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Effective and Efficient Ozone Use on Cooling Water Systems

MSc Dissertation

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Submitted to

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Johannesburg, 2014

DECLARATION

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

……
Signature of Nomcebo Nombuso Gina

……day of ……..…… 2013

PUBLICATION AND PRESENTATIONS FROM THIS RESEARCH WORK

1. Effective and Efficient Ozone Use on Cooling Water Systems. Nomcebo Gina, Dumisa Gina, Kevin Harding. School of Chemical and Metallurgical Engineering, University of the Witwatersrand, Johannesburg, South Africa. Air Products South Africa (Pty) Limited. (Presented at the SAICHE Conference. 17 – 19 September 2012). Presenting author underlined.

2. Effective and Efficient Ozone Use on Cooling Water Systems. Nomcebo Gina, Dumisa Gina, Kevin Harding. School of Chemical and Metallurgical Engineering, University of the Witwatersrand, Johannesburg, South Africa. Air Products South Africa (Pty) Limited. (Presented at the Renewable Energy and Water Postgraduates Conference 28 March 2013). Presenting author underlined.

3. Decomposition of ozone in water, Chemical Technology. Harding, K; Ntimbani, R; Mashwama, P; Mokale, R; Mothapo, M; Gina, N; Gina, D (2013)

EXECUTIVE SUMMARY

This dissertation reports on the effective and efficient use of ozone in cooling water treatment systems. The study focuses on proving that ozone treated systems will:

(1) Improve compressor energy consumption;
(2) Improve the heat exchangers efficiency through limited scale deposition and fouling;
(3) Reduce water consumption; and
(4) Encourage or support corrosion at high concentrations compared to when cooling water is chemically treated.

For this study, data log readings from compressor heat exchanger approach temperatures were used for energy saving calculations and equipment efficiency (scaling). Using conservation of energy principles and municipal power costs, it was found that over four years, R425 991 was saved. Conventional chemical cooling water treatment systems showed high approach temperatures, resulting in high scaling rates and high energy consumption in the compressors. In contrast, ozone cooling water treatment systems showed a lower approach temperatures which resulted in lower scaling rates and lower energy consumption in the compressors.

Also, for this study data log readings from cooling water flow rates and weekly water quality analyses were used for water saving calculation and corrosion predictions. In ozone cooling water treatment systems, there was a reduction in makeup water use confirming water savings. According to Mosugelo (2010) water quality is a bigger contributor to corrosion than ozone is. In cooling water treatment systems with good quality makeup water, ozone treated systems were found to have lower corrosion rates in the heat exchangers than conventional chemicals systems.

It can be concluded that effective and efficient use of ozone in cooling water treatment provides triple bottom line benefits (economic, social and environmental). Environmental benefits include effluent disposal reduction, water and energy conservation. Social benefits include safety and health impacts. Ozone treated cooling water systems are a technically practical, cost-effective and sensible alternative when compared to conventional cooling water treatment systems.

DEDICATION

I dedicate this work to;

The first and foremost, the most deserving; my God, Savior King Jesus Christ and my father God Almighty for loving me unconditionally, the great interest and wisdom he is tirelessly showing in my life.

My loving husband, my best friend, love of my life; Dumisa Cornelius Gina, for his encouragement, love and support in helping me pursue further study and reaching my full potential.

The two little man, my Pride and Joy, apple of my eye;

Thuthuka: I never knew what full of energy and appreciative meant, until we were blessed with you. You are young yes, yet you teach us what life is all about everyday. You are the best!

Phambili: you gave the best hugs! But you were gone before we knew it and Only God knows why. May your soul rest in peace.

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I would like to thank God for keeping me this far and for giving me the wisdom, the courage and the strength to achieve this.

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I would also like to acknowledge Wits University and Air Products South Africa for their financial support, allowing me to do this study, seeing a potential in me and for providing all resources, facilities and the appropriate learning environment to enable a successful research.

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CHAPTER 1

1. INTRODUCTION

1.1 Background

Industrial and commercial operations are compelled by national and international legal requirements to find environmentally friendlier alternatives for water treatment (South African National Water Act 36 1998, ISO1400:2004). It is the writer's view that in a short while such operations will be faced with an ultimatum to comply with legal requirements or be required to close down their operations. Natural resources, *e.g.* water and energy, are being depleted and the damage is irreversible (The Water Project, 2013).

Water conservation should be a business priority for both commercial and industrial facilities. Large amounts of water usage in commercial facilities are situated in areas such as large laundries and food processing industry. Industrial water supply of greater than 50% is used for cooling water systems (You *et al.*, 1998). Alsheyab and Munoz (2007) stated that cooling water systems are one example where industrial operations can exploit an opportunity of water conservation.

In South Africa, cooling water is mainly treated with conventional chemicals such as:

1) Corrosion inhibitors for corrosion control, *e.g.* zinc phosphate;
2) Biocides for biological organism elimination or control, *e.g. s*odium hypochlorite;
3) Dispersants for dispersion of dissolved solids, *e.g.* phosphonate; and
4) pH control, *e.g.* sulphuric acid (Mulyandasari, 2011).

A typical cooling water treatment programme consists of these four different chemicals. Although it is acceptable to use conventional chemicals for cooling water treatment, the evidence still suggests that this use comes with problems (Kitzman *et al.,* 2003). These include:

1) Environmental degradation as a result of the toxicity of blowdown and low cycles of concentration, hence water obliteration;
2) High operating costs as a result of inefficient heat transfer;
3) Inefficient equipment as a result of high corrosion and scaling rate;
4) Personnel health and safety issues as a result of exposure or handling.

An alternative to conventional chemicals is ozone. According to, Rice and Wilkes (1992) and CryoGas International (2009 and 2011), ozone use is being fast tracked due to environmental pressures and economic benefits it offers. The sole benefit use of ozone include (Rajagopaul *et al*., 2008; Panjeshahi *et al.*, 2009):

1) Decreased heat exchanger approach temperatures – as a result of reduction in compressor energy consumption;
2) Improved heat exchanger efficiency because of lack of scaling;
3) Water saving because of reduced use of make-up water;
4) Improved disinfection;
5) Lower corrosion rates – thus improved equipment life and integrity;
6) Lower operating costs.

However, there are negative factors related to ozone use. Boner and Peter (1999) stated that ozone capital costs were high compared with conventional chemicals. Tierney (1997) showed that the annual expenditure at the Kennedy Space Center (KSC) prior to converting conventional chemical treatment to ozone was about one-third of the total ozone operation and maintenance costs.

According to CryoGas International (2013), Information Handling Services Inc. acknowledged Ozonix water treatment technology as a pioneer in energy innovation that helped companies reduce costs. In addition, Ozonix technology reported an increased treatment efficiency and eliminated liquid chemicals from wastewater treatment operations. Further, Tierney (1997) stated that Kennedy Space Center (KSC) attained an annual water savings of $48,000 or 32 million gallons. Subsequent studies by Zentox

(2012) have tested and proven that the Return on Investment (ROI) at KSC, Vehicle Assemble Building, has been attained between the periods of 6 to 36 months. This ROI period shortens as chemicals, water and energy charges escalate.

Conventional chemical use gives birth to wastewater that is concentrated with hazardous chemicals. This wastewater requires high treatment costs and is environmentally unfriendly. Air Products South Africa (Pty) Ltd claims to be "enjoying great financial success with the use of ozone in its own cooling water cooling towers" (Air Products, 2011).

1.2 Problem Statement

1.2.1 General Problem

Industrial and commercial operations worldwide are faced with the dilemma of finding a water treatment method that is effective and environmentally friendly. The most commonly used conventional chemical, chlorine, is extremely toxic and forms trihalomethanes, a potential carcinogen (Meitz, 2013).

1.2.2 Specific Problem

Air Products South Africa (Pty) Ltd invested in an ozone generator in 2009 as an alternative to traditional chemical water treatment systems for cooling towers. This investment was mainly justified by hypothetical cost and efficiency benefits. Four years later the claimed cost and efficiency benefits of ozone use had not been quantified. There was therefore a need to investigate the true benefits of ozone use on the Air Products South Africa (Pty) Ltd cooling water treatment systems. Furthermore, electricity tariff increases, expected water tariff increases, legislative pressures and the degradation of resources has emphasised the importance and need for an alternative to traditional cooling tower water treatment systems.

1.3 Research Questions

This research aimed to answer the following questions:

1) Is there a reduction in compressor energy consumption as a result of ozone use?
2) What is the scale deposition and fouling rate in heat exchangers in ozone-treated systems versus conventional chemically treated systems?
3) How much water has been saved as a result of using ozone and what is the equivalent water cost saving?
4) Are ozone cost benefits greater than the cost of heat exchanger equipment integrity and life because of high corrosion rates?
5) What are the chemical cost savings and environmental benefits that result from using ozone?

1.4 Research Objectives

The objectives of this research were to:

1) Quantify energy savings as a result of possible reduced compressor energy consumption with ozone use;
2) Review heat exchanger efficiency in terms of scale deposition and fouling in ozone-treated systems versus conventional chemical water treatment systems;
3) Evaluate if water is conserved and the related cost saving in ozone cooling water treatment systems;
4) Assess corrosion rates in conventional chemical *vs.* ozone heat exchangers;
5) Quantify chemical cost savings and qualify the environmental benefits as a result of using ozone.

1.5 Hypothesis

It has been postulated that using ozone to treat cooling water has some cost and efficiency benefits. The following hypotheses pertain to ozone cost and efficiency benefits for cooling water treatment use. Ozone treated systems will:

1) Improve compressor energy consumption;
2) Improve heat exchanger efficiency through limited-scale deposition and fouling;
3) Reduce water consumption compared to chemically treated cooling water;
4) Encourage or improves corrosion; and
5) Offer cost benefits and be more environmentally friendly than conventional chemicals.

1.6 Research Report Layout

To attain the research objectives, Chapter 2 presents a literature review that refers to previous research carried out on ozone and conventional chemical use on cooling water treatment.

Chapter 3 explains the research design and method, including the sources of data and how this was converted into useful information for research analysis.

Chapter 4 reports on the results and delivers a discussion on them.

Finally, Chapters 5 and 6 conclude the research and provide recommendations respectively.

CHAPTER 2

2. LITERATURE REVIEW

This chapter comprises a literature review on ozone- and chemical use in cooling water treatment. Water loss and electricity costs are discussed first, followed by the literature on the history of ozone and perspectives on ozone in the South African context. Cooling water system fundamentals and factors (microbiological organisms, corrosion, suspended solids and scale and deposit control and elimination) are then discussed. Further, ozone background, application guidelines and benefits are discussed. Finally, a comparison between ozone use as a standalone versus conventional chemical use is reviewed.

2.1 Water and Electricity Costs

The reduction of water sources and possible water tariff increases makes it a priority to recycle and make better use of water (Donnelly, 2012). Keister (2001) acknowledged that cooling tower water maintenance is commonly abandoned, which results in issues such as downtime, non-compliance with environmental laws and high water and energy use. Cooling tower blowdown can be contaminated with undesirable hazardous chemicals, which results in health and safety concerns (Keister, 2001).

The previous United Nations Secretary General Kofi Annan (2002) stated that: "access to a secure, safe and sufficient source of fresh water is a fundamental requirement for the survival, well-being and socioeconomic development of all humanity. Yet, we continue to act as if fresh water were a perpetually abundant resource. It is not."

South Africa has a National Energy Regulator (NERSA), which has approved an average electricity price increase of over 20% each year since 2008. Moreover, NERSA has approved annual electricity price increases of 8% for 2013-2018 (Moneyweb, 2013). The confirmed constant escalating electricity tariffs in the coming years, and forecasted ascending water tariffs, The Water Project (2013), will be a large business utility cost.

These price increases place an emphasis on the necessity for efficient and effective cooling water treatment systems that can offer efficient water and energy savings.

2.2 Ozone Water Treatment History and South African Perspective

In 1977 the National Aeronautics and Space Administration (NASA) became a pioneer in ozone use for cooling water treatment (Lin and Yeh, 1993). Tierney (1997) recommended ozone use at NASA on the Kennedy Space Centre (KSC) cooling towers following two independent engineering studies that were conducted to investigate the most feasible treatment method. Ozone's booming success, Parker (1995) and CryoGas International (2010 and 2013), has resulted in further use of ozone in Florida Parachute Refurbishment Facility (PRF) wastewater treatment at NASA (Water Energy, 2013).

The four main larger (30 to above ML/d) waterworks users of ozone in South Africa are Umgeni Water, Midvaal Water and Magalies. Ozone use in the South African raw water industry is growing rapidly; especially as a pre-oxidant in the pre-treatment and intermediate stages of the process chain (Rajagopaul *et al*., 2008). The water treatment plant in Windhoek, Namibia, is the only other large-scale ozonation plant for drinking water in Southern Africa (Strydom, 2004).

In addition, the following waterworks using ozone for treatment include Plettenberg Bay (Bitou Municipality), Delmas, Rietvlei, Roodeplaat, Themba Water Treatment Works and UShaka Marine World (Ozonize, 2013). The ozone studies described below are an alternative to conventional chemicals for water treatment.

- Pilot studies from an ozone pre-feasibility study at Sasol Chemical Industries recommended the optimum ozone rate of 1.3 mg/l on a full-scale plant (Perrot and Van Aartsen, 2002).
- Ozone was found capable of treating the Merisol Sasolburg site effluent to the required concentration, average of 355 mg/L, of chemical oxygen demand under acidic and alkaline pH conditions (Mooketsi, 2008).

2.3 Cooling Water Systems

Water treatment is essential for eliminating the impurities that are naturally found in water. The removal of these impurities is crucial to prevent corrosion, scale formation and fouling of heat transfer surfaces throughout the system equipment (Department of Energy Handbook, 1993). Major industries such as refrigeration systems, process plants and power stations gave birth to cooling towers and cooling water systems (Burger *et al.*, 1981). Process plants, including air separation units, are extremely temperature sensitive plants. Therefore, an efficient cooling water system is critical.

2.3.1 Description of a Cooling Water System

A cooling water system consists of:

1) A cooling tower;
2) System piping;
3) Heat exchanger; and
4) A water pump (Kusmierz, 1999).

Cooling towers are used to eliminate excess heat that is generated in industrial operations such as power stations and chemical plants as well as domestically in air conditioning units (Nalco, 2009). Figure 2-1 shows a typical cooling water system. Generally, manufacturing practices use water as a solvent to remove heat. This is mainly because it is cheaper and abundant.

According to Kusmierz (1999), 80% of the heat is removed by evaporation in the cooling tower. The airflow that runs through the cooling tower removes the remaining heat. A small percentage of the recirculation rate leaves the cooling tower as drift.

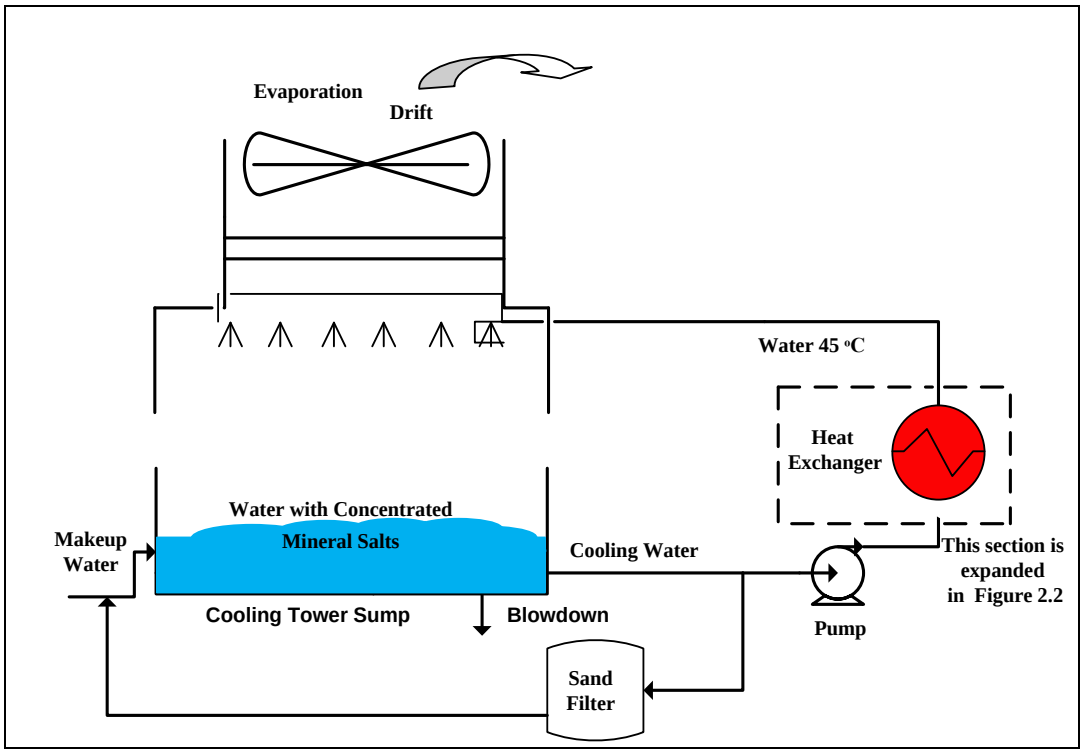

Figure 2-1 Typical cooling tower (adapted from Kusmierz, 1999).

The heat exchanger is used to transfer energy from the process stream to the water through convection and conduction. Figure 2-2 shows the heat exchanger process stream that is being cooled within the compressor system. Cooling water is piped to a cooling tower where it ejects heat to the atmosphere. Cooling tower openings on the sides allow for effective mixing of water and air. It is important to note that cooling tower evaporation is composed only of water. A high percentage of the materials dissolved in the water remain concentrated in the basin water. Thus, with more water evaporating, dissolved mineral salts are continually becoming more concentrated.

The sand filter removes suspended solids in the cooling water system. If these suspended solids are not removed they clog the heat exchanger tubes. A sand filter usually consists of a bed of granular material such as sand or anthracite through which water flows in a downward direction (Department of Energy Handbook, 1993; RCSL, 2013). Cycles of concentration are defined by the degree of the concentration of dissolved solids. The

water discharged from the system is controlled such that chemical concentration, suspended and dissolved solids in the water are reduced or do not accumulate in the cooling system. This discharged water is defined as blowdown. It is standard practice to recycle the water at least five times before it is blown down.

Typically, fully automated cooling water systems use conductivity meters to measure the conductivity in the cooling tower basin and in the make-up (MU) water line and control the cooling tower blowdown rate. In general, MU water will come in the cooling tower at about 200 Micro-Siemens/Centimetre and the blowdown is typically done at a cooling water conductivity set point of 1500 Micro-Siemens/Centimetre.

2.3.2 Heat Exchanger / Compressors System

Compressors are used to compress main air feed, product and re-compress recycle streams. Compression is the act of reducing the volume that a given mass of gas occupies. Gas temperature and pressure increase when a gas is compressed. A stage takes gas from one pressure level to another (Energy Efficiency Guide, 2006). Figure 2-2 shows a typical three-stage, water-cooled product compressor and how the gas is passed through each stage of compression to the next.

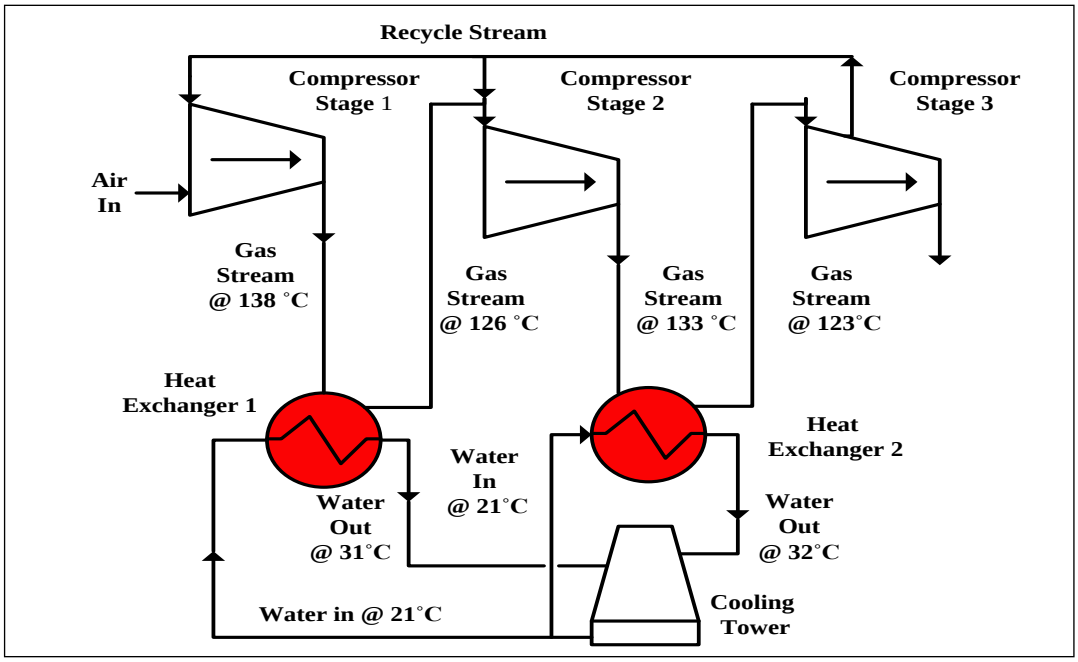

Figure 2-2 Typical three stage heat exchanger or compressor system

The heat from the compressor process is removed in heat exchangers. The heat exchanger is therefore critical equipment. It is also affected largely by scaling and corrosion. Scaling results in inefficient compressor energy consumption and corrosion results in equipment damage (Seneviratne, 2007; RCSL, 2013).

