failure.

In examining the theoretical foundation of repairable systems analysis techniques, Coetzee(1997b) developed these two formats of the NHPP model for practical use by maintenance analysts. In both these cases the expected number of failures over the interval (0,t] will be given by

$$\int_0^t \rho(T) dT = E[N(t)] \qquad \textbf{5-6}$$

There is thus a very basic distinction between the probabilistic modelling of parts and systems. In the specific case of HP heaters, the time to the first failure t_1 can be described by a common distribution function $F(t)$ whereas the times between successive failures $t_2,....,t_i$ are modeled by a sequence of distribution functions called a point process (Ascher and Feingold, 1984). These ideas become evident when one considers the application of each of the results of the functions derived from models for parts and for systems.

The common distribution $F(t)$ of random failure times of independent parts describes the probability of first and only failure of a similar part at time t. $F(t)$ is based on the times to first failure of a known number of identical but independent parts. These parts have already failed at different points in the past but act as a guide to the expected life of a part which has not yet failed.

However the number of expected failures at time t for a specific system is described by the point process, $E[N(t)]$. $E[N(t)]$ is based on a specific sequence of failures from that system which occurred before t.

Using the series $t_2, t_3, ...t_{14}$ of failure times from section 5.2 the parameters for the ρ_2 intensity function was determined to be $\beta = 1.085$ and $\lambda = 0.0036$ resulting in a near linear trend line for the expected number of failures following the TTFF in Figure 17. Also note that the cumulative probability of TTFF as determined in section 5.3.1 is also plotted but discontinuous to the expected number of failures, $E(N(t))$, of the Power Law intensity function ρ_2.

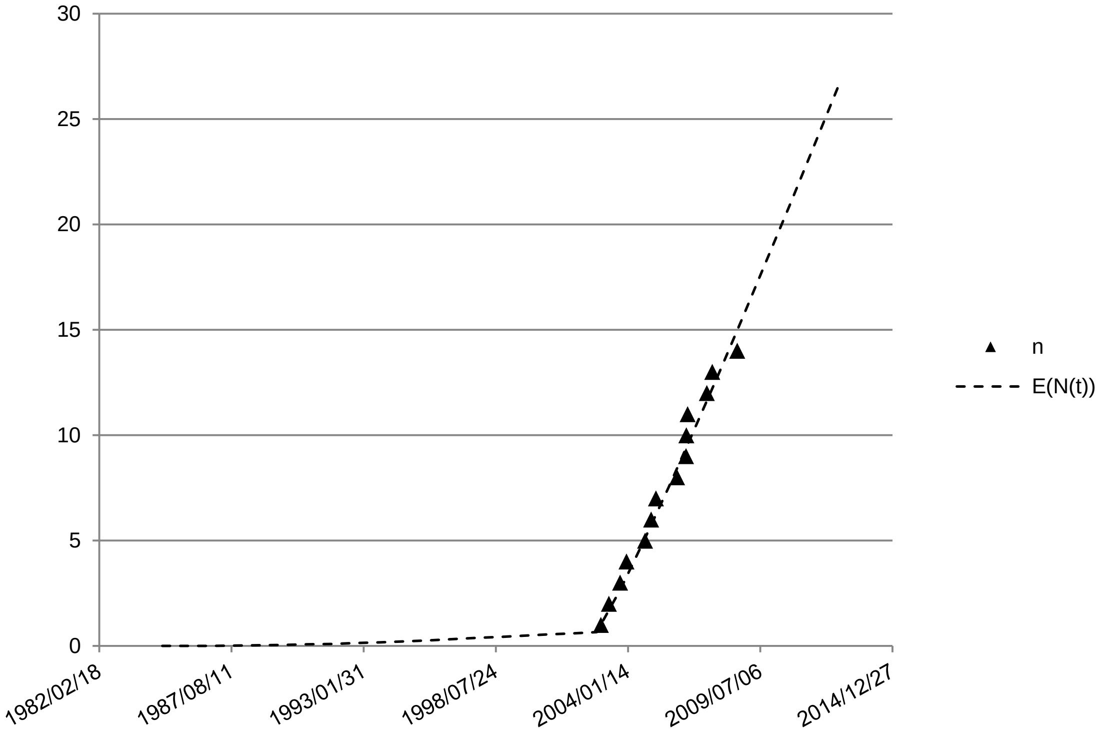


Figure 17 - Expected number of tube failures E(N*(t)*)

5.4.1 Imperfect repair

It is known that the failure process not only depends on the mechanisms of failure within a system but also the quality of repair. As discussed in paragraph 5.3, after a tube failure occurs the affected tubes are plugged which implies that the ability of the heater to increase feedwater temperature will be worse than like-new.

Because the failed tubes are plugged, preventing any heat exchange, the effective heat transfer area of the heater is diminished marginally. The additional operating cost incurred for reduced outlet temperature due to tube plugging is significant but generally much less than the cost impact of having the heater out of service (Linley, 1987).

This concept of *imperfect maintenance* is important to consider because the effective feedwater heating following a repair will be adversely affected. Imperfect repair in this instance refers to the reduced capability of the heater following a repair rather than the quality of the execution of the repair. Thus it cannot be assumed that when tube leaks are repaired, the heater is returned to a "as good as new" condition as described in section 5.3.1 but rather to a "bad as old" condition (Ascher and Feingold, 1984). It should be noted that the execution of a repair leaves the rate of occurrence of failure of the heater undisturbed and would thus be classified as minimal repair (Barlow and Hunter, 1960).

If one consider that a random number of tubes, n_i, fail at a random time, t_i, where $i = 1,2,...k$ represents the expected number of failure cycles at any given time $t_k > t_i$, a heater will operate from t_i to a later time t_k with a reduced number of tubes equal to $\sum_{i=1}^{k} n_i$. The number of tubes plugged inside a heater reduces the effective heat transfer surface and consequently reduces the efficiency of the heat exchanger. To illustrate, consider the following expression in equation 5-7 for the total heat transfer rate, Q, between two fluids with temperature differential, ΔT_w, separated by a (tube) wall with heat transfer coefficient, h (Kakaç, 1999):

$$Q = hA\Delta T_w \tag{5-7}$$

The heat exchanger performance will increase if the term, hA, is increased (Kakaç, 1999). Due to the plugging of tubes, the heat transfer area, A, is reduced over the life of the heater. This implies that each tube failure cycle will reduce the performance of the heater marginally and will force said heater to operate at a reduced efficiency up until the end of its life.

However, the heat transfer coefficient h is not only a function of the tube material, but also of the flow velocity inside the HP heater tubes. As the tubes are periodically plugged, due to failure, the flow velocity inside the tubes increase. The increase in velocity improves the heat transfer between the steam outside the tubes and the feedwater inside the tubes and consequently compensates for the reduction in surface area. This phenomenon occurs to such an extent that the reduction in heater performance is not significantly affected by tube plugging, at least not initially.

Referring to Figure 19 it is important to consider that it is not within the scope of this study to prove or disprove these results but they are merely used as an indication of the reduction in heater performance due to tube plugging.

The suppressed feedwater outlet temperature can be approximated by the intersection of two equations each arranged to simultaneously compute the Logarithmic Mean Temperature Difference for the condensing zone as shown in Figure 18 (Linley, 1987).

After deducting the temperature rise in the subcooler Curve A and Curve B is plotted to find an intercept for a specified plugging ratio.

Curve A

$$\begin{aligned} LMTD &= \left(\frac{q_f \times C_p}{h \times A_p}\right) \\ Q &= q_f \times \Delta t \times C_p \\ Q &= A \times h \times LMTD \end{aligned} \tag{5-8}$$

Where

Q = Duty [W]

q_f = Feedwater flow [kg/s]

h = Rate [W/m^2-K]

A_p = Heat Transfer Area after plugging [m^2]

Δt = Feedwater temperature rise [K]

C_p = Feedwater specific heat [J/kg-K]

A = Heat Transfer Area [m^2]

Curve B

$$\begin{aligned} LMTD &= \left(\frac{GTD - LTD}{\ln\left(\frac{GTD}{LTD}\right)}\right) \\ GTD &= T_c - t_1 \\ LTD &= GTD - \Delta t \end{aligned} \tag{5-9}$$

Where

GTD = Greater Terminal Difference [K]

t_1 = Feedwater inlet temperature (after subcooling zone) [K]

LTD = Lesser Terminal Difference [K]

T_c = Saturation Temperautre in condensing zone [K]

Δt = Feedwater temperature rise [K]

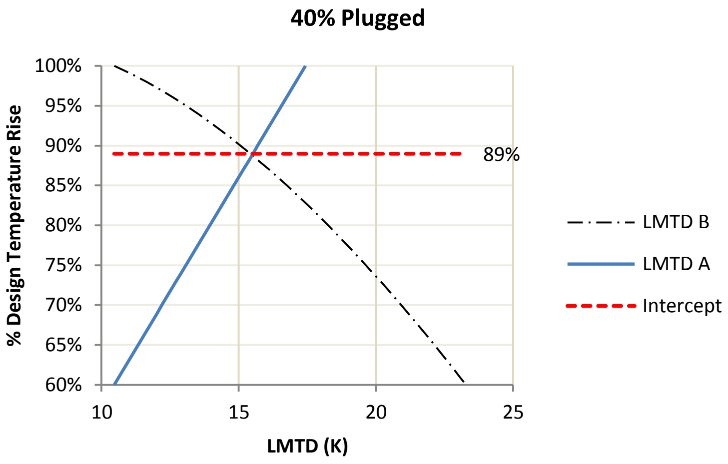


Figure 18 - Approximate FWH outlet temperature loss due to plugging

However, it is known that when the heater has been fully plugged there can be no heat transferred and thus, in this state, the outlet temperature loss will also be 100%. This logically results in an assumed exponential curve for the expected outlet temperature loss for the remainder of the life of the heater, as added to Figure 19.

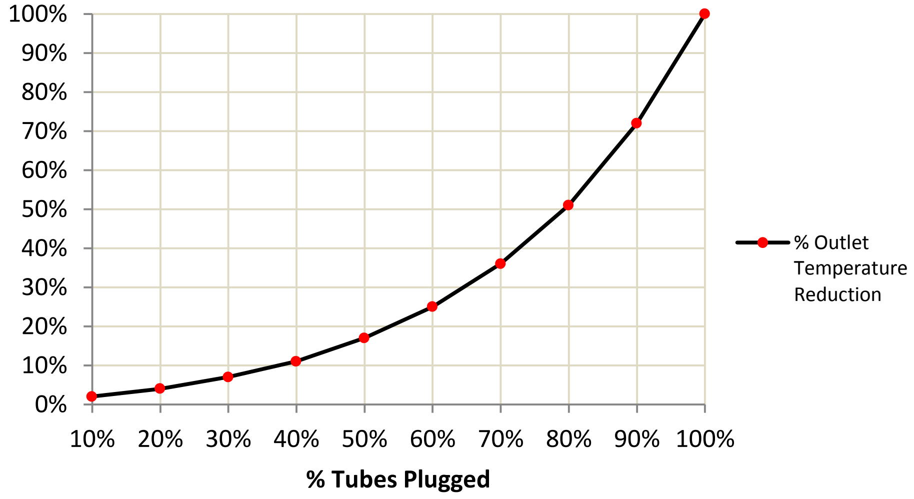


Figure 19 - HP Heater Inefficiency during plugging

The cost of imperfect repair must be incorporated into the cost of failure to account for additional fuel burnt during the inefficient uptime of HP heaters. This has a significant impact on operating costs as the cumulative number of tubes plugged increases after every failure cycle.

5.5 Goodness of fit

Because heaters must be replaced before all the tubes fail, useful life analysis is based on the observed lifetimes of a sample of the total number of tubes. This means that there is uncertainty in the data due to the limited size of the sample. *Goodness-of-fit* tests are a way to quantify this uncertainty.

The Kolmogorov-Smirnov Goodness-of-fit test (K-S test) is an appropriate tool for small and large sample sizes where the distribution is continuous and completely specified (Jardine and Tsang, 2013). A concern arises when one considers that the K-S test can only be applied to a continuous distribution $F(t)$ (Jardine and Tsang, 2013). NHPP models can consequently not be tested by a K-S test as it was originally not developed for parametric cases (Coetzee, 1997b).

Fortunately the chi-square goodness-of-fit-test is used primarily for discrete data sets but can also be adapted for continuous distributions. When considering the TTFF's of a sample of 12 HP heaters in Table 2 the K-S test was done for the 12 failures fitted to the Weibull distribution with $\beta = 2.66$ and $\eta = 6787$ to determine if the data can be represented by the said distribution. According to the general K-S Goodness-of-Fit test, the test statistic is calculated as $d_{\max} = 0.155$. With a 10% level of significance and sample size of 12 failures the critical value of the test statistic is found as $d_{\alpha} = 0.338$. From this it is seen that $d_{\max} < d_{\alpha}$ and the distribution can be accepted as representative of the data set.

For the expected and actual failure times of the intensity function presented in section 5.4 the chi-square test was performed and with $\chi^2 = 0.81 < \chi^2_{crit,0.01,12} = 3.57$. Thus it is accepted that the data $t_2, t_3, \ldots t_{14}$ is adequately described by the expected number of failures, $E(N(t))$, according to the power law intensity function, $\rho_2(t)$ with $\beta = 1.85$ and $\eta = 0.0036$.

5.6 Confidence Intervals

Probabilistic techniques involve the quantification of the probability of an expected result occurring, based on prior knowledge. Even though these techniques are useful in providing better understanding of data, they are limited by uncertainty. This uncertainty, as with goodness-of-fit, can be quantified by confidence intervals and indicates the level of statistical confidence. Statistical confidence is the fraction of times the confidence interval will include the actual variable (O'Connor and Kleyner, 2011). The confidence interval is bordered by the upper and lower confidence limits and a larger sample size will intuitively decrease the confidence interval around the failure function.

Because heaters must be replaced before all the tubes fail, useful life analysis is based on the observed lifetimes of a sample of the total amount of tubes. This means that there is uncertainty in the data due to the limited size of the sample. *Confidence intervals* are a way to quantify this uncertainty. For Weibull data the ranks used to determine the vertical axis coordinates is found from the median ranks which correspond to 50% confidence interval (O'Connor and Kleyner, 2011). So it can be said that with a 50% certainty, the next tube failure will occur within the next ∞ hours. This does not say anything about the confidence of the plotted data and it has as good a chance to occur outside the colour area of the curve as inside.

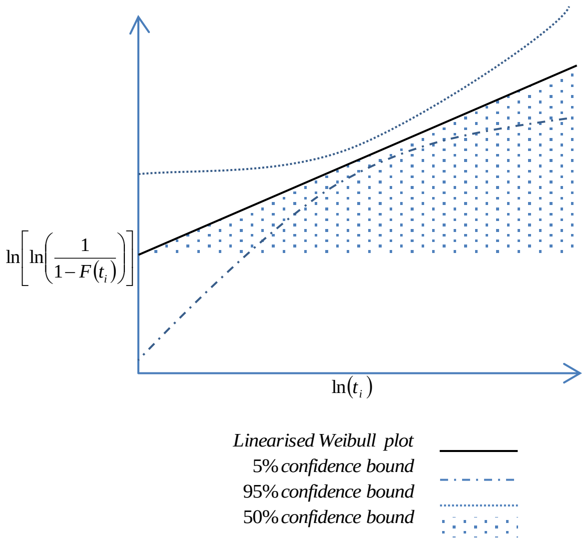


Figure 20 - Two-sided confidence bound for Weibull distribution

Because median ranks are linearized by $\ln\left[\ln\left(\frac{1}{1-F(t)}\right)\right]$ to plot a straight line, the 5% and 95% ranks must also be transformed in this manner to correctly calculate the vertical coordinates for the $\ln(t_i)$ time intervals on the horizontal axis.

Confidence intervals for $F(t)$ can be modelled on the normal approximation to the binomial function where the cumulative probability of failure has the expected value $E\left[\hat{F}(t)\right] = F(t)$ and variance $V\left[\hat{F}(t)\right] = F(t)(1-F(t))/n$. If the sample size n is large and $F(t)$ is not too close to 0 or 1 the binomial distribution assumes a shape approximated by the normal probability density function which can be used to find interval estimates for $F(t)$. To find a $100(1\text{-}\alpha)$ % confidence interval for the cumulative probability of failure, $F(t)$ is replaced by $\hat{F}(t)$ in the binomial distribution variance formula to result in equation 5-10 (Leemis, 2009). The parameter *z* is the inverse value of a normally distributed probability density function with mean 0 and variance 1 for a significance level of $\frac{\alpha}{2}$.

5-10

$$\hat{F}(t) - z_{\alpha/2}\sqrt{\frac{\hat{F}(t)\left[1-\hat{F}(t)\right]}{n}} < F(t) < \hat{F}(t) + z_{\alpha/2}\sqrt{\frac{\hat{F}(t)\left[1-\hat{F}(t)\right]}{n}}$$

For the NHPP Power law, as described in section 5.4, the confidence limits for both parameters, β and λ, can be determined and consequently the upper and lower bounds of statistical confidence can be determined for the intensity function, $\rho(t)$.

Because it is known that the cumulative intensity function $\int_0^t \rho(T)dT$ results in the expected number of failures $E[N(t)]$ at time *t*, the confidence intervals can be determined similarly to equation 5-10 where *k* is the total number of observed failures.

5-11

$$\hat{E}[N(t)] - z_{\alpha/2}\sqrt{\frac{\hat{E}[N(t)]}{k}} < E[N(t)] < \hat{E}[N(t)] + z_{\alpha/2}\sqrt{\frac{\hat{E}[N(t)]}{k}}$$

5.7 Conclusion

The results of a Laplace trend test under synchronous and asynchronous sampling varies significantly when applied to HP heater tube failure data. This implies that the time to the initial failure is of another failure dispensation than the series of failures after the initial failure.

A non-homogeneous Poisson process adequately describes the failure process following the TTFF under synchronous sampling.

Feedwater heater performance is affected by tube plugging after tube failures occur. The influence is found to be marginal initially but increasing exponentially over time as determined by the LMTD.

The K-S test can be used to test the goodness of fit for the Weibull distributed TTFF but the Chi-squared test is applied to test the fit of the NHPP to the recurring failures, which follows the first failure.

The erroneous application of the incorrect analysis technique to a data set will not only warp the interpretation of the results but also the outcome of the techniques that should be used to verify those results.

6 Consequence of Heater Tube failure

6.1 Introduction

The constituents of the total costs of HP heaters is identified by considering how they improve business productivity while in service while a framework for the estimation of expected replacement cost for an HP heater is also discussed.

6.2 Variable cost of repair

In the electric utility industry, one of the main cost components is primary energy. This primary energy consumption can only be reduced by increasing the efficiency of the plant. When critical part of the plant experience failure unexpectedly, efficiency deteriorates and more primary energy is required to produce the same amount of product.

The fundamental objective of business is profit and profit can be increased in different ways. Profit will increase if product price or volume is increased. If the market requires more product and more product is sold, more profit is made. Also, when costs are reduced, more profit is made.

The management of maintenance has no influence on the market but has a significant influence on production capacity and thus, production costs by keeping critical assets in service as expected. Production costs are however only a part of total costs which comprises of variable costs and fixed costs (Campbell & Reyes-Picknell 2015).

Variable costs are dependent on the output of the business. More output requires more input which refers to variable costs. These would include raw materials like coal, contracted workers, commissions paid, etc. (Christensen et al. 2008).

Regenerative feedwater heaters contribute significantly to the Rankine vapour cycle used in the generation of electricity. In order to quantify the economic value of this contribution one needs to look closely at the conversion of chemical energy to mechanical work. The cost of chemical energy in the form of coal is easily quantifiable in terms of cost per ton (C_{coal}). It is also known what measure of specified chemical energy is contained within a ton of coal.

Coal mines are contracted to provide coal with a minimum heating value (CV_{coal}) to ensure proper combustion in the power station steam generators. Any downtime of a heater failure will cause a loss in cycle efficiency and add to the variable cost of additional fuel burnt as well as a loss of revenue.

