THE DEVELOPMENT OF A RISK-BASED MODEL TO PREDICT CORROSION FATIGUE FAILURES IN SUB-CRITICAL BOILERS

by

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DIE ONTWIKKELING VAN 'N RISIKO-GEBASEERDE METODOLOGIE OM KORROSIE-VERMOEIDHEID VAALINGS TE VOORSPEL IN SUB-KRITIESE KETELS

deur

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SUMMARY

THE DEVELOPMENT OF A RISK-BASED MODEL TO PREDICT CORROSION FATIGUE FAILURES IN SUB-CRITICAL BOILERS

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The increased energy demand within South Africa has led to continued periods of load shedding. This has had an adverse impact on industry, quality of life and the economy as a whole. A larger requirement for production time, reduced downtime and an enlarged focus on health and safety have steered industry towards a paradigm shift in inspection and maintenance. These activities have progressed from a predominantly time-based (prescriptive) approach towards a risk-based approach.

Generally accepted standards like BS EN 16991:2018 and API RP 580 give a comprehensive outline of the basic elements for developing, implementing and maintaining a risk-based inspection program. API RP 581 takes this outline one step further and contains the quantitative methods that support the minimum guidelines presented by API RP 580. Similarly, Kent W. Mühlbauer's approach has developed a relative risk ranking model for petroleum and gas pipelines, which outlines a qualitative method for representing risk. None of these models are however directly applicable to predicting the failure of pressurised boiler equipment due to the mechanism of corrosion fatigue.

API RP 580 / 581 was primarily developed for the oil and gas industry and have practical limitations when applied to pressurised equipment typically found in utilities. BS EN 16991:2018 supplies a framework for utilities, but doesn't go into the specific detail of how to structure, formulate and apply a risk based management model. The methodology laid out by Kent W. Mühlbauer, while practical and easily implemented, was designed for oil and gas pipelines.

A systematic methodology to evaluate the risk associated with specific failure mechanisms in boilers, such as corrosion fatigue, does not exist or is not readily available. A comprehensive risk-based predictive model, using aspects of the abovementioned standards and guides, was developed to demonstrate the predictability of corrosion fatigue in sub-critical boilers. Weightings were assigned to contributory causes to corrosion fatigue, which then allocated relative risk ranks to certain segments within a boiler. Operators and owners of boilers can derive benefit from this model by focusing inspection, maintenance and alteration activities on those equipment locations with the highest relative risk score.

Keywords: Asset Management, Risk based inspection, Corrosion Fatigue, Boilers, Pressure Parts, Relative Risk, Qualitative, failure prediction

RESEARCH OUTPUTS

Journal article

Conference presentations

Oral presentations

Poster presentations

DECLARATION

I declare that the dissertation/thesis, which I hereby submit for the degree M.Eng Metallurgy at the University of Pretoria, is my own work and has not previously been submitted by me for a degree at this or any other tertiary institution.

ETHICS STATEMENT

The author, whose name appears on the title page of this dissertation/thesis, has obtained, for the research described in this work, the applicable research ethics approval.

The author declares that she has observed the ethical standards required in terms of the University of Pretoria's Code of Ethics for Researchers and the Policy guidelines for responsible research.

Signature

Bianca Rode

Month Year

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In memory of Mr. P. Doubell

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LIST OF ABBREVIATIONS

Abbreviation	Description
AL	Action Levels
ALARP	As Low As Reasonably Possible
API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
AVT(O)	Oxidising all-volatile treatment
AVT(R)	Reducing all-volatile treatment
BTF	Boiler Tube Failure
CF	Corrosion Fatigue
CFC	Corrosion Fatigue Cracking
CPD	Condensate Pump Discharge
D	Drum Unit
DAI	Deaerator Inlet
DF	Damage Factor
EIC	Environmentally Induced Cracking
EI	Economiser Inlet
EPPEI	Eskom Power Plant Engineering Institute
EPRI	Electric Power Research Institute
FFP	Fit For Purpose
F_{ms}	Management System Factor
GMR	General Machinery Regulations
HAZOP	Hazard and Operability Analysis
HIC	Hydrogen Induced Cracking
IPP	Independent Power Producers
IRP	Integrated Resource Plan
KKS	Kraftwerk Kennzeichen System
NEMA	National Environmental Management Act
O	Once-through Unit
OT	Oxygenated Treatment

Abbreviation	Description
RIMAP	Risk Based Inspection and Maintenance Procedures for European Industry
SCC	Stress Corrosion Cracking
SF	Safety factor

CHAPTER 1 INTRODUCTION

1.1 BACKGROUND

Providing adequate and sustainable forms of energy is indispensable for the continued development and economic growth of South Africa. Economic growth enables South Africa in meeting environmental and social challenges, especially those associated with poverty. Additionally, affordable energy at sufficient quantity, is essential for improving the quality of life by raising living standards (Rogner & Popescu, 1999). The integrated resource plan (IRP), which was gazetted in October 2019, shows a plan to increase the installed energy generating capacity by 35% in 10 years.

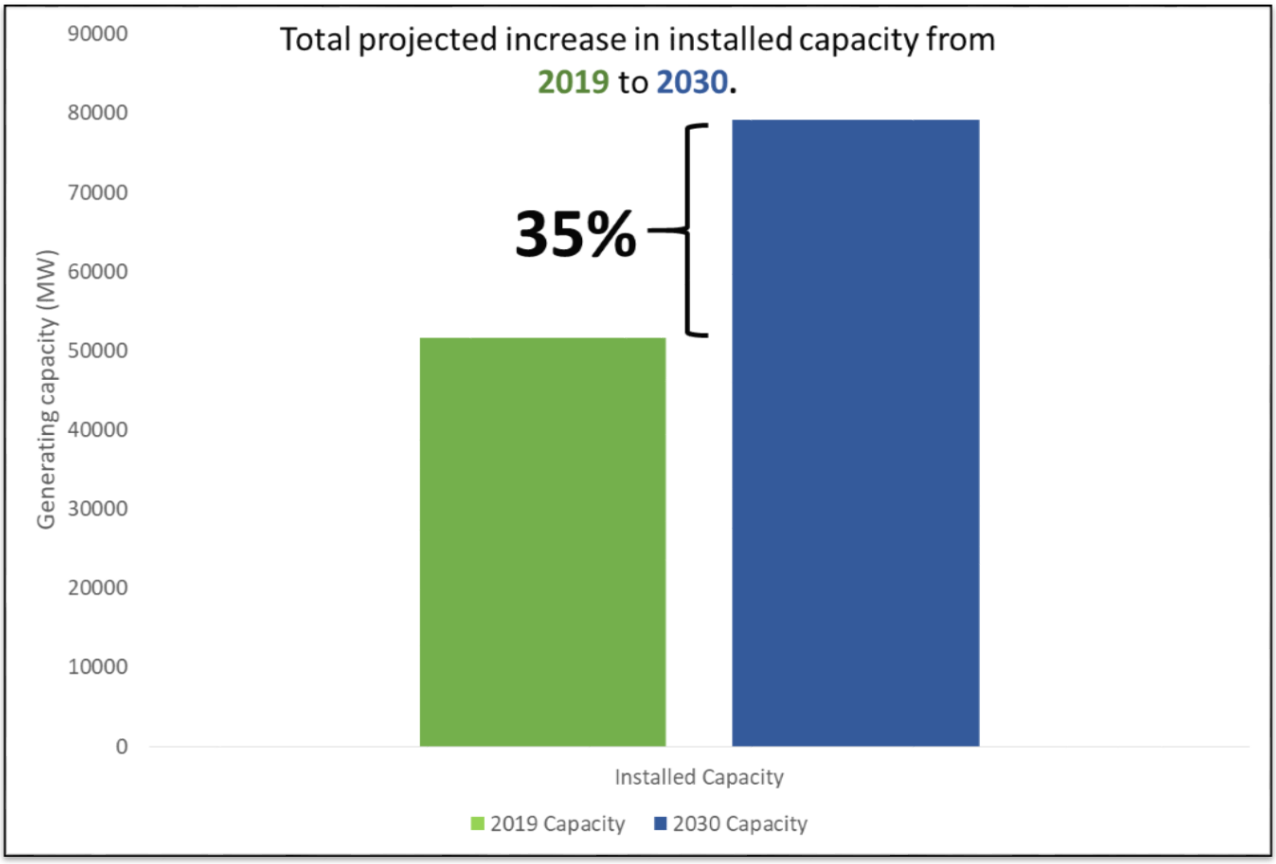

Figure 1: Increase in installed energy capacity (Government Gazette, 2019).

Coal contributes about 59% of South Africa's energy supply (Ratshomo & Nembahe, 2018). Within the commercial electricity generation sector (excluding embedded generation), 72% of electricity was generated by coal fired power stations in 2019 – see Figure 2 (Government Gazette, 2019).

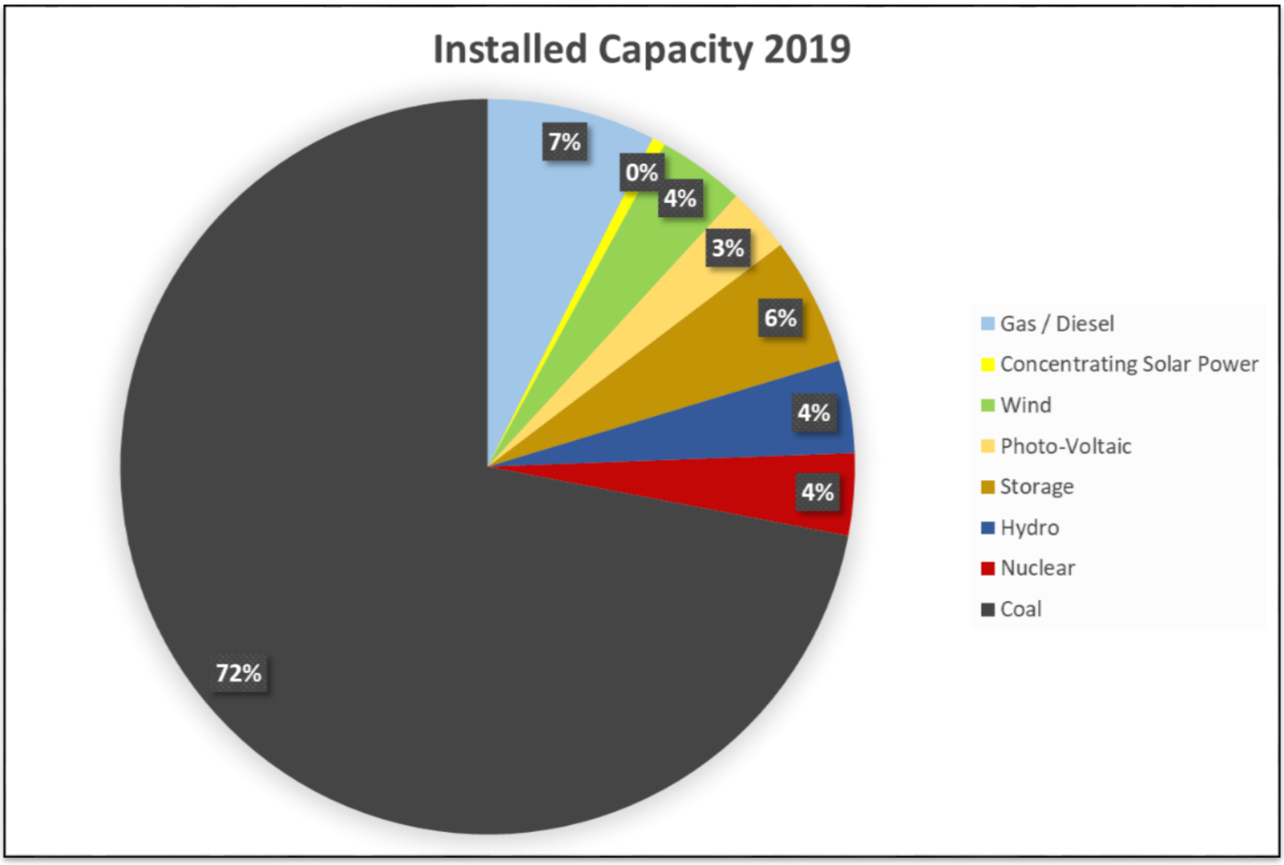

Figure 2: South African electricity generating capabilities in 2019 (Government Gazette, 2019).

The integrated resource plan (IRP) draws a map towards transforming the South African generation grid towards more renewable technologies and incorporating independent power producers (IPPs) into the system. Nonetheless, as can be seen in Figure 3, 42% of the capacity will still be coal fired power stations by 2030.

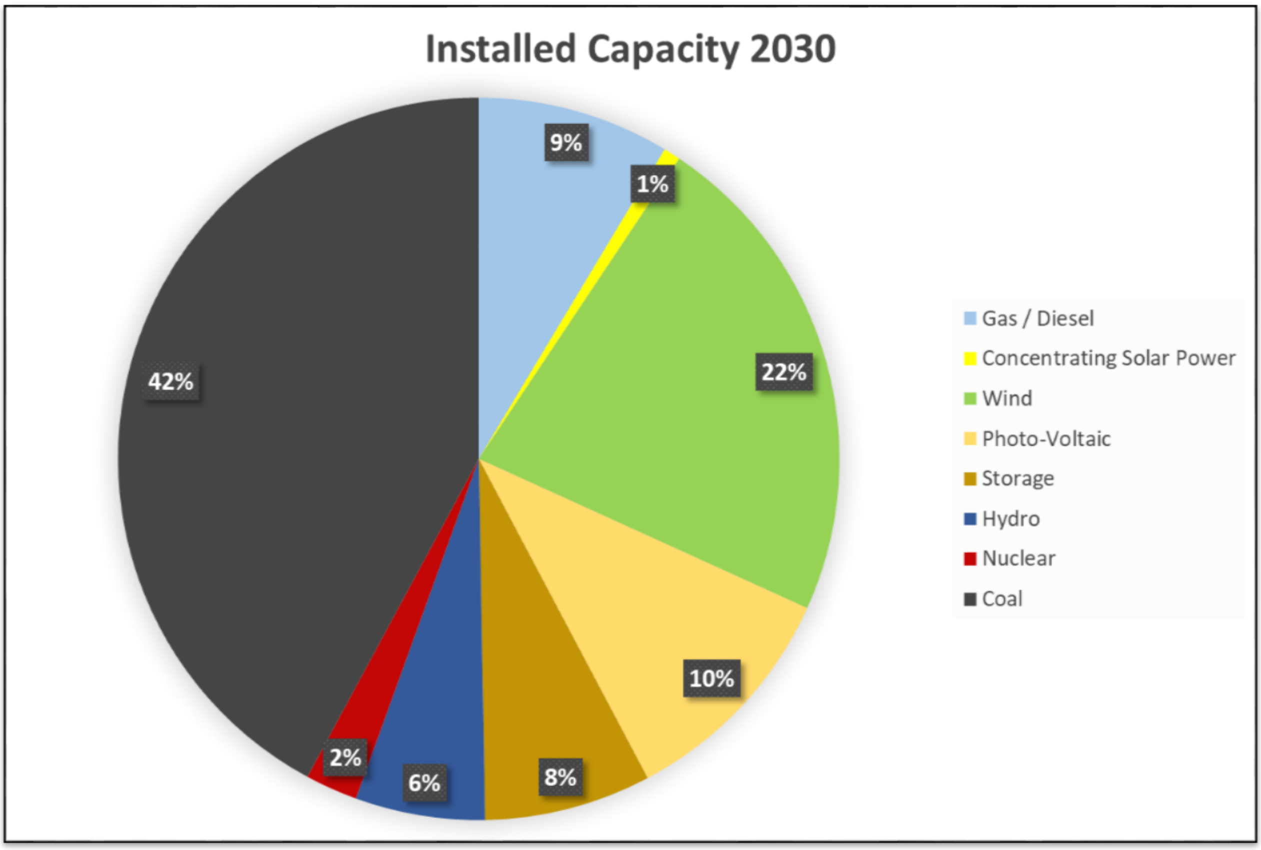

Figure 3: South African electricity generating capabilities in 2030 (Government Gazette, 2019).

According to the Government Gazette (2019), coal fired power stations within South Africa are aged (reaching the end of their 50 year design life), with the newest two stations struggling with design flaws and delayed commissioning. Both stations have been de-rated and will not be capable of delivering the full original complement of electricity. While it might be a popular notion to shut down some of the older power stations, these power stations have undergone significant refurbishment, and may end up being more reliable than the newer stations. One power station in particular has also undergone abatement, which makes it one of the only stations that is compliant to the National Environmental Management Act (NEMA): Air Quality, 2004.

Partially de-commissioning these plants will not be cost effective, as the electricity shortage will have to be supplemented by extremely expensive diesel peaking units. The future of these power stations are questionable while current regulation prohibits a competitive market (Ratshomo & Nembahe, 2018). However, it is not outside the realm of possibility that these power stations may find a second life if regulations can be loosened and these stations can be sold to IPPs. Kelvin Power Station is a prime example of where a relatively small and old power station can add value to the national grid while being operated by independent entities (Kelvin Power, *SA*).

Regardless of who is generating the electricity, the IRP clearly shows a continued dependence on coal and coal fired power stations. The industry at large will benefit from smarter maintenance practices in order to sustain or even increase generating capacity. This is further supported by only a 10% decrease in coal capacity according to the 2019 IRP – see Figure 4.

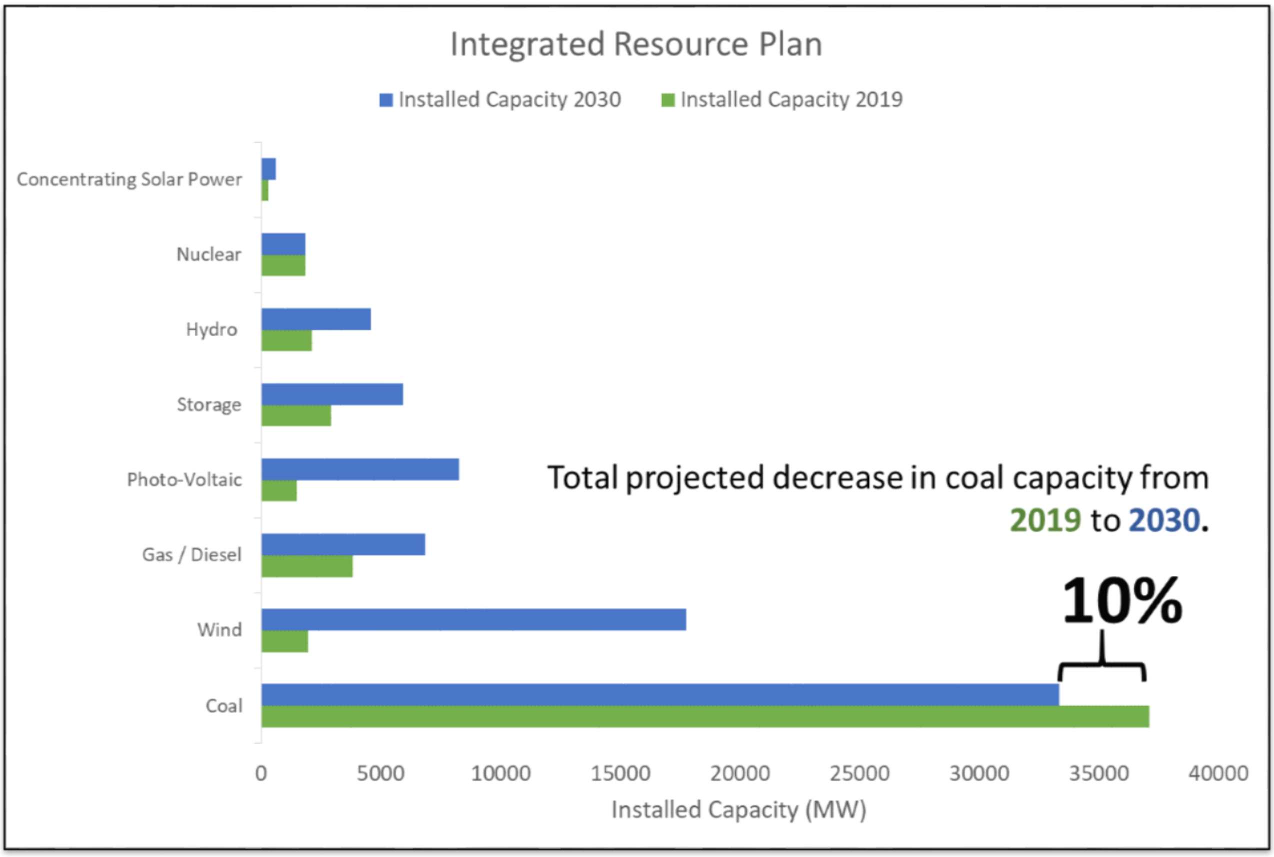

Figure 4: South African IRP showing the current and projected generation capacity (Government Gazette, 2019).

1.2 RESEARCH PROBLEM

High value assets (like boilers) have a significant effect on a business and can positively or negatively impact the management of business units unrelated to the high value asset itself (Institute of Asset Management, 2008). An effectively or ineffectively managed asset can influence the reputation of the company and morale of employees, which in turn, impacts how well management tools and programs are implemented, and regulations adhered to. All these aspects stimulate a company in positive and negative ways, the importance of which is often overlooked in favour of more easily quantifiable aspects.

Traditional asset management strategies have been focused on a prescriptive inspection philosophy, which has often resulted in excessive plant downtime and unnecessary loss in production and revenue. This is because such a strategy promotes high rates and volumes of inspection that lead to increased outage durations and high unavailability. Certain equipment are also adversely affected by being shut-down and opened for inspection, while others experience their worst operating conditions during shut-down and start-up (Ledimo, 2013).

The Electric Power Research Institute (EPRI) have conducted several boiler tube failure (BTF) statistical surveys and have ranked the mechanisms responsible in descending order below (Dooley & Chang, 2000):

1. Corrosion Fatigue
2. Fly Ash Erosion
3. Under Deposit Mechanisms (Hydrogen Damage and Acid Phosphate Corrosion)
4. Long Term Overheating/Creep
5. Short Term Overheating
6. Sootblower Erosion
7. Fireside Corrosion (Waterwall, Superheater, Reheater)

A systematic methodology to evaluate the risk associated with corrosion fatigue failures of boiler tubes in coal-fired boilers does not exist. If such a programme can be developed, it will be valuable to power plant owners / operators, because such a program should limit the number of shut-downs, increase boiler availability and extend the life of the boiler.

Complex boiler systems have always been data rich environments, and with the advent of the digital age, this trend has increased significantly. As a result of so many data gathering tools and applications being readily available to businesses these days, finding the data is not really the problem. In fact, it has become exceedingly tempting to gather too much data, to such an extent that it becomes impossible to assemble it into a coherent whole. When it comes to big data, the key is knowing what data and subsequent information is valuable, and what should be ignored. A systematic risk model will aid in differentiating between valuable data and data with lower worth.

Additionally, it has become imperative to extend the life of high value assets (like boilers) due to the high cost associated with fabricating and erecting new units. An influential study by Bent Flyvbjerg (2014), estimated that nine out of ten mega projects go over budget. This makes it essential to determine what to inspect / replace /repair, when to inspect / replace / repair and optimising inspection / replacement / repair methods.

1.3 RESEARCH OBJECTIVES

The main objective of this study is to apply risk-based processes in order to create a relative risk ranking model for boilers by focussing on the corrosion fatigue mechanism of boiler tubes. The main objective will be achieved by means of the following secondary objectives:

- Building a risk model, which will act as a framework
- A questionnaire that can be populated by any boiler owner
- Risk ranking in a standardised risk matrix
- Implementation and demonstration of the accuracy of the risk model by comparing the results of the model to that obtained from a commercial power plant

1.4 RESEARCH HYPOTHESIS

This study will consist of a literature review (secondary data analysis / archival study) and an empirical study. The aim is to determine a process and establish a useable methodology for an asset management program based on a risk model. A systematic methodology to evaluate the risk associated with corrosion fatigue failures in boilers can be developed using a combination of principal aspects from a combination of risk standards and manuals, as well as fundamental knowledge of the corrosion fatigue mechanism.

1.5 LITERATURE REVIEW

The literature review will include studying nationally and internationally published academic literature. This will be performed to obtain a comprehensive understanding of risk management, corrosion fatigue and data practices. Risk management will touch on various quantitative and qualitative approaches, with the four main sources being:

1. The Kent W. Mühlbauer handbook
2. Risk-based inspection framework - BS EN 16991:2018,
3. Risk-Based Inspection by American Petroleum Institute (API) - API 580
4. Risk-Based Inspection Technology by American Petroleum Institute (API) - API 581

Corrosion fatigue will be analysed as a failure mechanism, and because it consists of the interaction between corrosion and fatigue, an in-depth study of the underlying mechanisms will also be conducted.

1.6 EMPIRICAL RESEARCH

The empirical study will be performed using information from an actual power station (Mazibuko, 2014 & Meyer, 2017). This study will include both direct and indirect observation and experience of events on that power station.

CHAPTER 2 LITERATURE REVIEW

2.1 CORROSION FATIGUE

Below follows an in-depth discussion of the corrosion fatigue mechanism in order to understand the data requirements for a corrosion fatigue risk model. Corrosion fatigue is notoriously difficult to manage by inspection due to the location and morphology of cracking.

2.1.1 Background

A broad definition of corrosion is the tendency for a material to deteriorate due to it interacting with its environment (U.S. Department of Energy, 2014). For this to occur, a fluid-based environment requires electrolytes (Ahmad, 2006). Pure or distilled water has limited amounts of dissociated H^+ and OH^- ions and is subsequently a poor conductor of electricity. The current carrying capability of water is increased by the addition of acids, bases and salts that can dissociate into ions and is the foundation of boiler corrosion (U.S. Department of Energy, 2014).

Fatigue occurs when a material weakened by repeatedly applied (cyclic) loads. The damage incurred is progressive and localised with the nominal maximum stress values that cause such damage being below the ultimate tensile stress limit, or the yield stress limit. As the magnitude of the stress cycle increases the number of cycles to cause failure decreases. The “endurance limit” is the stress below which a material will last indefinitely (U.S. Department of Energy, 2014).

As suggested by the name, corrosion fatigue cracking (CFC) occurs as a result of the interplay between corrosion and fatigue. The susceptibility and rate of fatigue cracking is typically increased in a corrosive environment (Ahmad, 2006). A corrosive environment therefore reduces the endurance limit of a material. CFC does not require a specific environment and both alloys and pure metals are susceptible (Raghava, 1998). CFC is one of several failure mechanisms that consists of the interaction between stress and environment (Dooley & McNaughton, 2007). Other mechanisms with the stress-environment interaction are categorised as environmentally induced cracking (EIC) and are known as stress corrosion cracking (SCC) and hydrogen induced cracking (HIC). The distinction among various stress and environment driven failure mechanisms is illustrated in Figure 5 (Dooley & McNaughton, 2007). This distinction is semi-artificial and largely characterised by whether the stress or the environmental aspect seems to be predominant, and whether the mechanism is intermittent (cyclic) or continuous (static).

There is no unifying theory for corrosion fatigue and each alloy coupled with its unique environment will exhibit different behaviours, depending on the temperature, heat treatment condition and slip characteristics (Duquette, 2005). The result is the accumulation of damage through the interaction of the two main contributors. As illustrated in Figure 5, all three EIC phenomena can interact, and it is often difficult to distinguish between them (Jones, 1985).