Electrical energy is the main requirement for compressor operation. It is important to make a note that the compressor system operation cost is far more than the cost of purchasing the compressor itself (Energy Efficiency Guide, 2006). Figure 2-3 shows cost components of a typical compressor. Effectively and efficiently managed compressor system energy savings can range from 20% to 50% of electricity consumption, hence hundreds of thousands of rands saved over the lifetime of a compressor (Energy Efficiency Guide, 2006).

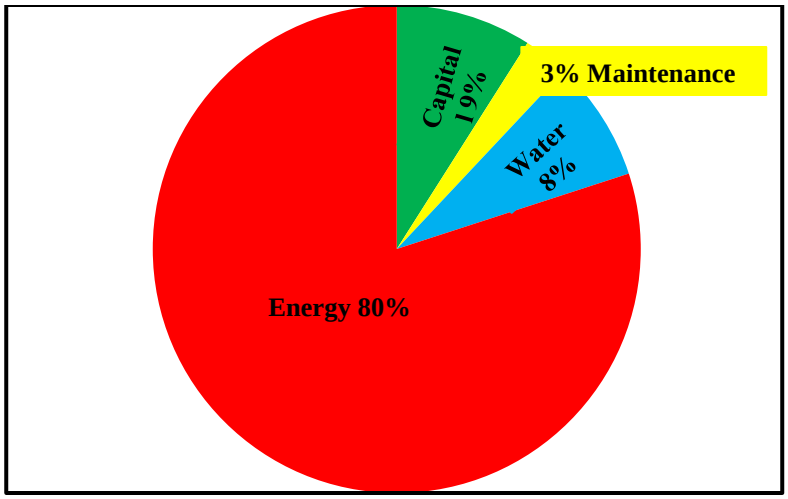

Figure 2-3 Costs of components in a typical compressed system lifetime (adapted from Energy Efficiency Guide, 2006)

A major portion (80%) of the energy in the compression system is converted to heat. This heat must continuously be removed or the compressor will overheat and shut down. Reducing the operating temperature of the compressor will proportionately reduce the energy input requirements. Burger (1981, 1983, and 1991) has emphasized that the colder the water to the equipment, the less energy is required to produce the same degree of work at lower costs. Nalco (2009) also confirmed that colder cooling water is an energy saving opportunity in the compression system. Inefficient heat exchanger heat transfer denotes high energy consumption by the compressor and escalation in energy costs.

2.3.3 Effects of Efficient and Inefficient Cooling Tower Operation

Cooling tower water management programmes are often unsuccessful due to abandoned control (Keister, 2001). Optimal conditions are likely to be different for various cooling water treatment systems or options, hence operating conditions will also be different (Bott and Tianqing, 2004).

Effective elimination or control of the four main cooling tower problems; scaling, biological microorganism, corrosion and pH control are objective requirements for a successful cooling water treatment system (Keister, 2001). Optimal energy efficiency and

equipment efficiency can be evaluated through operational relations and performance between system equipment. Listed in Table 2-1 is the latest literature on heat exchanger claims in light of scaling, water temperature and efficiency.

Table 2-1 Effects of scale and stream temperature on heat exchanger efficiency

	If there is	Then there will be a(n)
Anuje *et al.* (2013)	A 1°C increase in cooling water temperature	Decrease of 2% in thermal heat exchanger efficiency
Seneviratne (2007)	Fouling by scale or microbiological growth	Decrease in heat transfer efficiency
Nalco (2009)	A fouled compressor heat exchanger	Increase in the next compression stage gas temperature
Keister (2001)	About 1.5 mm of scale	Decrease of 12.5% in thermal heat exchanger efficiency
	A slight presence of biofilm with no scaling	Increase in compressor energy consumption
Woods (2007)	A 10°C increase in inlet gas temperature to compressor	Increase of 2% horsepower requirements.

Further, the findings shown in Table 2-2 support the conclusion that a decrease in cooling water temperature will result in a reduction in compressor energy consumption.

A colder condensation temperature improves production efficiency at a lower cost (American Society of Heating, Refrigerating, and Air-Conditioning Engineers Equipment Handbook, 2008). The compressor and condenser energy saving is said to be the most important option to improve energy efficiency of cooling towers (Energy Efficiency Guide, 2006). From Table 2-2 it is evident that there is a correlation between approach temperature and compressor energy consumption.

Table 2-2 Cooling water temperature versus compressor energy correlation

	Approach temperature decrease of	Results in reduction in compressor energy consumption
Nalco (2009)	1°C	1% to 2%
Burger *et al.* (1991)	0.6°C	2.5%
	2.2°C	10%
McNicholas (2002)	3°C	1%.
Energy Efficiency Guide (2006)	1°C	2.7%.

Therefore, the primary objective of the cooling water system should be to make the cooling water colder because this offers an energy saving benefit (Burger *et al.*, 1991). Maintenance and water treatment are the critical aspects that affect the life and energy efficient operation of evaporative cooling equipment (You *et al.*, 1998). Hence, inefficient operation results in poor performance and economic loss; for example, through water loss, equipment damage, poor equipment efficiency and poor heat transfer (Department of Energy Handbook, 1993).

2.4 Cooling Water Treatment System

Water is a key raw material that is widely used and abused in industry. Main uses include, but are not limited to, heating, cooling and dissolving. Plant performance is linked to how water is used, both from a design and operational perspective, i.e. designing and constructing the plant with water reclamation and re-use technology (ies). Hence, plant performance optimisation has to do with effective water utilisation (Woollen, 2005). Section 2.4.1 discusses four water-quality concerns. These are microbiogical elimination and management, scale and deposit control, corrosion control and suspended solids dispersion control (American Society of Heating, Refrigerating, and Air-Conditioning Engineers, 2000). The use of conventional chemicals for water treatment is being shunned by most market segments due to environmental pressures and process economics gains (Challener, 2011).

2.4.1 Microbiological Elimination and Management

The most critical portion of the cooling tower treatment system is microbiological elimination and management. Cooling tower problems such as corrosion, microbiological scaling or fouling are born, in part, by unsuccessful microbiological elimination and management (Seneviratne, 2007). Conventional chemical biocides are generally used for the elimination and management of microbiological growth. Most of these biocides are toxic. There are two types of biocides; Oxidising and non-oxidising biocides (Song *et al*., 2009). According to Karsa (2007), oxidising biocides were found to be more effective than non-oxidising biocides.

Typical cooling tower treatment oxidising biocides include chlorine, chlorine dioxide, hypochlorite and ozone (Karsa, 2007). Typical non-oxidising biocides include glutaraldehyde, amines, isothiazolones, organo-sulphur compounds and quaternary ammonium salts. Properties of the listed oxidising biocides are given in Table 2-3. These properties are effectiveness, commonality and safety concerns. Ozone is the most effective and the strongest biocide from the list below. This is the reason why ozone is able to oxidise most microorganisms.

Table 2-3 Typical oxidising biocides (Domingue *et al.*, 1988; Elsmore, 1994 and Murthy *et al*., 2005)

Biocides and Reaction	Effectiveness	Common Use	Comments Safety Concerns
Ozone $O_3 \rightarrow O_2 + O$	2.07V; $2e^-$	New but Growing	Naturally unstable.
Hypochlorite $HOCl \leftrightarrow H^+ + OCl$	1.48V; $2e^-$	Very Common	Very good against organisms found in swimming pool water
Chlorine $Cl_2+H_2O \rightarrow HOCl + HCl$	1.36V; $2e^-$	Very Common	Extremely toxic. Forms trihalomethanes
Chlorine dioxide $Cl_2 + 2\ NaClO_2 \rightarrow 2\ NaCl + 2\ ClO_2$	0.95V; $2e^-$	Very Common	Less hazardous to human health than chlorine

Most non-oxidising biocides including isothiazolones are effective in the control of bacteria fungi and algae (Videla, 2002). Kim *et al.* (2002) stated that chlorinated phenolics' biocidal effect can be an enhancing one through the addition of amines in water.

2.4.2 Scale and Deposit Control

Scale deposits result from precipitation and crystal development at surfaces that mix with water (Keister, 2001). Precipitation can take place on the surfaces or in the bulk water when solubility rates are exceeded. The heat transfer inefficiency and water distribution inefficiency is caused by scale deposit accumulation in cooling water systems. Scale and deposit control is therefore critical for effective cooling water treatment.

Scale or fouling rate is dependent on the make-up and system water chemistries; *i.e.* hard, moderately hard or soft water. Hard water leads to more scale and fouling formation due to that when hard water is heated, the carbonates precipitate out of solution. Soft water is more corrosive since it lacks two positively charged salts that coat the equipment hence equipment surfaces are exposed (Yiasoumi *et.al.,* 2005).
The standard causes of scale formation are water chemistries with:

1) High alkalinity which results in a decrease in solubility and precipitation.
2) High total dissolved solids.
3) High temperatures.
4) Low flow velocity.
5) Elevated temperatures generally increase salt solubility. Some salts like calcium carbonates are less soluble at high temperatures and cause deposit formation.

The increased temperature in the heat exchanger can precipitate some dissolved solids. These precipitants end up blocking pipes (Figure 2-4).



Figure 2-4 Heat exchanger tubes clogged up with $CaCO_3$ precipitated solids

The clogging of tubes with dissolved solids puts a limitation on the number of times make-up water can be recycled (cycles of concentration). Tubes clog because the more the cooling water is recycled the more the dissolved solids concentrate (Keister, 2001).

2.4.3 Corrosion Control

Corrosion is defined as the oxidation of metals which takes place in the three electrochemical reaction steps: 1) loss of hydrogen 2) gain of oxygen 3) loss of electrons. This three-step process results in equipment damage and loss (RCSL, 2013). According to Keister (2001), mild steel is the most common metal used in cooling water systems yet it is more susceptible to corrosion than most other metals, such as copper and stainless steel. Corrosion in water replenishing systems such as cooling towers is a big concern for industry. As such, corrosion inhibitors are widely used for corrosion control, to decrease or eliminate it in pipes, heat exchanges and other equipment.

Most metals of construction corrode at different rates when they come in contact with water (Keister, 2001). Below are some of the factors that can result in an unacceptable corrosion rate in a water cooling system if not properly managed (Charng and Lansing, 1982):

1) Oxygen dissolved in water;
2) Alkalinity and acidity;
3) Total dissolved solids;
4) Microbial growth; and
5) Water velocity.

2.4.4 Suspended Solids Dispersion Control

Cooling towers behave in a similar manner to scrubber heat exchangers (coolers) in that they do not just cool water by using air but they also scrub dust and other particles out of the air into the cooling tower sump. These particles end up floating in the cooling system water as suspended solids. Suspended solids that are not removed in the cooling tower end up blocking tubes and packing in the process (Nalco, 2009). The deposition of suspended material in heat-exchange equipment is called “fouling”.

An example of a direct contact after cooler (DCAC) packing that has been clogged by suspended solids is shown Figure 2-5. Although the recycling of cooling water presents a saving of water in the short run, it can also result in fouling if the water is over recycled.



Figure 2-5 Clogged packing inside direct contact after cooler (DCAC) vessel

2.5 Ozone Systems

2.5.1 Background

Ozone is an invisible gas which smells like the air after an electrical thunderstorm in spring, yet unsteady and should be manufactured and used onsite. According to the Environmental Protection Agency (1999), ozone is the most effective oxidant – even more effective than chlorine. The maximum 8 hour recommended exposure limit is 0.1 ppmv (Occupational Health and Safety Act 85 of 1993). This value of 0.1 ppmv is used to set the first-alert sound and the visual alarm point in the ozone system. At levels as low as 0.01 to 0.04 ppmv ozone can be detected by smell. Ozone exposure to human health is harmful at the levels and durations that are specified above (Rajagopaul *et al.*, 2008).

Ozone is formed by passing oxygen or air through a high voltage corona (electrified field) that splits the molecular oxygen into atomic oxygen (Figure 2-6). Subsequent to the split some of the oxygen atoms (O^{-2}) join with oxygen molecules (O_2) to form ozone. Some of the oxygen atoms simply combine to form oxygen (Parker *et al.*, 1995).

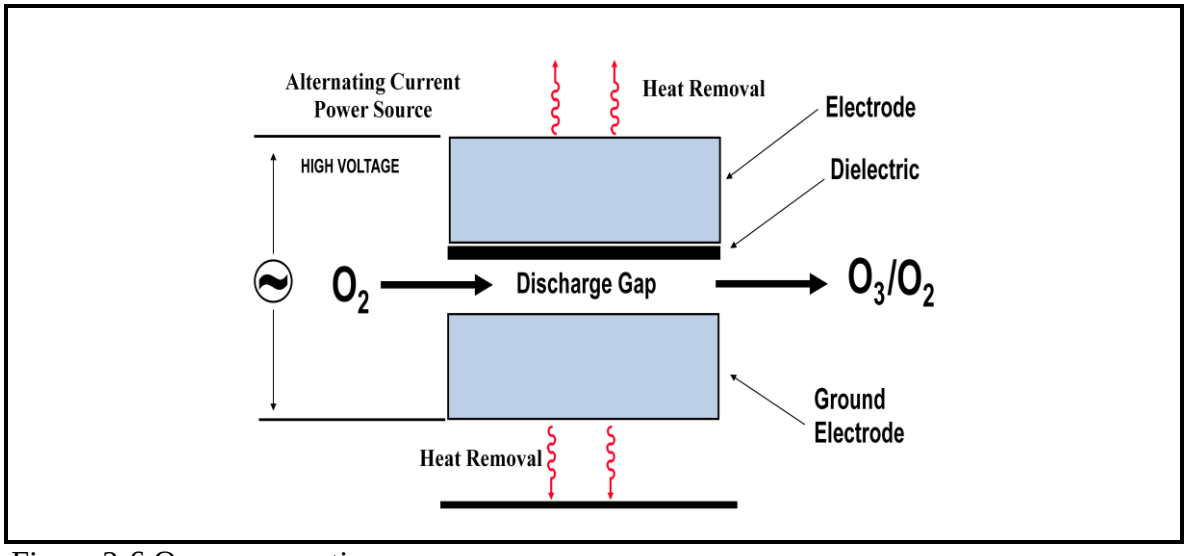

Figure 2-6 Ozone generation

According to Suslow (n.d.) oxidation redox potential (ORP) is the voltage at which oxidation occurs at the anode of an electrochemical cell while reduction occurs at the cathode of the same electrochemical cell. ORP is measured in millivolts (mV).

2.5.2 Ozone Chemistry

Wedeco and Trailigaz (2007) believe that molecular ozone is a strong oxidant with a biological effect that results in almost instantaneous cell death of microorganisms.
According to the schematic below (Figure 2-7) ozone either reacts directly with components in the solution or breaks down to secondary oxidants (Fedler *et al*., 2012). Secondary oxidants include hydroxyl radicals (OH), oxygen and hydroxide depending upon the pH and chemistry of the solution in which it is dissolved.

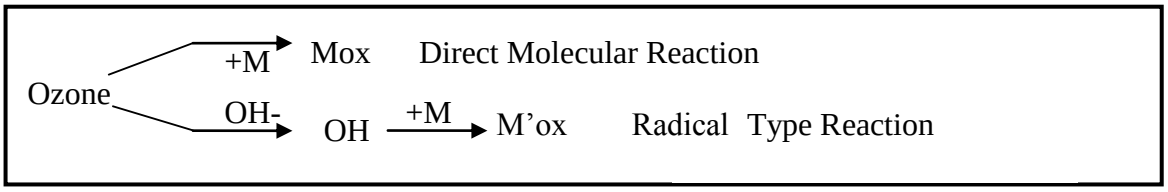

Figure 2-7 Ozone in water

A pH of greater than 7.5 is recommended to avoid corrosion. When the pH increases, O_3 is rapidly decomposed by OH^- to the hydroxyl free radical OH° (Rajagopaul *et al.,* 2008). The OH° free radical is more oxidising than O_3 alone but has a lower action on disinfection. Eriksson *et al.,* (2009) and Sotelo *et al.,* (1989) agreed that ozone is destroyed more rapidly as the water temperature increases, hence a maximum acceptable water temperature of 40°C is advisable. At a temperature of 55°C, ozone rapidly decomposes.

2.5.3 Description of Ozone Treatment System

A full ozone treatment programme includes: feedgas supply equipment, ozone generator, and contacting system (consisting of side stream injector and water pump), (McGrane,

1991). The equipment would be installed in a suitable room/enclosure fitted with appropriate health and safety devices, including an off-gas venting valve.

Alsheyab and Munoz (2007) stated that ozone is generally produced on-site from air or oxygen gas and introduced preferably directly into the cooling water via sidestream injection. It may also be introduced under certain conditions directly into the cooling tower reservoir, shown as optional in
Figure 2-8 below. Once ozone is dissolved in water it proceeds to oxidise organic contaminants and microorganisms. The dosing is controlled automatically by the system-programmable logic controller (PLC) and varies with the water demand.

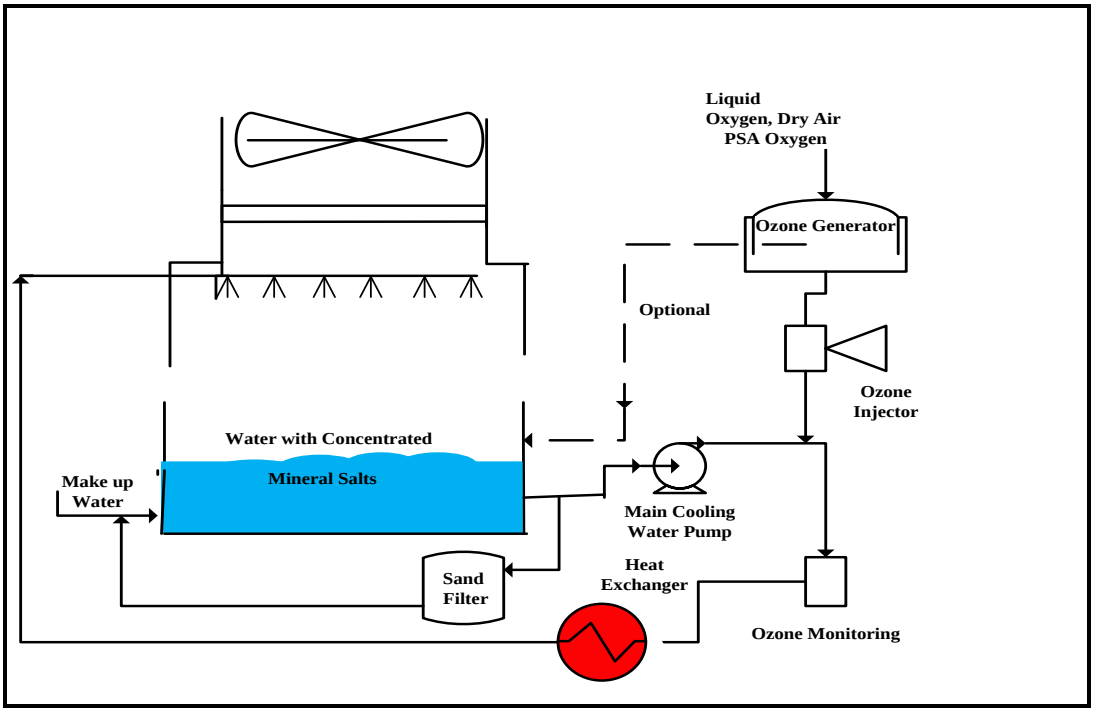

Figure 2-8 Flow diagram of a typical ozone water cooling treatment system, Adapted from Panjeshahi (2009)

Below in Figure 2-9 is a photograph of the typical ozone container standing next to the cooling water tower treatment system.

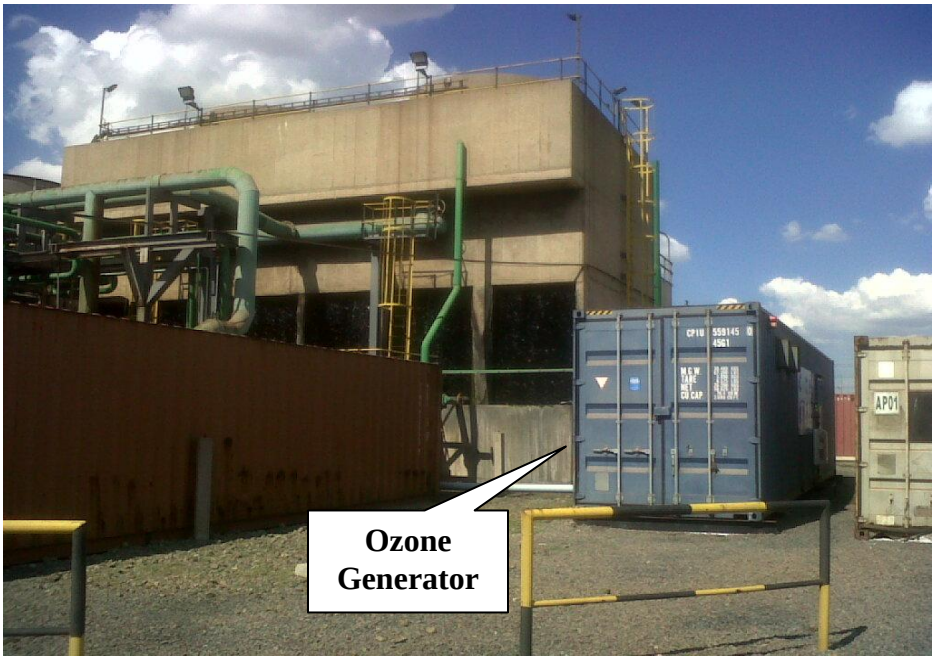

Figure 2-9 Typical ozone generator next to the cooling tower

As already mentioned, ozone can be used solely in cooling water treatment replacing four chemicals. McGrane (1991) acknowledged that ozone has proven to be an extraordinary biocide and is an effective cooling water treatment option. Listed below are some of the disadvantages of ozone (Boner and Peter, 1999):

- At comparative contact times and concentrations it can be toxic compared to some conventional chemicals
- Mixing is required due to ozone being less soluble than chlorine in water
- Capital costs are high compared with conventional chemicals
- Ozonation is not economical for wastewater with high levels of suspended solids, biochemical oxygen demand (BOD), chemical oxygen demand, or total organic carbon

2.6 Application Guidelines

The inconsistent literature on ozone performance in water cooling treatment systems can be coupled to a lack of in-depth understanding of:

1) How water chemistry and / or dissolved organic matter and other water pollutants impact on treatment processes; and

2) Optimal operating conditions or variables (such temperature, pH, ozone dosage rate *e.t.c*) for ozone in water treatment.