Assuming that the demand remains constant, the difference in the cost of additional coal burnt and revenue lost during heater downtime should give an indication of the profit lost per unit time of HP heater downtime.

6.2.1 **Steam Cycle**

The regenerative preheating of feedwater by steam which has previously performed some form of work is a special case of the cogeneration of heat and mechanical work (Szargut, 2005). It is important to note the contribution of these heaters to the steam cycle and the effect of different variables on the quantification of this contribution.

Because of the idea of cogeneration, one is inclined to argue that the isolation of a regenerative feedwater heater from the steam cycle would add steam flux to the turbine and perform additional shaft work through expansion. This is correct. However, due to the fact that the bled steam used to preheat the feedwater has more potential for heat transfer to feedwater than shaft work in the turbine, cycle efficiency when including the feedwater heater is increased.

Only expanding steam in the turbine can perform shaft work and will thus always contain a portion of rejected heat in the condenser. This rejected heat does not do any work because the heat is transferred to external cooling water and this reduces efficiency. The portion of heat rejected in the condenser is reduced by feedwater heaters.

Feedwater heaters transfer the heat from steam to feedwater which is internal to the system, thus rejecting less heat and increasing efficiency. Isolating the feedwater heaters thus causes more heat to be rejected from the internal process compared to the identical amount of steam preheating the feedwater.

Simulations

In an attempt to quantify the effect of the high pressure feedwater heaters on the steam cycle efficiency, initially some calculations were done using the existing process parameters of the operating plant. Because of the complexity of the plant in question, various assumptions had to be made and only an approximate 2% cycle efficiency reduction was calculated with one HP heater bank out of service.

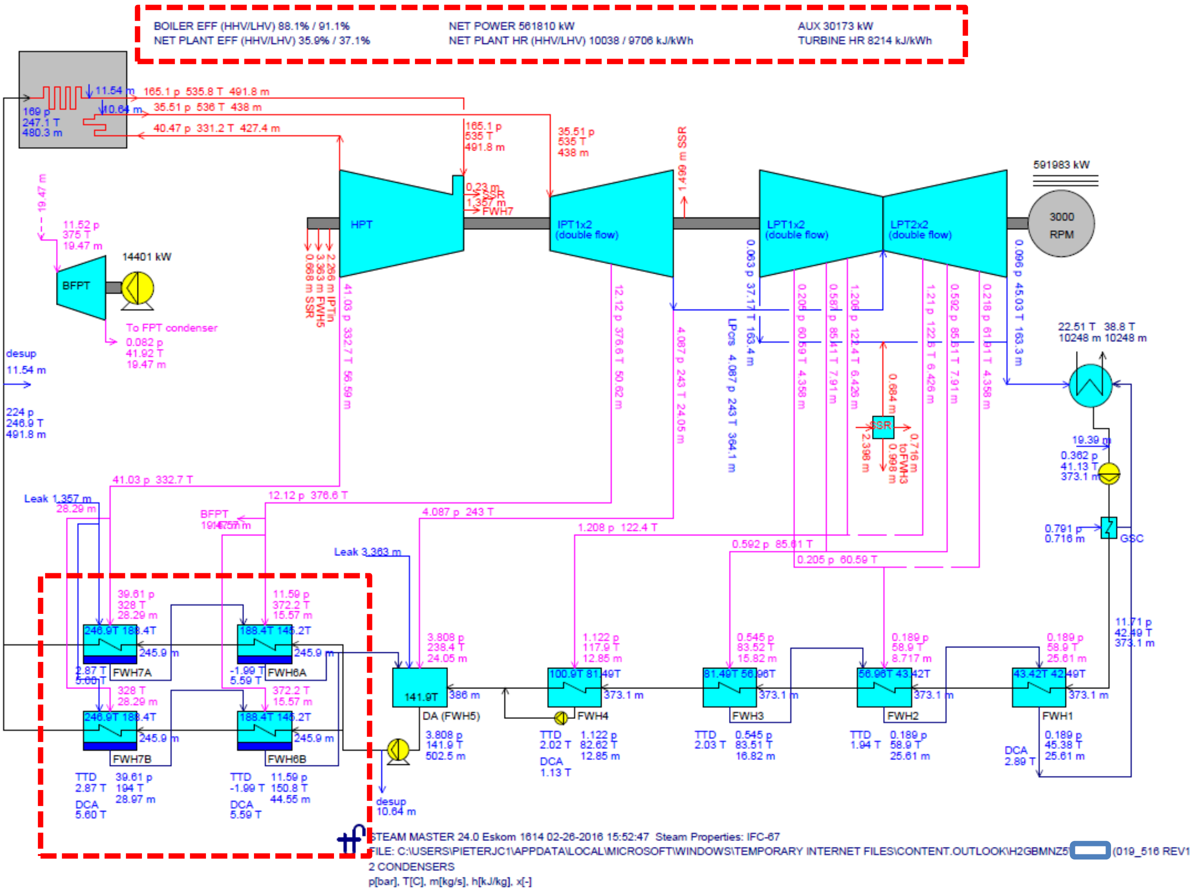


Figure 21 - DPS heaters in service

Eskom utilises a software suite called *Thermoflow* to model and simulate steam process parameters for various thermal design applications. Different *Thermoflow* products exist for the thermal engineering of conventional steam plant modelling and simulation. Two such products of *Thermoflow* frequently used are *Steam Master* and *Steam PRO*. *Steam PRO* allows the efficient creation of new plant designs whereas *Steam Master* enables the evaluation of the performance of those designs at conditions where operational parameters are out of design windows. *Steam Master* calculates the changes in process performance when design parameters are adjusted and simulates the expected performance of a power plant at different operating conditions, such as feedwater heater bypass (Thermoflow, 2016). Simulations were done on *Steam Master* for two different scenarios for a 600MW unit.

The first scenario represents a unit at full load with heaters in service. For the calculation of parameters by *Steam Master* the heat input into the boiler is kept constant. Changes can be observed in holistic parameters such as heat rate and cycle efficiency as summarised in the table below for low heating value (LHV) and high heating value (HHV) coal.

The first scenario represents a unit at full load with heaters in service. From Figure 21 the high pressure heaters are indicated by the dotted area indicating the four heaters arranged in two parallel banks of series heaters. From this diagram it is also clear to see that the entire bank containing both heaters must be isolated to repair one of the heaters when a failure occurs. The effect of this will be evaluated in Figure 22 by observing the process performance parameters highlighted by the dashed area at the top of the diagram.

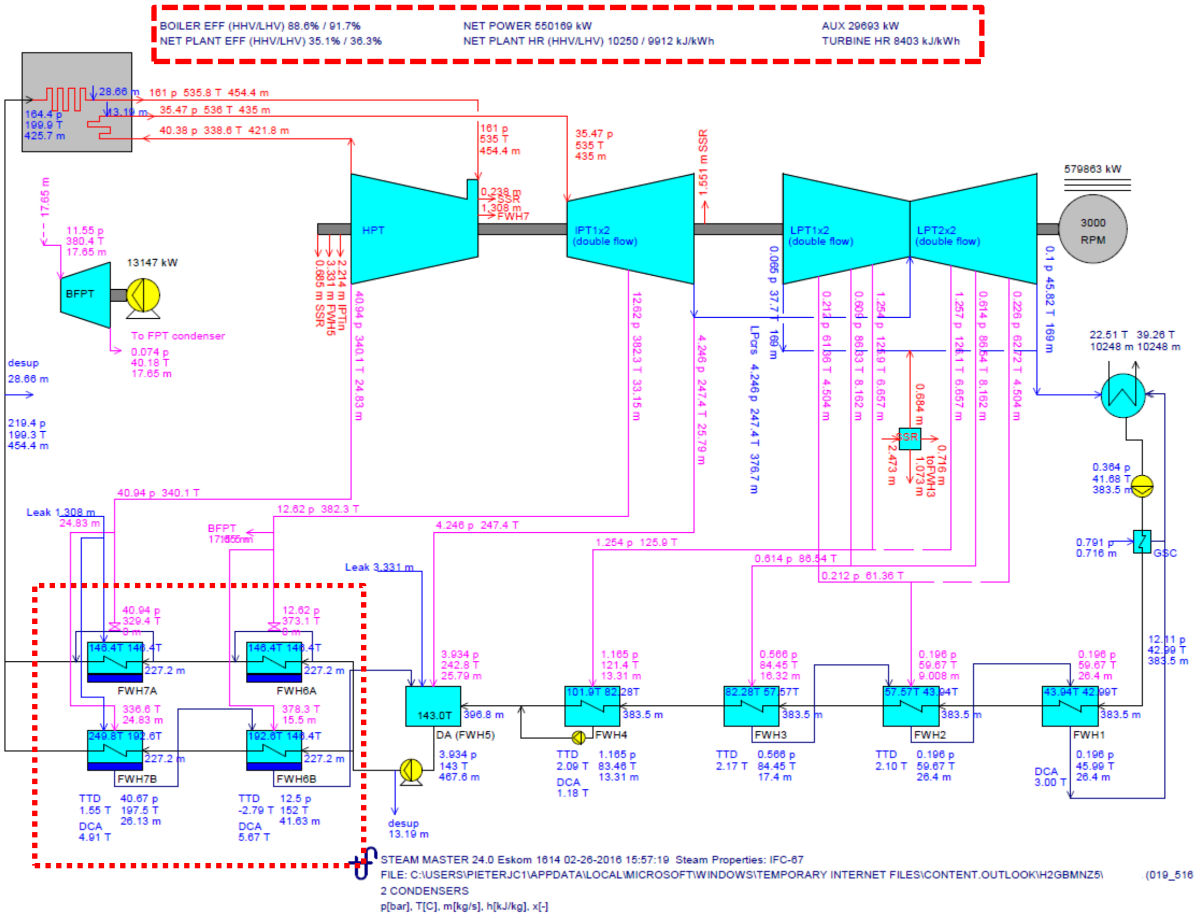


Figure 22 - DPS heater bank isolated

In the diagram above the A-bank is bypassed and isolated from the cycle. NO other changes were made whatsoever to the parameters of the simulation. This isolation is confirmed from the "0m" indicated above each heater signalling zero mass flow of bled steam and also no temperature difference over the A-bank can be observed. This has a significant impact on the temperature of the feedwater to the economiser and the effect of this can be seen in the performance of the cycle in the dashed area at the top of the diagram. For the calculation of parameters by *Steam Master* the heat input into the boiler is kept constant and the turbine output varies as the heaters are isolated. Changes can rather be observed in more holistic parameters such as heat rate and cycle efficiency as summarised in the table below.

		HP Heaters in service	HP Heater bank isolated
Net Plant Efficiency	LHV	35.9%	35.1%
	HHV	37.1%	36.3%
Net Plant Heat Rate	LHV	10038 $[^{kJ}/_{kWh}]$	10250 $[^{kJ}/_{kWh}]$
	HHV	9706 $[^{kJ}/_{kWh}]$	9912 $[^{kJ}/_{kWh}]$

Table 4 - Performance effects of heater isolation

In the table above "Net Plant Efficiency" is expressed in terms of percentage and indicates the proportion of chemical energy from coal which is converted to mechanical energy to eventually turn the turbo generator set. Conversely, "Net Plant Heat Rate" is expressed in terms of energy per time unit of power and indicates the amount of external energy required from coal to produce a time unit of power. The heat rate of the plant is easy to associate with the units in which electricity is sold to the consumer i.e. kWh and is the main source of revenue for Eskom.

6.2.2 Failure cycle downtime

Considering that the thermal efficiency deteriorates by 0.8% when one of two HP heater banks are out of service, naturally more fuel is needed to sustain the load which was required before the isolation of the heater. When a feedwater heater experiences a failure, the unit operators register a load loss. This is done on an integrated *generation power sales system* (GPSS) which is the computer interface for planned and unplanned load losses in the entire Eskom fleet. So, in the case of any unexpected failure a loss is registered in megawatt (MW) on the GPSS and the unit load is reduced.

A method of least cost dispatch is applied to ensure that the stations producing electricity at the lowest cost is utilized optimally to supply the base load. During specific periods in the course of a year the revenue generated from the sale of electricity varies significantly. In the national grid the load losses caused by the downtime of equipment at one station may be recovered by another given the situation that adequate surplus generation capacity exists to address total demand. In the unexpected event of high demand exceeding supply, the surplus is made up by the most expensive generating units in the fleet due to least cost dispatch.

The sporadic failure of tubes in feedwater heaters unavoidably result in corrective maintenance. This action is unscheduled but necessary to return a component to a functional state and prevent consequential damage to other components within the system. Tube leaks and their associated unscheduled downtime negatively affect the availability of feedwater heaters which significantly improves the efficiency of the power plant.

Even though a repair cycle is triggered by a failure, the duration of the repair and the time up to the failure is assumed to be independent of each other.

The time it takes to repair a tube leak can also be modelled using statistical distributions (Ebeling, 2010). It is important to note that even though the repair time of a heater can be interpreted as the time from tube leak detection to re-commissioning, this may be misleading. The reason for this is because downtime caused by a tube leak in a heater may consist of various stages and the duration of each of those stages may vary significantly. These stages may include, for example; isolation time, plugging time and commissioning time.

The downstream temperature of the heater is a measure of its efficiency to pre-heat feedwater, in the figure below time is plotted against temperature to illustrate a possible repair cycle for a tube leak in a heater.

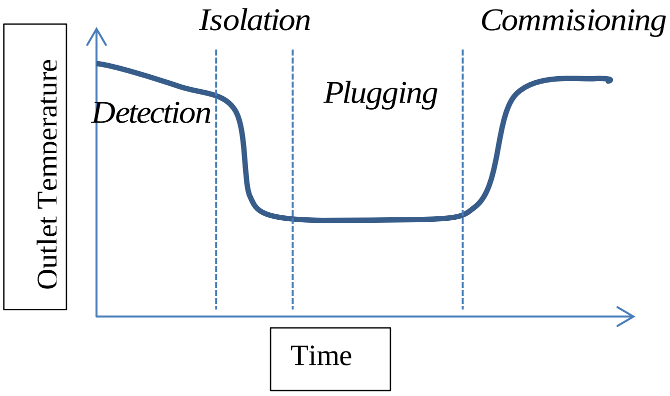


Figure 23 - Tube leak repair phases

Initially the temperature deteriorates and a diagnosis is made to determine if the heater should be isolated (detection phase). The feedwater isolation valves are closed and only when the heater bank is completely isolated can the repair process start. The plugging of the tube is done by an appropriate method, depending on the design of the heater and when the plugging is completed, the heater bank can be commissioned.

Typically each tube leak incident will have a different total repair time. These repair times, as with the tube failures themselves, are distributed according to some probability density function. The normal distribution applies to simple maintenance tasks where a component repair consistently requires a fixed amount of time with little variation.

The lognormal distribution applies to most maintenance tasks which consists of various activities with different durations (Blanchard and Fabrycky, 2011). These characteristics are well aligned with repairable systems of which the repair times are known to be log normally distributed (Ananda and Gamage, 2004)

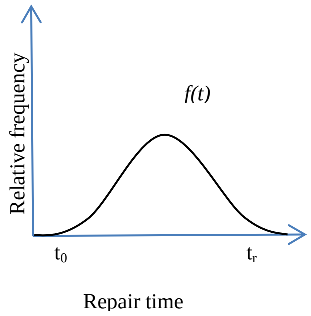


Figure 24 - Normally distributed repair time

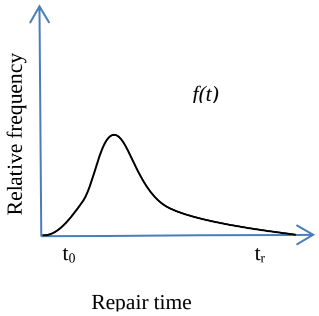


Figure 25 - Lognormal distributed repair time

As with tube failures, the duration of the next tube leak repair can be estimated using statistical probability. It is thus important to determine how the repair times for a heater are distributed to infer the probable cost of future repairs. The cumulative repair time over the life of the heater determines the maintenance cost which must be offset against the total lifecycle cost of the component.

6.2.3 Revenue loss

As mentioned in paragraph 6.2.2, a load loss is registered on record to reflect the plant's capability to produce electricity. Naturally when a HP heater bank is taken out of service a conscious decision is taken by the human operator to reduce the load of the unit to compensate for its ability to function at full capacity. This loss of capacity results in loss of revenue $\Delta C_{revenue}$ which can be described by the product of change in capacity ΔP following a HP heater bank failure and the amount C_{unit} received per unit sold for transmission.

$$\Delta C_{revenue} = C_{unit}\left[P_2 - P_1\right] \quad \textbf{6-1}$$

Unfortunately in the environment specific to the Eskom Power Generation (Gx) business revenue cannot form a part of variable cost. Due to the difference in operating conditions, coal costs, technology etc. various power stations deliver electricity at different costs of production. The method of least cost dispatch is applied to ensure that the stations producing electricity at the lowest cost is utilized optimally to supply base load at the lowest cost. During specific periods in the course of a year the revenue generated from the sale of electricity varies significantly due to time of use tariffs. In the national grid the load losses caused by the downtime of equipment at one station may be recovered by another given the situation that adequate reserves exists to address total demand. In the unexpected event of high demand exceeding supply, the surplus is made up by the most expensive generating units in the fleet due to the method of least cost dispatch.

Supply to the national grid is directly controlled at the point of generation and in turn this is indirectly controlled by the scheduling of generation by the grid operator (Catalão, 2016). The reason for the control of the national grid is primarily reliability and supply stability but also has economic implications.

For a monopoly system the objective of the economic optimization of electricity transmission is to minimise operating costs. The scheduling of generation capacity specifies how generation resources must be utilised to provide the most economical electricity to consumers at an acceptable level of reliability.

Schedules are based on the results of optimization algorithms which integrate independent variables such as unit commitment, expected reserve and least cost dispatch. Unit commitment gives an indication of which generation resources will be online at a specified time whereas the objective of least cost dispatch is to allocate capacity in such a way as to minimise the costs of generation (Catalão, 2016).

Due to the uncertainties regarding demand on the grid, schedules must be supported by operating reserves which are needed to maintain the required level of reliable capacity in the case of fluctuations in demand. Least cost dispatch relies on the optimization of variable cost of various generating resources and will require the power plants with the lowest operating costs to have the highest possible utilization. If an unexpected failure is experienced at a power plant, such as an HP heater tube failure, a power plant with a higher operating cost must compensate for such a loss and will then reduce the generation reserve margin.

The annual revenue generated from electricity sales from Eskom SOC Ltd. is regulated by the National Energy Regulator of South Africa (NERSA) and subsequently an average price per unit of electricity can hypothetically be applied to all stations. However, due to the large fleet of 23 power stations the total revenue is reallocated at the end of each financial year based on the costs incurred by a specific station. This results in a station's revenue being limited by the electricity sales of the entire fleet, but controlled by the costs incurred by that individual station.

This holistic reallocation approach deems it impractical to attempt to accurately calculate the expected loss in revenue, for an individual generator at a specified station in the fleet, based on the reduced availability of a single HP heater. Changes in a single station's revenue can thus not be readily isolated from the rest of the fleet and much less singled out as a primary driver to motivate the replacement of unitized capital equipment in Eskom.

When considering feedwater heater failures and the overall effect of such failures on plant operation, the greatest negative impact is the cost of replacement power when a sudden component failure occurs (EPRI, 2003).

This further supports the loss of primary energy as a driver for cost of failure due to the fact that a less cost effective power generating unit will be required to supply the capacity which is lost due to an unexpected failure. The cost of each failure is thus a function of the expected downtime for each heater and forms a significant driver for lifecycle costs.

