Optimisation of Defoamer in a Bio-Reactor

James Mangundu

A research report submitted to the Faculty of Engineering and the Built Environment, Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in partial fulfilment of the requirements for the degree of Master of Science in Engineering.

Johannesburg 2017

DECLARATION

I declare that this research report is my own unaided work. It is submitted to 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.

10TH day of AUGUST, 2017

Table of Contents

ACKNOWLEDGEMENTS

Zetachem (Pty) Ltd is acknowledged for providing the reagents, samples and equipment used for the purpose of this study and for authorizing this work to be done. Further acknowledgement is extended to the Management of the "host" company for granting permission for plant trials on their site. The following people are also acknowledged for their contribution to the successful completion of this study: my Supervisor, Doctor Kevin Harding, for his patience in giving valuable guidance in academic research protocols; Mr. Mohau B. Mofokeng for all the assistance he offered me, and my son Tatenda Mangundu for his understanding and co-operation when I had to spend long hours away from him studying and putting together this work.

ABSTRACT

The success rate in the use of defoamers for controlling foam lies in finding the optimal concentration of defoamer for each foam type. Due to the dynamic nature of the foaming conditions in bio-reactors, using one concentration of defoamer across all foaming conditions may not be efficient. Where the plant design requires the use of defoamers for foam control, finding the right defoamer concentration ideal for each foam type becomes key. The objective of this study was to examine the following questions: first, can a more dilute form of Zeta Airspel 300® defoamer achieve complete foam knock-down and lengthy foam stay down times in the bio-reactor? And second, can this be achieved at a lesser cost than using 100% concentrated defoamer. To examine these questions, two sets of experiments were performed, batch experiments and plant trials, with defoamer concentrations ranging from 1%-100%. Defoamer samples with 40% concentration and above managed to completely reduce foam in both the batch experiment and in the bio-reactor. The rates of foam decay were faster with increase in defoamer concentration and foam suppression times were lengthier with increase in defoamer concentration. The economic evaluation of the plant trial results showed that 90% defoamer concentration was the least costly option of all. This discovery suggests that different defoamer concentrations can be used optimally depending on foaming conditions present in the bio-reactor at each given time. Future studies should focus on conducting longer plant trials during periods of different foaming conditions to be able to develop a model that predicts the most cost effective defoamer concentration for each particular foam type.

LIST OF FIGURES

LIST OF TABLES

SECTION 1

INTRODUCTION

1.1 Brief introduction to the use of activated sludge processes

Wastewater treatment systems that uses activated sludge technology have increasingly become common in many parts of the world. The reason for this being that they are considered to arguably be the most effective and versatile of all wastewater treatment methods (Gerardi, 2002). By definition, the activated sludge treatment process, is made up of three basic components: a reactor, a sedimentation tank/clarifier and a recycle system for solids removed from the clarifier being returned to the reactor (Tchobanoglous et al., 2003).

Pre-treatment is sometimes employed before effluent is received by the activated-sludge systems, but this is determined by the constituents of the influent streams. The pre-treatment processes may be in form of primary sedimentation tanks (-which are effective for removal of settleable solids), cooling tower units (-to lower the temperature of influent to levels that allow efficient bio-degradation of organic matter in the bio-reactors), and equalization basins (-to balance the influent flows into the bio-reactors to avoid surges).

Mixed liquor in the bio-reactor contains microorganisms responsible for biodegradation of organic matter and is kept in suspension by air supplied from the bottom of the reactor, hence, the name suspended-growth process. Tchobanoglous *et al*. (2003) clarifies the role of biological processes in activated-sludge reactors as the removal of soluble organic matter to enable the

processes of biological nitrification and denitrification as well as phosphorus removal. The micro-organisms present in the bio-reactor of the activated-sludge process treat the influent water by feeding on waste components converting them into living tissue for their growth, multiplication and energy (Ekama et al., 1999)

The main purpose of wastewater treatment is to remove or reduce harmful constituents in the wastewater (suspended solids, biodegradable organics, pathogens, nutrients, priority pollutants, refractory organics, heavy metals and dissolved inorganics), to levels below those prescribed by discharge permits to ascertain protection of public health and the environment (Tchobanoglous et al., 2003). Appendix C contains the limits of each of the components of wastewater and the minimum requirements, thereof, for disposal of wastewater into public rivers in South Africa (DWA Guidelines, 2010). To mention but a few, the minimum requirement for chemical oxygen demand in treated wastewater before disposal is 75mg/L, 0.25mg/L for residual chlorine and the pH of the wastewater should be between 6.5 and 9.5.

The separation of liquid and solids takes place in the clarifier. Biological wastewater treatment methods have been engineered to emulate what happens in nature but at a much faster rate so that the ever increasing wastewater volumes discharged from communities can be treated before being discharged into the environment (van Haandel and van der Lubbe, 2007). In South Africa, it is a constitutional right for people to live in an environment that is not harmful to their health or wellbeing (South African Constitution, 108 of 1996).

1.2 Problems of excessive foaming in activated sludge processes

It has been widely reported that activated-sludge wastewater treatment plants all over the world often experience problems of sludge bulking and excessive foaming. There is extensive information in literature on the causes and control of excessive foaming in activated sludge processes(Dhaliwal et al., 1991; Ekama et al., 1999; Jenkins et al., 2004; Mamais et al., 2011; Pitt and Jenkins, 1990; Pretorius and Laubscher, 1987; Soddell et al., 1993). The actual causes of excessive foaming in activated sludge processes remains an area of many conflicting views by many scholars, but the general consensus is that excessive foaming is often linked to the presence of filamentous actinomycetes of the genus *Gordonia amarae* (previously known as *Norcardia),* (Lechevalier, 1975; Pipes, 1978b; Dhaliwal, 1979; Awong *et al*., 1985; Lemmer, 1986; Pretorius and Laubscher, 1987) or *Microthrix Parvicella* (Jerkins *et al*., 1985; Richards, 1986; Pitt and Jerkins, 1990; Tchobanoglous et al., 2003). These actinomycetes have been reported to be very hydrophobic due to the presence of mycolic-acids in their cell walls (Stainsby *et al*., 2002; de los Reyes and Raskin, 2002). The hydrophobicity and the morphological characteristics causes these microorganisms to get attached to air bubbles in the mixed liquor and rise to the surface of the liquid resulting in increased surface activity and leading to foam stability (Mamais et al., 1998; de los Reyes, Rothauszky and Raskin, 2002; Davernport and Curtis, 2002). The presence of surfactants and bio surfactants is linked to foam generation while the presence of actinomycetes is associated with stabilizing the foam that has already been generated.

The excessive growth of foams in activated sludge systems have undesirable knock-on effects such as safety hazards (in the event of spillages of foam out of the bio-reactors), deterioration in effluent quality, general housekeeping menace, risks of soil and water pollution and can be a source of unpleasant odours (Huangfu, 2012; Mamais et al., 2011; Pipes, 1978; Pretorius and Laubscher, 1987). However, all indications are that focus on treatment of biologically generated foam is merely addressing the symptoms of a much larger problem and does not in itself solve the underlying causes of this phenomenon in the long run (Karakashev and Grozdanova, 2012; Wanner, 1994). Nonetheless, the requirement for defoaming remains a key component in numerous applications. Many industrial processes result in accumulation of unwanted foam that requires the removal of the foam by either chemical or physical methods. Examples of well-known industrial processes where defoaming is required are: radioactive waste treatment, wastewater treatment, oil and gas recovery, food and beverages production, pulp and paper making and medical applications (Garrett, 1993a).

1.3 Methods of foam control in activated sludge processes

Literature reviewed suggests that there is no universal method that can be employed for control of excessive foaming in activated sludge processes(Denkov et al., 2014a; Pelton, 1996). This is due to the variances in plant designs, effluent constituents, and a wide range of causal microorganisms, environmental conditions, and effluent permit discharge requirements among other factors. Although the methods employed tend to be case specific, the methods used to control excessive foam can be classified into to four basic groups:

(1) Pretreatment of influent streams before entering the activated sludge reactors,

(2) Adjustment of operating conditions of the activated sludge process,

(3) Addition of chemicals,

(4) Manipulating the design of the activated sludge process

-or a combinations of some of these methods (Pantano and Watts, 1984; Sezgin and Karr, 1986).

Many studies of foam control methods in activated sludge systems consider the use of antifoams to be a costly and uncertain method because foams generated by biological processes are often more stable and resistant to most commercial antifoam agents (Pitt and Jenkins, 1990; Richards et al., 1990; Tchobanoglous et al., 2003). Although antifoams are more precisely defined as chemicals that prevent formation of foam and defoamers as those that destroy foam that's already formed, (Denkov et al., 2014b; Garrett, 1993a), in the industry these terms are used interchangeably to mean the same thing. The term defoamer will be assigned to the chemical used for this study.

In activated sludge systems where the use of defoamers is opted for as the method of choice for foam control, municipalities and industries are faced with the challenge of the continual need to reduce operating costs allocated for defoamer use and the requirement to comply with effluent discharge permit regulations to avoid payment of hefty fines and persecution by authorities.

The balance becomes even more difficult to maintain when the bio-reactors are not being operated optimally, resulting in generation of a thicker and much more stable foam type. This foam type significantly reduces both the foam knock-down rate of the defoamer and the foam

stay down times (author's personal experience). This results in high defoamer usages leading to a substantial increase in the cost of treating the foam. To keep the cost of foam treatment within set budgets using defoamers requires a properly crafted strategy of continual and consistent investigation of the most optimal operating conditions of bio-reactors coupled with focus on optimization of defoamer application methods (Karakashev and Grozdanova, 2012).

1.4 Aim

The aim of this research is to reduce foam treatment cost in a bio-reactor by using the most optimal defoamer concentration to control foam.

1.5 Objectives

The objectives of this research were:

- To identify the most optimal defoamer concentration that can control foam in a bio-reactor.
- To identify the most cost-effective defoamer concentration that controls foam in a bio-reactor.

