Limitations of current cooling water treatment processes to control cooling water chemistry in wet cooled power plants

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DECLARATION

I Lungile Lucia Maswanganyi hereby declare that the dissertation, which I herewith submit, apart from the recognised assistance of my supervisors, is my own work and that it has not been previously submitted by me to obtain a degree at another University or Institution.

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ABSTRACT

In a coal-fired power plant, recirculating cooling water exchanges latent heat energy with the exhaust steam in the condenser and transports the heat to the cooling tower for evaporative cooling. The water lost in the evaporative cooling tower is continuously replenished by make-up water or effluent generated within the power plant processes. Due to the make–up water and effluent generated from the station chemistry quality, challenges relating to the recirculating cooling water, such as scaling, fouling, and, at times, corrosion are experienced. These challenges impact the performance and operation of the cooling system, leading to thermal efficiency losses. The investigation uses quantitative analysis and deductive evaluation to describe the effect of recirculating cooling water on plant performance. Thermal efficiency as a measure of a wet cooled power plant's overall performance for the past four to five years was assessed on four wet cooled power plants. The condenser and cooling tower performance was the focus area for the investigation.

Fouling and scaling (dirty heat transfer surface) has an influence on recirculating cooling water flow, inlet and outlet temperatures, heat transfer leading to vacuum, and back pressure challenges on the condenser. The higher the demands on the plant components with respect to pressure and temperature, the purer the recirculating cooling water must be. To assess the chemistry of the recirculating cooling water, parameters such as calcium carbonate precipitation potential (CCPP), alkalinity, hardness and pH were modelled on power BI and R studio. The observations indicate that operating outside the guidelines has a detrimental effect on the performance of the power plant. Calculated performance indicators like the condenser cleanliness factor and terminal temperate difference contribute to the condenser back pressure, whereas the cooling tower range and approach influence the effectiveness of the tower. The correlation between recirculating cooling water chemistry and plant performance is evident from the results, taking into consideration the time lag between plant exposure and the actual effect on the plant.

The management and control of the recirculating cooling water side treatment to control cooling water chemistry will positively influence the power plant performance especially the heat transfer systems in the power plant. The effect of scaling and fouling is revealed to be among the significant parameters that affect the condenser and the cooling tower performance, although further research must be conducted to obtain the actual correlation between recirculating cooling water chemistry and plant performance, particularly condenser back pressure and cooling tower effectiveness. The investigation will be advantageous in addressing major factors contributing to and influencing power plant thermal efficiency decline.

The power generation industry in general must extend a significant effort toward the optimal conditioning of cooling systems. A good conditioning method simultaneously reduces scaling, fouling, and corrosion of equipment in the cooling systems. The costs associated with maintaining cooling water chemistry within the recommendations stipulated in the chemistry guidelines are likely to be less than those associated with the maintenance or replacement of heat exchangers and piping, and the outages associated with those efforts.

Keywords: CCPP, power plant efficiency, recirculating cooling water chemistry and conditioning, side stream treatment, TTD

PRESENTATIONS AND PUBLICATIONS

Observations during the investigation were presented and submitted for conference proceedings and journal publication.

Conference proceedings:

[1] Maswanganyi, L.L., Gericke,G., Waanders, F.B., & Fosso Kankeu, E. August 2019. *Limitations of current cooling water treatment process to control cooling water chemistry in wet cooled power plants.* 6th Eskom Power Plant Institute Student Workshop, Section 4A, page number 47 to 49, Johannesburg.

[2] Sibiya, L.L., Gericke, G., Waanders, F.B., & Fosso Kankeu, E. November 2019. *Management of Cooling Water Chemistry of Wet Cooled Power Plants in South Africa.* 17th International Conference on Science, Engineering, Technology and Waste Management (SETWMA), page number 167, Johannesburg (https://doi.org/10.17758/EARES8.EAP1119282).

[3] Maswanganyi, L.L., Gericke, G., Waanders, F.B., & Fosso Kankeu, E. November 2020. *Restrictions of cooling water treatment softening in a wet cooled power plant.* 7th Eskom Power Plant Institute Student Workshop, Section 7, page 54 to 56, Online Kwazulu Natal.

[4] Maswanganyi, L.L., Gericke, G., Waanders, F.B., & Fosso Kankeu, E. November 2020. *Restrictions of cooling water treatment softening in a wet cooled power plant.* 18th International Conference on Science, Engineering, Technology and Waste Management (SETWMA), page number 134, Johannesburg (https://doi.org/10.17758/EARES8.EAP1120219).

Journal publications:

[1] Maswanganyi, L.L., Gericke, G., Tamane, T., Waanders, F.B., & Fosso Kankeu, E. *Limitations of current cooling water treatment process to control cooling water chemistry in wet cooled power plant Part 1: Inconsistencies in the cooling water chemistry*. Submitted for journal publication.

[2] Maswanganyi, L.L., Gericke, G., Tamane, T., Waanders, F.B., & Fosso Kankeu, E. *Limitations of current cooling water treatment process to control cooling water chemistry in wet cooled power plant Part 2 Impact of poor cooling water chemistry on power plant performance*. Submitted for journal publication.

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LIST OF ABBREVIATIONS AND ACRONYMS

CCPP	Calcium Carbonate Precipitation Potential
CCW	Concentrated Cooling Water
CD	Condensate Depression
CEDI	Continuous Electro Deionisation
CF	Cleanliness Factor and Concentration Factor
CoC	Cycles of Concentration
CV	Calorific Value
CW	Cooling Water
EPRI	Engineering Power Research Institute
HEI	Heat Exchange Institute
IC	Ion Chromatography
ICP-OES	Inductively Coupled Plasma Atomic Emission Spectroscopy
LIMS	Laboratory Information Management System
LSI	Langelier Saturation Index
M-Alk	Methyl Orange Indicator changes at pH 4.5
MF	Microfiltration
ML	Mega Liter= 1000000 Liters
Mg/kg	Milligram per Kilogram
MIC	Microbiologically Influenced Corrosion
Mpa	Mega pascal
NTU	Nephelometric Turbidity Unit
OEM	Original Equipment Manufacturer
P-Alk	Phenolphthalein Indicator changes at pH 8.3
Ppm	Parts per million
RO	Reverse Osmosis
SP	Salt Passage
SR	Salt Rejection
STEP	Station Thermal Efficiency Performance
TDS	Total Dissolved Solids
TH	Total Hardness
TR	Temperature Rise
TS	Saturation Temperature
TTD	Terminal Temperature Difference
UF	Ultrafiltration
USO	Unit Send Out
ZLED	Zero Liquid Effluent Discharge
VGB	Vereinigung Der Grosskraftwerksbetreiber

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DISSERTATION STRUCTURE

Chapter 1: Background and rational of the study

This chapter focuses on the background and motivations for the study. Included in this chapter are the introduction, chemistry background and research problem linked to the purpose of the study. The overall aim and objectives deduced from the problem statement are discussed, including questions that need to be answered.

Chapter 2: Literature review

The chapter deliberates on the literature relevant to the study. The chapter incorporates the cooling water requirement in a wet cooled power plant, the different side stream treatments available for recirculating cooling water, challenges experienced in the recirculating cooling water cycle, and the requirement according to the guidelines by Electrical Power Research Institute (EPRI) for managing recirculating cooling water chemistry. Included in the literature review is the impact on the power plant if the chemistry is out of specification.

Chapter 3: Inconsistencies in cooling water chemistry.

The chapter focuses on the historical evaluation and analysis of the recirculating cooling water chemistry over five years. The chemistry performance is compared to the chemistry requirement as per the cooling water standard (Technology, 2016) . Wet cooled power plants with the same side treatment for recirculating cooling water are selected for the investigation. Performance over time and seasonal variations are evaluated.

Chapter 4: The impact of poor cooling water chemistry on power plant performance.

The chemistry performance evaluated in Chapter 3 is linked to the condenser and evaporative cooling tower heat exchange performance. The impact of the chemistry on plant performance is evaluated using plant conditions and operating parameters.

Chapter 5: Conclusions, observations and recommendations deducted from the study are discussed.

CHAPTER 1: BACKGROUND AND RATIONALE

1.1 Recirculating cooling water application and its constituents

Water is widely used in industrial applications, for potable water supply and also as a cooling medium in power generation plants because of its unique properties. Water is readily available and accessible by nature in a non-toxic form. In most cases, water is contaminated by external bodies, for example, acid mine drainage, agriculture, industrial effluent discharged without treatment, sewage, wastewater plant discharge, etc.(Kemmer & McCallion, 1979). When contaminants concentrate up to the point where they are no longer able to remain in solution, they precipitate or crystallise out of the water to form scale and fouling on heat transfer surfaces. In a power generation recirculating cooling water process, some of these contaminants are, for example, algae and bacteria that can enter the cooling water system from the surrounding area and the make-up water source (Edzwald, 2010). Ambient conditions and nutrients can rapidly contribute to their development and propagation, deteriorating the water quality, fouling cooling systems, and encouraging corrosion.

Fouling due to crystallisation of insoluble salts on the surfaces of heat transfer systems is a common challenge in industrial processes application (MacAdam *et al.*, 2004). The major elements responsible for fouling in this regard are the sulphates and carbonates of magnesium and calcium, although phosphate, salts associated with barium, and silica-related scaling (Rathinam *et al.*, 2018) are significant in evaporative recirculating cooling systems (MacAdam *et al.*, 2004). and potable water supply industries (Mavredaki *et al.*, 2007). Some of these solutes, including calcium carbonate and calcium phosphate at elevated temperatures, become less soluble and promote scaling, a phenomenon known as inverse solubility (Ebbing *et al.*, 2005). The factors contributing to corrosion, scaling and fouling in cooling water systems include recirculating cooling water temperature, flow velocity, chemical composition, chemical treatment, etc. (MacAdam *et al.*, 2004). Calcium carbonate scaling, corrosion and microbiological fouling of heat transfer equipment are undesired conditions in wet cooled power plants.

1.1.1 Calcium carbonate scale formation

Calcium carbonate is predominantly present in recirculating cooling water, and due to its solubility characteristics, results in scale deposition on heat transfer surfaces (Sultan Khan *et al.*, 1996). The formation of calcium carbonate scale onto a heated surface follows numerous steps. The first and most significant is the initiation period, in which the deposition takes place. The initiation period is influenced by recirculating cooling water pH, temperature, flow rate the material of the heat transfer surface, and the calcium carbonate level of supersaturation(Epstein, 1983). Defined by the carbonate equilibrium system (McDonald, 2006). at elevated pH, calcium carbonate scale formation is advanced. The carbonate system displayed in Figure 1-1 shows that, at pH levels above 10.5, scale formation is enhanced (McDonald, 2006). Dissolved carbon in solution is distributed into carbonic acid, bicarbonate, and carbonate as a function of pH (Lower, 1999). As the water pH increases, so does the conversion of bicarbonate to carbonate, and hence the potential to form scaling due to calcium carbonate precipitation (Pääkkönen *et al.*, 2012). As observed in Figure 1-1, for pH values less than 6.5, mostly carbonic acid exists; at pH values between 6.5 and 10.5, the bicarbonate ion dominates, and above 10.5, the carbonate ion dominates the system. The degree to which calcium carbonate is formed depends on the pH of the recirculating cooling water.

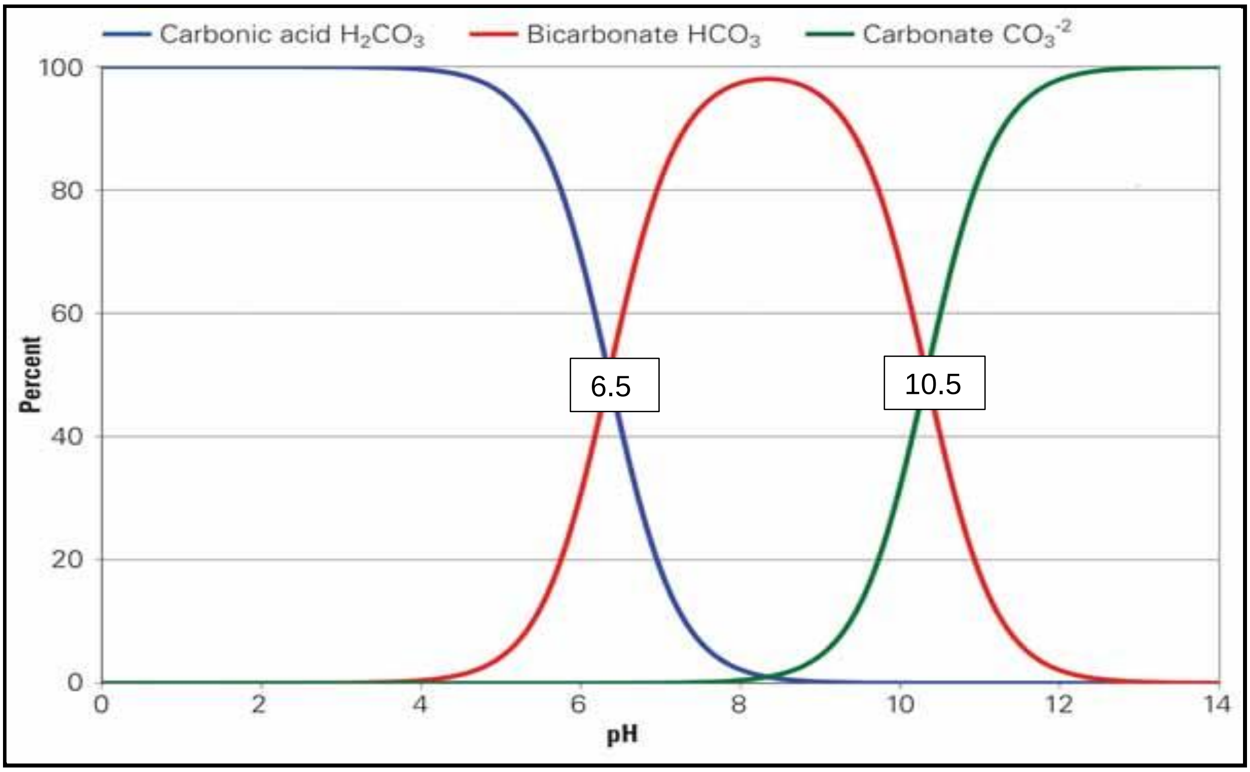

Figure 1-1: Dissolved carbonate in correlation with solution pH and how carbonate ions are distributed in the carbonate system at different pH levels (Lower, 1999)

Although the effect of temperature is not well defined. Literature shows that any change in the surface temperature may decrease, increase, or have no effect on the fouling rate (Awad, 2011). The effect of surface temperature on fouling is yet to be understood. Practically, more fouling is expected at elevated temperatures for recirculating cooling water due to its scaling potential. As the temperature rises, the chemical reactions become faster, and a loss of activity on some antifoulants is experienced (Awad, 2011). The calcium carbonate scaling precipitation potential increases with increasing surface temperature and increases exponentially at temperatures above 60ºC(Awad, 2011; Bansal *et al.*, 2000). Bansal and MÜller-Steinhage (2001), showed that the fouling resistance measured for calcium sulphate fouling on a plate heat exchanger was 50% lower at 85ºC than at 90ºC (Bansal *et al.*, 2000). Flow velocity can also significantly contribute to the degree at which fouling and mineral scale can form on a heated surface. Bansal *et al.* (2000) in their investigation showed that the fouling resistance decreases at lower flow velocities. As an example, suspended matter in the recirculating cooling water will deposit at low velocity regions like the water box and the shell side of the condenser.

1.1.2 Microbiological fouling

Microbiological growth caused by microorganisms, algae, fungus and even bivalvia can produce impurities (biofilm) that interfere and inhibit the heat transfer (Bott, 1995). In addition, these organisms create conditions and an environment for microbiologically influenced corrosion (MIC) or accelerate under-deposit corrosion production.

1.1.3 Recirculating cooling water management

Wet cooled coal-fired power plants have developed and established chemistry standards as guided by the Electrical Power Research Institute (EPRI) and the Vereinigung Der Grosskraftwerksbetreiber (VGB) to ensure plant integrity. These standards have limits and targets for recirculating cooling water chemical, biological control and monitoring (EPRI, 2012). Wet cooled power plants are expected to execute operating conditions that will ensure governance to the prescribed standards. The optimum process for recirculating cooling water treatment will be the process that effectively controls the cooling water chemistry and allows cycles of concentration (CoC) (Keister, 2008) that will ensure zero liquid effluent discharge (ZLED) (Oesterholt Koeman-Stein, Lambèr, 2016). CoC is the concentration of the non-evaporative element in the recirculating cooling water divided by the concentration of the same element in the make-up water. Make-up water is the amount of water required to replace the water lost by evaporation and blowdown(Apache Junction, s.a.; Van Zyl & Premlall, 2005). Blowdown is a term used for water that is removed from the recirculating cooling water to reduce contaminants build-up in the cooling system. Blowdowns discard a portion of the concentrated salts and contamination present in the recirculating water, either manually or automated as per the power plant requirements. Blowdowns are calculated and considered according to the number of cycles of concentration to manage and control scale formation (Matson & Harris III, 1979a). The recirculating cooling water system CoC calculation, indicated by Equation 1-1, is dependent on the cooling and make-up water limiting parameter. The limiting parameter is the chemical specie that will reach the specified threshold when concentrating the water through evaporation. Conductivity at 25ºC as a function of the total dissolved ionic solids can also be used as a quick indicator of CoC. The conductivity limit for wet cooled power plant concentrated cooling water systems has been set at less than 4000 µS/cm at 25°C (Committee, 2016; Technology, 2016)

The conductivity limit has been set for the following reasons:

- To minimize galvanic corrosion in highly saline conditions.
- To prevent damage to adjacent vegetation by salts released from the cooling tower drift.
- To allow sufficiently high cycles of concentration to be reached to obtain "zero liquid effluent discharge".

It must be clearly understood that the conductivity limit should not be viewed in isolation, as some ions are more corrosive than others (Committee, 2016). The lower the make-up water conductivity, the higher the CoC, and the higher the make-up water conductivity, the lower the CoC (Schutte, 2006).The CoC in the cooling system is calculated according to Equation 1-1.

$$\boldsymbol{Cycles\ of\ Concetration} = \left(\frac{\boldsymbol{Specified\ threshold\ for\ specie\ in\ CW}}{\boldsymbol{Same\ specified\ specie\ in\ make{-}up\ water}}\right) \qquad \text{Eq. 1-1}$$

1.2 Background and rationale

To achieve a higher thermal efficiency of a steam cycle process, exhaust steam extracted from the turbine is condensed at low pressure (temperature), which dependents on the conditions and quality of the recirculating cooling water. The variations in the recirculating cooling water parameters (physical and chemical) affect the characteristics that describe the condenser performance, such as effectiveness, transfer net flow, vacuum, and steam pressure, which have a considerable effect on the performance of the plant. It is imminent and clearly illustrated in Figure 1-2 that a significant amount of energy loss in the steam cycle process occurs through the main heat exchanger (condenser),also, demonstrated in Figure.1-2,is where energy is lost in different parts of a thermal power plant (Larsen *et al.*, 2013).

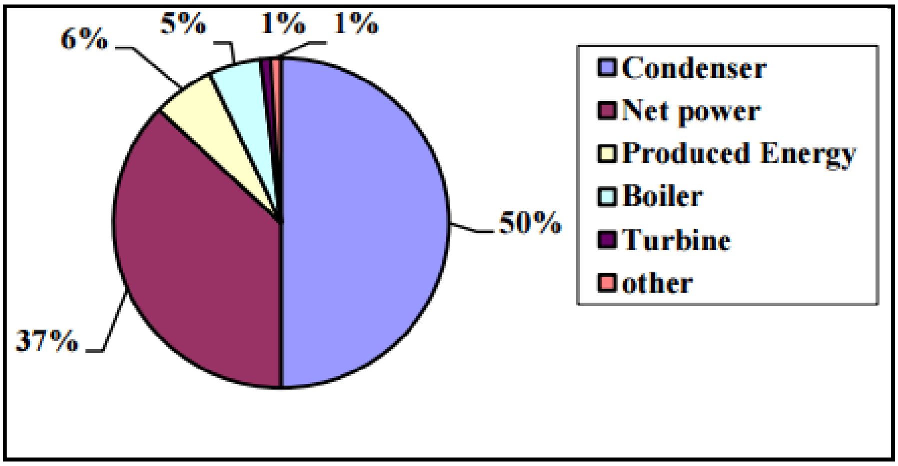

Figure 1-2: Ratio of energy losses in a power plant (Aljundi, 2009)

Condenser performance is greatly affected by aspects such as scale on the outside (steam side) of the tubes and by scale and fouling on the recirculating cooling waterside. Fouling and scale will effectively shield the tube wall (Figure.1-3). The consequences are deteriorating heat transfer capacity, reduction in the cross-sectional surface area, significant pressure drop, augmented pumping power, and reduced power output in the components (Bhatt, 2006)These lead to increased production and maintenance costs (Maree *et al.*, 2013). Scaling, corrosion, deposition and fouling of the heat transfer equipment will influence the chemical cleaning regime and frequency. The contaminant will define the type of cleaning and its duration. Every time the condenser is taken out of service for maintenance, i.e. pressure cleaning, chemical cleaning, condenser tube repair/replacement, production is lost. Chemical cleaning is generally defined as cleaning a fouled or scaled heat exchanger using chemicals to dissolve some or all of the elements contributing to the deposit. (Zhai & Rubin, 2010). Figure 1-3 shows a representation of the difference between fouled and clean condenser tubes.

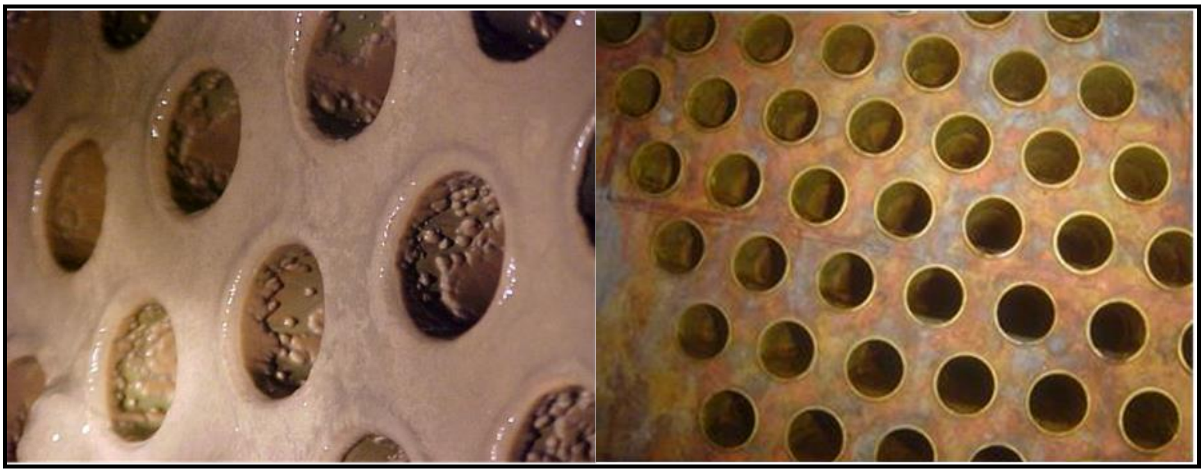

Figure 1-3: Excessive scale formation on a clean condenser tube (left); condenser tubes after chemical cleaning (right) (Committee, 2016).

1.3 Research problem

1.3.1 Introduction

Dissolved solids and impurities accumulate in the recirculating cooling water to levels at which scaling, fouling, and corrosion occur. Recirculating cooling water side stream treatment has been considered, namely, softening, decarbonisation, ion exchange, neutralisation and desalination (Epstein, 1983; Matson & Harris III, 1979 a,b) which would assist in the management and control of these impurities. In all these treatment processes, a 10% side stream (Figure 1-4) of the recirculating cooling water is treated to remove sufficient dissolved solids so that scaling, fouling, and corrosion can be controlled to tolerable chemistry intensities (Altman *et al.*, 2012). Except for the lime soda treatment process, these treatment processes are expensive and produce saline effluent that must be disposed of. Saline solution is the concentrated salt water that is left after the treatment process.

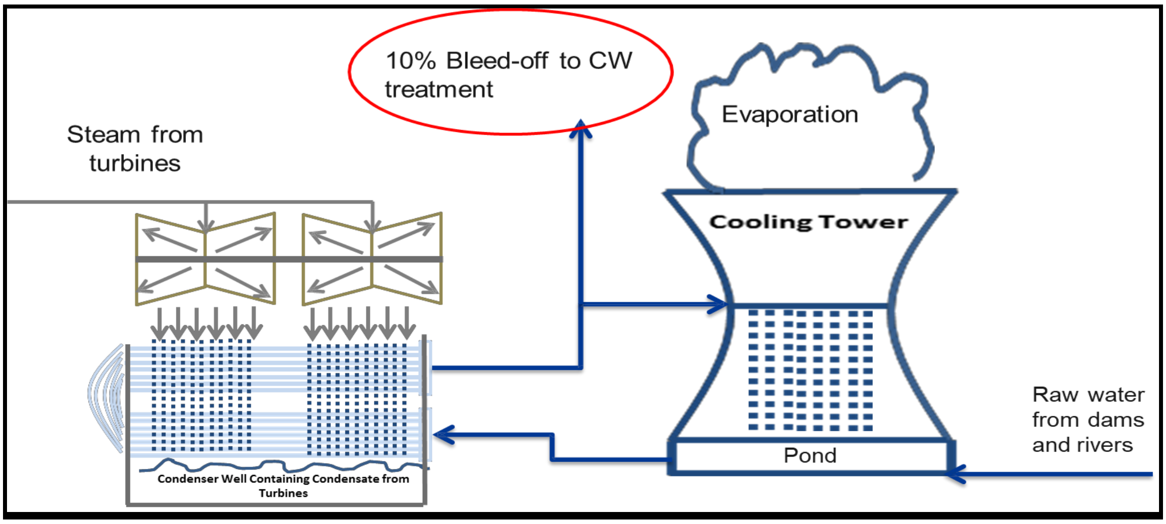

Figure 1-4: Cooling water system with 10% side stream treatment (Committee, 2016).

1.3.2 Problem statement

Most wet cooled thermal power plants are old and ageing (ESKOM, 2015), the water sources are contaminated, and the quality is declining, which affects the design conditions (Mkabane, 2015). These thermal power plants cannot afford to modify and refurbish their equipment every time the water quality changes. As a result, the recirculating cooling water chemistry in these power plants is deteriorating. The power plants are designed with different side stream treatments, shown in Figure 1-4, indicated by the 10% bleed off on the cooling water return line, which is currently struggling to control and mitigate the degradation of the recirculating cooling water chemistry. Side stream treatment softening needs to be optimised to accommodate the design changes and properly control the cooling water chemistry within specifications. It is therefore important to establish the extent of the out of specification chemistry in power plant cooling systems.

1.4 Hypothesis

The overall plant performance efficiency of a wet cooled power plant is negatively affected and impacted by poor recirculating cooling water chemistry management and control.

1.5 Purpose

In the study, the focus is on the performance of the recirculating cooling water chemistry using the lime soda treatment process. The purpose will be to evaluate and analyse the chemistry data, assessing critical parameters such as the calcium carbonate precipitation potential (CCPP), alkalinity, and pH, relating the chemistry to the condenser and cooling tower performance. The objective is to observe condenser and cooling tower efficiency and to show that cooling water chemistry directly affects and contributes to performance.

Other factors to be considered during the research

- Cooling water flow rates
- Condenser temperatures (inlet and outlet variations, calculated temperature rise)
- Condenser pressure affecting steam net power output of the turbine
- Air ingress
- Condenser back pressure
- Cooling tower performance indicators (range, approach, and effectiveness)

The outcome of the study will assist in ensuring the long-term plant health of condenser and cooling systems, which will greatly improve condenser and overall power plant efficiency.

1.6 Research questions

1. Does the poor quality of the recirculating cooling water affect and reduce the heat transfer capacity of the condenser and the cooling tower in a wet cooled power plant?
2. How can the wet cooled power plant using lime softening side treatment optimise the process for cooling water chemistry improvement?
3. Which chemical parameters can be used as a guide with the most impact on the performance of the cooling system?
4. How can the wet cooled power industry correlate the effect of recirculating cooling water quality to the power plant performance?