6.2.4 Cost of coal

Coal is delivered to power plant by the ton and is priced accordingly given by C_{ton}. Being the primary fuel of the plant, each unit mass of coal has a specified amount of internal chemical energy or calorific value (CV) and is given in mega joule per kilogram *or* in this case transformed to kilo joule per ton. The cost of energy is then given by

$$C_{energy} = C_{ton} \times \frac{1}{CV} \qquad \textbf{6-2}$$

As described at the end of paragraph 6.2.1 the net plant heat rate (HR) describes the consumption of chemical energy to produce power and is given in $\frac{kJ}{kWh}$. The cost of primary energy per hour of operation in a power station can then be approximated by the product of the cost of energy and the change in heat rate following an HP heater bank failure.

If it is assumed that the heat rate and power produced during a failure condition is given by HR_2 and P_2 respectively and that the heat rate and power produced during a non-failure condition is given by HR_1 and P_1 respectively, the cost of coal during a failure cycle can be described as follows;

$$\Delta C_{coal} = C_{energy}\left(P_2 HR_2 - P_1 HR_1\right) \\ = \frac{C_{ton}}{CV} \times \left(P_2 HR_2 - P_1 HR_1\right) \qquad \textbf{6-3}$$

6.3 Fixed cost

Production costs are only a part of total costs which comprises of variable costs and fixed costs (Campbell & Reyes-Picknell 2015). Fixed costs are those which do not vary with variable production and includes general and administrative costs such as wages and materials needed to perform a repair (Christensen et al., 2008). In the case of an HP heater tube leak repair the fixed costs will mainly be dependent on the wages of artisans and the number of tubes to be plugged. Two plugs per tube are used and usually two door seals per heater are replaced following the repair.

The fixed cost of repair for every HP heater tube leak varies for various stations. Some stations may use in-house personnel to execute a repair whereas other stations may opt for contractors with specialist skills and equipment. This can have a significant impact on the optimal replacement time of an HP heater as it directly influences the operational expenses and serves as an input into the life cycle cost estimation.

The total estimated cost C_f of a failure cycle is the sum of both variable cost C_{var} and fixed costs C_{fix}.

6.4 Cost of Replacement

6.4.1 **Estimation**

Because the focus of economic analysis is the future consequences of current decisions, these consequences are not known with absolute certainty. Cost estimations form the foundation of any economic analysis and the results are only as good as the inputs from which they are calculated (Newnan et al., 2009). The accuracy of a highly detailed analysis can be nullified by poorly estimated future costs.

Some general types of estimates can be defined by distinguishing between their various accuracies which in turn draws attention to their purpose. These are normally referred to as rough estimates, semidetailed estimates and detailed estimates (Newnan et al., 2009). Rough estimates are used for high level planning and initial evaluation which tend to involve numbers with low level of detail.

Rough estimates generally require accuracy within -30% and +60%. The asymmetric estimating errors accommodate decision makers in their tendency to underestimate rather than overestimate costs and when projects run behind schedule, costs may also escalate. Semidetailed estimates used for budgeting purposes at the conceptual stages of projects require additional time and resources and this increased level of sophistication improves the general error margin to -15% and +20%.

Detailed estimates are within -3% and +5% and are used during the detail design and contracting phases. Detailed estimates require the most time and resources and can be made from quantitative models, design drawings and specifications and supplier quotations (Newnan et al., 2009).

In general, the job of estimation is challenging due to the fact that the future is unknown. There are however very few situations where an entirely new estimate must be calculated. Most new products and technologies have a comparable counterpart with existing estimates. This allows for the concept of “estimation by analogy” to use previous costs of similar products or projects to anticipate the cost of future products or projects (Newnan et al., 2009).

Various estimating models can be used to estimate costs at the different design levels. From the HP heater replacement projects surveyed in Eskom a combination of two distinct models could be identified, segmenting and cost index models.

A segmenting model decomposes a project into smaller individual sections. These lower levels are weighted and estimated to be added together for the final estimate. This is common in engineering estimating and can be applied for any level of accuracy (Newnan et al., 2009).

Contract price adjustments (CPA’s) are also calculated in this manner during the period of execution of the project. As seen during an HP heater replacement project at an Eskom power plant, the CPA’s are calculated by the summation of weighted portions of the contracted costs.

These weights may vary for different projects but in the cited case was weighted with 89% labour costs, 5% steel, 3% mechanical materials and 3% transport. In combination with the segmented cost model cost indexes are also used to reflect historical changes in engineering costs (Newnan et al., 2009).

Cost indices reflect the relative changes in groups of cost items and can be used as an indicator for the expected change in historical costs. The value of a sum of money today will have less buying power over a year’s time, depending on the growth of the existing inflationary economy. In South-Africa the Producer Price Index (PPI) tracks the rate of change in the prices charged by producers of goods and services. Statistics South Africa publishes PPI’s for different industries. PPI’s are compiled for agriculture, forestry and fishing; mining and quarrying; electricity and water; intermediate manufactured goods; imports and exports; and construction. The PPI is widely used by businesses as a contract escalator and as a general indicator of inflationary pressures in the economy (statssa, 2013). However, because PPI’s covers such a vast number of industries, the PPI indices used in the Eskom projects surveyed is based on the Steel and Engineering Industries Federation of South Africa (SEIFSA).The SEIFSA PIPS (Price and Index Pages) provides access to independent market specific indices, which ensures that CPA's are reasonable to both the clients and their suppliers (SEIFSA, 2015).

For the application of determining the replacement cost of industrial equipment installed inside a power plant, one must look in the manufacturing sector to determine how the buying power of money has changed over time. Since we want to determine how the value of the original equipment compares to the value of replacing the equipment, we need to look at the heavy engineering and manufacturing sector to establish how PPI has grown. This will indicate the rate at which the cash value of a heater has deteriorated over time.

When considering the application of the time value of money and using variables, one could argue that if a heater is acquired at year zero for sum *A* then that same heater, one year later will be acquired for the same amount *A* with an additional growth amount determined by the PPI.

If it is found that the price for heaters increases by *i*% per annum, then after one year the price of the same heater can be estimated at $\left(A+\frac{i}{100}A\right)$. For year *n* the future value of a known sum *A* is given by

$$A_n = A\left(1+\frac{i}{100}\right)^n \qquad \textbf{6-4}$$

Similar to the case of equation 6-4 the average annual growth rate over a period of *n* years can also be described in terms of the PPI points over the same period. If PPI_t indicates the index value at year *t* and PPI_{t+n} indicates the value of the index at some point in future then the average annual growth rate *i* for the period *n* is given by

$$\frac{PPI_{t+n}}{PPI_t} = (1+i)^n$$

$$or$$

$$i = \left(\frac{PPI_{t+n}}{PPI_t}\right)^{\frac{1}{n}} - 1 \qquad \textbf{6-5}$$

(Newnan et al., 2009)

For projecting the future purchase costs of equipment the average rate of price increases over an extended period may be the best predictor of future rates (Newnan et al., 2009). This closely coincides with the estimation method of analogy where the actual replacement value is known at a specific time

t in the past and another actual replacement value for the same product is known at time $(t+n)$ then the nominal annual growth rate i can be found from equation 6-5.

6.4.2 Effect of Inflation

Inflationary effects are important to consider as it influences the purchase power of money and in most economies inflation reduces the value of money (Newnan et al., 2009). The acquisition cost of an asset cannot mathematically change its value but if inflation takes place this is not true (Jardine and Tsang, 2013).

There are two ways in which the estimation of costs can consistently be treated in replacement analysis (Shamir and Howard, 1979). Firstly, prices include inflationary effects and projects nominal prices and interest rates. Secondly, prices are represented as inflation free and no inflationary effects are included in either price or interest rates. If nominal costs are used where the purchase cost is related to the year in which they are spent, inflation must be taken into account (Jardine and Tsang, 2013).

Most organisations conduct their capital equipment replacement analyses using real or inflation free prices and interest rates reflecting the present day value (Jardine and Tsang, 2013). Hence, the historic purchase costs will be inflated to reflect real costs and future costs must be deflated to reflect real costs.

The relationship between inflation f, nominal interest i and real interest i' is given by

$$\begin{aligned} &i = i' + f + (i')(f) \\ &or \\ &i' = \frac{i-f}{1+f} \end{aligned} \qquad \textbf{6-6}$$

In equation 6-6 the inflation f represents the deflating value of money measured as an annual rate of increase in the cost of the procurement of a new HP Heater. Nominal interest i is the business discount interest rate.

The real interest rate i' indicates the inflation free annual growth in current value terms. It must however be stressed that this real interest rate i' will only be applied to known values of the acquisition cost A after being discounted to current value using the appropriate market discount interest rate i.

6.5 Conclusion

Maintenance keeps productive assets available and understanding the constituents of total costs enables logical decision making and justified increases in the maintenance budget. Maintenance is crucial for a business to achieve its objectives by keeping assets performing to an acceptable standard. HP heaters improve business productivity by improving steam cycle efficiency. The duration of HP heater downtime must be minimised to reduce the cost of failure. Eskom redistributes profits at the end of each financial year and it is thus impossible to estimate the effect of HP heater downtime on revenue generated for a specific unit in a power plant.

The variable cost of repair is the additional coal burnt during heater downtime and fixed cost is the expenditure not related to the output of the plant.

Estimating the capital cost of a replacement heater can be done by using a combination of various techniques that emulate the inflation of HP feedwater heater replacement projects.

7 Financial Risk exposure

7.1 Introduction

The issue to be addressed by the modelling of life cycle cost (LCC) is to find the replacement age of equipment where the total cost is a minimum. As the replacement age of equipment increase, their operational cost also increase per unit time whereas the purchase cost decreases per unit time. The purchase cost is, in very simplified terms, defined as the purchase price divided by the replacement age.

7.2 Construction of model

In a classical case, where a system is made up of replaceable units whose wear accumulates over time, it is generally less costly to replace the unit before the system has failed. There are always costs involved in maintenance. There are costs incurring when only observing wear in a unit, with replacing a unit before a failure and replacing a unit after it has failed. Naturally replacement before failure is preferred if the cost incurred after failure is comparatively high.

Many examples give attention to the replacement of capital equipment. However, the problem is treated deterministically rather than probabilistically implying that all costs are known before the construction of the model is initiated (Jardine and Tsang, 2013). Probabilistic methods must be explored together with discounted cost models to accurately determine optimal replacement time, even outside of the data sample time window.

As discussed in section 5.3 the probability of HP heater tube failures continuously increase. Due to this increase the exposure to the risk of the consequence of such failure also continuously increases. At this time t we can quantify the expected financial risk.

$$C(t) = \frac{C_p + (E[N(t)] + 1) \times C_f}{t + TTFF} \tag{7-1}$$

In the model above a deterministic situation is described where the first failure occurred at time $TTFF$. The expected number of failures in time t following $TTFF$ can then be described by a point process model to find $E[N(t)]$. It is then known that the expected number of failures at time t after $TTFF$ is given by $(E[N(t)]+1)$. If the expected number of failures in the total time in operation is multiplied by the expected cost of a failure C_f, the total expected operational cost of the heater is given by $(E[N(t)]+1)\times C_f$. C_p in this case represents the purchase cost of a new heater at the evaluation time t.

The reason for this partially deterministic approach, where it is assumed that the first failure has already occurred, is that in Eskom most of the heaters installed have already experienced a first failure but there is no quantified manner to determine when the optimal replacement time is. The model represented by equation 7-1, even though still elementary, is a marked improvement on the current means of determining replacement time which does not at all consider probabilistic quantification of any sort.

While equation 7-1 represents the notion behind LCC it does not account for the time value of money. For the motivation of any capital equipment decision, the appropriate discount interest rate *i* must be used to account for the minimum acceptable rate of return (MARR) of the business. It is in this aspect where equation 7-1 is found to be lacking. For the replacement of components over a timeframe of weeks or months, equation 7-1 would be an accurate representation of reality. However, the replacement of HP heaters may occur only once in decades. This necessitates the time value of money to be considered in determining the optimal replacement time.

The present day value of a sum of money to be spent at some time in future is obtained by discounting at the appropriate discount rate *i*. Equation 6-2, for the sum of A_n received n years from now, will then become

$$A = A_n \left(\frac{1}{1 + \frac{i}{100}} \right)^n \tag{7-2}$$

where $\left(\frac{1}{1 + \frac{i}{100}} \right) = r$ is termed the discount factor (Jardine and Tsang, 2013).

The objective of an economic life model is to determine the optimal replacement time which minimizes the total discounted costs of operating and maintaining the equipment over an extended period of time. Thus it would be recommended only to replace an HP heater when the present value of operations and maintenance costs exceed the costs required for capital recovery.

To determine the total discounted cost to the end of life of equipment which is already purchased and installed it must be clear when cash flows occur. Considering that most HP heaters will only be replaced once, the cycle cost of operation can be represented by

$$C(t) = C_1 r^1 + C_2 r^2 + \ldots + C_t r^t + Ar^t \qquad \textbf{7-3}$$

$$= \left(\sum_{i=t}^{t} C_i r^i \right) + Ar^t$$

(Jardine and Tsang, 2013)

where C_i is the total current cost per failure cycle and *A* the estimated current cost of replacement. In this case *t* is an integer representing the number of years from initial installation.

Following the installation of an HP heater, regardless of the length of its service life, it is scrapped upon replacement. Thus in equation 7-3, the salvage value is zero and therefore omitted.

7.3 Conclusion

In considering the economic life of HP heaters, it is prudent to include the time value of money. Due to the exceptionally long service time of HP heaters, discounting cannot be omitted from cost modelling. The discount rate combines the MARR and the inflation of HP heater replacement projects to determine the real rate of change in the value of money.

8 Case Study – DPS Unit 1 High Pressure Feedwater Heater 5B replacement

8.1 Introduction

The subject of this case study is a fully operational unit of a South African thermal power plant. Due to commercial reasons the identity of this plant has been omitted but will be referred to as DPS.

The expected number of tube failure will be estimated using a conditional discontinuous probability function consisting of a Weibull distributed TTFF followed by a NHPP representing the failures that may follow. Cost of failure is determined as the total cost during HP heater downtime whereas the cost of imperfect repair is determined as the cost of additional coal consumed during the uptime of a less efficient heater following tube plugging.

The capital cost of HP heater replacement is estimated and combined with probabilistic results to determine the expected annual cost profile over the life of the heater.

Variation analysis is conducted to confirm which inputs can change the results the most significantly before briefly mentioning a proposed failure recording facility with a connected intranet server.

8.2 Description of DPS

DPS is a 3600MW power station consisting of 6 × 600 MW units commissioned in 1984 with 4 HP heaters per unit. DPS have experienced chronic tube failures on numerous heaters and have also executed HP heater replacements in 1997 and 2012. Tube failure data is well documented from installation and procurement information is also available, making DPS suitable candidate for analysis[2].

Feedwater heating systems are arranged in different layouts, depending on the requirements of the power plant when it was originally constructed. A common feedwater heater layout found in Eskom is that of DPS. Four heaters are arranged in two banks in parallel, with each bank consisting of two heaters in series (GEC, 1982).

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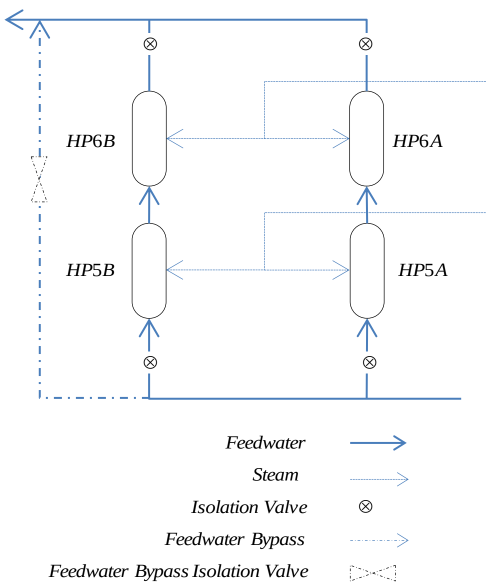
[2] Also considered for analysis was HPS, a 2000MW power station consisting of 10 × 200 MW units commissioned in 1976 with 6 HP heaters per unit. HPS has experienced a higher number of tube failures but lacks the completeness of the DPS data and procurement information is also inadequate. The failure data was nonetheless subjected to probablistic analysis and is presented in Appendix B.



(GEC, 1982)

Figure 26 - Simplified Feed heating System Layout 1

From Figure 26 it can be seen that the individual banks can be isolated independently but due to the fact that each bank consists of two heaters in series, the failure of a single heater will cease the feedwater flow to its downstream counterpart. When a fault on a heater is detected, the entire bank must consequently be taken out of service.

8.3 Expected Number of Failures - $E[N(t)]$

Tube failure data for a high pressure feedwater heater at DPS is displayed in Table 5. The leftmost column indicates the number of failures, the center column contains the interarrival time to each corresponding failure and in the rightmost column, each respective date.

n	t_i	Date
1	7004	2002/12/05
2	117	2003/04/01
3	170	2003/09/18
4	98	2003/12/25
5	280	2004/09/30
6	91	2004/12/30
7	77	2005/03/17
8	319	2006/01/30
9	132	2006/06/11
10	9	2006/06/20
11	18	2006/07/08
12	290	2007/04/24
13	82	2007/07/15
14	378	2008/07/27

Table 5 - Failure data

A simple scatter plot of the failure dates are displayed in Figure 27. Here it seems that the failure occasions which occur sequentially form a monotonic trend relative to calendar time. This observation of tube failure was done over the course of several years and clearly indicates consistency in the failure dispensation. However, it is clear that the arrival time of the first failure does not belong to this dispensation of interarrival times. This is clear in the results of a Laplace trend test for the failure data under synchronous and asynchronous sampling. With synchronous sampling the time to first failure (TTFF) is excluded and Laplace statistic is found to be -0.95. With asynchronous sampling the same statistic is found to be 4.53. This indicates a trend under asynchronous sampling but no trend under synchronous sampling.

Because of the operational dependence of feedwater heater tubes, the sequential occurrence of failures is significant to consider under stochastic modelling. The stochastic point process synonymous with systems' failure processes allows for the application of the power law process. The power law process is a stochastic point process model taking a generalized form of the homogeneous point process. This generalized form enables the power law process to emulate various stochastic processes by the variation of two determining parameters β and λ. This parametric approach gives the power law mathematical tractability for the modelling of non-linear trend as well as linear trends. In turn this aligns the power law process model with the Non Homogeneous Poisson Process group of statistical modelling functions.

An eyeball analysis of the synchronous and asynchronous sampling models in Figure 28 indicates that the sampling method can have a significant effect on the relevance of a model with respect to the failure data. Under asynchronous sampling the parameters were found to be $\beta = 7.549$ and

$\lambda = 1.87e-29$ under synchronous sampling $\beta = 1.085$ and $\lambda = 3.31e-3$. Without considering the effect of sampling the entire dataset is taken and tested for increasing or decreasing rate of occurrence of failure (ROCOF). Taking into account the entire dataset, including TTFF, gives the impression of an increasing ROCOF. This is confirmed by the Laplace test statistic of 4.53 and large β =7.549. This approach of blind application, represented by the solid line of asynchronous sampling, corresponds well with the expected exponential curve found in Bell (1991) but upon closer inspection it is found to be a poor fit to the actual data. Relative to the asynchronous model, the synchronous sampling model, represented by the dotted line seems to be a significant improvement on the asynchronous sampling approach. This is confirmed by the application of a chi-square test for both models.