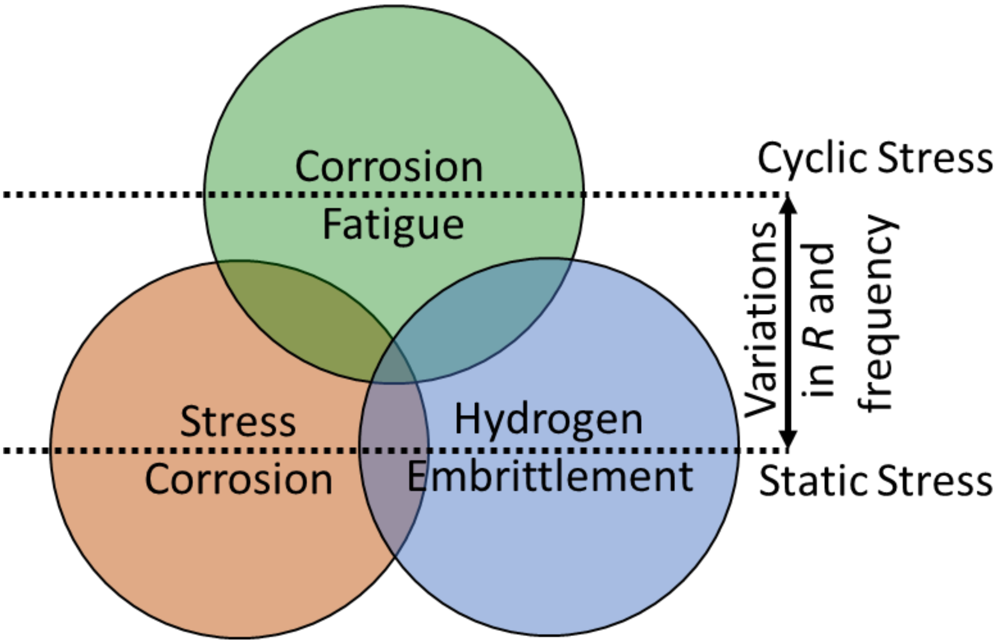

Figure 5: A Venn diagram showing the relationship between stress corrosion, corrosion fatigue, and hydrogen embrittlement, where *R* represents the ratio of minimum stress to maximum stress (Jones, 1985).

In summary; corrosion fatigue requires a

1. cyclic stress,
2. is accelerated in high temperatures,
3. does not require a specific environment,
4. both alloys and pure metals are susceptible.

Cracks are usually transgranular, unbranched and blunt tipped, with multiple stop-start locations and have corrosion product inside (Raghava, 1998).

2.1.2 Mechanisms

Understanding the basics of corrosion fatigue is necessary for identifying and preventing it. Therefore, a practical understanding of the underlying environmental and stress aspects should first be obtained.

Corrosion is a natural process, which converts a refined metal to a more chemically stable form, such as its oxide, hydroxide, or sulphide (Cramer & Covino, 2003). It is the gradual destruction of materials (usually metals) by chemical and / or electrochemical reaction with their environment (U.S. Department of Energy, 2014). Oxidation occurs when a material / medium loses electrons, while reduction occurs when electrons are gained. The formation and dissolution of oxide is predicated on this process.

Magnetite (Fe_3O_4) is a protective oxide layer that forms on carbon and low alloy steels in a high temperature and pressure environment. (Why carbon and low alloy steel? Because the majority of corrosion fatigue is seen on tubes which consist of carbon or low alloy steel.) This protective layer can be damaged mechanically, chemically or by a combination. The four possible mechanisms of corrosion fatigue are:

1. *Film rupture / stabilisation* involves rupturing the protective film and subsequent re-oxidation of the metal when it is exposed to the electrolyte after the initial localised attack (Ahmad, 2006).
2. *Mechanically-assisted chemical dissolution* occurs when material dissolution causes vacancies (Dooley & McNaughton, 2007). These vacancies are then driven by a stress field to accumulate at the crack tip and results in crack growth (Dooley & McNaughton, 2007).
3. *Hydrogen assisted cracking (or embrittlement)* occurs when carbon steels are exposed to a watery solution and the free hydrogen is subsequently absorbed into the metal. The electrochemical process embrittles the material in the vicinity of the corroding surface, making it susceptible to cracking when a load is applied (Ahmad, 2006).
4. *Strain-induced corrosion cracking* is similar to the film rupture model and is related to the local disruption of protective oxide. Destabilisation can occur as a result of the environment / electrolyte, by the application of a mechanical strain or as a result of material characteristics (Dooley & McNaughton, 2007).

2.1.2.1 Crack Initiation

Corrosion fatigue can therefore be induced by chemical or mechanical means. Those cases where disturbance of the magnetite layer occurs by chemical means, usually emerges at pre-existing active locations and takes the form of pits. Dooley & McNaughton (2007) have found that when mechanical dissolution is the primary culprit, multiple corrosion “paths” or an array of cracks are produced. Whether chemically or mechanically induced, the initial rupture of the protective oxide film will accelerate the effect of corrosion fatigue by exposing additional substrate metal to corrosion, and by producing crack-like defects that further concentrate stress.

The regularly spaced cracking associated with corrosion fatigue has been attributed to stress relaxation of the area directly adjacent to the crack. The maximum resultant stress will be between the existing crack and another crack or other pre-existing stress concentrator (Dooley & McNaughton, 2007). The increased strain on the oxide layer will result in the next crack forming between these two features.

2.1.2.2 Crack Propagation

The Paris equation is an analytical expression of the stress intensity factor and crack growth and is given by:

$\frac{da}{dN} = C(\Delta K)^n$ - Equation 1

Where da/dN is fatigue crack growth rate, ΔK is the stress intensity factor range (K_{max}-K_{min}), C and n are constants (available in the literature for specific alloys and environments) (Ahmad, 2006).

Fatigue crack growth has three basic regions. Region A is where the crack is initiated and begins to propagate. Region B is steady-state crack growth rate and Region C is the region where crack growth accelerates until fracture occurs (Ahmad, 2006).

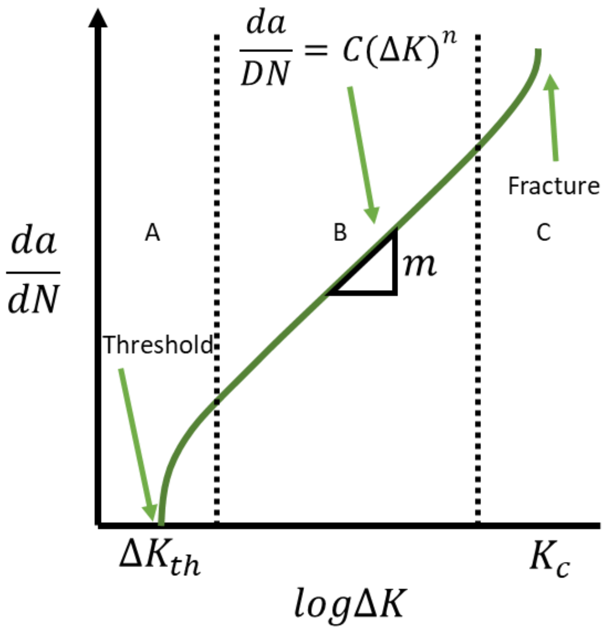

Figure 6: Graph illustrating the three basic crack growth regions (Ahmad, 2006).

The corrosion fatigue crack growth rate increases with an increase in the stress ratio $R=K_{min}/K_{max}$. Corrosion fatigue life is generally increased by a corrosive environment (Ahmad, 2006), as illustrated in Figure 7.

A high stress amplitude will result in lower environmental contributions, but may lower the fatigue life of a component. This kind of crack propagation will have more fatigue characteristics, while a low amplitude will favour environmental interaction. For instance, a higher load ratio will lead to a higher mean load and subsequently accelerate the interaction between environment and crack tip (Ahmad, 2006).

The rate of transfer of the environmental species, or the time available for interaction between the environment and the cracks is also important. If the loading rates / frequencies are too fast, insufficient time would be available for the species to reach the boundary layer, and the damage would be purely mechanical in nature (Ahmad, 2006). However, if the mean tensile stress (interacting with the crack) is high, the stress intensity at the crack tip will be higher and consequently expose the crack for a longer period of time to the corrosive environment. Corrosion fatigue rates will increase because a larger surface area is exposed to the corrosive environment.

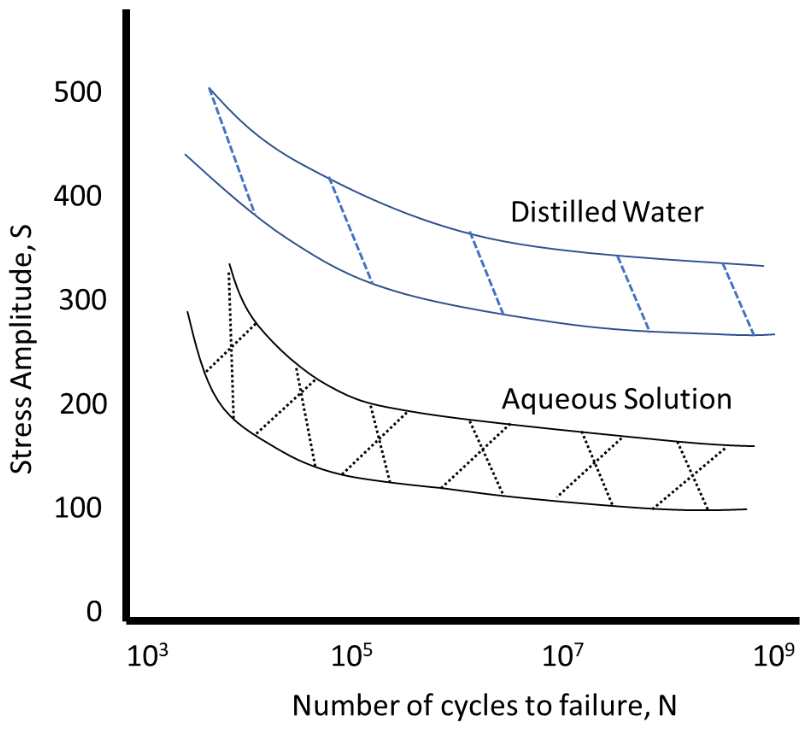

Figure 7: Graph showing the effect of a corrosive environment on the fatigue life of a material (Ahmad, 2006).

The interaction of environment and stress is more complex than expressed in Figure 7. An increase or decrease in the pH of the electrolyte within a crack is largely dependent on the extent to which the electrolyte is refreshed by the opening and closing of the crack during the fatigue cycle. Initiation and propagation of a corrosion fatigue crack is subject to the nature of the reactions taking place at the crack tip and electrolyte interface. In order to evaluate the rate of initiation and propagation, full knowledge of the electrolyte chemistry is required (Hart, Tennant & Hooper, 1978).

In summary, a corrosive environment will decrease the load necessary to induce CF. A higher load ratio and loading rate will accelerate the CF mechanism, except in those instances where it is so high that pure fatigue occurs.

2.1.3 Operational Factors

Operational regime and practices have a significant effect on the prevalence of corrosion fatigue in boilers. Table 1 provides a summary of operational factors and the effect they have on a unit's susceptibility to corrosion fatigue.

Table 1: Operational factors and the effect on corrosion fatigue susceptibility.

No.	Operational Factor	Effect
1	High frequency of boiler start-up / shut-down	A source of thermal stress cycles – see Figure 10 (Dooley & Chang, 2000)
2	Significant operating hours	A source of thermal stress cycles – see Figure 10 (Dooley & Chang, 2000)
3	Improper chemical cleaning	Improper chemical cleaning can result in an increase of corrosion fatigue failures. In those units where pre-existing cracks exist, the acid can remove the protective oxide within the crack and expose the underlying material to the corrosive environment (Dooley & Chang, 2000)
4	Lack of feedwater chemistry control (dissolved oxygen)	Above 135°C dissolved oxygen has a significant effect on corrosion fatigue crack initiation (Dooley & Chang, 2000). The relationship is made more complex due to the lowered solubility of oxygen at higher temperatures. During start-up the dissolved oxygen can be as high as

No.	Operational Factor	Effect
		8,000 ppb, but by the time that the highest level of strain is applicable at the corrosion fatigue locations, the oxygen level in the boiler water should be low (< 10 ppb) – see Figure 8 (Dooley & McNaughton, 2007).
5	Lack of feedwater chemistry control (pH)	Depressing pH to lower than 8 during start up can cause corrosion fatigue in phosphate treated units when there is phosphate hideout return (see Figure 9) and in all-volatile treatment (AVT) units by CO_2 ingress (Dooley & Chang, 2000).
6	Boiler layup conditions	Improper boiler layup procedures can result in pitting and aggravate corrosion fatigue, particularly if the pH was depressed and dissolved oxygen levels were not controlled (Dooley & Chang, 2000).
7	Boiler water contamination	The amount of cycles required to initiate corrosion fatigue is much lower in boilers with contaminated water – see Figure 11 (Dooley & Chang, 2000).
8	Strain reversal frequency	Corrosion fatigue initiation potential is increased at lower strain reversal frequencies. This is because lower frequencies allow for the corrosive aspects of the mechanism to take full effect.
9	Ramp-up or shut-down rates	Faster ramp-up rates or forced cooling will increase the magnitude of the cyclic strains (Dooley & Chang, 2000).
10	Temperature range	Corrosion fatigue is prominent during intermediate temperatures (149°C -316°C) (Dooley & Chang, 2000).

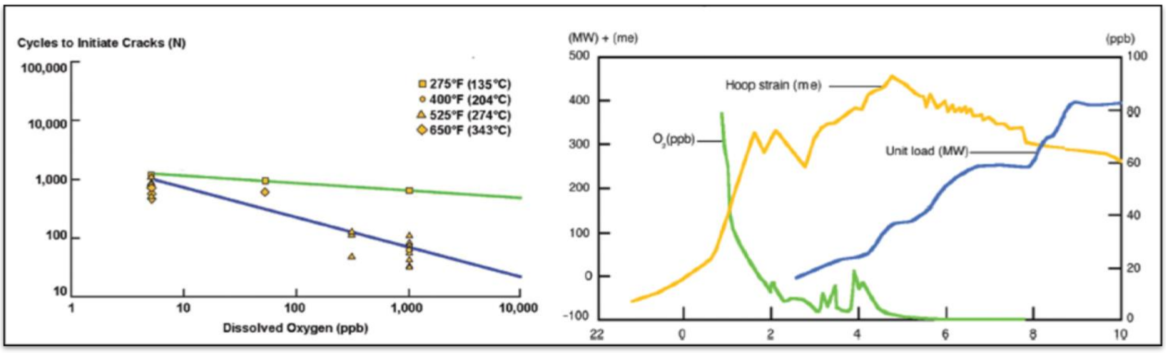

Figure 8: The effect that dissolved oxygen has on corrosion fatigue (left) and measured during boiler start-up (right) (Dooley & Chang, 2000). The x-axis on the right hand graph represents time from start-up in hours.

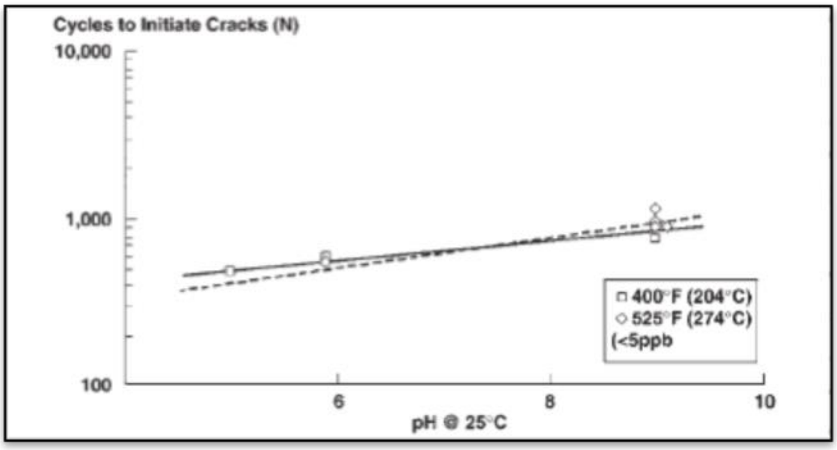

Figure 9: The effect of pH on corrosion fatigue crack initiation (Dooley & Chang, 2000).

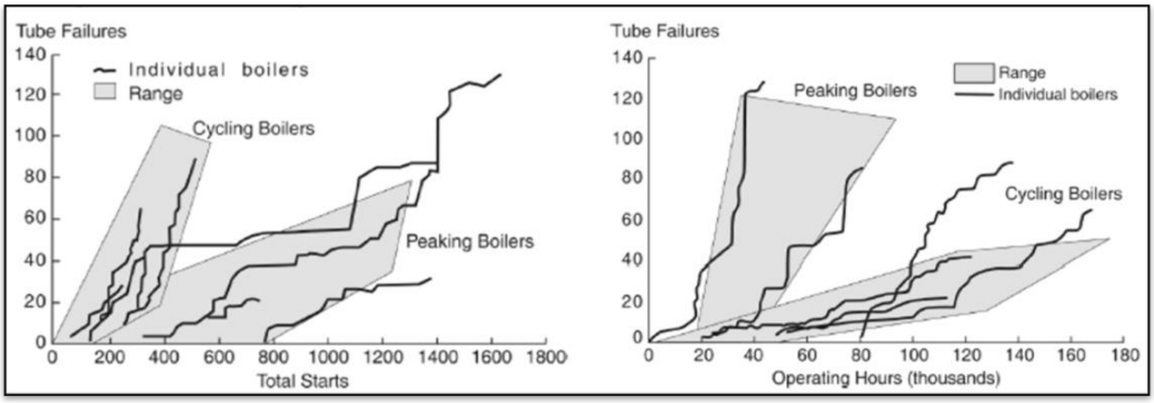

Figure 10: Corrosion fatigue tube failures vs total starts (left) and corrosion fatigue tube failure vs operating hours (right) (EPRI, 1996).

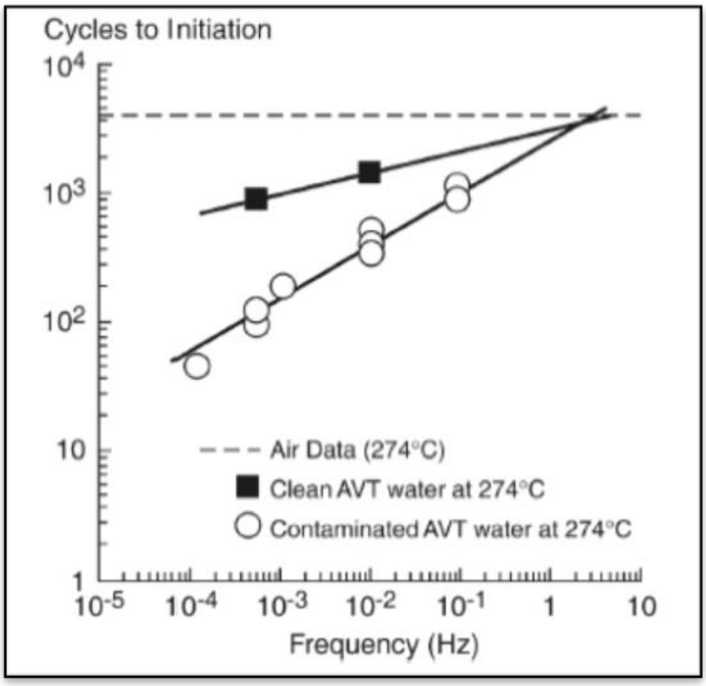

Figure 11: The effect that loading frequency and cycle chemistry has on corrosion fatigue crack initiation (Dooley & Chang, 2000).

2.1.4 Feedwater Chemistry

The generation and transportation of corrosion products (hematite and magnetite) occurs mainly due to corrosion and flow accelerated corrosion of feedwater heaters, economisers, deaerators and drain-lines (Dooley, 2005). “All-ferrous” feedwater systems are those that have no copper in the feedwater system, but may have copper-based condenser tubing (Dooley, 2005).

Controlling feedwater chemistry is an essential component of controlling not only the overall reliability of power stations, but also to mitigate the impact that the corrosion component of corrosion fatigue has. Dooley (2005) found that there are three main feedwater treatment systems namely (see more detail in Table 2):

1. Reducing all-volatile treatment – AVT(R)
2. Oxidising all-volatile treatment – AVT(O)
3. Oxygenated Treatment – OT

Since 1988 South African power stations have implemented a systematic conversion from AVT(R) to OT / AVT(O) (Dooley, 2005). Oxidising chemical treatments are not viable for mixed metallurgy systems, however this is less relevant in the South African context because most power stations have converted to fully ferrous systems (Eskom Heritage, 2020).

During the course of this dissertation reference will be made to "Once-through" and "Drum" type boilers. In a "Once-through" type boiler the water flows through the economizer, furnace wall, evaporating and superheating tubes, without recirculation (Ganapathy, 2013). A "Drum" type boiler utilises the difference in density of water/steam to circulate the water. It also has a steam drum that acts as a phase-separator, hence the name (Ganapathy, 2013).

Table 2: Feedwater limits for boiler systems (Dooley, 2005).

Parameter	AVT(R)	AVT(O)	OT
pH	All-ferrous: 9.2-9.6 Mixed metallurgy: 9.0-9.3	9.2-9.6	D 9-9.4 O 8-8.5
Cation Conductivity (µS/cm)	≤0.2	<0.2	<0.15
Fe (ppb) at El	<2	<2(<1)	<2(0.5)
Cu (ppb) at El	<2	<2	
Oxygen (ppb) at El	<5 (<2)	<10	D 30-50 O 30-150
Oxygen (ppb) at CPD	<10	<10	<10
Reducing Agent	Yes	No	No
ORP (mV) at DAI	-300 to -350	Not needed	Not needed

Notes: El – Economiser Inlet, CPD – Condensate Pump Discharge, DAI – Deaerator Inlet, D – Drum Unit, O – Once-through Unit.

Action Levels (AL) at certain sampling locations give guidance for corrective actions that should be implemented during and after excursions (Dooley, 2005). The amount of exposure that a boiler experiences during an excursion event is the product of the magnitude and the duration of the exposure (Dooley, 2005).

$Exposure = Magnitude \times Duration$ - Equation 2

EPRI has defined four actions levels, and can be seen summarised in Table 3. An "Action Level" occurs when excursion values trigger corrective action responses that is needed to return the affected parameter to within specification, inside a defined duration from first identification. The magnitude of the excursion defines the Action Level to which the excursion is assigned and which in turn defines the duration that the unit is allowed to run at that Action Level. Should the cause of the excursion not be remedied within the recommended timeframe, the next highest Action Level takes effect (Dooley, 2005).

Table 3: EPRI description of various action levels (Dooley, 2005)

Action Level	EPRI Description
Normal	Long term system reliability is assured by operating within this regime. These values include a safety margin that will avoid concentration of contaminants at surfaces and under deposits.
Action Level 1	Accumulation of contaminants may potentially occur and values should therefore be returned to normal within one (1) week.
Action Level 2	Impurity accumulation and corrosion will occur and values should be returned to normal within 24 hours.
Action Level 3	The unit should be shut down within four (4) hours as rapid corrosion could occur.
Action Level 4 (Immediate shutdown)	Clear evidence of rapid boiler and turbine corrosion exist, which must trigger immediate shutdown in order to limit the damage.

2.1.5 Location

EPRI has developed a figure with susceptible corrosion fatigue locations and stress ranks as seen in Figure 12, with the numbers described in Table 4 (Dooley & McNaughton, 2007). The stress ranks are based on the screening influence diagram proposed by Dooley & Chang (2000), seen in Figure 23. This metric rank is used to rank stress from low to high on a relative scale (where A is high and D is low). The column "Potential Modifications" in Table 4, are modifications which can be made, that will ideally lower the stress rank in the area.

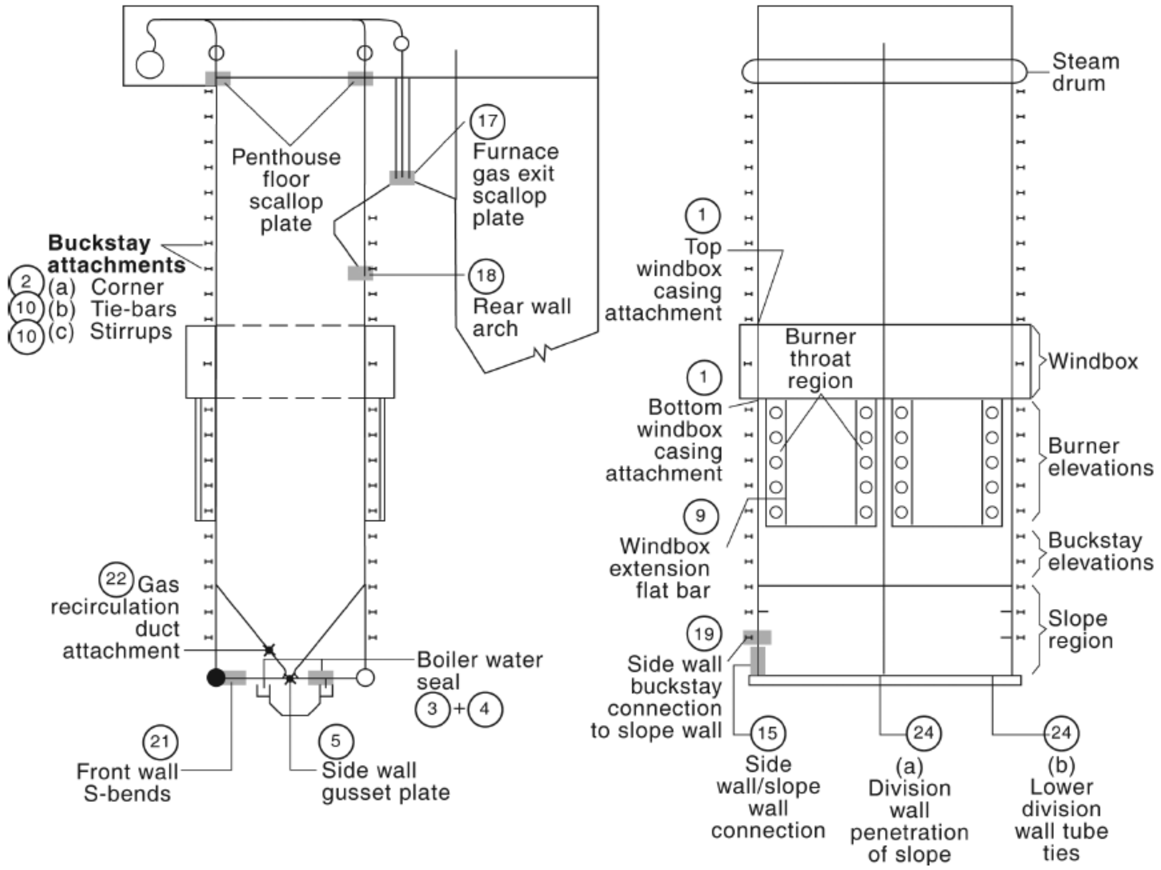

Figure 12: Typical corrosion fatigue failure locations in a tangentially-fired boiler (Dooley & McNaughton, 2007).

Table 4: Corrosion fatigue failure site list with descriptions, stress ranking, and potential modifications (Dooley & McNaughton, 2007; EPRI, 1996).