1.7 Overall aims

The overall aims of the investigation were:

- The demonstration and impact of poor recirculating cooling water quality on operational wet cooled power plant performance by observation and analysis of chemistry parameters.
- Assessment of the possible impact of recirculating cooling water inconsistency on the performance of the condenser and cooling system of a coal-fired power plant
- Ensuring plant availability and reliability, and effective power production in wet cooled power plants.

1.8 Objectives and goals

The aim will be achieved by pursuing the following goals

- To demonstrate the correlation between recirculating cooling water chemistry control and power plant performance through data analyses.
- To show the importance of maintaining a sound and healthy recirculating cooling water chemistry and operating within the open recirculating cooling water chemistry guidelines and standards.
- To evaluate the chemistry parameters that influence the development of scaling on the heat transfer surface.
- To demonstrate the purpose of a side stream recirculating cooling water treatment system in a wet cooled power plant.

CHAPTER 2: LITERATURE REVIEWS

2.1 Introduction

The emphasis of this chapter is the understanding of cooling water chemistry, the current treatment regimens, control of the water chemistry and the significance of cooling water analytical chemistry to overall power plant efficiency.

Cooling water chemistry involves numerous challenges, as the cooling medium in fossil power plant the chemistry can become detrimental and, to some extent, irreversible. This has caused a great impact on the power production industry, which will remain until the controls that are currently in place, i.e. side stream softening treatment of cooling water, are working and reliable. Side stream softening treatment decreases suspended solids and debris in the cooling water, leading to less fouling in the system. Suspended solids are a good source of nutrition for microbiological organisms; therefore, a decrease in the suspended matter will hinder the growth of microbiological organisms. In addition, side stream softening treatment reduces the potential of scaling and corrosion of the recirculating cooling water on the cooling systems.

Lime treatment, also known as the Clarks process, is one of the oldest and most popular side stream treatments for cooling water technologies. It was established around the 19th century, and the process greatly expanded as the demand for industrial water treatment started growing. The lime side treatment in the power industry is normally used for the removal of calcium, magnesium, silica, phosphates, and alkalinity from cooling water to prevent scaling of the cooling systems. This is achieved by precipitating scale-forming compounds such as calcium sulphate and carbonate, magnesium hydroxide, magnesium silicates, calcium orthophosphates, etc. from the cooling water and desludging them.

Several studies were conducted on the lime treatment process and how it should operate to remove hardness, heavy metals, and other contaminants leading to scale formation and predictions (Potgieter-Vermaak *et al.*, 2006). Some researchers investigated the effects on operational costs and water quality when lime treatment is considered for municipal water production (Slater-Williams, 2015). Relatively little consideration has been given to the lime process and whether the lime softening chemical treatment on cooling water yields the required results. The Electrical Power Research Institute (EPRI) and the National Science Foundation have sponsored and invested in lime softening investigations for cooling water treatment, as more work on the treatment is required, taking into consideration the variations in the make-up water quality. A notable exception is a study by Liang *et al.* (1980), which compared a computer simulation of lime soda ash data with data from laboratory experiments. However, from the study, more experimental work needs to be carried out. Open recirculating cooling systems are still suffering from scaling, fouling, and corrosion, where recirculating cooling water is the cooling fluid. Other treatment controls are discussed, including cooling water make-up and how it merges into the cooling water chemistry.

2.2 Why cooling in a power plant?

A thermoelectric fossil power generation process generates electricity by boiling conditioned demineralised water in a boiler. Demineralised feed water into the boiler is conditioned by the addition of chemicals like caustic or ammonia to increase the pH and protecting the system. The steam produced from the boiler is used to turn a turbine, which drives an attached generator, generating power. Subsequently, the exhaust steam that has passed through the turbine and the generator, is sent to a heat exchanger to be cooled or “condensed” back into the water (Alabrudzinski *et al.*, 2016). Cooling in a power plant is required because the equipment’s for example the condenser do not operate efficiently and optimally when temperatures increase beyond a certain point, and some components can be damaged by extreme temperatures (Cheremisinoff, 2019; Wassung, 2010). Cooling these components is necessary for effective power generation. The heat removed from the exhaust turbine will be ejected as excess heat into the environment (Fleischli & Hayat, 2014). Condensate from the condenser is pumped back to the boiler for reuse so that more electricity can be produced/generated (Fleischli & Hayat, 2014). Cooling is an integral part of the power plant process it creates a pressure gradient allowing the steam to flow within a closed loop system.

2.3 Circulating cooling water processes

There are different cooling technologies employed in a thermoelectric power plant, namely, once-through cooling, closed cooling cycles, dry cooling as well as hybrid cooling (Zhang *et al.*, 2017). In once-through cooling system, large quantities of water are required for cooling therefore, most of the power plant are situated nearby water sources i.e.: rivers, lakes, dams, etc. (EPRI, 2012). This makes the process vulnerable to water shortages and extremely high temperatures in times of drought (Hanson *et al.*, 1977). The cooling water is pumped from the water source and directed to the heat exchangers and the main condenser for cooling (Water, 2012). The heat from the exhaust steam is absorbed by the cooling water and released back to the water body. Once-through cooling does not circulate and recycle the water; the high water temperature released downstream can harm and kill aquatic organisms (Madden *et al.*, 2013).

Cooling in a closed cooling process is accomplished by circulating cooling water between the main condenser and the evaporative cooling tower. Latent heat is absorbed by recirculating cooling water from the condenser and dissipates by evaporation through the cooling towers. The water losses through evaporation are far greater than in the once-through system, and as a result, the water consumption is much higher. In addition, the salt concentration increases. To replenish the water lost through evaporation and dilution of the salt concentration, the system is compensated by make-up water. Make-up water can be derived from different water sources, depending on the power plant water management policy; this may include but is not limited to mine water, effluent from the site, raw water, rainwater, etc. (Fleischli & Hayat, 2014).

The third cooling process employed in wet cooled power plants is dry cooling. The process has similarities to the closed recirculated system but uses dry cooling towers instead of evaporative cooling towers. In dry cooling towers, ambient air is used for cooling, and water is preserved, meaning no water is required for cooling, water withdrawals are minimal, and the impact on aquatic life is eliminated (Water, 2012). The trade-off for these benefits is a greater impact on overall power plant efficiency. The overall efficiency of the dry cooling process is reduced compared with circulated water cooling, as the effectiveness of the dry cooling process will solely rely on environmental conditions, i.e. temperature and humidity ((Jović *et al.*, 2018). During hot and arid weather conditions, the efficiency of the plant deteriorates; as the heat transfer will be greatly affected, not much heat can be extracted. One major advantage of the dry cooling process is greater plant flexibility; the location of the plant does not rely on nearby available water sources, and the need for cooling water and water withdrawals is eliminated. According to the EPRI guideline for cooling water systems, the overall capital, operational, and maintenance costs for the dry cooling process are higher compared to other cooling systems (EPRI, 2012).

Combining a dry and wet cooling system is another cooling technology employed in power plants, normally referred to as hybrid cooling systems. This type of cooling is designed to be operated as wet cooling during high-temperature conditions and dry cooling during winter seasons. Wet cooling systems supplement efficiency losses during high-temperature conditions (Fleischli & Hayat, 2014).

Previous researchers have investigated the components of the cooling system (Castro *et al.*, 2000; Müller-Steinhagen, 1999; Panjeshahi *et al.*, 2009)water conservation, reuse (Mkabane, 2015), and other characteristics of the cooling system. Not much deliberation has been given to the cooling aspect of the side stream treatment and how it affects the overall performance and efficiency of a power plant. Kohli & Frenken, (2011) focused on the main cooling mechanisms employed in the non-contact heat exchanger, once-through and closed-loop, both of which use cooling water.

Cooling water side stream treatment is a major contributor to cooling water chemistry, and without proper management and control (Goodenough & Reuter, 2014a), things can go wrong rapidly. Wet cooled power plants are exposed to load losses due to high cooling tower outlet temperatures that are associated with problems like scaling, fouling, and corrosion, especially on the cooling tower fills. This comes with a huge plant performance impact and alternative reduction in power plant efficiency. The largest and most well-known power utility in South Africa has been struggling to sustain power production. Plants are ageing and maintenance is overdue, which creates problems like prolonged planned outages. It is common practice to put preventative control measures in place rather than addressing a problem that might take longer to resolve. Scaling is one of these problems, which is exceedingly difficult to correct after long exposure. In some cases, even mechanical high-pressure cleaning will not completely remove the scale; chemical interventions will be required, which forces the plant to be offline. In some severe cases, the scaling, fouling, and corrosion challenges have become so detrimental and irretrievable that replacement of the cooling systems is the only option (Buecker, 1997a).

Rankine cycle for power generation

The Rankine cycle is a closed thermodynamic cycle generating electric power that transforms heat into work using water as conventional working liquid. The working fluid in a Ranking cycle usually limits the efficiency of the system because the temperature variation over which the fluid can function is fairly small (condenser temp around 30 degrees and turbine entry temperature around 565 degrees celsius (Borunda *et al.*, 2016), to prevent the pressure extending to the supercritical phase (Albright & Vanek, 2008). To overcome this, the boiler can be integrated or followed by a super heater if the heat source fluid temperature allows it (Larsen *et al.*, 2013). In Figure. 2-1, the Rankine cycle, where steam is prevented from entering the superheat region after expansion, is shown. The result is a decrease in energy removal by the condensers as the temperature and pressure of the working fluid remain below critical (Larsen *et al.*, 2013). A condenser is considered the most important operating component in a power plant unit, with the primary function of creating a vacuum by condensing the exhaust steam. To fully understand the function of the condenser, the heat transfer principles, including the Ranking cycle, should be considered (said Ali, 2010)

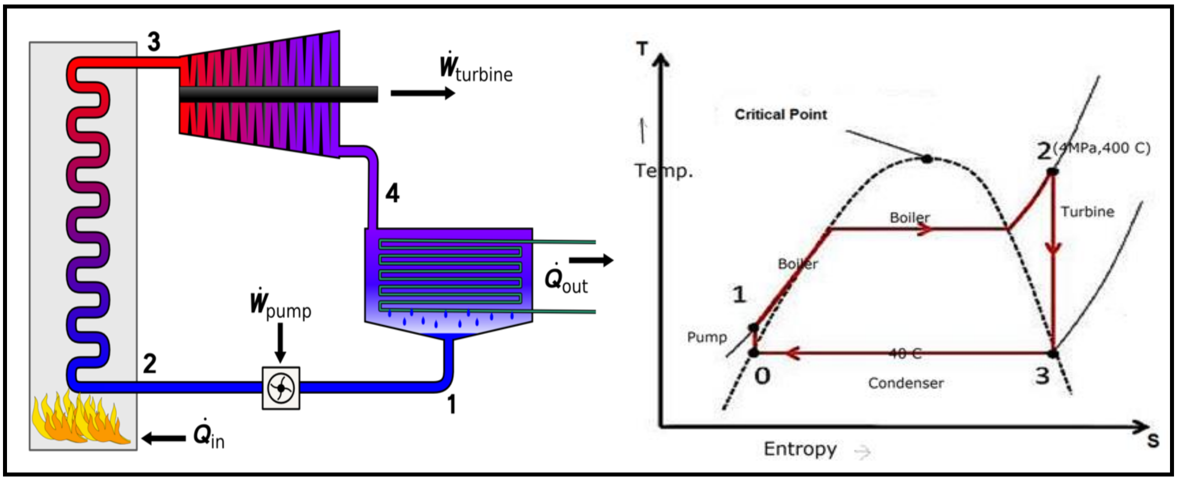

Figure 2-1: Organic four state Rankine cycle (left); four main devices used in the Rankine cycle (right) (Larsen *et al.*, 2013).

The Rankine cycle process comprises of systems where vapour/steam is generated at the preferred temperature and pressure. The generated vapour is expanded in the turbine that is attached to the generator for power production. The exhaust steam from the low-pressure turbine, which is the preceding phase of the expansion, is condensed in the condenser. Remaining latent heat is extracted using recirculating cooling water. The condensed steam, referred to as condensate, is recuperated into the system for power production (said Ali, 2010).

The process displayed by Figure 2-1 can be described as follows:

Stage 1-2: Water is generally used as a working fluid due to its high degree of specific conductivity and capability to absorb and transport heat. Water flow can be easily controlled either through gravity or by pumping with little energy requirement from low pressure to high pressure.
Stage 2-3: As the feed water enters the boiler at high pressure, it is heated by the fuel source from the boiler furnace to dry saturated steam (above 300 degrees). This occurs at constant pressure.
Stage 3-4: The dry saturated steam expands over high-pressure to low-pressure turbine blades, turning the turbine to generate electricity. During this process, temperature and pressure drop as some of the steam condenses.
Stage 4-1: At constant pressure and temperature, the wet steam is further condensed in the condenser to become saturated liquid. The physical properties remain stable as the water experiences a phase change. This process is assisted by the temperature in the cooling coils. In a perfect Rankine cycle, the pump and turbine would be isentropic, i.e., there is no entropy in the pump or turbine, and hence system productivity is maximised.

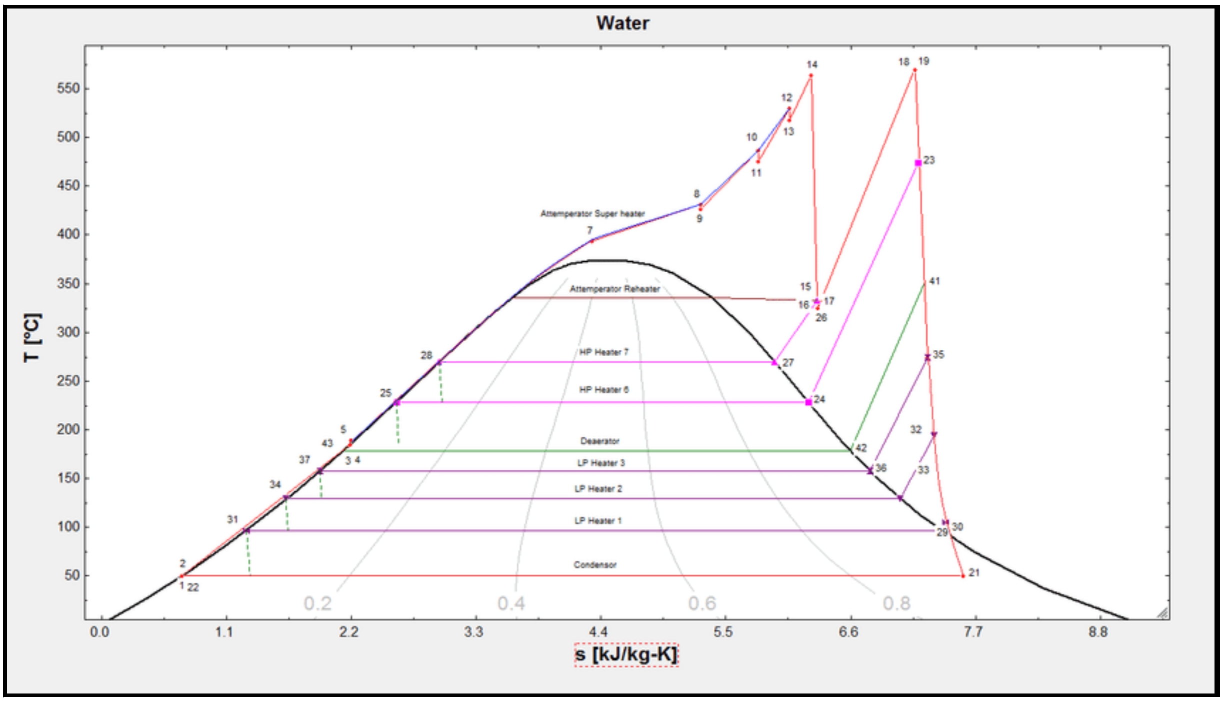

Figure 2-2: Supercritical ranking cycle as obtained for the Medupi Power Station in Lephalale (Kumar *et al.*, 2015)

Figure 2-2 represents a supercritical Rankine cycle; in this cycle, the working fluid (water) pressure is increased beyond critical pressure. The temperature continues to increase as more heat is applied to the above critical temperature (temperature exceeding 600 degrees), and supercritical pressure of about 22.1 Mpa. The condensation phase as the heat is rejected will remain in the subcritical phase. Supercritical Rankine cycles are occasionally referred to as trans critical cycles; the reason for this is that the condensation from steam to water is the main stage for heat rejection (Borunda *et al.*, 2016)Heat rejection returns the water to a subcritical phase. The conditions and characteristics of the working fluid, including the temperature of the fuel source, are contributors to selecting the supercritical Ranking cycle. Supercritical Rankine cycles are more advantageous when the heating fuel is at an advanced temperature.

2.4 Cooling water as a cooling medium in wet cooled power plants

Increasing freshwater scarcity and the rising cost of clean water supply have contributed to greater water conservation efforts worldwide, and especially in South Africa (Buecker, 1997a,b; Matson & Harris III, 1979a; Mkabane, 2015)). Wet cooled power plants boil conditioned purified water/ultra-pure to generate steam, which turns the turbine and generates electricity. Purified water has a conductivity of less than 0.1µS/cm. The energy or heat used to boil the water is generated by burning fuel, either coal, oil, nuclear reactions, or solar energy. The condensation occurs at a pressure below atmospheric, and this condition is referred to as a vacuum in the condenser, also observed in the Rankine cycle discussed above.

Different condensers are employed in wet cooled power generation plants, for example, jet or surface condensers.

- The cooling process in a jet condenser is achieved by condensing exhaust steam directly into the scattered cooling water. The condensed water leaving the condenser should be of the same quality as the cooling water. The condensate returned to the boiler must be pure; therefore, the cooling water that is mixed with the condensate must be equally pure (Drbal *et al.*, 2012)
- The steam surface condenser is a heat exchanger of the shell-and-tube type that receives saturated exhaust steam (8% to 15% moisture) from the main turbine reject. The exhaust steam is condensed to a liquid by the transfer of heat to cooling water circulating through the condenser tubes. For this phase change to occur, the amount of heat transferred to the circulating cooling water must be at least equal to the latent heat of vaporisation, a function of both steam quality and pressure.

The exhaust steam from the turbine is sprayed onto the outer surface of the condenser tubes, where cooling water is circulating. There is no direct contact between the cooling medium and the exhaust steam during the cooling process; in this regard, Table 2-2 can be used as a guide for cooling water requirements and quality necessary for cooling. This will assist in managing cooling water contaminations in case of any leakages. The heat rejected by the turbine cycle to the condenser is equivalent to the amount of heat transferred by the condenser to the cooling water, i.e. the turbine cycle and condenser are always in thermal balance. Mathematically, this thermal balance can be expressed as follows (Jović *et al.*, 2018):

$$Q = mcw \cdot cp \cdot TR = U \cdot A \cdot LMTD \qquad \text{Eq. 2-1}$$

Where:

Q = Condenser heat transfer rate

U= Condenser overall heat transfer coefficient

A= Condenser tube heat transfer surface area

LMTD= Log mean temperature difference

The ideal or target operating pressure of a condenser is determined by the temperature and quantity of cooling water when waterside fouling and in-leakage are minimal (Larsen *et al.*, 2013). The heat absorbed from the condenser by the recirculating cooling water will be dispelled in the cooling towers, either using natural or forced draft air cooling. During the cooling process, some part of the cooling water is lost through evaporation and needs to be replenished (Frayne, 2010).The source of make-up water is normally derived from the ocean, wells, rivers, creeks, canals, ponds, reservoirs, lakes, groundwater, or other supply sources (Cheremisinoff, 2019). Even sewage treatment plants effluent serves as a source for some facilities. The quality of the surface water from lakes and rivers can vary widely, as it is influenced by seasonal climate changes and discharges from sewage plants. Regardless of the source, the water will contain impurities (Cheremisinoff, 2019).

Surface water should naturally contain fewer dissolved solids than well water but with an increased concentration of suspended matter. The source may become very turbid during periods of heavy rainfall, which introduces particulates, loose vegetation and sometimes colloidal silica to cooling water (Buecker, 1997b). The composition of the water source will greatly influence the choice of treatment control.

2.5 CW side stream treatment processes currently employed

Cooling systems are linked to industrial processes, for example, in a power generation process where cooling systems release heat from the power plant process to the environment, therefore, failure of cooling systems is undesirable. Recirculating cooling water conditioning practise moderates scaling, fouling and corrosion of equipment in the cooling systems. Conditioning processes based on the addition of chemicals tailored to a specific circumstance are common practice but may lead to high operational costs and a substantial impact on cooling tower blowdowns (Panjeshahi *et al.*, 2009).

The selection of a suitable unit process and incorporation of the process into an overall water treatment plant is a complex task (Edzwald, 2010). Aspects considered during design for most treatment plants include:

- Capital for construction, including running costs, initial construction, and annual operating and maintenance costs
- Regulatory requirements and compliance, including safety, health, environment, and quality
- Site capabilities and preference
- Process reliability and flexibility
- Location for the site, site establishment requirements, and constraints and handling
- Raw water quality and treatment options

2.6 Conventional clarification

There are several treatment options for the removal of suspended materials; the treatment option selected must ensure that the required quality is achievable. Conventional clarification in water treatment involves the coagulation and flocculation stage, followed by sedimentation. The process will address most suspended material consisting of large and colloidal particles, both able to be settled by gravity and by the aid of coagulant and flocculants.

Coagulation is the fundamental pre-treatment process for conventional water treatment clarification. The process destabilises the colloidal particle by charge neutralisation (Spellman, 2013), and the nature of the colloidal particle is changed. A coagulant is added to the water to destabilise the particles and agglomerate them to form larger particles by the addition of a flocculant. This allows for the particles to settle into the sedimentation tank and be removed by desludging. Adsorption and precipitation processes use the coagulation process for the removal of soluble material. In recirculating cooling water, coagulation, flocculation, clarification and filtration are critical steps that combine to achieve the best treatment for the plant (Edzwald, 2010). The role of coagulation for the removal of organic matter has emerged in recent years. In many treatment processes, TOC controls the coagulant dosing rather than turbidity (Wang *et al.*, 2008).

During the coagulation process, chemicals are added to enhance the removal of suspended and organic matter; aluminium and ferric salt are widely used as coagulants. Enhanced coagulation is pH-dependent; ferric and alum coagulants have the potential to reduce the water pH and making the process ineffective, in addition, affecting the growth of the flocs during the process (Cao *et al.*, 2010). The best coagulation process for the water source in question should be identified at different pH levels with various coagulants to find the optimum dose (Qin *et al.*, 2006). Primary coagulants that are most common and widely used include, amongst others, aluminium sulphate, aluminium chloride, ferric chloride, ferric sulphate, sodium aluminate, polymeric coagulants, polyelectrolytes, aluminium polymers, etc. ((Spellman, 2013).

Coagulants used in water chemistry for alkalinity removal:

$$\boldsymbol{Al_2(SO_4)_3 + 6NaHCO_3 = 2Al(OH)_3 + 3Na_2SO_4 + 6CO_2} \quad \text{Eq. 2-2}$$

$$\boldsymbol{Fe_2(SO_4)_3 + 6NaHCO_3 = 2Fe(OH)_3 + 3Na_2SO_4 + 6CO_2} \quad \text{Eq. 2-3}$$

$$\boldsymbol{Na_2Al_2O_4 + 4H_2O = 2Al(OH)_3 + 2NaOH} \quad \text{Eq. 2-4}$$

Equation 2-3 and 2-4 shows the formation of the aluminium ion that will take effect in the neutralisation of the negatively charged colloidal particle in water. The product (aluminium hydroxide) from the reaction will precipitate and settle. The same reaction is observed in Equation

2-3, where ferric hydroxide will neutralise the negatively charged colloidal matter and be removed through sedimentation (Schutte, 2006).

2.6.1 Flocculation

In most water treatment processes coagulation is followed by the flocculation process. The destabilised colloidal matter will remain in suspension because the particle size is small and therefore cannot settle to the bottom of the sedimentation tank. To assist in settling the particles, a flocculant is added to agglomerate the particles, creating bigger floc that can be able to settle. Retention time is critical during the flocculation process (Edzwald, 2010)

2.6.2 Sedimentation

The destabilised agglomerated colloidal particles settle at the bottom of the sedimentation tank and are physically removed from the water. While the process can be used alone in the pre-treatment of cooling water, it normally follows coagulation or precipitation in the conventional water treatment process. Sedimentation falls within the category of clarification technologies; the particles formed will settle by gravitational force because their density is higher than the water density, and they are removed by desludging at frequent intervals. If sludge is not removed, the performance of the sedimentation tank will be affected, and eventually, the quality of the clarified water will deteriorate. The clean water leaves the clarifier at the top through collection troughs (Schutte, 2006).

There are different types of settling tanks, either circular or rectangular, depending on the plant capacity and the objectives for the treatment process, from which a suitable design will be selected. The objective is to ensure that the clarified water is free of any flocs. Where flocs are relatively light, a process such as dissolved flotation can be considered (Edzwald, 2010).

2.6.3 Chemical precipitation (lime softening)

The lime softening process works by converting calcium and magnesium bicarbonates to calcium and magnesium carbonate by chemical precipitation with the use of lime ($Ca(OH)_2$) (Slater-Williams, 2015). The lime softening process was developed in the 19th century (1841) (Amiri, 2013), by Thomas Clark and in the 20th century, the process expanded for use in the industrial sector (Pizzi, 2011). During the discovery period it was called and referred to as the Clark process (Green, 1957). The lime process can also be used in the reverse osmosis and ion exchange process as a pre-treatment phase for the reduction of heavy metals (Amiri, 2013). Heavy metals have the potential for scaling and fouling in most water treatment processes.

In the power industry, lime is introduced into the hot duct stream tapped from the condenser return line entering the clarifiers. Lime ($Ca\ (OH)_2$) in this regard is primarily used to regulate the alkalinity and pH of the cooling water. A certain amount of lime must be added to obtain an optimum pH in the clarifier. This optimum pH (10.2 (McDonald, 2006) will allow for the complete conversion of bicarbonate to the scaling product calcium carbonate ($CaCO_3$) and soluble magnesium carbonate ($MgCO_3$). To address the soluble magnesium carbonate, excess lime is added to increase the pH further and convert magnesium carbonate to magnesium hydroxide ($Mg(OH)_2$) (Amiri, 2013). The produced magnesium hydroxide has an added benefit of trapping silica and lowering its concentration. Concentrated cooling water with silica concentration have a possibility of forming magnesium silicate scale, which is extremely difficult to remove.

2.6.4 Cold lime softening

The cold lime softening process occurs at ambient conditions. By adding lime to concentrated cooling water, the reactions taking place are (Spellman, 2013):

$$\boldsymbol{CO_2 + Ca(OH)_2 = CaCO_3 + H_2O} \qquad \text{Eq. 2-5}$$

$$\boldsymbol{Ca(HCO_3)_2 + Ca(OH)_2 = 2CaCO_3 + 2H_2O} \qquad \text{Eq. 2-6}$$

$$\boldsymbol{Mg(HCO_3)_2 + 2Ca(OH)_2 = Mg(OH)_2 + 2CaCO_3 + H_2O} \qquad \text{Eq. 2-7}$$

To ensure that hardness is reduced, pH and alkalinity are critical measurements in the lime process. Continuous monitoring will be required to verify if the process is operating optimally, where hardness is controlled and managed to acceptable limits, according to the required chemistry standard for cooling water treatment used in the wet cooled power plant or as guided by Electric Power Research Institute (EPRI) and Vereinigung Der Grosskraftwerksbetreiber (VGB).