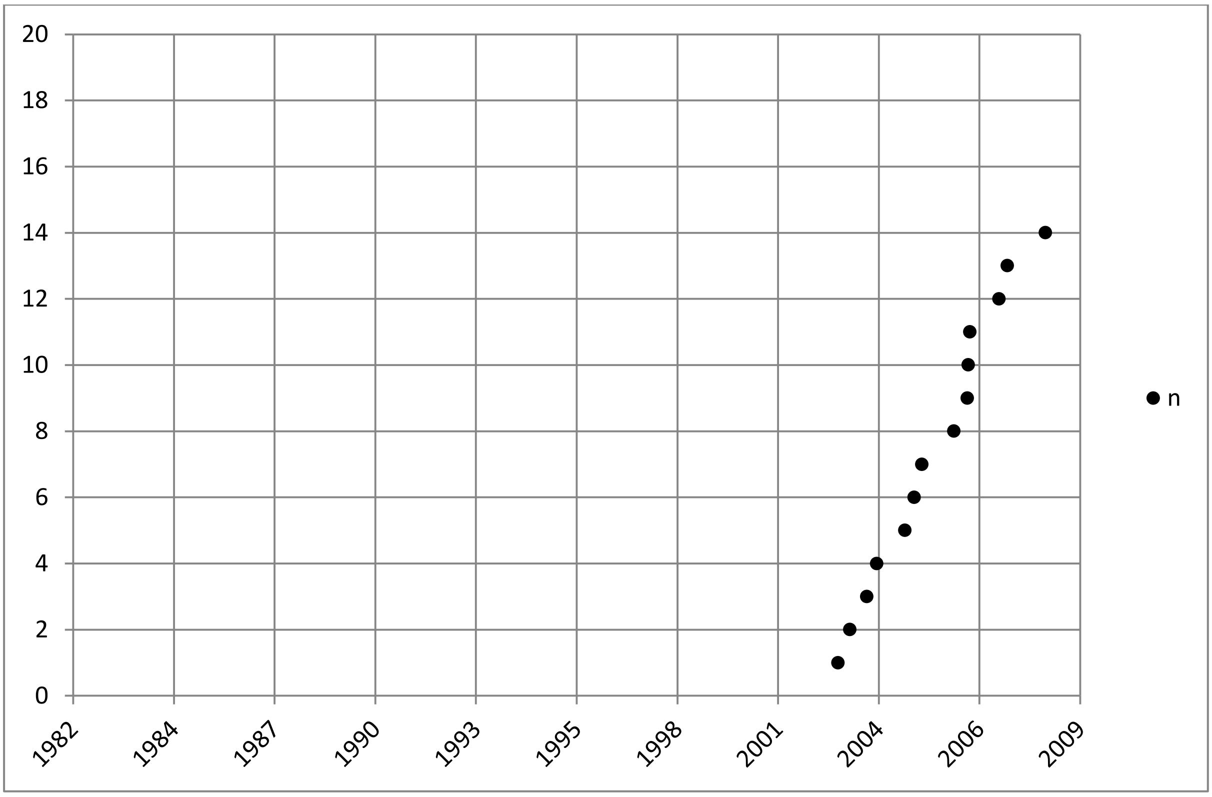


Figure 27 - Tube failure process

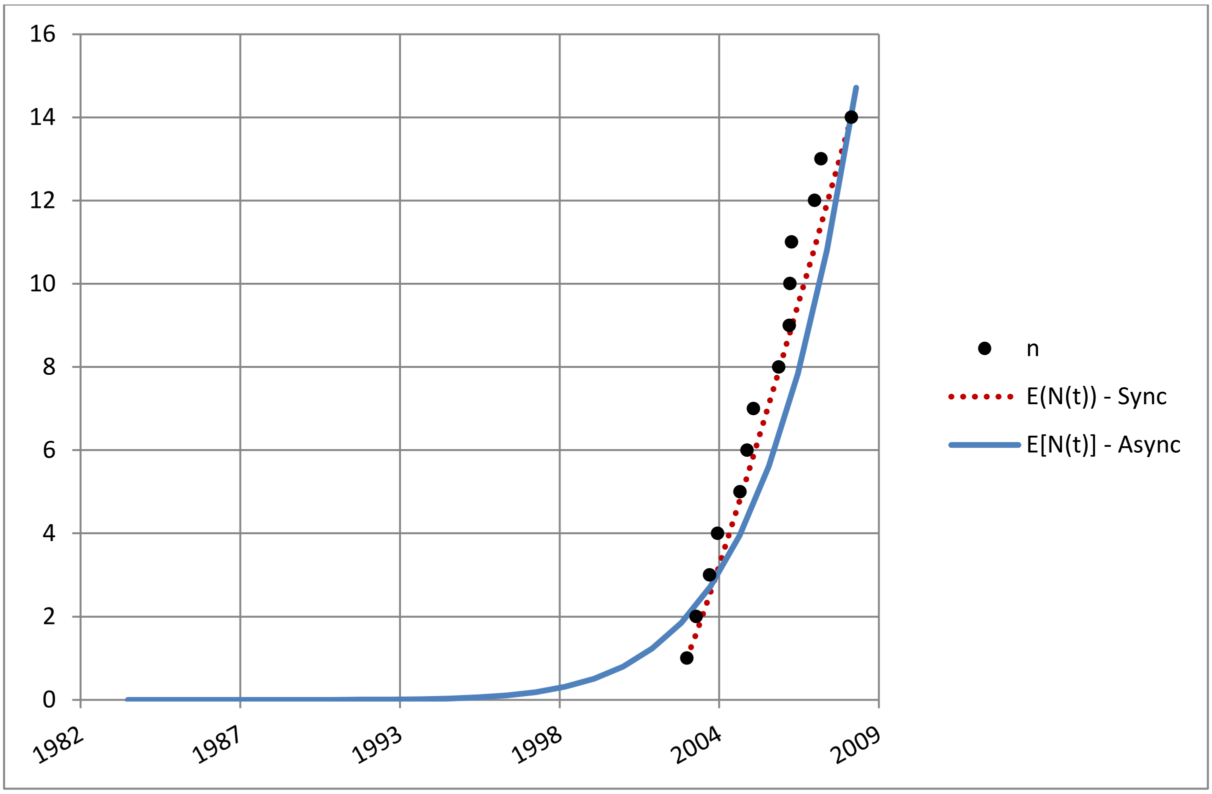


Figure 28 - Asynchronous vs Synchronous sampling

The chi square test takes into account the degrees of freedom, v, which is determined by the sample size, n, and the number of parameters in the probability function, c. The asynchronous model's χ^2 statistic is calculated at 6.74 with a critical value, χ_c^2, of 6.3. This critical value is the χ^2 distribution value with 12 degrees of freedom and 90% significance level is smaller than the test statistic. With $\chi^2 = 6.74 > \chi^2_{c,0.1,12} = 6.3$ the null hypothesis of failure data being represented by Power Law process with $\beta = 7.549$ and $\lambda = 1.87e-29$ is rejected at 90% significance level and 12 degrees of freedom. However, the synchronous model's χ^2 statistic is calculated at 1.43 with a critical value, χ_c^2, of 5.58. This critical value is the χ^2 distribution value with only 11 degrees of freedom and also 90% significance level is greater than the test statistic. With $\chi^2 = 1.43 < \chi^2_{c,0.1,11} = 5.58$ the null hypothesis of failure data being represented by Power Law process with $\beta = 1.085$ and $\lambda = 3.31e-3$ cannot be rejected at 90% significance level and 11 degrees of freedom.

Apart from the execution of a goodness of fit test for the synchronous case, confidence intervals are also calculated and plotted in Figure 29.

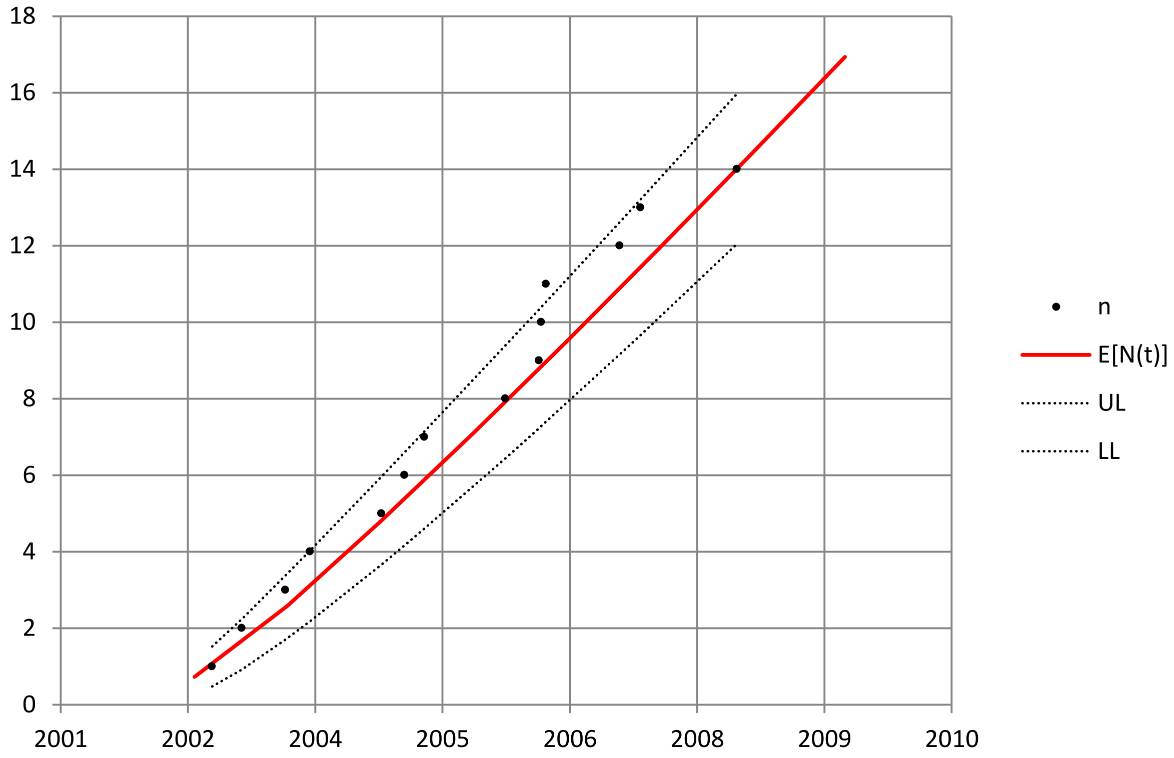


Figure 29 – Synchronous Power Law Process with 95% confidence intervals

Similarly, the synchronous Cox & Lewis model, also discussed in section 5.4 has been applied to the failure data in Figure 30.

This model's χ^2 statistic is calculated at 0.96 also with a critical value, χ_c^2, of 5.58. With $\chi^2 = 0.96 < \chi^2_{c,0.1,11} = 5.58$ the null hypothesis of failure data being represented by a Cox & Lewis process with $\alpha_0 = -5.073$ and $\alpha_1 = 6.85e-6$ cannot be rejected at 90% significance level and 11 degrees of freedom.

This implies that both models discussed in section 5.4 adequately describe the failure process. Because the Power Law does not require iterative calculation, it is preferred by the author. Also, the sampling of failure data significantly impacts the relevance of statistical modelling, even if this modelling is applied through an accepted approach.

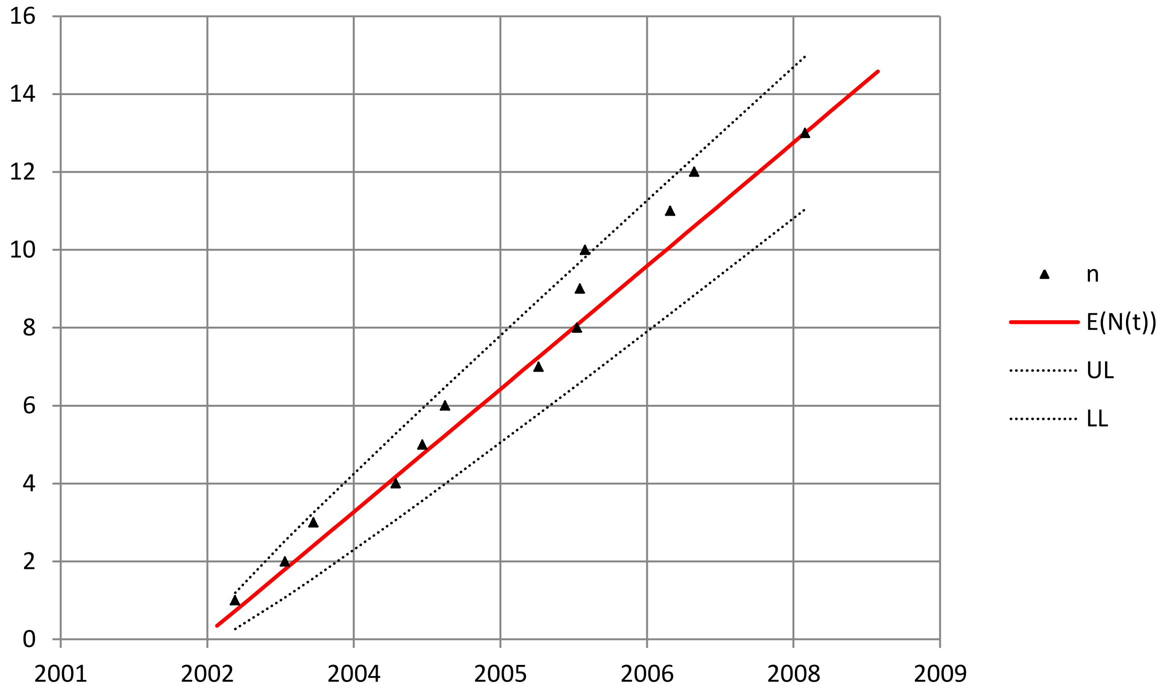


Figure 30 - Synchronous Cox & Lewis Process with 95% confidence intervals

It is not possible to continue without addressing the obvious omission of the first failure. Clearly the sequence of failures are accurately represented by a Non-homogeneous Poisson process under synchronous sampling where the interarrival times $t_2, t_3 ... t_n$ is considered, but the obvious absence of t_1 must be addressed.

As mentioned in Ascher & Feingold (1984) the TTFF of the Power Law process is Weibull distributed and thus it seems appropriate to model the TTFF, t_1,with a Weibull distribution. This would however require a sample of TTFF's from an identical distribution in order to infer the expected TTFF. This is an important consideration as the expected number of failures inferred by the Power Law is completely dependent on t_1. Thus to find the expected TTFF of a specific heater, a Weibull analysis will be done on a sample of heaters which are subjected to similar operational conditions. Considering the data in Table 6 we have all number 5 heaters at DPS which already experienced an initial tube failure and their corresponding times. These heaters are of identical design and construction, operate independent of each other, under similar operational circumstances, and thus the times are IID and a Weibull analysis can be performed.

Heater	Time to First Failure
U1A	7896
U2A	2061
U4A	9118
U5A	8245
U6A	4862
U1B	7004
U2B	5624
U3B	3785
U4B	5780
U5B	2298
U6B	5249

Table 6 - HPH 5 TTFF data

In determining the parameters describing the distribution of the data the shape parameter was found to be, $\beta_d = 2.837$, and the scale parameter was found to be, $\eta_d = 6333$ days. This implies that the characteristic life of the number 5 heaters is 6333 days or approximately 17 years. This is the life at which 63.2% of the population is expected to experience an initial tube failure. This can be graphically represented in Figure 31 where the expected cumulative probability of the first failure $E[F(t)]$ is represented by the solid line and the actual TTFF's relative to the estimated median ranks $F(t)$ are given by the points. Figure 31 also indicates the upper limit (UL) and lower limit (LL) for a 95% confidence interval.

The median ranks are determined by Benard's approximate for a sample size of 11 and is also used for a Kolmogorov-Smirnoff Goodness-of-Fit test with a 90% significance level detailed in Table 7. For 90% significance and a sample size of 11 the critical value, d_α, is 0.338. From the final column in Table 7 the critical value of the K-S test statistic, $d_{\max}$, is 0.17. With $d_{\max} < d_\alpha$ we cannot reject the hypothesis that the TTFF data can be distributed by a Weibull distribution with $\beta_d = 2.837$ and $\eta_d = 6333$.

i	t	$F(t_i)$	$\ln(t)$	$\ln\ln\left(\frac{1}{1-F(t_i)}\right)$	$\left(\frac{t_i}{\eta}\right)^{\beta}$	$F(t)$	$\hat{F}(t_i)$	$F(t_i)-\hat{F}(t_i)$	$F(t_i)-\hat{F}(t_{i-1})$
1	2061	0.06	7.631	-2.759	0.041	0.041	0.061	-0.021	0.041
2	2298	0.15	7.740	-1.823	0.056	0.055	0.149	-0.094	-0.007
3	3785	0.24	8.239	-1.308	0.232	0.207	0.237	-0.030	0.058
4	4862	0.32	8.489	-0.935	0.472	0.376	0.325	0.052	0.140
5	5249	0.41	8.566	-0.632	0.587	0.444	0.412	0.032	0.119
6	5624	0.50	8.635	-0.367	0.714	0.510	0.500	0.010	0.098
7	5780	0.59	8.662	-0.121	0.771	0.538	0.588	-0.050	0.038
8	7004	0.68	8.854	0.118	1.330	0.736	0.675	0.060	0.148
9	7896	0.76	8.974	0.365	1.870	0.846	0.763	0.083	0.170
10	8245	0.85	9.017	0.643	2.114	0.879	0.851	0.028	0.116
11	9118	0.94	9.118	1.026	2.812	0.940	0.939	0.001	0.089

Table 7 - K-S test for heaters no.5 expected TTFF's

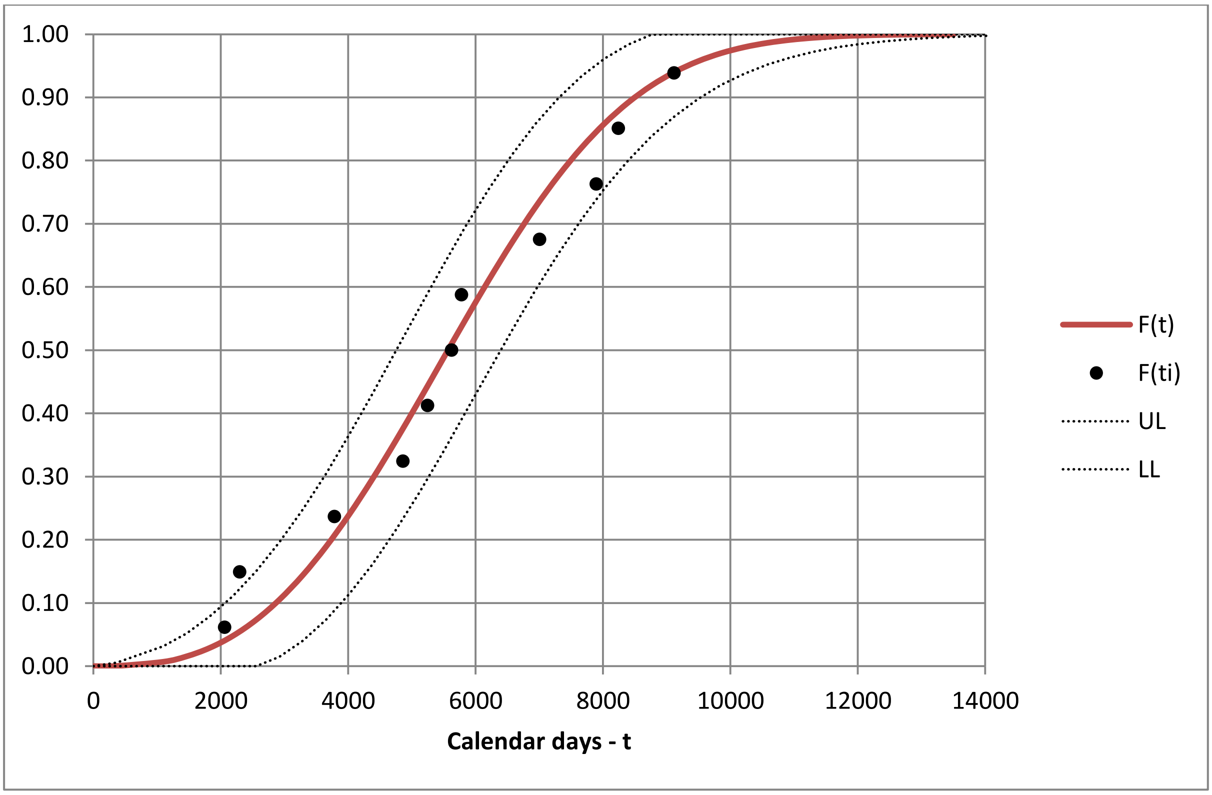


Figure 31 - Cumulative probability of TTFF for no. 5 heaters

Conveniently, the cumulative probability of the initial tube failure as described by $F(t)$ is only defined from 0 to 1. Thus only the time to initial failure of a heater is modelled by a Weibull distribution and subsequent tube failures by a NHPP. This can in general terms be expressed by the conditional discontinuous function below.