Therefore, a comprehensive holistic view and understanding of water chemistry and all cooling water treatment systems related factors is critical for optimal ozone performance.

The work on the application guidelines was done in conjunction with a group of other researchers. The work from this group was published on a research paper. Please refer to Harding *et al.*, 2013 for details on application guidelines.

2.7 Benefits of Ozone Use

It would seem that most businesses that are using ozone agree that ozone has benefits in cooling water treatment (Rajagopaul *et al*., 2008; Panjeshahi *et al.*, 2009). The claimed ozone use benefits range from: water saving and conservation; energy savings and equipment efficiency as a result of low corrosion rates and low fouling or scaling; chemical cost saving; and an excellent disinfection effect on microorganisms (Rice and Wilkes (1992) and CryoGas International (2009 and 2011).

2.7.1 Water Saving and Conservation

The claim that ozone offers water and cost-saving benefits at low scale rates and low corrosion rates is not convincing, even though it is not disproven. On the one hand, most research reports agree that the sole use of ozone for cooling water treatment is capable of conserving water hence cost savings as a result of water saving (Table 2-4 below). The research shown in Table 2-4 presents water saving and equivalent cost benefits from work that was done where a cooling water system was changed from using multiple chemicals for water treatments to solely using ozone. Application of ozone for cooling water treatment increases cycles of concentration, which results in vastly reduced blowdown, treatment costs and make up water volume (You *et al.*, 1998).

Table 2-4 Water and cost saving benefit as a result of using ozone

	Water Saving	Water Cost Savings/year
Tierney (1997)	+/- 32 million gallons / yr	$48,000
McNicholas (2002)	N /A	$107 929
Osgood (1991)	13 percent daily reduction	N / A
Panjeshahi *et al.*(2009)	46%	

Though it should be conceded that ozone offers water and cost-saving benefits at low scale rates and low corrosion rates, the evidence by Keister and Balog (1992) still suggests that:

1) Reasonably high cycles of concentration;
2) Reduction in blowdown volumes; and
3) Improved blowdown quality

Operational conditions are too severe and cannot possibly result in no scaling and low corrosion rates. Therefore, to make a final judgement, one would need to know:

- How much water has been saved by the use of ozone and what is the equivalent water cost saving?

- Are the claimed ozone costs benefits, *e.g.* water saving in cooling water treatment a trade off for heat exchanger equipment damage due to high corrosion rates? Or
  Can the claimed ozone use benefits and no scaling and low corrosion rates co-exist or not?

2.7.2 Equipment Efficiency and Energy Savings

Parker *et al.* (1995) showed that the use of ozone improves heat exchanger system performance in heat transfer because of lack of scaling. Manufacturers claim an average of 10% efficiency gain and case studies range from no improvement to 20% heat exchanger improvement (Parker *et al.,* 1995). Keister and Balog (1992) insist that a thick layer of scale was found on the test heat exchanger. Also, bulk precipitation was not observed in the research work they did. Furthermore, (Keister and Balog, 1992) claimed that where ozone was used successfully on cooling water treatment systems has been achieved under scaling conditions.

Liechti and Kaulbach's (1994) work provides evidence that water with ozone used on a test exchanger achieved a 30 times thinner biofilm as compared to an exchanger with water without ozone. McNicholas (2002) quantifies maintenance savings of $20 000 / year as a result of reduced heat exchanger cleaning times when ozone was used for cooling water treatment.

Where this argument usually ends is on the ability of ozone to solely control scaling and with no or low scaling rates (at higher cycles of concentration and at low or zero blowdown operation) and hence improve heat exchanger heat transfer. Whereas some, Keister and Balog (1992), are convinced that ozone is not a corrosion inhibitor and does not control scale, others maintain that:

- One of the ozone system's attributes is reasonably high cycles of concentration with no scale (Falcos, 2007).

- Ozone is not a corrosion inhibitor but Parker *et al.* (1995) stated that the low blowdown volumes due to high cycles of operation increase the pH of the recirculating water resulting in limited corrosion. Also, the precipitation of silicates and calcium carbonate is supported by the same pH condition where make-up water pretreatment is limited. The scale is removed at lower pH however; the corrosion rate from the ozone will increase.

Furthermore, Parker *et al.* (1995) stated that high corrosion rates as a result of low pH levels from ozone emphasises that it is critical to avoid this problem through the use of good-quality make-up water. The concluding question here is on the efficiency of ozone-treated heat-exchanger systems as compared to conventional chemical systems in terms of limiting scale deposition and fouling.

2.7.3 Chemical Cost Saving

Most ozone end-users for water treatment agree that there is a chemical saving benefit as a result of ozone use (Air Products South Africa (Pty) Ltd Company News, 2011; Rajagopaul *et al*., 2008). Rajagopaul *et al*., 2008 stated that "Midvaal water have reaffirmed a 30% overall savings in chemicals and a 50% reduction in chlorine was also noted when ozone was used". Table 2-5 below presents typical chemical cost saving for cooling water treatment of a system volume of 4 000 m^3.

Table 2-5 Chemical cost savings as a result of using ozone for water treatment (McNicholas, 2002)

Chemical	Cost Savings Per Annum
Inhibitor at 25 ppm	$115 000
Biocides	$100 000
Dispersant	$50 000

NOTE: For pH control the cost of acid is not shown above

Rajagopaul *et al*., 2008 and McNicholas, 2002 offers sufficient evidence that there is a chemical cost saving benefit due to ozone use, Strydom (2004) refutations are more

convincing since one of the barriers of entry for ozone cooling water treatment system are reasonably high capital costs and intensive electrical power requirement. The above stated, therefore poses a question on whether the chemical saving benefit due to ozone use is an disproportionate trade-off for intensive electrical power requirement and high capital cost?

After all, many believe that ozone is a more complex technology requiring complicated equipment and skills expertise, which will result in even more costs (Kruger *et al.*, 2009). However, this conclusion seems to ignore that chemical savings as a standalone do not give a proper cost saving representation as a result of ozone-alone use. Therefore, for a conclusive holistic view on cost saving as a result of ozone use one may want to do a comparison on ozone-treated cooling water system operating costs versus a conventional chemical-treated cooling water system's operating costs.

2.7.4 Potential Reduced Corrosion Rates

Some sceptics have accepted ozone to be an excellent biocide, but find it difficult to comprehend the reported ability to also control corrosion and scale under zero or decreased blowdown operation (Keister and Balog, 1992). Keister and Balog (1992) showed that the use of ozone as a standalone water treatment programme will result in corrosion rates of 10 to 20 times higher than could be obtained via the use of proven corrosion control chemistry. These authors, Keister and Balog (1992), acknowledge that the decrease in corrosion rate that was observed in their research was subsequent to the change from soft to hard make-up water. The use of soft water is the evident cause of 10 to 20 times higher corrosion rates and not the sole use of ozone under zero blowdown cooling tower operation.

Strittmmatter *et al*. (1992) and Smithee (1991) reported that corrosion rates in cooling water have little dependence on ozone, but are dominated by the water chemistry of the system. Water chemistry has an effect on the corrosion rate, hence the decrease in corrosion rate following the change in water quality to hard water in Keister and Balog's

(1992) research work. Strittmmatter *et al*. (1992) and Smithee (1991) are correct in their theory that corrosion rates in cooling water have little dependence on ozone because subsequent studies showed that the Simpson ozone treated cooling towers system revealed that failure mode related to corrosion in cooling towers was customarily related to lack of excellent water balance being sustained, especially where soft make-up water is concerned (Falcos, 2007).

Moreover, Table 2-6 reveals that the sole use of ozone in cooling water treatment is capable of achieving acceptable corrosion rates. Osgood (1991) stated that the high corrosion rates that are noted for grey cast iron in Table 2-6 resulted from the level of total dissolved solids being low. Table 2-6 below reaffirms that water quality influences corrosion rates, not the sole use of ozone.

Table 2-6 Ozone sole use on water treatment low corrosion rates successes

According to	Corrosion
Mueller and Ketchieif (2010),Meyer *et al.* (2003)	Nor scaling takes place at a cooling tower basin water pH of about 8.8.
EMSD (2007) McNicholas (2002)	Rate decreased on heat exchanger that was in operation with ozonated water for 27 months as compared to heat exchanger that was without ozonated water.
Liechti and Kaulbach (1994)	Behaviour cooling tower that demonstrated no change after 22 months
Osgood(1991) (Measurements done by National Water Management Corporation,1989 and 1990)	Rate on five tested metals was < 0. 1 MPY. Except grey cast iron had corrosion rates 1.30- 1.80 MPY
	Mild steel corrosion rates between 1.0 to 1.5 MPY and copper rate between 0.05 to 0.1 MPY,

NOTE: MPY = milli-inches per year.

Ozone is not a corrosion inhibitor. However, the higher concentration ratios resulting from the reduced blowdown volumes raise the pH of the circulating water, which helps protect the system from corrosion. The high pH condition will also promote the precipitation of silicates and calcium carbonate if pretreatment of make-up water is not provided. Falcos (2007) specifies the contributing factors to high corrosion rates on ozone use as a sole treatment for cooling water as: 1) operational shortcomings, 2) lack of ozone dosage monitoring, 3) ozone generator equipment maintenance and 4) water quality.

The above factors stated by Falcos (2007) is supplementary to reports noting successful corrosion control via standalone use of ozone and that water quality is the contributing factor to corrosion. Mosugelo (2010) carried out a corrosion rates comparison study on the Air Products South Africa (Pty) Ltd, Vanderbijlpark, cooling water systems that were treated with conventional chemicals against the system where ozone was used solely. The work revealed that ozone does not influence the rate of corrosion but the quality of the water. The Vaal River water was used as make-up source in the ozone-treated cooling tower. Effluent was a make-up water source for the chemical treated cooling tower. Corrosion is the primary factor affecting equipment integrity, longevity and reliability (Charles, 1990). Potential reduced corrosion rates as a result of using ozone for cooling water treatment offer equipment-replacement costs saving.

2.7.5 Improved Environmental and Regulations Compliance

Many researchers agree that ozone generates fewer toxic byproducts than conventional chemicals and has a half-life of 20 to 30 minutes (Osgood, 1991; Jyoti and Pandit, 2003). In cooling tower water where there are oxidisable impurities the half-life is 1 to 3 minutes. Thus, the treated cooling water can be discharged safely to the sewer system. On the other hand, water that is generated from most if not all of the four conventional chemicals (biocides, corrosion inhibitor, pH control and a dispersant) have a toxic chlorine agent or even more hazardous agents than chlorine, hence it is classed as effluent or wastewater.

Ozone use in most municipal-water treatment for pre-treatment reduces the amount of chlorine for post-treatment (Panjeshahi *et al.,* 2009). One may also argue that most conventional chemicals have an advantage over ozone in that ozone have regulated maximum average allowable concentration to which workers may be exposed over an 8-hour day and a short term exposure limit (South Africa OHS Act Regulation 85, 1993).

Low-quality blowdown that does not meet regulated specification is a liability that needs to be transformed to a savings. Globally, water is becoming an increasingly expensive

resource with mains, sewerage and trade effluent charges rising. Implementation of environmentally friendlier water-treatment alternatives for cooling water treatment supports continuous improvement of better management of our natural resources. Chapter 3 discusses methods that were used to qualify and quantify the benefits of solely ozone use as compared to conventional chemicals for cooling water treatment.

CHAPTER 3

3. RESEARCH DESIGN AND METHOD

This chapter presents the models and method- needed in the analysis of ozone benefits. It provides a discussion on energy-savings calculations, equipment-efficiency- and corrosion-rate calculations. Mass and energy balance are used to calculate the water savings in ozonated cooling systems.

The analysis of economic and environmental benefits of ozone requires various calculations and legislative bases; therefore, this chapter also briefly introduces the South African National Water Act 36 of 1998. The research also looks at regulations 10 and 15 of the OHS Act and Regulation 85 of 1993 relating to hazardous chemical substances in order to quantify and assess the benefits of ozone treated cooling water systems versus chemical treated cooling water systems.

3.1 Data Collection

For this research the data period used was between January 2005 and December 2012, with the data sourced from cooling-tower-operation records from Air Products South Africa (Pty) Ltd, Vanderbijlpark. To investigate the problem of efficiency and effectiveness the study used the following data:

a) Compressor heat exchanger approach temperatures as well as cooling water flow rates retrieved from log readings (Appendix A); and

b) Water quality analyses (on a weekly basis) as from GE Water and Process Technologies Inc. Water analyses included chemical analysis (pH, conductivity, hardness e.*t.c.*), corrosion rates indexes and cycles of concentration.

3.2 Energy Savings and Equipment Efficiency Methods

The energy saving (or loss) and equipment efficiency was calculated from historical process data. An efficient cooling water system was one where the approach temperature in the heat exchanger compressor decreased. This decrease in approach temperature would mean an improvement in a compressor heat exchanger target (approach temperature design target (for new equipment) : 5°C. An efficient heat exchanger compressor system results in a reduction in compressor power consumption. Poor heat transfer results in high compressor power consumption. According to the research done by Energy Efficiency Guide (2006), a decrease of 3°C in cooling water temperature would result in energy saving of about 1%.

3.2.1 Energy Savings

The calculation of the cost benefit in cooling a compressor efficiently as shown by the reduction in compressor power consumption is given below. The heat balance, equation 1, is for the multi-stage compressor system, with cooling between stages.

$$H = U\ A\ \Delta\ T_{LogMean} = L + Q_{Sensible} \qquad \text{Equation 1}$$

Where:

H = Energy process gas, kW

U = Heat transfer coefficient, kW/ (m^2 ^oC)

A = Heat transfer Area, m^2

L = Latent heat of water, kW

$Q_{sensible}$ = Sensible heat of water, kW

Assumptions:

- At steady state,
- Energy is conserved, no radial heat transfer and
- No change in phase and infinitely long heat transfer surface

Heat exchanger equation 1 becomes:

$$H = Q_{Sensible} = m\, C_P\, \Delta T \qquad \text{Equation 2}$$

$$\int_{to}^{t1} H = \int_{to}^{t1} Q = \int_{to}^{t1} mC_p \Delta T \qquad \text{Equation 3}$$

Where:

m = mass flowrate of water

Cp = Specific heat capacity of water, 4.186 Kilojoules/gram °C

$H_1^{to} - H_0 = {}^{t1}(mC_p\Delta T)^{to}$

$$\frac{H1^{to} - Ho^{t1}}{\Delta t} = \frac{(mC_p\Delta T)_{to} - (mC_p\Delta T)_{t1}}{\Delta t} \qquad \text{Equation 4}$$

$$\Delta H = mC_p\ (T_0 - T_1)$$

Assumptions:

The listed below are constant over temperature range:

- Cp, Specific heat capacity of water
- m, mass flowrate of water
- Volumetric flowrate of air

$$\Delta H = Const \text{ x } (T_2 - T_1)$$

According to Energy Efficiency Guide (2006) the relationship between energy consumption and temperature is 3

$$1\%\ \Delta H = 3 \text{ x } (T_2 - T_1) \qquad \text{Equation 5}$$

Equation 5 above shows that a decrease of 3°C in cooling water temperature would result in energy saving of about 1%.

Therefore, cost saving due to power saving is:

$$C = R \times C_E \text{ x } HL \times \frac{N}{\text{No.of Heat Exchangers}} \qquad \text{Equation 6}$$

Where:

C = Cost saving due to power saving, Rands
R = Ratio of 1% and 3°C,

1% is compressor energy consumption and 3°C is heat exchanger approach temperature improvement i.e.: decrease of 3°C results in energy saving of about 1% and increase of 3°C results in energy accumulation of about 1%.

C_E = Municipal energy costs, cents / kWh
HL = Compressor heat load, MW
N = Compressor number of stages

3.2.2 Equipment Efficiency: Scaling and Fouling

The standard method to predict the amount of scale formed is the Langelier Saturation Index (LSI). The LSI determines (at varying conditions) the probable amount of calcium carbonate precipitation, or solubility tendencies (Pryor and Fisher, 1993). The equation below, Equation 7, stated the relationship of pH, calcium, total alkalinity, dissolved solids and temperature as they correlate to the solubility of calcium carbonate in waters with a pH of 6.5 to 9.5.

The LSI is the difference between the actual pH (pHa) of a sample of water and the calculated pH in Equation 7 below. A positive LSI indicates that calcium carbonate is likely to deposit. A negative LSI shows that calcium carbonate is likely to dissolve. If LSI is zero, the water is at stability point.

$$pH = (pK_2 - pK_s) + pCa^{2+} + pAlk \qquad \text{Equation 7}$$

Where

pH = the pH at which water with a given calcium content and alkalinity is in equilibrium with calcium carbonate

pAlk = pH total alkalinity

pCa^{2+} = pH calcium content

K_2 = the second dissociation constant for carbonic acid

Ks = the solubility product constant for calcium carbonate

$$LSI = pH_a - pH \qquad \text{Equation 8}$$

The LSI does not quantify calcium carbonate precipitate, but measures the tendencies of dissolved solids to precipitate or stay in solution.

Pryor and Fisher (1993) have proven that the conventional indices (*e.g.* LSI) used to forecast calcium carbonate precipitation in conventionally treated cooling tower waters are not precise indicators of scaling potential in ozonated systems. As a result Pryor and Fisher (1993) devised that the practical approach, Practical Ozone Scaling Index (POSI), equation 9 predicts the upper limits of operating conductivity in ozonated systems much more accurately. The use of the conventional indices cannot predict constantly at what cycles of concentration scaling would begin to occur in an ozonated cooling system.

Water quality analysis results provide conductivity for cooling tower and MU water conductivity. Otherwise, Equation 9 calculates the maximum possible cycles of concentration (based on conductivity) that can be attained with no occurrence of scaling.

$$MC = \exp 10 \left(\frac{1}{\log} \text{ x } \frac{(Ca \text{ x } Mg)}{(Na+Cl)}\right) \text{x Alk x Conductivity}_{Makeup} \qquad \text{Equation 9}$$

Where:

MC	=	Maximum Conductivity, Micro-Siemens/Centimetre
Ca^{2+}	=	Calcium Hardness in the makeup water expressed as $CaCO_3$
Mg	=	Magnesium Hardness in the makeup water expressed as $CaCO_3$
Alk	=	Total Alkalinity in the makeup water expressed as $CaCO_3$
Cl	=	Chlorides in the makeup water expressed as Cl
Na	=	Sodium in the makeup water expressed as Na^+
Cond $_{(Tower)}$	=	Tower Water Conductivity, Micro-Siemens/Centimetre
Cond $_{(Makeup)}$	=	Makeup Water Conductivity, Micro-Siemens/Centimetre

Low cycles of concentration result in poor passivation of metal surfaces and therefore exposure to corrosion. Pryor and Fisher (1993) believe that ozone cooling water system should be recycled until the cooling tower water silica concentration and alkalinity exceed 150mg/l SiO_2 and 450mg/l $CaCO_3$ respectively.