Non-carbonate hardness, if present, is not affected by treatment with lime alone. If non-carbonate magnesium hardness is available in the concentrated cooling water and additional hydroxyl alkalinity is maintained, the magnesium is reduced, but the calcium rise in the treated water is proportion to magnesium reduction (Cheremisinoff, 2019) due to the following reactions:

$$\boldsymbol{MgSO_4 + Ca(OH)_2 = Mg(OH)_2 + CaSO_4} \qquad \text{Eq. 2-8}$$

$$\boldsymbol{MgCl_2 + Ca(OH)_2 = Mg(OH)_2 + CaCl_2} \qquad \text{Eq. 2-9}$$

In the cold lime treatments process, sodium aluminate may be employed to assist in the removal of magnesium hardness. Sodium aluminate hydrolysis forms a flocculation aid aluminium hydroxide, and in addition, assists in silica removal and sludge blanket conditioning. The reactions are as follows (Spellman, 2013):

$Na_2Al_2O_4 + 4H_2O = 2Al(OH)_3 + 2NaOH$ Eq. 2-10

$MgSO_4 + 2NaOH = Mg(OH)_2 + Na_2SO_4$ Eq. 2-11

$MgCl_4 + 2NaOH = Mg(OH)_2 + 2NaCl_2$ Eq. 2-12

Soda ash may also be used for non-carbonate calcium hardness reduction, according to the following reaction (Liang *et al.*, 1980):

$CaSO_4 + Na_2CO_3 = CaCO_3 + Na_2SO_4$ Eq. 2-13

$CaCl_2 + Na_2CO_3 = CaCO_3 + 2NaCl$ Eq. 2-14

The excess lime required for the treatment of any present non-carbonate hardness is indicated by the reaction below:

$MgSO_4 + Ca(OH)_2 + Na_2CO_3 = Mg(OH)_2 + CaCO_3 + Na_2SO_4$ Eq. 2-15

$MgCl_2 + Ca(OH)_2 + Na_2CO_3 = Mg(OH)_2 + CaCO_3 + 2NaCl$ Eq. 2-16

2.6.5 Warm lime softening

This process operates at temperatures between 49 and 60^{o}C. An increased temperature decreases the chemical solubilities of constituents such as calcium and magnesium, which make up hardness. Silica removal is an added benefit, resulting in a more efficient softening process (Spellman, 2013). In the power industry, hot lime treatment is preferred and more efficient when compared to the standard cold lime treatment (Cheremisinoff, 2019).

Advantages from lime softening treatment include the reduction in blowdowns, thus conserving water in the power plant, feed water pre-treatment for the desalination plant, and recovery of heat to conserve energy. Temperature control is critical because variations can cause the precipitation of lime scale.

2.6.6 Hot lime softening

Hot lime softening is similar to warm lime softening, but the temperature ranges between 100 and 120^{o}C, and the system is under pressure. The reduction of hardness can rise to less than 8mg\kg and less than 2 mg\kg silica reduction as calcium carbonate in the lime-soda ash treatment (Liang *et al.*, 1980). Magnesium will also be reduced because the magnesium hydroxide solubility decreases at elevated temperatures (Spellman, 2013). Silica reduction is an added advantage in the hot lime softening process. The reduction of silica occurs through the adsorption on the magnesium hydroxide precipitate. In some water treatment operations for cooling water treatment for optimum silica reduction, sludge is circulated back into the inlet of the sedimentation tank to improve sludge contact and enhance silica reduction.

2.7 Alternative side stream treatment processes for recirculating cooling water

2.7.1 Neutralisation

Acid is added in the recirculating cooling water to reduce the scaling possibility for scale producing salts by controlling the pH and alkalinity (Horner, 1968). Sampson (2010) modelled and revealed in his study that alkalinity neutralisation is directly proportional to the acid required, which depends on the pH to be archived for recirculating cooling systems. The treatment option is simple, although, with the addition of acid in the system, there is the potential of changing the chemistry to a corrosive environment (Keister, 2008). The operation of the system incurs high risk; safety should always be a priority in this regard. To reduce the handling of acid, the system should be automated; moreover, this will ensure there is no overdosing or underdoing of acid. Thus, the system is protected from scaling and corrosion. The acid should be diluted and properly mixed to protect the concrete and pipework from acid; where possible, acid-resistant coating and pipework can be utilised.

Sulphuric acid is by far the most common acid used for scale prevention in power plants with an evaporative cooling system. There is a limitation in the use of sulphuric acid, especially when the system is highly concentrated or the make-up water source has high levels of sulphates. Sulphuric acid dosages may contribute to calcium sulphate precipitation and scaling. In such cases, hydrochloric acid will be employed for neutralisation. In a hydrochloric acid neutralisation system, chloride levels must be measured and monitored. Stress cracking and pitting corrosion of most stainless steel materials are due to high levels of chlorine (Sampson, 2010).

The use of carbon dioxide has been occasionally attempted and proposed as a replacement for sulphuric acid or hydrochloric acid, depending on which is employed by the power plants. Carbon dioxide injection in the recirculating cooling water can lower the pH, but there are some limitations when it comes to alkalinity control (Wang *et al.*, 2005). As the water enters the tower to be cooled, aeration takes place and the carbon dioxide is stripped off; the treatment option is thus compromised. The system pH returns to equilibrium as the atmospheric conditions take effect. Carbon dioxide cannot be used as a replacement for acid. It is normally not considered a practical method of regulating pH and alkalinity in wet cooled cooling systems (Haney & Hamann, 1969).

2.7.2 Desalination

Cooling water treatment by desalination is considered an advanced treatment because of the removal and treatment of different constituents in water (Schutte, 2006). Membrane desalination has experienced significant growth in the past decades, and more studies have been and are being conducted to enhance its application, especially in cooling water chemistry control and other industrial applications (Greenlee *et al.*, 2009). The process of removing impurities, in this case, total dissolved solids (TDS), from water to produce clean water is called desalination. The desalination technology is the leading treatment option for water industries, especially on new build industries (Greenlee *et al.*, 2009). Some wet cooled power plants have the technology in place for cooling water treatment; based on the observed chemistry and also depending on the feed water quality, the technology has done exceptionally well. There are few limitations to the technology, and benefits include demonstrated universal treatment capabilities and competitive costs (Edzwald, 2010). Membranes with the greatest immediate application to cooling water are classified according to the particle size that can be removed by the membrane (EPRI, 2012). There are three main membrane stages used in desalination, i.e. filtration (ultrafiltration or nanofiltration), reverse osmosis (RO) and/or continuous electro deionisation (CEDI).

2.7.3 Microfiltration (MF) and ultrafiltration (UF)

Ultrafiltration and microfiltration membranes in the water industry usually remove the following.

UF - all suspended particles and bacteria, most colloids, viruses, and macromolecules larger than the media pore size. UF membranes can remove particles in the range of approximately 0.002 to 0.2 microns.

MF - suspended particles, bacteria, and colloids greater than the effective opening magnitude of the filter media. Considering the size as a base, MF can remove elements in the size range of 0.05 to 2 microns (EPRI, 2012).

MF and UF can use either dead-end or crossflow filtration. In dead-end filtration, in which there is a single filtrate stream and no reject stream, feed water is pumped as a single stream through the semi-permeable membrane, and impurities are retained on the exterior. In crossflow filtration, where there are separate permeate and reject streams, the water flows across the membrane.

2.7.4 Reverse osmosis

Reverse osmosis (RO) spiral wound membranes are designed to reject even the smallest impurities from water, including the monovalent ions (chlorides and sodium), biological and suspended impurities. RO also removes most particulate matter, including bacteria, viruses, and organic molecules, and therefore produces permeate of good quality (Schutte, 2006). In a scenario where two water solutions having different concentrations of soluble salts are separated by a semi-permeable membrane, water from the dilute compartment attempts to flow through the membrane into the concentrated compartment to establish an equilibrium in the concentrated compartment. A pressure differential is established, which is osmotic pressure (Vainrot *et al.*, 2008).

In a case where the two compartments are closed and a pressure greater than the osmotic pressure is applied to the compartment containing the concentrated solution, water flows through the semi-permeable membrane and into the compartment containing the dilute solution. This is the basis of reverse osmosis. The pressurised concentrated solution enters the membrane chamber, and part of the uncontaminated solvent permeates through the semi-permeable membrane and becomes the product. The concentrated solution is discharged as effluent to waste or circulated back into the process to be treated.

Not all salts will be removed by the membrane. A small percentage of each ion will permeate the spiral wound membrane along with the solvent as the product (Greenlee *et al.*, 2009). Each module will have a different rejection characteristic for each ion; the water flow is dependent on the module porosity, amongst other contributors. Salt passage (SP) is the portion of the ion (usually expressed as a percentage) to pass through the membrane, and salt rejection (SR) is the percentage rejected by the membrane.

The salt passage can be defined by SP (%) = 100*(concentration of an ion in product/concentration of an ion in feed).

Salt rejection as a performance indicator of the RO process against the Original Equipment Manufacturer (OEM) specification is calculated using Equation 2-17. Simplified salt rejection can also be given by 100-SP.

$$\boldsymbol{Rs} = \left(\mathbf{1} - \frac{\boldsymbol{C\ permeate}}{\left(\frac{\boldsymbol{C\ feed + C\ concentrate}}{\mathbf{2}}\right)}\right) * \mathbf{100}\% \qquad \text{Eq. 2-17}$$

Where $C_{concentrate}$ is the of salts in the reject stream (Wilf & Bartels, 2005), and C_{feed} is the feed concentration. As the membrane age and the feed water quality deteriorates, the performance of the plant is affected, and salt rejection declines. The OEM might offer high rejection rates; the industry should take cognisance of the fact that every piece of equipment has a certain lifespan, of which the duration is determined by several factors, e.g. feed pressure, temperature, water quality, operating conditions, etc. (Wilf & Klinko, 2001).

Another important performance indicator of the RO is the percentage recovery (%R) of the feed water. The overall percentage recovery (R) of an RO system is the percentage of feed water that is converted into permeate; this is given by Equation 2.18. Recovery (R) = 100*(product flow/feed flow)

$$\boldsymbol{Rw} = \frac{\boldsymbol{Q_P}}{\boldsymbol{Q_F}} \qquad \text{Eq. 2-18}$$

Where R_W is the percentage water recovery, Q_P is the product flow, and Q_F is the feed flow (Rahardianto *et al.*, 2007). Percentage recovery adjustments need to be normalised to account for changes in the feed pressure and temperature. According to Greenlee *et al.* (2009), recovery for most reverse osmosis technologies ranges from as low as 35% to almost 85%, also taking cognisance of the feed water conditions. No change in the process can be conducted in isolation, as it affects other parameters that will contribute to the overall performance of the process. Process recovery and salt rejection are used to estimate the concentration factor of the reject stream. The concentration factor (CF) is calculated by the formula: CF = (Feed flow/Rejection flow). CF is used to indicate the concentrate dissolved material.

The most common reverse osmosis membranes are made of a polyamide thin film composite construction, and the polyamide membrane is extruded onto a polysulphone porous support. Cellulose acetate membranes were used extensively in the past but require higher pressures and have a lower salt rejection than thin-film composite membranes (EPRI, 2012).

A study was conducted on a pilot scale by Altman *et al.* (2012), where the main objective was to establish the potential of reducing water intake and discharge in a recirculating cooling tower using desalination membrane technology. The product from the desalination plant was used as make-up into the cooling tower to dilute the recirculating water as it concentrates due to evaporation. The physical operating conditions and water quality on the plant during the study were continuously monitored. The monitoring included pressure, temperature, flow, and water chemistry. The outcome of the study indicated that water consumption and discharge for the plant decreased by 16 and 49%, respectively. The study demonstrated that operating the plant at elevated recoveries improved water conservation. Scaling was observed as one of the challenges during the study; therefore, scaling control should be optimised. Altman *et al.* (2012) mentioned in the study that it is economically feasible to treat recirculating cooling water using membrane technology as long as scaling, normalisation and optimisation are controlled and managed.

2.8 Challenges/problems in the cooling water system

Proper control of the cooling water quality is required to maintain the cleanliness of condenser tubes and therefore condenser performance. Cooling water chemistry deterioration results in either scale formation on water touched surfaces or erosion-corrosion in the condenser tubes. In addition, if the suspended solids in the cooling water are not maintained within the required limits, sediments and sludge will accumulate in the condenser tubes and ducts with a detrimental effect on performance. Table 2-1 presents an example of different impurities that can be found in water and the suggested treatment options (EPRI, 2012). Unfortunately, most wet cooled power plants have difficulty maintaining the cooling water within acceptable parameters, resulting in excessive condenser pressure and load losses, which necessitate off-load cleaning to be done(Committee, 2016).

Scale that accumulates on condenser tube surfaces has to be removed for the following reasons:

- it reduces heat transfer and condenser thermal efficiency,
- it promotes under-deposit corrosion mechanisms,
- it prevents online ball cleaning systems from operating correctly, and
- it impacts the quality of the eddy current testing on the main condenser.

Table 2-1: Impurities commonly found in water (Bhatia, 2003; EPRI, 2012)

Parameter	Chemical formula	Challenges	Treatment option
Turbidity	non-expressed in the analysis as units	Unappealing appearance to water; promotes pathogens regrowth, deposits in water lines, process equipment, etc.; affects most process practices	Filtration, sedimentation, coagulation and settling
Hardness	calcium and magnesium salts expressed as $CaCO_3$	the main source of scale in heat exchange components, boilers, pipelines, etc.; produce curds with soap, obstructs dyeing, etc.	softening; demineralisation; ion exchange, internal boiler water treatment; surface-active agents
Alkalinity	bicarbonate(HCO_3^-), carbonate (CO_3^{2-}), and hydroxide(OH^-) expressed as $CaCO_3$	foam and carryover of solids with steam; embrittlement of boiler material; bicarbonate and carbonate produce CO_2 in steam, a source of corrosion in the feed stream	lime and lime-soda softening; acid treatment; hydrogen zeolite softening; demineralisation de-alkalisation by anion exchange
Free mineral acid	H_2SO_4, HCI. etc., expressed as $CaCO_3$	Corrosion	Neutralisation with alkaline

Carbon dioxide	CO_2	corrosion in water lines, particularly steam and condensate lines	aeration, de-aeration, neutralisation with alkalis
pH	hydrogen ion concentration defined as: $$pH = \log\frac{1}{[H^{+}]}$$	pH range according to alkaline or acidic solution; in general; natural waters pH range is between 6.0-8.0	pH can be decreased by acids and increased by alkalis
Sulphate	SO_4^{2-}	Increases the solids content and conductivity of water, but is not usually significant, combines with calcium to form calcium sulphate scale	softening, demineralisation, reverse osmosis, electrodialysis, evaporation
Chloride	Cl^-	Increases the solids content and conductivity; increases the corrosive character of a solute	demineralisation, reverse osmosis, electrodialysis, evaporation
Nitrate	NO_3^-	Increases the solids content, less significant in industrial applications, elevated amounts can cause methemoglobinemia in children; useful for control of boiler metal embrittlement	demineralisation, reverse osmosis, electrodialysis, evaporation
Fluoride	F^-	cause of spotted enamel in teeth; dental decay management: less significant in industrial applications	adsorption with magnesium hydroxide, calcium phosphate, or bone black; alum coagulation

Sodium	Na^+	Increase the solids content and conductivity of water: when combined with OH^-, causes corrosion in boilers at specified conditions	demineralisation, reverse osmosis, electrodialysis, evaporation
Silica	SiO_2	scaling in boilers and cooling water systems; insoluble turbine blade deposits due to silica vaporisation	hot and warm process removal by magnesium salts; adsorption by highly basic anion exchange resins, in conjunction with demineralisation, reverse osmosis, evaporation
Iron	Fe^{2+} (ferrous) Fe^{3+} (ferric)	discolours water on precipitation; source of deposits in water lines, pipes, boilers. etc.; obstructs dyeing, tanning, papermaking, etc.	aeration; coagulation and filtration; lime softening; ion exchange; contact filtration; surface-active agents for iron retention
Manganese	Mn^{2+}	Similar to iron	Similar to iron
Aluminium	Al^{3+}	usually present as a result of floc carryover from clarifier; can cause deposits in cooling systems and contribute to complex boiler scales	Improved and enhanced clarification and filtration process
Oxygen	O_2	corrosion of water lines, heat exchange equipment, boilers, return lines, etc.	deaeration; sodium sulphite; corrosion inhibitors

Hydrogen Sulphide	H_2S	cause of "rotten egg" odour; corrosion	aeration; chlorination; highly basic anion exchange
Ammonia	NH_3	corrosion of copper and zinc alloys by formation of complex soluble ion	cation exchange with hydrogen zeolite; chlorination; deaeration
Dissolved Solids	None	Defines as the total amount of dissolved solids, determined by evaporation; elevated concentrations are objectionable because of process intrusion and as a cause of foaming in boilers	lime softening and ion exchange by hydrogen zeolite; demineralisation, reverse osmosis, electrodialysis, evaporation
Suspended matter/solids	None	Defines as the measure of undissolved solids, determined gravimetrically; deposits in heat exchange equipment, boilers, water lines, etc.	subsidence; filtration, usually preceded by coagulation and settling
Total solids	None	Defined as the sum of dissolved and suspended solids, determined gravimetrically	Refer to "Dissolved Solids" and "Suspended Solids"

The effective operation of cooling water treatment systems continues to lean on the control of scaling, fouling, and corrosion. Though these conditions have not changed in nature, the operating challenges encountered have increased considerably (Puckorius & Strauss, 1995).

2.9 Cooling water chemistry requirements

Wet cooled power plants produce the greater part of waste (effluent) at power plants. To evade the impact of cooling water effluent, power plants operate their wet cooling systems at higher cycles of concentration (CoC). Cooling water in all, if not most, wet cooled plants in South Africa are therefore categorised as brackish water, regarded as more hostile in terms of corrosion and erosion when compared to freshwater (Farahani *et al.*, 2016).

Over and above the deterioration of raw water quality, the power plants have experienced, and are expected to continue experiencing, constraints during the operation and maintenance of wastewater management, cooling water systems and steam/water cycle, ultimately contributing to both additional effluent volume and salinity. Stringent application of water legislation and compliance to a zero liquid effluent discharge (ZLED) philosophy, as contained in the environmental policy, suggests that these effluents often contribute to unnecessary salinity in the cooling water system. Therefore, wet cooling systems are often operated beyond the specified thresholds to evaporate excess dirty water.

A major factor contributing to the degradation observed in brass-based condenser tubes within wet cooled power plants is the cooling water quality. It is also a major factor in the decision-making process regarding the selection of tube material when considering a condenser re-tube project (Bostwick, 1961; Goodenough & Reuter, 2014b; Krzywosz *et al.*, 1992; Sinha, 2010). Due to freshwater being a scarce commodity worldwide (McCoy, 1974), recovered water and other degraded water supplies are used as make-up to the power plant cooling systems. Conditioning and treatment are required for the recovered water before it can be used for any application in the power plant. Excess polluted mine water and the stringent application of legislation implies that the recovered water must be treated before disposal. For a power plant to manage the cost and long-term liability of this activity, polluted mine water is in some cases recovered by the particular power plants and used for cooling (Edzwald, 2010).

2.10 Cooling water quality requirements

To effectively manage and control the recirculating cooling water chemistry, there are chemical parameters that must be monitored. In the event where any of the parameters is higher than the limit, surveillance is managed to extend risk management. The recommended frequency analysis on recirculating cooling water is given in Table 2-2. In cases where a limit is not given, the power plant needs to make a local decision depending on the observations associated with the parameter; in addition, the frequency can be increased based on the observed trend.

Table 2-2: Chemistry requirements for cooling water systems (Mensah *et al.*, 2013; Technology, 2016)

Parameter	Units	Limit or Range
Turbidity	NTU	As low as cost-effectively possible but < 100 NTU for continuous operation
pH	Range: 8,1 to 8,6 @ 25 °C. Optimum pH is 8.3	
Conductivity	$\mu S.cm^{-1}$	Conforms to the cycles of concentration being used but generally < 4000 μS.cm–1
Corrosion inhibitors	$mg.kg^{-1}$	In accordance with vendor and/or the power plant recommendations
Sodium	$mg.kg^{-1}$	< 500
Potassium	$mg.kg^{-1}$	< 500
Oil	$mg.kg^{-1}$	< 5 / Negotiable
Water losses	% loss	In accordance with evaporation and blowdown requirements
M-Alkalinity The guideline limits only and will not constitute an out of specification condition provided that the CCPP conforms to the specified limits	$mg.kg^{-1}$	(Depending on CCPP) 80 to 120 $mg.kg^{-1}$ as $CaCO_3$ without a crystal modifier dosing programme. (Depending on CCPP) 120 to 160 $mg.kg^{-1}$ as $CaCO_3$ with a crystal modifier dosing programme.
Total hardness as $CaCO_3$	$mg.kg^{-1}$	< 500

Calcium carbonate precipitation potential (CCPP) using Stasoft 4 at 38^{o}C	mg.kg$^{- 1}$	Calculated with Stasoft software without crystal modifier dosing: > 10 but < 30 mg.kg^{-1} as $CaCO_3$ with crystal modifier dosing: > 10 but < 45 mg.kg^{-1} as $CaCO_3$
Copper	mg.kg^{-1}	< 500
Iron	mg.kg^{-1}	< 500
Chlorides	mg.kg^{-1}	< 400
Sulphates	mg.kg^{-1}	Poor quality concrete power plants < 250 mg.kg^{-1} 250 mg.kg^{-1} High quality concrete power plants < 1500 mg.kg^{-1} if Na^+ < 500 mg.kg^{-1} < 1000 mg.kg^{-1} if Na^+ > 500 mg.kg^{-1} Note: Mg^{2+} to be < 160 mg kg^{-1} as $CaCO_3$
Magnesium	Mg (as $CaCO_3$) SiO_2	Mg (as $CaCO_3$) SiO_2 < 25 000
Silica (can produce difficult to remove scale)	<150 mg.kg^{-1} as SiO_2. While also taking cognisance of Mg × SiO_2 limitation	<150 mg.kg^{-1} as $SiO_{2.}$ While also taking cognisance of Mg SiO_2 limitation

2.11 The negative impact of poor cooling water chemistry

The effect of fouling can be measured by observing these challenges:

- Decreased heat transfer; deposits have low thermal conductivities, which diminishes the response to heat transfer through the reduction of heat transfer rates.
- Higher hydraulic resistance in the flow circuits, leading to additional pumping power in pumps and reduced mechanical power output in the turbine.
- Tube failures caused by corrosion.
- Mechanical imbalances axial shift and vibrations in turbines.

- Direct energy loss due to continuous or intermittent cooling water blowdowns to manage and control contaminant.
- The sluggish or incorrect response of control and instrumentation (thermocouples, thermostats).

Impurity control is a significant operational requirement that is fundamental for the optimum management of power plant assets (Bhatt, 2006). The main water contamination (demineralised water, recirculating cooling water, and auxiliary cooling water) results from:

- Ineffectively treated water streams initiating from the unfortunate quality of the input stream, operational and maintenance challenges during purification/transferring/pumping, etc of water.
- Condenser cooling water leaking to clean water streams.
- Effluent and dirty water leakage in the auxiliary cooling water stream.
- Boiler carryover (physical entry of chemicals into steam).
- Deposition of chemicals used for chemistry control.
- Corrosion products of copper alloys from preboiler systems (condenser, deaerator and feed water heaters).

Frequently, water quality-related challenges are allied not only with the presence of a variable but also with the collaboration between variables, as is the case with corrosion and scaling.

2.12 Factors affecting station thermal efficiency in a power plant

The main energy supplier in South Africa has experienced power shortages due to demand expansion coupled with ageing power plants that are due for planned outages. The fossil fuel operated power plants generate electricity, and the installed capacity is designed with boilers feeding steam into the turbine. The power output measured by the overall efficiency of these operational power plants has deteriorated, leading to reduced power production.

2.12.1 How is the efficiency measured in a power plant?

Combustion in fossil fuel operated power plants occur inside the boiler. Fuel reacts with the oxygen producing heat, where about 80% of fuel used for power production is pulverised coal (Affairs, 2011).

The **first phase** during combustion is the conversion of potential energy to heat energy; this stage carries about 90% of the efficiency in the power plant, with the reasons being:

i. During the combustion process, heat is transferred from the furnace to the water flowing inside the boiler tubes, practically during heat transfer; not all the heat generated in the boiler is transferred to the working fluid. A portion of the heat is lost as hot gases to the atmosphere.

ii. The quality of the pulverised coal contributes to the heat produced, where wet coal affects the combustion process. As the moisture from the coal vaporises, it removes some of the latent heat in the combustion chamber, which is released with the hot gases upon leaving the boiler.

iii. Other losses are due to radiation, hot ash discharged, and incomplete combustion in the boiler.

The **second phase** of the process is conversion, where heated water is converted into steam.

In drum boilers operating at a temperature range of around 570^{o}C and a pressure of less than 221 bar, the cycle efficiency is around 43% bar, with once-through boilers operating at supercritical conditions, temperatures around 600^{o}C; the cycle efficiency increased to almost 47%. This is mainly due to some of the explanations below:

i. The condensation process is one of the greatest losses of energy in the condenser.

ii. During the steam expansion from high to low pressure, losses are experienced on the turbine blades (Wiser, 2012).

iii. Maximum steam temperatures from the boiler affect the cycle efficiency. Plant designs and equipment that cannot handle temperatures above 600^{o}C create some of the limitations (Murehwa *et al.*, 2012).

In the **third phase,** the mechanical work done by the steam turbine is converted to turning the generator that produces electricity. 5% efficiency loss is due to the magnetic and copper losses in the generator, and about 3% is due to the step-up process from the transformer as electricity is transmitted to end-users.

Depending on the size of the power plant, auxiliaries can consume up to 6% of the power output. Auxiliaries include pumps, precipitators, fans, pulverisers, etc. (Drbal *et al.*, 2012).

The overall power plant efficiency and performance are determined by the individual equipment and components. This overall efficiency is a product of the boiler, turbine, generator and cycle efficiency, with the boiler efficiency around 85 to 90%, turbine efficiency around 80 to 90% and the generator efficiency around 98%. When the cycle efficiency is included, the turbo generator efficiency is reduced to below 40%, due to which the overall plant efficiency drops to between 32 and 42% (Drbal *et al.*, 2012).

The thermal efficiently of wet cooled power plants has decreased significantly, especially in one of the biggest power utilities in South Africa. This is indicated in Figure 2-3.

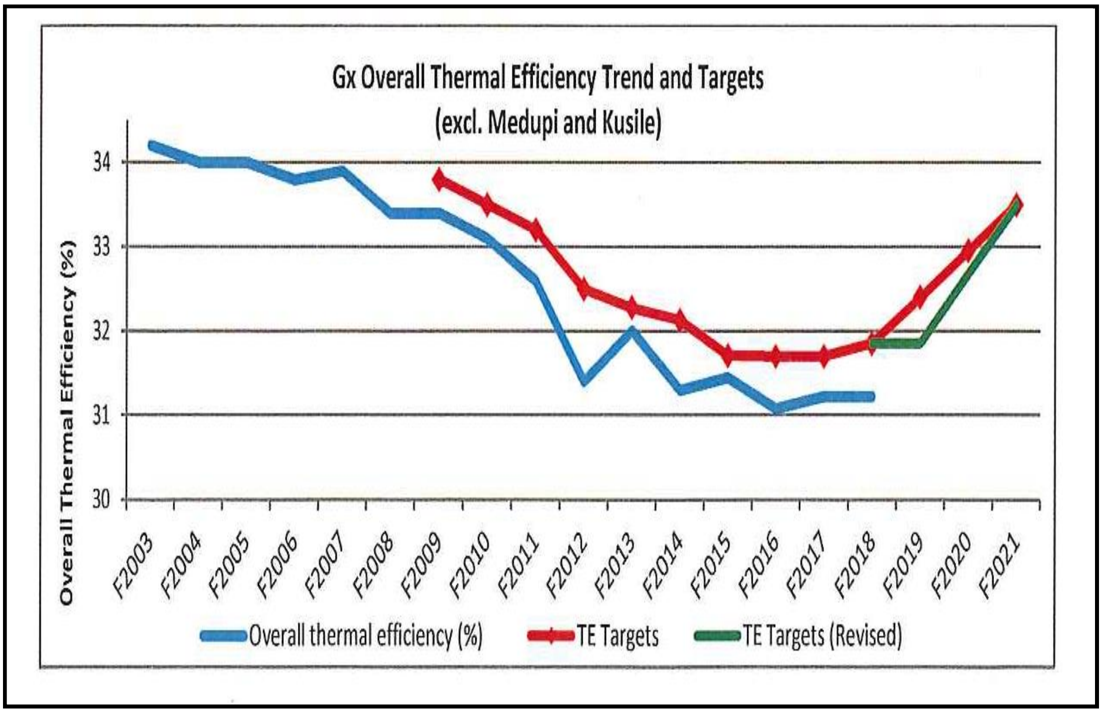

Figure 2-3: Overall thermal efficiency vs. a target of a fossil power plant in SA (ESKOM, 2015).