1.6 Report layout

The work begins with Chapter1 giving a brief introduction to the use of activated sludge processes in treatment of wastewater, the problems of excessive foaming, the use of antifoams in controlling foams and the current challenges on site associated with the use of defoamers. Chapter 2, is focused on reviewing the theory relating to basic principles of operations of the

activated sludge process, causes and control methods of excessive foaming paying special attention to the historical development in the use of defoamers as a method of foam control. Chapter 3 outlines the materials and methods used for laboratory experiments and plant trials of this work adopted from the current defoamer application method on site. Chapter 4 lays out the results of the laboratory experiments and plant trials performed with Zeta Airspel 300® defoamer. Discussion of the results of the laboratory tests and the plant trial is attended to in Chapter 6. Finally, Chapter 7 focuses on conclusions on the work performed, limitations of this work and recommendations for future studies.

SECTION 2

LITERATURE REVIEW: ACTIVATED-SLUDGE SYSTEM OPERATION, CHALLENGES AND SOLUTIONS

2.1 Historical development of the activated-sludge process

The origins of the concept of biological treatment of wastewater on a full plant scale size is credited to the work of Dr. G.J. Fowler of the University of Manchester, England who instructed Arden and Locket to carry out work at the Manchester Sewage Works (Tchobanoglous et al., 2003). The term activated sludge was given by Arden and Locket in 1914 after they realized that activated microorganisms were capable of aerobically stabilizing organic material in wastewater (van Haandel and van der Lebbe, 2007).

2.2 Description of the activated-sludge process

The activated sludge process is the most commonly used system for treatment of municipal wastewater, and is arguably the most effective and versatile of all wastewater treatment methods (Gerardi, 2002). The process is classified as biological because the responsibility of waste degradation is designated to microorganisms.

The activated sludge process can have many configurations, but has to include at least one reactor, one sedimentation tank and one recycle system (commonly known as Return Activated

Sludge) (Tchobanoglous et al., 2003). The reactor is aerated to keep the microorganisms responsible for treatment of the wastewater in suspension. The purpose of the sedimentation tank is for the separation of the solid and liquid components of the treated wastewater, and the Return Activate Sludge (RAS), circulates back to the reactor some of the concentrated sludge removed by gravity from the sedimentation tank (van Haandel and van der Lubbe, 2007). Figure 2.1 is a schematic flow diagram showing the basic components of the activated sludge process.

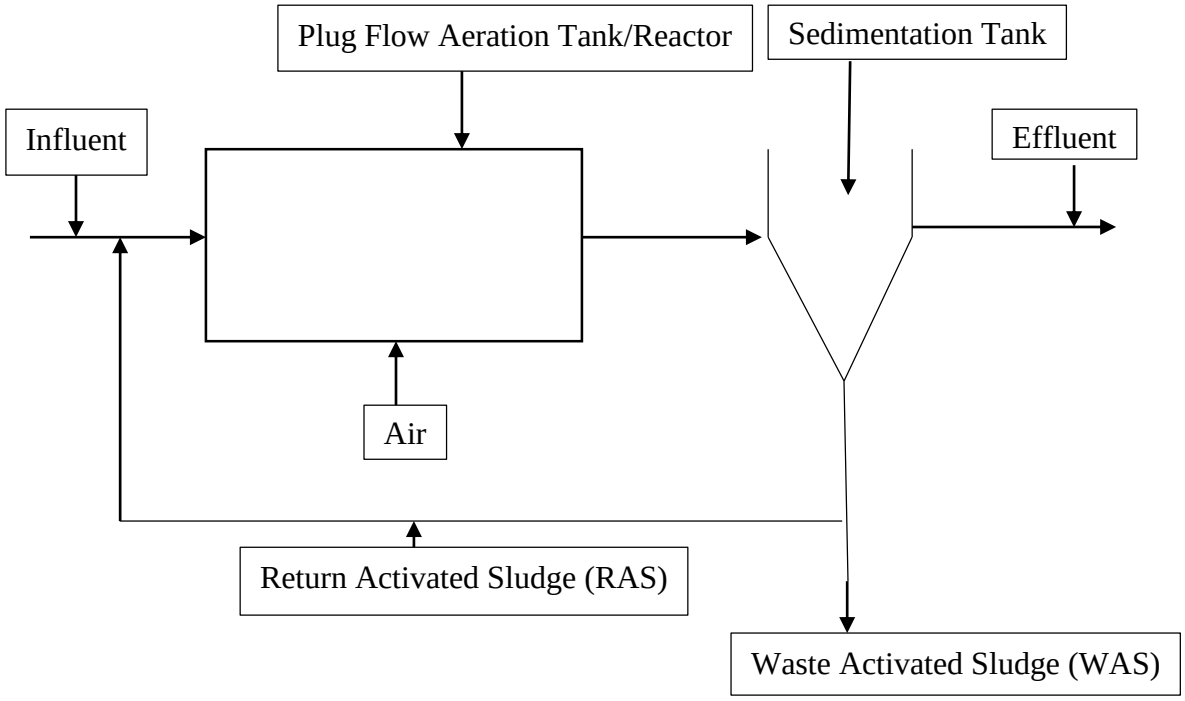


Figure 2 1: Schematic representation of a suspended growth biological treatment process adapted from (Tchobanoglous et al., 2003)

Often the activated sludge process is supported by preliminary physical and chemical processes and in some cases, post treatment processes, such as filtration and disinfection. The role of

primary treatment is to remove large settleable solids from the wastewater before it enters the bio-reactor. Chemical processes for pretreatment are usually there for pH adjustment purposes and in some cases coagulant addition is employed to improve the rate of sedimentation of the solids in the sedimentation tanks (Jenkins et al., 2004). In areas with hot climates primary treatment is avoided particularly for wastewater treatment works (WWT) that receive domestic wastewater to avoid problems of bad odor. Literature reviewed elaborates that options for substituting primary treatment may vary, from incorporating oxidation ditch systems, stabilization ponds, aerated lagoons or using a string of batch reactors (Eckenfelder and Cleary, 2013).

2.3 **Reactor configurations of the activated sludge processes**

According to Tchobanoglous et al., (2003) the first reactor configuration to ever be employed in treatment of wastewater was a plug-flow reactor which was designed with a length to width ratio of 10:1 or higher. Other authors site the stirred-tank batch reactors as the first ever reactor to be employed when several researchers began to blow air into sewage tanks to eliminate undesirable, bad odor caused by anaerobic conditions (Eckenfelder and Cleary, 2013; Jenkins et al., 2004). However, there is a general consensus that the early reactors faced major challenges the time industrial waste began to get discharged into domestic waste. The toxic nature of some of the industrial effluent affected the health of the microorganisms resulting in poor effluent treatment (Hao et al., 1988). This then prompted the development of the complete-mix activated sludge reactors, initially as a single step and then followed by a two staged system (Barnard, 1976). The two staged complete-mix activated sludge reactors were designed to target

biochemical oxygen demand (BOD) removal in the first stage while nitrification took place in the second stage.

2.4 Key factors on design of activated sludge processes

Proper design of an activated sludge process requires characterization of the wastewater constituents. There are various wastewater constituents that are considered in the design of activated sludge processes, however, the most important ones are: the content of carbonaceous substrates, nitrogenous compounds, phosphorus compounds, total suspended solids and alkalinity (Chambers and Tomlinson, 1982).

Carbonaceous constituents of wastewater are measured by biochemical oxygen demand (BOD) or chemical oxygen demand (COD). It is argued that wastewater with high concentrations of biodegradable COD or BOD require much larger aeration basin volumes, higher oxygen transfer needs and results in high levels of sludge production (Tchobanoglous et al., 2003).

The COD of a waste is made up of two components, the biodegradable and the non-biodegradable material. Both biodegradable and non-biodegradable materials have a portion that is dissolved/soluble and another that remains in a particulate state. The non-biodegradable material that is soluble passes through the treatment process without being changed and is found in the effluent. The fate of the soluble non-biodegradable constituents cannot be altered by the activated sludge system, it passes through the system without any alterations. However, the particulate non-biodegradable material will be assimilated by biomass and will form part of the sludge produced (Eckenfelder and Cleary, 2013; Ekama et al., 1999; Jenkins et al., 2004;

Pretorius and Laubscher, 1987; Tchobanoglous et al., 2003; Wanner, 1994). The fact that the non-biodegradable particulate COD is organic matter makes it be part of the volatile suspended solids and is referred to by the term non-biodegradable volatile suspended solids (nbVSS). There is also another component that is inert commonly referred to as nonvolatile suspended solids/inert solids present in the influent streams. The inert suspended solids portion is what remains after the volatile suspended solids (VSS) are removed from the total suspended solids (TSS).

There are three components that makes up biodegradable COD. These are, the soluble readily biodegradable material, the particulate biodegradable material and the colloidal biodegradable material (Ekama et al., 1999; Jenkins et al., 2004). The soluble readily biodegradable material is the first to be quickly assimilated by biomass while the particulate and colloidal biodegradable material will first have to be dissolved by enzymes before being assimilated(Tchobanoglous et al., 2003). As a result, particulate and colloidal biodegradable material takes longer to be consumed and are assigned a name, slowly biodegradable COD (sbCOD).

In essence, the quantity of the readily biodegradable COD in wastewater is the one that determines the performance of the reactor (Ekama et al., 1999; Jenkins et al., 2004; Tchobanoglous et al., 2003; Wanner, 1994). The reason for this is that if there is sufficient readily biodegradable soluble chemical oxygen demand (rbCOD), it gets assimilated more quickly by microorganisms in the bioreactor leading to an exponential growth of the floc-forming microorganisms which are responsible for efficient treatment of the wastewater. This

in turn enhances good settleability of sludge. In a plug-flow reactor, the oxygen requirement is always higher on the front part of the reactor due to higher levels of soluble readily biodegradable COD. Figure 2.2 shows the fractionation of COD in wastewater.