Location	Description	Stress Rank*	Potential Modification
1. Windbox casing	a) Continuous scallop plate; primarily corner tubes affected	B	No modification derived
	b) Filler bars	B	Replace cast filler bars with plate formed filler bars
2. Buckstay corners**	a) Rigid corner scallop plate connected to buckstay	B	Remove or relieve rigid corner
	b) Lug mounted tie-bar connected to tubes at corner	A	Same as for case (a)
	c) Tangent/membrane wall with filler bar connections	D	Remove filler bar

Location	**Description**	**Stress Rank***	**Potential Modification**
3. Boiler ash hopper seal plate	Continuous scallop plate welded to horizontal tubes	B	Change to U-bolt arrangement
4. Boiler seal heat shield (slag screen)	a) Continuous scallop plate welded to tubes	B	Short tangent bar (3-4 tubes) or a U-bolt arrangement
	b) 6-8 tube tangential bar	C	Same as for case (a)
5. Side wall gusset plate	Triangular plate between redirected tubes	A	Change to peg membrane
6. Division wall penetration of slope	a) Refractory box rigidly connected at the top and bottom	D	Remove rigid connections
	b) Continuous scallop plate	B	Use refractory box without rigid connections
7. Burner throat/gas offtake tube ties	a) Short bars welded between redirected tangent tubes	C	Replace tube ties with membrane bar
	b) Short bars welded between tubes in tangent tube wall	B	Weld bar on hot side to restore neutral bending axis to geometric axis of tube
8. Burner barrel mounts	Direct connection from burner barrel to waterwall	C	Use mounting plate between burner and wall; increase the number of attachment lugs
9. Windbox extension vertical seal	Windbox extension duct welded directly to vertical flat bar; flat bar is on outside of windbox, but could also be on inside	D	Install expansion plate between windbox casing and flat bar; remove flat bar on inside
10. Buckstay connections to waterwalls	a) Continuous scallop tie-bar	C	Use stirrups or lugs on membrane walls Tack weld to alternate tubes on tangent tube wall
	b) Continuous tangent bar tack welded to tubes - membrane wall - tangent tube wall	 D B	Same as for case (a)
11. Scallop tie-bars	Tangent tube waterwalls; most failures at corners or associated with abnormally high loads	D	Address source of stress Remove weld from every other tube
12. Miscellaneous waterwall penetration gusset plates**	a) Sootblower penetrations	D	Replace with peg membrane
	b) Burner throat and gas off-takes	C	
	a) Windbox strut attachment	D	

Location	Description	Stress Rank*	Potential Modification
13. Miscellaneous filler bar attachments**	b) Side wall buckstay/baffle wall connection	D	Replace solid filler bars with formed plate filler bars
	c) Slope wall support I-beam at side wall	B	
14. Penthouse floor attachments	Continuous scallop plate a) problems most common in corners	D	No modification determined
	b) more serious if connecting tubes carrying different media	B	
15. Side wall/slope wall seal	a) Scallop bar	D	Replace with refractory box
	b) Rod welded between tubes	B	
16. End of membrane	More serious adjacent to redirected tube	A	Cut back membrane
17. Furnace gas exit scallop plate	Continuous scallop plate - adjacent to redirected tubes	C	Move scallop plate farther from redirected tubes and cover with refractory
18. Rear waterwall arch	Continuous scallop bar - adjacent to separation of hanger tubes	D	Cut scallop bar at intervals to make discontinuous
19. Side wall buckstay connection to slope wall	a) Tangent bar tack welded to tubes	C	Replace with scallop bar Evaluate necessity of attachment
	b) Scallop bar tack welded on alternate sides of bar	D	
20. Side wall buckstay connection to baffle wall	Flat bar connection to baffle wall seal welded with filler bars at side wall - lowest connection affected	C	No modification derived
21. Lower front/rear waterwall S-bends	Immediately downstream of mud drums, with locating scallop bars between tubes	B	Remove scallop bars and replace affected bends
22. Gas recirculation duct scallop plate attachment	Continuous scallop bar	D	No modification derived
23. Furnace floor connection between nose tubes	Direct connection between nose tubes in opposite walls - filler bars used - natural gas-fired boiler only	C	Replace solid filler bars with formed plate filler bars No other modification derived
24. Division wall tube ties**	First set of tube ties above slope wall	D	No modification derived

Location	Description	Stress Rank*	Potential Modification
25. Riser and downcomer tube bends	Tubes/pipes external to boiler	NA	Replacement and temperature/strain

* Stress rank is for use in screening influence diagram. The listed stress rank applies to locations within the combustion or radiant sections of the boiler. "A" generally implies the highest stress rank; "D" the lowest (Dooley & McNaughton, 2007).
** Listed stress rank applies to locations within the combustion or radiant sections of the boiler

2.2 RISK METHODOLOGY

The focus of this paper will be on the listed risk-based methodologies, and seek to combine aspects of these methodologies into a usable risk model.

1. API RP 580 / 581 methodologies
2. BS EN 16991:2018 framework
3. Kent Mühlbauer's system

2.2.1 Risk

2.2.1.1 API RP 580 / API RP 581 Methodologies

Risk, as defined by the API RP 580 methodology, involves probability of failure (PoF) combined with consequence of failure (CoF) (API, 2009).

$Risk = PoF \times CoF$ - Equation 3

Failure is a leak or rupture of pressurised equipment as a result of a loss in containment (API, 2008). The risk of failure increases during operation due to an accumulation of damage. This makes probability a time dependent factor (damage accumulates over time), while consequence is independent of time. All plant owners have a certain risk appetite which is related to statutory, health and safety and environmental implications. These risk "targets" are pre-defined levels based on acceptable risk or consequence limits (API, 2008).

The risk process as described in API RP 580 is summarised in Figure 13 (API, 2009).

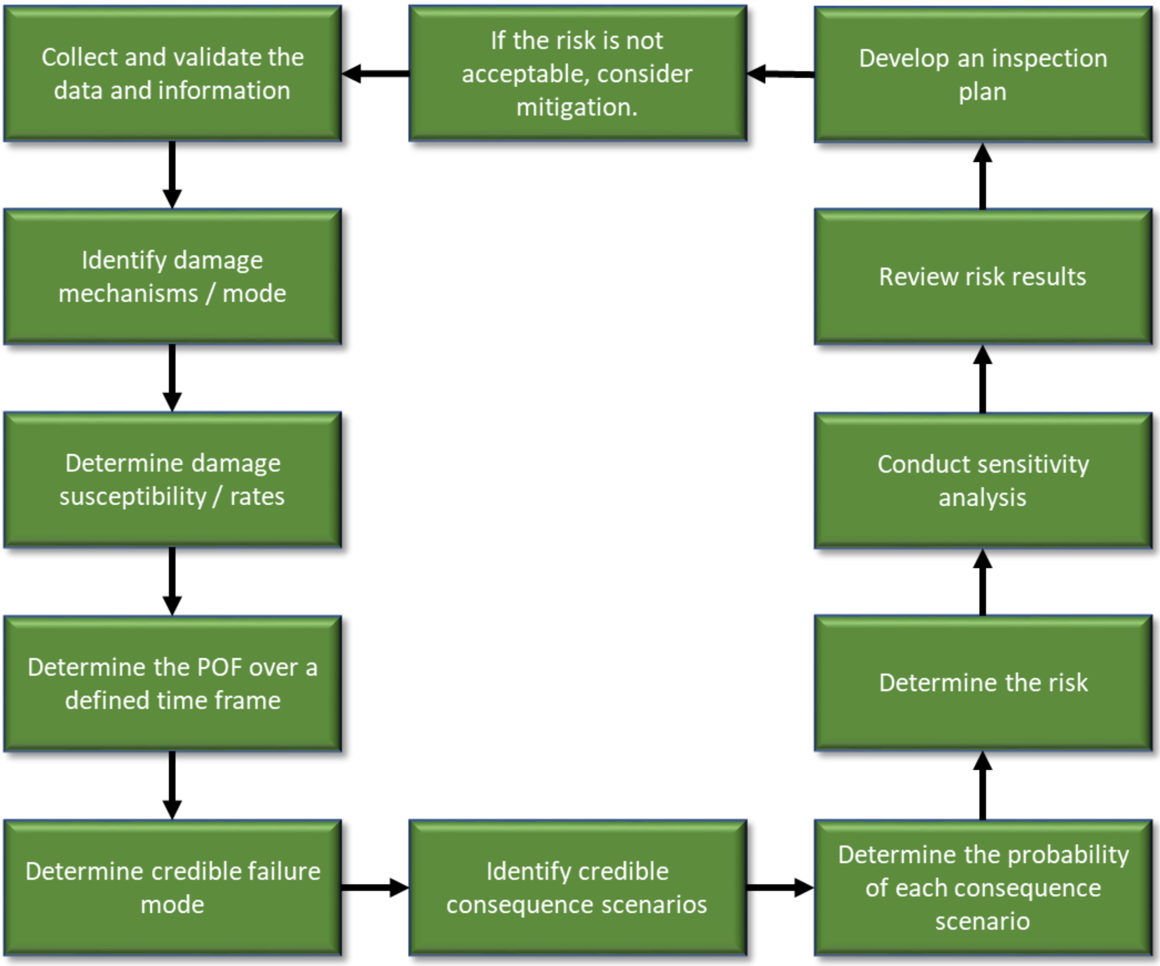

Figure 13: Risk process as described in API RP 580 (API, 2009).

2.2.1.2 The BS EN 16991:2018 Framework

BS EN 16991:2018 defines risk as the "combination of the probability of occurrence of harm and the severity of that harm" (British Standard, 2018). Within this definition the probability of occurrence includes the manifestation of a hazardous event, the exposure to such a situation and the possibility to limit any resultant harm (British Standard, 2018). BS EN 16991:2018 divides risk analysis into multiple phases: "Risk Screening", "Intermediate Analysis" and "Detailed Risk Analysis" - see Figure 14 for an example of a multi-level risk assessment. This multi-level risk assessment forms part of the risk process described in Figure 15 (British Standards, 2018).

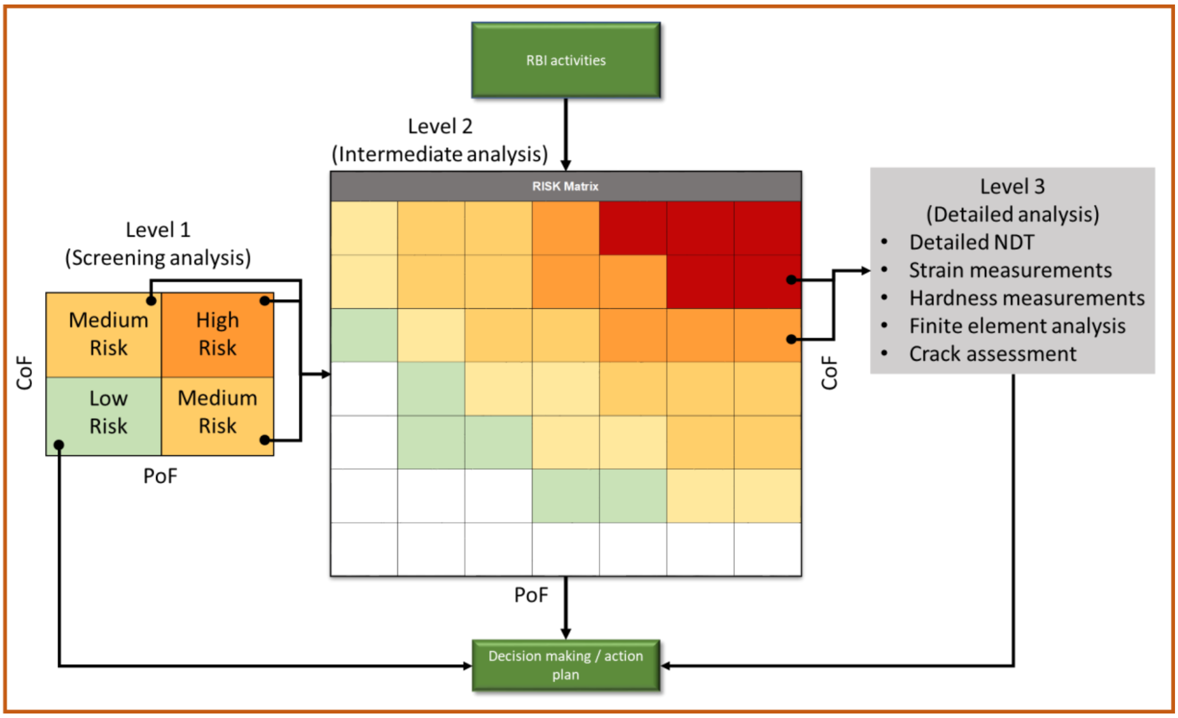

Figure 14: Multi-level risk assessment matrix – Source BS EN 16991:2018.

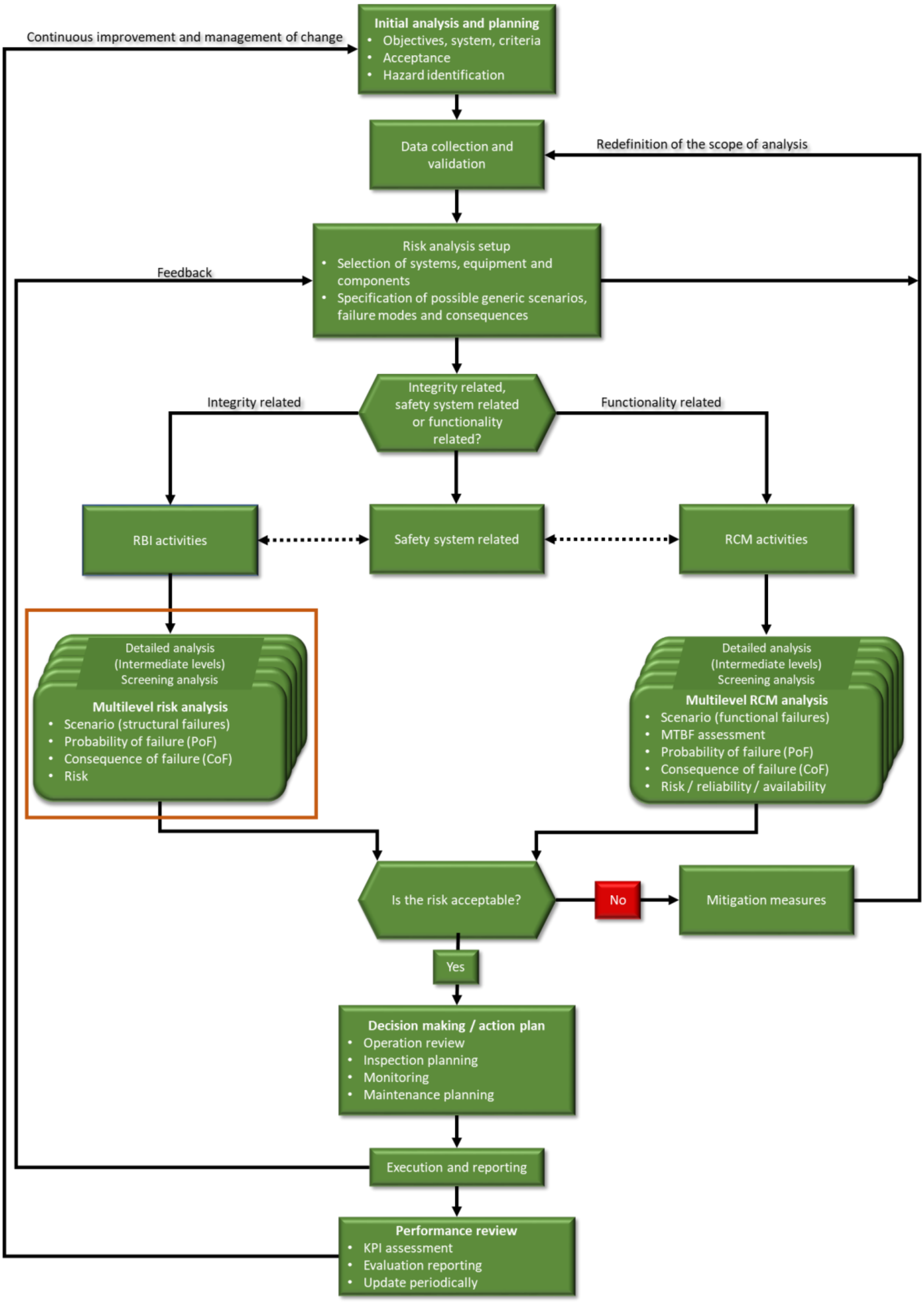

Figure 15: The risk process as described by BS EN 16991:2018.

2.2.1.3 Mühlbauer's System

Within the gas pipeline industry there exists a qualitative method developed by Kent Mühlbauer. Risk is defined as the probability of occurrence of an event that causes a loss and the associated magnitude of that loss (Muhlbauer, 2004).

$Risk = Likelihood \times Consequence$ - Equation 4

Mühlbauer follows a qualitative risk assessment approach, which is most often a subjective assessment based on good practice and experience. This methodology draws from standards like ASME B31.8S: Managing System Integrity of Gas Pipelines and API 1160: Managing System Integrity for Hazardous Liquid Pipelines. ASME B31.8S and API 1160 classify "threats" within three general categories:

1. Time dependant
2. Time independent
3. Stable

Time dependant threats in the context of a boiler would be related to damage mechanisms such as long-term overheating, erosion and corrosion. Stable threats are those related to manufacturing and installation defects, while time-independent threats are operation related, or as a result of vandalism or "acts of God" (Muhlbauer, 2004).

The result of a Mühlbauer assessment is a list of applicable threats together with a relative risk ranking. In the qualitative methods, the risk and potential consequences of its occurrence are presented descriptively. The benefit of this approach is that it can successfully estimate risk in situations where it is difficult to construct an accurate probabilistic model due to a lack of information. This method utilises numerical values that are assigned to the parameters that affect the risk associated with the operation of pipelines (Muhlbauer, 2004).

Risk can be expressed in absolute or relative terms. Absolute risk is a frequency-based estimate of the probability of failure consequence, for example, "number of fatalities per mile year for permanent residents within one-half mile of pipeline..." (Muhlbauer, 2004). Relative risk prioritises hazards within a system in order to allow for a comparative measure of current risks, in terms of both failure likelihood and consequence (Muhlbauer, 2004).

2.2.2 Probability of Failure (PoF)

2.2.2.1 API RP 580 / API RP 851 Methodologies

This standard defines the computation of probability of failure as (API, 2008):

$P_f(t) = GFF \times D_f(t) \times F_{MS}$ - Equation 5

Where $P_f(t)$ is the probability of failure, GFF is the generic failure frequency, $D_f(t)$ is the damage frequency factor and F_{MS} is the management systems factor.

The GFF is a set value, historically representative of the refining and petrochemical industry failure data (API, 2008). This value should give the failure frequency of a piece of equipment prior to exposure to an operating environment and specific damage mechanisms. GFF is therefore based on discrete hole sizes and is used to model release scenarios covering a range of events (from a leak to a burst) (API, 2008). Adjustment factors are applied to GFFs to account for damage mechanisms and reliability management practices (API, 2008). GFF is meant to be a reasonable estimate of failure based on a large data set within a company or industry and is based on historical data for a specific component. It is meant to be representative of failure due to degradation as a result of benign service, before taking any specific operational deviation into account (API, 2008).

The management system factor (F_{ms}) is based on how effective mechanical integrity and damage detection / management is implemented (API, 2008).

The damage factor ($D_f(t)$) is a statistical evaluation of the amount of damage that may be present as a function of time in service and the effectiveness of the associated inspection methodology (API, 2008). The damage factor is meant to statistically evaluate how much damage may be present as a function of time in service (API, 2009).

In order to determine the risk, it is essential to quantify the damage accumulated by implementing effective inspection methodologies and strategies (API, 2008). All components have a true PoF that is higher than zero, because of operational, design or manufacturing imperfections.

According to API 580 / 581, PoF is dependent on how well the independent variables, like flaw size, are known. The term “known” is potentially misleading, because some aspects and events are unforeseeable or rather, the variables involved are too complex to consistently quantify. Inspection is used to reduce the damage factor, because inspection lowers uncertainty. For instance, a damage factor for thinning is based on a metal loss parameter and will increase (further corrosion / erosion) or decrease (replacement) based on a minimum acceptable wall thickness value. However, when you have a situation where the wall thickness of the component is unknown or where the condition is uncertain / unobserved, the conservative methodology would be to assume that the equipment exists in a damaged condition, with the extent of the damage also being uncertain. Inspection, therefore, lowers risk, by lowering uncertainty.

2.2.2.2 The BS EN 16991:2018 Framework

Within the BS EN 16991:2018 standard, probability of failure is defined for a set period of time and based on the prediction of damage over that specified operating window (British Standard, 2018). The context of that period of time must include parameters that may fluctuate and parameters that are fixed. Probability of failure can be established by measuring inspection data, by calculations, by making use of operating data or by expert opinion. For degradation mechanisms that cannot be trended, it is suggested that redesign of the component or a suitable inspection and monitoring method can prevent failure (British Standard, 2018).

2.2.2.3 Mühlbauer's System

The Mühlbauer system defines probability as a "degree of belief regarding the safety of a pipeline" (Muhlbauer, 2004). This is essentially a combination of frequency, statistics and expert judgement applied to a system (within context). Frequency usually refers to the number of past events, however the amount and quality of data available is insufficient to cover / describe most events adequately. Statistics refers to the analysis of past events and normally do not imply anything about future events (Muhlbauer, 2004). Only in simple, closed-loop system, can statistics adequately predict future events. According to Mühlbauer, inductive reasoning and analysing the system as a whole, in combination with failure frequency and other statistics, is the most appropriate method to consistently calculate a probability of failure (Muhlbauer, 2004).

Figure 16 describes the number of failures over the life of a piece of equipment (Muhlbauer, 2004). The initial phase or "burn-in phase", refers to the stage where manufacturing / installation defects result in a high rate of failure. As these defects are eliminated, the equipment will enter a phase where the failure rate remains constant. Random events, like operational damage, tend to drive failures within this stage. The "wear-out" or final phase, tends to occur when equipment reaches end of life (equipment life may be shortened by inadequate operation and maintenance practices). The final phase is usually dominated by time-dependant failure mechanisms, like creep and corrosion (Muhlbauer, 2004).

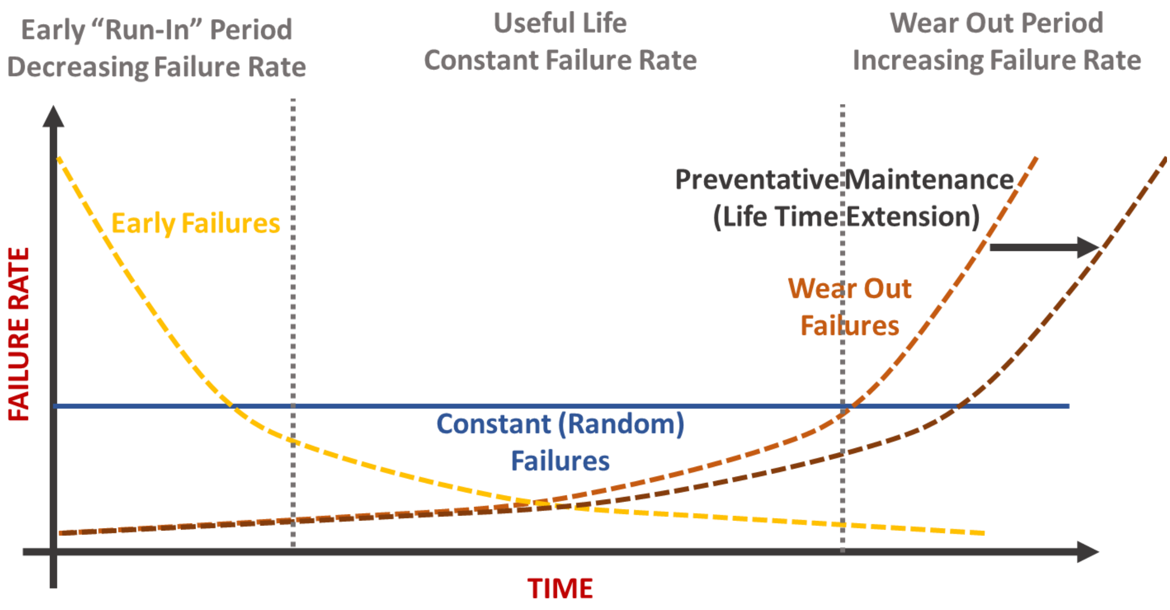

Figure 16: "Bathtub" curve, commonly used to describe failure rates.

2.2.3 Consequence of Failure (CoF)

Consequence refers to some kind of loss and can be grouped into direct or indirect categories, where the latter is more difficult to define than the former (Muhlbauer, 2004). Consequence is often quantified by assigning a monetary value to damages, however this is more complex where harm to life and environmental impacts are concerned.

Table 5: Example of indirect and direct consequences (Muhlbauer, 2004).

Direct Consequence	Indirect Consequence
Property damage	Litigation
Damages to human health	Government fines and penalties
Environmental Damages	Contract violations
Loss of product	Customer dissatisfaction
Repair Cost	Political reactions
Remediation cost	Loss of market share

2.2.3.1 API RP 580 / API RP 581 Methodologies

The API RP 580 / 581 standards have two levels for determining CoF, where level 1 is more simplistic than level 2. Level 1 is based on the consequence evaluation of a limited number of reference fluids, the hole size and the phase of the fluid, and is typically very conservative. Similar to fitness for service practices, Level 2 is a detailed consequence analysis that should be used in cases where the assumptions made in the level 1 analysis is not valid.

2.2.3.2 BS EN 16991:2018 Framework

BS EN 16991:2018 recommends that CoF analysis must focus on the highest aspect when considering individual consequences like health, safety, environment and business consequence. Consequence should never be averaged, because this will distort the risk results in cases where safety risk is less severe than business risk (British Standard, 2018).

It should be noted that the loss of containment (beyond the skin casing of a boiler) is an exceptional event, and therefore environmental and safety consequence for boiler internals is usually low. Financial consequence therefore drives the consequence model for boiler internals and will therefore be fairly simplistic in this case.

2.2.3.3 Mühlbauer's System

Characteristic of a risk assessment is the potential consequences and implies a loss of one kind or another. Mühlbauer groups consequence into direct and indirect categories, with a primary focus on more easily quantifiable direct cost (Muhlbauer, 2004). Direct cost of a boiler incident would typically be aspects related to a loss in production or the cost of oil used to start the boiler.

The consequence of failure can change depending on variables such as tube leak location, extent of secondary damage, ease of replacement etc.

2.3 RISK MANAGEMENT PROGRAMMES

An effective asset management, inspection and maintenance program requires clearly defined objectives and an idea of how it relates to the larger organisational structure. An outline of methods, intervals and extent of inspections and maintenance is required to minimise risk, while keeping costs at acceptable levels.

The phrase commonly referred to risk within in the industry is: As Low As Reasonably Possible (ALARP). Risk reduction measures need to be taken for items that exceed certain acceptance limits, with the basic outline of the process given in Figure 17 (British Standard, 2018).

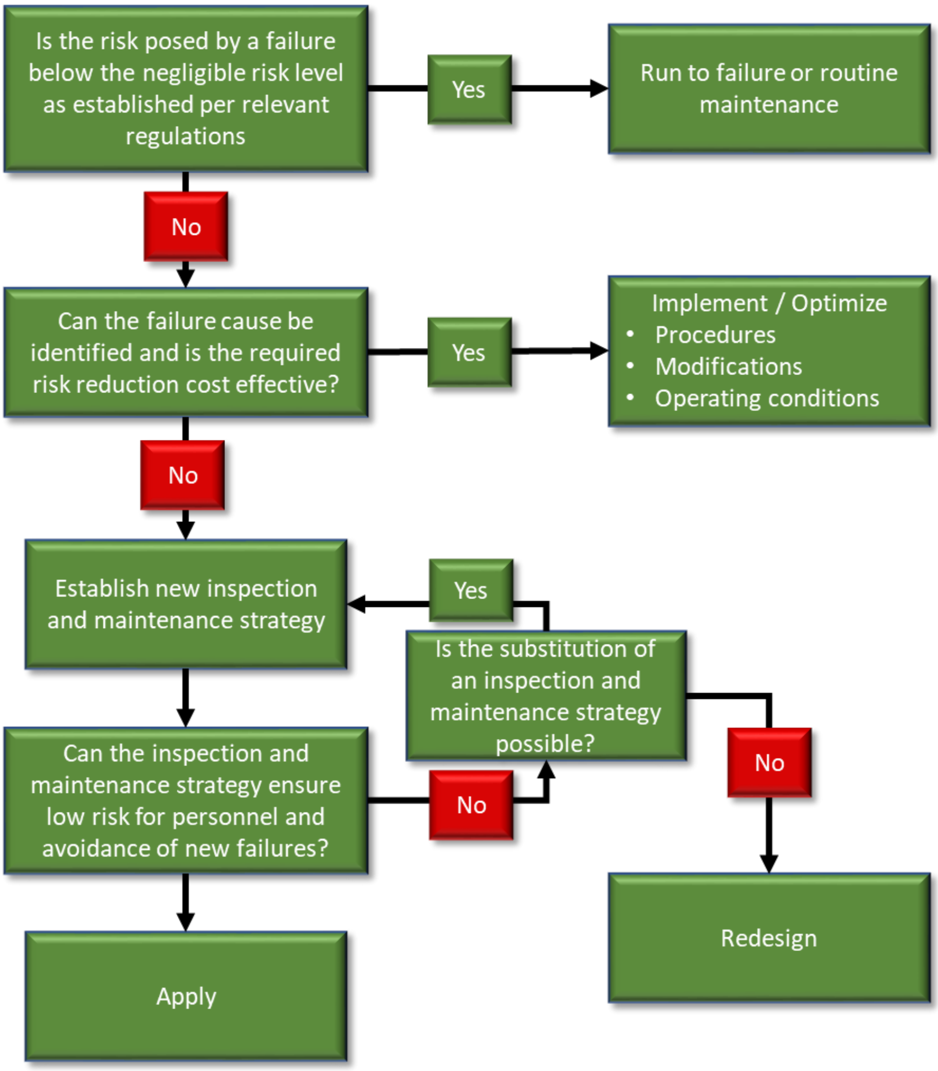

Figure 17: Decision tree for RBI application. Adapted from BS EN 16991:2018 (British Standard, 2018).