There are initiatives and recommendations from the Process Engineering Integration (PEI) in place for the power plants to restore their capacity and improve overall efficiency, but these are expected to yield results only in 2021.

These include but are not limited to:

a) Quality execution of philosophy-based outages as per schedule
    i. perform pre-and post-outage effectiveness
b) Implementing technical plant thermal efficiency impacting projects as planned
c) Drive coal data integrity by accurate reporting of coal quantities and qualities at measuring point with online elemental analysers, hammer samplers and/or coal laboratory analysis
    i. this will also minimise any potential carbon dioxide (CO_2) and coal burnt audit findings, and
    ii. ensure active power station participation with all relevant stakeholders
d) Ensure that power plant process engineering capability and capacity are maintained

Investigations are currently underway and based on the findings, according to a study conducted between 2014 and 2015 by Kumar *et al*. (2015), the main contributors currently affecting the condenser performance and overall thermal efficiency for recirculating cooling fossil power plant are:

1. Make-up water loss
2. Back pressure loss

The following parameters affect condenser back pressure:

- The recirculating cooling water inlet temperature
- Recirculating cooling water flow
- Dirty tubes (fouling)
- Air ingress

2.13 Operating conditions contributing to and influencing deposit formation

The heat transfer system will normally be fouled after it has been exposed to the poor cooling water chemistry for an extended period. These deposits will reflect the water chemistry changes over the history of the system. Deposit rate build-up can be used to project future condenser performance and the cost of fouling if the cooling water chemistry remains the same, which for the purpose of the study, will be neither advisable nor recommended.

2.13.1 Operational parameters with great impact

The mechanical shear force of the cooling water on the tube walls as it passes through the condenser or heat transfer systems is a function of the flow regime present in the tubes, for example, turbulent, transitional, or laminar flow. Another parameter is the bulk temperature of the cooling water and, more importantly, the tube wall temperature.

These parameters affect the deposition by basic mechanisms:

- The mechanical equilibrium for deposition or growth occurs when loose suspended solids deposits form and are removed by the mechanical action of the water. Initially, such deposits or slime form at a more rapid rate than the rate at which they are removed. As the loosely adherent deposit thickness increases, the shear force promotes a greater removal rate. This is the reason why slime or loose suspended solids deposits form rapidly and then reach a plateau or equilibrium point.
- The chemical equilibrium for the deposition of low solubility compounds in the water is affected by temperature. Foulants such as $CaCO_3$ may be soluble at the inlet water temperature but precipitate as the bulk water temperature increases in the main condenser and other cooling water systems. The tube wall is the highest temperature area of the equipment and the point where, sparingly, inversely soluble compounds are most likely to precipitate and form deposits.

- The growth rate of microbiological slime is also controlled by the bulk water and tube wall temperature. Microorganisms grow more quickly as the temperature increases within the operational temperature range encountered in the heat transfer systems. The temperature of the recirculating cooling water also affects the flow regime and shear force for a constant velocity.

2.14 Conclusion

The deterioration of circulation water system and infrastructure in a power is a major challenge to water production and processes in a power plant. There are different ways to reduce system exposure by using different materials, chemical treatment etc. To prolong the life of any equipment, water conditioning should be conducted as per the process requirement directed by guidelines and regulations. Scaling, corrosion and fouling of water systems due to highly concentrated cooling water is a frequent challenge in the power industry. In addition, changes due operations in the power plant will greatly affect the water chemistry, it is of paramount importance that every system employed to condition the water chemistry is optimised to accommodate these continuous changes.

Selection of the cooling water management system program and service provider based on some acquaintance of the cooling water chemistry and control required will increase the probability of gaining consistent and efficient water systems with determined efficiency at the lowest charge. Power plants must devote and allocate time and resources to the optimum operation of the cooling systems. Proper concentrated cooling water chemistry will minimise boiler and condenser tube failures, concentrated cooling water system blow downs, raw water make up while providing a long-term plant health and reducing cost to the power plant.

CHAPTER 3: INCONSISTENCIES IN COOLING WATER CHEMISTRY

3.1 Introduction

Cooling water chemistry challenges in thermal wet cooled power plants have become damaging and to some extent even irreversible (Buecker, 1997a). Scale, corrosion and deposit accumulation on the cooling systems impede heat transfer. Pitting due to corrosion can force a power plant to replace components, resulting in unplanned maintenance work and plant shutdown. Plant maintenance, either for mechanical and chemical cleaning, replacement, or repair, is expensive (Zhai & Rubin, 2010). This has caused a great impact on the power production industry and will remain, until the controls in place, are efficient and reliable (August, 2005), i.e. conditioning of cooling water by side stream softening. Scaling, fouling, and corrosion in the cooling systems using recirculating cooling water have production and economic implications. Heat transfer reduction between the cooling medium and the exhaust steam in a power plant can be due to the fouling and scaling that is formed on the condenser tubes. As a result, productivity and efficiency is negatively affected, which influences the economics of the plant (Nebot *et al.*, 2007).

Recirculating cooling water chemistry impurities/contaminants accumulate over time as the water evaporates through the evaporative cooling tower. Side stream softening has been designed to treat at least 10% of the recirculating cooling water to maintain the cooling water chemistry in the specification (Liang *et al.*, 1980). Due to operational constraints and make-up water quality deterioration, side stream softening is encountering challenges. The result, is the failure to control, regulate, and maintain the cooling water cycle chemistry within allowable chemistry limits (Technology, 2016). The conditioning of recirculating cooling water is a requirement and an essential function of wet cooled power plants. The quality and purity of the water used for cooling define the health of the heat transfer equipment (Shreve & Brink Jr, 1977). Efficient recirculating cooling water side stream treatment operation, optimise the cycles of concentration and reduce the blowdowns required (Frayne, 1999). The resultant is sustaining the cooling water chemistry in the specification, thus protecting the heat transfer system from being exposed to scaling, fouling, and corrosion (August, 2005). The volume of water removed by blowdowns or evaporation is replaced with fresh or treated water within the power plant to regulate the water balance within the system (Van Zyl & Premlall, 2005).

Side stream softening decreases suspended solids and debris in the cooling water, leading to less fouling of the system. Decreasing suspended solids also reduces biological growth from the cooling water cycle because suspended solids are a good source of nutrients for microbiological organisms (Duan *et al.*, 2012). Contaminants in the recirculating cooling water differ, depending on the water source and the treatment processes employed in the power production cycle. It is therefore important to treat, control, and maintain a specific quality by conditioning the recirculating cooling water for the required application. The importance of this is sometimes underestimated (Shreve & Brink Jr, 1977). The power generation industry is known to consume a significant amount of raw water, ranging in quality, of which the majority is used as a cooling medium. The critical chemistry analytical parameters that influence the quality of the cooling water and the subsequent performance of the condensers evaluated in this study are conductivity, total dissolved solids (TDS), turbidity, hardness, pH, alkalinity and the saturation index calcium carbonate precipitation potential (CCPP) (Bhatia, 2003). Condenser recirculating water inlet temperature as an operational performance indicator is discussed. A rise in this parameter impacts the efficiency of the cooling process(Attia, 2015). MacAdam *et al.* (2004) indicated that, as much as temperature affects scale formation, the saturation index of the recirculating cooling water, flow velocity, and pH also contribute to the scaling challenges. Additional performance indicators that contribute to the performance of the condenser influenced by recirculating water quality are the cleanliness factor and corrected pressure (Zhao *et al.*, 2013). The cleanliness factor parameter characterises the degree of fouling in the condenser tubes. Recirculating cooling water temperature and condenser pressure, according to Zhao *et al.* (2013), are directly proportional. An increase in the condenser inlet temperature will increase the condenser pressure.

3.1.1 Conductivity

Reducing the make-up water and blowdown requirements are some of the reasons for operating at elevated cycles. The trade-off is making sure that the recirculating cooling water is operated within the set limits. Regulating cycles of concentration is a standard working procedure in wet cooled power plants to minimise scaling potential. Neglecting the cooling water chemistry leads to, increased water consumption, equipment failure, loss of production, safety and environmental violations. The power plants are failing to appreciate the cooling water chemistry as a critical part of the production and operating process. In addition, due to water-related changes worldwide, the market has been compromised (Keister, 2008). Conductivity is proportional to the amount of total dissolved ionic solids in water and can be used as a quick indicator of contaminant ingress, increased salt concentration (Bhatia, 2003), or system leakage. Depending on the raw water source and the cycles of concentration for the power plant, a limit for conductivity can be established. The conductivity limit is conducive to improved cooling water chemistry control, thereby minimising corrosion and scaling due to high saline water (EPRI, 2012). Taking in to consideration that although operating at higher cycles of concentration supports the zero liquid effluent discharge (ZLED) philosophy and promote water conservation (Mkabane, 2015) can be disadvantageous when not conducted properly.

3.1.2 Total dissolved solids

Organic and inorganic substances dissolved in any water body can be characterised as Total Dissolved Solids (TDS). Sulphates, chlorides, calcium, magnesium, sodium, and bicarbonates are some of the major ions that contribute to inorganic TDS (Thirumalini & Joseph, 2009). The reaction of chemical compounds found in recirculating cooling water with TDS creates insoluble scale on heat transfer equipment. TDS measurements are conducted using two methods: gravimetric and conductivity analysis. Gravimetric analysis is conducted by evaporating the water sample and measuring the residual mass. Though time-consuming, this analysis is the most precise. The second method for TDS measurement is by correlating it with electrical conductivity (EC), the relationship given by Equation 3-1 (Carlson, 2005)Studies have been conducted to determine the ratio between EC and TDS. The findings revealed that the correlation factor between the parameters is not always linear. The relationship depends on the type of water and salinity of the individual salts found in water (Rusydi, 2018).

$$\text{TDS}\ \left(\frac{mg}{L}\right) = \text{K* EC}\ \left(\frac{uS}{cm}\right) \qquad \text{Eq. 3-1}$$

3.1.3 Turbidity

The presence of colloidal and particulate matter affecting and reducing water clarity results in turbidity. Turbidity is one of the water quality measurement that can often be used to monitor waterborne constituents such as cryptosporidium, bacteria, Giardia cysts, etc. (Crittenden *et al.*, 2012). In cooling water chemistry, turbidity is a function of the presence of silt, clay, sand pulverised fuel ash, coal dust, etc. Make-up water, internal microbiological growth, and dust scrubbed from the air used in the cooling towers are the main sources of particulate matter (Technology, 2016). These particles are responsible for fouling heat exchanger surfaces, co-precipitation with calcium carbonate and calcium sulphate, influencing and enhancing corrosion. Monitoring and treatment are therefore important for effective process management and condenser performance. Conventional water treatment processes such as sedimentation and filtration with the aid of coagulants and flocculants can increase the effectiveness of turbidity and colloidal suspensions control (Fosso-Kankeu *et al.*, 2017). Power plants should develop and operate the cooling water systems within the specified turbidity limits guided by the EPRI (Committee, 2016). Operating above the limits has proved to be detrimental to the condenser tubes, leading to thinning and eventually a reduction power production (Technology, 2016).

3.1.4 Hardness (polyvalent cation content)

Hard water is classified into carbonate hardness and non-carbonate hardness, expressed in terms of dissolved magnesium and calcium salts like calcium carbonate equivalent ($CaCO_3$). Bicarbonate and carbonates of lime influence the carbonate hardness and sulphates, and chlorides of lime will contribute to the formation of non-carbonate hardness. Non-carbonate hardness, also known as permanent hardness, in water is due to magnesium and calcium soluble salts. These soluble salts exist in recirculating cooling water in the form of sulphates and chlorides. Carbonate hardness, synonymous with temporary hardness, results from the dissolved magnesium and calcium bicarbonates (Thompson, 1928). Sodium salts, iron, manganese or silica may be present in different concentrations, adding to the water-soluble impurities.

3.1.5 pH

pH is defined as the negative logarithm of the concentration of the hydrogen ions in an aqueous solution (Equation 3-2). pH control for recirculating cooling water is critical as it indicates a corrosive or scaling environment.

$$\boldsymbol{pH = -log_{10}[H]^{+}} \qquad \text{Eq. 3-2}$$

The effectiveness of the coagulation and lime softening treatment processes for hardness and colloidal matter removal is directly influenced by pH, especially in recirculating cooling water systems (Crittenden *et al.*, 2012). Operating at low pH levels may delay the process, whereas an elevated pH range affects the density and settling rate of the colloids (Bratby, 2016). An undesirable surface charge dominates at a higher pH range, and a positive surface charge dominates at a lower pH range (Bratby, 2016).

3.1.6 Alkalinity

Alkalinity is the ability of water bodies to resist change in pH. The primary source of alkalinity is due to the presence of weak acids that consume hydrogen ions without changing the system pH (Snoeyink & Jenkins, 1980). The alkalinity analysis in water measures the level of hydroxide (OH^-), bicarbonate (HCO_3^-), and carbonate (CO_3^{2-}) ions in water as absorbing constituents (Iriarte-Velasco *et al.*, 2007).

$$\boldsymbol{Alkalinity}\ [\boldsymbol{HCO_3^-}] + 2[\boldsymbol{CO_3^{2-}}] + [\boldsymbol{OH^-}] - [\boldsymbol{H^+}] \qquad \text{Eq. 3-3}$$

Alkalinity testing is related to three important pH values as observed in the carbonate system from Figure 3-1, the P-, M-, and OH alkalinity tests. Equation 3-3 represents the total alkalinity of the system.

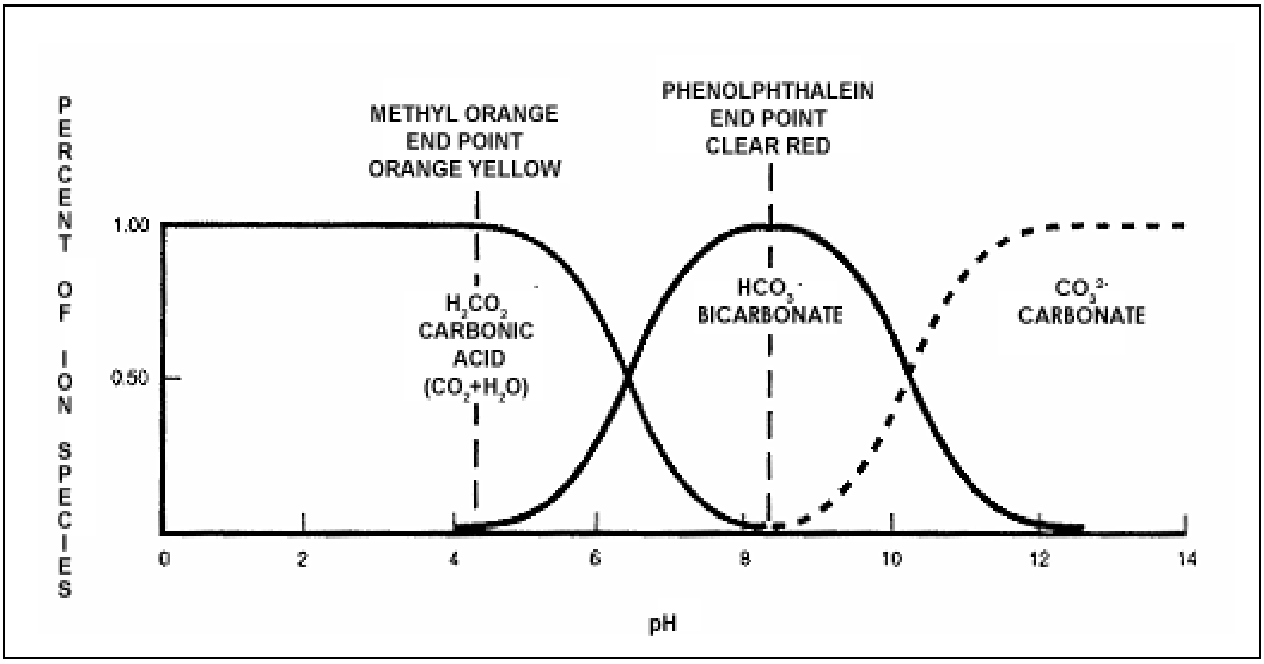

Figure 3-1: Carbonic acid, bicarbonate, and carbonate distribution as a function of pH (Edzwald, 2010).

3.1.6.1 M-Alkalinity

Any bicarbonates, carbonates and hydroxide available in the solution depending on the pH are measured. The amount of acid required to drop the pH to 4.3, as observed in Figure 3-1, quantifies the M-alkalinity present in the system. The measurement is determined by the methyl orange endpoint during titration. The desired operational M-alkalinity for the power plant with wet cooling must be controlled between 80 and 120 mg/kg, according to the customised standard adopted from the EPRI guidelines (Technology, 2016). When lime is dosed into recirculating cooling water containing calcium and magnesium bicarbonate salts, a reaction takes place to form a calcium carbonate ($CaCO_3$) precipitate and water. The potential for hardness deposition is affected by alkalinity (Boyd *et al.*, 2016).

3.1.6.2 P-Alkalinity

P-Alkalinity is the volume of acid required to decrease the pH to approximately 8.3. This is also called carbonate alkalinity, determined by a phenolphthalein indicator when a sample of water is being titrated. The concentration of any carbonates and hydroxide in the system is measured at this stage; the conversion is from carbonates to bicarbonates (Snoeyink & Jenkins, 1980).

3.1.6.3 OH-Alkalinity

At pH above 8.3, where carbonates would have been precipitated out of solution (Figure 1-1), OH alkalinity measurements can be undertaken. Taking in to cognisance, for a solution with a pH value above 10, the system will be prone to scaling due to the presence of hydroxides. Hydroxides react with the carbon dioxide in the atmosphere and form bicarbonates, eventually precipitating as calcium carbonate (Boyd *et al.*, 2016). Table 3-1 is used as a guide during the optimisation and treatment of the recirculating cooling water system. The optimum pH required for the hardness to be precipitated out of solution is when 2P=M, and this occurs when the pH during the clarification process is at 10.2. When the pH is below or above 10.2, the risk for scaling of the cooling water system due to bicarbonates and hydroxide ions increases. Table 3-2 is an example of how the calculation is done, taking into account the pH, P-alkalinity and M-alkalinity in the system.

Table 3-1: Control conditions achievable in a cooling water lime system treatment (McDonald, 2006)

Titre	pH	Bicarbonate as mg\kgCaCO3	Carbonates as mg\kg $CaCO_3$	Hydroxide as mg\kg $CaCO_3$	Comments
2P<M	8.3<pH<10.2	M-2P	2P	0	Under treatment of lime scaling due to bicarbonates
2P=M	pH=10.2	0	2P	0	Optimum condition, all bicarbonates converted to carbonates
2P>M	pH>10.2	0	2(M-P)	2P-M	Over treatment of lime, hydroxide presence

Table 3-2: Example of the relationship between P, M, and OH alkalinity

pH	**P-Alk**	**M-Alk**	**2P**	**2P-M**	**HCO_3^-**	**CO_3^{2-}**	**OH**
9.7	25	70	50	-20	20	50	0
10.2	30	60	60	0	0	60	0
10.5	35	50	70	20	0	30	20

3.1.7 Saturation index calcium carbonate precipitation

The calcium carbonate precipitation potential can be defined as the quantity of calcium carbonate ($CaCO_3$) expected to precipitate from over-saturated water or dissolved by water at a specific temperature (Kim *et al.*, 2009). In water bodies, the formation of scale and corrosion can be predicted using various indices, such as the calcium carbonate precipitation potential (CCPP) (Temkar *et al.*, 1990). or the Langelier Saturation Index (LSI), to name a few (Saifelnasr *et al.*, 2013). CCPP measurement is used by the wet cooled power plants for cooling water chemistry control and management. This measurement allows the power plant operating staff to respond to changes in the plant and protect the recirculating cooling system from dissolved or precipitated calcium carbonate (MacAdam *et al.*, 2004). Dissolved calcium carbonate releases carbon dioxide, which decreases the pH of the system and promotes corrosion.

Table 3-3 gives the specifications (Technology, 2016) of the critical cooling water parameters influencing recirculating water chemistry control as guided by EPRI (EPRI, 2012).

Table 3-3: Specification of circulating water in wet cooled power plants (Technology, 2016)

Parameter	**Limit or range**
Conductivity	Conforms to the cycles of concentration being used but generally < 4000 (µS/cm)
Turbidity	As low as cost-effectively possible but < 100 NTU for continuous operation
pH	Range: 8, 1 to 8, 6 @ 25 °C. Optimum pH is 8.3
Total Hardness	Total calcium and magnesium
Calcium	200 to 500 mg.kg-1 as $CaCO_3$
Magnesium	Mg (as $CaCO_3$) · SiO2 < 25 000
“M” Alkalinity	80 to 120 mg.kg^{-1} as $CaCO_3$
Total Dissolved Solids (TDS)	Not specified
Calcium Carbonate Precipitation Potential (CCPP)	Calculated with Stasoft Software at 38^{o}C > 10 but < 30 mg.kg^{-1} as $CaCO_3$

3.1.8 Temperature

During the power plant design phase, the cooling medium, together with ambient conditions, is taken into consideration as these factors contribute greatly to the performance of the plant. Cooling water temperature affects many parameters, including solubility, viscosity, density, the rate of chemical and biological activity, vapour pressure, etc. (Crittenden *et al.*, 2012). Water is normally the coolant of choice for wet cooled power plants (Attia, 2015; Van Rooyen, 2014). Bhatia (2003) indicated that, although most salts should become soluble at elevated temperatures, calcium carbonate tends to precipitate out of solution, exposing the cooling system to scaling and deposition.

3.2 Methodology

Statistical evaluation of the chemistry data from three South African power plants in Mpumalanga and one in the Free State was conducted. Data used during the analysis range from the year 2014 to 2019. The period chosen for the study was influenced by data availability from the selected power plants, 2020 was not considered due to the Covid 19 pandemic, access to site could not be permitted due to the regulations. Plant A, B, and C are the power plants from the Mpumalanga region and Plant D is in the Free State. The make-up water used in these power plants was from different water sources with different qualities, which will contribute to and affect the treatment control. The Mpumalanga plants receive their raw water make-up from the Komati, Usutu and Vaal water schemes, which comes at a fairly good quality compared to the Free State plant. The average water intake ranges between 3 and 4Ml in a month, with Plant B being the lowest, at an average of 1.5 Ml. There is a variation in the make-up water figures, depending on the different water management strategies implemented by the power plants. These power plants have a lime softening side stream treatment for the control and management of the recirculating cooling water. The chemistry requirements are standard, indicating that they are reachable and achievable (Table 3-3). The chemistry of the recirculating cooling water forms part of the performance evaluation on these power plants; operating beyond the specifications will be used to assess the overall performance of the plant. Due to the temperature effect on some of the chemistry parameters, seasonal changes were observed. The cooling water chemistry from the power plants of interest was captured on a Laboratory Information Management System (LIMS). The data were extracted, modelled/plotted, analysed and interpreted to understand and evaluate the cooling water chemistry performance.

The analytical chemistry analysis was conducted using the instrumentation indicated in Table 3-4, every technique used, including R, power BI model and CCPP is explained.

Table 3-4: Laboratory instrumental technique and chemical analysis (Technology, 2016).

Instrumental technique	**Parameter(s)**
Turbidity Meter HACH 2100N/P	Turbidity in NTU
Auto titrator model make	pH, conductivity, “M” Alkalinity, “P” Alkalinity, Chloride, Ca Hardness, Total Hardness
ICP OES model make	Ca as $CaCO_3$, Mg as $CaCO_3$. Na, K, Fe, Cu, PO_4, Zn, SiO_2, SO_4^{2-}

3.2.1 Turbidity measurement

Turbidity is the cloudiness or haziness of a fluid. It measures the extent to which the intensity of light passing through water is reduced by suspended matter, comparing the amount of light passing through a given water sample with that passing through a standard sample (Pavelich, 2002). A unit for turbidity measurements is called the Nephelometric Turbidity Unit (NTU), and the limit for a wet cooled power plant is less than 100 NTU.

3.2.2 Auto titrator measurement

An auto titrator is used for the analysis of various chemistry parameters (Table 3-4); conductivity and alkalinity will be the only parameters discussed.

3.2.3 Conductivity determination

The conductivity of a sample is dependent on the number of ions in a solution. Each ion is independent and contributes to the total conductivity. Conductivity is the total of the positive ions plus the total of negative ions. According to EPRI and the guidelines developed for the power plant, the safe operating limits for recirculating the cooling water cycle should be between 8.1 and 8.6 for pH, and below 4000µS/cm for conductivity (Table 1-3 and Table 3-3).

3.2.4 M-alkalinity and P-alkalinity determination

The alkalinity is measured by titrating a water sample with standard acid to a designated pH and recorded as P-, M-, or T-alkalinity. P-alkalinity is titrated with phenolphthalein to pH 8.3, M-alkalinity with a methyl orange indicator to pH 4.6, and T-alkalinity with a total alkalinity indicator to pH 4.5 (McDonald, 2006).

3.2.5 Inductively coupled plasma atomic emission spectroscopy (ICP-OES)

Elemental analysis by ICP-OES is a trace level; the multi-elemental analysis uses the emission spectroscopy technique, where an inert gas plasma is used to evaporate, ionise and atomise the sample, resulting in the radiation of a characteristic wavelength of the desired element. The wavelength is used to identify elements and the amount of radiation that is used to measure the concentration of the elements in the sample (Olesik, 1991). The procedure is applicable for the analysis of metals like Na, Al, Zn, Cu, Fe, K, Mg, Ca, PO_4, and Si in water samples to monitor and control corrosion products. Mg and Ca are analysed to monitor hardness and scale formation monitoring. Na, Al, Zn, Cu, Fe, K, Mg, Ca, and PO_4 in streams are analysed for environmental purposes. Metals on sewage water systems are measured using the ICP-OES for compliance with health and environmental monitoring.

3.2.6 R studio

To analyse and compute the collected data, R studio software was used, interfaced with power BI. R is an open-source programming language and a software environment for statistical computing and graphics. Scatter plots from R were used to demonstrate data so that the highest density region of the data and the outliers can be observed (Van der Loo, 2012). The limits, according to the chemistry standards, were used to define the upper and lower ranges in plotting the scatter plots, the mean, and the interquartile ranges were defined during the computing of data according to R. Histograms and density plots were used to observe the nature and behaviour, giving insight on skewness and distribution of the data. Figure. 3-2 as an example, shows the distribution of data on the histogram for plant B calcium carbonate precipitation potential using R, with the frequency ranging between 40 and 70% for the out of specification values during the summer season.

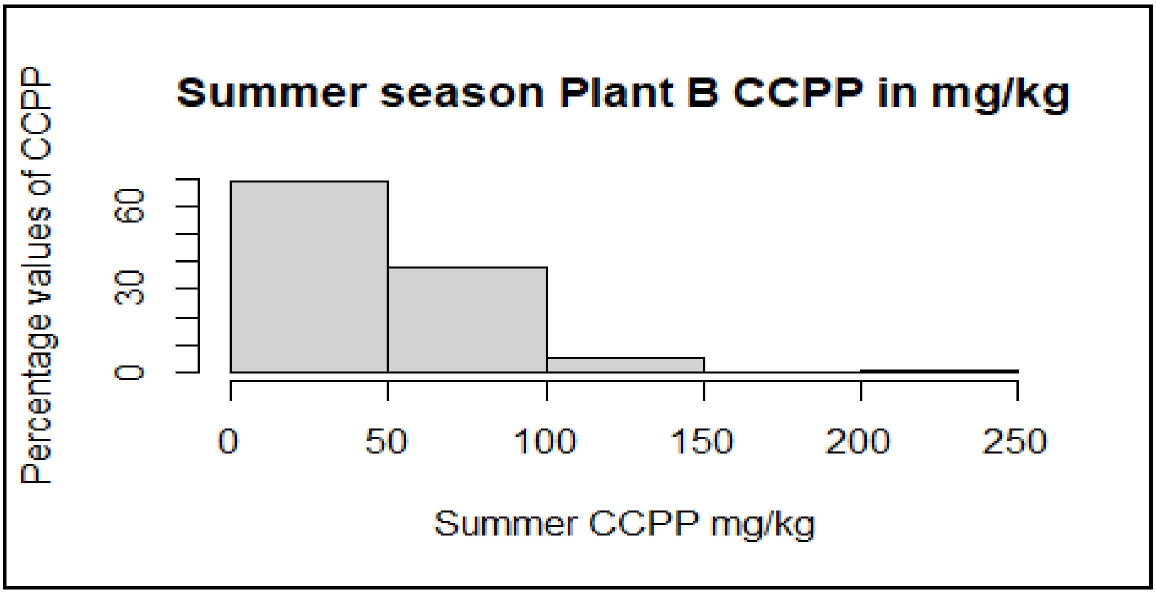

Figure 3-2: Plant B calcium carbonate precipitation potential histogram for summer season using R.