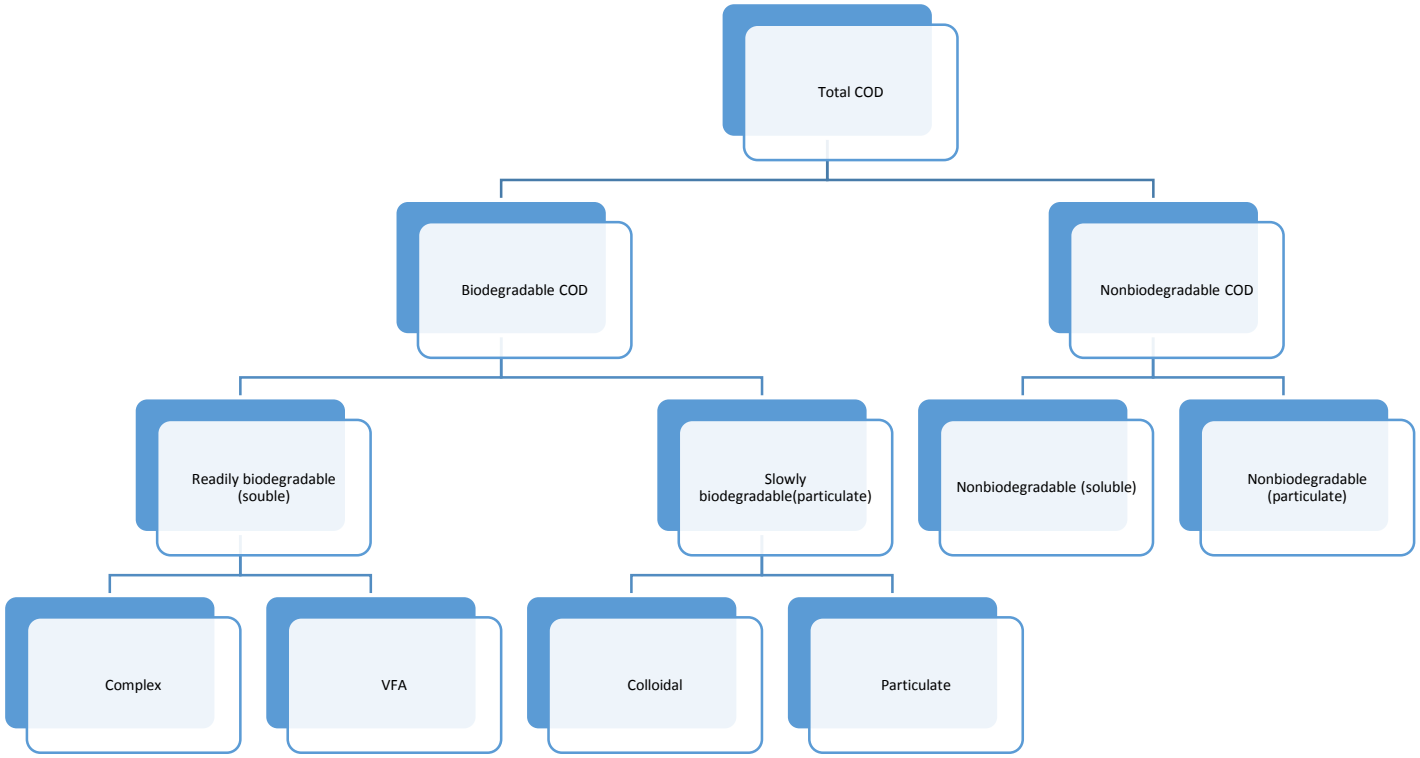


Figure 2 2: Information on the COD fractionation used in detailed design of activated-sludge processes. Modified from (Tchobanoglous et al., 2003)

Wastewaters also contain nitrogenous constituents. The Total Kjeldahl Nitrogen (TKN) is a sum of ammonia and organic nitrogen found in wastewater. Between 60-70% of the TKN is made up of ammonia which is readily available for bacterial synthesis and nitrification. The organic nitrogen portion is made up of particulate and dissolved/soluble nitrogen. Both the particulate and dissolved components of organic nitrogen are made up of biodegradable material and non-biodegradable material.

The soluble degradable nitrogen will be removed at a much faster rate than the particulate degradable portion. About 6% of the non-degradable VSS is made up of organic nitrogen (Barnard, 1976). The particulate non-biodegradable organic nitrogen is incorporated into sludge while the soluble non-biodegradable organic nitrogen goes with effluent exiting the clarifiers. The amount of soluble non-biodegradable nitrogen in wastewater is found in very minute levels, 1-2mg/L(Tchobanoglous et al., 2003). Figure 2.3 shows the fractionation of nitrogen in wastewater, used for detailed design of nitrification and denitrification processes.

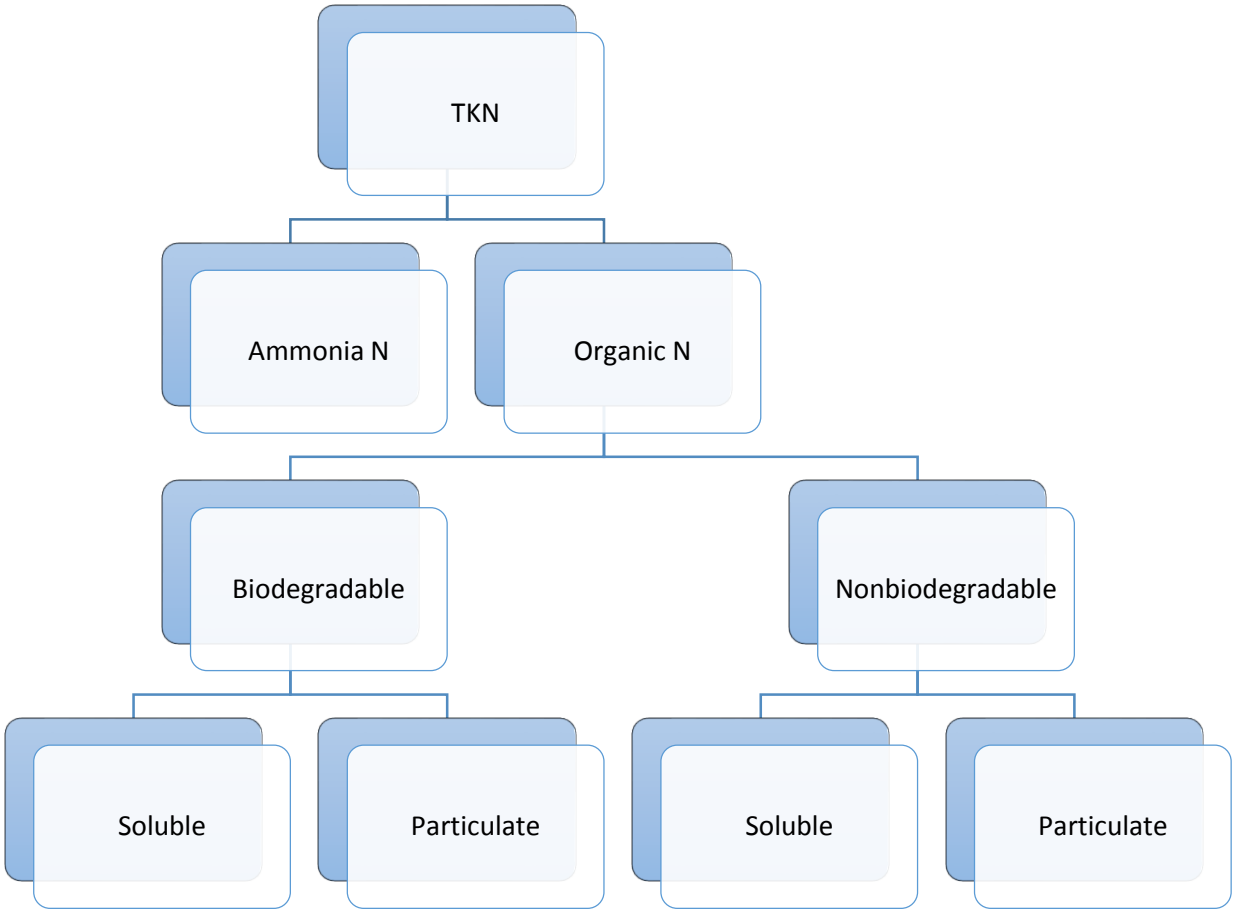


Figure 2 3: Fractionation of nitrogen in wastewater used in detailed design of nitrification and denitrification. Modified from (Tchobanoglous et al., 2003)

Many scholars believe that biological nitrification process in the bio-reactors thrives under alkaline conditions (Downing and Nerenberg, 2008; Ekama et al., 1999; Gerardi, 2002; Jenkins et al., 2004). This is where maintaining residual alkalinity buffer becomes essential to avoid the pH of the wastewater from decreasing to below 6.7. It is believed that nitrification process gets adversely affected when the wastewater pH falls under 6.7 (Gerardi, 2002). This requires that the alkalinity be monitored and in some cases has to be increased by adding chemicals such as Soda Ash or lime. The desired residual alkalinity required in the aeration basins after complete nitrification is 50mg/L (Lemmer, 1986). Other authors argued that optimal pH range for nitrification is between 7.2 -8.0, (Gerardi, 2002) while Tchobanoglous et al (2003) recommended a pH range of 6.8-7.4 and residual alkalinity of between 70 and 80mg/L as $CaCO_3$.

Of all operational conditions affecting nitrification in the aeration basins, temperature has the most significant influence because it affects the growth of nitrifying bacteria and consequently, the rate of nitrification (Vardar-Sukan, 1998). High temperatures favour the growth of nitrifying bacteria while low temperatures reduces growth and lowers the rate of nitrification. The optimum temperature for the growth of nitrifying bacteria is considered to be 30°C (Jenkins et al., 2004; Soddell and Seviour, 1990; Tchobanoglous et al., 2003).