$$E[N(t)] = \begin{cases} F(t) & ,t < TTFF \\ E[N(t-TTFF)]+1 & ,t \geq TTFF \end{cases} \tag{8-1}$$

In the specific case of the failure data presented in Table 5 this equation is written with the parameters β & λ for $E[N(t)]$ and β_d & η_d for $F(t)$ as below.

$$E[N(t)] = \begin{cases} 1-\exp\left[-\left(\dfrac{t}{\eta_d}\right)^{\beta_d}\right] & ,t < TTFF \\ \lambda(t-TTFF)^{\beta}+1 & ,t \geq TTFF \end{cases} \tag{8-2}$$

$$= \begin{cases} 1-\exp\left[-\left(\dfrac{t}{6.333}\right)^{2.837}\right] & ,t < 7004 \\ 3.31e-3(t-7004)^{1.085}+1 & ,t \geq 7004 \end{cases}$$

The results of the function relative to fixed intervals of calendar time is given in and presented graphically in Figure 32.

t	E[N(*t*)]
1983/10/02	0.0
1984/10/04	0.0
1985/10/08	0.0
1986/10/11	0.0
1987/10/15	0.0
1988/10/18	0.0
1989/10/21	0.0
1990/10/25	0.1
1991/10/29	0.1
1992/10/31	0.1
1993/11/04	0.2
1994/11/07	0.2
1995/11/11	0.3
1996/11/14	0.4
1997/11/17	0.4
1998/11/21	0.5
1999/11/25	0.6
2000/11/27	0.6
2001/12/01	0.7
2002/12/05	0.7
2003/12/08	3.0
2004/12/11	5.3
2005/12/14	7.6
2006/12/18	10.0
2007/12/22	12.5
2008/12/24	15.0

Table 8 - Expected number of tube failures

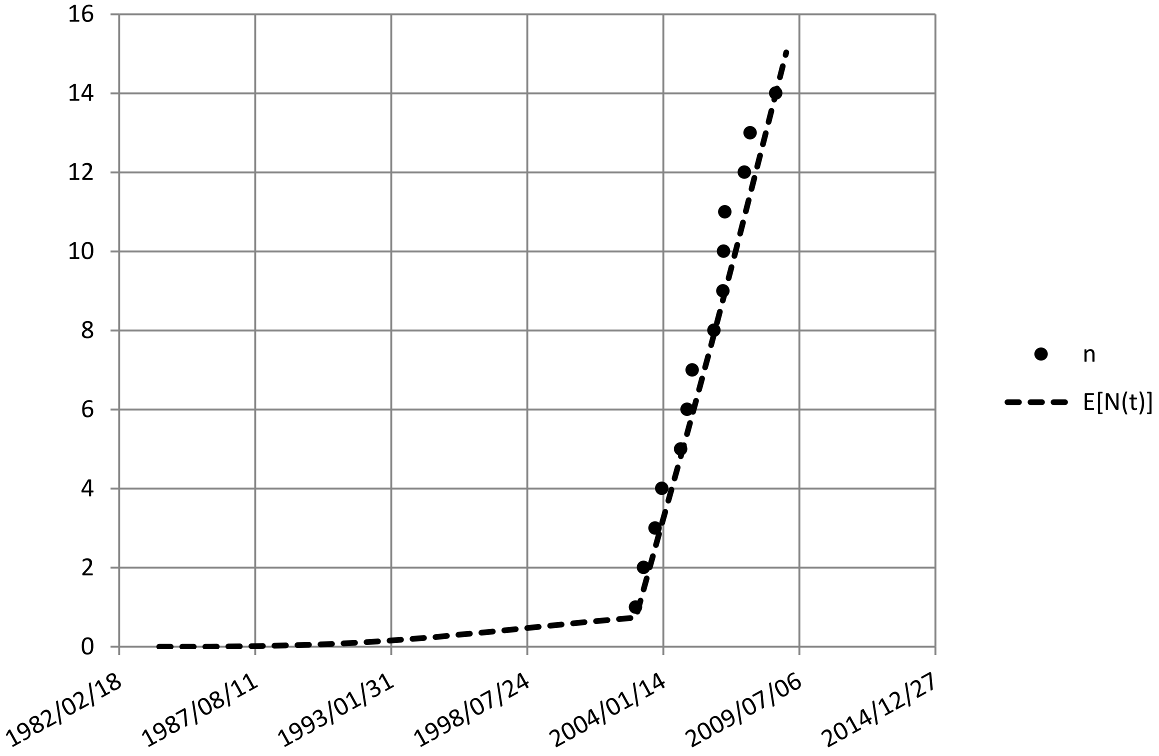


Figure 32 - Expected number of tube failure instances

Due to the conditional function's dependence on the occurrence of the initial tube failure and no quantified correlation between TTFF and $\beta \& \lambda$, the values of the NHPP parameters are still unknown at TTFF. The function can nonetheless be applied to accurately quantify the impact of deviation from the optimal replacement time as explained in the following section.

8.4 Cost of Failure – C_f

The consequence of tube failures is the loss of operation of heaters and the consequential loss of efficiency of the steam cycle during heater downtime. The layout of HP heaters in the feedheating plant makes it impossible to isolate only one heater during a failure. Two parallel banks, each containing two heaters, is installed on each 600MW unit. In the case of a tube failure, both heaters in a bank are isolated simultaneously. This reduces the final feedwater temperature which increases the energy consumption of a 600MW power unit by approximately 212 kJ/kWh. This consequence can be quantified in actual currency value given some relatively constant parameters namely, coal quality, coal cost and failure cycle downtime. Coal quality is taken as 21.1 MJ/kg and is found from existing plant efficiency report from August 2015 together with the coal price of R 192.85 from the same source. The failure cycle downtime is found from operational data for the entire power plant over a five year period and was found to be 8 days on average for the specific unit in question. The criteria used in this this regard to identify a tube failure was as follows:

If the differential temperature over heater 5 AND heater 6 is less than 10°C AND the unit produces more than 5MW, the bank is out of service. This data may be contaminated with HP heater tests and other possible causes of downtime for HP heaters. Thus the downtime days are only summated if more than 4 consecutive days are found in the data.

From Figure 33 it can be seen that unit 1 heater bank B downtime is found to be approximately 8 days.

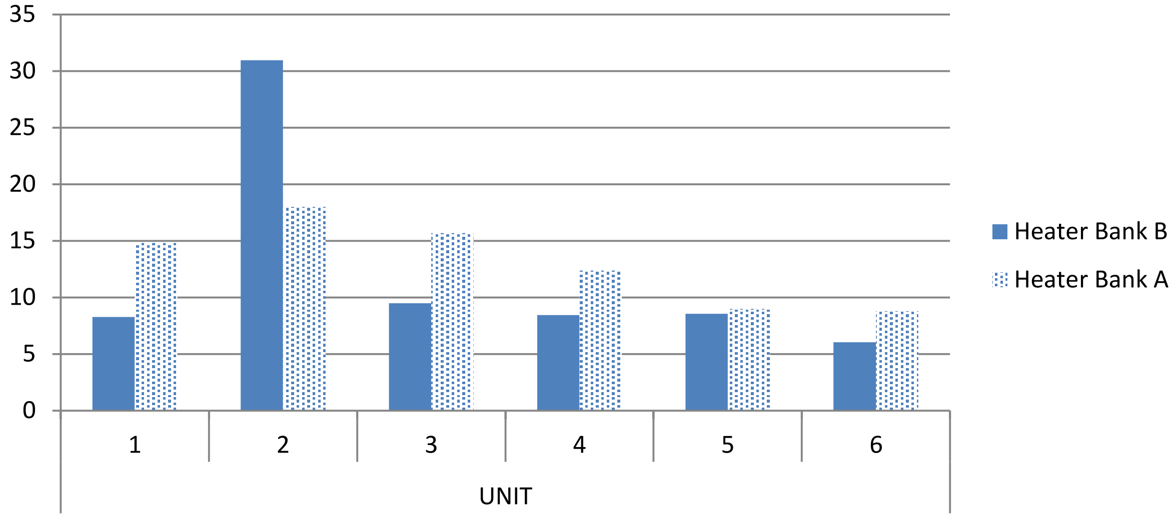


Figure 33 - HP Heater downtime days

Together with the variable cost of failure, the fixed cost of failure is also accounted for as approximately R 8 140 per failure cycle according to data provided by the power station.

Thus the cost, C_f, of a failure cycle was found to be R 231 356 with the assumptions above.

8.5 Cost of Imperfect Repair – C_{im}

Hundreds of tubes make up the tube bundle inside an HP heater. As these tubes fail and are plugged the heat transfer area inside the heater decreases and reduces the temperature of the exiting feedwater. As with the complete isolation of a bank of two heaters, the plugging of multiple tubes will also marginally increase the energy consumption of the boiler during its time in operation. To illustrate, consider the following figure.

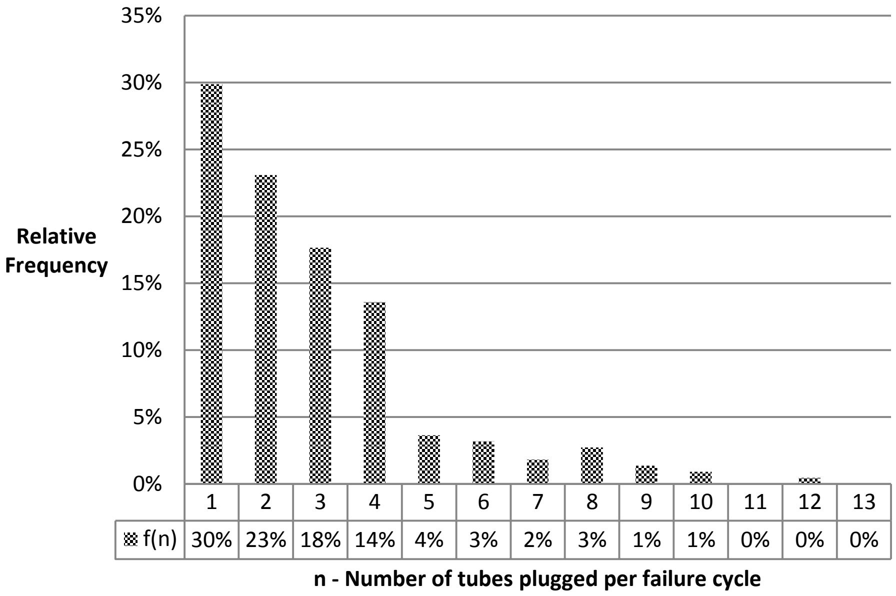


Figure 34 - Tube failure histogram

Figure 34 represents the relative failure frequency of the number of tubes during each failure cycle for all failure instances at DPS Power station. From this it can be seen that the probability that more than 4 tubes will fail during a failure cycle is less than 10 %. To determine the expected number of tubes during a failure cycle one must consider the following:

$$E[N(n)] = \sum_{n=1}^{\infty} nf(n) = 2.8$$

Thus for every expected number of failure cycles at a specified time, $E[N(t)]$, there is a constant linear accumulation of expected tube failures of 2.8, independent of time. This can be quantified in actual cost as a function of coal cost per ton. When both heaters are fully plugged, the boiler will consume 212kJ/kWh more than when both heaters are good-as-new. Each HP heater has 354 tubes which results in 708 tubes per bank. Thus every failure cycle of a heater will result in an additional reduction in net plant heat rate for the following period of operation.

From section 5.4.1 it can be seen that the reduction in performance, measured in outlet temperature loss, remains minute up until 40% tubes plugged. However, when the heater has been fully plugged there can be no heat transferred and in this state the outlet temperature loss will also be 100%. This results in an exponential curve for the expected outlet temperature loss for the remainder of the life of the heater.

This causes a compounding effect of the operational cost due to the continuous failure of tubes over time as seen in Figure 35 where the cost of loss of heater effectiveness is associated with failure cycles over calendar time as depicted in Table 5. This is the cost associated with imperfect repair and represented by C_{im}.

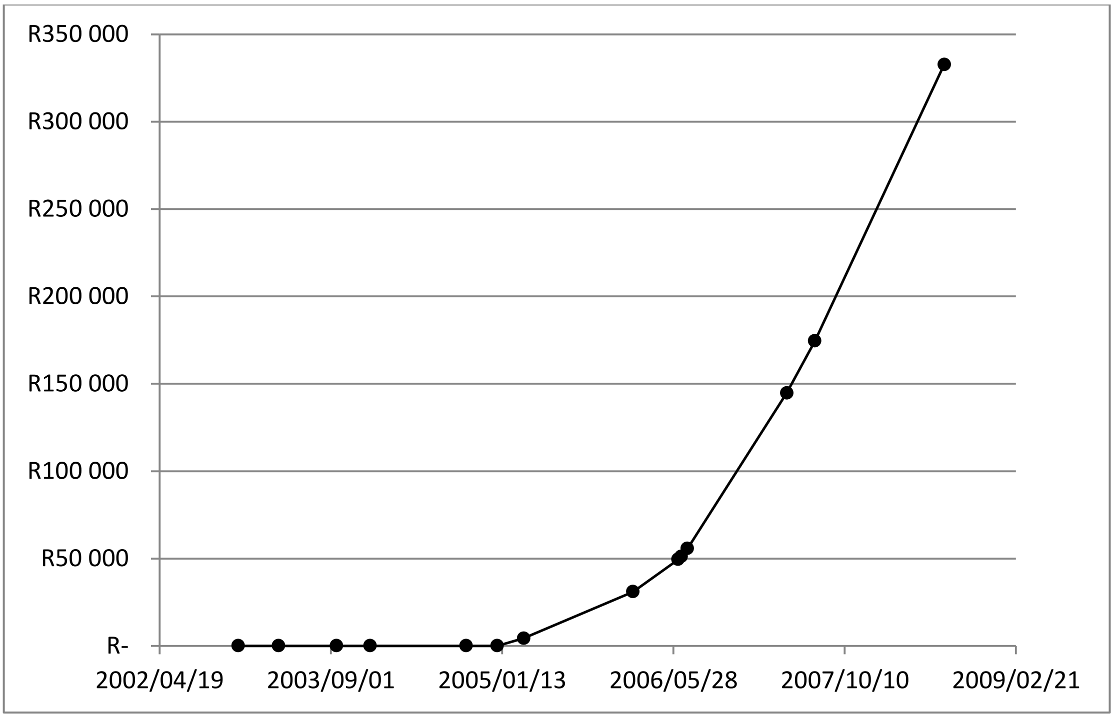


Figure 35 - Cost of Imperfect repair C_{im}

8.6 Estimating Cost of replacement - C_p

Cost of replacement, C_p, is also expected to increase over time. Due to the fluctuation in the value of local currency, the inflation of labour rates and the relationship between these factors, C_p increases in actual cost over time. To estimate the future cost of replacement, there must be a foundation to use a starting point. One such starting point is a HP heater replacement project which was completed at DPS Power station in 1994.

In 1994 a contract was placed to procure 2 HP heaters from a contractor for approximately R 1 485 750 each excluding installation, transport and VAT as seen in Table 9. This cost consisted of approximately 30% foreign content at a Rand/Dollar exchange of 3.45. This implies that the rate at which the estimated actual value of C_p escalates is dependent on both the rate of change of local content pricing, foreign content pricing and rand/dollar exchange rates. To account for inflation contract price adjustments (CPA's) are agreed upon during the contracting phase. CPA's follow an industrial producer price index (PPI) to escalate the contract value for the duration of the contract and consists of 89% labour and 11% basic materials.

This partitioning was consistent in all CPA's surveyed for HP heater procurement. To reduce the number of variables during estimation it is assumed that the local and foreign portion of the price escalate at the same rate which makes the function only dependent on the local labour PPI and the rand/dollar exchange rate. It must be considered that the installation of HP heaters occurs during a unit downtime period known as a General Outage and thus has no variable cost implications.

These expected values of C_p was thus determined by only using a single starting cost in 1994 and general macro-economic indicators which are readily accessible to the public. The current estimation of the expected cost of replacement in 2016 is determined to be R 17 092 055, within 1% of the actual quoted price from the same contractor for like-for-like equipment replacement. This equates to a compounded annual escalation of 12% and will yield the actual expected C_p.

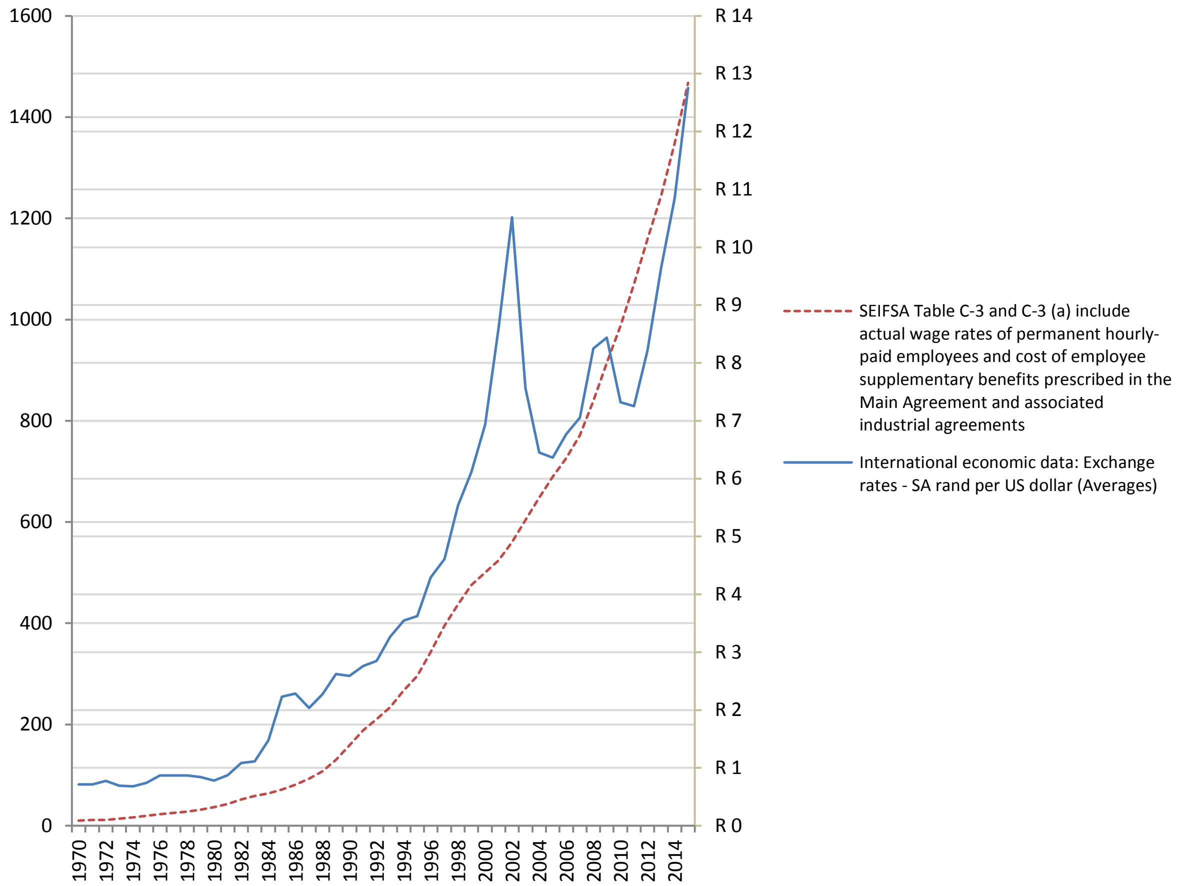


Figure 36 - Local Labour Inflation and Rand/Dollar Exchange Rates

Thus if the R/$ exchange rate is known and the local labour inflation is known over a specified number of years in future, the real inflation adjusted C_p can be estimated with 30% foreign content priced in American dollar. This notion is confirmed by a quotation from an HP heater vendor which indicated that the purchase price for a replacement HP heater for DPS power station would amount to approximately R 17.25m excluding installation.