3.2.3 Approach Temperatures

The rate of fouling was also monitored through log sheets for heat exchanger approach temperature. A continuous increase in approach temperature indicated that the heat exchanger was most probably fouling. These are the same readings that were used for quantifying energy saving as detailed in 3.2.1. The heat exchanger shell and tube discharge lines are fitted with temperature probes to measure approach temperature as shown in Figure 3-1 below

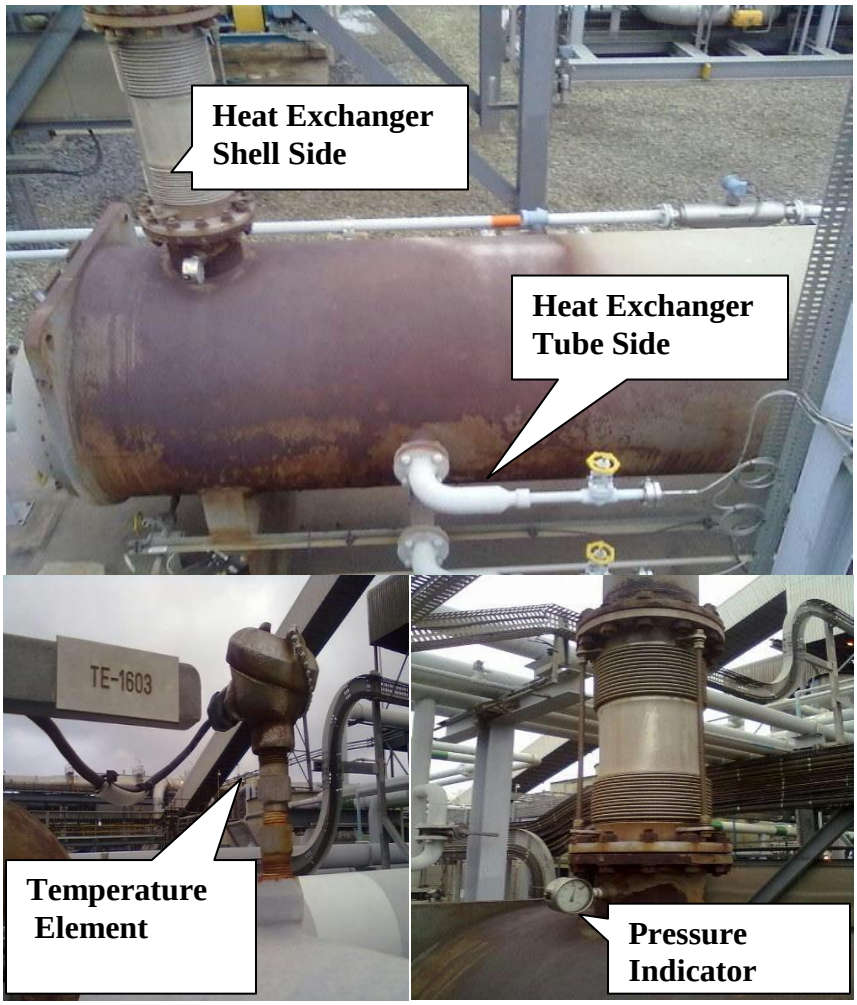

Figure 3-1 Heat Exchanger temperature probe insertion and indicator points

The cooling water flows through the heat exchanger tubes to remove heat from the process stream then recirculates back to the cooling tower for cooling, as shown in Figure 2-1. As the cooling water flows through the inside of the heat exchanger tubes, scale deposits and fouling accumulate on tube surfaces. The rate of scale deposits and fouling formation is mainly dependent on water quality. Increase in scale or fouling rate decreases heat transfer through the heat exchanger tube surface. The increase in scale results in a decrease in cooling water utilization and an increase in process stream temperature. At constant flowrate and surface area, increases in temperature difference between the cold and hot fluid can be associated to an increase in fouling factor as described below:

$$q = U_d A_O \Delta T_{LogMean}$$ Equation 10

Where:

U_d = overall design coefficient of heat transfer, in kW/ (m^2 ^oC), based on unit area of the outside tube surface

A_o = Overall area, m^2

$\Delta T_{LogMean}$ = Difference of water outlet and inlet temperatures, ^oC

The overall heat transfer coefficient represents the total resistance to heat transfer from one fluid to another. Equation 11 below shows this relationship.

$$U_d = \frac{1}{\frac{1}{h_o} + R_o + R_k + \frac{R_i A_o}{A_i} + \frac{A_o}{h_i A_i}}$$ Equation 11

Where:

U_d = overall design coefficient of heat transfer, in *k*W/ (m^2 ^oC), based on unit area of the outside tube surface

h_o = film heat transfer coefficient average unit – surface conductance of fluid on the outside of tubing, in kW/ (m^2 ^oC).

h_i = film heat transfer coefficient average unit – surface conductance of fluid inside tubing in, kW/ (m^2 ^oC).

R_o = unit fouling resistance on outside of tubing, in m^2 ^oC/ kW.

R_i = unit fouling resistance on inside of tubing, in m^2 ^oC/ kW.

R_k = unit resistance of tubing outside in hour m^2 outside tube surface ^oC/ W.

A_o / A_i = ratio of outside tube surface to inside tube surface.

3.3 Water Saving Methodology

For this analysis, since no flow meters were installed in each stream, a material (mass) balance was used, equation 12. To determine the mass balance of water flowing in the system, an energy balance was conducted across the compressor heat exchangers.

$$V_m = V_{RE} + V_B + V_D + V_{EV} \quad \text{Equation 12}$$

Defined below are losses that control the cooling tower operation of conventional chemicals and ozone treated cooling water systems;

Where:

V_m = Volumetric flow of make-up, m^3/hour
V_{EV} = Volumetric flow of evaporation, m^3/hour
V_D = Volumetric flow of drift losses, m^3/hour
V_B = Volumetric flow of blow down, m^3/hour
V_{RE} = Volumetric flow of recirculation, m^3/hour

The material balance was conducted around the cooling tower based on Figure 2-1. When a mass balance is conducted on a cooling tower system cycles of concentration become the basis of these computations.

3.4 Corrosion Rate Quantification

Corrosion and its effects have been studied using corrosion coupon methods for a very long time. Corrosion coupon method is the most cost-effective and efficient method of quantifying corrosion and its effects. This method looks at the change in mass of the coupon overtime. The coupon insertion points are in the cooling tower return line, where the water temperature is more or less the same as the heat exchanger water temperature. Hence, whatever corrosion rates that are quantified through a coupon should be the same as the actual corrosion rates in the heat exchangers.

3.4.1 Preparation of Coupons for Installation in the Cooling Towers

There were three different types of metal corrosion coupons prepared: stainless steel, brass and mild steel. Each coupon was etched with a unique sample number for traceability. Figure 3-2 shows a coupon that was taken out of the recirculation line for demonstration. The coupons were mechanically cleaned and polished using a grinder to remove the surface oxide layer and were washed with distilled water followed by ethanol and later dried in a desiccator. The mass and dimension of each coupon were taken with the use of a scale and Vernier calliper.



Figure 3-2 Coupon that has been taken out of the return water line, for demonstration

To keep the coupon clean laboratory gloves were worn to prevent contamination from moisture and oils present on fingers. Coupons were then attached on the coupon holder, secured by nut and bolt and screwed in place (Figure 3-2 and Figure 3-3 below). Before and after harvesting, each coupon was placed in a well labelled moisture proof envelope. These coupons were harvested from a corrosion rack placed at the cooling water return line (Figure 3-4 and Figure 3-5). In the corrosion rack the coupons are exposed to chemically- and ozone-treated cooling water. The exposure time of these coupons was up to three months due to that history have proven this to be the realistic duration.

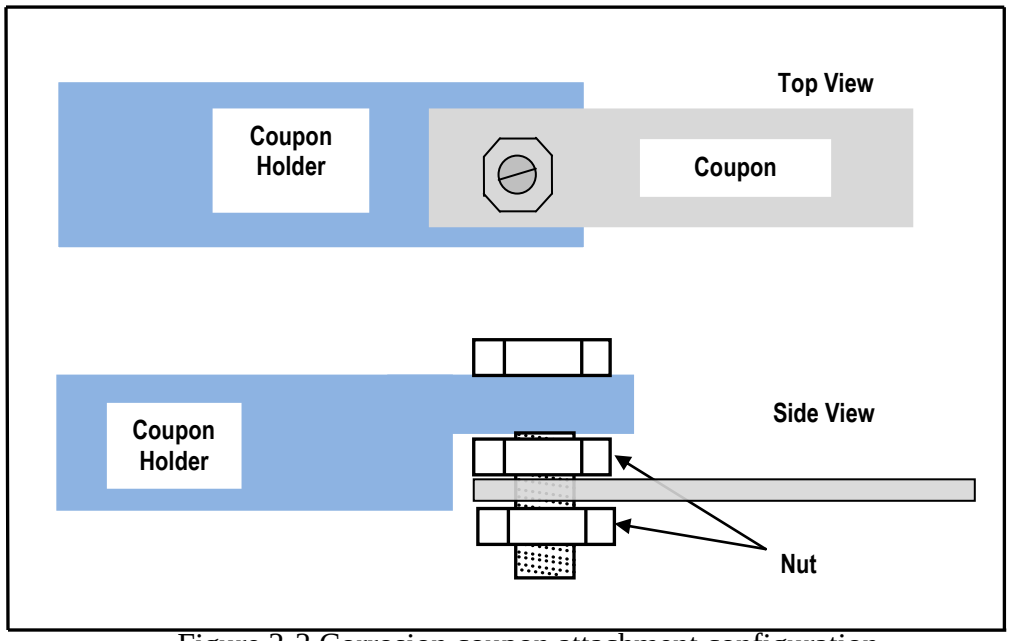

Figure 3-3 Corrosion coupon attachment configuration



Figure 3-4 Corrosion coupon insertion



Figure 3-5 Corrosion coupon insertion points

3.4.2 Corrosion coupon cleaning and weighing laboratory procedure

After the exposure time had elapsed, the corrosion coupons were photographed after before they were cleaned and after cleaning. Visual inspection was done next in order to determine the type of corrosion that had taken place and analysed to see if any scale or foreign material existed. The ccorrosion coupons were then placed in a glass beaker in a drying oven at 105°C for a minimum of one hour. The glass beaker with the corrosion coupons was then removed from the oven and allowed to cool in desiccators.

The weights of the corrosion coupons were taken and were recorded. The corrosion coupons were then immersed and swirled in a beaker containing 10% sodium hydroxide solution. This was done to dissolve the organic portion of the deposits. Tweezers were used if required to remove larger organic material. The corrosion coupons were then removed from the solution and were rinsed with tap water. Light brushing was also done

to remove soft deposits. Coupons were further rinsed with acetone and the drying process was repeated. The corrosion coupons were again immersed in a 50% hydrochloric acid solution for a period of one to three minutes to remove scale deposits. Tweezers were used if required.

Once again corrosion coupons were rinsed, under running tap water and these coupons were immersed in a 10% sodium carbonate solution to neutralize the acid. A final rinse was done under tap water and dried. The coupon was weighed and recorded. Weight loss was calculated and matched to serial numbers.

3.4.3 Reporting of Results

The corrosion rate, dimensional change or loss of metal thickness per unit time and referred to as mils-per-year (mpy) was calculated with the use of equation 13 below:

$$\frac{\text{mills}}{\text{annum(mpy)}} = \frac{WL_{coupon}}{A \times 16.4} \frac{\times 365}{ET \times \rho} \qquad \text{Equation 13}$$

Where:

WL_{Coupon}	=	Weight Loss of Coupon, (g)
A	=	Total Exposed Area of Coupon, (cm^2)
ET	=	Exposure Time, (days)
ρ	=	Density of metal, (g/cm^3)

The corrosion rate weight loss can be expressed in various measurements. At the end what matters is expressing the amount of metal damage due to corrosion, irrespective of units used. The mils-per-year (mpy) corrosion rate units of measure have been used since they are commonly used unit for corrosion rates and are also believed to be the best in expressing penetration rates without decimals or large numbers.

$$\text{Area (A)}(cm^2) = 2\left((L \times W) + (L \times T) + (W \times T)\right) - \pi r^2 \times T) \qquad \text{Equation 14}$$

L = Corrosion coupon length, cm

W = Corrosion coupon width, cm

T = Corrosion coupon thickness, cm

D = Diameter of the hole on the corrosion coupon, cm

3.5 Operating-Costs Saving in Cooling Water Treatment

The equations below were used to calculate the monthly operating costs of ozone-treated and conventional chemically treated cooling water systems.

$$CCWTC = \text{BD Volume Loss Costs} + MUH_2O \text{ Costs} + \text{Chemical Costs} \qquad \text{Equation 15}$$

Where:

CCWTC = Chemical Cooling Water Treatment Costs, Rands

BD = Blowdown

MU = Makeup

$$OCWTC = \text{BD Volume Loss Costs} + MUH_2O \text{ Costs} + \text{Costs for } O_3 + \text{ECosts} \qquad \text{Equation 16}$$

Where:

OCWTC = Ozone Cooling Water Treatment Costs, Rands

BD = Blowdown Water Costs, Rands / kilolitre

MUH_2O = Make-up Water Costs, Rands / kilolitre

ECost = Ozone Generator Electricity Costs, Rands/KW

NOTE : Wastewater treatment costs are not included.

3.6 Qualitative Environmental Compliance Review against related Legislation

This section explores the method that was used for assessment of conventional chemicals versus ozone use alone on cooling water treatment systems' ease of compliance with the water, personnel, health and safety and environmental regulations. The assessment was based on the listed identified pieces of legislation:

1. South African Occupational Health and Safety Act 85 of 1993 Regulations 10 and 15 relating to Hazardous Chemical Substances (SANS 10263-5:2009).
2. National Water Act (1998) Section 19.

CHAPTER 4

4. RESULTS AND DISCUSSION

This chapter presents the results of the study and discusses the benefits of using ozone as a standalone water treatment programme. Ozone is compared to conventional chemicals in cooling water treatment systems at the Air Products South Africa (Pty) Ltd, Vanderbijlpark facility. The focus of this section will be quantifying energy, water savings (or losses), chemical savings and equipment efficiency.

4.1 Cost Saving as a result of Energy Savings and Equipment Efficiency

4.1.1 Energy Savings

Costs saving results are presented in Table 4-1 below, where ozone-treated cooling water systems were compared with a chemically treated system. The negative figure denotes that the approach temperatures deteriorated; this represents a loss in rands. The positive figures denote that approach temperatures improved; this represents a gain in rands. A zero figure means that there was neither loss nor gain. Energy saving calculations on how the numbers in Table 4-1 were obtained are given in Appendix D.

Table 4-1 Ozone-treated cooling tower cost saving as a result of energy savings

Time	Ozone Treated		Chemical Treated	
	Compressor Heat Exchangers		Compressor Heat Exchangers	
	K803	K1003	K703	K702
Year 1	-R 7,046	-R 97,424	This is new equipment; it didn't exist at this period.	-R 112,102
Year 2	R 17,133	-R 20,335		-R 59,583
Year 3	R 2,387	R 14,271		-R 43,200
Year 4	R 0,000	-R 81,771	-R 87,259	-R 90,056
Total four-year period cost Saving or loss	R33 791		-R392 200	

Note: Total four-year period cost saving or loss is a sum of year 1 to 4.

According to Table 4-1, the calculated total cost in year 1 on K803 was -R 7 046. This was when the ozone cooling water treatment system was commissioned. The results show that for year 2 and year 3 there were savings, meaning that the system was operating efficiently. Over the period of four years a saving of R425 991 was observed. This figure consists of ozone saving of R33 791 plus an opportunity cost saving of R392 200 if chemicals had been used.

4.1.2 Equipment Efficiency

In the period March 2005 to September 2007 in Figure 4-1 and Figure 4-2 an inconsistent trend with a high scale of accumulation in approach temperatures is observed throughout all three heat exchanger stages. However, subsequent to the third quarter of 2007 a consistent trend with a low scale of accumulation in approach temperatures is observed throughout all three stages in Figure 4-1 and Figure 4-2. A significant step change in September 2007 is observed in the 3rd stage, Figure 4-1.

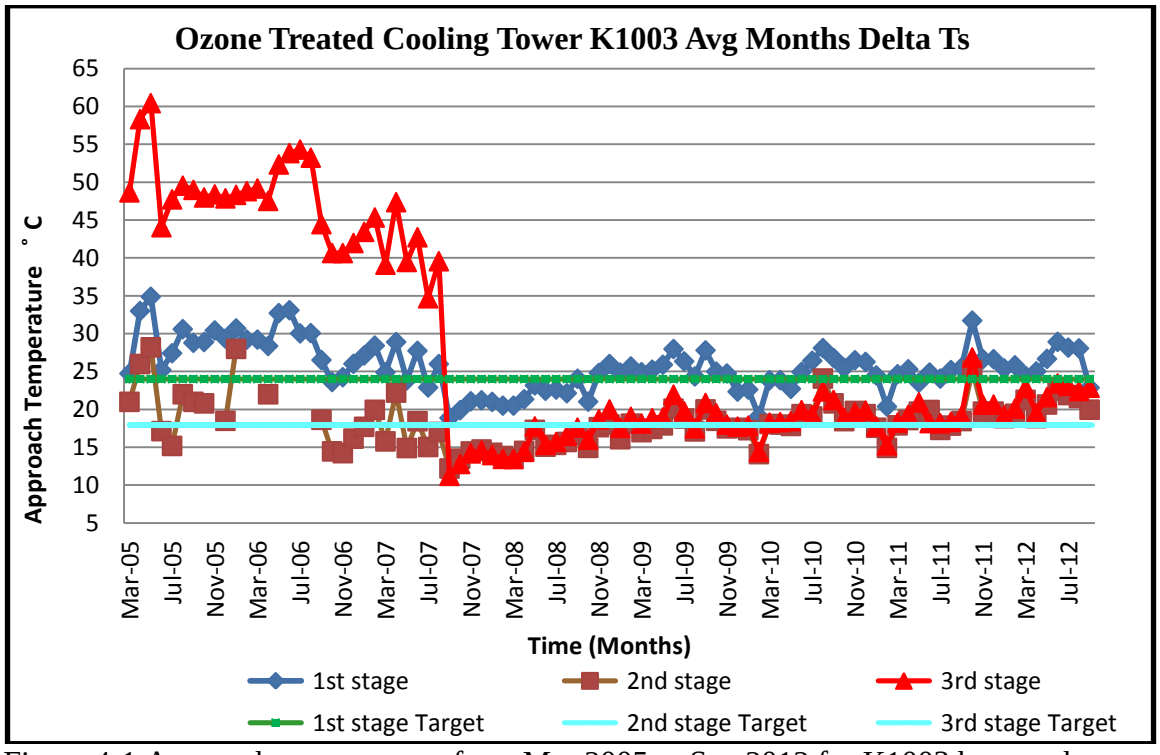

Figure 4-1 Approach temperatures from Mar 2005 to Sep 2012 for K1003 heat exchanger

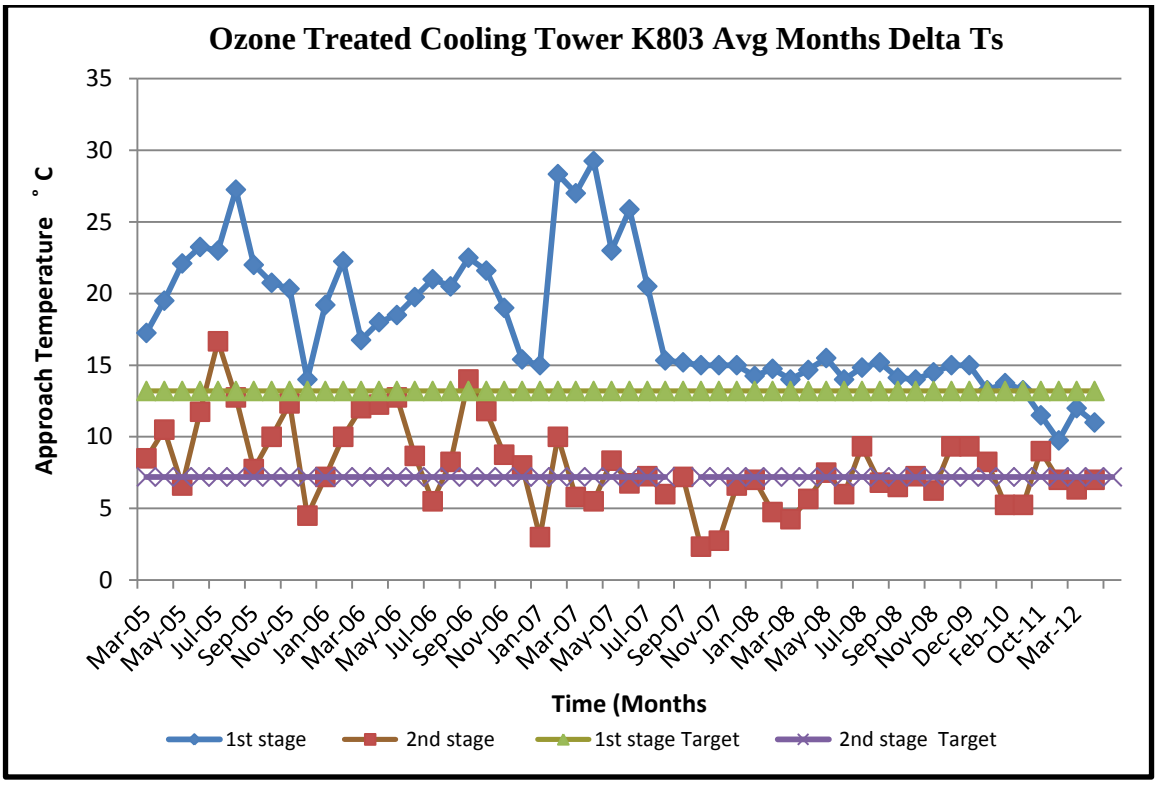

Figure 4-2 Approach temperatures from Mar 2005 to Sep 2012 for K803 heat exchanger

The observed inconsistent trend with a high scale of accumulation in approach temperatures during the period of March 2005 to September 2007 was when conventional chemicals were used. The observed changes in approach temperature in Figure 4-1 and Figure 4-2 in the third quarter of 2007 were following compressor heat exchanger cleaning and a switch to ozone use. A stable trend with low scale of accumulation in approach temperatures is observed after the third quarter of 2007 in both Figure 4-1 and Figure 4-2 due to ozone use.