In most parts of the world temperature varies greatly between seasons. Where this is the case, ensuring that the aeration basin performance is maintained requires the adjustment of operational parameters such as Mean Cell Residence Time (MCRT), Solids Retention Time (SRT), Food to Microorganism Ratio (F/M Ratio), Mixed Liquor Volatile Suspended Solids

(MLVSS) and the oxygen requirements (Gerardi, 2002). In summary, since temperature affects the growth and activity of microorganisms in the aeration reactor, the MLVSS, MCRT and SRT required for complete nitrification is inversely proportional to the temperature. That is, the higher the temperature, the lower the MCRT, MLVSS and the SRT needed and the opposite is the case for lower temperatures.

2.5 **Process Control Parameters**

Reviewed literature (Garrett, 2016; Jenkins et al., 2004; Tchobanoglous et al., 2003) argues for the activated sludge process to be controlled at all times to meet the following objectives:

(1) To oxidize dissolved and particulate biodegradable organic materials in wastewater,

(2) To capture and incorporate non-settleable suspended and colloidal solids into biological fibre or biofilm and remove them from the wastewater,

(3) To transform nutrients such as Nitrogen and Phosphorus or remove them from the wastewater before disposal and

(4) To remove trace organics and inorganics from wastewater. To make sure these objectives are met under a wide range of operating conditions, it is key to give special focus to process control.

The following key process parameters must be monitored and controlled:

(1) Optimum dissolved oxygen levels inside the aeration basins,

(2) Return activated sludge (RAS) (has to be regulated), and

(3) Waste activated sludge volumes (WAS) (Ekama et al., 1999; Tchobanoglous et al., 2003; Wanner, 1994).

To achieve this, the oxygen uptake rate (OUR) and the mixed liquor suspended solids (MLSS) and mixed liquor volatile suspended solids (MLVSS) have to be measured.

In the secondary clarifiers, tests have to be done to monitor the suspended solids in the effluent stream. The settleability of the sludge is tested using the sludge volume index measurement (SVI) and the sludge blanket level has to be monitored to determine the frequency of sludge removal/desludging.

2.6 **Operational problems of the activated sludge process**

The three main problems associated with the operation of the activated sludge processes are, sludge bulking, rising sludge and excessive foaming (commonly referred to as Norcadia foam) (Davenport and Curtis, 2002; Jenkins et al., 2004; Rossetti et al., 2005; Tchobanoglous et al., 2003; Wanner, 1994).

Sludge bulking results in high suspended solids in the effluent exiting the secondary clarifiers such that the treated effluent fails to meet the desired effluent discharge permit standards .The high suspended solids in the effluent can also lead to clogging of filters and result in inadequate disinfection (Richards et al., 1990).

Wanner (1994) classified the sludge bulking phenomenon into two categories, one caused by excessive growth of filamentous organisms (filamentous bulking) and the other caused by presence of excessive amount of extracellular biopolymer (viscous bulking). The filamentous sludge does not settle well due to its bulkiness while the viscous sludge does not settle well because it is highly hydrophilic so it retains a lot of water and cannot be easily separated from the supernatant (Ekama et al., 1999).

The problem of rising sludge takes place in the clarifiers affecting sludge with good settling characteristics which under normal conditions could be easily separated from the effluent. The most common cause of rising sludge is denitrification in the clarifiers where nitrites and nitrates get converted to nitrogen gas(Tchobanoglous et al., 2003). As the formed nitrogen gas rises, it carries sludge with it and results in carry over of solids in the effluent.

The third and probably most common and problematic operational problem is the generation of excessive foaming in the aeration basins, and in some cases is equally problematic in the sedimentation tanks.

2.7 **Excessive foaming problems in the activated sludge process**

Heard et al. (2007) define foam as a collection of bubbles separated by thin liquid or lamellae. For foam to be generated, there has to be a source of air/gas bubbles and a surface-active agent. Examples of well-known surface-active agents present in wastewaters are detergents, greases, fats, oils and a wide range of bio-surfactants produced by microorganisms.

The increase in foam volumes can only be achieved if the lamellae are stable enough to resist drainage and subsequent burst of the foam bubbles. The stability of the lamellae is credited to presence of a number of factors such as the increase in the viscosity of the liquid phase (Myers, 1988) and or the presence of hydrophobic particles between the bubbles that prevents drainage (Leja, 1982).

Wastewaters treated in activated sludge systems have a potential of providing all the ingredients required for the formation of stable foams. The source of air bubbles is provided for by the blowers in aerated basins, and the surfactants are some of the constituents of the wastewater such as detergents, fats, oils and bio-surfactants produced by microorganisms.

Reviewed literature argue that during the exponential growth phase of bacteria, bio-surfactants were produced which resulted in a significant drop in the surface tension of the water leading to persistent foaming (Heard et al., 2008; Pantano and Watts, 1984). The main conclusion of the work by Heard et al (2007) was that *Gordona amarae* do not cause foaming, it is the bio-surfactants that they produce which stabilizes foam by reducing the drainage rate of foam films leading to accumulation of foam.

Excessive foaming is an operational problem widely reported in activated sludge plants all over the world. Suddell and Seviour (1990) and Jenkins *et al* (1993) associate the presence of thick brown, viscous, stable foam generated in activated sludge processes to the presence of filamentous actinomycetes of the *Norcardia* species, mostly *Norcardia amarae*. Although in reality, further studies have revealed the presence of a much more diverse range of

actinomycetes in the foam e.g. *Rhodococcus* species, mycobacterium species, *Gordona* species, *Tsukamurrela* species and Microthrix parvicella (Soddell and Seviour, 1994), this type of foam is still commonly referred to as *Norcadia* foam in many texts.

Soddell and Seviour (1994) thoroughly studied the relationship between temperature and growth rates of various organisms causing excessive foaming in activated sludge processes from temperatures ranges of between 5-50 °C. Their studies revealed that some of the Norcardia amarae species had fast growth rates only on a temperature range of between 15-35 °C. Therefore, foaming problems under lower temperatures than 15 °C and above 35 °C should in reality, not be credited to *Norcardia amarae*. They also found out that other species e.g., *Rhodococcus buensis* species and *Rhodococcus rhodococcus* species had fast growth rates in a wider range of temperatures of between 5-45°C. These studies helped to further clarify the earlier controversy by Pitt and Jenkins (1990), Dhaliwal (1991) about whether *Norcadia* foaming could occur at lower temperatures. The answer to this would be a clear yes, that is, if the term *Nocardia* foam was to be used loosely, because certain foam causing microorganisms were found to grow very fast in low temperatures.

The *Norcardio* forms examined by Soddell and Seviour (1994) and by other researchers (Lechevalier, 1975; Sezgin *et al*., 1988) showed very similar microscopic morphology but were very diverse because they exhibited a wide range of growth rates and also differed immensely in their physiology. This work emphasized the need to first determine the specific type of microorganisms present in each case before picking a potential control strategy for control of excessive foaming. For example, trying to solve excessive foaming by reduction of MCRT may

not solve the foaming problem if the species causing the excessive foaming problem has a fast growth rate at the existing mixed liquor temperatures, because they would still multiply fast enough to continue casing foaming problems even with lower MCRT.

This work is groundbreaking because in previous literature there was a lot of conflicting and confusing views with some scholars associating *Norcardia* foam with long mean cell residence times, low F/M ratios and higher temperatures (Pitt and Jenkins, 1990) while on other occasions, Dhaliwal (1979), found no relationship between *Norcardia* growth and MCRT. The current knowledge helps to highlight the role that temperature plays in the growth of foam causing microorganisms.

2.8 **A review of foam control methods – Case studies**

Over the years there has been a wide variety of methods that have been employed in attempting to control excessive foaming in activated sludge processes. Some of the methods employed where successful for some sites while not so successful on others, some methods that succeeded would only be effective for limited time periods and then fail afterwards, some methods would be successful in controlling excessive foaming but would affect the effective treatment of wastewater (e.g. reduction of aeration rates, reduction of SRT etc.), other methods would completely fail (Blackall et al., 1991) while others would have a greater success rate but result in higher operating costs (Mamais et al., 2011).

There is no disputing however, that although a lot of effort has been invested in trying to find the best options of controlling excessive foaming without adverse effects on the treatment efficiency of the activated sludge system (Karakashev and Grozdanova, 2012; Pantano and Watts, 1984), a universal solution employable in all situations does not exist yet.

This shows the complex nature of the subject matter and the wide range of combination of factors that can result in the excessive foaming phenomenon (Stainsby et al., 2002). This section seeks to summarize some of the traditionally employed methods, and the more recent ones, highlighting their successes, shortfalls and relevance or irrelevance to the site being studied.

A quick-fix method with immediate results in foam control is to radically reduce the airflows into the bio-reactors. This cuts the main source of air bubbles and would definitely stop foam from overflowing from the bio-basins (Richards et al., 1990), but will result in other operational problems such as high suspended solids in the effluent streams caused by incomplete treatment and reduction in the nitrification efficiency of the system.

Another commonly employed technique is the reduction of sludge age (MCRT), which has been employed successfully to solve the problem of *Norcadia* foam in Atlanta at the Utoy Creek WPCP, R.M Clayton WPCP and at the South River WPCP (Jenkins et al., 2004). However, this solution was not sustainable as it affected the nitrification requirements resulting in failure of these plants to meet the required effluent permit discharge standards.

Excessive foaming problems have also been suppressed by the addition of toxic chemicals such as chlorine and hydrogen peroxide (Chang et al., 2004; Ramothokang et al., 2003). However, these methods are often short term solutions since they are relatively expensive and in majority of cases foaming problems resume once dosing has been stopped. They also create other safety concerns such as high risk exposure to the operators during use because of their toxic nature. Chlorination of organic matter also has a risk of formation of carcinogenic compounds as by-products of the process (Trihalomethanes), please refer to Appendix C for the guidelines of the minimum requirements of chloride concentrations in treated wastewater. For these reasons, chlorination cannot be adopted as a permanent solution to excessive foaming problems.

There are some methods that have been successfully employed on a bench scale size to control *Norcadia* foam e.g., coagulant addition (Mamais, Kalaitzi and Andreakadis, 2011), the feast-fast operation method (Tsang et al., 2008).