Each power station is a complex system, with geographical, operational and management challenges uniquely its own. While some power stations were constructed using one kind of design, other power stations can have multiple designs. For instance an old South African power station has six 30MW chain grate boilers and seven pulverized coal fired boilers of 60MW (Kelvin Power, *SA*). On top of that, no unit is ever constructed the same, with variation in material, fabrication and installation quality.

Data sets must be identified during the initial RBI analysis, and a thorough investigation undertaken to determine the data quality and integrity prior to the risk assessment. The initial analysis must start with a good description of the system. This includes relevant system data such as location, dimensions, materials, temperature, pressure etc. Applicable damage mechanisms and failure modes should be identified and defined in relation to the system.

2.3.1 Scope

As part of defining the scope it is essential to know who the audience is and what **need** the risk assessment is meant to address. The effectiveness of the risk assessment and associated activities is directly equivalent to how well the scope is defined.

Table 6: Essential elements for defining the scope effectively (Knaflic, 2015).

1. Purpose	**What is the need that must be addressed?** Compile a list of realistic / achievable objectives.
2. Audience	**Who will see the results and who will use the results?** Successful communication is dependent on knowing the audience that is being communicated to (Knaflic, 2015). In the world of risk assessments, the audience is varied, therefore results must be provided in such a way that it resonates with the audience.
3. Uses	**What will the results be used for?** This question is informed by the purpose as well as the audience. Risk assessments seldom have a single use, and are utilised by many different audiences for multiple purposes. For instance, the safety department can use it to motivate for more resources or tighter regulations, while the planning department can delay replacements or inspections.
4. Resources	**What / who is available to do the risk assessment and carry out any actions related to it?** It is crucial to establish the condition of the data, software (if applicable), hardware, staff and finances.

From the outset it is important to define the battery limits of system. For instance, this report will focus on the internal pressure parts of a boiler (from inlet to outlet header). These systems are generally defined in accordance to the functions that they perform. All auxiliary systems like downcomers, main steam piping and rotating equipment will be excluded from this evaluation. The equipment and components should be broken down into functional locations (like the VGB PowerTech's Kraftwerks-Kennzeichen-System (KKS) Identification System for Power Plants). The more granular the break-down of the system is, the more focused, manageable and meaningful the evaluation can be. For instance, a waterwall in the area of the windbox will be more prone to corrosion fatigue failures than the waterwall further up, because of the increased restraint due to attachments and the presence of tube manipulations around the burners.

2.3.2 Unit Age

During the 1960s to 1970s, boilers were designed with large wall thickness tubes and headers. Facilities that were constructed in the 1980s and onwards have been fabricated with lower wall thicknesses, in part to reduce construction cost and in part due to advances made in materials. The age of the unit is therefore important not only because of degradation due to longer operating hours, but also the construction and material advances of the era.

Asset life expectancy is being extended beyond originally designed time-scales. It is, therefore, important when planning to extend operational life beyond design limits to be able to accurately gauge asset control status. Life extension may well require re-appraisal of risks and major changes to planned activities. Throughout the planning stage, the RBI methodology should agree with the current planned asset life. Consequently, future business and operational requirements for an asset should, where practicable, be made known to those responsible for setting and implementing the RBI program.

2.3.3 Materials

Boilers are constructed according to certain code requirements, with a single power station often having multiple different designs. Units constructed according to BS or ASME codes, while similar in many regards, have different code requirements. Understanding the code requirements and equivalent specifications are essential, as there are inherent concerns w.r.t weldability, high temperature and pressure resistance, heat transfer and corrosion resistance, to name but a few. Knowledge of the construction code and material specifications will allow facilities to be proactive when doing maintenance planning. Information like outside diameter, wall thickness and length are also essential when doing focused replacements.

2.3.4 Operational History

Information like whether the unit has run as a baseload station or whether it has been load-following is essential when evaluating failure mechanisms like fatigue, over-stressing and corrosion fatigue. In a similar way information on cycle chemistry, lay-up procedures, management practices, thermal excursions, ramp-up rates and cooling procedures are important.

2.3.5 Failure Data

Often historical failure information has not been adequately recorded or captured on a central database (this is especially true before the advent of the digital age). Capturing as much information on the failure mechanism and location of the failure is essential. It is never too late to start recording this kind of information. Capturing design changes and component replacements are equally relevant. A well-documented and implemented Management of Change (MoC) is the foundation of reliability and integrity related data management.

2.3.6 Data Processing

The next step is converting the above data into useable information that can lead to repeatable results. Repeatable and predictable results are the cornerstones of an effective asset management strategy. The data should be packaged in such a way that the essential information is easily interpreted and effectively understood by those responsible for the asset. Following an RBI methodology will result in repeatable and auditable programmes. Accordingly, the auditability of the program should be such that the methodology, the input data, the decision criteria and the results are documented in a way that can be peer reviewed (British Standard, 2018).

In cases where the data is incomplete or quality is questionable, the uncertainty associated with the risk should be assessed and skewed toward the conservative. The purpose of this is to increase the effort and resources dedicated to the data collection and creation process.

RBI can be approached from a qualitative, semi-quantitative or fully quantitative direction. The initial risk screening is typically a qualitative method that relies on descriptive terms or a ranking system. Care must be taken to design the criteria in such a way as not to lose objectivity (British Standard, 2018).

2.3.7 Visual Representation

The neuroscience associated with the human senses and communication is beyond the scope of this document. As seen in Figure 18, it is essential to note that:

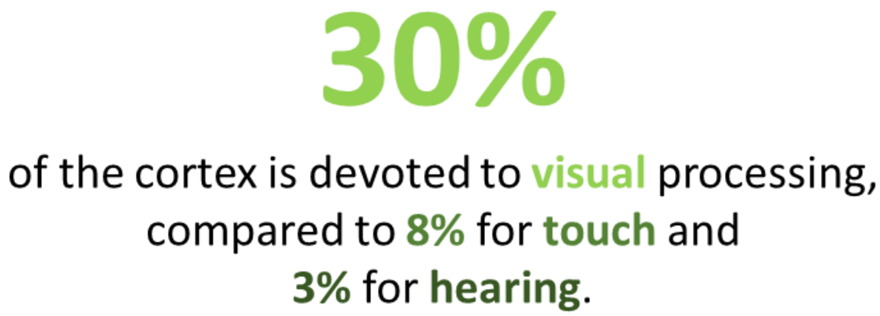

Figure 18: The cortex and human senses (Grady, 1993).

It can take as little as ***13 milliseconds*** for the brain to identify images (Trafton, 2014). Information that is presented using visual supports were found to be **43% more persuasive**. In particular, visual support can make a presenter seem more concise, clearer, more professional, more persuasive, and more interesting (Vogel, Dickson & Lehman, 1986). Representing data in a visual manner is an essential communication tool. Structuring results to resonate with the audience will assist in telling the story needed for effective decision making to take place.

Results are not the only thing that must be structured. The process of recording and inputting information is the foundation of quality. Simplification and repeatability can be built into the process by standardising methods of recording, using templates, digitising, automating etc.

CHAPTER 3 CONCEPTUAL RISK MODEL

3.1 INTRODUCTION

A boiler risk model is a set of rules that can be used to predict future boiler performance. The purpose of a risk model is to calculate and represent risks, in either a relative or absolute sense. As discussed in previous sections, understanding the risks associated with complicated engineering systems and the accompanying failure mechanisms, outside of a controlled laboratory environment, can prove to be impossible. A well-structured risk model can focus risk efforts towards the more likely failure mechanisms and locations, and enable more accurate failure frequencies to be estimated. A model seeks to increase the understanding of risk at the expense of realism (Muhlbauer, 2004).

The index model assigns numerical values to important conditions and activities that increase or decrease the total risk score (Muhlbauer, 2004). The weighting assigned to each variable represents the importance of the item in the risk assessment and is based on statistics or on engineering judgment, depending on the availability of data. Each section of the boiler is scored based on all of its attributes. The various boiler segments will be ranked according to their relative risk scores. The relative risk score then indicates areas where repairs, inspections, and other risk mitigating efforts should be focused (Muhlbauer, 2004).

The biggest advantage of the indexing model is that a broad spectrum of information can be included, however this can also be the biggest drawback due to the possible introduction of subjectivity in the scoring. Therefore consistency should be introduced into the scoring, and the weightings should reflect real risk as closely as possible. It is essential to do a sensitivity analysis after setting up the model. Not all the variable weightings will be correct as demonstrated in actual failure and research data (Muhlbauer, 2004).

3.2 SEGMENTING

A boiler usually does not have a constant risk score across its length and breadth. As conditions across the boiler and along the pressure parts change, so too does the risk picture. Segmenting is the practice of defining risk areas which have more or less a constant risk score. Segmenting the boiler into many smaller sections will increase the accuracy of the assessment, but will require more effort. Inversely, larger sections will reduce effort as well as accuracy.

It was decided to use larger sections, due to the academic nature of this dissertation. The boiler has been segmented into three primary “Systems” with their associated “Equipment” as shown in Figure 19.

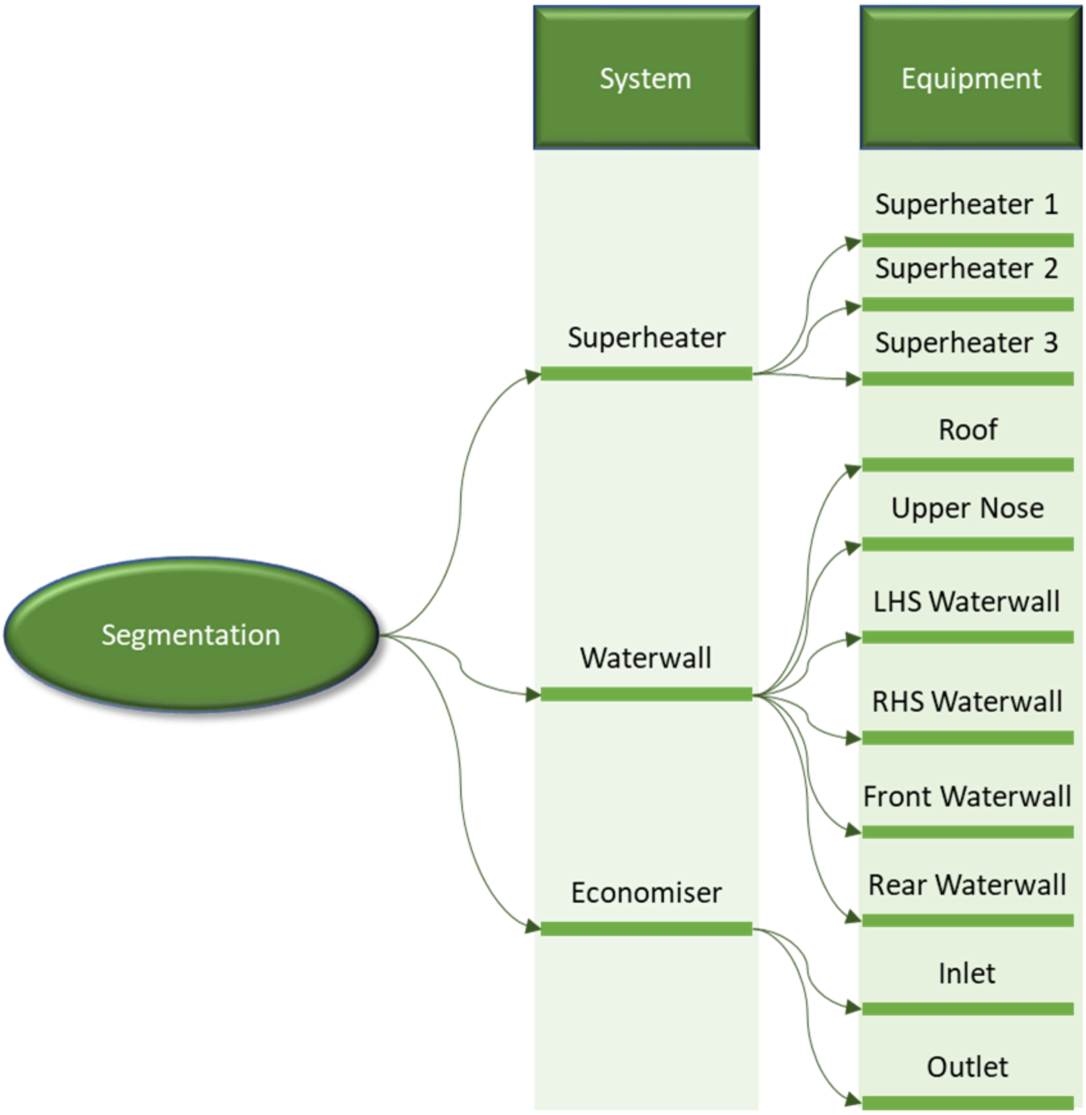

Figure 19: Segmentation of the boiler pressure parts included in this study.

3.3 PROBABILITY OF FAILURE

Information from Dooley & McNaughton (2007) was used to formulate the questions asked in order to determine the probability of corrosion fatigue. The probability model is based on a combination of API 581 and Kent Mühlbauer.

3.3.1 Management System Factor

A management system adjustment factor is based on the influence of power station's management system on the integrity of boiler pressure parts (Drożyner & Veith, 2001). This factor accounts for the probability that accumulating damage which results in failure will be discovered in a timely manner (Drożyner & Veith, 2001). The percentages assigned in this example can be changed on a case-by-case basis, depending on where focus should be directed. The highest percentages were assigned to those aspects that could be effectively managed by an inspection and maintenance program. For instance, "Design" only accounts for 20% of "Quality Control", because it is not something that can be changed easily or cost effectively. Lower percentages were also assigned to those aspects that have a lower direct impact on the mechanism, like "Health and Safety".

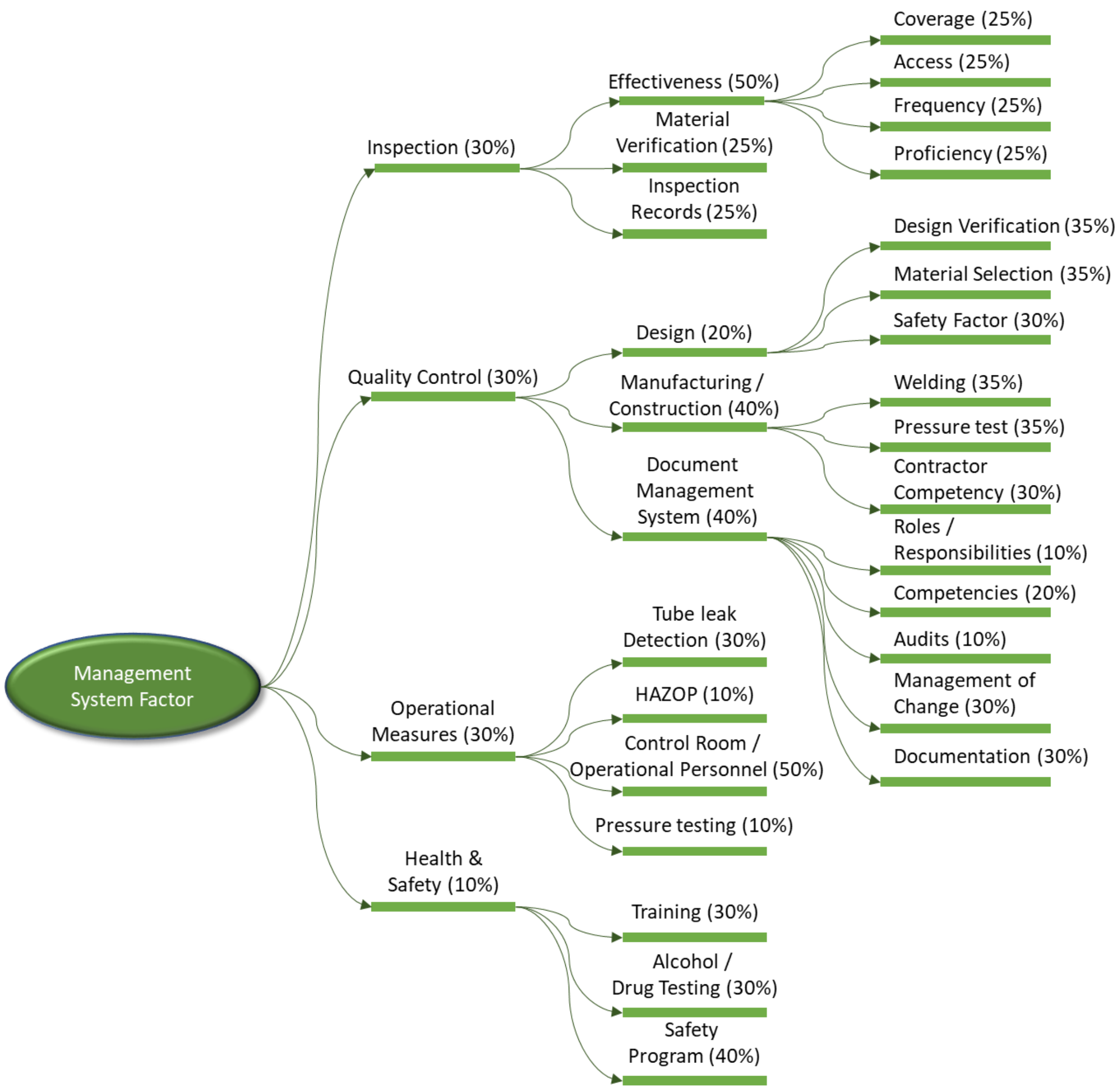

Figure 20: Diagram showing how the management system factor was determined.

3.3.1.1 Inspection

As stated in Chapter 2.2.2, inspection is a measure of how well the damage in the boiler is ascertained and understood. Inspection is divided into:

a) Effectiveness
b) Material verification
c) Inspection records

a) <u>Effectiveness</u>

Inspection effectiveness is an amalgamation of various factors like; coverage, access, frequency and technician proficiency (Heerings, Trimborn, & Den Herder, 2006).

- ***Coverage***

The coverage of Non-destructive Testing (NDT) must give assurance that it can adequately identify the damage mechanism and the extent of damage (API, 2006).

Are enough components inspected?	Pts.
NDT adequately identifies corrosion fatigue and the extent of damage	0
NDT does not adequately identify corrosion fatigue and the extent of damage	7

- ***Accessibility***

A major factor in detecting corrosion fatigue is the accessibility of the component to NDT. Typically, it is very difficult to get good access to the cold side of a waterwall in order to do NDT, while it is much easier on a superheater.

How accessible is this component w.r.t NDT?	Pts.
Excellent	0
Good	2
Average	3.5
Below average	6
Poor	7

- ***Frequency***

The interval at which inspection occurs must be such that damage will be reliably detected and can be managed or repaired so that it does not adversely affect the subsequent operation period.

Will the inspection frequency reliably detect the failure mechanism?	Pts.
Yes, the inspection frequency is adequate	0
No, the inspection frequency is inadequate	7

- ***Technician Proficiency***

The effectiveness of inspections rely heavily on the proficiency of the NDT technician carrying out the tests.

How proficient is the NDT technicians in general?	Pts.
Proven record of proficiency, with regular spot checks	0
Proven record of proficiency, but no verification	3.5
Not proficient	7

b) <u>Material Verification</u>

When material arrives, it is important to verify that it is per the specifications. Good control and a robust verification system can avoid accepting and using sub-par materials. It has become a norm within the engineering industry to pay particular attention to material verification due to large amounts of sub-standard, but inexpensive, materials being supplied.

Are materials inspected when they arrive and prior to installation?	Pts.
No proof of material verification	0
All materials and components were verified as to their authenticity and conformance to specifications prior to their installation.	7

c) <u>Inspection Records</u>

Keeping detailed and relevant inspection records are essential to future planning and Hazard and Operability Analysis (HAZOP) studies. It becomes very difficult to procure spares, do focused replacements or even plan outage durations without detailed inspection information.

Are there inspection records?	Pts.
Inspection records signed and stamped	0
Inspection record exist, but no validation	3.5
No inspection records	7

3.3.1.1 Quality Control

Quality control (QC) is a process through which an organisation pursues the maintenance and improvement of product quality. Quality control is divided into:

a) Design

b) Manufacturing / Construction
c) Document Management System

a) Design

The design of pressure parts significantly impacts how well the component will withstand certain damage mechanisms (API, 2008).

- ***Design Verification***

This leads into the third consideration, which is design verification, and can be applied to new designs as well as modifications.

Were/ are old and new designs checked and verified?	Pts.
Designs were checked and signed	0
Not checked	7
Unknown	7

- ***Material Selection***

Material selection has become par for the course and should be fit for purpose. Two supercritical power stations in South Africa serves as examples where the final stage Superheater material selection was changed from the original design of ASME SA213 T91 to SA-213 TP347H material (NS Energy Staff Writer, 2009). This change was made because international experience showed that ASME SA213 T91 led to significant problems and excessive tube failures at steam temperatures above 540°C (NS Energy Staff Writer, 2009).

Are there control documents and procedures that govern all aspects of material selection and verification and are they in use?	Pts.
Control documents exist and signed	0
No documentation	7
Unknown	7

- ***Safety Factor***

Pressure equipment are designed with safety factors (SF) in order to account for uncertainties in design, materials, manufacture, inspection and operation (Darlaston, 2004). As an example, older boilers were constructed with relatively large wall thickness / safety factors, because steel was reasonably inexpensive and there were still uncertainties in the technology. However, in modern times, wall thickness has decreased significantly and is somewhat offset by newer technology and advances in metallurgy.

Was the safety factor used during the design of the component fit for purpose?	Pts.
Yes	0
Yes, but conditions have changed and SF is no longer fit for purpose (FFP)	3.5
No	7
Unknown	7

b) Manufacturing / Construction

After construction and fabrication activities, it is incumbent on the owner to ensure that certain verification activities occur (Department of Labour, 2017).

➢ ***Weld Inspection***

The importance of good welding / joining practices during the construction of boiler pressure parts are essential when it comes to those self-same pressure parts reaching their design life. The residual stress caused by poorly executed welding is a significant contributor to corrosion fatigue. It is incumbent on the owner to insure that the replacements made are up to standards.

Are welds / joints inspected after replacements have been made?	Pts.
100% inspection of all joints by industry-accepted practices	0
Inspection occurred, but sub-par results	3.5
No proof of inspection	7

➢ ***Pressure Test***

If any critical defects were missed during the construction phase, a hydrostatic pressure test should reveal them and allow for repairs.

Was there a post construction hydrostatic pressure test?	Pts.
Yes, pressure test was conducted correctly	0
Yes, but procedures were not followed correctly	3.5
No	7
Unknown	7

➢ ***Contractor Competency***

Within South Africa the responsibility for the safe operation of the boilers rests with the Owner and designated General Machinery Regulations (GMR) 2.1. They must ultimately ensure that contractors working on the boiler have the correct competencies, which can be related to education, training and experience (Department of Labour, 2017).

Are contractors audited for competency?	Pts.
Always (before every job)	0
Frequently (more than once a year)	1
Regularly (once a year)	3.5
Seldom (lees than once a year)	5
Never	7

c) Data Management System

In modern times data is increasingly seen as an organisational asset that aids in informed decision making, optimised operations and reduce costs. If an organisation doesn't have proper data management systems in place it can result in incompatible data, inconsistent data and low quality data sets. Data problems will adversely affect the ability of a business to do analytics and result in flawed decisions that can lead to loss in revenue or even disaster (Fisher & Kigma, 2001).

- ***Roles and Responsibilities***

Defining the roles and responsibilities within and organisation will clarify what needs to be done and by whom. It enables effective communications between employees and avoids wasted energy by duplicating work. If roles and responsibilities are not clearly defined it can result in potential disaster when key tasks are overlooked.

Are roles and responsibilities clearly defined?	Pts.
Yes	0
No	7

- ***Competency***

Competency is time-based, meaning that it develops over time, and can also deteriorate over time. The process of developing competency is a combination of training, mentoring and experience (Fisher & Kigma, 2001). To be competent, personnel working individually or in teams, must have the ability to carry out their assigned duties, to recognise their limitations and take appropriate action to mitigate risk (Fisher & Kigma, 2001).

Do personnel have the appropriate competencies?	Pts.
Personnel are exposed to regular training and mentoring programmes. Those in senior roles have the appropriate experience.	0
Personnel are not exposed to regular training and mentoring programmes. Those in senior roles do not have the appropriate experience.	7

- ***Audits***

The results of audits are used to modify unwanted behaviours or unfavourable findings as part of a continuous improvement process. Audits can be used as performance measures that evaluate effectiveness within an organisation.

Is there a regular auditing program?	Pts.
Yes	0
No	7

- ***Management of Change***

Change is necessary to meet varying circumstances, make critical improvements or respond to emergency conditions. Careful consideration must be given to the safety and environmental implications that result from any change. Without proper review, a change may result in unsafe conditions, process hazards, or operating problems.

Is there a management of change system in place and is it actively used?	Pts.
Yes, there is a management of change program in place and it is actively used	0
Yes, but program is not actively used	3.5
No	7

- ***Document Management System***

Having a proper document management system can save a company a lot of revenue and effort. Knowing where to find documents and which document is the latest version can streamline processes and avoid duplication of effort. Having access control can limit the risk of sensitive information being shared.

Is there a formal document management system in place and is it actively being used?	Pts.
Yes, there is a document management system in place and it is actively used	0
Yes, but system is not actively used	3.5
No	7

3.3.1.2 Operational Measures

Operations is one of the major functions in an organisation and must be managed closely in order to avoid damage. Operational measures are divided into:

a) Tube Leak Detection
b) HAZOP

c) Control Room / Operational Personnel
d) Pressure Testing

a) Tube Leak Detection

A functional tube leak detection system is essential for plant health. Traditional tube leak detection utilises acoustic sensors to detect tube leaks. The amount of make-up water can also be an indication of a tube leak, depending on the severity. Shutting down for a tube leak repair, within the South African context, is a complex balance between immediate loss of load (which could have load shedding implications depending on the condition of the national grid) and accumulation of secondary damage (and longer down times) due to the leak. Early detection and location can inform relevant personnel on the optimal time to shut down for repairs (Najumnissa & Shajahan, 2013). For instance a tube leak located on a waterwall has a lower probability for causing extensive secondary damage as opposed to a tube leak on an economiser or superheater tube; and can therefore be run for an extended period of time. Information gathered by tube leak detection systems can also aid in identifying the root cause of the failure by coupling it to operational events prior to failure.

How effective is the tube leak detection system?	Pts.
Highly effective	0
Moderately effective	3.5
Not effective	7

b) Hazard Identification and Inspection

Hazard and Operability Analysis (HAZOP) is an organised and methodical method for system examination and risk management. HAZOP is often used as to identify potential hazards in a system as well as potential operability problems.

Is there a hazard identification methodology and is it used?	Pts.
HAZOPs are conducted	0
HAZOPs are conducted but are not fit for purpose	3.5
HAZOPs are not conducted	7

c) Control Room / Operational Personnel

The decisions made by control room personnel can have significant effect on boiler availability and profitability. Most boilers are run effectively under “normal” conditions, regardless of operator competency. However, poor decisions made during abnormal events have led to an estimated $20 billion annual loss within the process industry (Bitto, 2017).

Good operator decisions are facilitated by ensuring that (Bitto, 2017):

1. The boiler operating system is integrated
2. That the correct information is transferred from the machine to the operator
3. That the operators are competent
4. That the control room environment is ergonomic

Are any of these measures applicable to the control room and personnel?	Pts.
Well integrated system, efficient transfer of information, operators are competent and the environment is ergonomic.	0
Control room personnel are familiar with the system and competent	2
Meets minimum standards	3.5
Inappropriate reaction to alarms	7

a) <u>Pressure Testing</u>

Pressure testing provides basic proof of leak tightness and can be applied in-service to provide assurance for the quality of repairs (Wintle *et al*, 2001). Pressure testing can also be used in circumstances where there is a lack of access for inspections.