The imbalances in cooling water distribution on the heat exchanger compressors might be the reason for the observed varying temperature trend behaviors between stages (Figure 4-1 and Figure 4-2) i.e.:

- A significant step change in the 3rd stage as compared to the slight decrease in 1st and 2nd stage temperatures in September 2007 shown in Figure 4-1; and
- A constant rise in stage 2 temperatures as compared to the observed decrease in stage 1 temperatures, September 2007, as shown in Figure 4-2.

There are noticeable peaks in the period August 2007 to August 2012 in Figure 4-3. The peaks in Figure 4-3 are averaged at 23°C throughout all the compressor stages. The overall trend of Figure 4-3 is linearly upward, with a high scale of accumulation in approach observable through the analysis period. The observed trend in Figure 4-3 was when only conventional chemicals were used for the period August 2007 to August 2012.

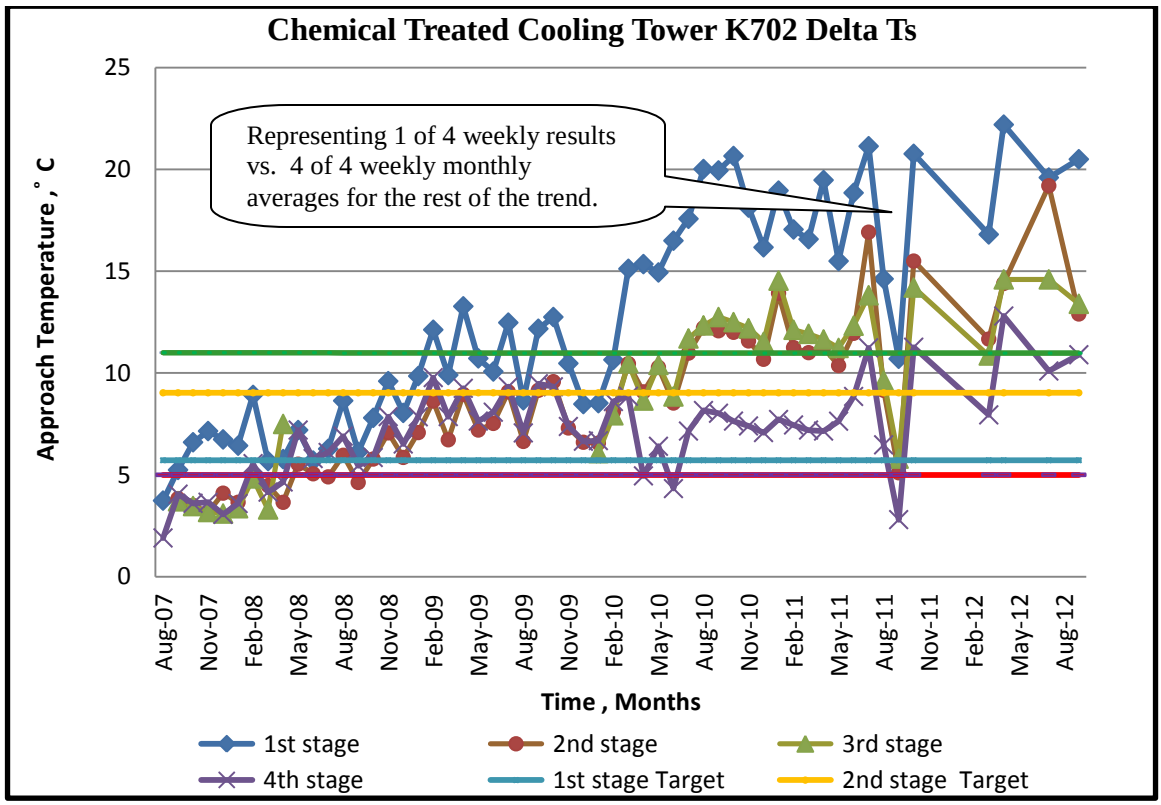

Figure 4-3 Approach temperatures from Mar 2005 to Sep 2012 for K702 heat exchanger

Heat exchanger compressor K703 approach temperatures are shown below in Figure 4-4 An target approach temperature of 2°C and a target of 5°C by design were shown and plotted against the actual approach temperatures for stages 1 to 6. The lower initial approach temperature target of 2°C in heat exchanger compressor K703, was a result of the compressor being fairly new. This heat exchanger was installed and has been in operation for less than two years. Nevertheless, a considerable upward trend with a high scale of accumulation in approach temperature trend is observed. The observed trend in Figure 4-4 was when only conventional chemicals were used for the period August 2007 to August 2012.

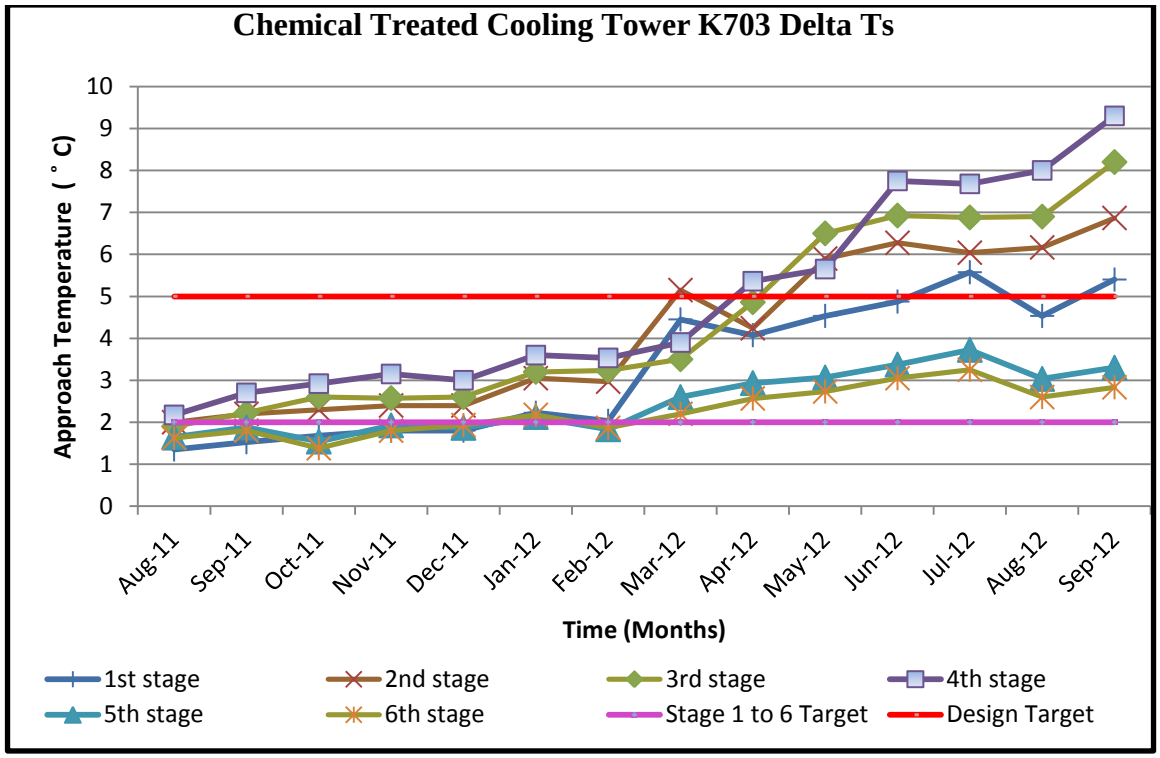

Figure 4-4 Approach temperatures from Mar 2005 to Sep 2012 for K703 heat exchanger

The upward trend with a high scale of accumulation in approach temperatures in Figure 4-3 and Figure 4-4 shows inefficient heat exchanger heat transfer. This inefficiency may be due to acids and/or dispersants being overdosed. Poor pH and/or dispersion control in a cooling water system will result in an alkaline cooling water system that will have high

tendencies to precipitate and suspended solids that may block tubes. Either of these will result in scale or fouling, which will cause inefficient cooling.

Approach temperature trends comparison between ozone, Figure 4-1 and Figure 4-2 chemical treated heat exchangers, (Figure 4-3 and Figure 4-4)

When approach temperature graphs and approach temperatures are looked at as an indicator for heat exchanger fouling, it can be noted that the approach temperatures rate of scale accumulation in chemical treated cooling systems (Figure 4-4 and Figure 4-4) is higher than ozone-treated cooling systems, Figure 4-1 and Figure 4-2.

A low scale of accumulation in approach temperatures for chemically treated heat exchanger compressor K703, Figure 4-4, would have been expected since this heat exchanger compressor was at the time of use only for 1.5 years. This means that the rate of heat transfer resistance contributors such as fouling and scaling would be expected to be mininal. Since conventional chemicals were being used for treatment on this tower a high scale of accumulation in approach temperatures is evident.

The same trend, a high scale of accumulation in approach temperatures, was observed with K702, Figure 4-3, the other chemical-treated compressor heat exchanger. This is mainly because there is a limit to chemical cleaning. Accumulation of, for example, dissolved solids, chemical solute concentration in the water system causes approach temperatures to increase by a degree or two. When this happens, it is an industry best practice to mechanically clean heat exchangers.

4.2 Operating Costs Saving for Ozone-treated Cooling Tower Water Treatment

This subsection shows typical monthly operating costs of ozone- and chemical-cooling water treatment, as adapted by the Air Products South Africa (Pty) Ltd, Vanderbijlpark, cooling water system.

Table 4-2 Ozone- versus chemical-cooling-water monthly operating costs

	Treatment System	
	Conventional Chemical	Ozone
Biocide	R 25 046	N/A
Corrosion Inhibitor		
Acid (pH Control)		
Dispersant		
Cost of Treatment: fixed cost depreciation of Ozone generator over 10 years	N/A	R18 000
Ozone Generator Electricity Cost / months		R3 234
Make-Up Water Cost	R36 817	R20 454
Oxygen Consumption /month	N/A	R2 848
TOTAL	R61 863	R44 536
Total Monthly Water and Chemical Savings on this Tower	R17 327	

The above results are based on the factors that follow.

- 70,000 m^3 of water per month.
- Blowdown loss cost not included.
- Costs saving due to improved approach temperatures.
- Electricity cost based on latest 2012 tariffs of about 20% annual increases.
- Make up water on chemical treatment 24.35 m^3 / hr as compared to ozone makeup water which is 13.53 m^3 / hr
- The analysis was done on the tower that was previously on chemical treatment and now on full-scale ozone treatment.

4.3 Water Saving due to Ozone Use

Water utilisation on a full-scale ozone-treated cooling tower is shown in Figure 4-5. Cooling tower losses are as defined in Section 2.1 of this report. Drift and evaporation losses were calculated at a fixed recirculation rate.

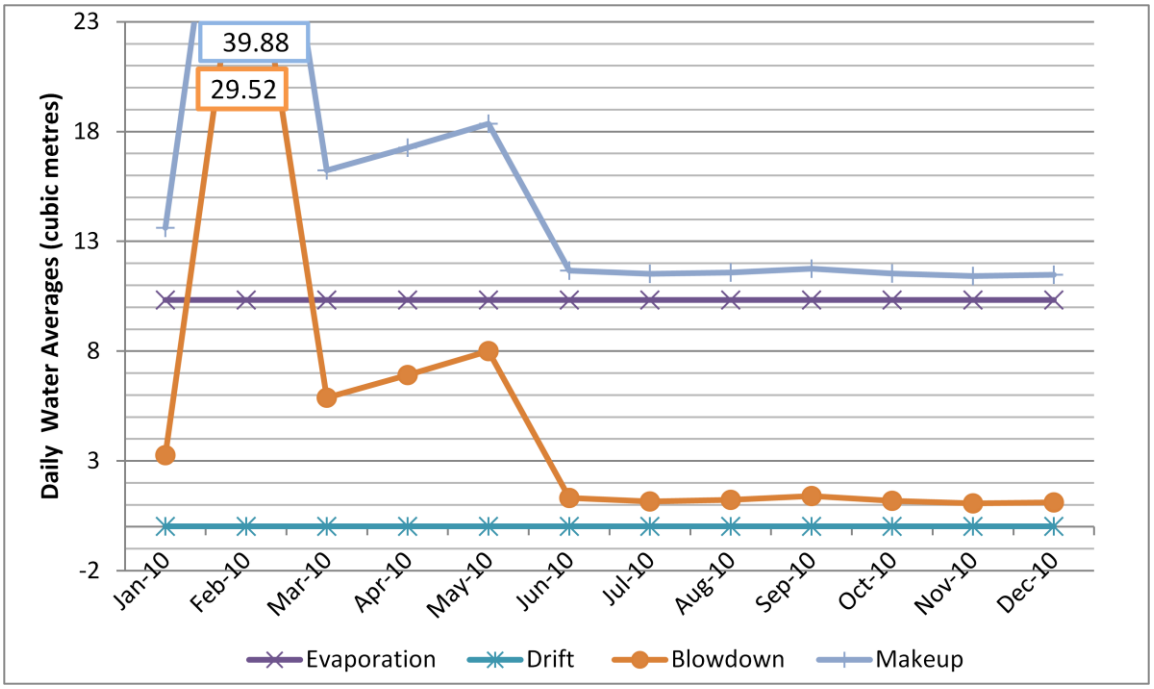

Figure 4-5 Water utilisation on the ozone-treated cooling tower

From Figure 4-5 it can be seen that the makeup and blowdown rate decreased drastically. This water reduction was due to the cooling tower being operated at higher cycles of concentration due to ozone use.

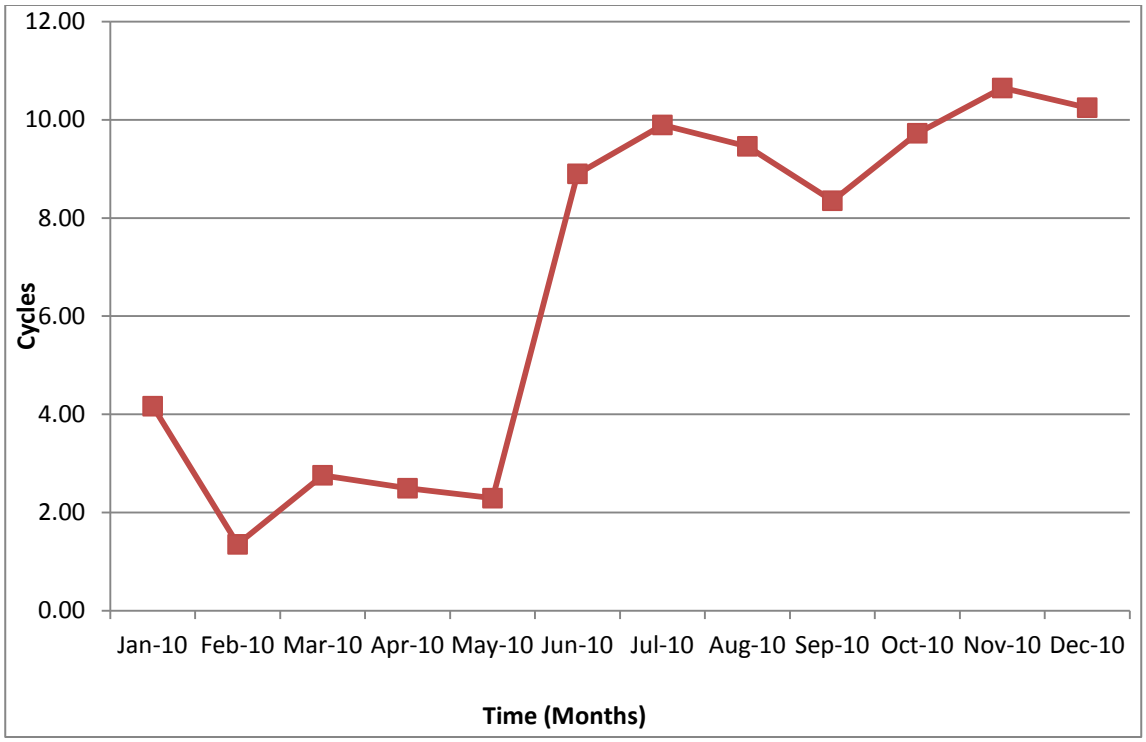

Figure 4-6 Cycles of concentration on the ozone-treated (D) Cooling Tower

Figure 4-6 shows that there was an improvement in cycles of concentration as from the month of September when the cooling tower was switched from being treated with conventional chemicals to ozone.

4.4 Corrosion Effects

This section presents the results of corrosion effects when ozone-treated cooling tower systems were compared with a chemically treated tower systems. Corrosion methodology details are given in Section 3.4 of this report. The control limits are given in Table 4-3 below.

Table 4-3 Corrosion Coupon Targets

No.	Coupon Type	Target (mpy)
1	Carbon Steel	2
2	Stainless Steel	0.2
3	Brass	0.2

4.4.1 Stainless Steel Corrosion Rate Analysis

The results of the stainless steel corrosion-rate coupon in ozone versus chemical cooling tower is shown in Figure 4-7. Corrosion-rate targets for the stainless steel material are 0.2 mpy, as shown in green circles. From Figure 4-7 it can be noted that both the chemically treated coupon and the ozone-treated coupon were below the 0.2 mpy target for most of the 5-year research period. However, two major peaks of 6.1 mpy in the third quarter of 2009 and 5.5 mpy in the third fourth quarter of 2011 were noted on the ozone-treated coupon and chemically treated coupon respectively.

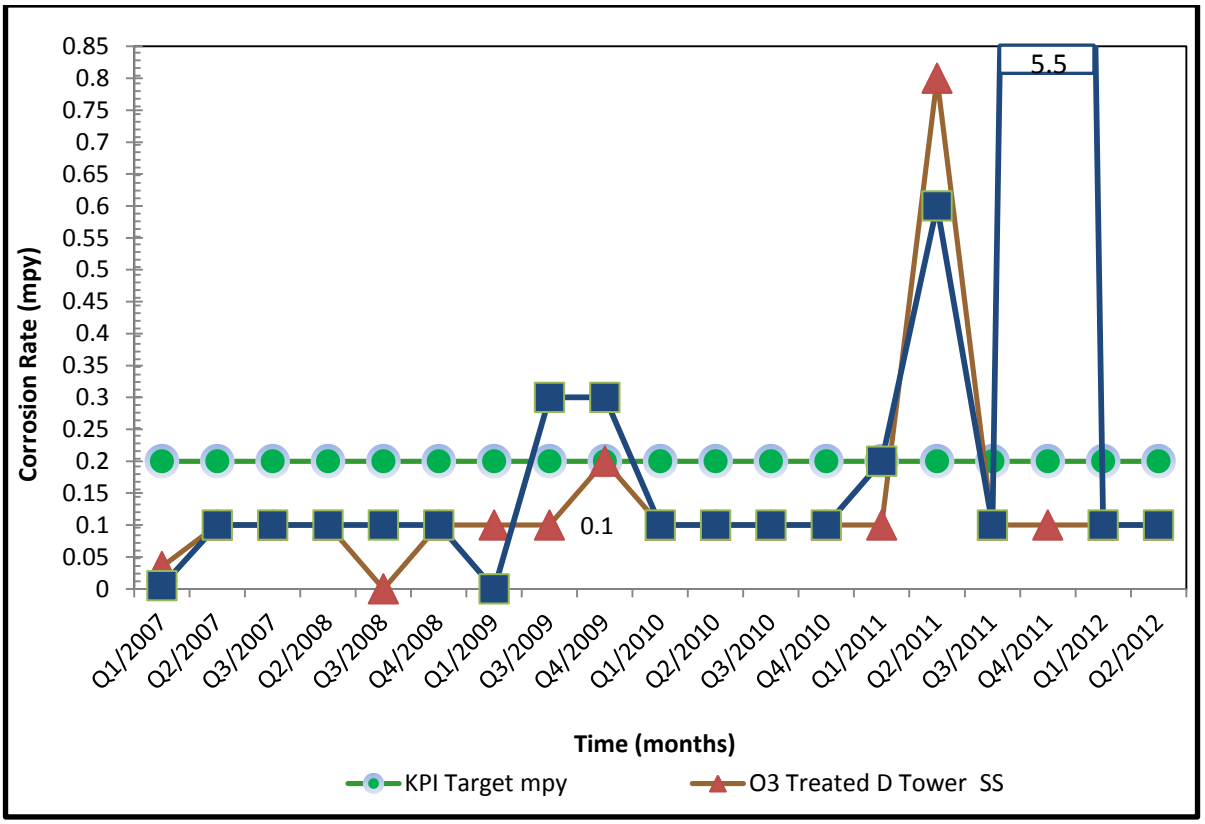

Figure 4-7 Stainless steel ozone *vs.* chemical coupon corrosion rates in cooling towers

4.4.2 Brass Analysis Corrosion-rate Analysis

The results of the brass corrosion rate coupon in ozone versus chemical cooling tower are shown in Figure 4-8. The corrosion-rate target for the brass material is also 0.2 mpy, as shown in green circles in Figure 4-8 below. It can be noted that the corrosion rates measured in both coupons exposed to the ozone treated and chemically treated cooling water were outside the 2 mpy target for the first year of the research period. A major peak of 16.9 mpy in the second quarter of 2008 is noted for the chemically treated coupon.

The highest peak of 1.1 mpy in the second quarter of 2008 is noted for the chemically treated coupon. A highest peak of 0.7 mpy is noted for the ozone-treated coupon at the second quarter of 2011. The high corrosion rate in the ozone treated coupon can be attributed to the passivation-period requirements for all ozonated systems. Ozone systems require a period of three months' passivation. In these three months a protective layer of calcium carbonate forms on material surfaces. This layer prevents metal surfaces from being oxidised.