Maimais et al., (2011) investigated the use of a number of coagulants to incorporate filamentous organisms into the flocs, remove them from the system and achieved an 80% reduction in the foaming propensity of the resultant mixed liquor. Some of the coagulants that were also used in this experiment are: ferrous chloride, ferric chloride, hydrated aluminium sulphate, polyaluminium chloride and organic cationic polymer.

Mixed liquor samples for the experiment were taken from aeration basins of two full scale wastewater treatment facilities that employed the activated sludge system for nutrient removal.

Coagulants were dosed at various concentrations into 500ml foam samples. The efficiency of each coagulant was determined by:

(1) Microscopic evaluation of the mixed liquor before and after coagulant addition.

(2) (2) Measuring the foaming propensity of the activated sludge sample, and

(3) Measurements of the diluted Sludge Volume Index.

This work revealed that the addition of coagulants achieved removal of filamentous organisms from the mixed liquor resulting in foam control with benefits of improved settleability of sludge. An economic evaluation performed showed that cationic polymer was the more effective coagulant and the least costly followed by polyaluminium chloride.

Although coagulant addition, especially organic coagulant resulted in reduction of the foaming propensity of the mixed liquor. However, this method may not be ideal to employ on facilities treating large volumes of wastewater. Also, considering that the National Water Act waste discharge standards guidelines stipulates a concentration of 0.25mg/L for chlorides disposal, with future recommended concentration of 0.014mg/L, chemicals that contain chlorides may generally not be accepted on a full plant scale size due to the potential in increase of the residual chlorides in the effluent. High chloride levels are also not desired in the make- up water for cooling towers, they foam hydrochloric acid when mixed with water which results in corrosion of the metal plates on the cooling towers. In plants that uses centrifuges and incinerators, the addition of chemicals with non-biodegradable components is also not highly recommended because they would potentially contribute to air pollution and violating the guidelines of the National Emission Standards for Hazardous Air Pollutants (Masters and Ela, 2014). Acid rain deposition is one of the resultant consequences of air pollution.

The feast-fast operation method (Tsang et al., 2008) is a method that was employed on a bench scale size successfully. This method involved separation of floc-forming microorganisms from the filamentous organisms and seeding them in parallel flasks before passing influent with long-chain fatty acids, oils and fats. This type of waste degrades slowly and is more suitable for the filamentous bacteria (hence term feast), while floc-forming bacteria are not suited to digest this type of substrate (hence term "fast"). But since the two organisms were seeded in separate vessels, there was no competition for substrate which could favor one type of microbe over the other. The laboratory tests yielded good results on the effluent treatment and did not result in excessive foaming. While this method showed good results on a laboratory scale, on a full plant scale it is difficult to maintain constant the composition of constituents of the wastewater and also other factors such as the reactor temperature will change with seasons. The likelihood of conditions favoring growth of other types of organisms cannot be ruled out which would imminently result in changes to the microorganism species present in the reactors.

The Selective Foam Wasting Technique Method (Richards et al, 1990), is the one that promised to have universal application. This method was employed at the Utoy Creek WPCP in Atlanta to solve the problem of *Nocardia* foam successfully. This method involved reengineering the activated sludge basin by building a separate auxiliary tank used to receive *Nocardia* foam decanted from the aeration basin. This was achieved by increasing the airflows to promote building up of bigger volumes of foam which is believed to separate the majority of the *Nocardia* microorganisms from the mixed liquor due to their hydrophobicity. This foam was decanted into a vessel, got separated from the mixed liquor flowing to the clarifiers and the

Norcardia foam was allowed to be dried or wasted to the centrifuges and disposed of on the incinerators.

.

The only limitation to this method is the availability of space to build the foam receiving tanks on an existing site as well as capex for putting up the infrastructure required to handle the decanted sludge. Where there is no limitation to the above, this may be a permanent solution to handling problems of excessive foams.

Last but not least, another method of controlling excessive foaming that is employed is the use of antifoam agents/ defoamers (Garrett, 1993b, 2015a; Karakashev and Grozdanova, 2012). The use of antifoams in controlling foam in activated sludge processes has got a fairly high success rate although it is considered to be an expensive method. This method will be reviewed in more detail since it is the method that is being used permanently for foam control on the site under investigation.

2.9 **Overview of the history of studies of antifoams**

Pioneering studies in the use of antifoams is credited to S. Ross in the late 1930s. This was followed by studies on the physical methods of studying antifoams by a number of researchers such as Harkins in 1941, followed by J. Robinson and W. Woods in 1948 (Eckenfelder and Cleary, 2013).

During the 1970s and 1980s saw Kulkarini et al, Dippenaar A, and Garret P. experimenting with combining oils and hydrophobic particles as antifoam agents (Jenkins et al., 2004). Theoretical Models of antifoam performance were developed during the late 1980s and 1990s by Pelton R and Garret P, including the limits to the applicability of these methods (Saayman et al., 1997).

The late 1990s saw advances on experimental techniques for studying antifoams by introduction of different variants of the Film Trapping Technique Methods(Ivanov et al., 1998). This was made possible by the capacity of these researchers for studying "antifoam action" within thin liquid films (Pelton, 1996).

The years between 1996 and 2004 saw the latest knowledge being developed by Denkov N when he managed to harness the most successful type of Film Trapping Technique and the Interferometric Thin Film set-up of Scheludko to study "antifoam action" under different conditions (Mamais et al., 2011).

Present work on antifoam studies is more focused on alternative methods of design and control of foam stability and recognition that "foaminess and rate of foam decay" depends on the surfactant adsorption layers on the bubble surfaces (Soddell et al., 1993). As a result, foaminess and foam durability can be designed by good choice of surfactants, their respective concentrations and the methods of foam generation. There seem to be more focus on scrutinizing the mechanisms of foam generation which produces the initial foam. This leads to

a general mass balance equation: "Foaming capacity of frothers = Foam Production = Foaminess – Average rate of foam decay" (Tchobanoglous et al., 2003).

2.10 A review on different antifoam types and how they work

From a historical perspective, the first antifoams to be put in use between the 1940s and 1970s were oil based followed by antifoams made up of a combination of oil and hydrophobic particles from the 1970s to present day (Karakashev and Grozdova, 2012). Denkov et al (2014) categorizes the present day antifoams (oil plus hydrophobic particles), into two categories, those that prevent foam generation (commonly referred to as antifoams), and those that those that destroy foam that has already been formed (defoamers). Kougais et al., (2013) describes modern defoamers and antifoams as chemicals made up of a combination of oil and hydrophobic particles. The oils that are employed can vary from natural oils (rapeseed or sunflower), and fatty acids (oleic, octanoic and derivatives of natural fatty acids). Hydrophobic particles on the other hand may come in the form of siloxanes (polydimethylsiloxane) and esther (tributyphosphate) and others.

A further observation was made that some antifoams reduce foam fast and were named fast antifoams, while others reduce foam much slower, and were named slow antifoams (Denkov et al., 2014a). Following this observation, studies focused on understanding the mechanism by which antifoams work was made possible by the capability of combining the Film Trapping Technique method with the Interferometric Thin Film method of Scheludko to be able to study the action of antifoams under different conditions (Denkov et al., 2014b).

As has been already mentioned, all modern antifoam agents are made up of two components, the oil and hydrophobic particles. The role of each of the components in reducing foam is going to be looked at separately although in reality the two do complement each other when reducing foam.

Literature reviewed (Denkov et al., 2014b; Garrett, 2015b; Karakashev and Grozdanova, 2012; Pelton, 1996) summed up the mechanism by which oil antifoams destabilize foam films into the following three actions:

(1) That oil droplets act as hydrophobic bridges between film surfaces of foam bubbles

(2) That the oil displaces the adsorbed surfactants on the film surfaces of the foam making them unstable and rupture and

(3) That the oil rapidly spreads on the film surfaces of the foam bubbles, squeezing the liquid causing the bubble to collapse.

For the antifoam to act as a hydrophobic bridge, the first step is that it has to enter the space between bubbles. Studies on the ability of the antifoam droplets to be able to enter this space were determined by measuring the "entering coefficient" of the particular antifoam and a conclusion was drawn that the entering coefficient has to be positive, for the oil to be naturally drawn into the gap between two bubbles that are in contact (Denkov et al., 2014). It was argued that the pressure between two foam bubbles that are in contact acts as an entry barrier for the antifoam particles to get through (Nikolov and Wasan, 1997). This "entry barrier" was determined and was established that pressures lower than 15Pa are considered low entry barriers while those above are considered high entry barriers (Denkov et al., 2014).

The ability for antifoams to naturally spread on the aqueous surface of the foaming solution to reach more foam bubbles was cited as another critical factor in the effectiveness of an antifoam (Garrett, 2016). When studies for the ability for the spreading were performed, focus was given on the spreading coefficient which (Denkov et al., 2014a) argued that it had to be positive. Studies done on the hydrophobic particles on the other hand were found to destabilize the foam bubbles by perforating the walls of the foam bubbles/lamellae (Denkov *et al*., 2014). The impact of this process was then seen to be determined by two key factors, the size of the particle and the shape of the particle with spherical particles having less impact than those with shapes with sharp edges (Karakashev and Grozdanova, 2012). All the same, for the defoaming to be effective, these particles also have to enter the space between bubbles and also have to be spread to cover the longest surface area possible. So the entering ability and the spreading ability is still as equally important to the effectiveness of the hydrophobic particles as it is for the oil droplets.

On the other hand, other scholars argued that having a positive entry coefficient and a positive spreading coefficient alone does not automatically result in an effective antifoam compound (Karakashev and Groznova, 2012). The key factors to effectiveness of the antifoaming agent was described as having to find the optimal concentration where the antifoaming agent will be most effective (Denkov *et al*., 2014). The reason given for this was that when the concentration of the antifoam is below the optimal level it will not be effective and when the concentration is above the optimal range it acts as a stabilizer to the foam.