Figure 3-3, modelled example, represents the same data observed in Figure 3-2 showing the actual trend and limits for the summer season using the power BI model; average yearly figures are presented on the trend.

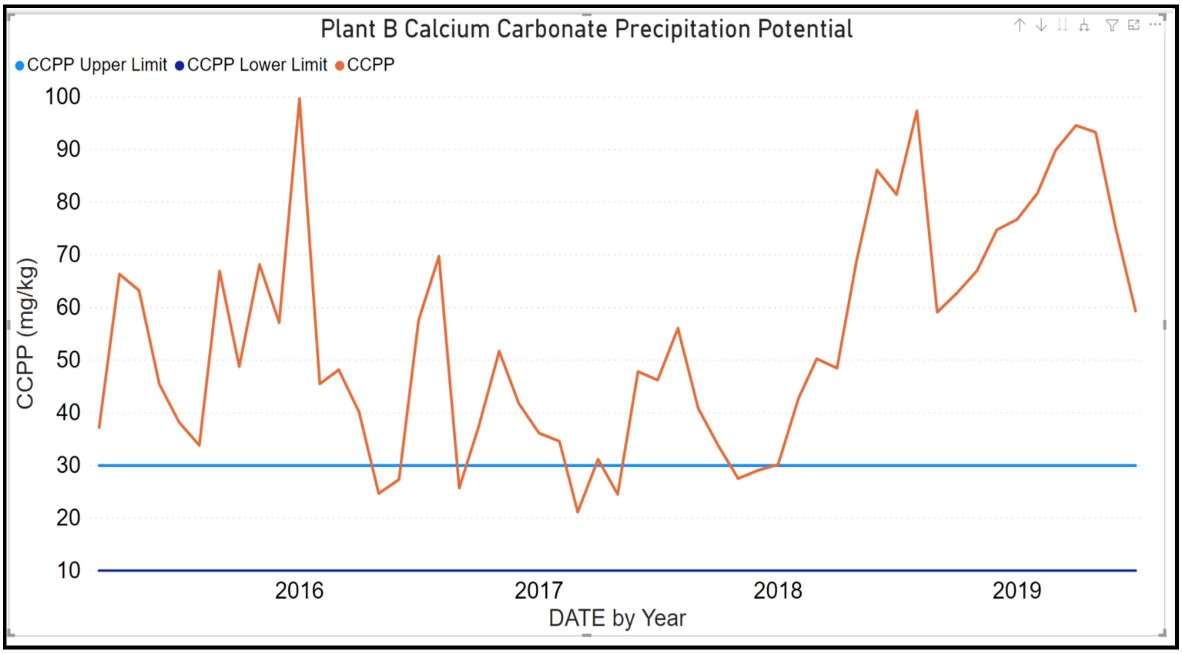

Figure 3-3: Plant B summer season for the years 2015 to 2019; calcium carbonate precipitation potential using Power BI. The bottom orange line represents the CCPP lower limit, and the blue top line is the CCPP upper limit for the plant of interest.

3.2.7 Calcium carbonate precipitation potential calculation

The CCPP for cooling water was modelled on the Stasoft software (Loewenthal *et al.*, 1988); analytical chemistry parameters incorporated in the calculation were calcium hardness, pH, and alkalinity analysis obtained using the auto titrator, chlorides and sulphates analysis from the IC (Ion Chromatography) instrument, and sodium analysis using the ICP (Inductively Coupled Plasma) spectroscopy. Figure 3-4, demonstrated example confirms the observations in Figure 3-2 and Figure 3-3, summer data for Plant B using R scatter plots software. Out of 113 observations, the chemistry data were within specification 70 to 80% of the time during the summer season.

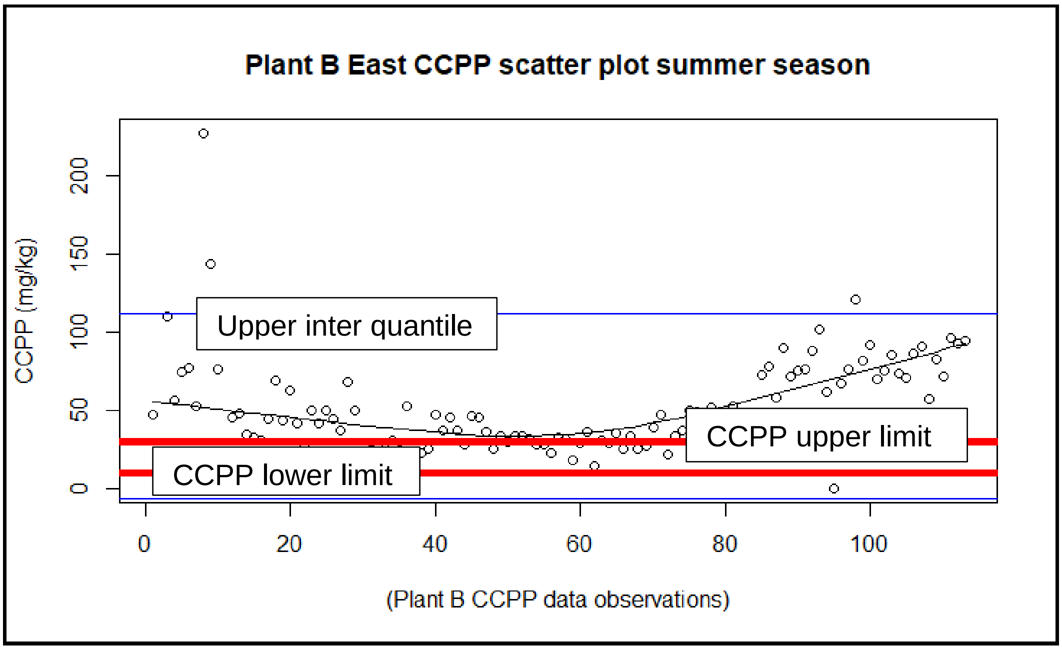

Figure 3-4: Plant B scatter plot using R studio for calcium carbonate precipitation potential in the summer season.

The model recorded observations by displaying the data points on R, taking into consideration the limits for calcium carbonate precipitation potential, the mean and the lower and upper quantile from the mean. The code used for determining the scatter plot, using R studio for CCPP analysis, is given below. Red lines represent the lower and upper limit where CCPP should have been controlled, and the blue lines will be the lower and upper quantile range calculated from the mean. An example of the code is given below:

```
Summer_Scatter_Original <- scatter.smooth(Summer$VALUE,  main = "Data with Outliers",
xlab = "(CCPP)", ylab= "Data (units)")
abline(h=10 , col = 'red', lwd = 5)
abline(h=30 , col = 'red', lwd = 5)
abline(h= SummerLowerOutlierLimit, col = 'blue')
abline(h= SummerUpperOutlierLimit, col = 'blue')
```

3.3 Results and discussion

The results delineated below indicate that the analytical chemistry across the targeted plants experienced a significant change over the years, with the average performance deteriorating by more than 50% between the years 2014 and 2019. The chemistry of the recirculating cooling water was out of specification, the data quality is poor, and the controls to address the out of specification chemistry are not effective. This common behaviour and practice across the power plants is a concerning matter. A calculation for the amount of out of specification data on selected parameters (M-alk, CCPP, sulphates, and pH) over the years was conducted using scatter plots on the R studio model (Figure 3-4). Limits for the safe operating margins of the cooling water were used as a guide to detect and identify the out of range values for each parameter (Table 3-3).

3.3.1 Plant A outliers

The chemistry data were modelled on R studio to identify the out of range parameters, as guided by Table 3-3. The scatter plot coding was used to be able to separate clean data from raw data. In addition, the scatter plot assessment does indicate the total number of observations, representing how many are within and outside the range. The calcium carbonate precipitation potential (CCPP) in the recirculating cooling water on the north side of Plant A was about 80% out of specification for the years evaluated. The CCPP variable depends on other parameters to be modelled, which, according to Figure 3-5, are between 40 to 80% out of range. The total hardness limit is not indicated, although literature states that the permanent hardness can be calculated using the difference between the total hardness and M-alk. The permanent hardness, if found during the analysis, will indicate that the recirculating cooling water system will be exposed to a very difficult and challenging scale to remove and manage. The M-alk observations are shown to be constantly above the limit, with an average of 78%. This is a great concern because lime softening treatment is designed to control and remove alkalinity during the operating process of the plant, according to the guideline given in Table 3-1. The south side recirculating cooling water chemistry, though not operated within the set limits, is at lower percentage levels. The overall calcium carbonate precipitation potential at the south side of the cooling water system averages between 40 and 60%, as indicated in Figure 3-6 and Table 3-5. During the summer seasons, the pH for the north and the south side cooling water systems is mostly out of specification at a very high percentage level compared to other parameters. The data analyses reveal the pH measurement approaching almost 100% out of range during summer conditions.

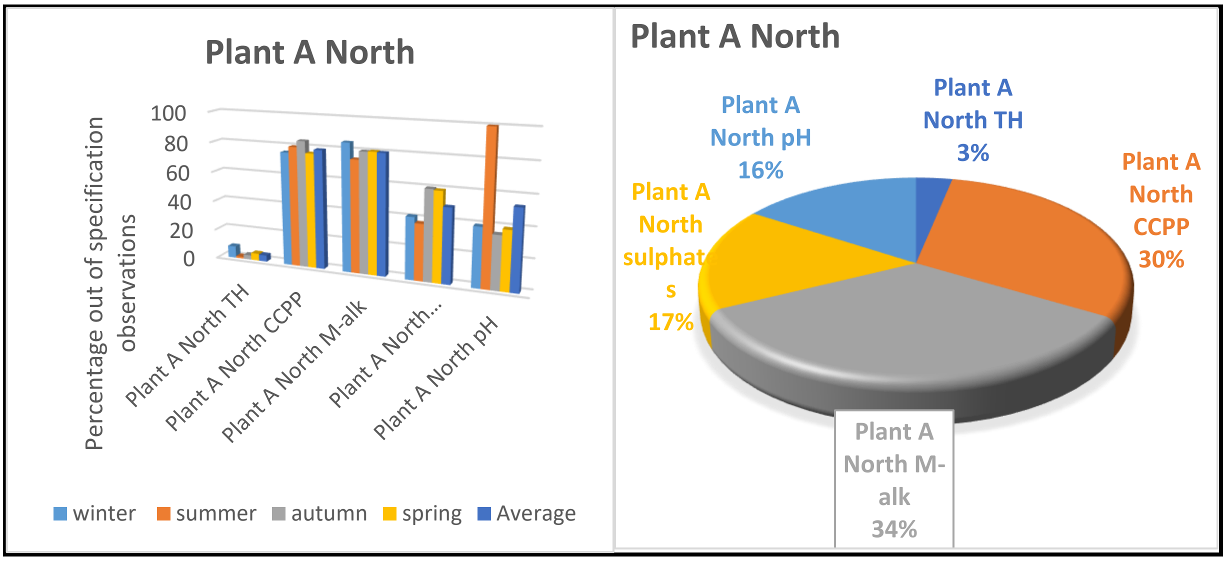

Figure 3-5 (a): The overall performance averaged for a year taking into consideration seasonal contributions and changes and Figure 3-5(b): Plant A north side chemistry calculated percentage using R modelling. Out of specification parameters observation for total hardness, CCPP, M-Alk, sulphates, and pH.

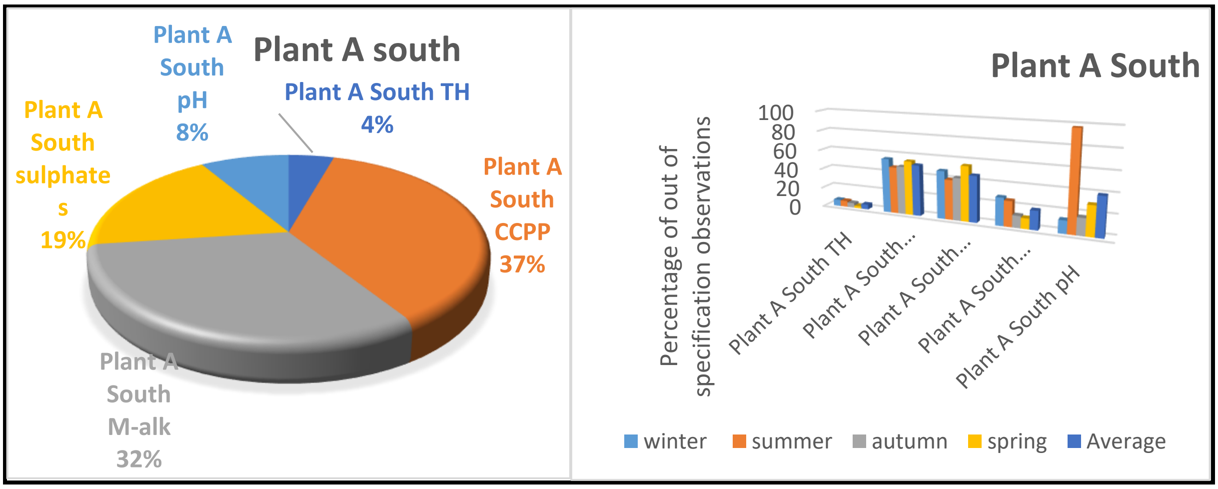

Figure 3-6 (a): Plant A south side performance over the year's modelled percentage out of specification observation. Total hardness, CCPP, M-alk, sulphates, and pH observations. Figure 3-6 (b): The overall performance averaged for a year taking into consideration the seasonal contributions and variations.

The cooling water chemistry performance graphical display shown in Figure 3-6 (a) is presented on Table 3-5. The calculations were conducted after filtering the clean data from raw data. The calcium carbonate precipitation potential has an average of more than 50% above specification, with the highest contributor to the CCPP calculation being M-alk.

Table 3-5: Plant A seasonal observations calculated for the south side cooling water chemistry performance. Data displayed on a tabular format with the actual percentage levels and averaged for the year.

Seasons	**Winter**	**Summer**	**Autumn**	**Spring**	**Average**
Plant A South Total Hardness (TH) (mg/kg)	6.61157	6.17284	4.701835	2.290076	4.94408
Plant A South Calcium Carbonate Precipitation Potential (CCPP)	55.26316	47.36842	48.7013	54.78261	51.52887
Plant A South M-alk (mg/kg)	48.20937	40.12346	42.66055	55.26718	46.56514
Plant A South Sulphates (mg/kg)	28.02548	25.5814	12.06897	10.52632	19.05054
Plant A South pH	12.91209	97.69231	17.27689	30.07634	39.4894

3.3.2 Plant B observations

Observations for the winter and summer seasons for the years 2015 to 2019 indicate that the specifications given by Table 3-3 have not been met. The performance of the plant, considering the two seasons, accounts for 50% of the year’s chemistry deterioration. The calcium carbonate precipitation potential mean values range between 40 and 60 mg\kg, which is above the set limit of 10 and 30 mg\kg. The summer and winter season variations displayed in Figure 3-7 and Figure 3-8 for M-alkalinity measurement as one of the critical parameters are constantly out of range. The M-alkalinity values captured fall within the upper inter quantile range, with a mean of 220 mg\kg and 180 mg\kg for winter and summer respectively. This is above the upper limit of 120 mg\kg by more than 34% for summer and 83.33% for winter. The outliers above the upper quantile limit affect the distribution and mean of the data; 13% of the data falls outside the upper quantile, as indicated in Figure 3-7, the highest being above 2500 mg\kg, which is questionable. The red lines (Figure 3-7 and Figure 3-8) denote where the plant should be operated, and the blue lines will be the lower and upper quantile calculated, based on the mean value. This indicates that the data are not verified upon approval.

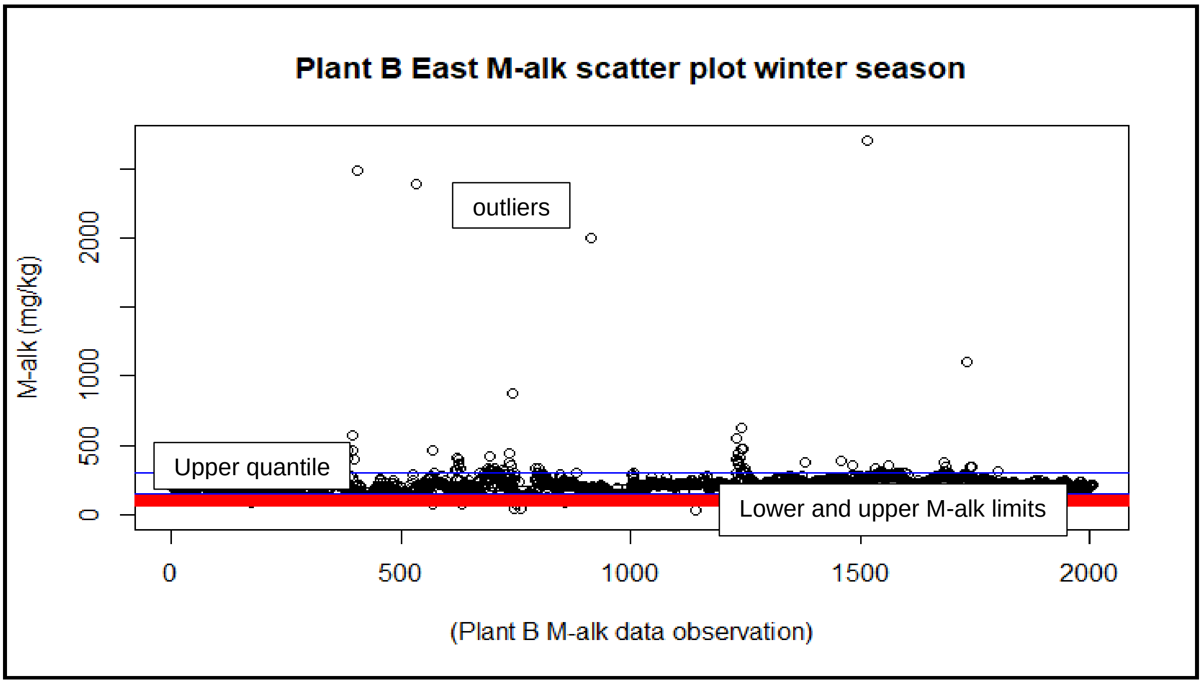

Figure 3-7: Plant B winter season M-alkalinity performance modelled on R using scatter plot observations.

The red lines indicate where the M-alkalinity of the system should be operated, and the blue lines measure the lower and upper quantile from the calculated mean. Observations above the upper quantile are considered outliers.

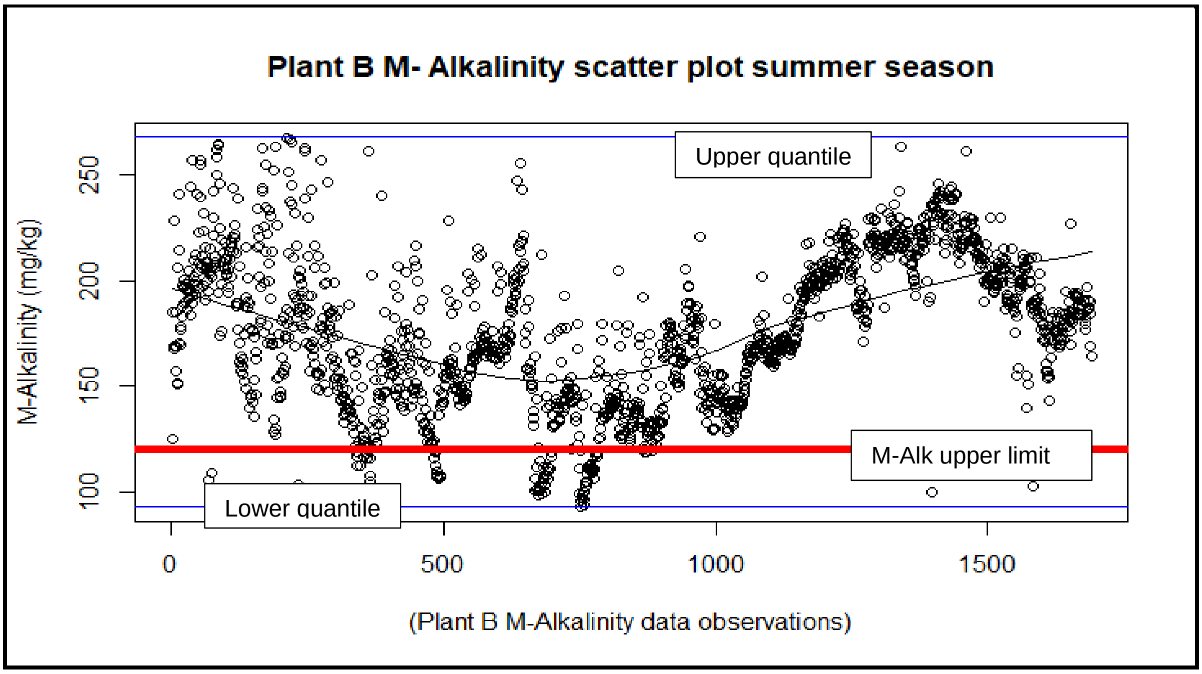

Figure 3-8: Plant B summer season M-alkalinity modelled on R, using scatter plot observations.

The red lines indicate where the M-alkalinity of the system should be operated, and the blue lines measure the lower and upper quantile from the calculated mean. Observations above the upper quantile are considered outliers.

3.3.3 Plant C observations

The interpretations of the performance of Plant C follow a similar pattern, as reflected by Plant A. The M-alkalinity and pH across the seasons show above 65% out of specification captured measurement, subsequently contributing to the calcium carbonate precipitation potential measurement. M-alkalinity, as observed in Table 3-6, has been consistently out of range throughout the years for all seasons. The plant was operated with the M-alkalinity at an average of 94%. Figure 3-9, in summary, implies that, from the parameters used to calculate the calcium carbonate precipitation potential, out of 100% of the pie chart, the biggest contributor was M-alkalinity measurement. The continuous struggle with M-alkalinity has affected the buffering capacity of the recirculating cooling water, consequently making the water fairly unstable and detrimental to the cooling systems.

Table 3-6: Calculated and averaged seasonal performance of critical parameters for Plant C south side cooling water chemistry.

Seasons	**Winter**	**Summer**	**Autumn**	**Spring**	**Average**
Plant C South Total Hardness (TH) (mg/kg)	7.602339	7.608696	6.962025	5.298013	6.867768
Plant C South Calcium Carbonate Precipitation potential (CCPP)	90.05848	84.86486	93.67089	88.23529	89.20738
Plant C South M-alk (mg/kg)	96.30735	92.41983	94.21769	94.02985	94.24368
Plant C South sulphates (mg/kg)	29.24282	41.30435	33.42037	21.63588	31.40085
Plant C South pH	77.40134	94.0858	65.332	70.756	76.89378

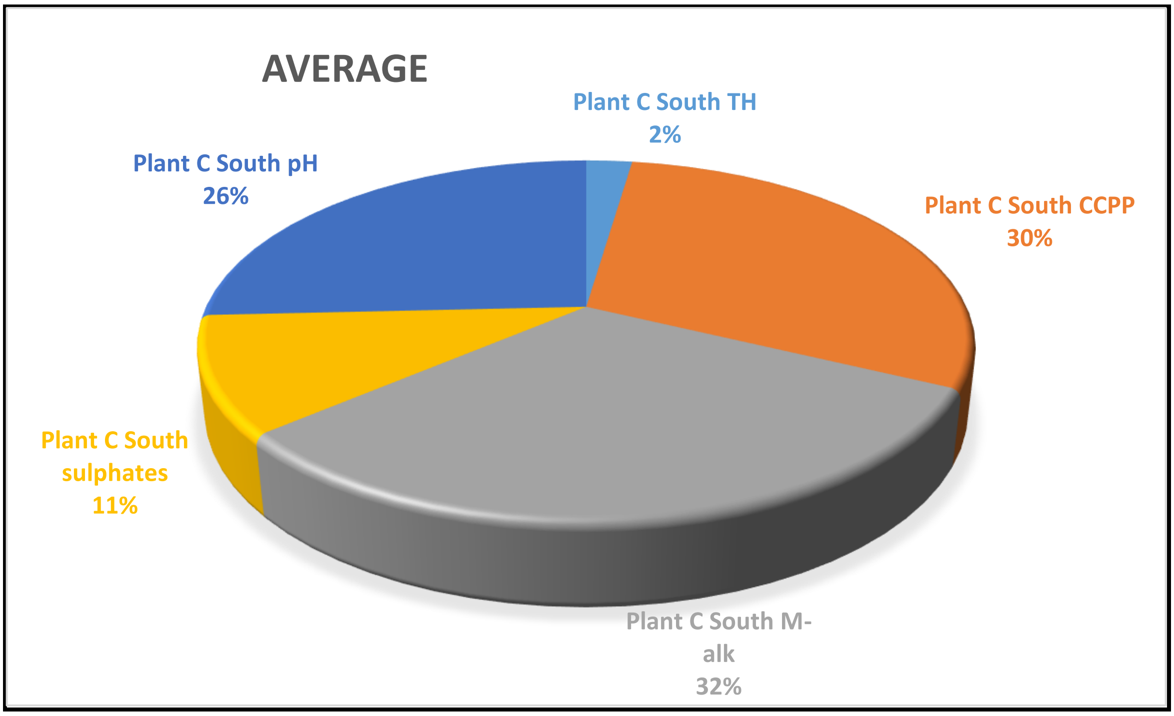

Figure 3-9: Plant C south side cooling system performance, comparing the critical parameters used for the for the calcium carbonate precipitation potential calculation. The largest portion of the pie taken by M-alkalinity observations as the highest out of specification measurement.

3.3.4 Plant D observations

Plant D M-alkalinity and CCPP data during the winter season were plotted on the density curve to observe how the data distribution over the years varies. Figure 3-10 demonstrates that more than 50% of the time, for the years considered, the M-alkalinity control ranged from 100 to about 170 mg\kg, with the specification lower limit being 80 and the upper limit 120 mg\kg (Table 3-3) for wet cooled power plants. The calcium carbonate precipitation potential distribution curve observed in Figure 3-11 confirms the similar pattern, where most of the data are concentrated between 10 and 50 mg/kg, with a calculated mean of 30 for CCPP mg/kg. Although there are outliers and out of normalities on the plant, the chemistry control is approaching the requirements given in the cooling water guideline. The density plot visualisation for both the M-alkalinity and CCPP data are distributed and accumulated towards the left. The observations indicate that the cooling water chemistry for Plant D can be controlled close to the target. The power plant has the potential of operating within the limits, considering the probabilities given by Figure 3-10 and 3-11.