Ozone-treated tower corrosion rate was outside of the specifications for the whole year in 2010 and the first and second quarter of 2011. The chemically treated tower was outside of the target for the most part of the research period. Only quarter three of 2008 and quarters three and four of 2009 were the corrosion rates on target.

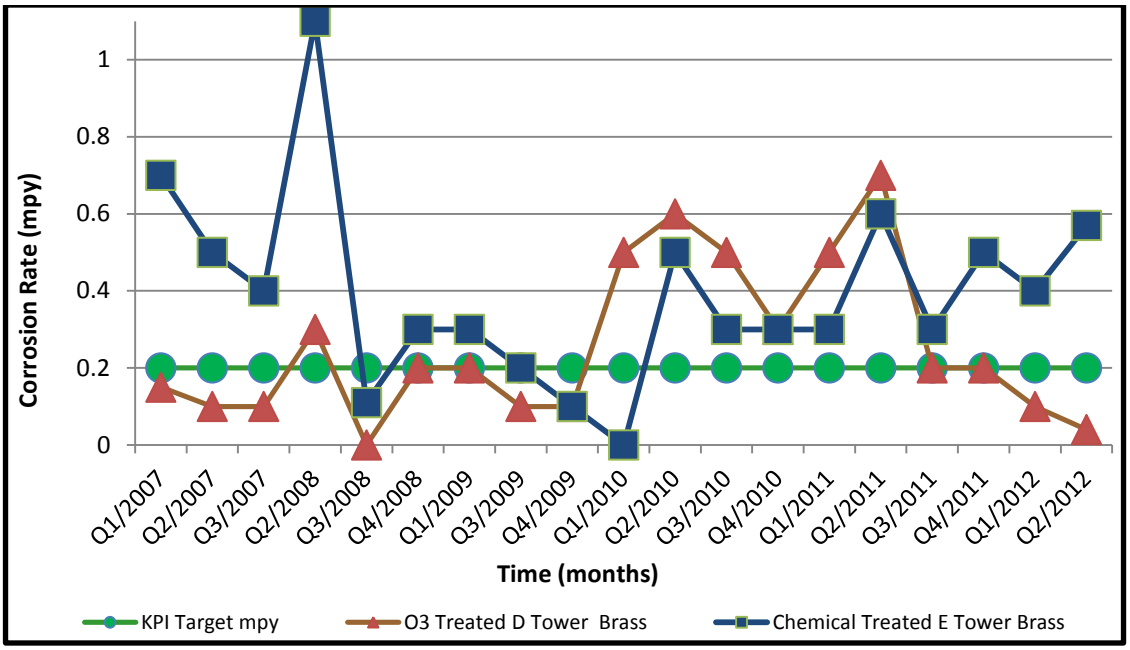

Figure 4-8 Brass-ozone- versus chemical-treated coupon corrosion rate

4.4.3 Mild-steel Corrosion-rate Analysis

The results of the mild-steel corrosion-rate coupon in ozone *vs.* chemical cooling tower are shown in Figure 4-9. The corrosion-rate target for the mild steel material is 2 mpy as shown in green circles. It can be noted that the corrosion rates measured in both coupons exposed to the ozone treated and chemically treated cooling water were outside the 2 mpy target for the first year of the research period. A major peak of 16.9 mpy in the second quarter of 2008 is noted for the chemically treated coupon.

A major peak to the value of 10.1 mpy is noted on the ozone-treated coupon in the first quarter of 2010. The high corrosion rate in the ozone treated coupon was as a result of instability in the water quality caused by external factors. As a result the corrosion rates in the ozone treated tower were outside of specifications for the whole of 2011. The chemical treated tower was within target between the fourth quarter of 2008 and the third quarter of 2011.

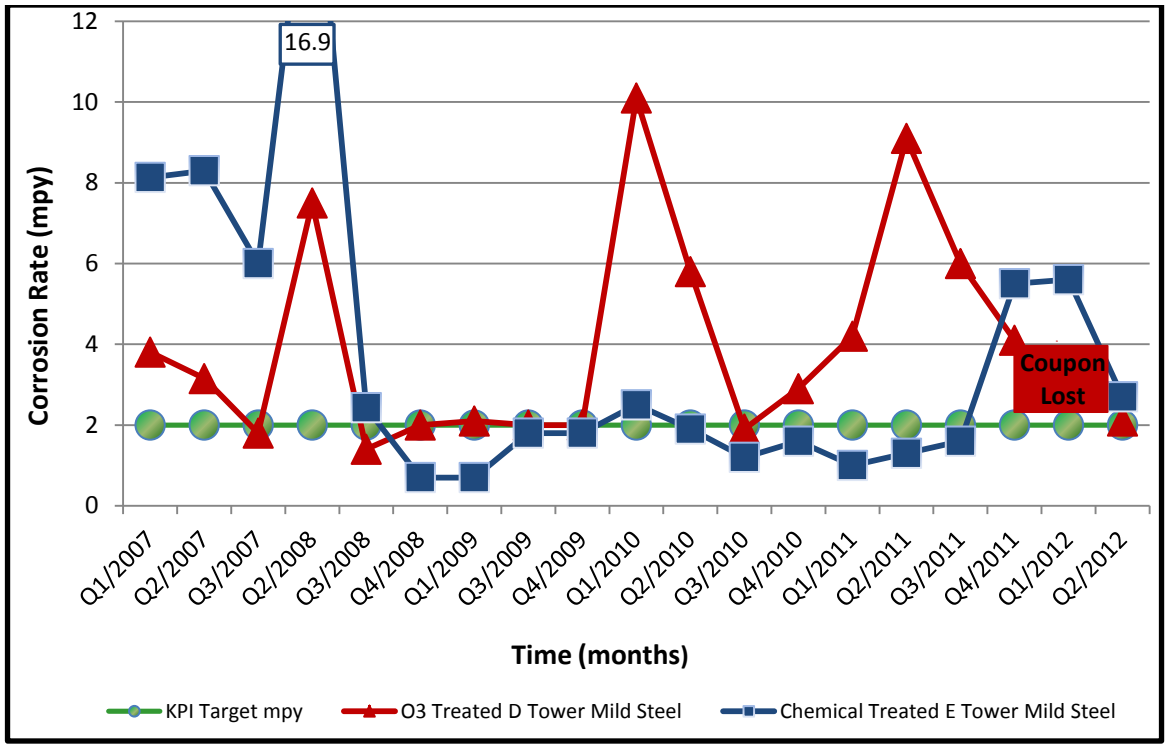

Figure 4-9 Mild-steel-ozone versus chemical-treated coupon corrosion

A major peak of 6.1 mpy in the third quarter of 2009 and other peaks shown in Figure 4-7, Figure 4-8 and Figure 4-9 on the ozone-treated cooling towers were due to:

- Poor filtration resulting in under deposit corrosion;
- Poor control of ozone residuals in the system; and
- Instability or rapid changes of makeup water quality with delayed ozone residual change.

The listed above are a combination of operational and maintenance shortcomings that are the main challenges that hinder at effective and efficient use of ozone in cooling water treatment. Rajagopaul et al. (2008) stated that the most of the ozone plants larger waterworks in South Africa are faced with:

- Maintenance issues that are not resolved in time
- Lack of accessible technical expertise for problems beyond the operator or maintenance personnel;
- Changes in raw water conditions that effectively did not require ozone.

- General process expertise in waterworks operations did not appear to be sufficient to operate a sophisticated ozone plant

High corrosion rates of 5.5 and 5.6 mpy in the fourth quarter of 2011 and first quarter of 2012 in chemical-treated cooling towers were seen as a result of dosing equipment failure, which resulted in an acid overdose in the tower. The acid-dosing system was stopped so that the system could be refurbished, which explains the improvement in the second quarter of 2012. Other possible reasons for the high-corrosion rates could be under-deposit corrosion, low pH or poor passivation because of inadequate dosing of corrosion inhibitor.

4.5 Corrosion Rates Correlations with other Results

4.5.1 Correlation of corrosion rates between the three metals

In both ozone treated and chemically treated water, stainless steel did not show much effects of corrosion as compared to brass and mild steel. The results reveal that brass is the most vulnerable metal to corrosion followed by mild steel and lastly stainless steel under both conditions. Comparing the corrosion rates for brass, Figure 4-8, and mild steel, Figure 4-9, chemical exposed coupons had higher corrosion rates compared to ozone treated coupons.

4.5.2 Correlation of corrosion rates with other results presented

Where major peaks and high corrosion rates were observed for mild steel (for ozone treated) and brass (for both ozone and chemical treated) in Figure 4.9 and Figure 4.8 in Q2/2008, Q2/2010 and Q2/2011, a decrease in approach temperatures was seen in Figure 4-1 and Figure 4-2, ozone treated heat exchangers and Figure 4-3 and Figure 4-4, chemical treated heat exchangers. This decrease in approach temperatures indicated that when corrosion rate was high the scaling rate was low in the heat exchangers. Ozone approach temperature declined in Figure 4.1 during the months of April, May and June 2011.

4.6 Water-treatment-related Legislation and Environmental-compliance Analysis

The identified water-treatment regulations requirements were extracted and are listed in the first column of Table 4-4. Ozone- and conventional chemical-treatment systems were reviewed against each regulation requirement. A conclusion was drawn against each requirement as easy or complex. In the last column are comments on each requirement for both ozone- and chemical treatment.

Table 4-4 Summary of Qualitative Assessment of Conventional Chemicals versus Sole Use of Ozone's Ease of Compliance Linked with Related-Legislation Requirements.

Management-practice Requirements: Interpretation	Ease of Compliance		Comments
	Conventional Chemicals	Ozone	
National Water Act 36 of 1998			
Section 19(1) Establish a pollution management plan and monitoring programmes. Any person using land should take reasonable measures to prevent any water pollution from occurring, continuing or recurring.	Complex	Easy	Conventional chemically treated water generates hazardous wastewater (blowdown) concentrated with toxic chemicals that cannot be recycled without intensive treatment. Ozone-treated blowdown is not hazardous.
Section 22(2) (c) The discharge or disposal of wastewater must comply with any applicable standards (e.g. in South Africa, regulation no. 991 purification of waste water or effluent).	Complex	Easy	
Section 22(2) (c) (d) The waste of water is not allowed	Complex	Easy	Ozone 1) increases cycles of concentration up to 15 vs. 2 chemicals cycles; 2) offers the ability to recycle and decrease blowdown rate.
Water conservation measures	Complex	Easy	

Table 4-4 Summary of Qualitative Assessment of Conventional Chemicals versus. Sole Use of Ozone's Ease of Compliance Linked with Related-Legislation Requirements. (cont.)" here

Management-practice Requirements : Interpretation	Ease of Compliance		Comments
	Conventional Chemicals	Ozone	
Occupational Health and Safety Act Regulations 10 and 15 relating to Hazardous Chemical Substances, SANS 10263-5:2009 Requirements			
Control of exposure to Hazardous Chemicals Subtances Ensure that the exposure of employees to HCS is either prevented or controlled.	Complex	Easy	Ozone can be used alone instead of using four hazardous conventional chemicals that contaminate the working environment.
Storage configuration and quantity limits	Complex	Easy	Ozone is solely used for water treatment, making it easy to comply with this requirement as compared to four different chemicals that have diverse requirements.
Waste collection, disposal, and effluent discharge permit requirements	Complex	Easy	Ozone does not produce effluent as compared to conventional chemicals.
Health and safety information and training	Complex	Easy	Ozone health and safety properties are easy to understand and manage as compared to those of conventional chemicals. Interaction modelling of the four various conventional chemicals is complex.
Air monitoring	Easy	Complex	Air monitoring is critical in ozone containers. Natural ventilation is sufficient for conventional chemicals.

CHAPTER 5

5. CONCLUSION

For this research it can be concluded that effective and efficient sole use of ozone can result in economic and environmental benefits. The Air Products ozone-treated cooling tower in Vanderbijlpark showed that:

5.1 About 360 m^3 of water has been saved per month. This saving is progressive with increasing water costs, but currently stands at R16 363 per month.

5.2 Roughly 10% compressor energy reduction was possible where there was an improvement of about 3°C in approach temperatures. An actual saving of R425 991 was observed over the four-year period investigated. This saving would be progressive with escalating electricity costs.

5.3 Heat exchangers in ozone treated systems were more efficient than in conventional chemically treated systems. The observed improvement in the ozone-treated heat exchanger approach temperatures proved that these heat exchangers were more efficient than the conventional chemically treated systems. This is in line with the declaration of Anuje *et al.* (2013): every 1°C increase in cooling water temperature corresponds to a 2% decrease in chiller efficiency.

5.4 Ozone-treated heat exchanger approach temperature trends confirmed that the ozone-treated heat exchangers were scale free and biofilm free as compared to the equivalent chemical-treated cooling water system.

5.5 If water quality is well controlled, ozone-treated heat exchangers last longer than conventional chemical-treated heat exchangers, since low corrosion rates increase equipment life.

5.6 The cost benefits of ozone use on cooling water treatment systems result in a domino effect of equipment efficiency and optimal operation of cooling water systems, reducing scale and corrosion rates. Therefore, cost benefits due to using ozone on cooling water treatment systems, are mainly due to equipment efficiency and avoided costs on chemicals use for cooling water treatment.

5.7 Ozone-treated cooling towers offer better compliance with national and international legislation as compared to hazardous conventional chemicals.

CHAPTER 6

6. RECOMMENDATIONS

The analysis on the Vanderbijlpark cooling tower system using Vaal Dam water has provided evidence that the sole use of ozone in cooling water treatment systems is technically practical, cost effective and meets the requirements of a successful cooling water-treatment system.

Below are recommendations for proposed future research work on ozone cooling water systems.

It is recommended that:

An investigation is performed to predict optimal application guidelines specifically for Air Products. This will ensure that the predicted benefits of ozone are attained.

A heat exchanger network synthexis study be undertaken to optimise heat transfer efficiency.

An investigation be performed to determine cooling water treatment process control optimisation. This might be done through:

- Investing in modern and on-line measurement for just-in-time process control improvement and long-term trend-records benefit;
- A study aimed at upgrading critical equipment such as more reliable, minimal maintenance ORP probes or the use of dissolved ozone monitoring/control.

An investigation be performed into appropriate quality control indicators such as Practical Ozone Scaling Index (POSI) or Ion Association Model for forecasting scale and corrosion in the ozone case.

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8. APPENDICES

8.1 APPENDIX A: Extract from a Compressor Heat Exchanger Temperature Log Sheet

Compressor K703 Chemical Treated Cooling Water

1st stage	2nd stage	3rd stage	4th stage	5th stage	6th stage	Motor	Dish Press	Suction Temp	C/tower Temp.	Date
Δ T Heat Exchanger Stage Temperatures, °C						Amps	KPa	°C	°C	
1.9	2.4	2.6	3.5	1.8	1.6	152.37	31.5	28	21.4	23/10/2011
1.8	2.4	2.7	3.5	1.6	1.5	151	27	29.9	24.4	30/10/2011
1.6	2.2	2.3	3	2	1.8	127	30.8	25.5	15.5	06/11/2011
1.7	2.3	2.6	3.2	t2	1.7	129	25.2	26.8	16.2	13/11/2011
2	2.5	2.8	3.2	1.8	1.7	155.9	31.7	29.7	22.9	20/11/2011
1.9	2.6	2.6	3.2	1.9	2	146	31.6	29.2	23.3	27/11/2011
1.8	2.4	2.6	2.9	1.8	2	142	31.6	29.7	22.6	04/12/2011
1.1	1.9	2	2.4	1.7	1.7	117.4	31.3	29.5	22.2	11/12/2011
2.5	2.9	3.2	3.7	2.1	2.1	155.16	30.8	30	22.7	17/12/2011
1.2	2	2.1	2.3	1.6	1.8	118	31.2	29.7	22.3	01/01/2012
1.6	2.4	2.4	2.7	1.9	2	123.88	31.8	28.4	21.1	15/01/2012
2.7	3.5	3.7	4.1	2.2	2.2	155.24	31.5	30	24.2	22/01/2012
3.4	4.3	4.6	5.3	2.8	2.7	151	32	29.9	23.4	29/01/2012
1.6	2.7	2.9	3.2	1.9	2	115.7	28.4	30.3	23.3	05/02/2012
2.5	3.4	3.7	4.1	2	1.9	116	25.5	30	22.2	26/02/2012
5.4	5.9	6.5	6.8	2.9	2.4	165	30.4	25.5	20.2	04/03/2012
3.5	4.4	4.8	5.2	2.3	2	133.7	26.3	27.1	20.1	25/03/2012
4.1	5.2	5.7	6.3	2.7	2.5	146	31.9	24.3	16.1	01/04/2012
0.2	1	1.7	2.1	-1.8	-1.9	152.7	30.5	27.6	25.4	08/04/2012
1.8	2.9	3.5	4.2	0.2	0	142	31	24.9	19.8	15/04/2012
5.2	6.1	6.8	7.3	3.2	2.8	151	30.5	26	19.4	22/04/2012
5.2	6	6.6	6.9	2.9	2.4	156	29	25.3	18.2	29/04/2012
5	5.9	6.5	7.1	3	2.7	154.11	32.2	22.8	16	13/05/2012
5.2	6.3	6.8	7.6	3.3	2.8	156	31.5	23	15.5	20/05/2012

Compressor K702 Chemical Treated Cooling Water

1st stage	2nd stage	3rd stage	4th stage	Motor	Flow	Comp Suct Temp	Cooling Tower Water Temp	Date
Δ T Heat Exchanger Stage Temperatures, °C				Amps	N/m3/hr	°C	°C	
24	23.8	23.9	8.9	141	16525	30.2	18	02/01/2011
15.4	11.1	12.1	7.3	116	13647	28.5	17	09/01/2011
18.1	11.3	12	7.2	129	15157	29.5	19	16/01/2011
14.3	10.2	11.3	6.5	112	12997	30.2	20	23/01/2011
23	13.2	13.4	8.7	144	16480	29.8	19	30/01/2011
16.2	11.7	12.6	8	114	13619	28.2	16	06/02/2011
15.5	10.5	11.5	6.8	117	13638	29.3	19	13/02/2011
21.2	12.2	12.6	7.9	137	15860	30.2	19	20/02/2011
15.3	10.6	11.8	7.1	116	13570	28.3	16	27/02/2011
16.3	11.1	12	7.3	116	14118	27.2	15	06/03/2011
14.6	9.6	10.8	6.1	116	13601	28.1	18	13/03/2011
15.8	11.1	12.1	7.3	118	13752	28.8	18	20/03/2011
19.6	12.2	12.8	8.1	134	15884	28.6	19	27/03/2011
20.6	11.5	11.6	6.9	143	16466	27.8	22	03/04/2011
22	12.3	12.5	7.6	145	16760	27.3	19	10/04/2011
23.1	13	13.2	8.5	146	16941	26.9	19	17/04/2011
12.2	8.2	9.3	5.6	119	13926	26.7	20	24/04/2011
14.9	9.1	10	6.4	125	14900	24.3	18	08/05/2011
16.8	11.5	12.4	9	123	14169	24.6	18	22/05/2011
14.8	10.5	11.3	7.5	116	13432	27.6	16	28/05/2011
13.3	9	9.9	6.3	118	14055	28.8	16	05/06/2011
24.8	14.2	14	10.2	144	16980	26.9	13	12/06/2011
18.5	11.9	12.4	9	124	15199	26.1	12	19/06/2011
18.8	12.7	13	9.9	121	14723	24.8	1	26/06/2011
16.6	16.3	9.6	9.9	123	15630	24.6	8	03/07/2011
17.8	10.9	11.3	8.2	123	14398	29.2	9	10/07/2011
16	8.2	8.6	5.6	128	14918	24	10	16/07/2011
17.4	22.7	13.3	10.1	123	14350	23.9	10	24/07/2011
37.9	26.5	26.3	22.4	148	17200	28.4		31/07/2011

Compressor K1003 Ozone Treated Cooling Water

Date	1st stage	2nd stage	3rd stage	Comp Suct Temp	Cooling Tower
	Δ T Heat Exchanger Stage Temperatures ,°C			°C	Water temp
02/01/2011	24.5	17.5	17.8	29.6	20
09/01/2011	25	18	18	27	18
16/01/2011	24.6	17.9	18.2	27.7	19
23/01/2011	24.5	17.6	17.8	29.5	20
30/01/2011	23.9	16.9	17	29.7	20
06/02/2011	26.3	19.4	19.9	27.7	17
13/02/2011	25.5	18.7	19.1	28.6	19
20/02/2011	25.8	19	19.4	27.2	17
27/02/2011	24.3	17.5	17.9	26	17
05/03/2011	24.9	18.1	18.4	26.3	17
12/03/2011	24.6	17.8	18.2	26.7	18
19/03/2011	24.2	17.4	17.8	28.1	20
27/03/2011	24.9	18.3	18.6	26.8	19
24/04/2011	25.3	18.6	19.3	26.5	20
08/05/2011	22.9	19.1	20.3	6.5	19
22/05/2011	23.8	19.8	21	7.1	18
28/05/2011	23.9	20.2	21.5	12.3	14
05/06/2011	22.4	18.4	19.7	4.2	16
12/06/2011	25.8	18.8	19.4	22.3	11
19/06/2011	27.4	20.3	21.1	20.8	8
03/07/2011	25.7	18.4	19.1	21.5	8
10/07/2011	24.7	17.3	18	22.1	8
24/07/2011	23	25	16	22	7
31/07/2011	26.1	19	19.7	24.2	12
06/08/2011	21.9	15.1	15.8	20.1	14
14/08/2011	24	17	18.3	21	14
21/08/2011	26.8	20.6	21.6	21.6	14
28/08/2011	23.6	16.5	17	24.5	14
04/09/2011	25.2	17.8	18.5	21.3	7
18/09/2011	24.7	17.4	17.8	23.4	10
25/09/2011	25.7	18.4	18.8	24.4	10