Given the dynamic nature of the foaming conditions in activated sludge processes due to the ever changes in influent constituents and other many factors mentioned in previous sections, it is very important to establish the optimal concentration of antifoams for different foaming conditions. This is what ultimately what makes the difference between effective and probably cost effective use of defoamers and ineffective and costly use. This here was the key motivating factor to this investigative work.

2.11 **Deactivation of mixed solid-oil compounds**

The deactivation or loss of defoaming strength of these defoamers is described as to come into effect when there is separation or dispersion between the oil particles and the solid particles (Denkov et al., 2014). A simplified explanation to this is that the separation of the two results in loss of strength and ultimately loss of deforming power because the complementary role of each part would have been lost. The defoaming capacity of the mixed solid-oil compounds was explained as being more effective when the defoamer was less dispersed in the medium (Kougias et al., (2013).

2.12 **Motivation of this study**

The reviewed literature is on the studies of the use of activated sludge processes in treatment of wastewater suggest that this method is very effective and robust in efficient removal and reduction of pollutants in wastewaters justifying why this method is very popular in many parts of the world despite some operational hurdles encountered in its application such as sludge

bulking, rising sludge and excessive foaming (Brown et al., 2001; Eckenfelder and Cleary, 2013; Pantano and Watts, 1984; Wanner, 1994).

There is no denying that there been extensive studies over the years in the causes of excessive foaming in the activated sludge processes and in various control methods (Brown et al., 2001; Eckenfelder and Cleary, 2013; Ekama et al., 1999; Huangfu, 2012; Pitt and Jenkins, 1990), as much as there has been great focus on the use of antifoam agents, understanding their modes of action and applicability in various industrial processes (Denkov et al., 2014b; Garrett, 2015a; Pelton, 1996).

However, this study aims at changing the existing perception that the use of antifoams in controlling excessive foaming in activated sludge processes is generally regarded as an uncertain and expensive method (Karakashev and Grozdanova, 2012) by putting more focus on optimization of the application methods of defoamers in conjunction with employing other operational methods that have shown promising results in resolving this challenge (Jenkins et al., 2004; Pagilla et al., 1996). The reason for this being that there will always be a need for use of antifoam in specific scenarios as a foam control method. And also, having understood from the reviewed literature that determination of the optimal concentration of antifoam (Karakashev and Grozdanova, 2012), among other factors has a major influence on their effective use, it became necessary to investigate optimal concentration of defoamer to control foam optimally.

The issue of determining optimal concentration seems to be the main contributing factor to the general perception that use of antifoams in activated sludge systems is a costly method. This is

because the nature of foam types in activated sludge systems tends to be very dynamic and in contrary, the commercial antifoams are supplied at a constant concentration and are expected to cope with all foaming conditions.

Kogais (2013) argues that there are three distinct foam types found in activated sludge systems at any given moment, namely: " (a) White, frothy, not particularly stable foam with few or no filaments (microscopic examination) caused usually by high Food to Microorganism Ratio loading or during plant start up situations, (b) White/brown foam, stable and containing fine particles of mixed liquor solids usually caused by presence of filamentous bacteria that produce extra cellular substances, surface active causing foaming, and (c) Dark, stable, heavy "chocolate mousse" foam characterized by presence of higher life forms such as rotifers, low F/M, long sludge age". It must be noted, however, that the three types of foam types described more often than not may exist as a mixture (author's personal experience), and the composition of the foam tends to vary in short time intervals. This is what makes it particularly challenging to use one defoamer concentration across all foam types.

In order to counter this short coming of using one defoamer concentration across all foam types, if more focus is put on optimization studies, there is potential of coming up with new ideas that will in future lead to a reduction in the cost of foam treatment by matching different defoamer concentrations to different foaming conditions. This might require an approach to reengineer the bulk storage tanks on site to hold defoamers of different concentrations and to immediately put in service the defoamer concentration that will be most appropriate to the foam type at any given time.

SECTION 3

SITE DESCRIPTION

3.1 Description of the bio-plant

Due to a nondisclosure agreement between the host company and the author of this work, the exact name of the site is not disclosed. Also the actual data of the operating parameters on site during the plant trial period such as MLVSS, SRT, F/M ratio etc. will not be published.

The Water Recovery unit where this study was performed consisted of an activated sludge water treatment bio-plant. The treated streams from the bio-plant were used to supply process cooling water to various upstream plants. As has been explained in Chapter 2, the activated sludge is a technology where microorganisms are used to treat effluent emanating from the various upstream processes of the factory. The micro-organisms do this by feeding on the waste components converting them into living tissue for their growth, multiplication, energy and release water, carbon dioxide and sometimes nitrogen depending on the conditions in the bio basins. Oxygen for the microorganisms was provided for through bubbling of air supplied by blowers from the base of the bio basins. Figure 3.1 shows a schematic flow diagram of the site.

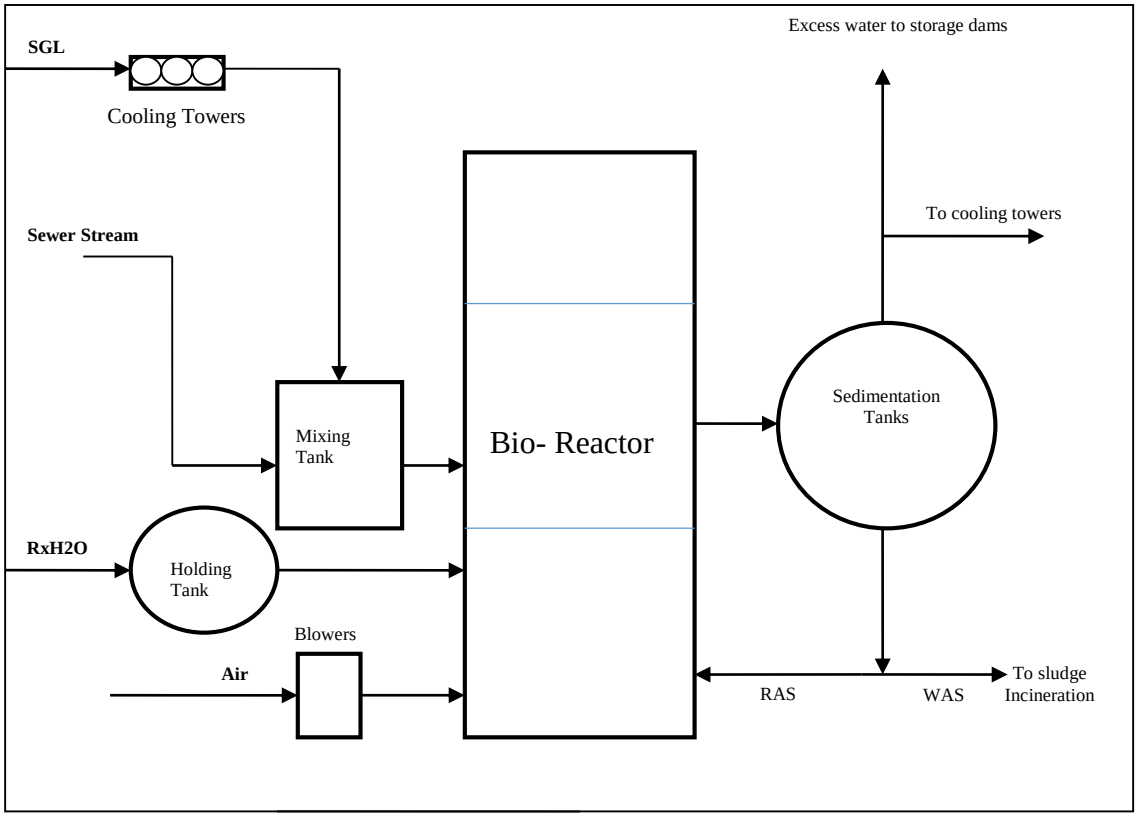


Figure 3 1: Schematic diagram of the bio-plant

The feed streams to the bio-reactors on this site comprised of three streams of industrial effluent, namely, the Stripped Gas Liquor (SGL), the Reaction Water (RxH2O) and the rundown from the factory in the oily water sewer system.

The Stripped Gas Liquor stream enters the Water Recovery unit at a temperature of approximately 90ºC. These temperatures are too high for efficient biodegrading and the stream was subsequently cooled down in cooling towers before the water got mixed with the oily water sewer system feed in a cement mixing tank and distributed between the bio-basins. The flow rate of this stream into the bio-basin was 1 700 m^3/h.

The Reaction Water feed stream entered the bio-plant at approximately 45ºC – 58ºC at a stainless steel vessel before being released into the bio basins. This stream had very low pH, averaging between pH 2 and 3 with a flow rate of 600 m^3/h.

The Rundown from the factory in the oily water sewer system stream entered the Water Recovery Unit at ambient temperature at a flow rate of 1200 m^3/h and was mixed with the cooled SGL in the mixing tank before getting released into the bio basins.

The operating parameters that have shown to give good activated sludge process performance over the years are listed in Table 3.1.

Table 3 1: Operating parameters of bio-reactor on site

Parameter	Range
Bio basin MLSS	6 200 – 9 700 mg/L
Return activated sludge MLSS	>13 000 mg/L
Sludge age	12-18 days
Temperature	30-35ºC

Due to the feed stream compositions, aerobic microbial action and mechanical mixing by aerators, the bio-basins had a propensity to foaming. As a result, dosage of antifoam was necessary to control the foam within acceptable levels in the basins, at all times. The treated water from the bio-basins overflowed to settling tanks in order to separate the water from the sludge. The water overflowed from the settling tanks as make up water for process cooling and is pumped to the designated process cooling towers.

The sludge at the bottom of the settling tanks was split into two streams. One part, Return Activated Sludge (RAS), was pumped back to the bio-basins, while the other part, Waste Activated Sludge (WAS), was pumped to the sludge incinerators where it got dewatered and incinerated.