Does pressure testing occur at appropriate times and are there procedures in place to govern how they are conducted?	Pts.
Yes	0
Yes, but procedures are not actively followed	3.5
No	7

3.3.1.3 Health and Safety

An inadequate health and safety program can result in serious injuries or fatalities. A work-related illness or injury can result in decreased productivity, finances and reputation. Health and safety is divided into:

a) Training
b) Alcohol / Drug Testing
c) Safety Program

a) <u>Health and Safety Training</u>

Regular training in health and safety can help keep employees safe during dangerous or unexpected situations.

Is there a health and safety training program?	Pts.
Scheduled training	0
No training	7

b) Alcohol / Drug Testing

Part and parcel of any health and safety program, especially within the industrial sector, is a drug and alcohol testing program. Employees are often operating heavy equipment or are responsible for the operation and maintenance of critical assets. Impaired judgement can lead to delayed on inappropriate responses at critical junctions.

Is there a drug / alcohol testing program?	Pts.
Functioning drug / alcohol testing program	0
No Screening	7

c) Safety Programmes

Under the OSH Act of South Africa it is a requirement that there should be a documented safety programmes in place that governs all actions with regards to safe work (State President's Office, 1993).

Is there a working safety program in place?	Pts.
Company that promotes safety to a high degree	0
Safety not endorsed	7

3.3.2 Damage Factor

The damage factor is meant to evaluate how much damage may be present as a function of time in service (API, 2009). In the case of corrosion fatigue it is related to the material, operations and residual stress or excessive restraint acting onto the component. The percentages assigned in this example can be changed on a case-by-case basis, depending on where focus should be directed. The highest percentages were assigned to those aspects that could be effectively managed by an inspection and maintenance program. For instance, "Material" only accounts for 20% of "Damage Factor", because it is not something that can be changed easily or cost effectively.

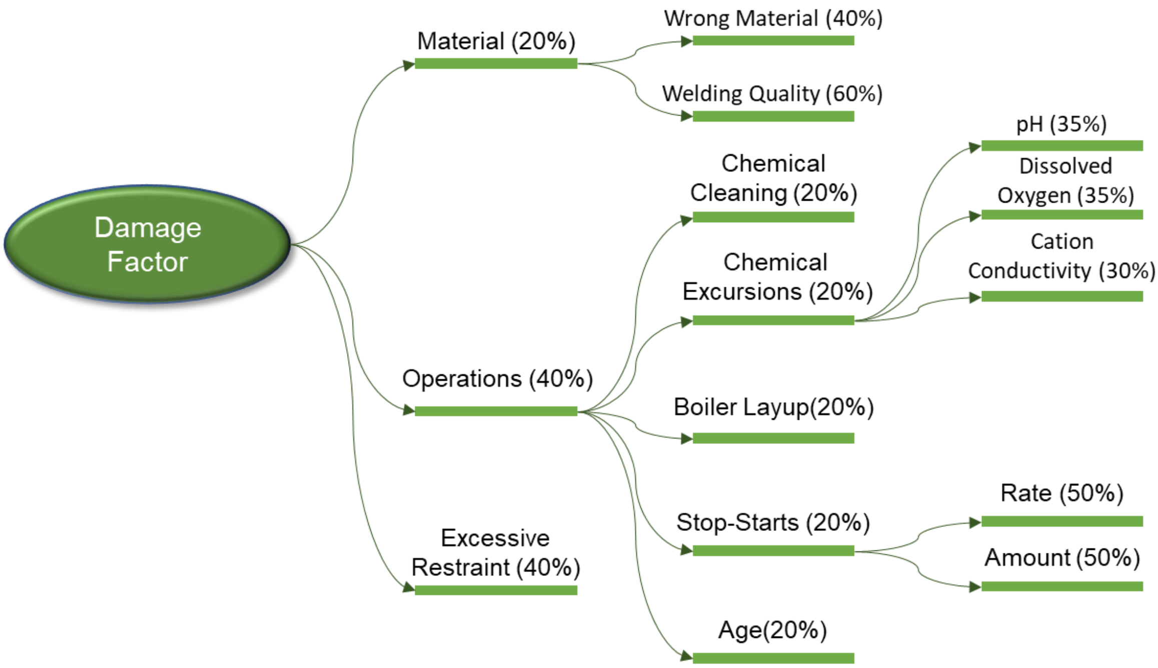

Figure 21: Diagram showing how the damage factor is determined.

3.3.2.1 Material

Material has a strong influence on the imitation and propagation of corrosion fatigue and is divided into:

a) Wrong Material
b) Welding Quality

a) <u>Wrong Material</u>

Pressure parts are designed with certain material and mechanical properties in mind. During emergency repairs or occasions where there is extreme time pressure, the wrong material can be used. This can be in the form the component consisting of the wrong material or using the wrong filler material during welding.

Are there historic evidence of the wrong material being installed?	Pts.
No	0
Yes	7
Unknown	7

b) <u>Welding Quality</u>

During installation or fabrication there have been occasions where welding quality has been poor. This can be related to a number of environmental or social factors, however not all the bad welding can be replaced immediately. Plans are often made to remediate the poor welding, but repairs are not often actioned. The poor welding will consequently remain in service and go undetected for years and act as stress raisers or failure initiation points.

Was there any historical issues with welding in this area?	Pts.
No	0
Yes, but not extensive	3.5
Yes, numerous defects have been found	7
Unknown	7

3.3.2.2 Operations

Operational factors can influence how corrosion fatigue initiates, how prevalent the mechanism is, as well as how it propagates. Operations have been divided into:

a) Chemical Cleaning
b) Chemical Excursions
c) Boiler Lay-up
d) Stop-Starts
e) Age

a) <u>Chemical Cleaning</u>

Chemical cleans by hydrochloric acid can exacerbate corrosion fatigue failures (Dooley, 2005). Improper chemical cleaning can result in severe damage, with the acid cleaning removing the protective oxide within pre-existing cracks and exposing the underlying material to the corrosive environment (Dooley, 2005).

How many chemical cleans using a hydrochloric acid solution has the boiler been exposed to?	Pts.
None	0
One	3.5
More than one	7

b) <u>Chemical Excursions</u>

Controlling water chemistry is an essential part of limiting corrosion fatigue failures. EPRI defines dissolved oxygen, pH, and cation conductivity as the “three major corrosion effects” when it comes to corrosion fatigue (Dooley & McNaughton, 2007).

- ***pH***

Corrosion fatigue typically occurs in boilers that have had problems maintaining boiler water and feedwater limits, with indications of large pH swings. Hydrogen damage, acid phosphate corrosion and caustic gouging are three waterside underdeposit corrosion mechanisms that are superficially similar (Dooley &

McNaughton, 2007). Hydrogen damage is typically caused by a source of low pH (acidic), while caustic gauging is as a result of high pH levels (caustic) (Dooley & McNaughton, 2007). Acid phosphate corrosion occurs with the addition of mono- and / or di-sodium phosphate (Dooley & McNaughton, 2007). Boilers with recorded incidents of these underdeposit corrosion mechanisms are typically more prone to corrosion fatigue failures occurring.

How many hydrogen damage, acid phosphate corrosion or caustic gouging events resulting in tube failures have occurred over the life of the boiler?	
None	0
One	3.5
More than one	7
Unknown	0

The pH at blowdown should be in the following ranges for the different water chemistry treatment regimes (Dooley, 2005).

What is the boiler pH at blowdown?

If AVT(O)	If AVT(R) - Mixed Metallurgy	If AVT(R) - All Ferrous	If OT- Drum Type	If OT- Once Through Type	Pts.
9.2-9.6	9.0-9.3	9.2-9.6	9.2-9.4	8-8.5	0
9.7-10	9.4-10	9.7-10	9.5-10	8.6-10	3.5
8-9.1	8-8.9	8-9.1	8-9.1	7-7.9	3.5
< 8, > 10	< 8, > 10	< 8, > 10	< 8, > 10	< 7, > 10	7

- ***Cation Conductivity***

Cation conductivity is a measurement of the conductivity of the water after removing cations from the sample and is an indirect measurement of corrosive species like chloride and sulphate (Dooley, 2005).

What is the cation conductivity (µS/cm)?

if AVT(R) or AVT(O)	if OT	Pts.
≤0.2	<0.15	0
>0.2	>0.15	7
Unknown	Unknown	7

- ***Dissolved Oxygen***

Above 135°C dissolved oxygen has a significant effect on corrosion fatigue crack initiation (Dooley & Chang, 2000). The relationship is made more complex due to the lowered solubility of oxygen at higher temperatures. During start-up the dissolved oxygen can be as high as 8,000 ppb, but by the time that the highest level of strain is applicable at the corrosion fatigue locations, the oxygen level in the boiler water should be low (< 10 ppb) (Dooley & McNaughton, 2007). This is particular concern at power stations where oxygen has been high due to blow down issues. This relationship can be seen in Figure 22.

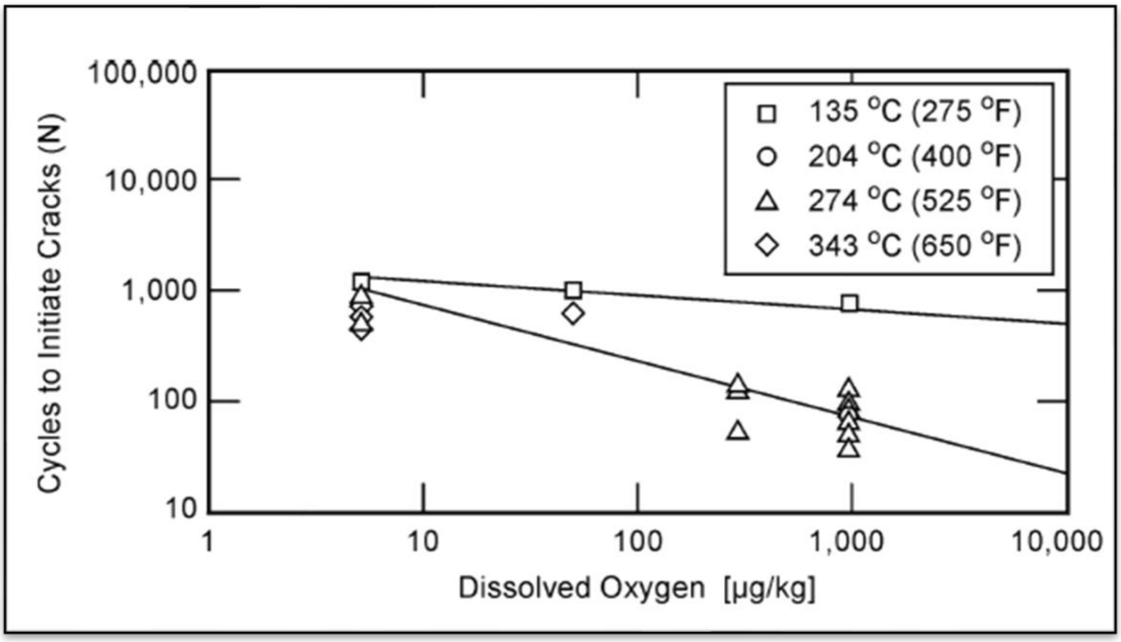

Figure 22: How dissolved oxygen effects the initiation of corrosion fatigue cracking (Dooley & Chang, 2000).

What is the feed water at the economizer inlet, dissolved oxygen (ppb)?

If AVT(R)	If AVT(O)	If OT- Drum Type	If OT- Once Through Type	Pts.
<5	<10	30-50	30-150	0
< 20	< 20	< 50	< 150	7
> 20	> 20	> 30	> 30	7

c) **Boiler Lay-up**

Boiler lay-up refers to shutting down and storing a boiler that is not in use for an extended period of time. Boiler lay-up conditions have been suspected to aggravate damage by corrosion fatigue, particularly if the pH was depressed and dissolved oxygen levels were not controlled (Dooley & McNaughton, 2007). Both conditions lead to pitting, and pits can be initiating centres for corrosion fatigue (Dooley & McNaughton, 2007).

What actions are taken for shutdown corrosion protection:
(a) N_2 cap on drum and treated water if boiler not drained.
(b) Refill drained boiler with chemically treated water to control pH and oxygen.
(c) Ensure dry storage if drained.
(d) Monitor and adjust pH and oxygen in boiler water during wet layup.

	Pts.
Actions (a) to (d)	0
Actions (a) and (b)	3.5
No action	7

d) <u>Stop-Starts</u>

Controlling the rate and minimising the number of start-ups will decrease the amount of stress cycles that the boiler is subjected to.

- ***Rate***

Fast start-up or cool-down rates will increase the magnitude of the thermal strain. Excessive restraint can be imposed on the structure of the boiler by improper cold pull, residual stress from welding and insufficient room for expansion during start-up due to filled ash boxes.

What are the average ramp-up or shut-down rates?	Pts.
Rates within recommended ranges	0
Rate of cooling and start-up higher than recommended	7
Unknown	7

- ***Amount***

South African boilers have mostly been designed and operated within a baseload model. Fatigue-effects induced by excessive stop-starts are therefore comparatively low.

What are the total boiler cold starts?	Pts.
Less than 10 cold starts	0
More than 10 but less than 100 cold starts	3.5
More than 100 cold starts	7
Unknown	7

e) <u>Boiler Age</u>

It should be noted that South African boilers (in many cases) are operating beyond their initial design life. To account for the collective effect, Figure 23 has combined operating hours and number of unit starts into equivalent operating hours (Dooley & Chang, 2000). The influence diagram integrates the three basic influences on failure of boiler tubes by corrosion fatigue: stresses, environment, and unit operating history

(Dooley & McNaughton, 2007). The chemical environment parameter evaluation is represented by line E1–E4 (Dooley & McNaughton, 2007). Where E1 represents operating with EPRI guidelines or better and decreasing water chemistry control is represented by E2–E4 (Dooley & McNaughton, 2007).

What is the equivalent operating hours for the boiler?	Pts.
Less than 30 000 hours	0
Between 30 000 and 50 000 hours	2
Between 50 000 and 90 000 hours	3
Between 90 000 and 140 000 hours	5
More than 140 000 hours	7

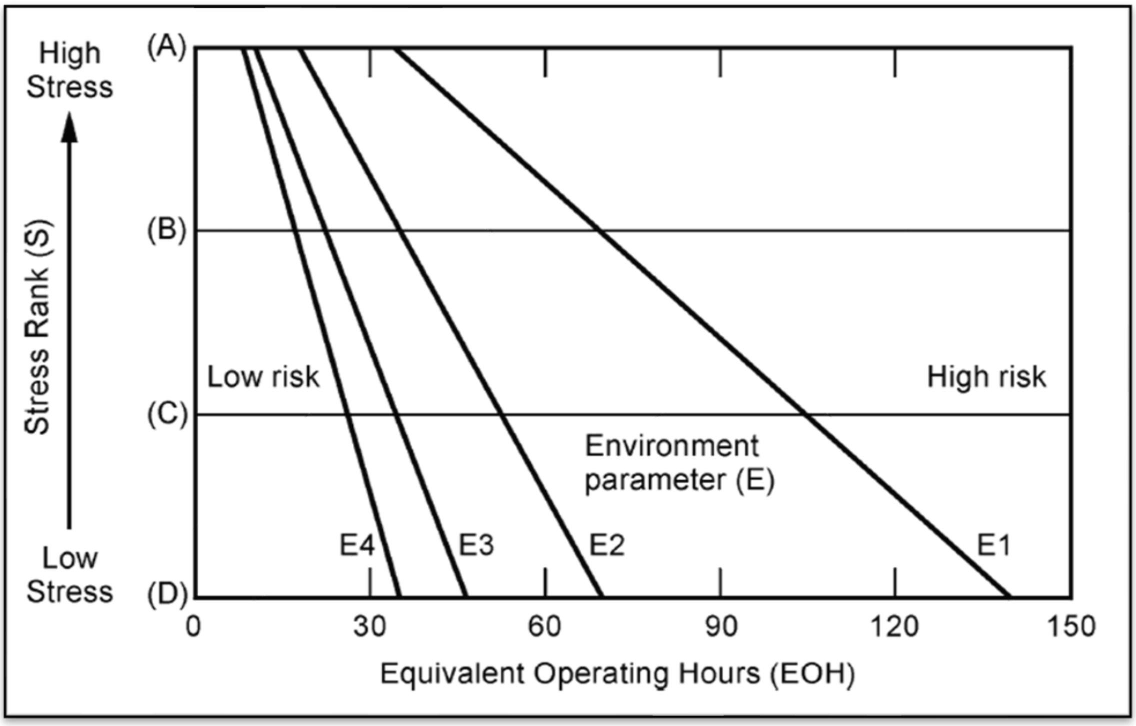

Figure 23: Influence diagram for corrosion fatigue in waterwall tubes (Dooley & Chang, 2000).

3.3.2.3 Excessive Restraint

Table 7 should be used to define how areas within the boiler are sectioned for the risk assessment. Areas with excessive restraint are penalised more than areas with low restraint and are large dependent on the kind of attachment used to secure tubes in place.

What is the stress rank at this location?	Pts.
D	0
C	3
B	5
A	7

Table 7: Stress rank for various boiler locations as defined by EPRI (Dooley & McNaughton, 2007).

Equipment Number	Location	Description	Stress Rank
1	Windbox casing	Continuous scallop plate	B
1	Windbox casing	Filler bars	B
2	Buckstay corners	Rigid corner scallop plate connected to buckstay	B
2	Buckstay corners	Lug mounted tie-bar connected to tubes at corner	A
2	Buckstay corners	Tangent/membrane wall with filler bar connections	D
3	Boiler ash hopper seal plate	Continuous scallop plate welded to horizontal tubes	B
4	Boiler seal heat shield (slag screen)	Continuous scallop plate welded to tubes	B
4	Boiler seal heat shield (slag screen)	6-8 tube tangential bar	C
5	Side wall gusset plate	Triangular plate between redirected tubes	A
6	Division wall penetration of slope	Refractory box rigidly connected at the top and bottom	D
6	Division wall penetration of slope	Continuous scallop plate	B
7	Burner throat/gas offtake tube ties	Short bars welded between redirected tangent tubes	C
7	Burner throat/gas offtake tube ties	Short bars welded between tubes in tangent tube wall	B
8	Burner barrel mounts	Direct connection from burner barrel to waterwall	C
9	Windbox extension vertical seal	Windbox extension duct welded directly to vertical flat bar; flat bar is on outside of windbox, but could also be on inside	D
10	Buckstay connections to waterwalls	Continuous scallop tie-bar	C
10	Buckstay connections to waterwalls	Continuous tangent bar tack welded to tubes membrane wall	D
10	Buckstay connections to waterwalls	Continuous tangent bar tack welded to tubes tangent tube wall	B
11	Scallop tie-bars	Tangent tube waterwalls; most failures at corners or associated with abnormally high loads	D
12	Miscellaneous waterwall penetration gusset plates	Sootblower penetrations	D

12	Miscellaneous waterwall penetration gusset plates	Burner throat and gas off-takes	C
13	Miscellaneous filler bar attachments	Windbox strut attachment	D
13	Miscellaneous filler bar attachments	Side wall buckstay/baffle wall connection	D
13	Miscellaneous filler bar attachments	Slope wall support I-beam at side wall	B
14	Penthouse floor attachments	Continuous scallop plate problems most common in corners	D
14	Penthouse floor attachments	Continuous scallop more serious if connecting tubes carrying different media	B
15	Side wall/slope wall	Scallop bar	D
15	Side wall/slope wall	Rod welded between tubes	B
16	End of membrane	More serious adjacent to redirected tube	A
17	Furnace gas exit scallop plate	Continuous scallop plate adjacent to redirected tubes	C
18	Rear waterwall arch	Continuous scallop plate adjacent to separation of hanger tubes	D
19	Side wall buckstay connection to slope wall	Tangent bar tack welded to tubes	C
19	Side wall buckstay connection to slope wall	Scallop bar tack welded on alternate sides of bar	D
20	Side wall buckstay connection to baffle wall	Flat bar connection to baffle wall seal welded with filler bars at side wall lowest connection affected	C
21	Lower front/rear waterwall S-bends	Immediately downstream of mud drums, with locating scallop bars between tubes	B
22	Gas recirculation duct scallop plate attachment	Continuous scallop bar	D
23	Furnace floor connection between nose tubes	Direct connection between nose tubes in opposite walls	C
24	Division wall tube ties	First set of tube ties above slope wall	D
25*	Superheater inlet tubes	Rigid corner scallop plate connected to buckstay	B
26*	Superheater outlet tubes	Rigid corner scallop plate connected to buckstay	B
27*	Superheater inlet tubes	Tangent/membrane wall with filler bar connections	D

28*	Superheater outlet tubes	Tangent/membrane wall with filler bar connections	D
29*	Superheater inlet tubes	Tangent/membrane wall with filler bar connections	D
30*	Superheater outlet tubes	Tangent/membrane wall with filler bar connections	D
31*	Economiser inlet tubes	Tangent/membrane wall with filler bar connections	D
32*	Economiser outlet tubes	Tangent/membrane wall with filler bar connections	D

*These equipment locations have been added to account for the superheater and economiser.

3.4 CONSEQUENCE OF FAILURE (COF)

For this model we will only consider financial consequence and exclude environmental and safety consequence. This is because boiler tube leaks seldom result in a breach of the skin casing.

To model true financial consequence requires a case-by-case approach, because of the large amount of variables at play. For instance the location of the tube leak will influence the amount of secondary damage as well as the mean time to repair (due to the requirement for scaffolding or the amount of damage incurred). However, the decision to shut down is not just predicated on leak location, and additional factors like contractor availability, electricity demand, public holidays or social unrest can take precedence.

To simplify further, this model will only combine fuel cost and revenue lost as a result outage duration (which will be based on accessibility). To calculate the cost of an outage the following equation will be used:

$$CoF(Rand) = \left(Revenue\ per\ Megawatt.hour\left(\frac{R}{MWh}\right) \times Boiler\ Capacity(MW) \times Outage\ Duration\ (h)\right) + \left(Fuel\ Cost(R)\right)$$ – Equation 6

3.5 RISK

Risk is a consolidation of probability and consequences as represented in the risk matrix below. The weightings which contribute to both probability and consequence have been assigned a maximum value of 7, therefore to simplify representation, the risk matrix is 7x7. The likelihood factors of the risk matrix were derived from a combination of likelihood factors in API 580 and BS EN 16991. The financial consequence was modified to fit the highest possible direct cost expenditure possible when considering fuel cost for start-up as well as MWh lost due to shut down.

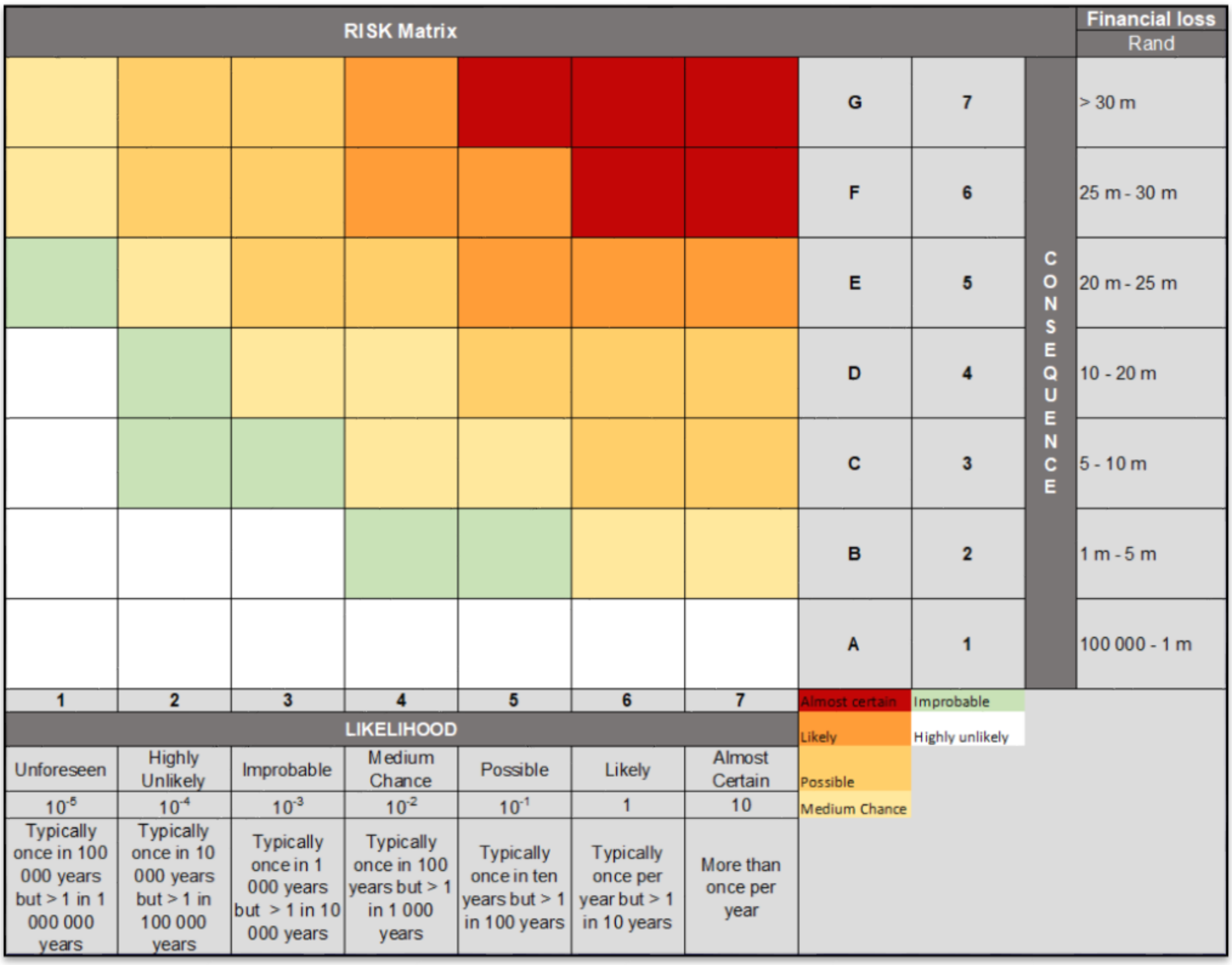

Figure 24: Risk matrix used to represent risk scores.

3.6 PROCESS FLOW

For the developed model, the process for determining the risk can be summarised in the process flow diagram shown in Figure 25. The process flow diagram seeks to summarise the detail discussion and methodology followed in Chapter 3 and applied in Chapter 4.