Compressor K803 Ozone Treated Cooling Water

Date	1st stage	2nd stage	Motor	Flow	Comp Suct	Cooling Tower Water temp	Comp Disch Press
	Δ T Heat Exchanger Stage Temp.,°C		Amps	N/m3/hr	Temp	°C	KPa
13/12/2009	16	6	58	6.8	14	22	21
20/12/2009	15	11	56	6.5	2	21	21
26/12/2009	14	11	56	6.8	1	23	21
03/01/2010	14	9	58	6.8	-2	22	19
10/01/2010	13	11	58	6.9	-4	21	21
17/10/2010	12	2	59	6.8	-10	25	21
24/01/2010	13	5	52	6.8	-9	23	19
31/01/2010	13	8	56	7	0	24	19
07/02/2010	14	4	60	6.8	-2	22	18
14/02/2010	14	11	60	6.8	0	24	20
20/02/2010	14	4	57	6.8	0.5	23	20
28/02/2010	13	2	58	6.8	1	22	19
07/03/2010	13	3	60	7	0	22	19.5
14/03/2010	13	3	59	6.9	2	23	19
20/03/2010	13	5	57	7	0.2	21	18
28/03/2010	14	10	58	7.8	6	22	18
03/04/2010	14	9	62	7	0	22	20
09/05/2010	13	9	58	6.7	-4	21	20
15/05/2010	13.5	11	57	7.2	-6	19	18
23/05/2010	12	9	57	7	-7	16	19
30/05/2010	11	6	56	7	-7	18	20
06/06/2010	14	11	58	7.8	-6	13	20
12/06/2010	12	10	57	6.9	-2	17	20
07/11/2010	11	8	51	6	0	22	19
03/04/2011	12	10	51	5.8	0	22	20
10/04/2011	12.5	9	50	7.8	-1	19	19
17/04/2011	12	11	52	7.8	-4	19	18
24/04/2011	13	10	52	8.6	-2	20	19
01/05/2011	14	11	52	6.1	-4	17	20

8.2 APPENDIX B: Water Quality Analysis

Service Report January 2009

Chemical Analysis(mg/l)		Borehole	M/U Municipality	Mittal Vaaldam M/U	Mittal Industrial M/U	501 Cooling Tower	K101 Cooling Tower	AB Cooling Tower	C Cooling Tower	D1 + D2 Cooling Tower	DCAC Cooling Tower	E Cooling Tower	Recommended values		
													LSL	USL	USL
Temperature °C	60														
Total Hardness	as $CaCO_3$	No Sample	20	40	30	490		190		360		760	0	1500	1500
Calcium Hardness	as $CaCO_3$		10	30	20	250		100		150		420	0	600	600
P' Alkalinity	as $CaCO_3$		0	0	0	75		0		0		0	0	200	200
M' Alkalinity	as $CaCO_3$		65	67	67	504		61		109		60	0	500	500
Chlorides	as Cl		23	18	21	639		104		227		201	0	200	200
Conductivity	uS/cm		212	199	199	4010		824		910		1904	0	2000	6500
pH			7.55	7.17	7.06	9.06		7.71		7.72		7.72	7.2	7.5	7.5
Bioscan													0	200	200
Total Iron	as Fe			0.41	0.43	1.53		1.97		0.28		0.69	0	3	3
Phosphate	as PO_4			0.5	0.3	3.7		9.3		7.4		7.1	7	12	12
Filtered Phosphate	as PO4					3.3		9.1		5.2		6.8			
Copper	as Cu			4.8	4.5	2.5		3.6		5.7		4.5			
Zinc						0.22		1.09		0.77		0.64	2	3	3
Turbidity (FAU)				5	4	42		34		21		12		20	20
pH_s						6.24	#NUM!	7.49	#NUM!	7.06	#NUM!	6.91			
Rz						3.42	#NUM!	7.26	#NUM!	6.40	#NUM!	6.09	4	7	7
Li						2.82		0.22		0.66		0.81	-0.2	2.5	2.5
Free chlorine				0.08	0.04	0.31		0.13		0.12		0.08	0.2	0.5	0.5
Cycles of Concentration **						20.15	0.00	4.14	0.00	4.57	0.00	9.57	3	7	5

Service Report February 2009

Chemical Analysis(mg/l)		Borehole	M/U Municipality	Mittal Vaaldam M/U	Mittal Industrial M/U	501 Cooling Tower	K101 Cooling Tower	AB Cooling Tower	C Cooling Tower	D1 + D2 Cooling Tower	DCAC Cooling Tower	E Cooling Tower	Recommended values		
													LSL	USL	USL
Temperature °C	60														
Total Hardness	as $CaCO_3$	No Sample\	30	50	60	620		220		360		400	0	1500	1500
Calcium Hardness	as $CaCO_3$		10	20	40	300		130		310		230	0	600	600
P' Alkalinity	as $CaCO_3$		0	0	0	70		0		0		0	0	200	200
M' Alkalinity	as $CaCO_3$		51	67	71	551		44		113		31	0	500	500
Chlorides	as Cl		20	33	36	781		116		302		146	0	200	200
Conductivity	uS/cm		192	256	289	4830		839		895		1327	0	2000	6500
pH			7.39	7.26	7.13	8.98		7.20		7.89		7.27	7.2	7.5	7.5
Bioscan													0	200	200
Total Iron	as Fe			0.56	0.32	0.46		2.13		0.19		0.50	0	3	3
Phosphate	as PO_4			0.9	0.5	2.7		9.4		6.6		8.2	4	7	7
Filtered Phosphate	as PO4			0.8	0.5	2.5		9		6.4		7.9			
Copper	as Cu			2.1	3.3	3.1		4.1		1.1		3.0			
Zinc						0.23		0.67		0.42		0.71	2	3	3
Turbidity (FAU)				21	28	45		23		27		33		20	20
pH_s						6.13	#NUM!	7.51	#NUM!	6.73	#NUM!	7.44			
Rz						3.28	#NUM!	7.83	#NUM!	5.57	#NUM!	7.61	4	7	7
Lsi						2.85		-0.31		1.16		-0.17	-0.2	2.5	2.5
Free chlorine				0.10	0.17	0.22		0.11		0.40		0.19	0.2	0.5	0.5
Cycles of Concentration **						16.71	0.00	3.28	0.00	3.50	0.00	5.18	3	7	5

Service Report March 2009

Chemical Analysis(mg/l)		Borehole	M/U Municipality	Mittal Vaaldam M/U	Mittal Industrial M/U	501 Cooling Tower	K101 Cooling Tower	AB Cooling Tower	C Cooling Tower	D1 + D2 Cooling Tower	DCAC Cooling Tower	E Cooling Tower	Recommended values		
Temperature °C	60												LSL	USL	USL
Total Hardness	as $CaCO_3$	No Sample	20	40	30	490		190		360		760	0	1500	1500
Calcium Hardness	as $CaCO_3$		10	30	20	250		100		150		420	0	600	600
P' Alkalinity	as $CaCO_3$		0	0	0	75		0		0		0	0	200	200
M' Alkalinity	as $CaCO_3$		65	67	67	504		61		109		60	0	500	500
Chlorides	as Cl		23	18	21	639		104		227		201	0	200	200
Conductivity	uS/cm		212	199	199	4010		824		876		1904	0	2000	6500
pH			7.55	7.17	7.06	9.06		7.71		7.50		7.72	7.2	7.5	7.5
Bioscan													0	200	200
Total Iron	as Fe			0.41	0.43	1.53		1.97		0.28		0.69	0	3	3
Phosphate	as PO_4			0.5	0.3	3.7		9.3		7.4		7.1	7	12	12
Filtered Phosphate	as PO4					3.3		9.1		5.2		6.8			
Copper	as Cu			4.8	4.5	2.5		3.6		5.7		4.5			
Zinc						0.22		1.09		0.77		0.64	2	3	3
Turbidity (FAU)				5	4	42		34		21		12		20	20
pH_S						6.24	#NUM!	7.49	#NUM!	7.06	#NUM!	6.91			
Rz						3.42	#NUM!	7.26	#NUM!	6.62	#NUM!	6.09	4	7	7
Li						2.82		0.22		0.44		0.81	-0.2	2.5	2.5
Free chlorine				0.08	0.04	0.31		0.13		0.12		0.08	0.2	0.5	0.5
Cycles of Concentration **						20.15	0.00	4.14	0.00	4.40	0.00	9.57	3	7	5

Service Report April 2009

Chemical Analysis(mg/l)		Borehole	M/U Municipality	Mittal Vaaldam M/U	Mittal Industrial M/U	501 Cooling Tower	K101 Cooling Tower	AB Cooling Tower	C Cooling Tower	D1 + D2 Cooling Tower	DCAC Cooling Tower	E Cooling Tower	Recommended values		
Temperature °C	60												LSL	USL	USL
Total Hardness	as $CaCO_3$	No Sample\											0	1500	1500
Calcium Hardness	as $CaCO_3$		30	0	220	310	50	90	80	120	110	60	0	600	600
P' Alkalinity	as $CaCO_3$		0	0	0	0	0	0	0	0	0	0	0	200	200
M' Alkalinity	as $CaCO_3$		75	41	67	83	33	65	40	50	101	29	0	500	500
Chlorides	as Cl		24	241	354	500	216	476	522	485	399	542	0	200	200
Conductivity	uS/cm		173	895	2360	3200	897	1802	1890	1806	1555	1948	0	2000	6500
pH			8.35	5.83	7.49	8.16	6.83	7.60	7.12	7.47	7.86	6.92	7.2	7.5	7.5
Bioscan				2	770	120	55	24	29	15	140	7	0	200	200
Total Iron	as Fe			2.07	0.31	0.05	1.58	1.26	1.79	0.19	0.10	0.50	0	3	3
Phosphate	as PO_4			1.7	2.0	2.8	21.7	10.0	6.3	7.1	0.9	6.6	7	12	12
Filtered Phosphate	as PO4					2.5	21.4	8.9	6.1	6.8		6.2			
Copper	as Cu			4.6	2.6	4.2	3.1	4.1	3.7	4.7		4.0			
Zinc							1.99	1.25	0.87	0.67		0.51	2	3	3
Turbidity (FAU)				33	56	23	42	51	43	29	33	37		20	20
pH_S						6.92	8.06	7.54	7.80	7.53	7.25	8.07			
Rz						5.68	9.29	7.48	8.49	7.59	6.65	9.22	4	7	7
Li						1.24	-1.23	0.06	-0.68	-0.06	0.61	-1.15	-0.2	2.5	2.5
Free chlorine				0.31	0.12	0.24	0.04	0.20	0.29	0.17		0.29	0.2	0.5	0.5
Cycles of Concentration **						1.36	1.00	2.01	2.11	2.02	1.74	2.18	3	7	5

Service Report May 2009

Chemical Analysis(mg/l)		Borehole	M/U Municipality	Mittal Vaaldam M/U	Mittal Industrial M/U	501 Cooling Tower	K101 Cooling Tower	AB Cooling Tower	C Cooling Tower	D1 + D2 Cooling Tower	DCAC Cooling Tower	E Cooling Tower	Recommended values		
													LSL	USL	USL
Temperature °C	60														
Total Hardness	as $CaCO_3$	No Sample\	50	0	400		170	230	150	140		170	0	1000	1000
Calcium Hardness	as $CaCO_3$		20	0	180		80	120	80	60		70	0	600	600
P' Alkalinity	as $CaCO_3$		2	0	0		0	0	0	0		0	0	200	200
M' Alkalinity	as $CaCO_3$		60	22	134		39	53	42	57		24	0	500	500
Chlorides	as Cl		17	196	378		**422**	**406**	**677**	**422**		**634**	0	200	200
Conductivity	uS/cm		180	725	2200		**2130**	1725	**2590**	1661		**2360**	600	2000	6600
pH			8.51	**5.59**	8.17		**6.89**	7.46	**7.03**	7.63		**7.10**	7.2	8.2	8.2
Bioscan				1	500		12	40	10	18		43	0	200	200
Total Iron	as Fe			**0.56**	2.31		2.73	1.92	1.03	0.70		0.88	0	3	3
Phosphate	as PO_4			0.9	1.7		13.80	19.60	12.60	6.00		8.60	4		
Filtered Phosphate	as PO4						12.30	9.00	7.40			6.80		7	7
Copper	as Cu			*3.8*	*8.2*		*8.8*	*6.3*	*6.9*	*3.3*		*2.6*			
Zinc							**1.39**	**1.98**	**1.80**			**1.23**	2	1.5	1.5
Turbidity (FAU)				10	32		**51**	**22**	**37**	**31**		14		20	20
pH_s						#NUM!	7.82	7.50	7.80	7.77		8.09			
Rz						#NUM!	**8.75**	**7.54**	**8.56**	**7.91**		**9.09**	4	7	7
Li							**-0.93**	-0.04	**-0.77**	-0.14		**-0.99**	-0.2	2.5	2.5
Free chlorine				0.54	0.15		0.17	0.15	0.16	0.13		0.11	0.2	0.5	0.5
Cycles of Concentration **							2.94	2.38	3.57	2.29		3.26	3	10	3

Service Report June 2009

Chemical Analysis(mg/l)		Borehole	M/U Municipality	Mittal Vaaldam M/U	Mittal Industrial M/U	501 Cooling Tower	K101 Cooling Tower	AB Cooling Tower	C Cooling Tower	D1 + D2 Cooling Tower	DCAC Cooling Tower	E Cooling Tower	Recommended values		
													LSL	USL	USL
Temperature °C	60														
Total Hardness	as $CaCO_3$	No Sample\	60	80	240		280	270	170	300	430	400	0	1000	1000
Calcium Hardness	as $CaCO_3$		30	40	110		130	140	80	140	200	210	0	600	600
P' Alkalinity	as $CaCO_3$		0	0	18		0	0	0	0	7	0	0	200	200
M' Alkalinity	as $CaCO_3$		73	103	156		57	99	49	149	323	55	0	500	500
Chlorides	as Cl		23	220	4050		127	**248**	49	**301**	**304**	179	0	200	200
Conductivity	uS/cm		187	1307	2230		830	1233	**425**	1450	1737	1328	600	2000	6690
pH			8.32	**7.66**	8.91		7.76	8.15	7.60	**8.40**	**8.64**	7.56	7.2	8.2	8.2
Bioscan							80	55	24	20	18	85	0	200	200
Total Iron	as Fe			**0.97**	1.61		1.02	1.71	1.07	0.07	0.06	0.45	0	3	3
Phosphate	as PO_4			1.1	1.4		6.7	10.0	7.0	3.0	0.9	7.7	4	7	7
Filtered Phosphate	as PO4						6.4	8.6	6.6			6.9			
Copper	as Cu			*2.3*	*6.9*		*4.9*	*3.6*	*3.0*	*3.5*	*2.2*	*4.0*			
Zinc							**1.34**	**1.50**	**1.12**			**1.49**	2	1.5	1.5
Suspended Solids					21				18						
Turbidity (FAU)				19			**38**	14	**34**	9	11	15		20	20
pH_s						#NUM!	7.40	7.15	7.65	6.98		7.23			
Rz						#NUM!	**7.04**	6.14	**7.70**	5.55		6.90	4	7	7
Li					0.15		0.36	1.00	-0.05	1.42		0.33	-0.2	2.5	2.5
Free chlorine							0.34	0.19	0.19	0.11	0.09	0.22	0.2	0.5	0.5
Cycles of Concentration **							0.64	0.94	0.33	1.11	0.78	1.02	3	10	3

Service Report July 2009

Chemical Analysis(mg/l)		Borehole	M/U Municipality	Mittal Vaaldam M/U	Mittal Industrial M/U	501 Cooling Tower	K101 Cooling Tower	AB Cooling Tower	C Cooling Tower	D1 + D2 Cooling Tower	DCAC Cooling Tower	E Cooling Tower	Recommended values		
													LSL	USL	USL
Temperature °C	60														
Total Hardness	as $CaCO_3$	No Sample\	50	30			170	300	360	430	550	380	0	1000	1000
Calcium Hardness	as $CaCO_3$		20	10			80	140	190	200	250	190	0	600	600
P' Alkalinity	as $CaCO_3$		0	0			0	0	0	1	0	0	0	200	200
M' Alkalinity	as $CaCO_3$		24	45			80	77	163	197	284	42	0	500	500
Chlorides	as Cl		16	23			**208**	**251**	**739**	**340**	**623**	**477**	0	200	200
Conductivity	uS/cm		197	176			1156	1446	**3260**	1823	**3300**	**2260**	600	2000	0
pH			8.14	**7.26**			7.51	7.63	8.03	**8.41**	**8.27**	7.26	7.2	8.2	8.2
Bioscan				11			34	120	1	34	200	23	0	200	200
Total Iron	as Fe			**0.09**			0.65	2.06	2.69	0.18	0.07	0.51	0	3	3
Phosphate	as PO_4			0.7			6.00	10.00	7.40	3.30	1.80	6.80	4	7	7
Filtered Phosphate	as PO4						5.60	9.00	6.90			6.00			
Copper	as Cu			*2.8*			*2.2*	*3.9*	*5.1*	*3.5*		*4.8*			
Zinc							**1.75**	**1.22**	**1.45**			**1.66**	2	1.5	1.5
Turbidity (FAU)							19	16	**49**	12		17		20	20
pH_s						#NUM!	7.48	7.26	6.84	6.71	6.48	7.41			
Rz						#NUM!	**7.45**	6.90	5.65	5.01	4.69	**7.57**	4	7	7
Li							0.03	0.37	1.19	1.70	1.79	-0.15	-0.2	2.5	2.5
Free chlorine							0.29	0.14	0.12			0.22	0.2	0.5	0.5
Cycles of Concentration **							6.57	8.22	18.52	10.36	18.75	12.84	3	10	3

Service Report August 2009

Chemical Analysis(mg/l)		Borehole	M/U Municipality	Mittal Vaaldam M/U	Mittal Industrial M/U	501 Cooling Tower	K101 Cooling Tower	AB Cooling Tower	C Cooling Tower	D1 + D2 Cooling Tower	DCAC Cooling Tower	E Cooling Tower	Recommended values		
													LSL	USL	USL
Temperature °C	60														
Total Hardness	as $CaCO_3$	No Sample\	50	30			190	330	400	530		350	0	1000	1000
Calcium Hardness	as $CaCO_3$		20	10			90	160	210	250		220	0	600	600
P' Alkalinity	as $CaCO_3$		0	0			0	0	0	17		0	0	200	200
M' Alkalinity	as $CaCO_3$		24	45			58	61	45	222		66	0	500	500
Chlorides	as Cl		16	23			61	155	164	**303**		166	0	200	200
Conductivity	uS/cm		197	176			**433**	1113	778	1712		1498	600	2000	0
pH			8.14	**7.26**			7.86	7.72	7.55	**8.92**		7.50	7.2	8.2	8.2
Bioscan				11			71	4	220	23		110	0	200	200
Total Iron	as Fe			**0.09**			0.41	1.19	2.31	0.14		0.23	0	3	3
Phosphate	as PO_4			0.7			3.8	11.70	16.90	3.9		9.80	4	7	7
Filtered Phosphate	as PO4						3.4	11.00	16.70			9.40			
Copper	as Cu			*2.8*			*4.9*	*4.4*	*3.0*	*3.5*		*3.8*			
Zinc							**1.34**	**1.49**	2.30			**0.46**	2	1.5	1.5
Turbidity (FAU)							13	14	**36**	15		11		20	20
pH_s						#NUM!	7.52	7.29	7.29	6.56	#NUM!	7.14			
Rz						#NUM!	**7.19**	6.87	**7.04**	4.20	#NUM!	6.77	4	7	7
Li							0.34	0.43	0.26	2.36		0.36	-0.2	2.5	2.5
Free chlorine							0.13	0.15	0.17	0.18		0.12	0.2	0.5	0.5
Cycles of Concentration **							2.46	6.32	4.42	9.73	#DIV/0!	8.51	3	10	3