3.2 **Description of foam control on site**

The defoamer used for foam control on site (Zeta Airpel 300®) was stored in three 20m^3 capacity tanks. The outlets of Tank A and Tank B shared a common isolation valve on the outlet lines to the defoamer dosing pumps allowing the two tanks to be put on service at the same time. The suction of the defoamer dosing pumps shared a common manifold from which each pump drew defoamer before dosing to each designated bio-reactor to control foam. Figure 3.2 is a schematic showing the flow of defoamer from the storage tanks to the bio-basins.

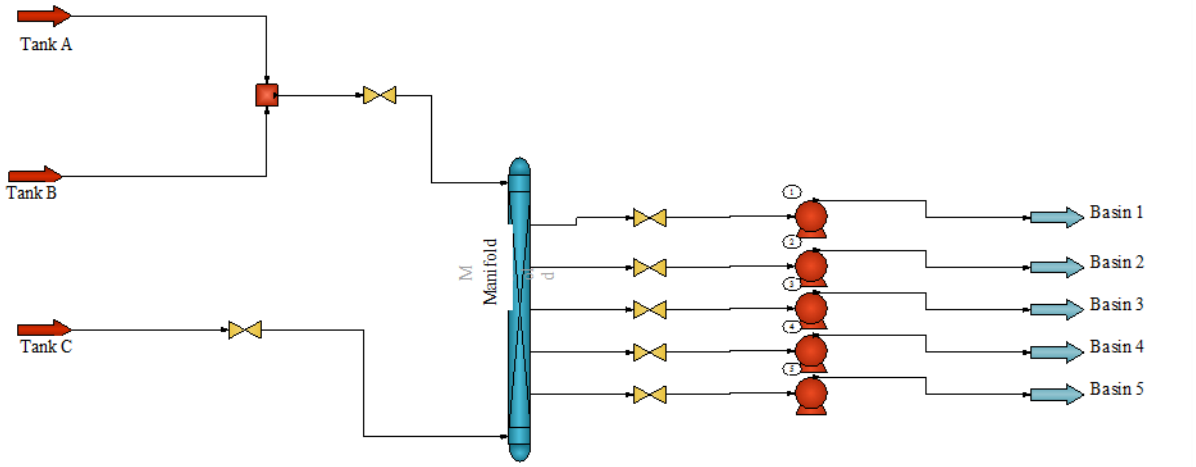


Figure 3 2: Layout of the defoamer dosing station

The foam height in the bio-reactor was measured with the use of a level probe installed in the bio-reactor as shown on Figure 3.3. The level probe was connected to a capacitance level transmitter that in turn was connected to a Programmable Logic Controller (PLC). The PLC was connected to the defoamer dosing pumps.

Figure 3.3: Foam height level probe in the bio-basin: foam height scenario (on site).

The defoamer dosing pumps were controlled by three modes, namely, the “Off” mode, the “Manual” mode and the “Auto” mode. On the manual operation mode the deformer dosing pump could be run at any output speed set up manually by the operator. On the Auto mode the defoamer dosing pump was controlled by a program in the PLC. On the Auto mode the dosing pump was switched on and off depending on the foam height measured by the level probe inside the bio-reactor.

There was a foam height set point of 72%. When the foam height in the bio-reactor was less than the foam height set point, the dosing pump remained on the “Off” mode. When the foam height surpassed the foam height set point, the PLC automatically switched the defoamer dosing pump on to start dosing defoamer. The defoamer was pumped through a network of pipes that runs from the defoamer dosing pump and ends inside the bio-basin.

The defoamer dosing pump was programmed to run at a predetermined output until the foam level in the bio-basin is reduced to below foam height set point. Once the foam height had been controlled to a level below foam height set point, the defoamer dosing pump got switched off. To ensure that the program is run efficiently, there was a data logger installed to record the actual foam height inside the bio-basin and the pump output activity as a back-up measure.

Logging the foam height and defoamer dosing pump activities was a very vital troubleshooting tool. It was used to identify the root causes during periods of unusually high defoamer usages and assists in finding a solution. For example, in the event of:

(1) Untimely equipment failures such as faulty capacitance level transmitters,

(2) Spikes of toxins in the influent streams such as high phenol levels, or any other factors that contributes to the increase of the foaming propensity of the mixed liquor.

If the dosing pump runs when the bio-basin foam height is less than the foam set point, this would indicate that the equipment is malfunctioning. When the defoamer dosing pump remains off when the foam height in the bio-basin was higher than the foam height set point, it would also indicate that the equipment was malfunctioning. If that anomaly was noticed, the problem was investigated and got fixed.

Brown et al (2001) performed similar work on conductimetric measurements of foams in a reactor with the use of a foam level probe connected to a Programmable Level Controller (PLC) linked to an antifoam dosing pump. The level probe was used as a continuous online measuring device similar to the dosing set up employed on the site. The defoamer dosing pump was controlled to only run when the height of foam in the reactor got to a predetermined height and to stop when the foam level was reduced to a predetermined level inside the reactor. This control model used a start and stop control mechanism.

SECTION 4

MATERIALS AND METHODS

The experimental work of this investigative research was divided into two parts. The first part were batch experiments performed in the laboratory and the second part were full plant trials on a bio-reactor. The purpose of the batch experiments was to screen the full range of defoamer concentrations (from 10-100%) to determine the minimum concentration that could achieve a complete foam decay and lengthy foam suppression times. The defoamer concentrations that managed to achieve complete foam decay in the batch experiments were selected to prepare samples for the plant trials.

4.1 Batch Experiments

4.1.1 Sample preparation for batch experiment

The current defoamer being used on site, was prepared by mixing vegetable oil (locally sourced in South Africa) with hydrophobic solid particles (chemical PP, imported from United Kingdom) on a w/w ratio of 1:1 and this w/w combination is referred to as 100% concentrated defoamer. As has been highlighted in the reviewed literature in section 2.9, all modern day defoamers are made up of two components, oil and hydrophobic solid particles in various combinations (Karakashev and Grozdova, 2012)

The defoamer samples used for both the batch experiments and the plant trials were prepared by mixing the same two components mentioned above vegetable oil and chemical PP (the

hydrophobic solid particles). Due to a nondisclosure agreement between the authors of this work and the suppliers of the samples, the real names of the imported hydrophobic chemical is not going to be published, for that reason, only letters will be used to describe the composition of the hydrophobic components of the defoamer. Also the specific gravity of the samples are not going to be disclosed. For further details on the composition of modern antifoams, refer to section 2.9.

The highest concentration of the defoamer samples used for both the batch experiments and the plant trials was prepared by mixing the same vegetable oil and chemical PP on a w/w ratio of 1:1(and the term 100% concentration was adopted). Each kilogram of the "100% concentrated sample" constituted 0.5kg of oil and 0.5kg of chemical PP.

The 1kg stock solutions prepared for the batch experiments ranged from 10%-100% concentration weight/weight (based on above explanation). Of that, only 0.1ml of each defoamer sample was dosed to control foam on each lag of the batch experiments. The formulas used to calculate the weight ratios per kilogram of each of the defoamer stock solutions are illustrated below followed by Table 4.1 which shows the weights of each of the components (oil + chemical PP) per kg of each sample.

The formula for calculating the weight/weight values of chemical PP and vegetable oil for the preparation of 1kg samples of defoamer:

1. For 100% defoamer concentration sample, 1 x 0.5kg (chemical PP) + 1 x 0.5kg (Oil) =1kg final weight.

2. For 90% defoamer concentration sample, 0.9 x 0.5kg (chemical PP) + 1.1 x 0.5kg (Oil) =1kg final weight.

3. For 50% defoamer concentration sample, 0.5 x 0.5kg (chemical PP) + 1.5 x 0.5kg (Oil) =1kg final weight.

Table 4 1: Breakdown of mass constituents of oil and chemical PP in 1kg of defoamer sample.

Concentration of Defoamer sample	Mass of chemical PP/kg of defoamer sample(kg)	Mass of Oil/kg of defoamer sample(kg)	Final mass of defoamer sample(kg)
100% defoamer sample	0.50	0.50	1
90% defoamer sample	0.45	0.55	1
80% defoamer sample	0.40	0.60	1
70% defoamer sample	0.35	0.65	1
60% defoamer sample	0.30	0.70	1
50% defoamer sample	0.25	0.75	1
40% defoamer sample	0.20	0.80	1
30% defoamer sample	0.15	0.85	1
20% defoamer sample	0.10	0.90	1
10% defoamer sample	0.05	0.95	1

4.1.2 **Description of batch laboratory experiment method**

The dynamic foam rise test, adopted for the batch experiment in the laboratory is the most commonly used laboratory procedure used for evaluating performance of antifoam emulsions(Bikerman, 1973; Ross and Suzin, 1985, Pelton, 1989).

The purpose of the batch laboratory experiment were to find the minimum defoamer concentration that could completely knock down foam in a graduated measuring cylinder and to find the minimum defoamer concentration that could completely knock down foam and suppress the foam generation for a prolonged period.