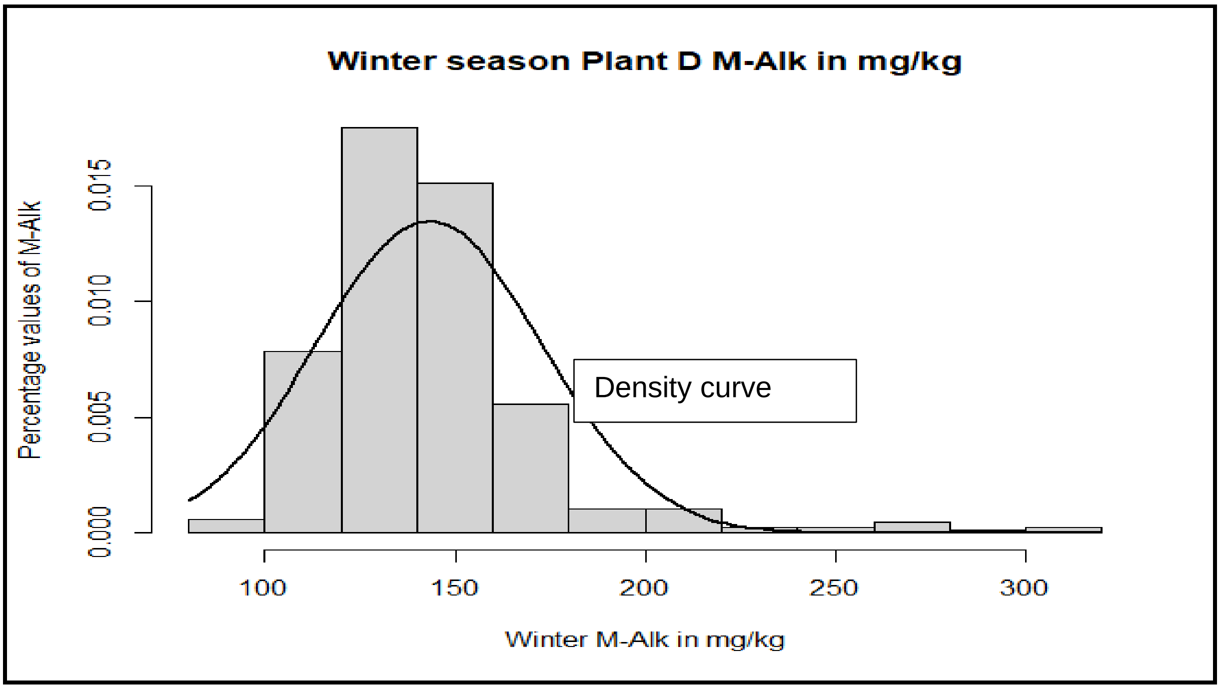

Figure 3-10: Plant D winter season east M-alk plant distribution density curve. The vertical axis on the graph reflects the M-alk measurements captured over the years.

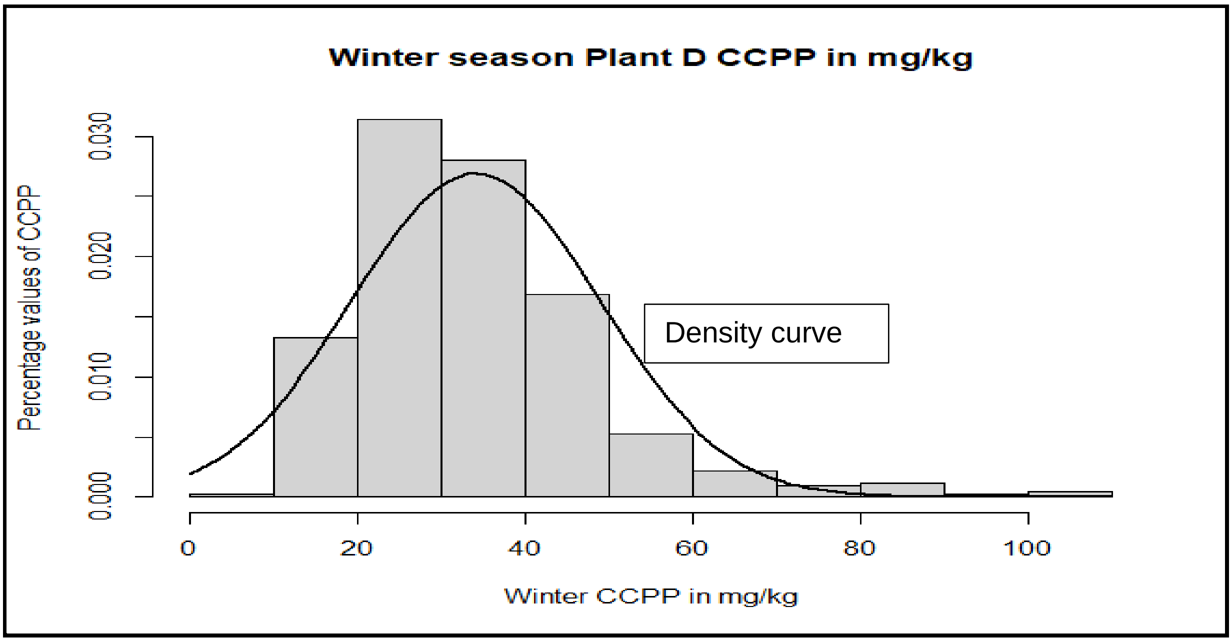

Figure 3-11: CCPP Plant D East: Plant D winter season calcium precipitation potential for the cooling water on the plant east side distribution density curve. The vertical axis on the graph reflects the calcium precipitation measurements captured over the years.

3.3.4.1 Plant D sulphates analysis evaluation

Sulphates measurement is one of the parameters used in the index calculation for calcium carbonate precipitation potential predictions. The analyses and evaluation for the levels of sulphates over the years indicate that sulphate control and management on the plant was on the borderline. Figure 3-12 shows an average performance of 50% out of specification on sulphate over the years, with the summer season exceeding the 60% above specification performance margin. Summer is the season; where the chemistry was mostly out of specification.

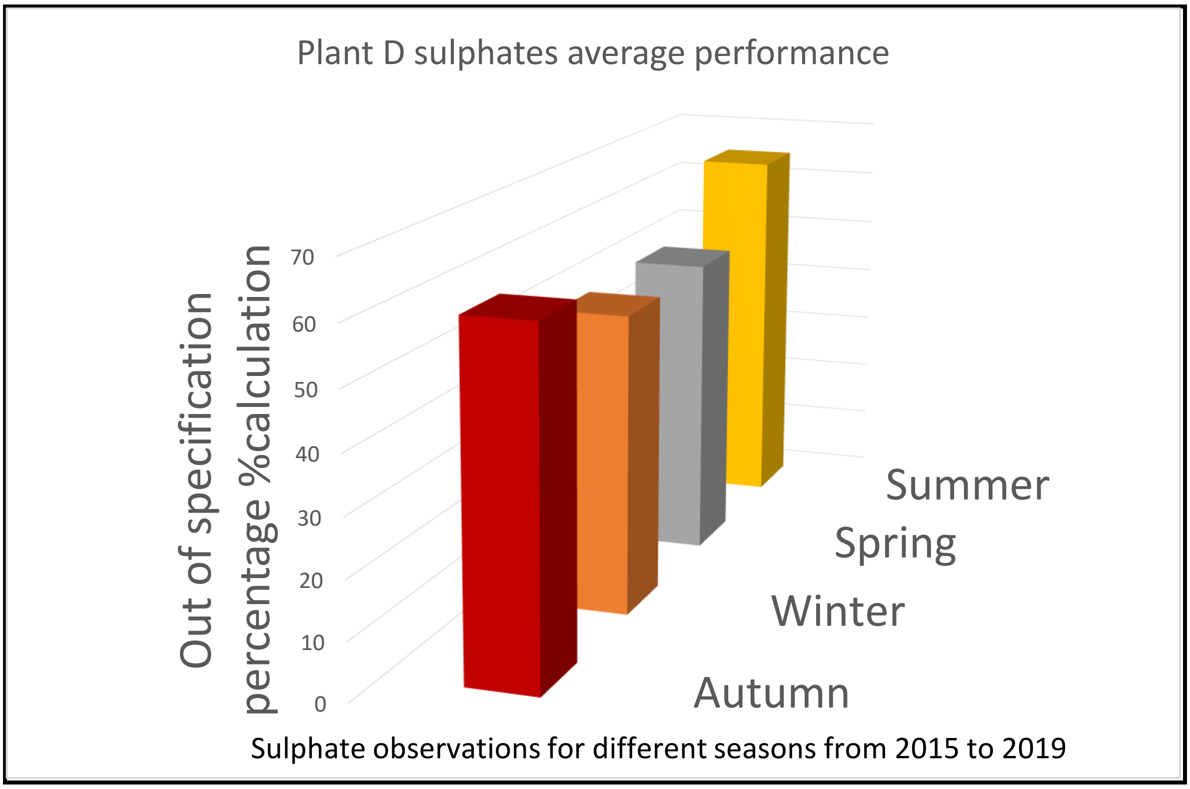

Figure 3-12: Plant D average percentage performance for sulphates for different seasons for the years 2015 to 2019. The calculated percentage records the out of specification measurements.

The historical data trended in Figure 3-13 show that the sulphates were out of specification until the year 2017, but great improvements were detected as of mid-2017 to 2019. The trend still confirms what was witnessed in Figure 3-12; for the time range selected, Plant D managed to bring the chemistry control within specification.

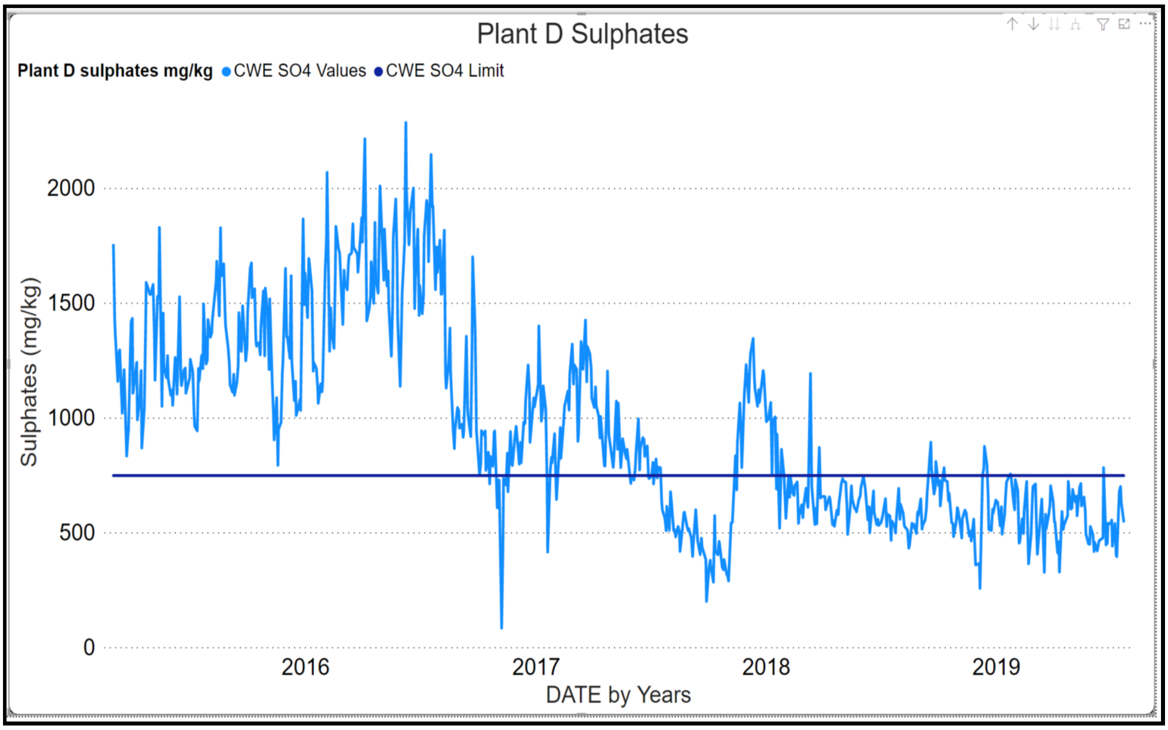

Figure 3-13: Sulphates measurement trend for Plant D, cooling water east side of the power plant for the years 2015 to 2019 with the limit of 750 mg\kg.

The first objective of lime softening treatment in recirculating cooling water is to control alkalinity, as guided in Table 3-1, and to remove the turbidity and suspended matter using the sedimentation process. Turbidity target for recirculating cooling water referring to the cooling water standard should be kept below 100NTU (Table 3-3). To gain perspective on the sedimentation process, turbidity measurements observed from the box plot in Figure 3-14 record a mean of below 100NTU over the seasons. This clearly shows that the sedimentation process for plant D is functional and, with optimisation and a minor adjustment to accommodate the plant changes that occurred over the years, performance will greatly improve. Plant D performance is consistent, although at times above the recommended limits; the process indicates steady-state behaviours with little variation through the seasons.

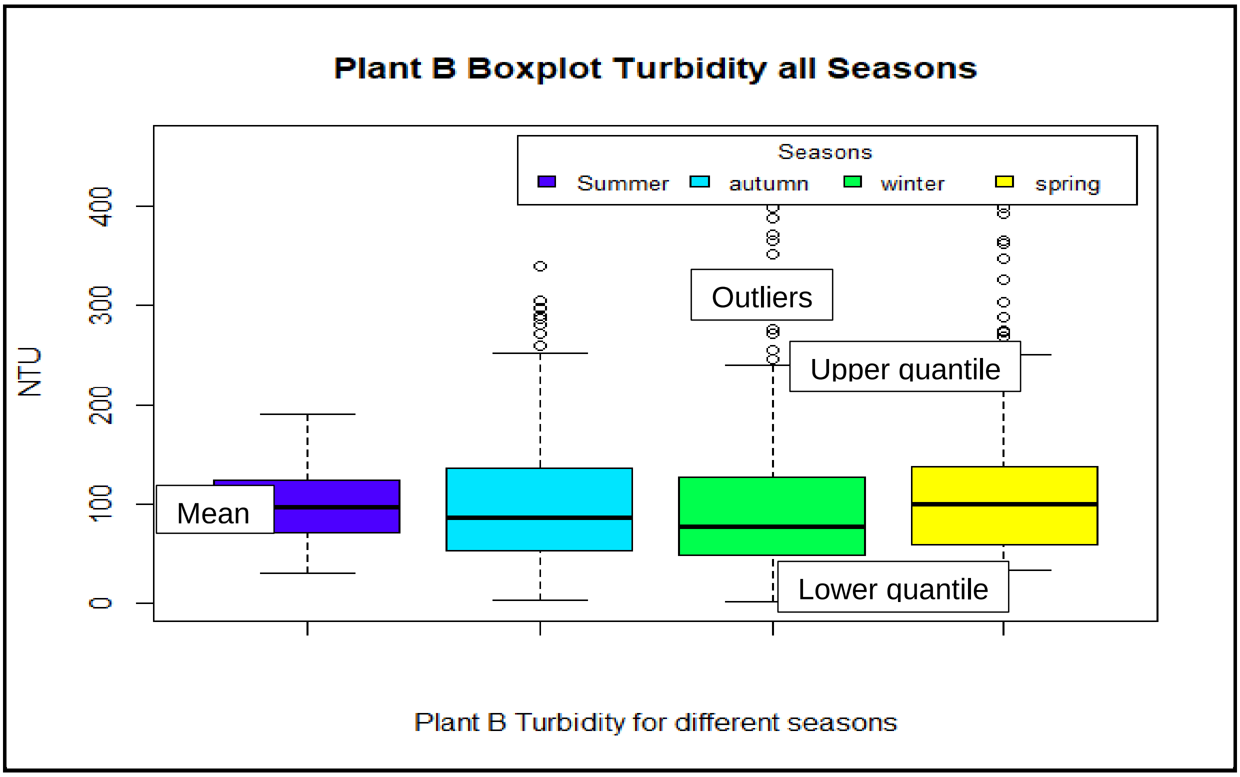

Figure 3-14: Plant D turbidity performance for all season's boxplot analysis using R studio.

3.4 Conclusion

The investigation conducted on the inconsistencies observed on the recirculating cooling water chemistry with lime treatment shows a very concerning pattern. The chemistry performance has been compromised, with more than 50% of the data showing values above specifications. Operating the plant with inconsistencies of such magnitude for more than five years is a great concern. CCPP is one of the quickest indices used to predict and guide operations, taking into consideration any potential harm to the plant and cooling system. Two models were used for data evaluation and analyses, R studio and power BI; the statistics and observations are in agreement. The scatter plots developed using R studio separated clean data from raw data and also gave a count of a total number of outliers from the observations. The mean values calculated for Plant A, B and C are situated above the upper limit range. This specifies that the investigated power plants were operated outside the cooling water chemistry standard.

The change in season implication is minimal and can be disregarded. Summer seasons do indicate a small percentage increase of the inconsistencies. The pH is one of the parameters that was concerning for summer season, followed by M-alkalinity. It is expected for pH to change when the temperature of the solution changes. In the case study, due to the inconsistencies, this could be related to the number of outliers recorded as the other seasons are between 40 and 60% out of range. Plant D seemed to be addressing and attending the inconsistencies for the out of specification data by far, with an average of 50% abnormalities compared to the other three plants. The probability density function indicates that the plant is likely to improve performance.

Comparing the analytical chemistry performance across the power plants. Plant C with an average CCPP of 90% struggled to control and maintain the recirculating cooling water quality. Plant D observations appeared to have great improvements with a potential to be within the specifications. Plant A and B average CCPP data ranged at 80% and 60% respectively. The cooling water chemistry standard has been developed to guide the power industry on chemistry conditions that are effective and reliable. Continuously operating the plant beyond these standards is detrimental to the cooling systems.

CHAPTER 4: THE IMPACT OF POOR COOLING WATER CHEMISTRY ON POWER PLANT PERFORMANCE

4.1 Introduction

To monitor the performance of the condenser, being the main heat transfer equipment after the boiler (Zhao *et al.*, 2013), various parameters are considered. These include, but are not limited to, condenser cleanliness, inlet or outlet recirculating cooling water temperatures, recirculating cooling water flow, condenser back pressure, condenser dissolved oxygen, condenser heat flux through the tubes, etc. (Otake *et al.*, 1983). Many performance models are used to define the condenser performance, including the Heat Exchange Institute (HEI) rating method and overall heat transfer rate calculations (Nebot *et al.*, 2007). Irregularities like blocked tubes, extreme air ingress, and fouling will indicate abnormalities, meaning there are deviations from nominal conditions; that is, operating and maintenance, including design conditions. Any observed changes by the power plant personnel could result in a proactive response and taking corrective actions. These actions could be either by optimising the recirculating cooling water chemistry, including chemical dosing regimens and the condenser tube cleaning operation, both online and offline (Alabrudzinski *et al.*, 2016). The cleanliness of the condenser tubes, terminal temperature difference (TTD) and the temperature rise (TR) calculations on the condenser significantly contribute to the overall performance. Any deviation will result in vacuum changes, leading to financial implications for the plant (Van Rooyen, 2014). To compensate for the plant losses experienced in the condenser, excessive fuel (pulverised coal) must be burnt. Increasing the heat load will require additional fuel to the boiler, an increase in demineralised water to produce steam, etc., which comes at an additional cost long term pant health reduction.

Similarly, the cooling tower operation affects the performance of the condenser and overall plant efficiency (Kumar *et al.*, 2015).The recirculating cooling water leaving the condenser expels the latent heat removed from the exhaust steam to the atmosphere through the evaporative cooling tower (Rahul Patel Sukhdev Gangwar, 2015). Using moving air is regarded as the most affordable and reliable means of extracting heat from recirculating cooling water (Kasten & Muller, 2007). A significant amount of recirculating water is lost during the evaporation process. As the recirculating water evaporates, salts concentrate, and the evaporative cooling tower is exposed to highly concentrated conditions, which, if not controlled, will lead to fouling, corrosion and scaling. In addition, contaminated make-up water from natural sources or effluent from the power plant is used to replace the water lost through evaporation. Figure 4-1 represents a schematic flow diagram between the condenser and the cooling tower in a wet cooled power plant. The critical parameters normally utilised to determine the performance of the cooling tower are (i) range, which is the difference between the inlet and outlet temperature of the recirculating water into the cooling towers, (ii) the approach, which is the difference between the cooling tower outlet and ambient wet bulb temperature, (iii) cooling tower effectiveness, which is the ratio of the range to the ideal range, (iv) heat load and (v) evaporation loss, to name a few. For the purpose of the investigation, only the range and the approach are considered, as they are temperature-dependent functions (Rahul Patel Sukhdev Gangwar, 2015)

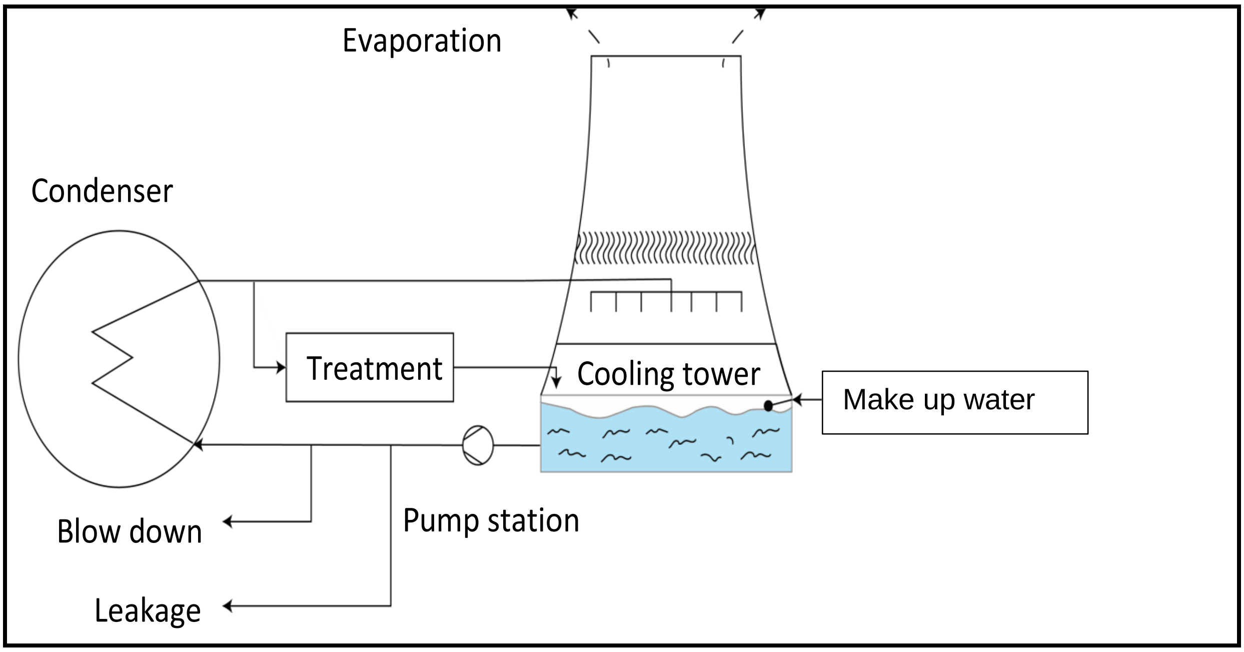

Figure 4-1. Schematic representation of an open recirculating cooling water system with a wet-cooled natural draft cooling tower and recirculating cooling water side stream treatment (Williams & Rasul, 2008).

The investigation aims to show the impact of poorly treated recirculating cooling water on power plant performance. The condenser performance as the main contributor to efficiency losses will be the primary area; in addition, cooling tower contribution to power plant performance will be the secondary area for consideration. This section focuses on the condenser parameters that are influenced by the recirculating cooling water chemistry. Fouling, scaling and corrosion of the condenser tubes by recirculating cooling water are chemistry-related challenges in a power plant. Operating parameters of the condenser and cooling tower that change due to the effect of fouling are analysed and the overall impact on the power plant performance assessed.

4.2 Background

The main contributor to the reduced cycle efficiency is the losses incurred in the condenser (Van Rooyen, 2014). Chapter 1 covered the scope and the effect displayed by Figure 1-3. (said Ali, 2010) conducted a study and modelled the effect of condenser pressure on the performance of a power plant operating on the Rankine cycle process. The conclusion revealed that an increase of pressure on the condenser will negatively affect the net power generated and the thermal efficiency of the power plant. Primary contributors are recirculating cooling water flow and inlet temperature. (Van Rooyen, 2014) established the same findings in his study comparing condenser back pressure and thermal efficiency. It is, therefore, substantial to understand and optimise the critical circumstances that affect the condenser backpressure for better control and management. Poor heat transfer will result in increased condenser backpressure and reduced efficiency. In addition, scaled and fouled condenser tubes will increase fluid frictional resistance and the hydraulic pressure drop, and decrease the cross-sectional flow area contributing to increased operational and maintenance expenditures (Casanueva-Robles *et al.*, 2005)

4.3 Methodology

The operating condenser and cooling tower conditions that change due to poor recirculating cooling water chemistry were investigated. These conditions were used as a guide to show their contribution to declining condenser and cooling tower performance. The collected operating data from a power plant were analysed to observe a pattern and performance behaviour change. The selected power plant for the investigation showed that the recirculating cooling water chemistry data were out of specification more than 80% of the time (Figure 4-2). The recirculating cooling water chemistry for this selected plant was discussed in Chapter 3 (plant C), and due to the chemistry performance, it was considered a probable case study to develop an accurate correlation for this investigation. The power plant condenser and cooling tower operational data were collected, analysed, modelled, and trended to demonstrate the plant's performance over time. Condenser temperature rise, temperature terminal difference, condenser cleanliness, cooling tower range, and approach were considered for a period of four years, from 2014 to 2018, for the investigation.

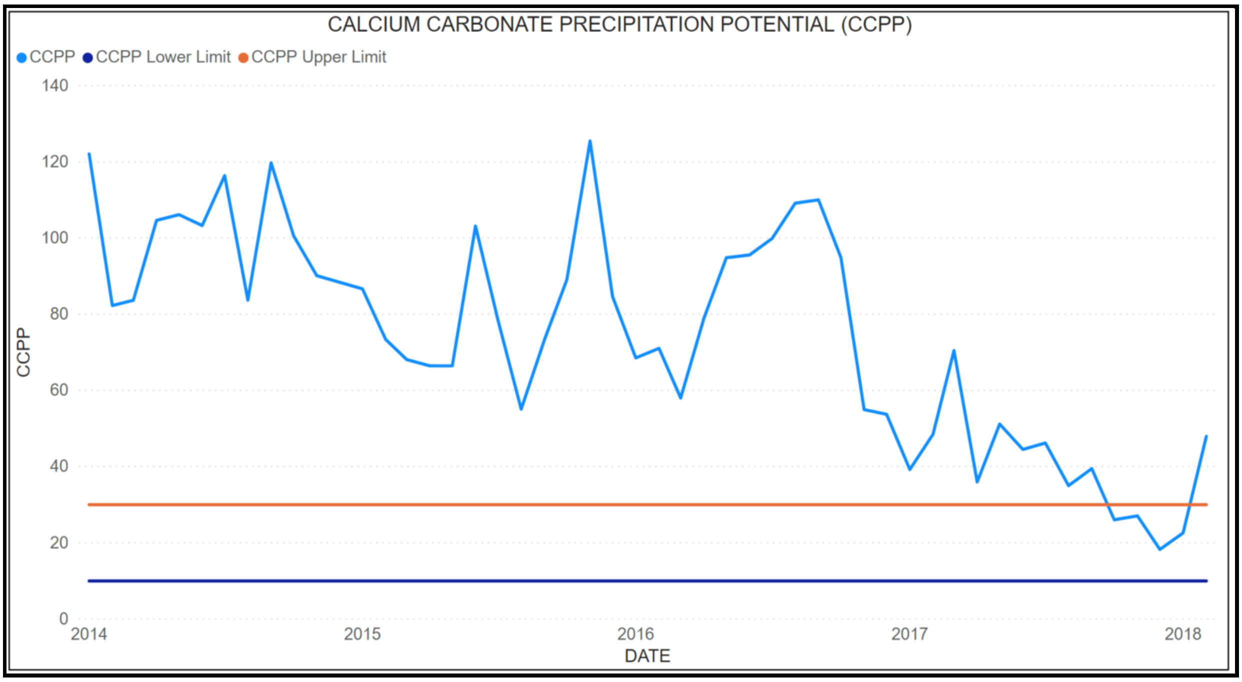

Figure 4-2: Calcium carbonate precipitation potential for the chosen plant (Plant C) over an extended period, from 2014 to 2018.