Year	R/$	Local Labour Inflation	Local Portion	Foreign Portion		Expected Actual Price	Inflation Adjusted
1994	3.55	14.29%	R 1 025 750	$129 590	R 460 000	R 1 485 750	R 14 849 993
1995	3.63	10.47%	R 1 133 134	$143 157	R 519 228	R 1 652 362	R 14 874 456
1996	4.30	16.04%	R 1 314 897	$166 120	R 713 723	R 2 028 619	R 16 447 197
1997	4.61	15.16%	R 1 514 258	$191 306	R 881 412	R 2 395 670	R 17 493 383
1998	5.53	10.56%	R 1 674 228	$211 517	R 1 170 034	R 2 844 262	R 18 705 606
1999	6.11	8.74%	R 1 820 590	$230 007	R 1 406 061	R 3 226 651	R 19 112 154
2000	6.94	5.23%	R 1 915 725	$242 026	R 1 678 524	R 3 594 249	R 19 174 377
2001	8.60	4.85%	R 2 008 659	$253 767	R 2 183 189	R 4 191 848	R 20 140 677
2002	10.52	6.84%	R 2 145 998	$271 118	R 2 851 221	R 4 997 219	R 21 624 813
2003	7.56	7.75%	R 2 312 225	$292 119	R 2 209 795	R 4 522 021	R 17 624 301
2004	6.45	7.32%	R 2 481 537	$313 509	R 2 022 109	R 4 503 647	R 15 808 808
2005	6.36	6.40%	R 2 640 251	$333 561	R 2 122 061	R 4 762 311	R 15 055 945
2006	6.77	5.31%	R 2 780 483	$351 277	R 2 377 146	R 5 157 629	R 14 685 739
2007	7.05	6.29%	R 2 955 357	$373 370	R 2 633 900	R 5 589 256	R 14 333 595
2008	8.25	8.75%	R 3 214 086	$406 057	R 3 350 670	R 6 564 756	R 15 162 651
2009	8.44	8.98%	R 3 502 745	$442 525	R 3 733 650	R 7 236 395	R 15 053 387
2010	7.32	8.02%	R 3 783 748	$478 026	R 3 500 178	R 7 283 925	R 13 646 865
2011	7.25	8.33%	R 4 098 769	$517 825	R 3 755 821	R 7 854 590	R 13 253 981
2012	8.21	8.22%	R 4 435 596	$560 379	R 4 600 673	R 9 036 269	R 13 733 064
2013	9.65	7.50%	R 4 768 270	$602 408	R 5 813 371	R 10 581 640	R 14 483 939
2014	10.84	8.29%	R 5 163 519	$652 342	R 7 074 255	R 12 237 774	R 15 086 607
2015	12.75	8.86%	R 5 620 813	$710 115	R 9 054 439	R 14 675 252	R 16 294 091
2016	14.27	8.47%	R 6 096 985	$770 273	R 10 995 070	R 17 092 055	R 17 092 055

Table 9 - HP heater replacement cost estimation

8.7 Total Equivalent Uniform Annual Cost – $C(t)$

These three cost components $C_f, C_{im} \& C_p$ must be continuously considered for fixed intervals of cumulative calendar time to determine the minimum cost per unit time of operation. To calculate this cost the value of fuel and capital equipment is assumed to be constant over time and the cost of external borrowing of 9% is taken as the nominal discounting interest rate (WorldBank.org, 2015).

As discussed in section 8.6 the expected cost of replacement feedwater heaters escalate at a rate of 12% and thus the real annual discount interest rate is determined to be -2.7% as per equation 6-6.

In pursuance of a function minimizing the total present cost over the lifetime of the heater, equation 7-3 is applied from section 7.1:

$$\begin{aligned} C(t) &= \left(C_1 r^1\right) + \left(C_2 r^2\right) + \ldots + \left(C_t r^t\right) + \left(A r^t\right) \\ &= \left(C_f + C_{im}\right)_1 r^1 + \left(C_f + C_{im}\right)_2 r^2 + \ldots + \left(C_f + C_{im}\right)_t r^t + C_p r^t \\ &= \sum_{i=t}^{t} \left(C_f + C_{im}\right)_i r^i + C_p r^t \end{aligned} \tag{8-3}$$

(Shamir and Howard, 1979)

However, in order to find the equivalent uniform annual cost over the given lifetime, the capital recovery factor must be considered.

$$EUAC(t) = \left[\sum_{i=t}^{t} \left(C_f + C_{im}\right)_i r^i + C_p r^t\right] \times CRF \tag{8-4}$$

Where

$$CRF = \frac{i(1+i)^t}{(1+i)^t - 1} \tag{8-5}$$

Following an iterative approach, the results for a fixed time interval of one year is displayed in Table 10 with the following calculated parameters:

Coal Price	R 192.85 per ton
Fixed cost of failure	R 8 140
Coal CV	2.11E+07 kJ per ton
Mean number of tubes plugged per failure cycle	2.8
Tubes per heater	354
Maximum Continuous Rating	600 000 kW
Maximum Net Plant Heat Rate differential with heater bank out of service	212 kJ per kWh
Mean days downtime per failure cycle	8
Constant time interval	365
Cost of replacement	R 17 092 055
Discount rate	-2.7%

Year	t	$E[N(t)]$	C_{im}	$(C_f + C_{im})_i\, r^i$	$EUAC(t)$
1983	1	0.0000	R -		
1984	2	0.0003	R 0	R 72	R 17 092 125
1985	3	0.0022	R 0	R 457	R 8 663 232
1986	4	0.0069	R 0	R 1 175	R 5 854 524
1987	5	0.0154	R 0	R 2 215	R 4 450 932
1988	6	0.0289	R 0	R 3 564	R 3 609 434
1989	7	0.0479	R 0	R 5 203	R 3 049 018
1990	8	0.0733	R 0	R 7 096	R 2 649 244
1991	9	0.1052	R 0	R 9 193	R 2 349 885
1992	10	0.1438	R 0	R 11 427	R 2 117 474
1993	11	0.1889	R 0	R 13 715	R 1 931 923
1994	12	0.2399	R 0	R 15 961	R 1 780 441
1995	13	0.2962	R 0	R 18 060	R 1 654 494
1996	14	0.3564	R 0	R 19 908	R 1 548 167
1997	15	0.4195	R 0	R 21 405	R 1 457 233
1998	16	0.4839	R 0	R 22 466	R 1 378 585
1999	17	0.5482	R 0	R 23 029	R 1 309 893
2000	18	0.6107	R 0	R 23 061	R 1 249 376
2001	19	0.6703	R 0	R 22 561	R 1 195 648
2002	20	0.7257	R 0	R 21 561	R 1 147 619
2003	21	2.5846	R 20 368	R 778 682	R 1 132 522
2004	22	4.7872	R 30 553	R 959 702	R 1 124 438
2005	23	7.1010	R 50 921	R 1 070 528	R 1 119 860
2006	24	9.4871	R 71 290	R 1 169 798	R 1 117 833
2007	25	11.9272	R 91 658	R 1 265 703	R 1 117 825
2008	26	14.4110	R 112 027	R 1 361 183	R 1 119 477
2009	27	16.9313	R 132 395	R 1 457 693	R 1 122 526
2010	28	19.4832	R 152 764	R 1 556 094	R 1 126 770
2011	29	22.0629	R 173 132	R 1 656 970	R 1 132 050
2012	30	24.6676	R 193 500	R 1 760 752	R 1 138 237
2013	31	27.2948	R 218 961	R 1 879 360	R 1 145 470
2014	32	29.9427	R 249 514	R 2 014 050	R 1 153 880
2015	33	32.6096	R 280 066	R 2 153 873	R 1 163 351
2016	34	35.2943	R 310 619	R 2 299 124	R 1 173 786
2017	35	37.9954	R 356 448	R 2 488 830	R 1 185 780
2018	36	40.7120	R 397 185	R 2 673 403	R 1 198 983
2019	37	43.4431	R 437 922	R 2 865 745	R 1 213 299
2020	38	46.1881	R 478 659	R 3 066 197	R 1 228 644
2021	39	48.9461	R 519 396	R 3 275 101	R 1 244 943
2022	40	51.7165	R 560 133	R 3 492 809	R 1 262 129
2023	41	54.4988	R 651 791	R 3 871 868	R 1 282 208
2024	42	57.2924	R 712 896	R 4 175 057	R 1 303 766
2025	43	60.0969	R 774 002	R 4 491 742	R 1 326 708
2026	44	62.9118	R 835 107	R 4 822 459	R 1 350 950
2027	45	65.7367	R 906 397	R 5 201 723	R 1 376 808
2028	46	68.5712	R 1 028 608	R 5 772 538	R 1 406 129
2029	47	71.4151	R 1 110 082	R 6 227 265	R 1 437 174
2030	48	74.2679	R 1 191 555	R 6 702 518	R 1 469 850

Table 10 - HP heater present value

From the table above it can be seen that the minimum total present value continuously decreases to reach a minimum at 2007 which coincides with a plugging ratio of 9%. An HP heater with an estimated lifetime of 25 years is common from an industry perspective (EPRI, 2009).

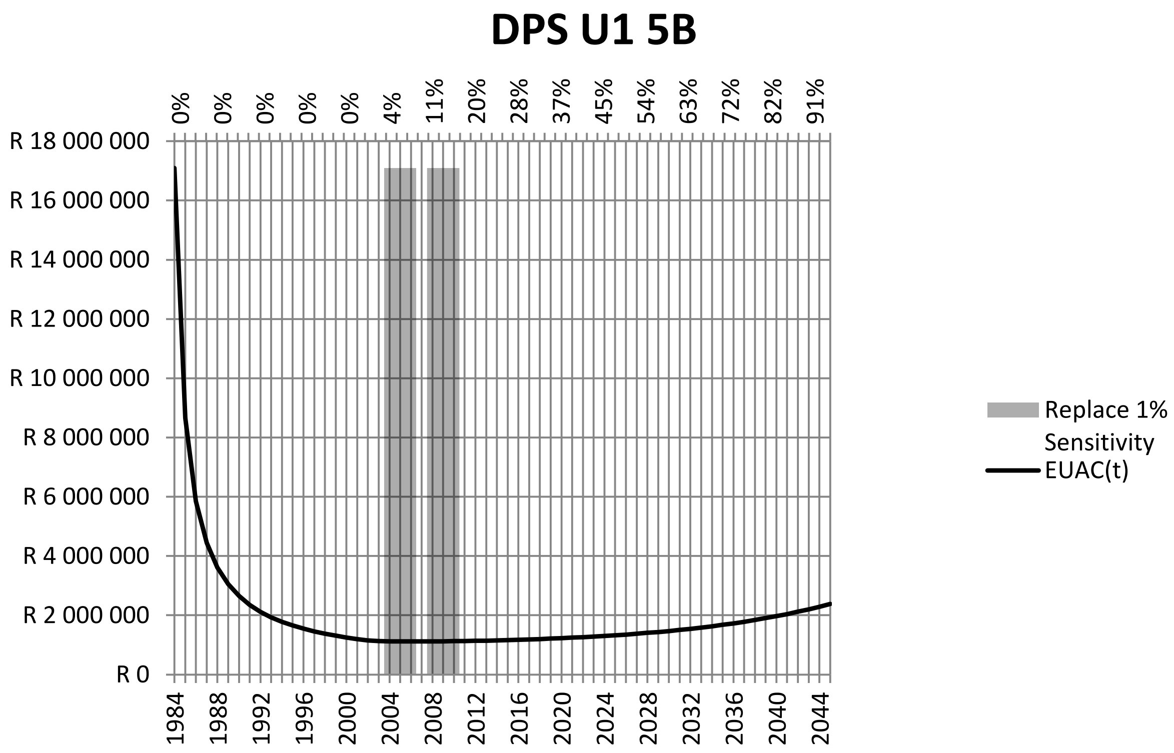


Figure 37 - Estimated present cost

Based on existing tube failure data and readily available macroeconomic indicators, the minimum life cycle cost can be determined. The use of existing data recording practices and reporting structures implies minimum infrastructure or policy amendment for the optimisation of decision support.

Elementary probabilistic and modelling techniques are applied to infer the optimal replacement time of unit 1 HP heater 5B at DPS power station. This technique can not only be applied to determine the optimal replacement time but also the consequence of sub-optimal replacement based on sensitivity analysis specifications. With a specified 1% sensitivity on minimum cost, a 9 year window is available for replacement.

This result is validated by a capital analysis where only the equivalent uniform annual cost (EUAC) for future years are considered. All past expenses are sunk costs and are not implicated in the replacement decision (Sepulveda et al., 1984). Here the annualised actual cost of operating and maintaining equipment is determined in order to compare to annualised actual capital cost. The annualised net present value of all expenses at some point in future will exceed the annualised cost of new equipment and indicates the prudent time to replace.

DPS power station can purchase HP heaters at R 17.25m in 2016 as mentioned in paragraph 6.4.1. In section 8.2 the expected failure free life of such a heater is determined to be 5630 days, amounting to approximately 16 years. Because no failures are expected during this period the expected operating and O&M costs are zero up to 16 years. Following the expected TTFF the annual operating costs increase similarly to the incumbent heater and thus the expected minimum cost life for the new heater is 16 years.

Year	Capital Recovery	O&M Cost	EUAC
2017	R 16 784 250	R -	R 16 784 250
2018	R 8 277 281	R -	R 8 277 281
2019	R 5 442 333	R -	R 5 442 333
2020	R 4 025 389	R -	R 4 025 389
2021	R 3 175 648	R -	R 3 175 648
2022	R 2 609 507	R -	R 2 609 507
2023	R 2 205 423	R -	R 2 205 423
2024	R 1 902 625	R -	R 1 902 625
2025	R 1 667 350	R -	R 1 667 350
2026	R 1 479 341	R -	R 1 479 341
2027	R 1 325 708	R -	R 1 325 708
2028	R 1 197 855	R -	R 1 197 855
2029	R 1 089 834	R -	R 1 089 834
2030	R 997 395	R -	R 997 395
2031	R 917 420	R -	R 917 420
2032	R 847 572	R -	R 847 572
2033	R 786 065	R 450 419	R 1 236 484
2034	R 731 507	R 540 139	R 1 271 646
2035	R 682 801	R 586 247	R 1 269 048
2036	R 639 070	R 623 313	R 1 262 383
2037	R 599 601	R 656 206	R 1 255 807
2038	R 563 814	R 686 654	R 1 250 468
2039	R 531 228	R 715 484	R 1 246 712
2040	R 501 442	R 743 161	R 1 244 603
2041	R 474 121	R 769 971	R 1 244 092
2042	R 448 980	R 796 106	R 1 245 085

Table 11 -Expected Equivalent Uniform Annualised cost of replacement heater

Thus the annualised cost of a new heater over 16 years is determined by the capital recovery factor (CRF) given by equation 8-5, which results in a EUAC of R 847 572 at a real inflation free interest rate of -2.7%.

This affirms the notion that immediate replacement is required in 2017 as the EUAC of O&M costs of R 954 871 exceeds that of annualised capital recovery as seen in Table 12.

Year	O&M Cost	EUAC
2017	R 954 870	R 954 871
2018	R 971 045	R 963 069
2019	R 985 458	R 970 737
2020	R 998 220	R 977 892
2021	R 1 009 431	R 984 550
2022	R 1 019 184	R 990 724
2023	R 1 069 606	R 1 002 939
2024	R 1 091 922	R 1 015 156
2025	R 1 112 166	R 1 027 152
2026	R 1 130 444	R 1 038 799
2027	R 1 154 392	R 1 050 804
2028	R 1 212 826	R 1 066 430
2029	R 1 238 668	R 1 081 962
2030	R 1 262 180	R 1 097 248
2031	R 1 320 625	R 1 115 159
2032	R 1 358 522	R 1 133 688

Table 12 - Equivalent Uniform Annualised Operation & Maintenance cost

8.8 Variation Analysis

The adjustment of any inputs as discussed in Chapters 5 and 6 will alter the results of the case study as in the previous sections in this chapter. Considering that common practice dictates the use of plugging ratio as determinant for replacement, the variation of optimal plugging ratio was evaluated for fixed variations in input values.

In Table 13 below, a listing is presented of inputs varied by -12.5% for a *Low Scenario* and +12.5% for a *High Scenario* to determine which inputs have the most significant influence on the optimal plugging ratio at replacement. For the case studies at DPS power plant the optimal replacement plugging ratio was 9%.

±12.5%	**Low Scenario**	**High Scenario**
Avg. Downtime	11%	6%
Coal Price	13%	6%
New Heater Price	13%	6%
Discount Rate	13%	4%
Tubes failed per cycle	10%	8%
Beta	21%	1%
Fixed Failure cost	9%	8%

Table 13 - Input influence on optimal % plugged

If the variation between the *Low Scenario* and the *High Scenario* is plotted as in Figure 38 it can be seen that all inputs can cause the optimal plugging ratio to deviate from 9%. However, variations in

ROCOF (represented by variations in Power Law parameter *β*) have the most significant influence on the optimal plugging ratio.

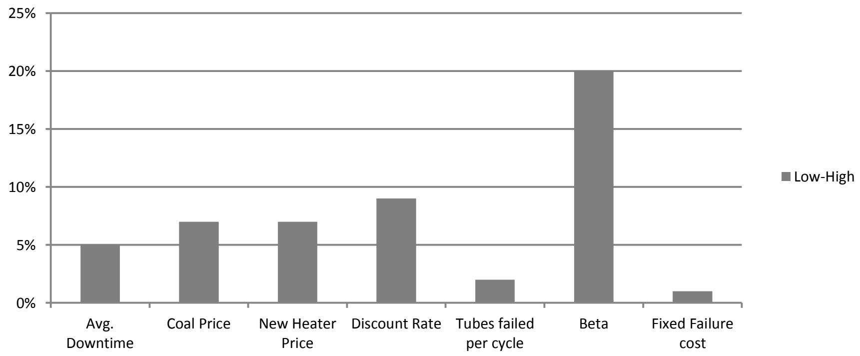


Figure 38 - Variation between Low and High scenarios for plugging ratio

In Table 14 the influence of the variation of inputs are examined for the optimal EUAC at replacement where a reduction in EUAC can be seen for all *Low Scenarios* and an increased EUAC can be seen for all *High Scenarios*. Again, it is the ROCOF of HP feedwater tube failures which have the most considerable influence on life cycle cost.