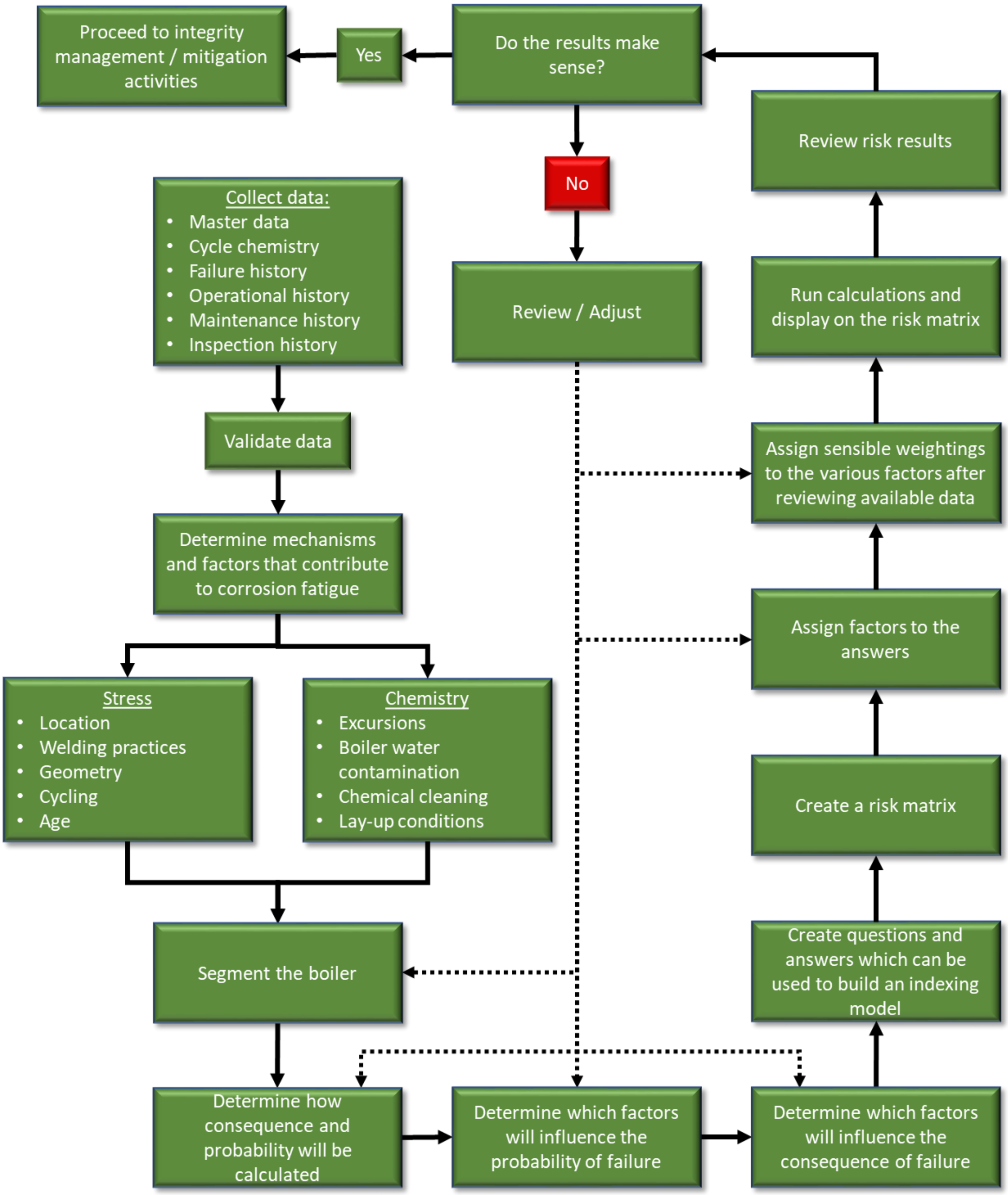

Figure 25: Process flow diagram of the model developed to determine the risk associated with boiler tube corrosion fatigue failures

CHAPTER 4 APPLICATION AND EVALUATION OF MODEL

4.1 POWER STATION

Using the methodology and background outlined above, a risk analysis was applied to three (3) units of a power station. The power station has the following key characteristics (Conradie *et al*, 2000; Eskom Heritage, 2020):

Installed Capacity:	1000 MW
Number Of Boiler Units:	9
Feedwater System:	Mixed Metallurgy (unit 1 – 7) / All-ferrous (unit 8 – 9)
Feedwater Treatment:	Reducing All-Volatile Treatment / Oxidising all-volatile treatment Historically phosphate treatments
Boiler Type:	Drum Unit, Rear Wall Fired
Fuel Type:	Pulverised Fuel (PF) – Coal
Original Boiler Design Life:	100 000 hours
Average Operating Hours:	190 000 hours
Special Conditions:	This power station was decommissioned and spent more or less 21 years in cold storage. Significant refurbishments were made before recommissioning the station.
Operating Mode:	Baseload

Failure records from this power station between January 2011 and December 2016 (a 6 year period) show that 35 corrosion fatigue failures occurred in total (Meyer, 2017). The second most active mechanism is fly ash erosion. Unit 5 was chosen because it has lower operating hours than Unit 6, but a similar number of failures (Meyer, 2017). The order of discussing the Units is purely numerical.

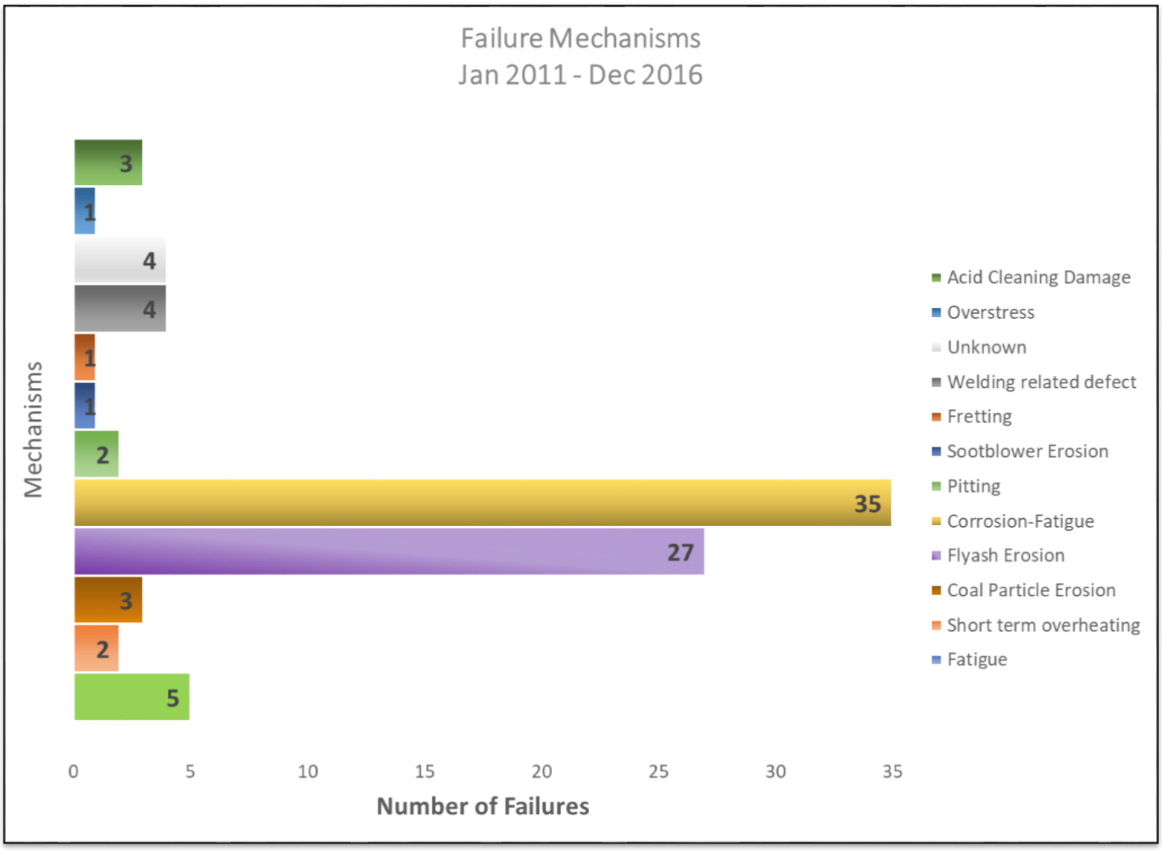

Figure 26: Failure mechanisms over a six (6) year period (Meyer, 2017).

The unit distribution of the corrosion fatigue failures can be seen in Figure 27 and Figure 28. It was decided to use Unit 7, Unit 9 and Unit 5 as the case studies because they had a total of eight (8), seven (7) and five (5) CF tube leaks respectively, within a 6 year period (Meyer, 2017).

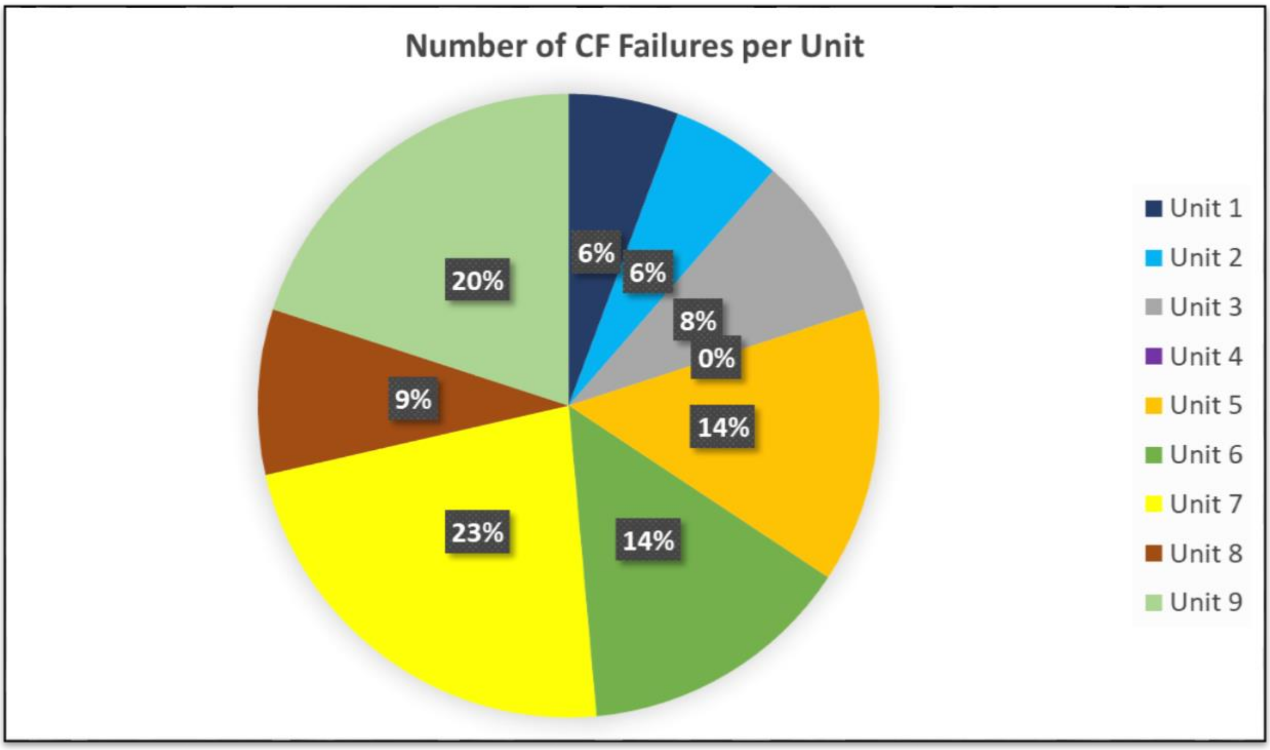

Figure 27: Number of corrosion fatigue failures for a period of 6 years (Meyer, 2017).

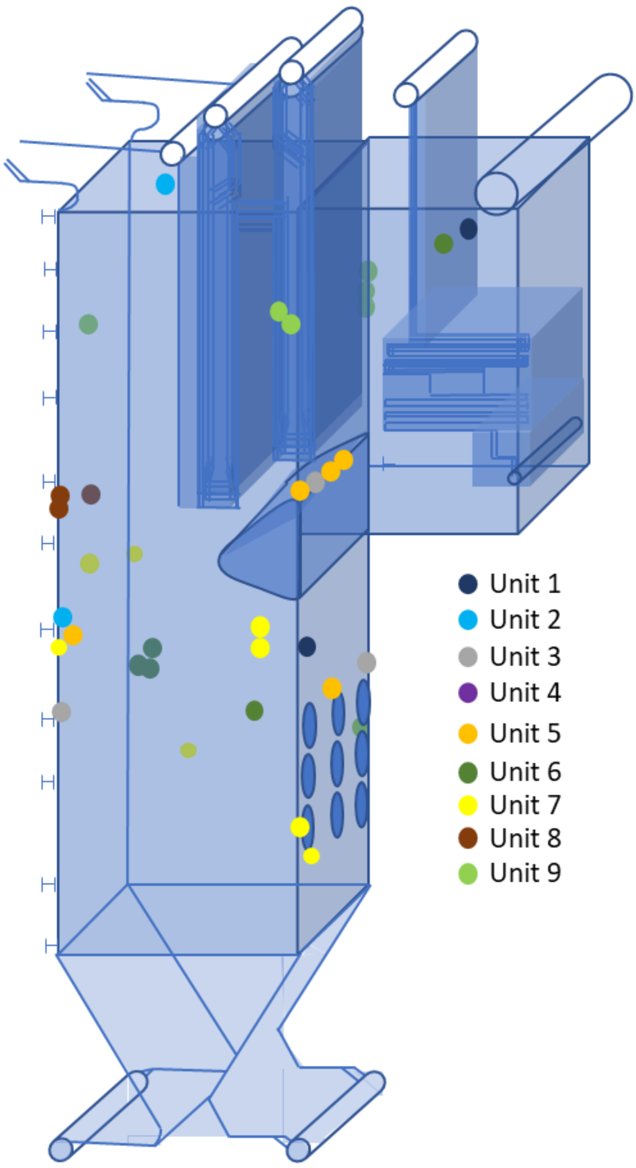

Figure 28: Corrosion fatigue failures. The colours correspond to those of the units depicted in Figure 27 (Meyer, 2017).

4.2 UNIT 5

4.2.1 Data / Information

Using the methodology and background outlined in Chapter 3, a risk analysis was applied to unit 5 of a power station. Unit 5 has the following key characteristics (Conradie *et al*, 2000; Eskom Heritage, 2020):

Installed Capacity: 100 MW

Feedwater System: Mixed Metallurgy

Feedwater Treatment: Reducing All-Volatile Treatment

Historically phosphate treatments

Boiler Type: Drum Unit, Rear Wall Fired

Fuel Type: Pulverised Fuel (PF) – Coal

Original Boiler Design Life: 100 000 hours

Average Operating Hours: 187 000 hours

Operating Mode: Baseload

This study only considers the internal pressure parts of a boiler, excluding header systems. The following information is relevant to the assessment:

Table 8: Pressure parts design information (Conradie *et al*, 2000).

Component	Material Grade	Outside Diameter (mm)	Inside Diameter (mm)	Wall Thickness (mm)
Waterwall Tubes	BS 3059 360	63.5	54.56	4.47
Superheater 1 Tubes	BS 3059 360 / BS EN 620 Gr. 27	47.63	38.69	4.47
Superheater 2 Tubes	BS EN 620 Gr. 27	50.8	41.04 / 35.56	4.88 / 7.62
Superheater 3 Tubes	BS EN 620 Gr. 27 / BS EN 622 Gr. 31	50.8	35.56 / 33.12	7.62 /8.84
Economiser Inlet Tubes	BS 3059 360	50.8	41.86	4.47
Economiser Outlet Tubes	BS 3059 360	50.8	41.86	4.47

4.2.2 Segmenting

The locations defined by EPRI were further refined and a new restraint map created based on the typical configuration of a pendant style boiler, which can be seen in Figure 29. Additional equipment numbers were added to account for the superheater and economiser systems. Unit 5 was segmented into general “systems” and “equipment” as per the equipment numbers and can be seen in Table 9 below (Dooley & McNaughton, 2007).

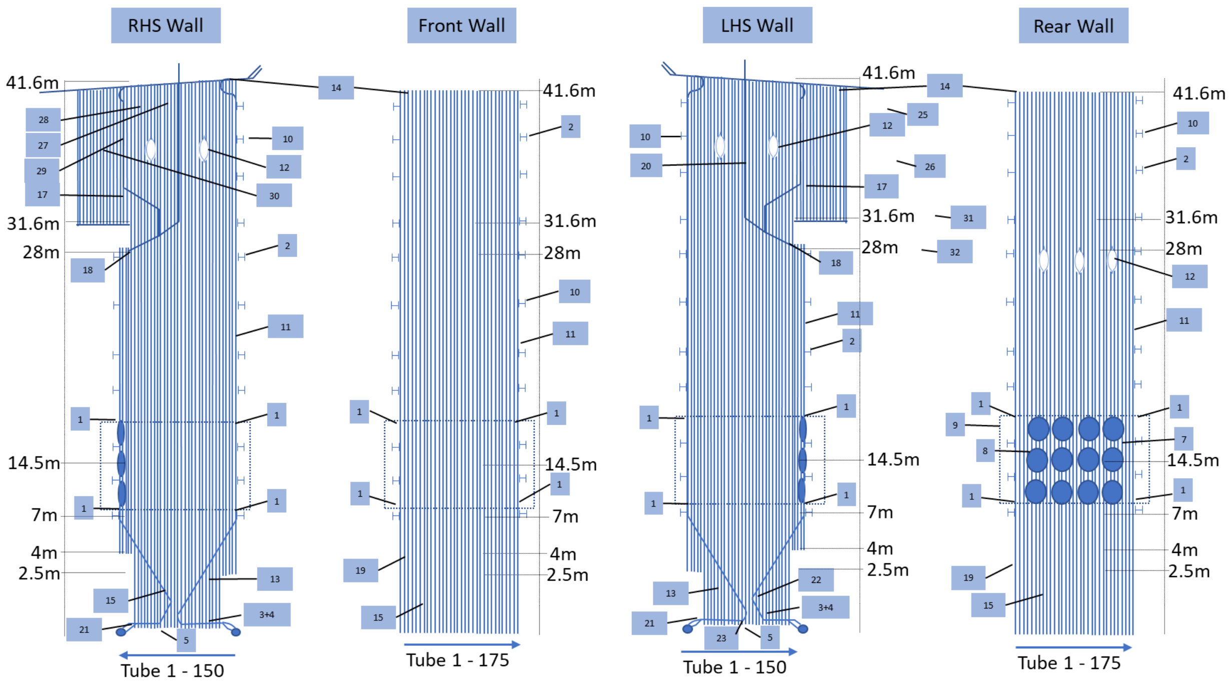

Figure 29: Stress rank as defined by EPRI for a typical configuration of a pendant style boiler (Dooley & McNaughton, 2007).

Table 9: Segmentation of Unit 5. Best fit descriptions were ascertained from information available on as-built drawings (Craddock, 2016).

System	Equipment	Equipment Location Number	Location	Description
Waterwall	Front Waterwall	1	Windbox casing	Continuous scallop plate
Waterwall	Rear Waterwall	1	Windbox casing	Continuous scallop plate
Waterwall	LHS Waterwall	1	Windbox casing	Continuous scallop plate
Waterwall	RHS Waterwall	1	Windbox casing	Continuous scallop plate
Waterwall	Front Waterwall	2	Buckstay corners	Tangent/membrane wall with filler bar connections
Waterwall	Rear Waterwall	2	Buckstay corners	Tangent/membrane wall with filler bar connections
Waterwall	RHS Waterwall	2	Buckstay corners	Tangent/membrane wall with filler bar connections
Waterwall	LHS Waterwall	3	Boiler ash hopper seal plate	Tangent/membrane wall with filler bar connections
Waterwall	RHS Waterwall	3	Boiler ash hopper seal plate	Continuous scallop plate welded to horizontal tubes
Waterwall	LHS Waterwall	4	Boiler seal heat shield (slag screen)	Continuous scallop plate welded to horizontal tubes
Waterwall	RHS Waterwall	4	Boiler seal heat shield (slag screen)	6-8 tube tangential bar

System	Equipment	Equipment Location Number	Location	Description
Waterwall	LHS Waterwall	5	Side wall gusset plate	6-8 tube tangential bar
Waterwall	RHS Waterwall	5	Side wall gusset plate	Change to peg membrane
Waterwall	Rear Waterwall	7	Burner throat tube ties	Change to peg membrane
Waterwall	Rear Waterwall	8	Burner barrel mounts	Short bars welded between tubes in tangent tube wall
Waterwall	Rear Waterwall	9	Windbox extension vertical seal	Direct connection from burner barrel to waterwall
Waterwall	Front Waterwall	10	Buckstay connections to waterwalls	Windbox extension duct welded directly to vertical flat bar; flat bar is on outside of windbox, but could also be on inside
Waterwall	Rear Waterwall	10	Buckstay connections to waterwalls	Continuous tangent bar tack welded to tubes tangent tube wall
Waterwall	RHS Waterwall	10	Buckstay connections to waterwalls	Continuous tangent bar tack welded to tubes tangent tube wall
Waterwall	LHS Waterwall	10	Buckstay connections to waterwalls	Continuous scallop tie-bar
Waterwall	Front Waterwall	11	Scallop tie-bars	Continuous scallop tie-bar
Waterwall	Rear Waterwall	11	Scallop tie-bars	Tangent tube waterwalls; most failures at corners or associated with abnormally high loads
Waterwall	RHS Waterwall	11	Scallop tie-bars	Tangent tube waterwalls; most failures at corners or associated with abnormally high loads
Waterwall	LHS Waterwall	11	Scallop tie-bars	Tangent tube waterwalls; most failures at corners or associated with abnormally high loads
Waterwall	Front Waterwall	12	Miscellaneous waterwall penetration gusset plates	Tangent tube waterwalls; most failures at corners or associated with abnormally high loads
Waterwall	Rear Waterwall	12	Miscellaneous waterwall penetration gusset plates	Sootblower penetrations
Waterwall	RHS Waterwall	12	Miscellaneous waterwall penetration gusset plates	Sootblower penetrations
Waterwall	LHS Waterwall	12	Miscellaneous waterwall penetration gusset plates	Sootblower penetrations
Waterwall	Front Waterwall	13	Miscellaneous filler bar attachments	Sootblower penetrations
Waterwall	Rear Waterwall	13	Miscellaneous filler bar attachments	Windbox strut attachment

System	Equipment	Equipment Location Number	Location	Description
Waterwall	RHS Waterwall	13	Miscellaneous filler bar attachments	Windbox strut attachment
Waterwall	LHS Waterwall	13	Miscellaneous filler bar attachments	Windbox strut attachment
Waterwall	RHS Waterwall	13	Miscellaneous filler bar attachments	Windbox strut attachment
Waterwall	LHS Waterwall	13	Miscellaneous filler bar attachments	Side wall buckstay/baffle wall connection
Waterwall	RHS Waterwall	13	Miscellaneous filler bar attachments	Side wall buckstay/baffle wall connection
Waterwall	LHS Waterwall	13	Miscellaneous filler bar attachments	Slope wall support I-beam at side wall
Waterwall	Roof Tubes	14	Penthouse floor attachments	Slope wall support I-beam at side wall
Waterwall	Front Waterwall	15	Side wall/slope wall	Continuous scallop plate problems most common in corners
Waterwall	Rear Waterwall	15	Side wall/slope wall	Scallop bar
Waterwall	RHS Waterwall	15	Side wall/slope wall	Scallop bar
Waterwall	LHS Waterwall	15	Side wall/slope wall	Scallop bar
Waterwall	Upper Nose Slope	17	Furnace gas exit scallop plate	Scallop bar
Waterwall	Upper Nose Slope	18	Rear waterwall arch	Continuous tangent bar tack welded to tubes tangent tube wall
Waterwall	Front Waterwall	19	Side wall buckstay connection to slope wall	Continuous scallop plate adjacent to separation of hanger tubes
Waterwall	Rear Waterwall	19	Side wall buckstay connection to slope wall	Scallop bar tack welded on alternate sides of bar
Waterwall	RHS Waterwall	19	Side wall buckstay connection to slope wall	Scallop bar tack welded on alternate sides of bar
Waterwall	LHS Waterwall	19	Side wall buckstay connection to slope wall	Scallop bar tack welded on alternate sides of bar
Waterwall	RHS Waterwall	20	Side wall buckstay connection to baffle wall	Scallop bar tack welded on alternate sides of bar
Waterwall	LHS Waterwall	20	Side wall buckstay connection to baffle wall	Flat bar connection to baffle wall seal welded with filler bars at side wall lowest connection affected
Waterwall	Front Waterwall	21	Lower front/rear waterwall S-bends	Flat bar connection to baffle wall seal welded with filler bars at side wall lowest connection affected

System	Equipment	Equipment Location Number	Location	Description
Waterwall	Rear Waterwall	21	Lower front/rear waterwall S-bends	Immediately downstream of mud drums, with locating scallop bars between tubes
Waterwall	Front Waterwall	23	Furnace floor connection between nose tubes	Immediately downstream of mud drums, with locating scallop bars between tubes
Waterwall	Rear Waterwall	23	Furnace floor connection between nose tubes	Direct connection between nose tubes in opposite walls
Superheater	Superheater 1	25*	Superheater inlet tubes	Direct connection between nose tubes in opposite walls
Superheater	Superheater 1	26*	Superheater outlet tubes	Rigid corner scallop plate connected to buckstay
Superheater	Superheater 2	27*	Superheater inlet tubes	Rigid corner scallop plate connected to buckstay
Superheater	Superheater 2	28*	Superheater outlet tubes	Tangent/membrane wall with filler bar connections
Superheater	Superheater 3	29*	Superheater inlet tubes	Tangent/membrane wall with filler bar connections
Superheater	Superheater 3	30*	Superheater outlet tubes	Tangent/membrane wall with filler bar connections
Economiser	Economiser Inlet	31*	Economiser inlet tubes	Tangent/membrane wall with filler bar connections
Economiser	Economiser Outlet	32*	Economiser outlet tubes	Tangent/membrane wall with filler bar connections

*These equipment location numbers have been added to account for the superheater and economiser.

4.2.3 Probability of Failure

4.2.3.1 Management System Factor

The management system factor can be ascertained predominantly by answering questions that would apply to all of Unit 5, with the exception of two questions that are system / equipment specific. A questionnaire was generated based on the outline given in Chapter 3 and the answers populated by the author based on the Unit 5 case study.

Table 10: General system questions and answers related to the management system factor (Craddock, 2016; Mazibuko, 2014).

Management System Factor Questions:	Answers:
How proficient is the NDT technicians in general?	Proven record of proficiency, but no verification

Management System Factor Questions:	Answers:
Will the inspection frequency reliably detect the failure mechanism?	Yes, the inspection frequency is adequate
Are materials inspected when they arrive and prior to installation?	All materials and components were verified as to their authenticity and conformance to specifications prior to their installation.
Are there inspection records?	Inspection record exist, but no validation
Were / are old and new designs checked and verified?	Designs were checked and signed
Was the safety factor used during the design of the component fit for purpose?	Yes
Are there control documents and procedures that govern all aspects of material selection and verification and are they in use?	Control documents exist and signed
Are welds / joints inspected after replacements have been made?	Inspection occurred, but sub-par results
Was there a post construction hydrostatic pressure test?	Yes, pressure test was conducted correctly
Are contractors audited for competency?	Regularly (once a year)
Are roles and responsibilities clearly defined?	No
Do personnel have the appropriate competencies?	Personnel are not exposed to regular training and mentoring programmes. Those in senior roles have the appropriate experience.
Is there a regular auditing programmes?	Yes
Is there a management of change system in place and is it actively used?	Yes, there is a management of change program in place and it is actively used
Is there a formal document management system in place and is it actively being used?	Yes, but system is not actively used
How effective is the tube leak detection system?	Moderately effective
Is there a hazard identification methodology and is it used?	HAZOP not conducted
Are any of these measures applicable to the control room and personnel?	Meets minimum standards
Do pressure testing occur at appropriate times and are there procedures in place to govern how they are conducted?	Yes, but procedures are not actively followed
Is there a health and safety training program?	Scheduled re-training
Is there a drug / alcohol testing program?	Functioning drug / alcohol testing program
Is there a working safety program in place?	Company that promotes safety to a high degree

Two questions are dependent on the location of the component, see Table 11.

Table 11: Location dependent management system factors (Craddock, 2016).