Service Report September 2009

Chemical Analysis(mg/l)		Borehole	M/U Municipality	Mittal Vaaldam M/U	Mittal Industrial M/U	501 Cooling Tower	K101 Cooling Tower	AB Cooling Tower	C Cooling Tower	D1 + D2 Cooling Tower	DCAC Cooling Tower	E Cooling Tower	Recommended values		
Temperature °C	60												LSL	USL	USL
Total Hardness	as $CaCO_3$	No Sample\	50	40			370	400	380	550		620	0	1000	1000
Calcium Hardness	as $CaCO_3$		20	20			190	220	170	290		330	0	600	600
P' Alkalinity	as $CaCO_3$		0	0			0	0	0	24		0	0	200	200
M' Alkalinity	as $CaCO_3$		61	66			84	92	149	348		84	0	500	500
Chlorides	as Cl		20	19			71	119	60	**242**		127	0	200	200
Conductivity	uS/cm		191	168			777	1166	854	1789		1506	600	2000	0
pH			8.21	**7.33**			7.80	7.81	7.88	**8.59**		7.55	7.2	8.2	8.2
Bioscan				30			59	98	220	110		76	0	200	200
Total Iron	as Fe			**0.20**			0.44	**3.04**	2.06	0.10		0.23	0	3	3
Phosphate	as PO_4			0.3			6.3	**9.70**	**7.30**	**2.4**		**9.60**	4	7	7
Filtered Phosphate	as PO4						6.0	9.30	6.90			9.30			
Copper	as Cu			*5.5*			*3.9*	*5.1*	*4.4*	*4.8*		*3.8*			
Zinc							**1.22**	**1.55**	**1.71**			**1.78**	2	1.5	1.5
Turbidity (FAU)							19	**25**	**22**	18		12		20	20
pH_s						#NUM!	7.07	6.98	6.87	6.30	#NUM!	6.85			
Rz						#NUM!	6.33	6.15	5.86	4.01	#NUM!	6.16	4	7	7
Li							0.73	0.83	1.01	2.29		0.70	-0.2	2.5	2.5
Free chlorine							0.13	0.15	0.17	0.18		0.12	0.2	0.5	0.5
Cycles of Concentration **							4.63	6.94	5.08	10.65	#DIV/0!	8.96	3	10	3

Service Report October 2009

Chemical Analysis(mg/l)		Borehole	M/U Municipality	Mittal Vaaldam M/U	Mittal Industrial M/U	501 Cooling Tower	K101 Cooling Tower	AB Cooling Tower	C Cooling Tower	D1 + D2 Cooling Tower	DCAC Cooling Tower	E Cooling Tower	Recommended values		
Temperature °C	60												LSL	USL	USL
Total Hardness	as $CaCO_3$	No Sample\	50	50			710	400	820	630	380	580	0	1000	1000
Calcium Hardness	as $CaCO_3$		20	30			400	220	460	310	230	300	0	600	600
P' Alkalinity	as $CaCO_3$		0	0			0	0	0	34	11	0	0	200	200
M' Alkalinity	as $CaCO_3$		56	69			102	109	60	425	332	60	0	500	500
Chlorides	as Cl		14	15			70	155	188	**212**	166	153	0	200	200
Conductivity	uS/cm		167	157			1460	889	1545	1575	1146	1929	600	2000	0
pH			8.06	**7.82**			8.01	8.03	7.75	**8.54**	**8.27**	7.77	7.2	8.2	8.2
Bioscan				4			27	85	55	27	52	16	0	200	200
Total Iron	as Fe			**0.24**			0.47	1.63	1.24	0.08	0.04	0.14	0	3	3
Phosphate	as PO_4			1.3			7.60	6.00	9.00	3.1	2.00	12.50	4	7	7
Filtered Phosphate	as PO4						7.40	5.50	8.50			12.20			
Copper	as Cu			*5.0*			*5.0*	*7.0*	*6.6*	*4.0*	*5.6*	*5.5*			
Zinc							1.01	0.97	1.43			1.67	0.5	1.5	1.5
Turbidity (FAU)							16	**21**	**42**	14	13	16		20	20
pH_s						#NUM!	6.69	6.89	6.86	6.18	6.40	7.05			
Rz						#NUM!	5.36	5.76	5.97	**3.82**	4.54	6.34	4	7	7
Li							1.32	1.14	0.89	2.36	1.87	0.72	-0.2	2.5	2.5
Free chlorine							0.20	0.19	0.21			0.20	0.2	0.5	0.5
Cycles of Concentration **							9.30	5.66	9.84	10.03	7.30	12.29	3	10	3

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Chemical Analysis(mg/l)		Borehole	M/U Municipality	Mittal Vaaldam M/U	Mittal Industrial M/U	501 Cooling Tower	K101 Cooling Tower	AB Cooling Tower	C Cooling Tower	D1 + D2 Cooling Tower	DCAC Cooling Tower	E Cooling Tower	Recommended values		
Temperature °C	60												LSL	USL	USL
Total Hardness	as $CaCO_3$	No Sample\	50	50			330	440	400	470	500	620	0	1000	1000
Calcium Hardness	as $CaCO_3$		20	20			180	250	190	210	240	340	0	600	600
P' Alkalinity	as $CaCO_3$		0	0			0	0	0	33	13	0	0	200	200
M' Alkalinity	as $CaCO_3$		60	48			80	43	70	346	293	47	0	500	500
Chlorides	as Cl		13	42			53	52	59	108	95	119	0	200	200
Conductivity	uS/cm		172	160			879	972	799	1228	1069	1666	600	2000	0
pH			8.22	**7.82**			7.81	7.50	7.80	**8.55**	**8.38**	7.60	7.2	8.2	8.2
Bioscan				35			110	110	240	100	140	55	0	200	200
Total Iron	as Fe			**1.26**			0.17	1.94	1.13	0.04	0.06	0.11	0	3	3
Phosphate	as PO_4			2.0			6.40	**8.90**	**8.00**	**2.5**	**1.70**	**13.30**	4	7	7
Filtered Phosphate	as PO4						6.20	8.40	7.70			13.00			
Copper	as Cu			*5.0*			*5.0*	*7.0*	*6.6*	*4.0*	*5.6*	*5.5*			
Zinc							1.12	1.00	1.34			1.55	0.5	1.5	1.5
Turbidity (FAU)							16	19	**32**	14	13	16		20	20
pH_S						#NUM!	7.12	7.25	7.15	6.43	6.44	7.10			
Rz						#NUM!	6.42	6.99	6.49	4.30	4.49	6.60	4	7	7
Li							0.69	0.25	0.65	2.12	1.94	0.50	-0.2	2.5	2.5
Free chlorine							0.21	0.17	0.19			0.20	0.2	0.5	0.5
Cycles of Concentration **							5.49	6.08	4.99	7.68	6.68	10.41	3	10	3

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Chemical Analysis(mg/l)		Borehole	M/U Municipality	Mittal Vaaldam M/U	Mittal Industrial M/U	501 Cooling Tower	K101 Cooling Tower	AB Cooling Tower	C Cooling Tower	D1 + D2 Cooling Tower	DCAC Cooling Tower	E Cooling Tower	Recommended values		
Temperature °C	60												LSL	USL	USL
Total Hardness	as $CaCO_3$	No Sample\	120	90			200	380	230	550	460	560	0	1000	1000
Calcium Hardness	as $CaCO_3$		60	40			95	200	125	240	250	240	0	600	600
P' Alkalinity	as $CaCO_3$		0	0			0	34	0	53	33	43	0	200	200
M' Alkalinity	as $CaCO_3$		78	62			217	252	108	359	343	275	0	500	500
Chlorides	as Cl		20	17			85	118	72	120	188	138	0	200	200
Conductivity	uS/cm		167	155			679	1305	736	1356	1418	1336	600	2000	0
pH			7.70	**7.30**			8.20	**8.40**	7.80	**8.43**	**8.41**	**8.40**	7.2	8.2	8.2
Bioscan				2			1	5	25	31	9	11	0	200	200
Total Iron	as Fe			**0.54**			0.65	1.49	0.81	0.09	0.16	0.10	0	3	3
Phosphate	as PO_4			0.9			5.80	7.2	30.20	3.00	2.50	10.60	4	7	7
Filtered Phosphate	as PO4						4.60	7.1	29.70			9.90			
Copper	as Cu			*5.0*			*4.4*	*4.9*	*3.0*	*4.1*	*8.0*	*4.8*			
Zinc							1.54	1.33	1.89			1.56	0.5	1.5	1.5
Turbidity (FAU)							11	19	**22**	13	13	18		20	20
pH_S						#NUM!	6.95	6.59	7.14	6.36	6.36	6.47			
Rz							5.70	4.78	6.47	4.29	4.31	4.55	4	7	7
Li							1.25	1.81	0.66	2.07	2.05	1.93	-0.2	2.5	2.5
Free chlorine							0.22	0.21	0.20			0.17	0.2	0.5	0.5
Cycles of Concentration **							4.38	8.42	4.75	8.75	9.15	8.62	3	10	3

8.3 APPENDIX C: Mass Balance and Practical Ozone Scaling Index on Ozone-treated Cooling Tower

Date	Conductivity	Cycles	Recirculation rate	Evaporation	Drift	Blowdown	Makeup
	Micro-Siemens/Centimetre		m^3 / hr				
January	910	4.5	861.24	10.33	0.021	2.952	13.31
February	895	3.5	861.24	10.33	0.021	2.952	13.31
March	876	4.4	861.24	10.33	0.021	2.952	13.31
April	1806	2.02	861.24	10.33	0.021	2.952	13.31
May	1661	2.29	861.24	10.33	0.021	2.952	13.31
June	1450	1.11	861.24	10.33	0.021	2.952	13.31
July	1823	10.36	861.24	10.33	0.021	2.952	13.31
August	1712	9.73	861.24	10.33	0.021	2.952	13.31
September	1789	10.65	861.24	10.33	0.021	2.952	13.31
October	1575	7.3	861.24	10.33	0.021	2.952	13.31
November	1228	7.68	861.24	10.33	0.021	2.952	13.31
December	1356	9.15	861.24	10.33	0.021	2.952	13.31

8.4 APPENDIX D: Operating Cost Calculations

Air Products Cooling tower D1 + D2

Chemical Operating costs						Ozone Costing					
Circulation						Circulation					
Rate	1602	m3/hr				Rate	1602	m3/hr			
	26.70	m3/min					26.70	m3/min			
Tower						Tower					lb
Volume	622	m3				Volume	622	m3	164315	Gallons	115.02 ozone/day
Delta Temp	6.6	C				Delta Temp	6.6	C			52.17 kg/day
											2174 g/hr
System						System					
loses						loses					3.5 g/m3
Evaporation	10.57	m3/hr	1% of Circulation rate per 10 C drop			Evaporation	10.57	m3/hr	1% of Circulation rate per 10C drop		
Blow down	12.17	m3/hr				Blow down	1.35	m3/hr	Calculated on Concentration ratio		
Drift	1.602		0.1% of Circulation Rate			Drift	1.602		0.1% of Circulation Rate		
Total Loss	24.35	m3/hr				Total Loss	13.53	m3/hr			
Therefore						Therefore					
Makeup						Makeup					
Water	24.35	m3/hr	17532.1415	10.82		Water	13.53	m3/hr			
Concentration ratio = Make-up water / Blowdown water				2.00		Concentration ratio = Make-up water / Blowdown water				10.00	
Cost of makeup water	2.1	R/m3				Cost of makeup water	2.1	R/m3			
Total Cost	51.14	R/hr				Total Cost	28.41	R/hr			
	36,817.50	R/month					20,454.35	R/month			
									Fixed cost depriciation of Ozone generator		
Cost of Treatment	100000	R/month	Fixed cost			Cost of Treatment	18,006	R/month	over 10 yrs		
Cost per m3 of water	1.4285714	R/m3	based on 70,000m3/month			Power Consumption	20	Kwh			
Cost for this tower	34.785995	R/hr				Cost of Power	0.2256	R/Kwh			
	25,045.92	R/month					4.512	R/hr			
							3248.64	R/month			
						Oxygen Consumption	522	kg/day			
						Oxygen Cost	2849	R/month			
Total Monthly cost for this tower						Total Monthly cost for this tower					
	61,863.41	R/month					44,557.80	R/month			

Total Monthly water and chemical Savings on THIS Tower	17,305.61
Potential Power Savings on D Plant	
For every 3 Deg C drop in approach temp of gas, we save 1% Power (This is achieved by cleaner heat transfere surfaces)	34,560.00
TOTAL	51,865.61

8.5 APPENDIX E: Energy Saving Calculations

	1	2	3	4
K803, Ozone Treated	R 7,045.50	-R 17,132.50	-R 2,387.00	R 0.00
K1003, Ozone Treated	R 97,423.57	R 20,335.18	-R 14,271.18	R 81,771.22
K703, Chemical Treated				R 87,259
K702, Chemical Treated	R 112,101.65	R 59,582.60	R 43,199.99	R 90,056.42

..+ve = Approach Temperatures deteriorated
..- ve = Approach Temperature Improving

0..25 25 cents/KW 5
9.5 kW
2/3.. 3 stage compressor ; 2 coolers

Equivalence in % x Water Costs (Cents/KWHr) x 1000 x Compressor Heat Load x 24 hrs x 7 days x 2/3 (3 stage compressor / 2 coolers)
0.01 3 0.0033

		DELTA T																		
	DATE	2009	Target	change	Equivalence in %	Power saving	2010	Target	change	Equivalence in %	Power saving	2011	Target	change	Equivalence in %	Power saving	2012	Target	change	Equivalence in %	Power saving
			° C			Rands		° C			Rands		° C			Rands		° C			Rands
Ozone Cooling Tower Treated	K803 Compressor				0.01					-0.01					0.00					0.0	
	Stage 1	15	15.00	0.00	0.00	7045.50	13.00	15.00	-2.00	-0.01	-17132.50	11.00	13.00	-2.00	-0.007	-2387.00	12.00	11.00	1.00	0.003	0.000
	Stage 2	9.00	6.00	3.00	0.01		6.00	9.00	-3.00	-0.01		8.00	7.00	1.00	0.003		7.00	8.00	-1.00	-0.003	
	K1003 Compressor				0.009					0.002					-0.001					0.01	
	Stage 1	25	22	3	0.010	R 97,423.57	25	25	-0.199	-0.001	R 20,335	25	25	-0.23	-0.001	-R 14,271.18	25	25	0.14	0.00	R 81,771
	Stage 2	18	16	2	0.006		19	18	1.309	0.004		19	19	-0.58	-0.002		21	19	2.42	0.01	
	Stage 3	19	16	3	0.010		19	19	0.518	0.002		19	19	-0.33	-0.001		23	19	3.99	0.01	
Chemical Treated Cooling Tower	K703 Compressor														0					0.008	
	Stage 1											2	2	0.000	0	R 0.00	4	2	3	0.009	R 87,259
	Stage 2											2	2	0.000	0		5	2	3	0.010	
	Stage 3											2	2	0.000	0		6	2	3	0.011	
	Stage 4											3	3	0.000	0		6	3	3	0.011	
	Stage 5											2	2	0.000	0		3	2	1	0.004	
	Stage 6											2	2	0.000	0		3	2	1	0.003	
	K 702 Copressor				0.010					0.005					0.004					0.008	
	Stage 1	10.913	7.182	3.731	0.012	R 112,101.65	16.132	10.913	5.219	0.017	R 59,582.60	17.364	16.132	1.232	0.004	R 43,199.99	19.777	17.364	2.413	0.008	R 90,056.42
	Stage 2	7.870	5.129	2.740	0.009		10.210	7.870	2.340	0.008		11.641	10.210	1.431	0.005		14.542	11.641	2.901	0.010	
	Stage 3		4.746				10.449			0.000		11.724	10.449	1.275	0.004		13.365	11.724	1.641	0.005	
	Stage 4	8.305	5.801	2.504	0.008		7.105	8.305	-1.200	-0.004		7.779	7.105	0.673	0.002		10.436	7.779	2.658	0.009	

8.6 APPENDIX F: Corrosion Coupons

ZCF 0067 mild steel coupon that was installed in the chemical treated cooling tower on the 25 August 2008 and was removed on the 29th September 2008 for analysis. The weight loss in grams after cleaning was found to be 0.0809 and the corrosion rate was calculated to be 2.43 mpy.

ZCI 1857 Mild Steel Ozone Treated that was installed in the ozone treated cooling tower on the 03 August 2009 and was removed on the 28th September 2009 for analysis. The weight loss in grams after cleaning was found to be 0.5131 and the corrosion rate was calculated to be 6.0 mpy.

DFP 473 is a brass coupon that was installed in the ozone-treated cooling tower on the 9 June 2010 and was removed on 14 September 2010 for analysis. The coupon was exposed in the chemical-treated cooling water system for a total duration of 97 days. The weight loss in grams after cleaning was found to be 0.0499 and the corrosion rate was calculated to be 0.5 mpy.

A brass corrosion coupon that was labelled as specimen DGF 720 was installed in the chemically treated cooling tower on 30 November 2011 and was removed on 23 April 2012 for analysis. The coupon was exposed in the chemical-treated cooling water system for a total duration of 145 days. The weight loss after cleaning was found to be 0.0527 g and the corrosion rate was calculated to be 0.4 mpy.

DFJ 514 Q3/2011 brass coupon that was installed in the chemical treated cooling tower on the 11th May 2011 and was removed on the 10th August 2011 for analysis. The weight loss in grams after cleaning was found to be 0.0275 and the corrosion rate was calculated to be 0.3 mpy.

DGF 731 Q1/2012 brass coupon that was installed in the chemical treated cooling tower on the 20th November 2011 and was removed on the 23rd April 2012 for analysis. The weight loss in grams after cleaning was found to be 0.0536 and the corrosion rate was calculated to be 0.4 mpy.

Mild steel corrosion coupon that was labeled as specimen, ZCI2111, was installed in the ozone-treated cooling towers on 9 June 2010 and removed on 14 September 2010 for analysis. The coupon was exposed in the chemical-treated cooling water system for a total duration of 97 days. The weight loss after cleaning was found to be 0.1673 g. The corrosion rate was 1.7 mpy. The table set out below shows coupons that were installed in ozone and chemical treated cooling water systems.

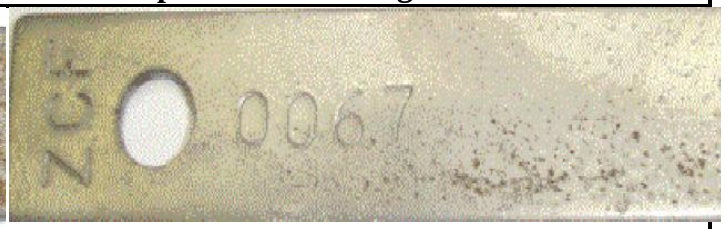
ZBR 2670 is a mild steel coupon that was installed in chemical-treated cooling towers, K 703/2, on 30 November 2011 and removed on 23 April 2012 for analysis. The coupon was exposed in the chemical-treated cooling water system for a total duration of 145 days. The weight loss in grams after cleaning was found to be 0.7114 g and the corrosion rate was 4.9 mpy. When this was averaged with other corrosion rate results, the rate was found to be 5.6 mpy for the first quarter of 2012.

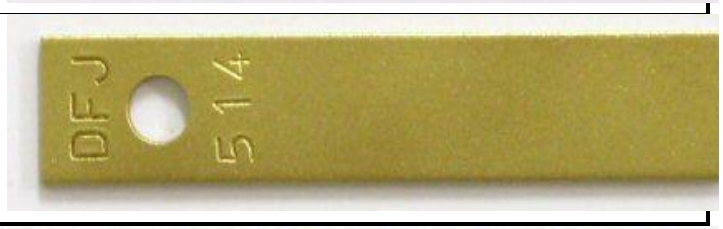
BCA391 is a stain steel corrosion coupon that was installed in the ozone treated cooling towers on 13th May 2010 and removed on 03rd August 2010 for analysis. The coupon was exposed in the ozone-treated cooling water system for a total duration of 82 days. The weight loss after cleaning was found to be 0.053 g. The corrosion rate was <0.1 mpy.

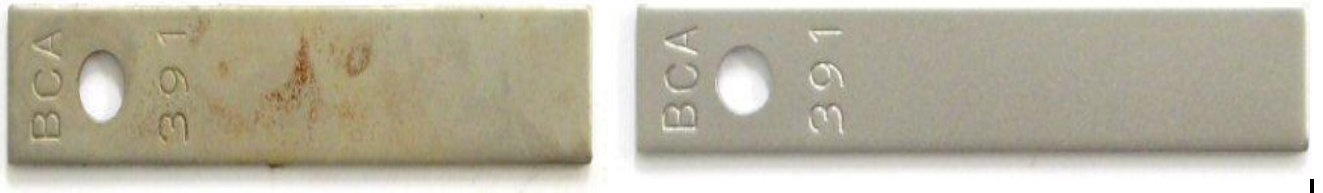
Stainless steel corrosion coupon that was labeled as specimen, ZBN115, was installed in the chemical treated cooling towers on 26th June 2008 and removed on 29th September 2008 for analysis. The coupon was exposed in the chemical-treated cooling water system for a total duration of 95 days. The weight loss after cleaning was found to be 0.1256 g. The corrosion rate was 1.4 mpy.

The table set out below shows coupons that were installed in ozone and chemical treated cooling water systems

Corrosion Coupons

	Coupon before Cleaning	Coupon after Cleaning
Q2/2008 Mild Steel Chemical Treated ZCF 0067		
Q1 2010 Mild Steel Ozone Treated ZCI 1857		
Q3/2010 Ozone Brass DFP 473		
Q3/2010 Chemical Brass DGF 720		

Q1 2011 Brass Chemical Treated DFY 879		
Q2 2011 Mild Steel Ozone Treated ZCN 4302		
Q2 2011 ZBR 0037		
Q3 2011 Brass Chemical Treated DFJ 514		
Q1/2012 Brass Chemical Treated DGF 731		

Q1/2012 Ozone-Tower Mild Steel ZCI2111	
Q1/2012 Chemical Mild Steel ZBR 2672	
Q1/2012 Chemical Mild Steel ZBR 2670	
Q3/2010 Ozone Treated Stainless Steel BCA 391	
Q3/2008 Chemical Stainless Steel ZBN115	