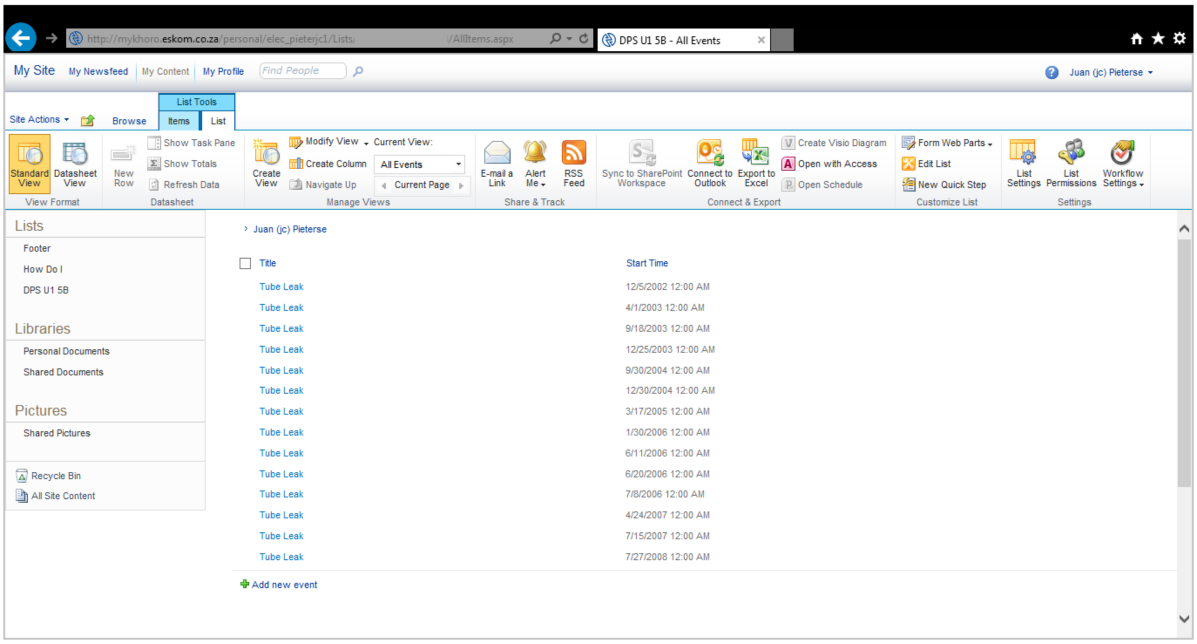
±12.5%	**Low Scenario**	**High Scenario**
Avg. Downtime	-1.7%	1.2%
Coal Price	-1.9%	1.3%
New Heater Price	-11.2%	10.6%
Discount Rate	-13.9%	12.1%
Tubes failed per cycle	-0.2%	0.2%
Beta	-24.9%	2.7%
Fixed Failure cost	-0.1%	0.2%

Table 14 - Input influence on EUAC

8.9 Implementation

An existing web based work share software suite, Microsoft Sharepoint, was utilized to propose a connection between failure data and the developed modelling workbook, as applied in the case study. This serves as a proposal for improved failure data record keeping and consequently, continuous analysis over the life of HP heaters.

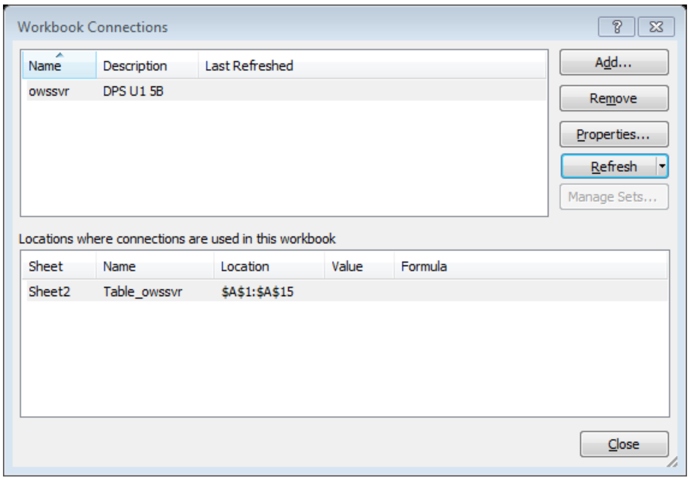
The failure data is captured in the web based calendar in Figure 39 and connected via an internal network server named *owssvr* (Figure 40) to the modelling workbook, shown in Figure 41. This implies that the data can be updated at the plant when failures occur and then analysed by any user with the required access to the shared modelling workbook.



› Juan (jc) Pieterse

☐ Title	Start Time
Tube Leak	12/5/2002 12:00 AM
Tube Leak	4/1/2003 12:00 AM
Tube Leak	9/18/2003 12:00 AM
Tube Leak	12/25/2003 12:00 AM
Tube Leak	9/30/2004 12:00 AM
Tube Leak	12/30/2004 12:00 AM
Tube Leak	3/17/2005 12:00 AM
Tube Leak	1/30/2006 12:00 AM
Tube Leak	6/11/2006 12:00 AM
Tube Leak	6/20/2006 12:00 AM
Tube Leak	7/8/2006 12:00 AM
Tube Leak	4/24/2007 12:00 AM
Tube Leak	7/15/2007 12:00 AM
Tube Leak	7/27/2008 12:00 AM

Figure 39 - DPS U1 5B Tube failure web based data

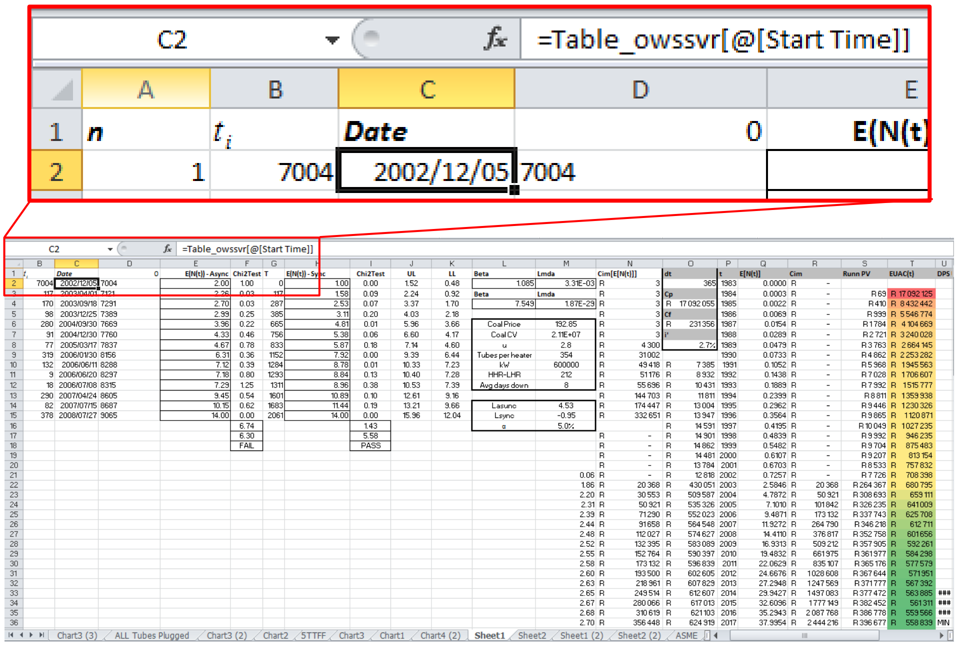


Name	Description	Last Refreshed
owssvr	DPS U1 5B	

Locations where connections are used in this workbook

Sheet	Name	Location	Value	Formula
Sheet2	Table_owssvr	$A$1:$A$15		

Figure 40 - Modelling workbook to Sharepoint server connection



C2 =Table_owssvr[@[Start Time]]

	A	B	C	D	E
1	n	t_i	Date	0	E(N(t)
2	1	7004	2002/12/05	7004	

Figure 41 - Modelling workbook with Sharepoint data server connection

8.10 Conclusion

Based on existing tube failure data and readily available macroeconomic indicators, the minimum life cycle cost can be determined. The use of existing data recording practices and reporting structures implies minimum infrastructure or policy amendment for the optimisation of decision support.

Elementary probabilistic and modelling techniques are applied to infer the optimal replacement time of unit 1 HP heater 5B at DPS power station. This technique can not only be applied to determine the optimal replacement time but also the consequence of sub-optimal replacement based on sensitivity analysis specifications. With a specified 1% sensitivity on minimum cost, a 9 year window is available for replacement.

This result is validated by a capital analysis where only the equivalent uniform annual cost (EUAC) for future years are considered. All past expenses are sunk costs and are not implicated in the replacement decision (Sepulveda et al., 1984). Here the annualised actual cost of operating and maintaining equipment is determined in order to compare to annualised actual capital cost. The annualised net present value of all expenses at some point in future will exceed the annualised cost of new equipment and indicates the prudent time to replace.

Without the need for a dedicated server, the use of Microsoft Sharepoint can be utilised to record failure data remotely and analyse up to date data without third party software integration. The developed workbook can readily be connected to the data server for rapid response to replacement queries.

9 Conclusions

9.1 Introduction

The research questions and research purpose are both addressed in this chapter. Findings concerning existing literature is discussed as well as subsequent recommendations. Constraints in applicability are mentioned and future work is proposed.

9.2 Research Questions

Revisiting the initial research questions in chapter 1:

> *1. What are the most significant cost factors involved in the lifecycle of HP feedwater heaters and how do they evolve over time?*

Tube failures are universally recognised as the most prominent cause of unplanned downtime in feedwater heaters. The tubes inside feedwater heaters are the most sensitive components and in the overwhelming majority of cases determine the usable life of the heater.

Tube failure data does exist in Eskom to accurately execute detailed failure analysis to deduce data driven results. Even elementary analysis based on tube failures is already a marked improvement in the existing replacement policies of HP heaters. The data can be used in a financial risk of failure model to qualify HP heater repair vs replacement decisions. Even though the results have proven to be promising, the methodology must still be applied to more HP heater tube failure data in Eskom.

The arrival time of the first tube failure, usually following the bulk of the operational life of the heater can in most cases observed, not be described by the same probabilistic function as the sequence of interarrival times to failure following the first failure of the same heater.

> *2. Can LCC methodology be applied to optimise HP feedwater heater replacement at Eskom?*

The minimum life cycle cost for HP feedwater heaters can be determined as demonstrated in a case study. The use of existing data implies minimum disruption to existing engineering and business processes but can significantly improve decision support.

While evaluating the effect on results, for the variation of the various inputs into the calculation, of annualised LCC it is clear that any change in input values affect the optimal replacement time.

Average downtime during tube plugging, contracted coal price, estimated cost of replacement and inflation free discount rate all have a similar influence on the optimal plugging percentage if varied by identical proportions of ±12.5%. These input variations can alter the optimal plugging ratio by between 5% and 10%.

The expected number of tubes plugged per failure cycle and failure cycle fixed cost have a much smaller impact on the optimal plugging ratio. By also varying these inputs by ±12.5% the optimal plugging ratio only varies by between 1% and 2%.

The most significant variation in optimal plugging ratio is caused the ±12.5% alteration in the Power Law parameter β which determines the tube failure ROCOF. The change causes a total 20% deviation from the optimal 9%.

All these input variations also affect total EUAC where tubes plugged per failure cycle and fixed cost of repair caused insignificant deviations of less than 1%, average downtime during tube plugging and contracted coal price cause small deviations of less than 4%.

Replacement price, discount rate and β cause significant changes to total EUAC of 20% or more for total variations of 25%.

9.3 Conclusions on the Research Problem

Revisiting the research purpose mentioned in chapter 1:

> *The purpose of this research is to develop an industry ready framework to find the optimal replacement time of HP feedwater heaters in Eskom based on minimum lifecycle cost.*
>
> *Data to perform this exploratory study is to be collected using existing reporting structures in the organization which is used to monitor the physical condition of feedwater heaters.*

By using existing data readily available in the Eskom business, the minimum life cycle cost for HP feedwater heaters in Eskom coal fired stations can be determined.

This information could accelerate decisions which maintain effective plant operation by improving planning and replacement scheduling. The combination of probability and consequence of failure form a foundation from which a decision can be made for the improved timing of replacement of heaters without any additional cost to the business.

In achieving the research purpose, the problem statement mentioned in chapter 1 is also addressed:

> *Eskom requires an improved understanding of the optimal age at which to replace HP feedwater heaters in coal fired power plants.*

9.4 Relation to literature

It is not prudent to rely on a fixed plugging ratio to initiate the procurement of new HP heaters in Eskom, as is the norm. Thus, in Eskom, it cannot be generally accepted that a feedwater heater is approaching replacement when approximately 10% of tubes have been plugged as mentioned by EPRI (2003).

From the data observed, no consistent evidence could be found of increasing ROCOF following the TTFF under synchronous sampling. This necessitates the use of a modified renewal process where the time to initial tube failure is not identically distributed to those that follow (Cox, 1962). These two phenomena, constant ROCOF and non-IID TTFF, can be seen throughout 30 different cases in Appendices A and B. Failure data was assessed for two unique designs and operating regimes from two different power stations. Hence, the TTFF in most cases will be handled as a discrete variable which initiates the synchronous sampling process used to determine the parameters of the NHPP.

In the cases where an increasing ROCOF was observed the increase was not significant enough to impress the universal existence of exponential growth in tube failures per unit time as indicated by Bell (1991). From a sample of 30 heaters subjected to the fitting of a NHPP Power law it was noted that the arithmetic mean of β was only 1.08.

With β being the exponent of the cumulative intensity function, it implies that it would be unlikely to find an HP heater deviating significantly from a constant ROCOF for tube failures in Eskom.

9.5 Recommendations

The physical impairment of feedwater heaters should not be the sole motivation for replacement as it may have several years of serviceable life remaining but not be economical to operate. Thus, the LCC approach as applied in the case study in Chapter 8 should be used in conjunction with existing capital investment qualification techniques already applied in Eskom.

Failure data forms the foundation of any residual life estimation problem. Quantitative failure data analysis is thus needed for plant management to improve the replacement planning of HP feedwater heaters. Special attention should also be given to the ROCOF of tube failures in HP heaters as it causes the greatest deviations of both LCC and optimal plugging ratio.

Tube failure data should be recorded diligently and subjected to the appropriate probabilistic methods to infer, within a specified time interval, the expected number of tube failure cycles for a specific heater. This should include proper record keeping of failures and continuous statistical analysis of recorded data to detect changes in the rate of tube failure. This can be done using the existing licenced work sharing software suite already implemented in the engineering business, connected a modelling workbook developed to conduct the case study in chapter 8.

9.6 Research constraints

External economic factors have a significant influence on the economic life of HP heaters. The failure cycle downtime, the fixed cost of repair, and replacement capital cost can alter the optimal replacement time of the heater by decades. Each of these factors can vary between different power stations and even among different units within a power station. Regardless of the variances in inputs, the framework of this research can be consistently applied where the required information is available.

HP heater downtime has been equated to the cost of fuel throughout this study to determine the operational costs of HP heaters over their entire lifecycle. This implies that the methodology contained in this research can only be readily applied to coal fired power plants. Consequently, this approach is not directly applicable to power plants where feedwater heater downtime cannot be translated directly to fuel cost such as nuclear or concentrated solar plants.

9.7 Future work

Due to the impact of repair time on the economic life of HP heaters, a serious consideration during the procurement of new HP heaters should be maintainability. If tube leaks cannot be repaired while the plant is on load the heater must remain out of service until a plant shut down occurs. Very little work could be found addressing the problems experienced with on-load tube plugging in HP feedwater heaters.

A study is required to determine what the main causes preventing HP heater tube repairs during on-load plant conditions and how their occurrence changes over time. This should be done in order to quantify the impact on HP heater availability and subsequent operational costs.

9.8 Conclusion

Tube failures are the most prominent cost consideration over the life of HP heaters. Tube failure data does exist in Eskom to accurately execute detailed failure analysis to infer data driven results. Even elementary analysis based on tube failures is already a marked improvement in the existing replacement policies of HP heaters. The rate at which tube failures occur is not universal but must be evaluated for individual heaters.

Life cycle cost methodology can and should be applied to determine the optimal replacement time for HP feedwater heaters in Eskom coal fired fleet rather than relying on a fixed plugging ratio of 10% to initiate replacement. This implies that the accuracy of tube failure data is crucial and that during tube repairs, the date and number of tubes must be recorded.

These findings are not applicable to nuclear or concentrated solar power plants. Additional research is also required to ascertain what the cost implications are of a lack of feedwater heater isolation, which prevents the on-load plugging of tubes.

END

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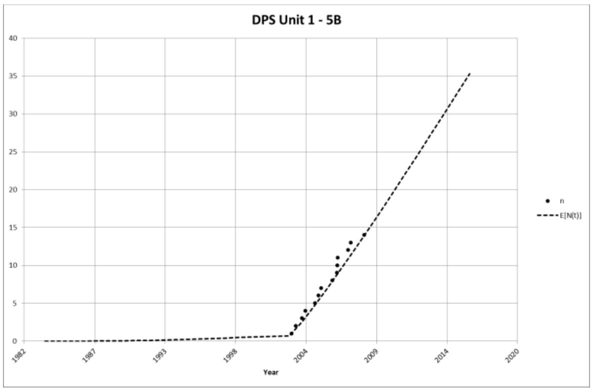
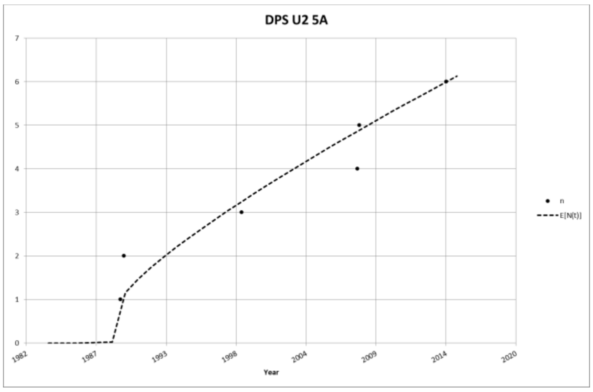
Appendix A

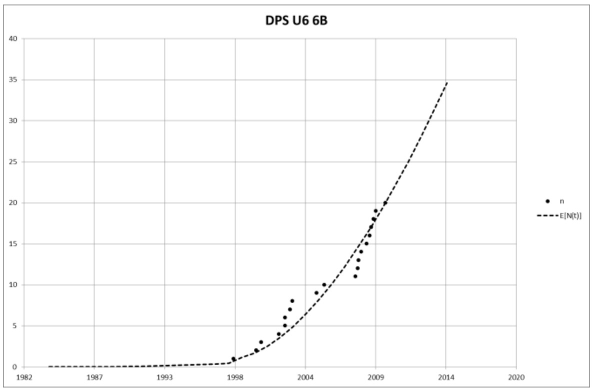
Graphical representation of DPS Power Station E[N*(t)*] functions with exponential parameters β shown in Table 15

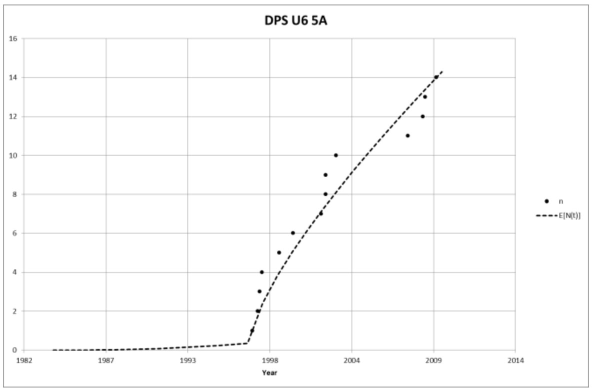
Heater	Beta
DPS U1 5B	1.085
DPS U2 5B	0.679
DPS U3 5B	1.576
DPS U5 5B	2.334
DPS U1 6A	0.859
DPS U2 5A	0.807
DPS U3 6A	0.591
DPS U4 6B	1.312
DPS U4 6A	1.319
DPS U5 6B	1.106
DPS U5 6A	0.949
DPS U6 5B	1.682
DPS U6 5A	0.768
DPS U6 6B	2.063

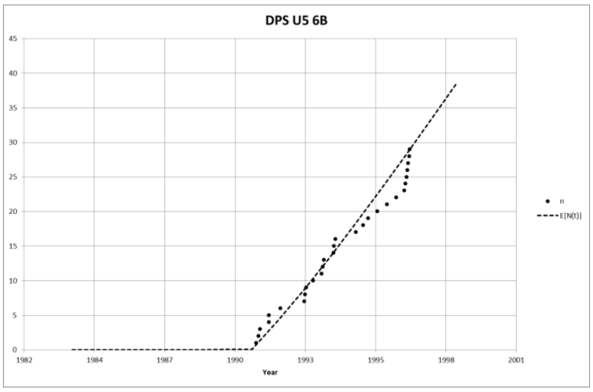
Table 15 - DPS HP Heaters β parameters










DPS U5 6B
45
40
35
30
25
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10
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1982
1984
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1998
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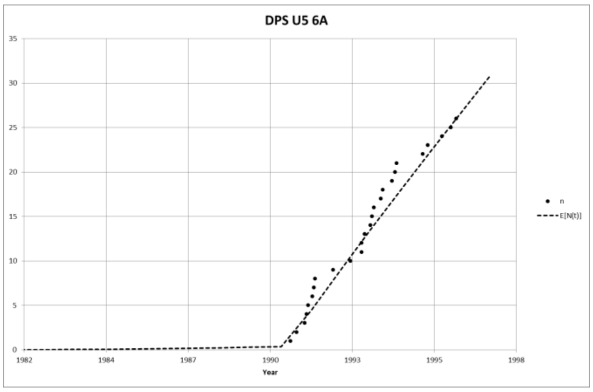
Year
n
E[N(t)]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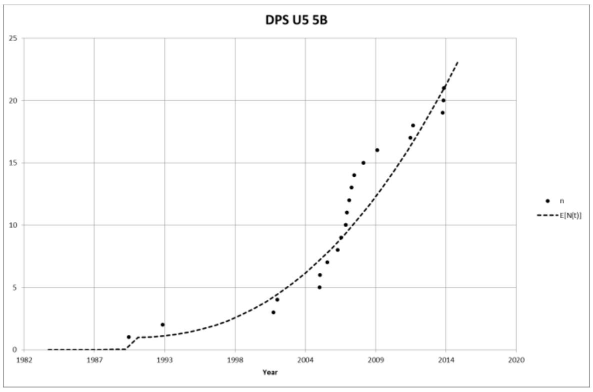
E[N(t)]