System	Equipment	Equipment Location Number	Are enough components inspected?	How accessible is this component w.r.t NDT?
Waterwall	Front Waterwall	1	NDT does not adequately identify corrosion fatigue and the extent of damage	Below average
Waterwall	Rear Waterwall	1	NDT does not adequately identify corrosion fatigue and the extent of damage	Below average
Waterwall	LHS Waterwall	1	NDT does not adequately identify corrosion fatigue and the extent of damage	Below average
Waterwall	RHS Waterwall	1	NDT does not adequately identify corrosion fatigue and the extent of damage	Below average
Waterwall	Front Waterwall	2	NDT does not adequately identify corrosion fatigue and the extent of damage	Below average
Waterwall	Rear Waterwall	2	NDT does not adequately identify corrosion fatigue and the extent of damage	Below average
Waterwall	RHS Waterwall	2	NDT does not adequately identify corrosion fatigue and the extent of damage	Below average
Waterwall	LHS Waterwall	3	NDT does not adequately identify corrosion fatigue and the extent of damage	Below average
Waterwall	RHS Waterwall	3	NDT does not adequately identify corrosion fatigue and the extent of damage	Excellent
Waterwall	LHS Waterwall	4	NDT does not adequately identify corrosion fatigue and the extent of damage	Excellent
Waterwall	RHS Waterwall	4	NDT does not adequately identify corrosion fatigue and the extent of damage	Excellent
Waterwall	LHS Waterwall	5	NDT does not adequately identify corrosion fatigue and the extent of damage	Excellent
Waterwall	RHS Waterwall	5	NDT does not adequately identify corrosion fatigue and the extent of damage	Average
Waterwall	Rear Waterwall	7	NDT does not adequately identify corrosion fatigue and the extent of damage	Average

System	Equipment	Equipment Location Number	Are enough components inspected?	How accessible is this component w.r.t NDT?
Waterwall	Rear Waterwall	8	NDT does not adequately identify corrosion fatigue and the extent of damage	Below average
Waterwall	Rear Waterwall	9	NDT does not adequately identify corrosion fatigue and the extent of damage	Below average
Waterwall	Front Waterwall	10	NDT does not adequately identify corrosion fatigue and the extent of damage	Below average
Waterwall	Rear Waterwall	10	NDT does not adequately identify corrosion fatigue and the extent of damage	Below average
Waterwall	RHS Waterwall	10	NDT does not adequately identify corrosion fatigue and the extent of damage	Below average
Waterwall	LHS Waterwall	10	NDT does not adequately identify corrosion fatigue and the extent of damage	Below average
Waterwall	Front Waterwall	11	NDT does not adequately identify corrosion fatigue and the extent of damage	Below average
Waterwall	Rear Waterwall	11	NDT does not adequately identify corrosion fatigue and the extent of damage	Below average
Waterwall	RHS Waterwall	11	NDT does not adequately identify corrosion fatigue and the extent of damage	Below average
Waterwall	LHS Waterwall	11	NDT does not adequately identify corrosion fatigue and the extent of damage	Below average
Waterwall	Front Waterwall	12	NDT does not adequately identify corrosion fatigue and the extent of damage	Below average
Waterwall	Rear Waterwall	12	NDT does not adequately identify corrosion fatigue and the extent of damage	Good
Waterwall	RHS Waterwall	12	NDT does not adequately identify corrosion fatigue and the extent of damage	Good
Waterwall	LHS Waterwall	12	NDT does not adequately identify corrosion fatigue and the extent of damage	Good

System	Equipment	Equipment Location Number	Are enough components inspected?	How accessible is this component w.r.t NDT?
Waterwall	Front Waterwall	13	NDT does not adequately identify corrosion fatigue and the extent of damage	Good
Waterwall	Rear Waterwall	13	NDT does not adequately identify corrosion fatigue and the extent of damage	Below average
Waterwall	RHS Waterwall	13	NDT does not adequately identify corrosion fatigue and the extent of damage	Below average
Waterwall	LHS Waterwall	13	NDT does not adequately identify corrosion fatigue and the extent of damage	Below average
Waterwall	RHS Waterwall	13	NDT does not adequately identify corrosion fatigue and the extent of damage	Below average
Waterwall	LHS Waterwall	13	NDT does not adequately identify corrosion fatigue and the extent of damage	Average
Waterwall	RHS Waterwall	13	NDT does not adequately identify corrosion fatigue and the extent of damage	Average
Waterwall	LHS Waterwall	13	NDT does not adequately identify corrosion fatigue and the extent of damage	Good
Waterwall	Roof Tubes	14	NDT does not adequately identify corrosion fatigue and the extent of damage	Good
Waterwall	Front Waterwall	15	NDT does not adequately identify corrosion fatigue and the extent of damage	Below average
Waterwall	Rear Waterwall	15	NDT does not adequately identify corrosion fatigue and the extent of damage	Good
Waterwall	RHS Waterwall	15	NDT does not adequately identify corrosion fatigue and the extent of damage	Good
Waterwall	LHS Waterwall	15	NDT does not adequately identify corrosion fatigue and the extent of damage	Good
Waterwall	Upper Nose Slope	17	NDT does not adequately identify corrosion fatigue and the extent of damage	Good

System	Equipment	Equipment Location Number	Are enough components inspected?	How accessible is this component w.r.t NDT?
Waterwall	Upper Nose Slope	18	NDT does not adequately identify corrosion fatigue and the extent of damage	Good
Waterwall	Front Waterwall	19	NDT does not adequately identify corrosion fatigue and the extent of damage	Good
Waterwall	Rear Waterwall	19	NDT does not adequately identify corrosion fatigue and the extent of damage	Good
Waterwall	RHS Waterwall	19	NDT does not adequately identify corrosion fatigue and the extent of damage	Good
Waterwall	LHS Waterwall	19	NDT does not adequately identify corrosion fatigue and the extent of damage	Good
Waterwall	RHS Waterwall	20	NDT does not adequately identify corrosion fatigue and the extent of damage	Good
Waterwall	LHS Waterwall	20	NDT does not adequately identify corrosion fatigue and the extent of damage	Good
Waterwall	Front Waterwall	21	NDT does not adequately identify corrosion fatigue and the extent of damage	Good
Waterwall	Rear Waterwall	21	NDT does not adequately identify corrosion fatigue and the extent of damage	Good
Waterwall	Front Waterwall	23	NDT does not adequately identify corrosion fatigue and the extent of damage	Good
Waterwall	Rear Waterwall	23	NDT does not adequately identify corrosion fatigue and the extent of damage	Good
Superheater	Superheater 1	24	NDT does not adequately identify corrosion fatigue and the extent of damage	Good
Superheater	Superheater 1	25	NDT adequately identifies corrosion fatigue and the extent of damage	Average
Superheater	Superheater 2	26	NDT adequately identifies corrosion fatigue and the extent of damage	Below average

System	Equipment	Equipment Location Number	Are enough components inspected?	How accessible is this component w.r.t NDT?
Superheater	Superheater 2	27	NDT adequately identifies corrosion fatigue and the extent of damage	Excellent
Superheater	Superheater 3	28	NDT adequately identifies corrosion fatigue and the extent of damage	Excellent
Superheater	Superheater 3	29	NDT adequately identifies corrosion fatigue and the extent of damage	Excellent
Economiser	Economiser Inlet	30	NDT adequately identifies corrosion fatigue and the extent of damage	Excellent
Economiser	Economiser Outlet	31	NDT adequately identifies corrosion fatigue and the extent of damage	Below average

4.2.3.2 Damage Factor

The damage factor can be ascertained predominantly by answering questions that would apply to an entire boiler, with the exception of two questions that are system / equipment specific. A questionnaire was generated based on the outline given in Chapter 3 and populated by the author based on the current Unit 5 case study (Mazibuko, 2014 & Meyer, 2017).

Table 12: General system questions and answers related to the damage factor

Damage Factor Questions	Answers:
Are there historic evidence of the wrong material being installed?	Yes
How many hydrogen damage, acid phosphate corrosion or caustic gouging events resulting in tube failures have occurred over the life of the boiler?	None
What is the boiler pH at blowdown?	9.4-10
What is the cation conductivity (µS/cm)?	Unknown
What is the feed water at the economizer inlet, dissolved oxygen (ppb)?	> 20
What actions are taken for shutdown corrosion protection: (a) N2 cap on drum and treated water if boiler not drained. (b) Refill drained boiler with chemically treated water to control pH and oxygen. (c) Ensure dry storage if drained. (d) Monitor and adjust pH and oxygen in boiler water during wet layup.	Actions (a) to (d)
What are the average ramp-up or shut-down rates?	Rates within recommended ranges
What are the total boiler cold starts?	More than 100 cold starts
What is the equivalent operating hours for the boiler?	More than 140 000 hours

Two questions are dependent on the location of the component, see Table 13.

Table 13: Location dependent damage factors (Craddock, 2016).

System	Equipment	Equipment Location Number	What is the stress rank at this location?	Was there any historical issues with welding in this area?
Waterwall	Front Waterwall	1	B	Yes, but not extensive
Waterwall	Rear Waterwall	1	B	Yes, but not extensive
Waterwall	LHS Waterwall	1	B	Yes, but not extensive
Waterwall	RHS Waterwall	1	B	Yes, but not extensive
Waterwall	Front Waterwall	2	D	Yes, but not extensive
Waterwall	Rear Waterwall	2	D	Yes, but not extensive
Waterwall	RHS Waterwall	2	D	Yes, but not extensive
Waterwall	LHS Waterwall	2	D	Yes, but not extensive
Waterwall	LHS Waterwall	3	B	Yes, but not extensive
Waterwall	RHS Waterwall	3	B	Yes, but not extensive
Waterwall	LHS Waterwall	4	C	Yes, but not extensive
Waterwall	RHS Waterwall	4	C	Yes, but not extensive
Waterwall	LHS Waterwall	5	C	No
Waterwall	RHS Waterwall	5	C	No
Waterwall	Rear Waterwall	7	B	Yes, numerous defects have been found
Waterwall	Rear Waterwall	8	C	Yes, but not extensive
Waterwall	Rear Waterwall	9	D	Yes, but not extensive
Waterwall	Front Waterwall	10	B	Yes, numerous defects have been found
Waterwall	Rear Waterwall	10	B	Yes, numerous defects have been found
Waterwall	RHS Waterwall	10	C	Yes, numerous defects have been found
Waterwall	LHS Waterwall	10	C	Yes, numerous defects have been found
Waterwall	Front Waterwall	11	D	Yes, but not extensive
Waterwall	Rear Waterwall	11	D	Yes, but not extensive
Waterwall	RHS Waterwall	11	D	Yes, but not extensive
Waterwall	LHS Waterwall	11	D	Yes, but not extensive
Waterwall	Front Waterwall	12	D	Yes, but not extensive
Waterwall	Rear Waterwall	12	D	Yes, but not extensive
Waterwall	RHS Waterwall	12	D	Yes, but not extensive
Waterwall	LHS Waterwall	12	D	Yes, but not extensive
Waterwall	Front Waterwall	13	D	Yes, but not extensive
Waterwall	Rear Waterwall	13	D	Yes, but not extensive
Waterwall	RHS Waterwall	13	D	Yes, but not extensive

System	Equipment	Equipment Location Number	What is the stress rank at this location?	Was there any historical issues with welding in this area?
Waterwall	LHS Waterwall	13	D	Yes, but not extensive
Waterwall	RHS Waterwall	13	D	Yes, but not extensive
Waterwall	LHS Waterwall	13	D	Yes, but not extensive
Waterwall	RHS Waterwall	13	B	Yes, but not extensive
Waterwall	LHS Waterwall	13	B	Yes, but not extensive
Waterwall	Roof Tubes	14	D	Yes, but not extensive
Waterwall	Front Waterwall	15	D	Yes, but not extensive
Waterwall	Rear Waterwall	15	D	Yes, but not extensive
Waterwall	RHS Waterwall	15	D	Yes, but not extensive
Waterwall	LHS Waterwall	15	D	Yes, but not extensive
Waterwall	Upper Nose Slope	17	B	Yes, numerous defects have been found
Waterwall	Upper Nose Slope	18	D	Yes, but not extensive
Waterwall	Front Waterwall	19	D	Yes, but not extensive
Waterwall	Rear Waterwall	19	D	Yes, but not extensive
Waterwall	RHS Waterwall	19	D	Yes, but not extensive
Waterwall	LHS Waterwall	19	D	Yes, but not extensive
Waterwall	RHS Waterwall	20	C	Yes, but not extensive
Waterwall	LHS Waterwall	20	C	Yes, but not extensive
Waterwall	Front Waterwall	21	B	Yes, but not extensive
Waterwall	Rear Waterwall	21	B	Yes, but not extensive
Waterwall	Front Waterwall	23	C	Yes, but not extensive
Waterwall	Rear Waterwall	23	C	Yes, but not extensive
Superheater	Superheater 1	24	B	Yes, but not extensive
Superheater	Superheater 1	25	B	Yes, but not extensive
Superheater	Superheater 2	26	D	Yes, but not extensive
Superheater	Superheater 2	27	D	Yes, but not extensive
Superheater	Superheater 3	28	D	Yes, but not extensive
Superheater	Superheater 3	29	D	Yes, but not extensive
Economiser	Economiser Inlet	30	D	Yes, but not extensive
Economiser	Economiser Outlet	31	D	Yes, but not extensive

4.2.4 Consequence of Failure

In this instance, consequence of failure is calculated purely on financial loss. This is determined by a combination of fuel cost and revenue lost from losing generating capacity.

It is assumed that it takes 60 tons of fuel oil to start a boiler and that the average cost of fuel oil is R7 800.00 per ton (Van Aswegen, 2014). This gives a base start-up cost of R468 000.00 per outage.

The average reported revenue per kilowatt hour in South Africa is 90.01 cents per kWh in 2019 (Staff Writer, 2019). A tube leak can result in an outage that averages between 18 and 240 hours, depending on the accessibility of the tube leak (Malomane, 2019).

Table 14: Start-up cost per outage (Staff Writer, 2019; Van Aswegen, 2014).

How accessible is this component w.r.t replacement?	Outage Duration	MW Lost	Cost (R/MWh)	Cost of Tube Leak (R)
Excellent	24	100	901	2162400
Good	61	100	901	5496100
Average	121	100	901	10902100
Below average	201	100	901	18110100
Poor	288	100	901	25948800

Table 15: Accessibility of various segments to replacement (Craddock, 2016).

System	Equipment	Equipment Location Number	How accessible is this component w.r.t replacement?
Waterwall	Front Waterwall	1	Poor
Waterwall	Rear Waterwall	1	Poor
Waterwall	LHS Waterwall	1	Poor
Waterwall	RHS Waterwall	1	Poor
Waterwall	Front Waterwall	2	Poor
Waterwall	Rear Waterwall	2	Poor
Waterwall	RHS Waterwall	2	Poor
Waterwall	LHS Waterwall	2	Poor
Waterwall	LHS Waterwall	3	Excellent
Waterwall	RHS Waterwall	3	Excellent
Waterwall	LHS Waterwall	4	Excellent
Waterwall	RHS Waterwall	4	Excellent
Waterwall	LHS Waterwall	5	Average
Waterwall	RHS Waterwall	5	Average
Waterwall	Rear Waterwall	7	Poor
Waterwall	Rear Waterwall	8	Poor
Waterwall	Rear Waterwall	9	Poor
Waterwall	Front Waterwall	10	Poor
Waterwall	Rear Waterwall	10	Poor
Waterwall	RHS Waterwall	10	Poor
Waterwall	LHS Waterwall	10	Poor
Waterwall	Front Waterwall	11	Poor

System	Equipment	Equipment Location Number	How accessible is this component w.r.t replacement?
Waterwall	Rear Waterwall	11	Poor
Waterwall	RHS Waterwall	11	Poor
Waterwall	LHS Waterwall	11	Poor
Waterwall	Front Waterwall	12	Below average
Waterwall	Rear Waterwall	12	Below average
Waterwall	RHS Waterwall	12	Below average
Waterwall	LHS Waterwall	12	Below average
Waterwall	Front Waterwall	13	Poor
Waterwall	Rear Waterwall	13	Poor
Waterwall	RHS Waterwall	13	Poor
Waterwall	LHS Waterwall	13	Poor
Waterwall	RHS Waterwall	13	Below average
Waterwall	LHS Waterwall	13	Below average
Waterwall	RHS Waterwall	13	Average
Waterwall	LHS Waterwall	13	Average
Waterwall	Roof Tubes	14	Poor
Waterwall	Front Waterwall	15	Good
Waterwall	Rear Waterwall	15	Good
Waterwall	RHS Waterwall	15	Good
Waterwall	LHS Waterwall	15	Good
Waterwall	Upper Nose Slope	17	Good
Waterwall	Upper Nose Slope	18	Good
Waterwall	Front Waterwall	19	Good
Waterwall	Rear Waterwall	19	Good
Waterwall	RHS Waterwall	19	Good
Waterwall	LHS Waterwall	19	Good
Waterwall	RHS Waterwall	20	Good
Waterwall	LHS Waterwall	20	Good
Waterwall	Front Waterwall	21	Good
Waterwall	Rear Waterwall	21	Good
Waterwall	Front Waterwall	23	Good
Waterwall	Rear Waterwall	23	Good
Superheater	Superheater 1	24	Average
Superheater	Superheater 1	25	Average
Superheater	Superheater 2	26	Excellent
Superheater	Superheater 2	27	Excellent
Superheater	Superheater 3	28	Excellent
Superheater	Superheater 3	29	Excellent
Economiser	Economiser Inlet	30	Average
Economiser	Economiser Outlet	31	Average

4.2.5 Risk

The probability and consequence laid out above were consolidated into a single risk matrix and can be seen in Figure 30. The numbers represented in the risk matrix is that of the equipment location number. Equipment location numbers 7, 10 and 17 are at the highest risk for corrosion fatigue based on this risk model, and are likely to occur once every 10 years on Unit 5.

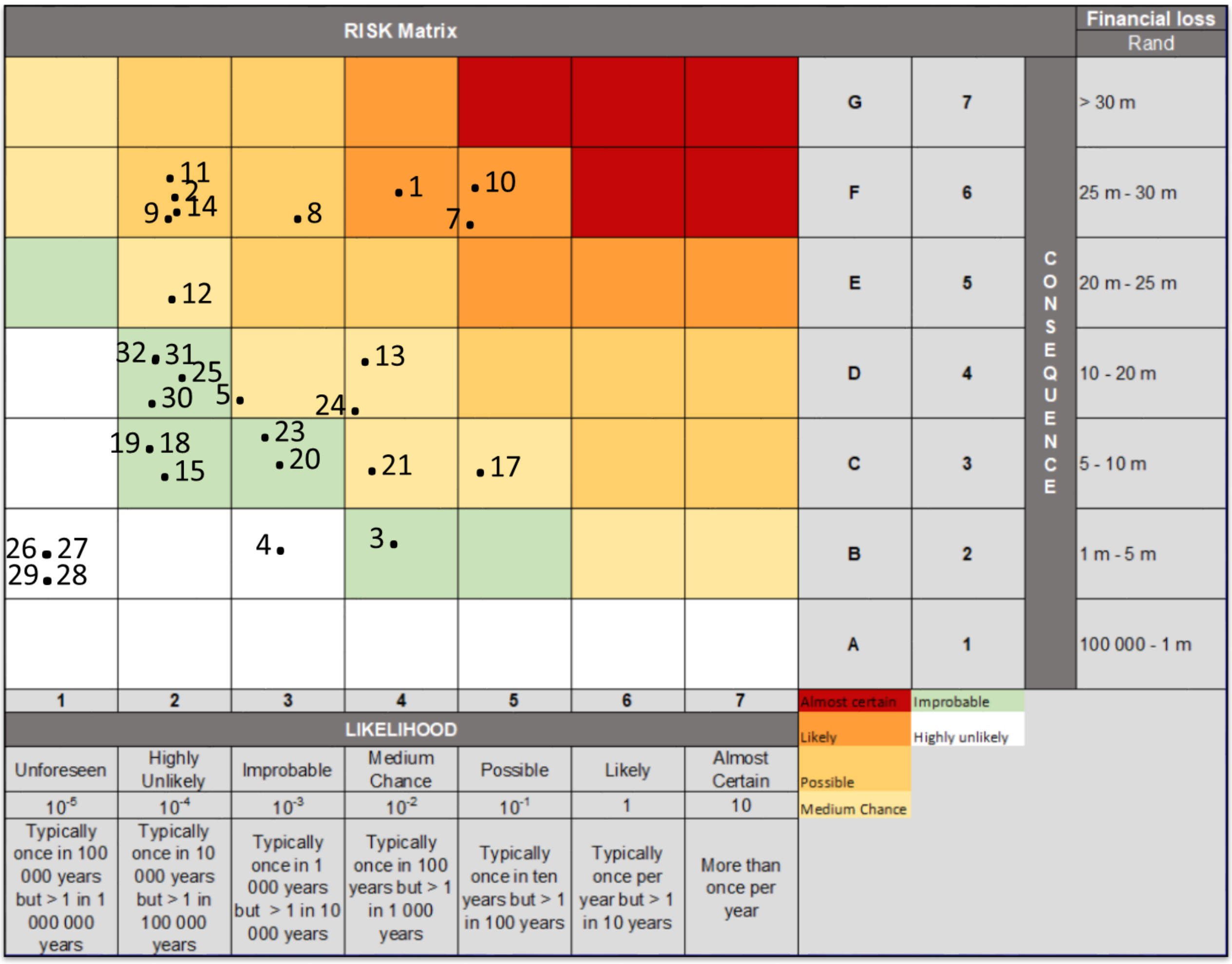

Figure 30: Risk matrix showing the various risk scores per equipment location number.

4.2.6 Risk Analysis

Unit 5 had five (5) failures within a 6 year period. The failure reports were analysed, plotted on schematic drawings (Figure 31) and tabulated as seen in Table 16. The majority of these failures (three failures) occurred on equipment number 17, followed by equipment number 7 (one failure) and equipment number 10 (one failure).

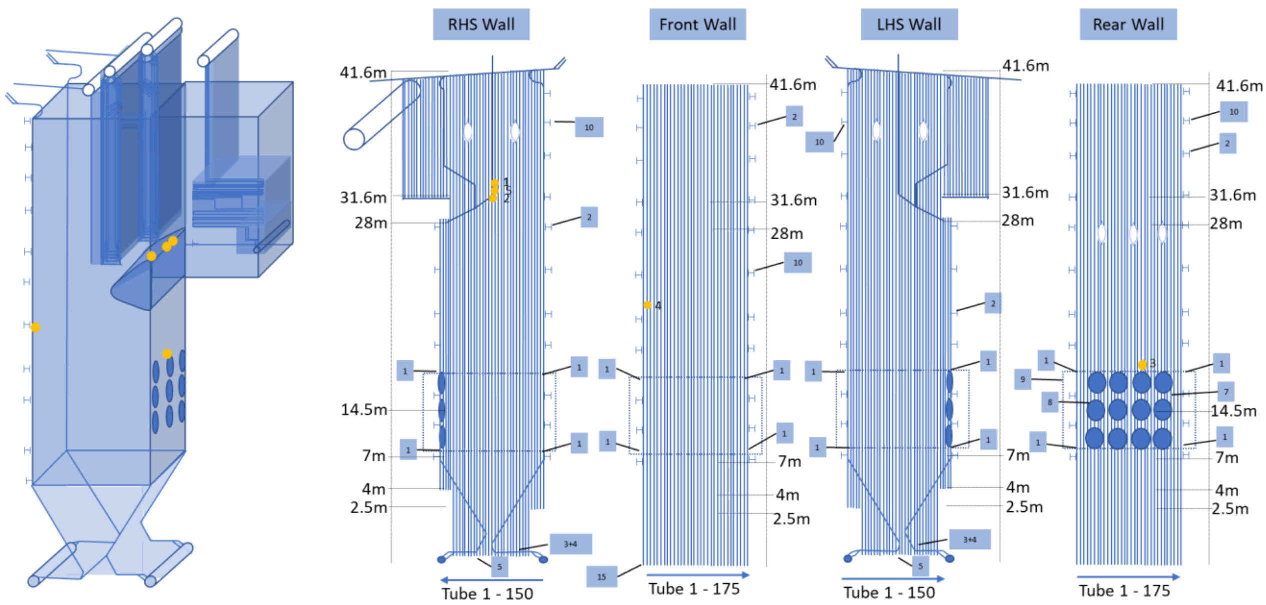

Figure 31: Unit 5 failure locations (Meyer, 2017).

Table 16: The five (5) failures that occurred on Unit 5 (Meyer, 2017).

Tube Leak	System	Equipment	Component	Equipment Location Number	Location	Description
1	Waterwall	Upper Nose slope	Tube 10 and 14	17	Furnace gas exit scallop plate	Continuous scallop plate adjacent to redirected tubes
2	Waterwall	Upper Nose slope	Tube 15	17	Furnace gas exit scallop plate	Continuous scallop plate adjacent to redirected tubes
3	Waterwall	Rear Waterwall	Tube 21 above burner	7	Burner throat tube ties	Short bars welded between tubes in tangent tube wall
4	Waterwall	Front Waterwall	Tube 4	10	Buckstay connections to waterwalls	Continuous tangent bar tack welded to tubes tangent tube wall
5	Waterwall	Rear Waterwall	Failure on upper nose tube 30 & 31	17	Furnace gas exit scallop plate	Continuous scallop plate adjacent to redirected tubes

4.2.6.1 Equipment Location Number 17

The risk model suggests that equipment number 17 of unit 5 will experience a failure once every 10 years. Actual failure results contradict this, with three failures having occurred within a six year period (Meyer, 2017). It was decided to investigate the failure reports in order to understand the root cause of the failures. The first two failures on equipment number 17 (upper nose) occurred within 17 days of each other (Meyer, 2017). The third failure occurred 4 years later and the root cause analysis indicated that the initial issue (excessive restraint and poor welding practices), were not addressed during the first two incidents (Meyer, 2017). The risk model would have been accurate, had the root cause been addressed during the initial failure. As it stands now the probability of failure should be adjusted to a higher factor of 6, especially considering that it is not known if the root cause was mitigated after the last failure occurred.

The average duration of an outage on equipment number 17 is 61 hours (Meyer, 2017). With the addition of a base cost for fuel oil (R468 000.00), this gives a total cost of R5 414 490.00 per outage. From this a consequence rating of C is possible for equipment number 17, which lines up with the results from the risk model.

4.2.6.2 Equipment Location Numbers 7 & 10

The probability of a failure occurring on equipment number 7 and 10 is once every 10 years, according to the risk model. A failure has occurred on both equipment numbers in the last 6 years, which still aligns with the prediction. However, because of uncertainty related to historical defects, it may be possible that more failures will occur in the remaining four year period.

Both tube leaks resulted in an average outage duration of 273 hours (Meyer, 2017). With the addition of a base cost for fuel oil (R468 000.00), this gives a total cost of R25 065 300.00 per outage. From this a consequence rating of F is possible for both equipment numbers, which lines up with the results from the risk model.

4.2.7 Risk Mitigation & Management

The ultimate purpose of this risk based approach is to optimise inspection and maintenance practices. This is done by identifying and focusing risk reduction efforts into the highest relative risk areas (Equipment number 17, 10 and 7). Incorporating actual failure data have lent a measure of credibility to the timelines represented by the probability factor. It is however recommend that risk adjustments be made based on actual failure records and the lack of repairs after prior failures.

The design life of a boiler is normally 50 years, however this power station was designed in the 60s with a design life of 25 years. Significant refurbishment have occurred, which has allowed this boiler to reach an operating life of 50 years. It is highly unlikely that this power station will run for another 2 years, much less another 50 years. Therefore, while there are equipment locations in this boiler that have high consequence ratings, the likelihood of their failure is extremely low.

The first iteration of mitigating actions should attempt to relieve the stress concentration. Relieving the stress concentration is often more expedient and cost effective than trying to address the corrosive issue.

Table 17: Possible mitigating actions to remove stress concentrations (The proposed actions were based on the studies of Dooley & McNaughton, 2007)

Equipment Number	Equipment Description	Records of welding defects in this area	Modifications	Inspection and replacement
7	Short bars welded between tubes in tangent tube wall	Yes, numerous defects have been found	Weld bar on hot side to restore neutral bending axis to geometric axis of tube	Non-destructive testing in the area where failures have occurred or outright focused replacements (depends on cost-benefit analysis)
10	Continuous tangent bar tack welded to tubes tangent tube wall	Yes, numerous defects have been found	Use stirrups or lugs on membrane walls. Tack weld to alternate tubes on tangent tube wall	Non-destructive testing in the area where failures have occurred or outright focused replacements (depends on cost-benefit analysis)
17	Continuous tangent bar tack welded to tubes tangent tube wall	Yes, numerous defects have been found	Move scallop plate farther from redirected tubes and cover with refractory	Replace tubes in this area, due to repeat nature of failures

It is not recommended to apply actions that could address the corrosion component of corrosion fatigue in the case of this power station. This is because action to address corrosion are often long term and expensive, and the IRP indicates that this power station is included in the planning of stations to be fully decommissioned in the next 2 to 5 years (Government Gazette, 2019). If the power station were to remain active for an extended period it would be recommended to review and adjust the feedwater treatment plan. Focussed replacements of problem areas within the boiler should also be considered, as pre-existing pitting or gauging will act as initiation sites for further damage.