4.3.1 Temperature rise (TR)

One of the measurements used to detect poor heat transfer in the condenser is the difference between the recirculating cooling water inlet and outlet temperature, known as temperature rise (Han *et al.*, 2012). The smaller the difference, the poorer the heat transfer. The change in temperature rise is mainly affected by high heat load or cooling water flow (Ali *et al.*, 2014). A decrease in the recirculating cooling water flow will influence an increase in the condenser back pressure; as a result, the vacuum in the condenser will deteriorate (Van Rooyen, 2014). The consequence will be a decrease in inefficiency. Ambient temperature, especially in summer seasons, will result in high recirculating cooling water inlet temperatures. High inlet temperatures affect the thermal conductance in the condenser (Ali *et al.*, 2014). The temperature difference/temperature rise (TR) in the condenser is calculated by Equation 4-1. For a given unit load, any change in the recirculating cooling water inlet temperature will change the TR value and eventually the performance of the condenser; fouled tubes are considered one of the contributors to temperature variation.

$$\boldsymbol{TR = T_{outlet} - T_{inlet}} \qquad \text{Eq. 4-1}$$

where:

T_{outlet} = mean recirculating cooling water outlet temperature

T_{inlet} = mean recirculating cooling water inlet temperature

4.3.2 Terminal temperature difference (TTD)

Another indicator used to monitor the condenser performance is the terminal temperature difference (TTD). TTD is the difference between the cooling water outlet temperature and the exhaust steam temperature (Van Rooyen, 2014) calculated using Equation 4-2. The consequence of scaled or fouled condenser tubes will cause an increase in TTD. As the heat transfer capabilities decline in the condenser, condenser back pressure and saturation temperature will progressively increase (Kumar *et al.*, 2015)

$$\boldsymbol{TTD = T_s - T_o} \qquad \text{Eq. 4-2}$$

where

T_s = saturation temperature of the exhaust steam

T_o = recirculating cooling water outlet temperature

4.3.3 Cleanliness factor

The performance of the condenser deteriorates gradually as the fouling and scaling inside the condenser tubes advance (Prieto *et al.*, 2001). The performance decline is influenced by several factors, such as recirculating cooling water chemistry, operating and design conditions, and so on (Putnam & Putman, 2001). The Heat Exchange Institute (HEI) has published and recommended guidelines and standards with regard to steam surface condenser design and operation (Cardenas, 2017). The condenser cleanliness calculation is one of the parameters used to evaluate the degree of scaling and fouling inside condenser tubes (Prieto *et al.*, 2001). The calculated cleanliness factor during operating conditions is compared to the design cleanliness factor to observe and estimate any fouling in the condenser. Prieto *et al.* (2001), mentioned that the estimation is acceptable when the conditions are at steady state and within the original equipment manufacturers (OEM) recommendations.

According to the HEI, the condenser cleanliness factor calculation is specified by:

The calculation for ideal conditions:

$$U = C \times \sqrt{\boldsymbol{V}} \qquad \text{Eq. 4-3}$$

where:

U= Heat transfer coefficient

C= empirical number determined from HEI tube testing

V= velocity

The design coefficient

$$U_{\boldsymbol{d}} = U_{\boldsymbol{i}} \times \boldsymbol{C_m} \times \boldsymbol{C_t} \qquad \text{Eq. 4-4}$$

where:

C_m is a tube metal correction factor, material and gage specific

C_t is a circulating water temperature correction factor

Taken from HEI tables based on condenser tube material

The cleanliness factor, expressed in percentage, is calculated by:

$$C_f = \frac{U_a}{U_d} \times \mathbf{100}\% \qquad \text{Eq. 4-5}$$

where:

U_a: from the design phase

U_d: design value calculated

U_a is normally chosen by the designer, depending on the material used in the condenser tubes. The Heat Exchange Institute 2012 version mentioned that condensers are normally designed with an 85% and 95% cleanliness factor for copper and brass alloys and harder tube materials respectively. For condensers operated without the taprogge system (continuous mechanical tube cleaning), fouling effects are common (Cardenas, 2017)

The historical data were analysed and evaluated against the target/predicted values to assess any deviations affected by scaling and fouling of the condenser and cooling tower (Goodenough & Reuter, 2014a)

Three operating parameters and recirculating cooling water cycles of concentration were considered for the evaluation of the evaporative cooling tower performance due to the limitation of cooling tower monitoring measurements at the power plant. Firstly, the cooling tower range, the cooling tower approach calculation, regarded as a better indicator for assessing the performance, given by Equation 4-6 and 4-7 and the cooling tower effectiveness in percentage. The cooling tower approach calculation takes into consideration the cooling tower cold recirculating water stream and the ambient wet bulb conditions (Kasten & Muller, 2007)

$$Range = CT_{inlet\ temp} - CT_{Outlet\ temp} \qquad \text{Eq.4-6}$$

$$Approach = CT_{outlet\ temp} - CT_{air\ inlet} \qquad \text{Eq.4-7}$$

where:

$CT_{\text{inlet temp}}$ = cooling tower inlet temperature

$CT_{\text{outlet temp}}$ =cooling tower outlet temperature

$CT_{\text{air inlet}}$ = cooling tower inlet wet bulb temperature

To evaluate the effectiveness, the trend of the cooling tower ambient wet bulb temperature and the recirculating cooling water hot stream temperature were considered. The cycles of concentration during the operation were assessed to observe the highest salt concentrations in the tower. Though operating at higher cycles does have a significant impact on water conservation, the trade-off will be fouling and scaling of the cooling tower and the condenser if the side stream treatment is not optimum to manage the cycles (August, 2005).

4.4 Results and discussion

The results indicate that the terminal temperature difference in the condenser fluctuated over the years. There was a constant decline observed from the east side units, whereas the west side units maintained a fluctuating trend. During the years 2016 and 2017, the TTD increased to above 15% at the west side units, as indicated in Figure 4-3, the projected TTD in relation to load was never archived. The actual condenser TTD calculated was always above the set target.

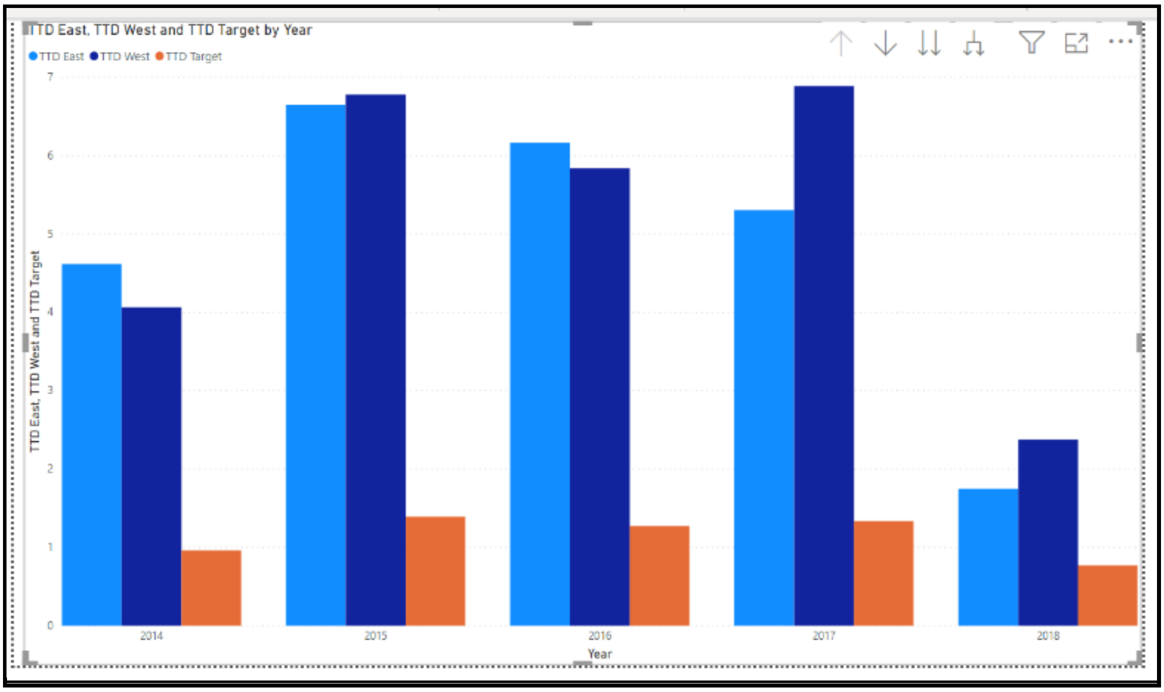

Figure 4-3: Calculated east TTD in light blue, calculated west TTD in navy blue, measured against target TTD in orange, from the year 2014 to 2018

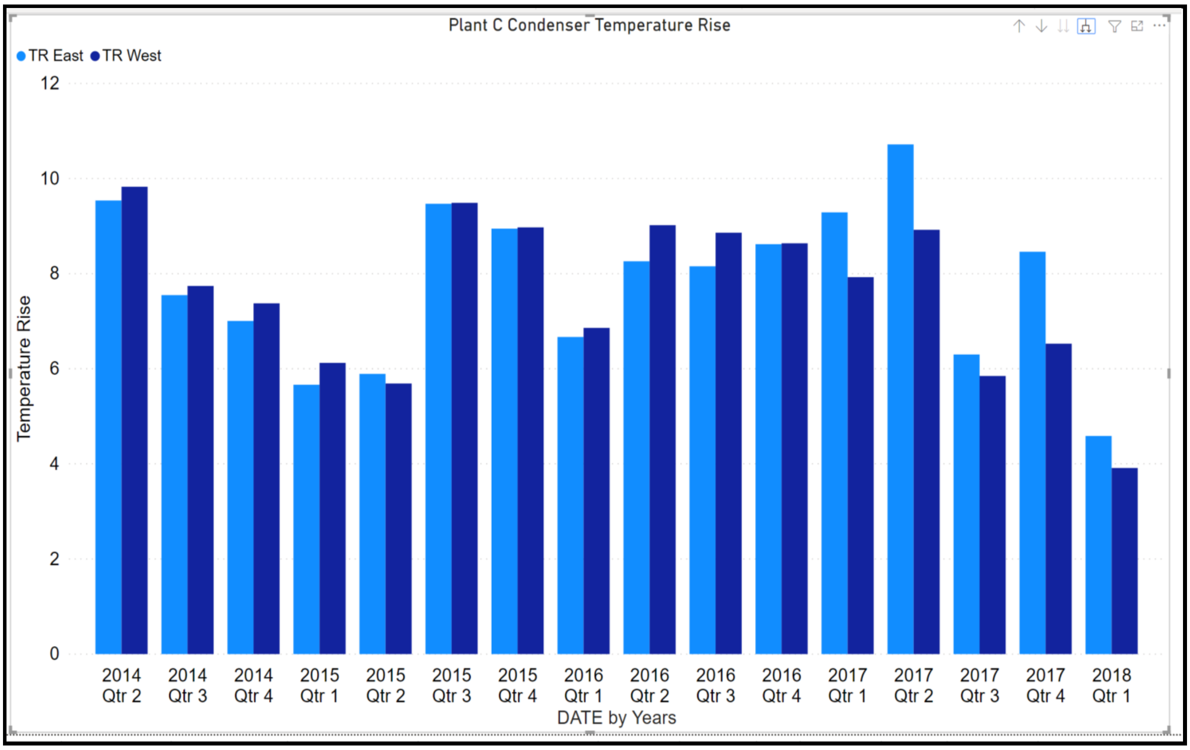

Figure 4-4: Condenser calculated temperature rise for the east and west side units for the years 2014 to 2018

Similar to the observations indicated in Figure 4-3, the temperature rise measured on this power plant fluctuated over the years. A previous researcher (Van Rooyen, 2014) indicated that the cooling water temperature difference between the inlet and outlet of the condenser should be in the margin of 6 to 10 degrees Celsius. A decline in the TR value indicates very poor heat transfer across the condenser, as depicted for example in Figure 4-4 during the years 2014 to 2015. The change in TR was significant; an improvement was observed toward the end of 2015, but in a very short space of time, a decrease was detected again. A similar behaviour change is observed during the years 2017 and 2018. The year 2018 results continued to decline to values lower than 4 degrees Celsius. This observation from the condenser indicates that the recirculating cooling water barely extracted an accurate quantity of latent heat from the exhaust stream. Figure 4-3 confirms an increase in TTD, coupled with a low TR, as observed in Figure 4-4, this is where the higher back pressure on the condenser was observed (Figure 4-5). Fouled and scaled condenser tubes contribute to the observed behaviour in the condenser. The recirculating cooling water flow can be regarded as one of the contributors to the variation observed from the condenser temperature rise, as shown in Figure 4-4. To mitigate the loss in flow, recirculating water inlet and outlet to condenser valves can be adjusted, but if the TR does not improve, the cause can be directly linked to a fouled or scaled condenser tube plate.

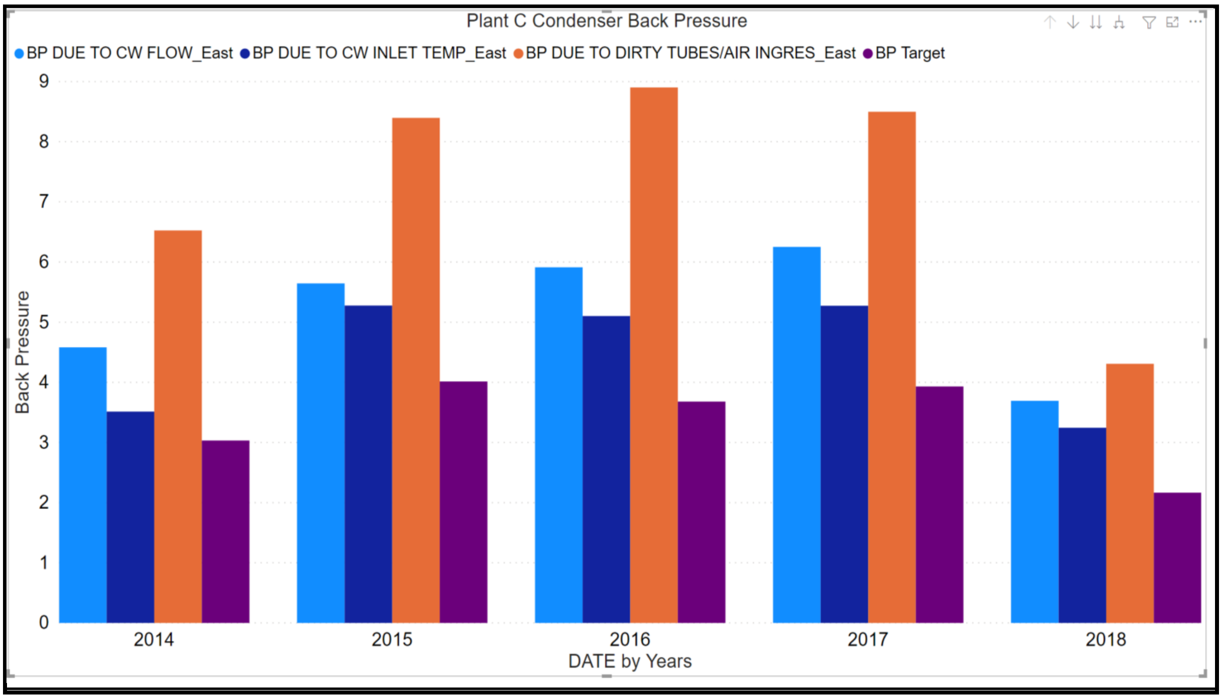

Figure 4-5: Condenser operating conditions influencing the condenser back pressure, recirculating cooling water flow, inlet temperature, dirty tubes measured against the projected back pressure with the load.

The condenser efficiency defined by Kumar *et al.* (2015) is the relation of the inlet and outlet temperature of the recirculating cooling water to the variance amongst the equivalent condenser exhaust steam temperature and the recirculating water inlet temperature. The condenser exhaust pressure has a substantial consequence for the efficiency of the steam generation cycle, as it directly affects the heat rate; steady control and management during operation is a requirement. Changes in the condenser back pressure influence heat rejection in the steam cycle. The recirculating cooling water inlet temperature to the condenser is one of the contributing parameters that influence the condenser back pressure. The performance of the cooling towers plays a major role in this regard. An increase in the recirculating water inlet temperature causes an increase in the condenser back pressure, which reduces the vacuum in the condenser, increases heat rate, and reduces efficiency. The same effect is observed when the recirculating cooling water flow decreases indicated by the change in TR, as observed in Figure 4-4.

Figure 4-5 represents an observation made about condenser back pressure influenced by recirculating water flow, inlet temperature, and fouled tubes. The results indicate that fouled condenser tubes contributed significantly to condenser back pressure. Figure 4-3 indicated that TTD during the 2014 to 2018 period was significantly high, a decrease in TR was observed in Figure 4-4 towards the end of 2014 beginning 2015, and back pressure increased from 2014 to 2016. A second observation where TR deteriorated was observed during the year 2017 and 2018 (Figure 4-4).

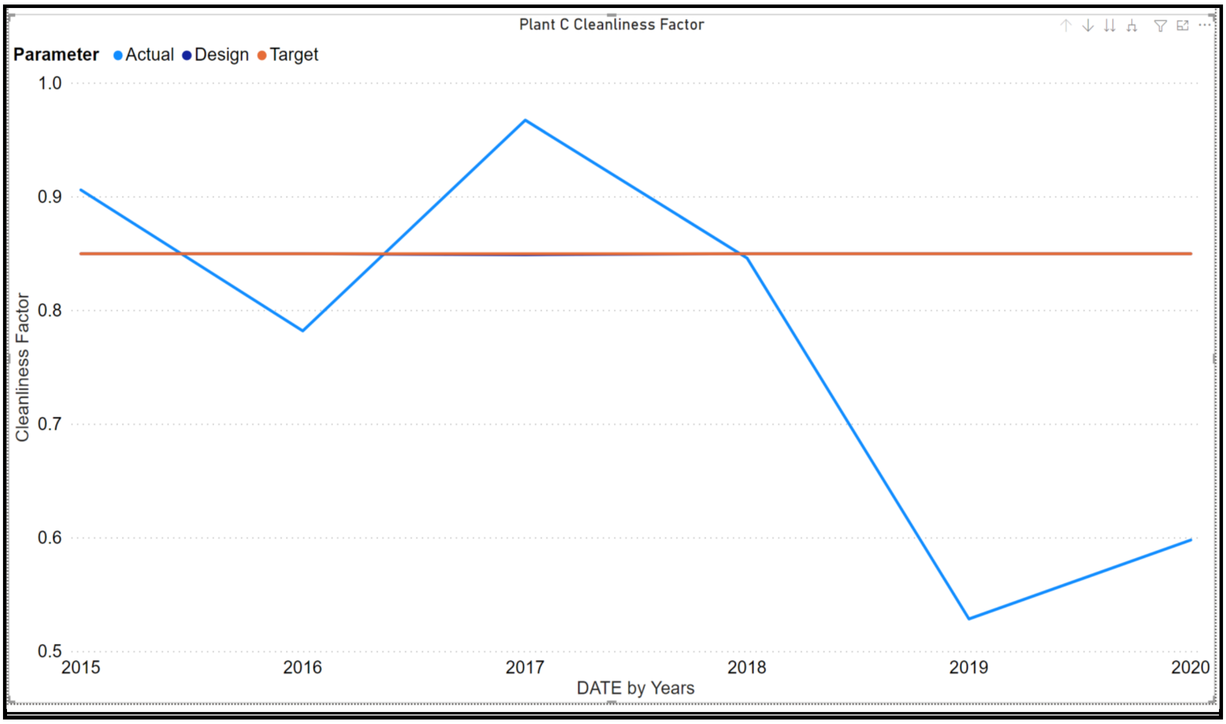

Figure 4-6: Plant C condenser cleanliness factor.

The cleanliness factor for the power plant in question influenced by design conditions was measured by calculating the ratio of the design specification recommended by the HEI to the actual operating conditions (heat transfer coefficient). The plant used for the study was designed to operate at a cleanliness factor of 85%. The proposed target incorporating the load and other plant operating conditions contributing to the cleanliness factor was set at 85% as well. A reduction is observed over the years; there was a significant change between 2017 and 2019, as displayed by Figure 4-6. The reason for integrating the cleanliness factor during the design phase is to accommodate any fouling that can occur in the condenser tubes. A decline in the cleanliness factor indicates that the condenser tubes are fouled or scaled.

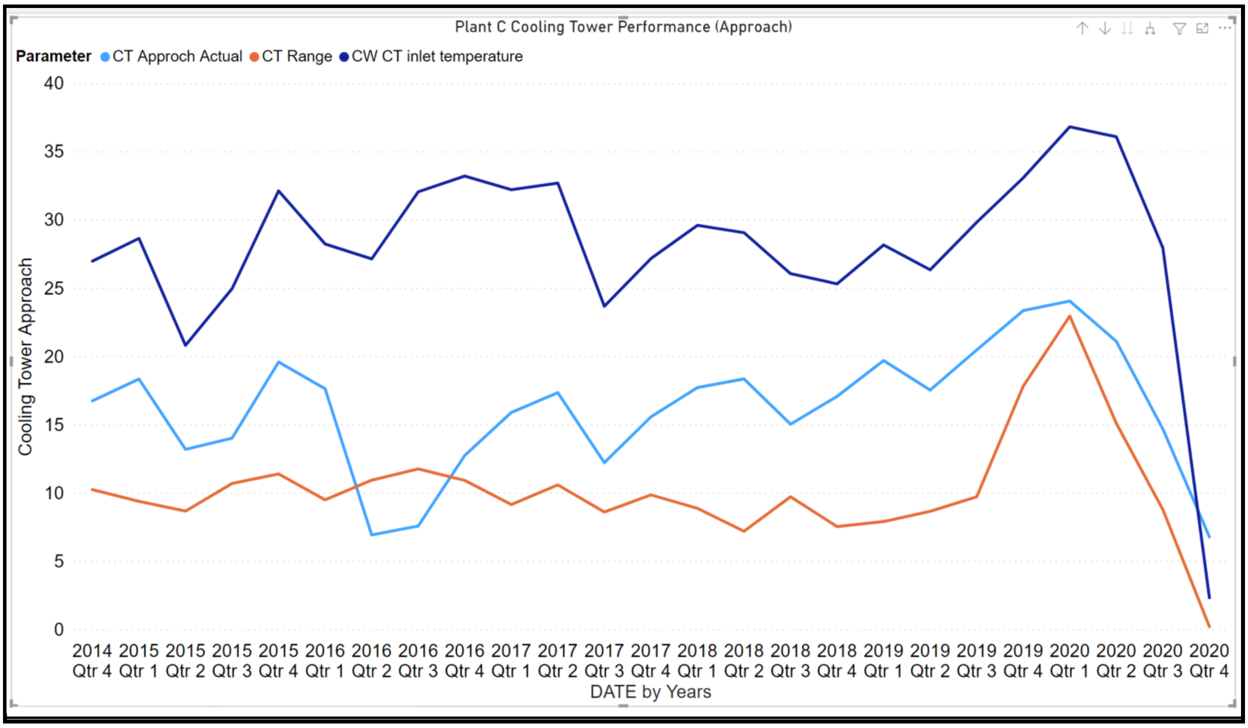

Figure 4-7: Cooling tower inlet temperature with calculated cooling tower range and calculated cooling tower approach variation.

Figure 4-7 displays a direct relationship between the cooling tower inlet temperature, the calculated cooling tower range and the calculated cooling tower approach. An increase in the cooling tower inlet temperature at the constant load will cause an increase in the calculated cooling tower range, as well as an increase in the difference between the cooling tower wet bulb temperature and inlet temperature (calculated cooling tower approach). The reason is that the driving force between the wet bulb temperature and the cooling tower inlet temperature increases. The wet-bulb temperature operating line will shift to institute equilibrium amongst hot and cold recirculating water temperature conditions. The relationship between the three parameters in Figure 4-7 is directly proportional; a change in any of the parameters indicates the effectiveness and performance of the cooling tower.

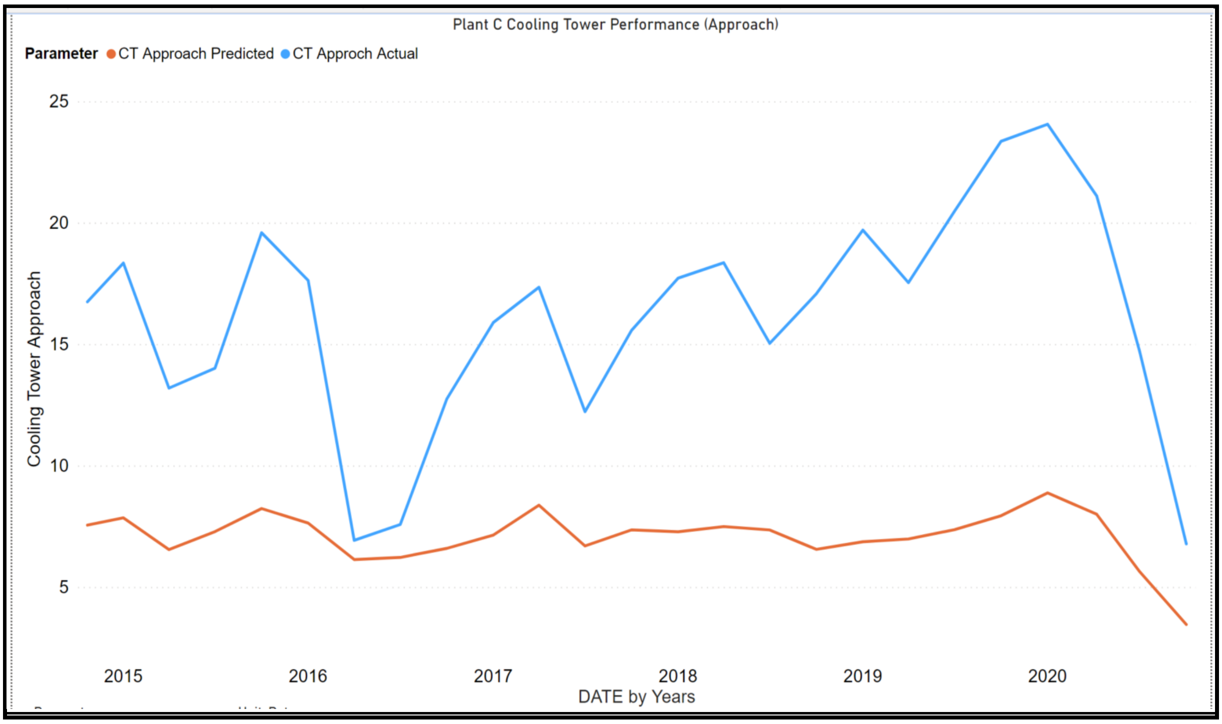

Figure 4-8: Cooling tower calculated approach and approach prediction for the projected load generated by the power plant.

In a wet cooled power plant, taking into consideration the operating and ambient conditions, load, and cooling tower design, a prediction of the operating approach can be projected. The results observed in Figure 4-8 indicate that the plant was operated above the predicted value. The year 2015 the plant was operated close to 60% above the predicted value; as the years progressed, the conditions deteriorated, approaching and exceeding 100% of the projected value. With ambient conditions being seasonal, the main effect could be related to recirculating water from the evaporative cooling tower and the heat transfer across the tower. As indicated above, the predictions will take load, size and airflow variations into account. The literature specifies that, the smaller the approach value, the more effective the cooling tower will be as observed in Figure 4-8. This observation from Figure 4-8 indicated that operating the plant within the predicted approach value was difficult to achieve, and as a result the efficiency of the tower was affected.