DPS U5 5B
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10
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1982
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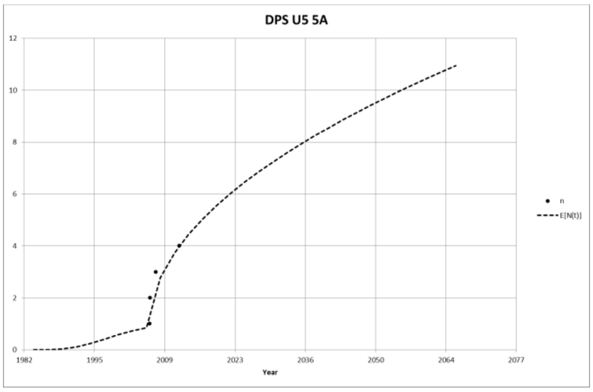
Year
n
E[N(t)]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2050
2064
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Year
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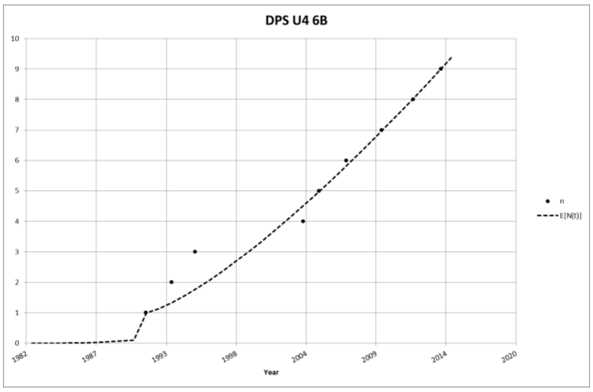
E[N(t)]


DPS U4 6B
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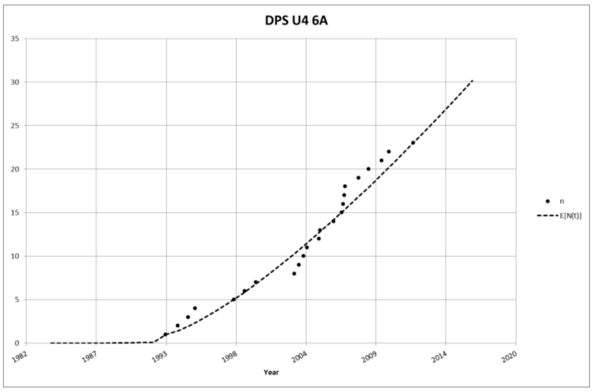
E[N(t)]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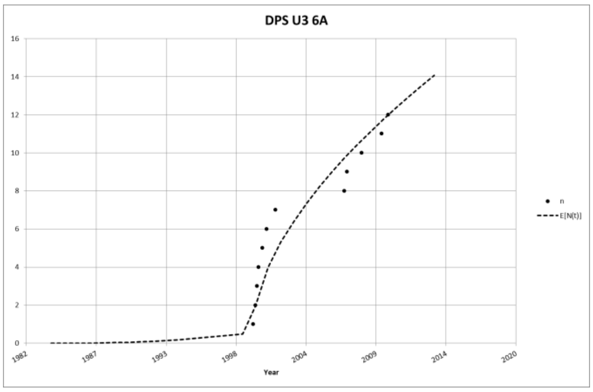
E[N(t)]


DPS U3 6A
16
14
12
10
8
6
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1982
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1993
1998
2004
2009
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Year
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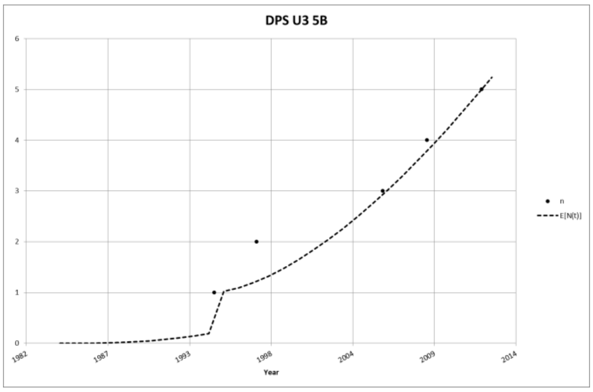
E[N(t)]


DPS U3 5B
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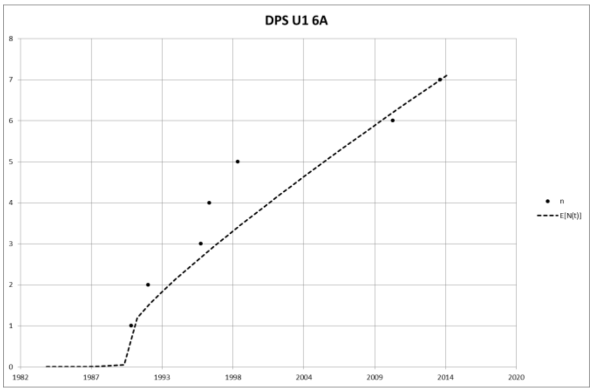
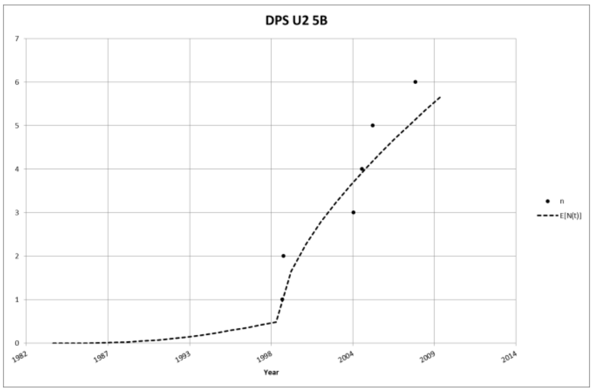
E[N(t)]



DPS U1 6A



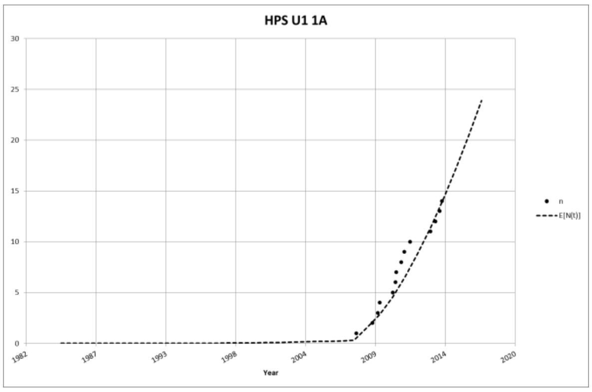
DPS U2 5B

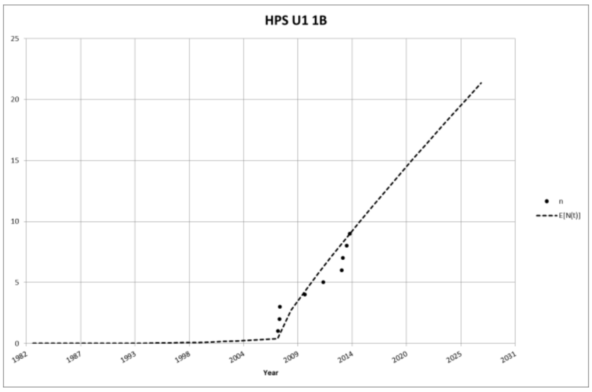
Appendix B

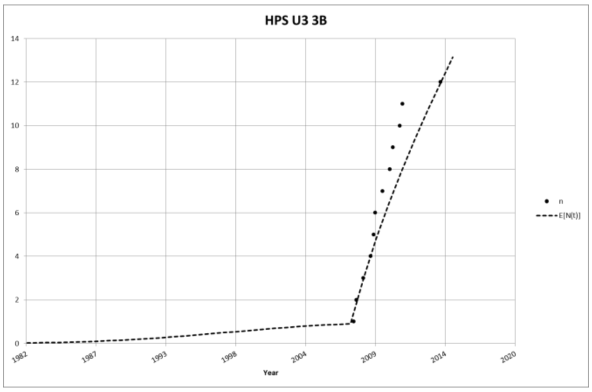
Graphical representation of HPS Power Station E[N*(t)*] functions with exponential parameters β shown in Table 16.

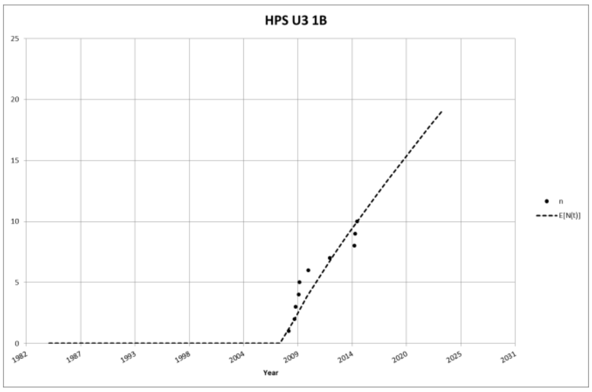
Heater	Beta
HPS U1 1A	1.496
HPS U1 1B	0.899
HPS U1 3A	1.070
HPS U1 3B	1.308
HPS U2 1A	1.011
HPS U3 3B	0.776
HPS U3 1B	0.863
HPS U4 2B	0.420
HPS U4 3A	0.890
HPS U5 1B	0.636
HPS U7 1A	1.543
HPS U8 1B	0.725
HPS U8 2A	1.840
HPS U10 1B	0.661
HPS U10 3B	1.504

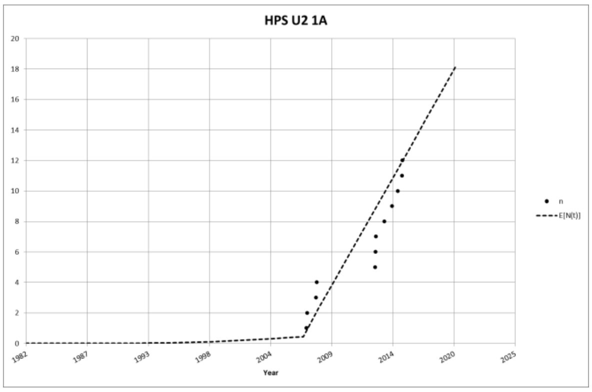
Table 16 - HPS HP Heaters β parameters










HPS U2 1A
0
2
4
6
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12
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16
18
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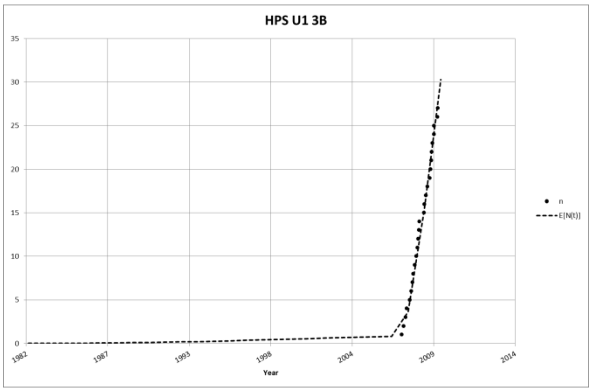
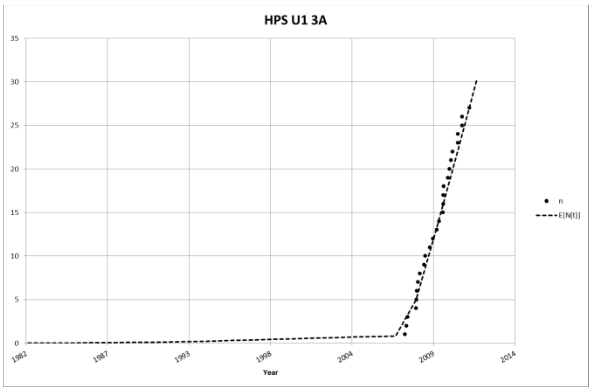
1982
1987
1993
1998
2004
2009
2014
2020
2025
Year
n
E[N(t)]


HPS U1 3B
0
5
10
15
20
25
30
35
1982
1987
1993
1998
2004
2009
2014
Year
n
E[N(t)]


HPS U1 3A
0
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20
25
30
35
1982
1987
1993
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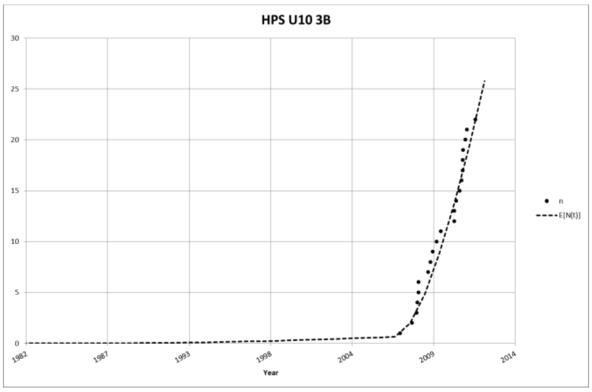
2004
2009
2014
Year
n
E[N(t)]


HPS U10 3B
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2004
2009
2014
Year
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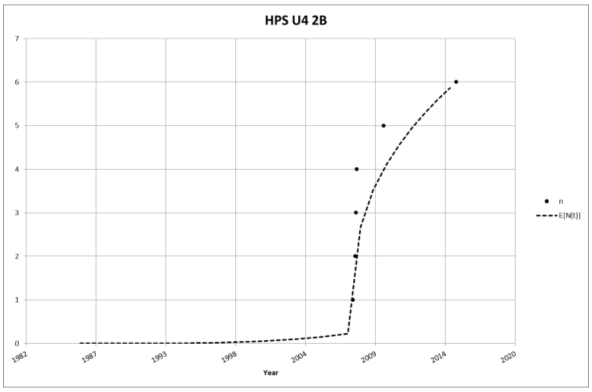
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2014
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Year
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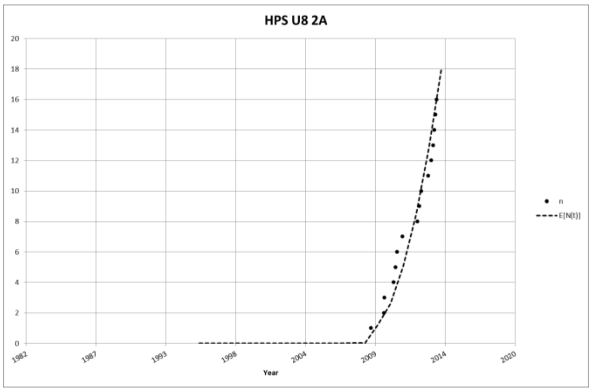
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Year
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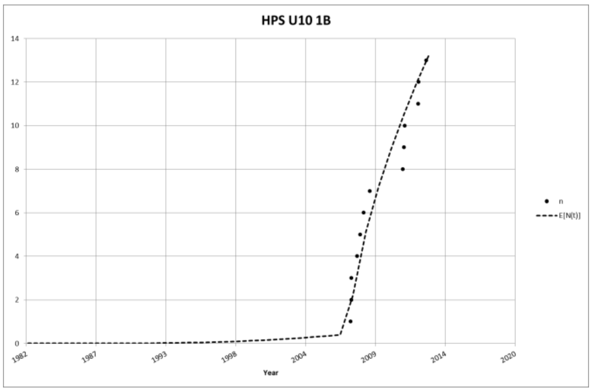
E[N(t)]


HPS U10 1B
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2
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12
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1982
1987
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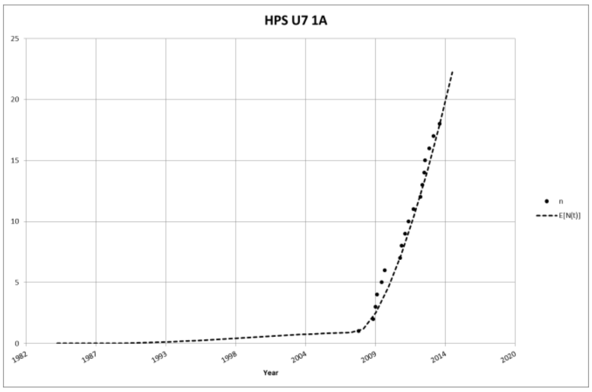
2009
2014
2020
Year
n
E[N(t)]


HPS U7 1A
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2014
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Year
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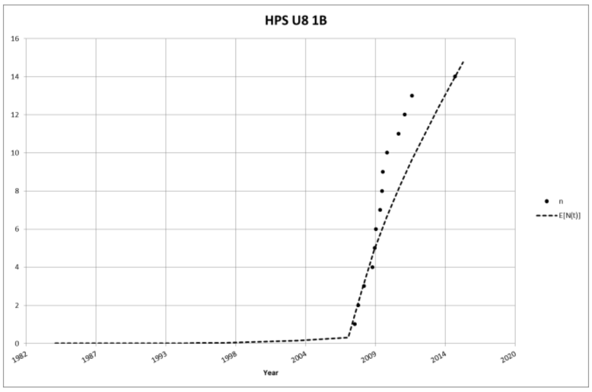
E[N(t)]


HPS U8 1B
16
14
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10
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2
0
1982
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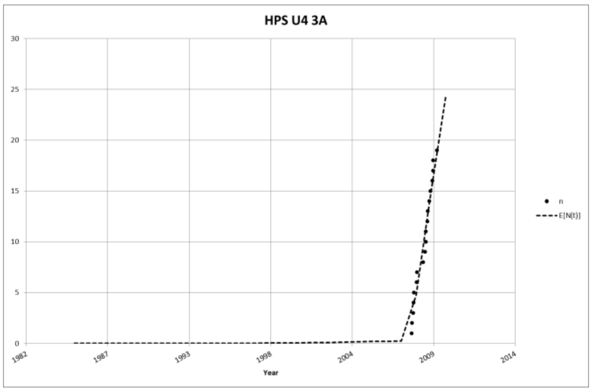
1998
2004
2009
2014
2020
Year
n
E[N(t)]


HPS U4 3A
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25
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15
10
5
0
1982
1987
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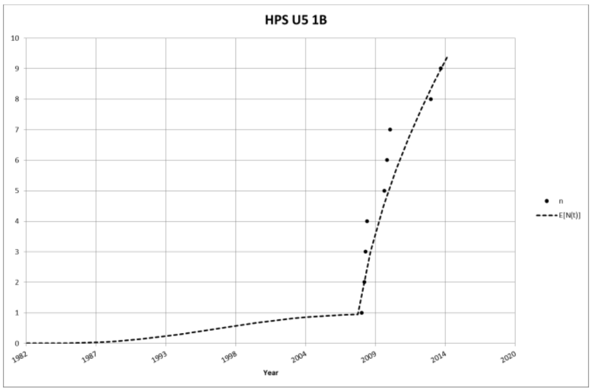
2004
2009
2014
Year
n
E[N(t)]


HPS U5 1B
10
9
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7
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3
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1
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1982
1987
1993
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2004
2009
2014
2020
Year
n
E[N(t)]