4.3 UNIT 7

4.3.1 Data / Information

Using the methodology and background outlined in Chapter 3, a risk analysis was applied to unit 7 of a power station. Unit 7 has the following key characteristics (Conradie *et al*, 2000; Eskom Heritage, 2020):

Installed Capacity:	111 MW
Feedwater System:	Mixed Metallurgy
Feedwater Treatment:	Reducing All-Volatile Treatment
	Historically phosphate treatments
Boiler Type:	Drum Unit, Rear Wall Fired
Fuel Type:	Pulverised Fuel (PF) – Coal
Original Boiler Design Life:	100 000 hours
Average Operating Hours:	181 372 hours
Operating Mode:	Baseload

This study only considers the internal pressure parts of a boiler, excluding header systems. The following information is relevant to the assessment:

Table 18: Pressure parts design information (Conradie *et al*, 2000).

Component	Material Grade	Outside Diameter (mm)	Inside Diameter (mm)	Wall Thickness (mm)
Waterwall Tubes	BS 3059 360	63.5	54.56	4.47
Superheater 1 Tubes	BS 3059 360 / BS EN 620 Gr. 27	47.63	38.69	4.47
Superheater 2 Tubes	BS EN 620 Gr. 27	50.8	41.04 / 35.56	4.88 / 7.62
Superheater 3 Tubes	BS EN 620 Gr. 27 / BS EN 622 Gr. 31	50.8	35.56 / 33.12	7.62 /8.84
Economiser Inlet Tubes	BS 3059 360	50.8	41.86	4.47
Economiser Outlet Tubes	BS 3059 360	50.8	41.86	4.47

4.3.2 Risk

The same risk ranking methodology was followed for Unit 7 as was described for Unit 5. Probability and consequence of failure were consolidated into a single risk matrix and can be seen in Figure 32. The numbers represented in the risk matrix is that of the equipment number. Equipment number 1, 2 and 7 are at the highest risk for corrosion fatigue based on this risk model.

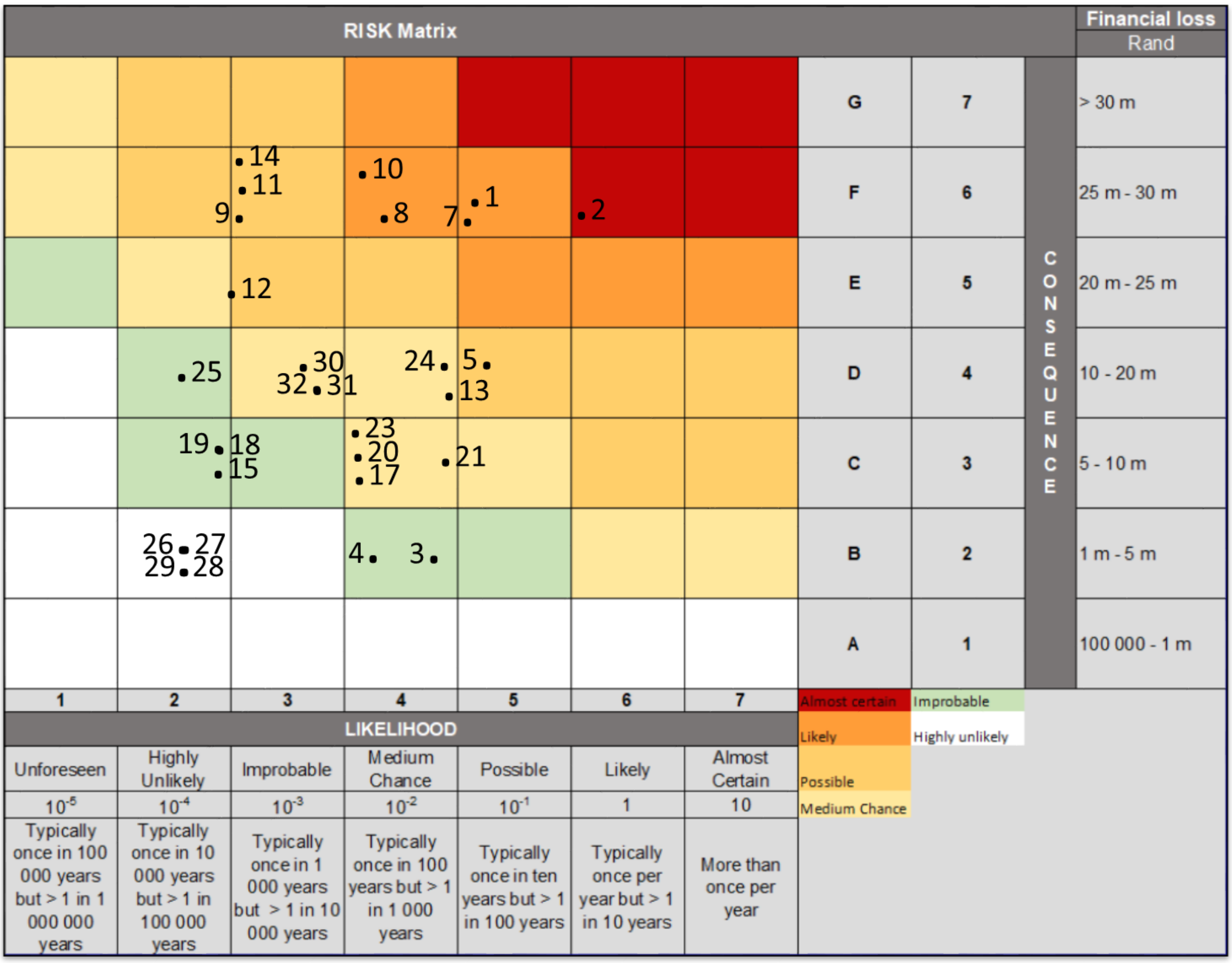

Figure 32: Risk matrix showing the various risk scores per equipment location number.

4.3.3 Risk Analysis

According to this model CF failures are likely to occur once a year on equipment number 2, while failure on equipment number 1, 7 and 5 could occur once every 10 years. Unit 7 had eight (8) failures within a 6 year period. The failure reports were analysed, plotted on schematic drawings (Figure 33) and tabulated as seen in Table 19. The majority of these failures occurred on equipment number 2, followed by equipment number 7 and equipment number 1.

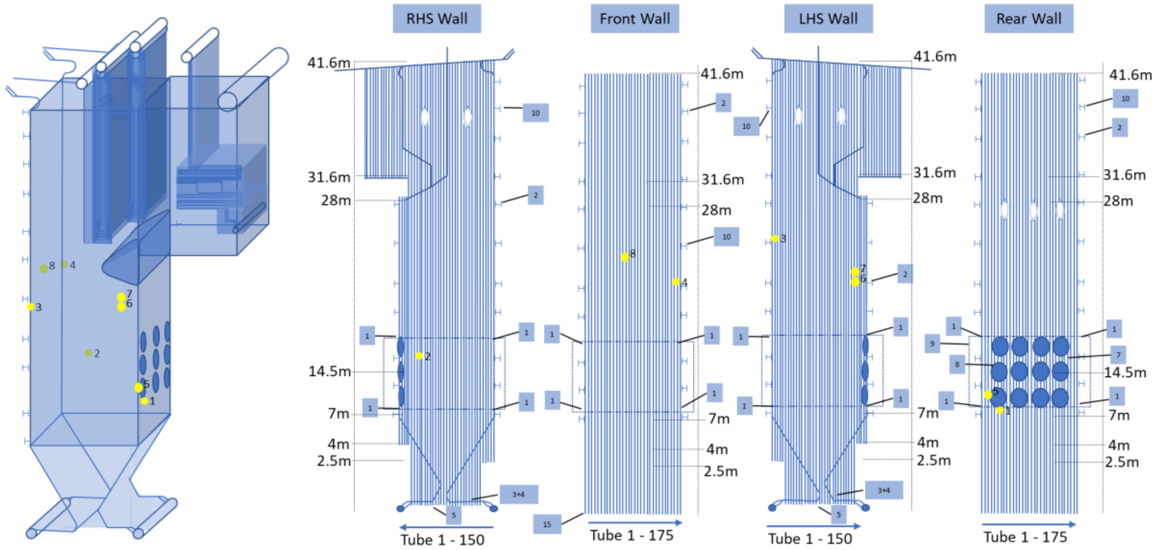

Figure 33: Unit 7 failure locations.

Table 19: The eight (8) failures that occurred on Unit 7.

Tube Leak	System	Equipment	Component	Equipment Location Number	Description
1	Waterwall	Rear Waterwall	Tube 48: below burner C1	7	Burner throat tube ties
2	Waterwall	RHS Waterwall	Tube 121	1	Windbox casing
3	Waterwall	LHS Waterwall	Tube 1	2	Buckstay corners
4	Waterwall	Front Waterwall	Corner of the right hand and the front wall, at Buckstay 7.	2	Buckstay corners
5	Waterwall	Rear Waterwall	Tube 28: next to burner C1	7	Burner throat tube ties
6	Waterwall	LHS Waterwall	LH side wall Tube 114.	2	Buckstay corners
7	Waterwall	LHS Waterwall	Evaporator LH side wall Tube 115: Attachment failure	2	Buckstay corners
8	Waterwall	Front Waterwall	Front wall: Attachment failure	2	Buckstay corners

4.3.3.1 Equipment Location Number 2

The risk model suggests that equipment number 2 of unit 7 will experience a failure no more than once every year, but at least once in 10 years. Actual failure results verify this, with five failures having occurred within a six year period (Meyer, 2017).

The outage duration as a result of failure for equipment location 2 is between 66 and 276 hours. This gives a total cost of between R7 123 732.00 and R28 071 036.00 per outage. This means that a consequence rating of F is possible if the worst consequence scenario is assumed.

4.3.3.2 Equipment Numbers 1 & 7

The probability of a failure occurring on equipment numbers 1 and 7 is once every 10 years, according to the risk model. Two failures have occurred on equipment numbers 7 and one failure has occurred on equipment number 1 in the last 6 years. The additional failure on equipment number 7 can be attributed to the highly stressed nature of the manipulations surrounding the burners in conjunction with poor welding practices. However, because of uncertainty related to historical defects, it may be possible that more failures will occur in the remaining four year period.

All three tube leaks resulted in an average outage duration of 260 hours (Meyer, 2017). With the addition of a base cost for fuel oil (R468 000.00), this gives a total cost of R26 470 860.00 per outage. From this a consequence rating of F is possible for both equipment numbers, which lines up with the results from the risk model.

4.4 RISK MITIGATION & MANAGEMENT

From the application of the risk model it was established that unit 7 has the following equipment location numbers with the highest likelihood to occur in descending order:

- Equipment location 2 – Typically once a year but more than once every 10 years
- Equipment location 1 – Typically once every 10 years but more than once every 100 years.
- Equipment location 5 – Typically once every 10 years but more than once every 100 years.
- Equipment location 7 – Typically once every 10 years but more than once every 100 years.

Incorporating actual failure data have lent a measure of credibility to the timelines represented by the probability factor. It is however recommend that risk adjustments be made based on actual failure records. The first iteration of mitigating actions should attempt to relieve the stress concentration. Relieving the stress concentration is often more expedient and cost effective than trying to address the corrosive issue.

Table 20: Possible mitigating actions to remove stress concentrations (The proposed actions were based on the studies of Dooley & McNaughton, 2007)

Equipment location	Equipment Description	Records of welding defects in this area	Modifications	Inspection and replacement
1	Continuous scallop plate	Yes, numerous defects have been found	No modification derived	Non-destructive testing in the area where failures have occurred or outright focused replacements (depends on cost-benefit analysis)
2	Lug mounted tie-bar connected to tubes at corner	Yes, numerous defects have been found	Remove or relieve rigid corner	Non-destructive testing in the area where failures have occurred or outright focused replacements (depends on cost-benefit analysis)
5	Triangular plate between redirected tubes	No	Change to peg membrane	No record of defects.
7	Short bars welded between tubes in tangent tube wall	Yes, numerous defects have been found	Weld bar on hot side to restore neutral bending axis to geometric axis of tube	Non-destructive testing in the area where failures have occurred or outright focused replacements (depends on cost-benefit analysis)

4.5 UNIT 9

4.5.1 Data / Information

Using the methodology and background outlined in Chapter 3, a risk analysis was applied to unit 9 of a power station. Unit 9 has the following key characteristics (Conradie *et al*, 2000; Eskom Heritage, 2020):

Installed Capacity:	111 MW
Feedwater System:	All Ferrous
Feedwater Treatment:	Oxidising all-volatile treatment – AVT(O)
	Historically phosphate treatments
Boiler Type:	Drum Unit, Rear Wall Fired
Fuel Type:	Pulverised Fuel (PF) – Coal
Original Boiler Design Life:	100 000 hours

Average Operating Hours: 198 938 hours

Operating Mode: Baseload

This study only considers the internal pressure parts of a boiler, excluding header systems. The following information is relevant to the assessment:

Table 21: Pressure parts design information (Conradie *et al*, 2000).

Component	Material Grade	Outside Diameter (mm)	Inside Diameter (mm)	Wall Thickness (mm)
Waterwall Tubes	BS 3059 360	63.5	54.56	4.47
Superheater 1 Tubes	BS 3059 360 / BS EN 620 Gr. 27	47.63	38.69	4.47
Superheater 2 Tubes	BS EN 620 Gr. 27	50.8	41.04 / 35.56	4.88 / 7.62
Superheater 3 Tubes	BS EN 620 Gr. 27 / BS EN 622 Gr. 31	50.8	35.56 / 33.12	7.62 /8.84
Economiser Inlet Tubes	BS 3059 360	50.8	41.86	4.47
Economiser Outlet Tubes	BS 3059 360	50.8	41.86	4.47

4.5.2 Risk

The same methodology was followed for Unit 9 as was described for Unit 5. Probability and consequence of failure were consolidated into a single risk matrix and can be seen in Figure 34. The numbers represented in the risk matrix is that of the equipment number. Equipment number 2 and 10 are at the highest risk for corrosion fatigue based on this risk model.

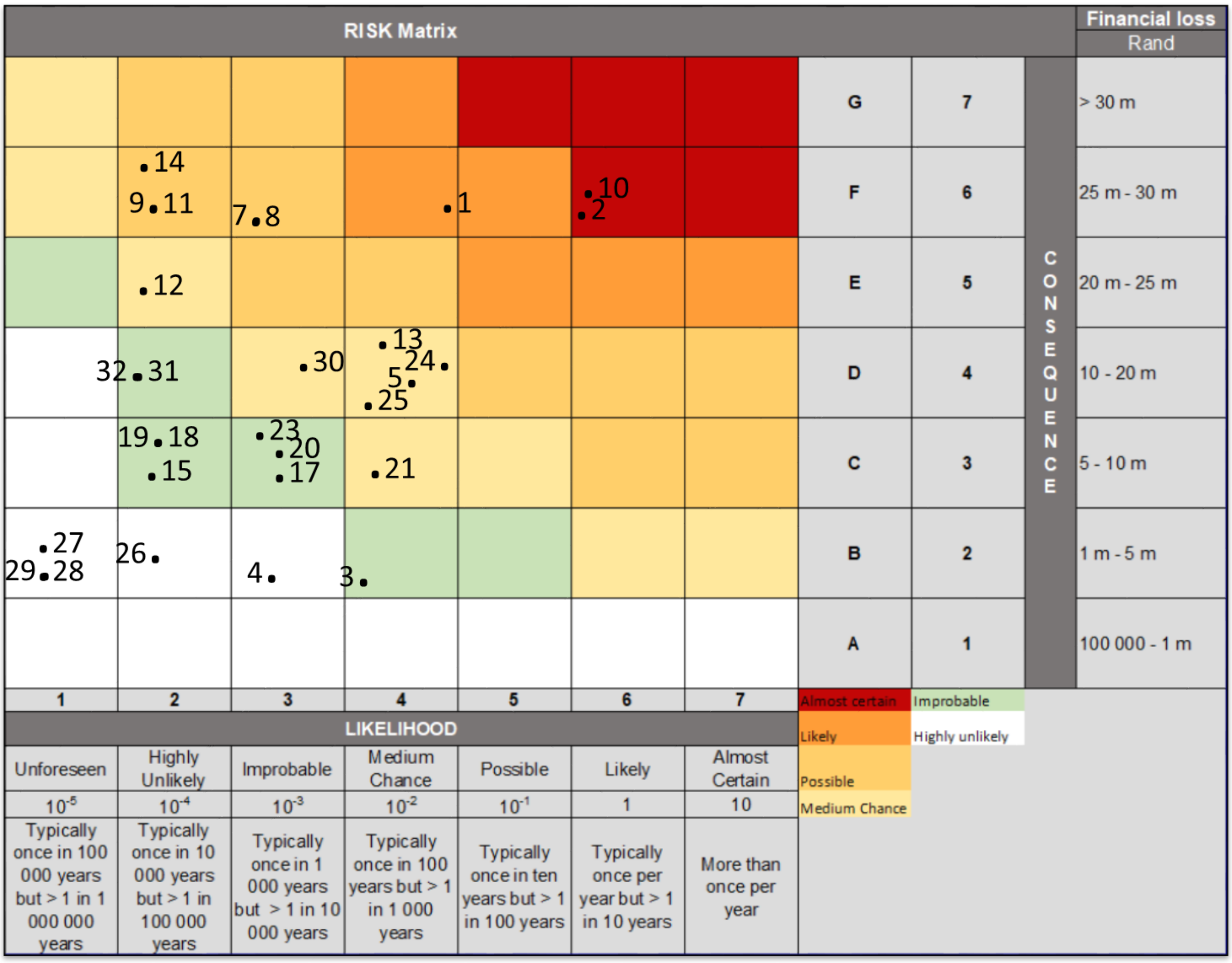

Figure 34: Risk matrix showing the various risk scores per equipment number.

4.5.3 Risk Analysis

According to this model CF failures are likely to occur once a year on equipment number 2 and 10. Unit 9 had seven (7) failures within a 6 year period. The failure reports were analysed, plotted on schematic drawings (Figure 35) and tabulated as seen in Table 22. The majority of these failures occurred on equipment number 10, followed by equipment number 2.

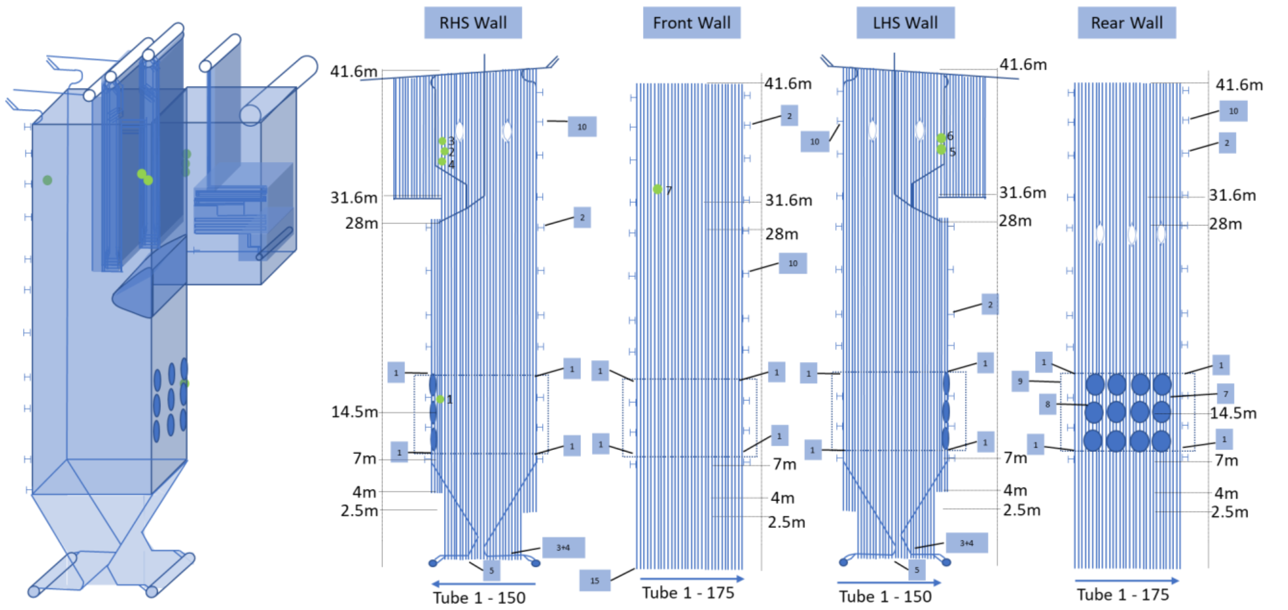

Figure 35: Unit 9 failure locations.

Table 22: The seven (7) failures that occurred on Unit 9.

Tube Leak	System	Equipment	Component	Equipment Location Number	Location	Description
1	Waterwall	LHS Waterwall	Tube 15: Left hand rear wallcorner in the vicinity of buckstay 8	2	Buckstay corners	Lug mounted tie-bar connected to tubes at corner
2	Waterwall	RHS Waterwall	RH Corner Buckstsay 2 and 3	2	Buckstay corners	Lug mounted tie-bar connected to tubes at corner
3	Waterwall	RHS Waterwall	Evaporator RH side wall Tube 174	10	Buckstay connections to waterwalls	Continuous tangent bar tack welded to tubes tangent tube wall
4	Waterwall	RHS Waterwall	Pinhole on attachment weld	10	Buckstay connections to waterwalls	Continuous tangent bar tack welded to tubes tangent tube wall
5	Waterwall	LHS Waterwall	Attachment weld failure	10	Buckstay connections to waterwalls	Continuous tangent bar tack welded to tubes

Tube Leak	System	Equipment	Component	Equipment Location Number	Location	Description
						tangent tube wall
6	Waterwall	LHS Waterwall	Evaporator LH side wall Tube 123.	10	Buckstay connections to waterwalls	Continuous tangent bar tack welded to tubes tangent tube wall
7	Waterwall	Front Waterwall	Evaporator Front Wall Tube 30	10	Buckstay connections to waterwalls	Continuous tangent bar tack welded to tubes tangent tube wall

4.5.3.1 Equipment Location Number 2

The risk model suggests that equipment number 2 of unit 9 will experience a failure no more than once every year, but at least once in 10 years. Actual failure results verify this, with two failures having occurred within a six year period (Meyer, 2017).

The outage duration as a result of failure for equipment location 2 is 249 hours (Meyer, 2019). With the addition of a base cost for fuel oil (R468 000.00), this gives a total cost of R25 370 739.00 per outage. This means that a consequence rating of F is possible.

4.5.3.2 Equipment Location Number 10

The risk model suggests that equipment number 10 of unit 9 will experience a failure no more than once every year, but at least once in 10 years. Actual failure results verify this, with five failures having occurred within a six year period (Meyer, 2017).

The outage duration as a result of failure for equipment location 10 is 83 hours (Meyer, 2019). With the addition of a base cost for fuel oil (R468 000.00), this gives a total cost of R8 768 913.00 per outage. This means that a consequence rating of C is possible. In the case of Unit 9, the location of the failures on equipment number 10, is fairly accessible when it comes to repairs. The risk model should be adjusted to reflect this reality.

4.6 RISK MITIGATION & MANAGEMENT

Incorporating actual failure data have lent a measure of credibility to the impact represented by the consequence factor. It is recommend that risk adjustments be made based on actual failure records. The first iteration of mitigating actions should attempt to relieve the stress concentration. Relieving the stress concentration is often more expedient and cost effective than trying to address the corrosive issue.

Table 23: Possible mitigating actions to remove stress concentrations (The proposed actions were based on the studies of Dooley & McNaughton, 2007)

Equipment Number	Equipment Description	Records of welding defects in this area	Modifications	Inspection and replacement
2	Lug mounted tie-bar connected to tubes at corner	Yes, numerous defects have been found	Remove or relieve rigid corner	Non-destructive testing in the area where failures have occurred or outright focused replacements (depends on cost-benefit analysis)
10	Continuous tangent bar tack welded to tubes tangent tube wall	Yes, numerous defects have been found	Use stirrups or lugs on membrane walls. Tack weld to alternate tubes on tangent tube wall	Non-destructive testing in the area where failures have occurred or outright focused replacements (depends on cost-benefit analysis)

CHAPTER 5 DISCUSSION OF RESULTS

The South African national energy grid has become increasingly unstable and unreliable over the past 15 years. A need for providing adequate and sustainable forms of energy was identified and is indispensable for the continued development and economic growth of South Africa. It is believed that smarter asset integrity management strategies, including risk-based inspection and maintenance practices, can lead to sustained or even increased generating capacity. This dissertation explored the principles and processes of risk-based inspection standards / guidelines as tools to optimise these practices.

Aspects of four (4) risk standards and / or guidelines were explored and combined into a risk model. Clear battery limits were defined by limiting the scope to corrosion fatigue, as well as only considering internal boiler pressure parts.

This model deviates from published practises and standards, such as that included in the standard API RP 580 / 581 methodology in that it does not use generic failure frequency to determine probability of failure. Generic failure frequency (for a particular industry, operator or power station) can be used to perform a sensitivity analysis and adjust factors to more accurately reflect reality.

Contrary to the API methodology, the damage factor used in the current study aimed at corrosion fatigue failures, does not act as a multiplier for the generic failure frequency, but rather follows the indexing method discussed in the Muhlbauer (2004) system. The corrosion fatigue mechanism was investigated and key aspects that contribute to the damage mechanism was assigned certain scores and weights. This was combined with the management system factor to comprise a relative probability score. The developed methodology and model were proven to be accurate because risky areas where predicted relatively accurately when the model was applied to units 5, 7 and 9 of a power station.

Corrosion fatigue is a notoriously difficult mechanism to inspect for. In this case it was assumed that a larger inspection program would not necessarily improve the risk assessment. This model showed that incorporating literature of the mechanism with the analysis of previous failure records and locations can indicate areas where risk is relatively high. Management of the risk was shown to be better approached by focusing on risk mitigating factors, and reducing contributory factors, such as stress concentration, through design alterations.

Historical inspection records within the boiler should also be used as an important input, as pre-existing pitting or gauging will act as initiation sites for further damage.

CHAPTER 6 CONCLUSION

A systematic methodology to evaluate the risk associated with corrosion fatigue failures of boiler tubes in coal-fired boilers did not exist. A methodology to evaluate the risk associated with corrosion fatigue failures in boilers has been developed and has been proven to be accurate. Implementing such a programme will be valuable to power plant owners / operators, by limiting the number of shut-downs, increasing boiler availability and extending the life of the boiler. A sensitivity analysis is required in order to adjust the risk factors to more accurately represent real conditions for individual boilers. An example of this was borne out in the proposed mitigation actions. It was found that an emphasis should be placed on a higher weighting for those activities which have the most benefit with the least effort / cost. When assigning risk scores one should take both historical information and future operation into account.

A risk model like this is inherently valuable because, even if it ends up being entirely inaccurate, the information and knowledge obtained during the exercise can be used to inform and adjust future actions. Following a risk based asset management strategy allows the user to move from a prescriptive inspection philosophy, to a predictive one. A predictive strategy promotes decreased rates and volumes of inspection that lead to shorter outage durations and high availability. A predictive strategy has major benefits when it comes to failure mechanisms (like corrosion fatigue) which are difficult to inspect for. Understanding the underlying damage processes and progression allows for focused inspection and replacements.

Drilling into the detail of each failure mechanism also allows for a standardised approach. The underlying chemical and mechanical processes are consistent, even though variables like time and temperature could affect the expression of the failure mechanism. This underlying consistency has allowed for the development of a standard set of questions, which would be relevant when applied to any boiler.

Future research could extend the topic to other failure mechanisms, until a robust and complete risk ranking model for boilers was developed. The benefit of an indexing model and relative risk ranking, based on a standardised approach, would mean that boilers could be benchmarked across the industry. The research topic could also be extended into rotating equipment, auxiliary equipment, main steam piping and header systems, creating a robust methodology for Utilities, similar to that developed by Muhlbauer for oil and gas transmission and distribution piping.

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