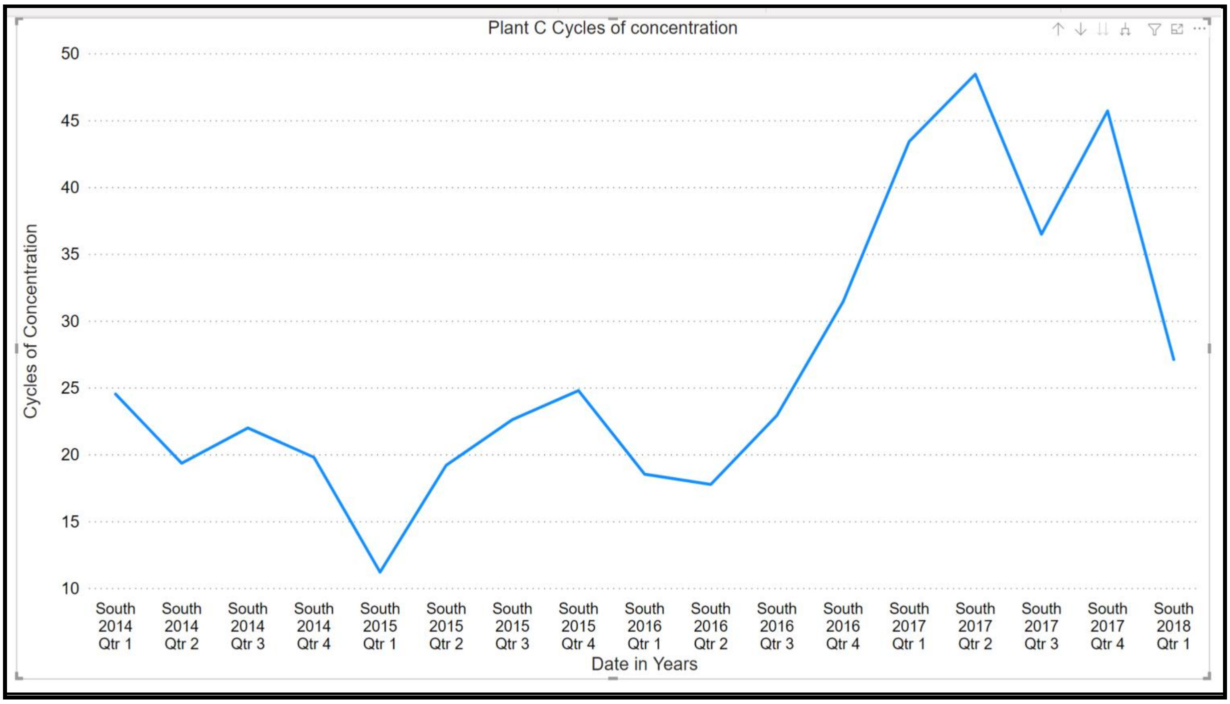

Figure 4-9: Recirculating cooling water calculated cycles of concentration for the year 2014 to 2018 for Plant C.

During the design phase of the cooling tower, different factors are taken into consideration. The cycles of concentration and the make-up water quality, which will contribute to the parameters that influence the efficiency improvement of a cooling tower. The recirculating cooling water cycles of concentration are one of the indicators on the performance of the cooling tower. The maximum cycles will depend on the make-up water quality. Plant C make up water is from the Vaal and Usuthu water scheme, operating at 7 cycles will be ideal for cooling water chemistry control and water conservation, guided by the cooling water chemistry standards and the water management guidelines/regulations. Figure 4-9 shows that, over the years 2014 to 2018, the cycles of concentration for Plant C fluctuated between 10 and 50 cycles. Operating the plant at constant elevated cycles is detrimental to the cooling system, as impurities accumulate in the recirculating cooling water, the heat transfer surface will be exposed to deposition and fouling. The cycles of concentration for Plant C increased significantly from the year 2015.

Table 4-1 demonstrates Plant C major losses acquired for the year 2019 and 2020 associated with operating the condenser and the cooling tower with out of specification cw chemistry. Over firing the boiler plant and increasing the heat load to accommodate the losses can be calculated using Equation 4-8. The calculated excess coal burnt monetary value from Equation 4-8 is used to determine the cost in relation to plant losses.

$$Excess\ coal\ burnt = \frac{Monetary\ loss}{Coal\ prce} \qquad \text{Eq.4-8}$$

Table 4-1: 2019 and 2020 Plant C partial load losses that resulted to excess coal burnt:

Year	Excess coal burnt due to poor vacuum (Tonnes)	Excess coal burnt due to loss of feed water temperature (Tonnes)	Excess coal burnt due to auxiliary power loss (Tonnes)
2019	171032	198174	137577
2020	104441	92755	68122

Power plant monitoring, recirculating cooling water management and control will reduce partial load losses and unit trips. The relationship between plant thermal efficiency, power output and coal burnt is calculated using Equation 4-9.

$$Plant\ Thermal\ Efficiency\ (\%) = \left[\frac{USOx1000x3.6}{Coal\ burnt\ xCV}\right]x100 \qquad \text{Eq. 4-9}$$

Where:

USO = Unit Sent Out (kWhSO)

CV = Calorific Value

As observed in Equation 4-9, power plant thermal efficiency and coal consumption are inversely proportional, an increase in coal consumption will reduce the efficiency of the process.

4.5 Water usage and power generated

The "thermal efficiency of a thermal power station", for a given period, is the quotient of the heat equivalent of 1 kWh and the average heat rate expressed in the same units. In the power industry the term “overall thermal efficiency” means the heat rate was calculated using the net station production (kWh sent out or USO).

Station Thermal Efficiency Performance (EtaPRO STEP) defines a method in a unique process to evaluate the thermal performance of a coal fired power plant. This evaluation reflects the condition, performance and operation of the plant and can be displayed as an index of the thermal performance.

To determine the water consumption for a power plant in ML either raw water and/or demineralised water consumed, the make-up demineralised water or raw water used is divided by the total USO as indicate by Equation 4-10. STEP is an instrument that can be used to drive the medium-term objectives of environmental sustainability and cost reduction through energy efficiency maximization.

$$Water\ used\ = \frac{Water}{kWhSO}\left(\frac{L}{USO}\right) \qquad \text{Eq. 4-10}$$

Where:

L =meters

kWhso = kilo watt hour sent out (USO)

The water performance in relation to the power generated, also called water efficiency measured as L/kWhSO is used in a power plant to monitor water consumption. An increase in the L/kWhSO measurement is a clear indication to poor water performance. The power plant has a set target for the L/kWSO measurement every financial year, the target can vary depending on the activities and outages planned during the financial year.

The historical data indicated by Figure 4-10 illustrates that over the years Plant C water usage has been deteriorating. This has resulted in high raw water intake as observed in Figure 4-11 and more environmental legal contraventions. As the power generated declined an increase in water efficiency increased Figure (4-10). The core reason for the poor water efficiency is the deterioration in technical performance i.e., poor recirculating cooling water chemistry management, lack of plant maintenance, condenser related load losses, water losses due to leaks and chemistry related failures in the plant etc.

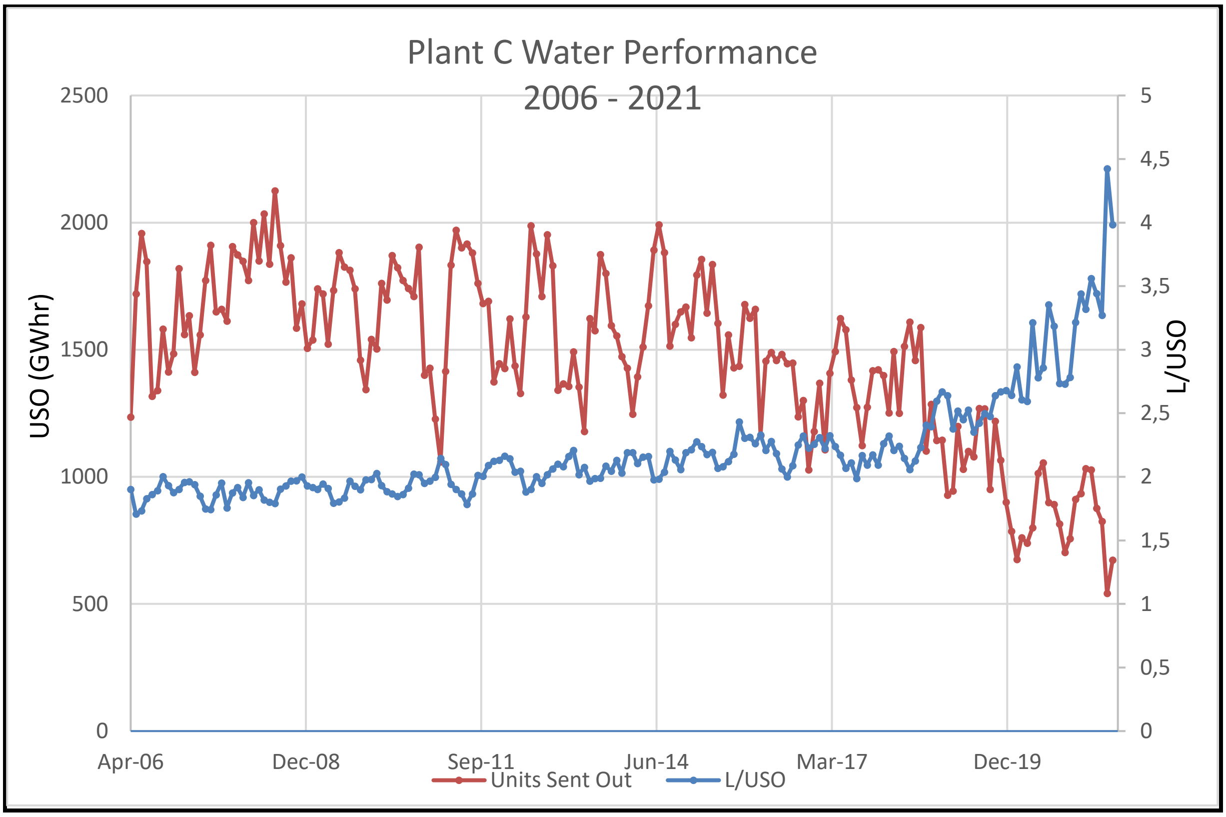

Figure 4-10: Plant C water performance in correlation to USO for the years 2006 to 2019

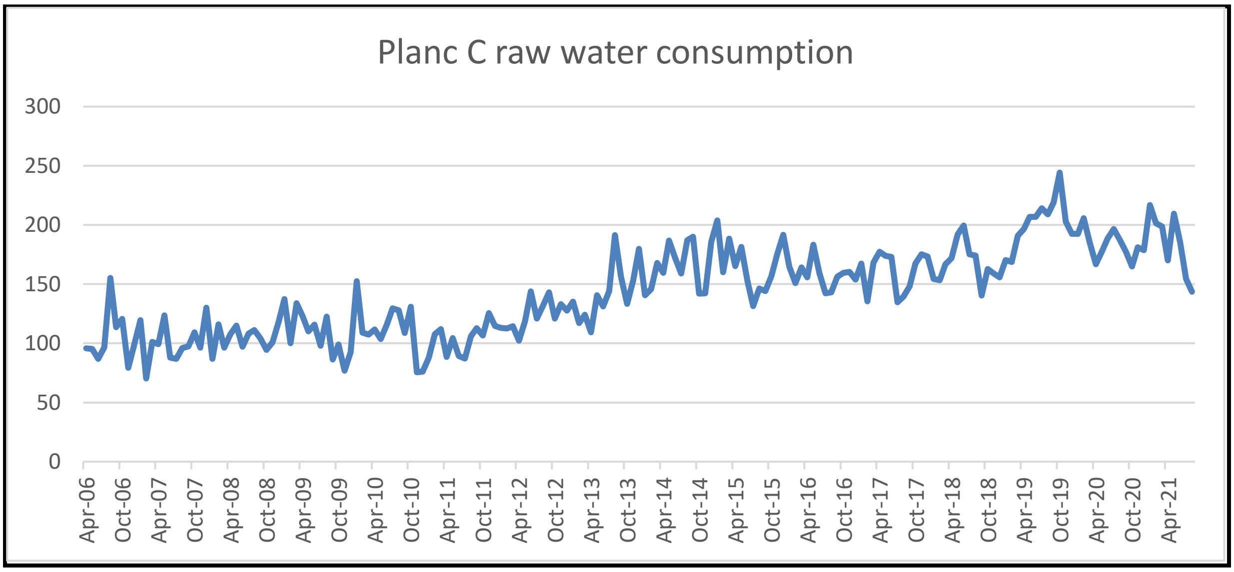

Figure 4-11: Plant C water consumption increase

The historical water management performance target as L/USO according to Figure 4-12 was never met. The set targets were reviewed to accommodate the poor technical state of the plant sadly there has been no improvement. The water targets are still subject to review while the power plants arrest the performance challenges.

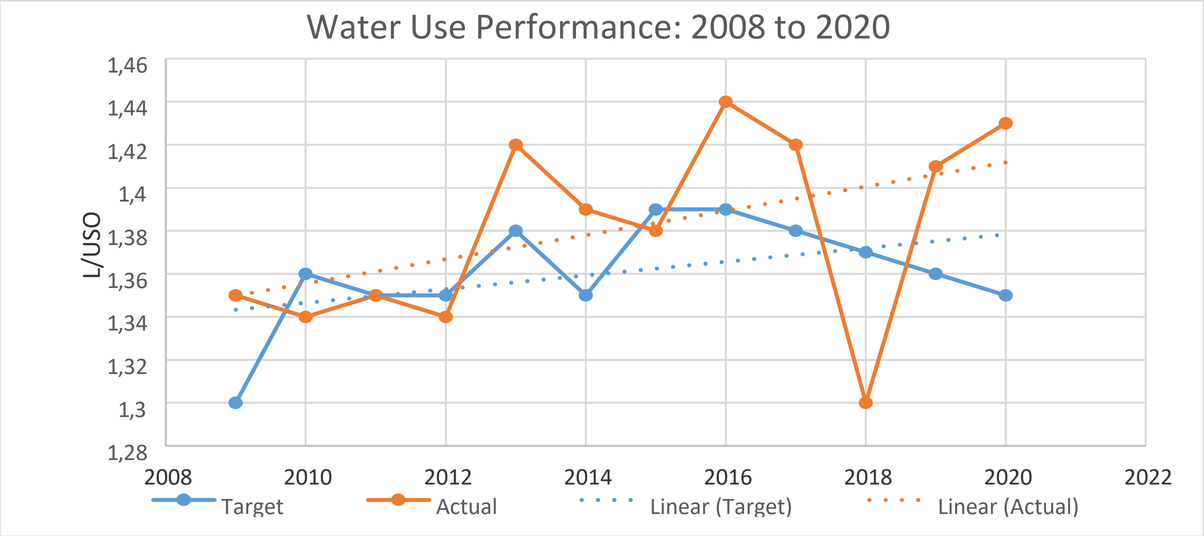

Figure 4-12: Overall water performance across the power plants

4.6 Conclusion

The scaling and fouling of the heat transfer surface influence plant performance. The investigation conducted revealed that fouling conditions looking at parameters such as, condenser TTD, TR, CF, cooling tower range and approach will affect the overall performance of the condenser and the cooling tower. Deterioration in any of these operating conditions will lead to recirculating water flow reduction, increased condenser back pressure, reduced vacuum, and an increased heat rate, eventually leading to poor reliability and reduced efficiency. Any compensation from the cycle to accommodate the changes in the condenser affects the overall efficiency of the plant. To address the challenge, the affected components will have to undergo chemical or mechanical cleaning. Chemical and mechanical cleaning in most power plants is conducted and planned when the unit is offload. Cooling systems are important in a power plant and should be operated with due care and precaution. Recirculating cooling water treatment needs to be efficient and effective as reasonably possible to ensure compliance to guidelines and standards developed for wet cooled power plants. The optimum operation of the recirculating cooling water side stream treatment is a requirement. Optimal conditions mean operating recirculating cooling water quality within specifications, quality maintenance and immediate attention to plant defects as well as plant inspections daily by system engineering to manage all plant losses. Fouling and scaling processes, their understanding and correlation to power plant efficiency are intricate and interconnected. To manage and control the risks related to the cooling system, the chemistry should be monitored and corrected when out of specification; if possible, online monitoring and measurement should be employed. In addition, water performance as L/USO has deteriorated as a results of power plant performance. This has contributed to an increase in raw after intake to accommodate the poor cooling water and chemistry performance.

CHAPTER 5: CONCLUSIONS, OBSERVATIONS AND RECOMMENDATIONS

5.1.1 Conclusions

The present study focused on demonstrating the impact of recirculating cooling water chemistry on power plant performance. Lime softening side treatment is employed at the power plants selected for the investigation to control and maintain the recirculating cooling water chemistry within specifications. The study aimed to emphasise the chemistry performance of wet cooled power plants and promote plant availability and reliability for continuous power production. This proved to be a challenge, with the recirculating cooling water chemistry controlled out of the specification for more than 50% of the time. The behaviour observed was consistent when comparing four different sites with different make-up water quality. Fouling, corrosion and scaling experienced within the cooling systems (condenser and cooling tower) are contributors to vacuum and pressure losses on the power plant main condenser. Although there is a time lag between the apparent chemistry and the actual performance of the plant, the chemistry data analysed over five years showed a correlation. Exposing the cooling system to such operating conditions at elevated temperatures has proven to take effect. The power plant performance as the years progressed deteriorated, confirmed by the cleanliness factor. This has confirmed to have a negative impact on power plant efficiency; when the condenser and cooling tower performances are affected, the efficiency is affected. In the case of scaling, corrosion and fouling, the impact is negative, and losses are incurred. To compensate for losses resulting from poor vacuum and pressure, the turbine load is reduced or the boiler heat load is increased by over firing the boiler plant; more cooling water pumps are put in service, increasing auxiliary power. The effort made to mitigate the loss, results in plant availability and reliability being compromised, power output reduced, and loss of efficiency.

From the data analyses, the calcium carbonate precipitation potential index used to evaluate the fouling, scaling, and the corrosive environment in the recirculating cooling water has proven to be constantly above the set limit. The acceptable range given for CCPP control is between 10 and 30 mg/kg for the plants considered during the investigation. The CCPP index was above 30 mg/kg more than 50% of the time over a five-year period. A CCPP index above 30 mg/kg exposes the cooling system to scale. Chemistry parameters incorporated in the CCPP, for example, alkalinity, pH, hardness, etc., were operated above the limits set as guided by the chemistry standard. The side stream lime softening treatment, when operated optimally, can control alkalinity, hardness, and pH. The objective of promoting the recirculating cooling water operation within the guidelines and standards given can only be achieved when the side stream is optimised and functional.

5.1.2 Observations

The make-up water chemistry plays a major part in keeping the cooling water chemistry within specifications; as the make-up water chemistry changes, the side stream treatment should be optimised to accommodate the change.

Flowmeter verifications to ensure flows are accurately read is a requirement, as the side stream treatment depends on optimal flow to treat the recirculating cooling water effectively, especially when recoveries are introduced as part of the make-up water or as effluent management for the power plant.

Calibrations of the level transmitters on the chemical tanks (lime, floc, coagulant, silo, etc.) to ensure proper chemical management and dosages are a prerequisite. Overdosing and underdosing will affect the performance of the side stream treatment and cost implications for the department responsible for purchasing the chemicals and keeping stock available. This will also affect the chemical availability surveillance leading to no available chemicals for treatment and delayed commercial processes. Chemical consumption is a good indicator of proper plant monitoring. Chemical availability will ensure that the softening treatment is continuous.

Overall mass and flow balances should be conducted to ensure that there are no overflows and chemicals dosages match the plant flow requirements. If there are deviations from design, adjustments should be made accordingly.

The instrumentation on the side stream treatment should be available and reliable; plant monitoring and data collection will give a broader perspective of what is occurring in the plant and what actions need to be taken.

Surveillance of the plant parameters is crucial; this will give an overview of plant performance and the frequency of changes.

In terms of plant maintenance, plant redundancy is one of the biggest challenges in lime softening side stream treatment. If any equipment fails, it should be repaired/replaced immediately; this will ensure continuous operation. When the plant is fully available and operational, optimisation can be properly implemented until the plant reaches stability. It is very difficult to optimise a plant that is not consistently operational, as it never reaches a steady state; this affects the overall performance of the plant and delays the treatment process, leading to unnecessary recirculating cooling water chemistry out of specification. It is advisable to keep all the spare equipment for the plant as stock items and readily available to reduce downtime periods that create additional challenges related to lime precipitation and settling.

The important parameters must be monitored frequently. Management endorsement and support of the recirculating cooling water chemistry strategies are key to successful implementation;

without these, failure of the cooling system is likely. Predefined methods to establish and maintain good chemistry for asset preservation should be a requirement. The main and key component of a successful treatment programme is communication between the operating, engineering, chemistry departments and station management. While from a chemistry perspective, the chemical treatment control can be kept within parameters, it is usually the process/system engineer who examines system/component internals for suggestions of treatment efficiency and/or notices a change in system performance, such as heat transfer. Findings from the inspections should be communicated to the chemistry department to make adjustments and changes to chemical treatment and the dosing regime. Frequently, it is the operating department that will first observe when any plant component is malfunctioning, for example, operating conditions changing or extreme leakage on any plant components. The findings should be logged and reported to be addressed immediately.
The power station financial implications as a results of load losses, outages and unit trips will increase exponentially if measures for optimal plant performance are not in place. The costs associated with maintaining cooling water chemistry within the recommendations stipulated in the chemistry guidelines are likely to be less than those associated with the repair or replacement of heat exchangers and piping, and the outages associated with those efforts. In the power generation industry, recirculating cooling water is the life of an efficient and reliable plant output.

5.1.3 Recommendations

It is recommended and suggested that the lime softening process investigation and optimisation be conducted taking into consideration changes in the recirculating cooling water chemistry. A guideline for operating and managing the lime softening process to be developed from the findings, as this will assist in managing and controlling the cooling water chemistry. In addition, a cooling water treatment trial pilot plant study incorporating lime softening side treatment with antifouling, anti-scaling and anti-corrosion agents be investigated. The investigation should incorporate, cooling systems performance from the chemistry and efficiency perspective, different chemical dosing regimens, temperature effects, plant metallurgy etc. The effectiveness of these chemical treatments can be compared and evaluated from a pilot-scale and the outcome rolled out to the actual power plants.

Data integrity and analytics to be conducted before the data is authorised and used, where possible data interpretation model can be explored. It is critical to ensure that; what is captured during operations aligns to the plant performance. Life dashboards which update automatically can be created where current plant performance is available and accessible to everyone. This will educate and inform employees about plant status and an appreciation of plant performance can be recognised. Advanced data analytics and modelling are significant, generated data, correlations of the different parameter for different processes will be a great tool for the power plant performance monitoring. The power generation industry should investigate how to manage, correlate and use data for power plant performance.

Awareness should be conducted so that an obligation for recirculating cooling water chemistry in the power industry is acknowledged. The investigation during the study highlighted that there is a gap in understanding the chemistry impact to power plant efficiency, as a result, the challenges observed during the study surfaced.

The strategy for improving plant reliability and availability should derive and employ processes which will, include but not limited to, defining the approach, determining the objectives, identifying the assignment, understanding internal and external aspects, performing data analytics etc. The resultant will be improved thermal efficiency, reduced load losses and guaranteed stable plant reliability with quality planned outages.

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APPENDIX A

Equations

$\boldsymbol{Cycles\ of\ Concetration} = \left(\frac{\boldsymbol{Specified\ threshold\ for\ specie\ in\ CW}}{\boldsymbol{Same\ specified\ specie\ in\ make{-}up\ water}}\right)$ Eq. 5-1

$Q = mcw \cdot cp \cdot TR = U \cdot A \cdot LMTD$ Eq. 2 1

Where:

Q = Condenser heat transfer rate

U= Overall heat transfer coefficient

A= Condenser tube heat transfer surface area

LMTD= Log mean temperature difference

$\boldsymbol{Al_2(SO_4)_3 + 6NaHCO_3 = 2Al(OH)_3 + 3Na_2SO_4 + 6CO_2}$ Eq. 5-2

$\boldsymbol{Fe_2(SO_4)_3 + 6NaHCO_3 = 2Fe(OH)_3 + 3Na_2SO_4 + 6CO_2}$ Eq. 5-3

$Na_2Al_2O_4 + 4H_2O = 2Al(OH)_3 + 2NaOH$ Eq. 5-4

$\boldsymbol{CO_2 + Ca(OH)_2 = CaCO_3 + H_2O}$ Eq. 5-5

$\boldsymbol{Ca(HCO_3)_2 + Ca(OH)_2 = 2CaCO_3 + 2H_2O}$ Eq. 5-6

$\boldsymbol{Mg(HCO_3)_2 + 2Ca(OH)_2 = Mg(OH)_2 + 2CaCO_3 + H_2O}$ Eq. 5-7

$\boldsymbol{MgSO_4 + Ca(OH)_2 = Mg(OH)_2 + CaSO_4}$ Eq. 5-8

$\boldsymbol{MgCl_2 + Ca(OH)_2 = Mg(OH)_2 + CaCl_2}$ Eq. 5-9

$\boldsymbol{Na_2Al_2O_4 + 4H_2O = 2Al(OH)_3 + 2NaOH}$ Eq. 5-10

$\boldsymbol{MgSO_4 + 2NaOH = Mg(OH)_2 + Na_2SO_4}$ Eq. 5-11

$\boldsymbol{MgCl_4 + 2NaOH = Mg(OH)_2 + 2NaCl}$ Eq. 5-12

$\boldsymbol{CaSO_4 + Na_2CO_3 = CaCO_3 + Na_2SO_4}$ Eq. 5-13

$\boldsymbol{CaCl_2 + Na_2CO_3 = CaCO_3 + 2NaCl}$ Eq. 5-14

$\boldsymbol{MgSO_4 + Ca(OH)_2 + Na_2CO_3 = Mg(OH)_2 + CaCO_3 + Na_2SO_4}$ Eq. 5-15

$\boldsymbol{MgCl_2 + Ca(OH)_2 + Na_2CO_3 = Mg(OH)_2 + CaCO_3 + 2NaCl}$ Eq. 5-16

$\boldsymbol{Rs = \left(1 - \frac{C\ permeate}{\left(\frac{C\ feed + C\ concentrate}{2}\right)}\right) * 100\%}$ Eq. 5-17

$\boldsymbol{Rw} = \frac{\boldsymbol{Q_P}}{\boldsymbol{Q_F}}$ Eq. 5-18

TDS ($\frac{\boldsymbol{mg}}{\boldsymbol{L}}$)= K* EC ($\frac{\boldsymbol{uS}}{\boldsymbol{cm}}$) Eq. 5-19

$\boldsymbol{pH = -log_{10}[H]^+}$ Eq. 5-20

$\boldsymbol{Alkalinity}\ [\boldsymbol{HCO_3^-}] + \boldsymbol{2}\left[\boldsymbol{CO_3^{2-}}\right] + [\boldsymbol{OH^-}] - [\boldsymbol{H^+}]$ Eq. 5-21

$TR = T_{outlet} - T_{inlet}$ Eq. 5-22

T_{outlet} = mean recirculating cooling water outlet temperature

T_{inlet} = mean recirculating cooling water inlet temperature

$\boldsymbol{TTD = T_s - T_o}$ Eq. 5-23

T_s = saturation temperature of the exhaust steam

T_o = recirculating cooling water outlet temperature

$U = C \times \sqrt{\boldsymbol{V}}$ Eq. 5-24

U= Heat transfer coefficient

C= empirical number determined from HEI tube testing

V= velocity

$U_{\boldsymbol{d}} = U_{\boldsymbol{i}} \times \boldsymbol{C_m} \times \boldsymbol{C_t}$ Eq. 5-25

C*m* is a tube metal correction factor,

C*t* is a circulating water temperature correction factor

$C_f = \frac{U_a}{U_d} \times 100\%$ Eq. 5-26

U_a: from the design phase

U_d: design value calculated

$Range = CT_{inlet\ temp} - CT_{outlet\ temp}$ Eq.4-6

$Approach = CT_{outlet\ temp} - CT_{air\ inlet}$ Eq.4-7

$Excess\ coal\ burnt = \frac{Monetary\ loss}{Coal\ prce}$ Eq.4-8

$Plant\ Thermal\ Efficiency\ (\%) = \left[\frac{USOx1000x3.6}{Coal\ burned\ xCV}\right] x100$ Eq. 4-9

Where: USO = Unit Sent Out and CV = Calorific Value

$Water\ used\ = \frac{Water}{USO} (\frac{L}{USO})$ Eq. 4-10