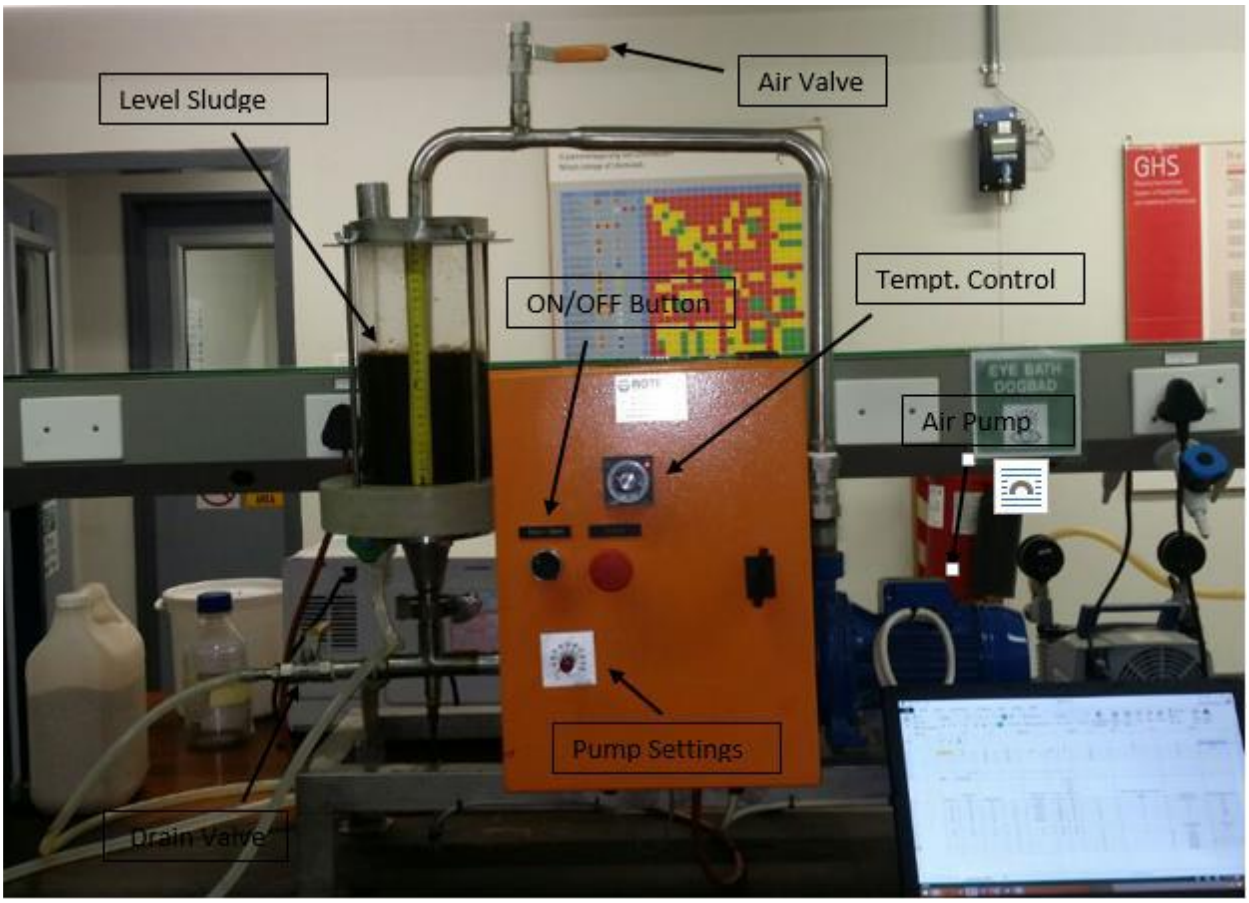


Figure 4.1: The dynamic foam rise test equipment for batch experiments

For the batch experiments, 3L mixed liquor samples were used to generate foam for each set of experiment. They were collected from a bio-basin that was used for full plant trials. Foam was generated by bubbling air at a controlled flow rate from the bottom of the graduated measuring cylinder containing mixed liquor before defoamer samples were dosed.to the foam columns that had already been generated. The foam decay rate and the foam suppression times were measured.

4.1.3 **Procedure for batch experiment**

1. Batches of 3L of mixed liquor were added into the measuring cylinder of the foam rig apparatus.
2. The height of the mixed liquor measured 16cm before foam was generated.
3. The mixed liquor sample was heat up to 40ºC using a heating element for the temperature to be the same as that in the bio-reactor.
4. The sludge sample was steered gently by passing through air at a controlled flow rate of 0.25L/minute from the bottom of the measuring cylinder while being heated.
5. Foam was generated by passing air through air stones at the bottom of the measuring cylinder at a controlled flow rate of 0.5L/minute until foam column rose by 10cm above the mixed liquor level to 26cm.
6. The height of the foam surfaces were recorded as function of time using a graduated cylinder and a stop watch.
7. The air was switched off and the sample was allowed to stand for 40 seconds to allow for liquid phase and the foam phase to separate.
8. A white masking tape was attached on the graduated measuring cylinder to be used for measuring the foam knock-down rate.
9. Air was again passed gently through the sample at a controlled flow rate of 0.25L/minute and 0.1ml of defoamer was immediately dosed to the foam.
10. The foam knock-down rates (foam decay rates) were recorded on the attached white masking tape at 10 seconds intervals.

11. The foam knock-down rates were measured until the foam volumes were completely knocked down or alternatively, if it was evident that after 60 seconds that the foam height was not getting reduced.
12. The air flow rate was increased again to 0.5L/minute to induce foam generation and the stop watch was simultaneously started to record the foam stay-down time.
13. This was followed by measuring the heights of the foam surface as functions of time until a height of 10cm above the mixed liquor sample was reached.
14. When the foam height reached 10cm above mixed liquor level, procedures 6-12 were repeated three times.
15. After 3 repeats with each sample, the air pump valve and the heat element valves were switched off and the sample was drained.
16. The measuring cylinder and the air stones were rinsed thoroughly with water then cleaned with alcoholic potassium hydroxide, followed by chromic acid and rinsed again with water.
17. Procedure 1-15 was repeated again for the next experiment.

It must be noted that the sole purpose of the batch experiment was to identify the minimum defoamer concentration that could be employed in the full plant trials only, so that the number of defoamer samples that could be used for the plant trials would be minimized. The reason being that, the permission to conduct plant trials was extended to only one day and also, the plant trials could only be run during day light times due to safety concerns on site. As result, the concentrations used for the batch experiments were not up scaled proportionally to the plant trial neither was an economic evaluation performed for the batch experiments. Also, due to contractual obligations between the defoamer supplier and the host company, only Zeta Airspel 300® defoamer could be used for this work.

4.2 **Plant Trials**

The purpose of the plant trials was to gather the following information:

(1) To determine the concentration of defoamer that could achieve complete foam knock-down at the quickest rate.

(2) To determine the defoamer concentration that could result in the lengthiest foam stay-down (suppression time) in a bio-reactor.

(3) To determine the most optimal defoamer concentration to control foam in a bio-reactor at the least coast.

To compare the foam knock-down rates and the foam suppression times in a bio-reactor, plant trials were performed using 30kg defoamer samples with concentrations ranging from 40%-100%. This was because during batch experiments, 40% concentration was the least to achieve complete foam knock-down.

4.2.1 **Samples preparation for plant trials**

The weight breakdown of chemical PP 104 and vegetable oil in the 30kg defoamer samples used for the plant trials are presented on Table 4.3. The formula for calculating the weight/weight values of chemical PP and vegetable oil for preparation of 30kg of defoamer samples is illustrated below:

1. For 100% concentration defoamer sample, 1 x 15kg (chemical PP) + 1 x 15kg (Oil) =30kg
2. For 90% concentrated defoamer sample, 0.9 x 15kg (chem. PP) + 1.1 x 15kg (Oil) =30kg.
3. For 50% concentrated defoamer sample, 0.5 x 15kg (chem. PP) + 1.5 x 15kg (Oil) = 30kg.

Table 4. 2: Breakdown of mass of oil and chemical PP in 30kg samples.

Concentration of Defoamer sample	**Mass of chemical PP/30kg of defoamer sample(kg)**	**Mass of Oil/30kg of defoamer sample(kg)**	**Final mass of defoamer sample(kg)**
100% defoamer sample	15.0	15.0	30
90% defoamer sample	13.5	16.5	30
80% defoamer sample	12.0	18.0	30
70% defoamer sample	10.5	19.5	30
60% defoamer sample	9.0	21.0	30
50% defoamer sample	7.5	22.5	30
40% defoamer sample	6.0	24.0	30

4.2.2**Method for economic evaluation of plant trial results.**

The cost make up of 1kg of the 100% concentrated defoamer was constituted as follows:

(1) The cost of the locally sourced vegetable oil, equivalent to 28.57% of total cost and,

(2) The cost of the imported component (chemical PP), equivalent to 71.43% of total cost. Calculations for the economic evaluation of the plant trial results were done using an assumed selling price value of ZAR35/kg (for 100% concentrated sample only). Based on these values, the cost of 0.5kg of the vegetable oil component in each 1kg of 100% concentrated defoamer sample was ZAR10 and the cost of 0.5kg of chemical PP in each 1kg defoamer sample (100% conc.) was ZAR25.

The rest of the defoamer samples used for the plant trials were prepared using the same vegetable oil and chemical PP, (the hydrophobic solid particles) but, with various different mixture weight ratios. The approach taken was to reduce the 15kg weight component of chemical PP by 10% while increasing the weight component of the oil by 10% simultaneously so that the sum of both weight components could be summed up to 30kg.

Method for calculating the cost of each of the 30kg samples of defoamer employed:

1. For 100% concentration defoamer sample, (15kg/0.5kg) x ZAR25 (chemical PP) + (15kg/0.5kg) x ZAR10 (Oil) = ZAR1050.

2. For 90% concentration defoamer sample, ((0.9 x 15kg)/0.5kg) x ZAR25 (DP104) + ((1.1 x 15kg)/0.5kg) x ZAR10 (Oil) =ZAR1005.

3. For 50% concentration defoamer sample, ((0.5 x 15kg)/0.5kg) x ZAR25 (chemical PP) + ((1.5 x 15kg)/0.5kg) x ZAR10/kg (Oil) = ZAR825

Table 4. 3: Breakdown of cost of oil and chemical PP in each 1kg of defoamer sample

Concentration of Defoamer sample	Cost of chemical PP component (ZAR)	Cost of Oil component(ZAR)	Cost of 1kg of defoamer Sample(ZAR)	Cost of 30kg defoamer sample (ZAR)
100% defoamer sample	25.0	10.0	35.0	1050
90% defoamer sample	22.5	11.0	33.5	1005
80% defoamer sample	20.0	12.0	32.0	960
70% defoamer sample	17.5	13.0	30.5	915
60% defoamer sample	15.0	14.0	29.0	870
50% defoamer sample	12.5	15.0	27.5	825
40% defoamer sample	10.0	16.0	26.0	780

As can be seen on the values on Table 4.3, the cost of 1kg of defoamer samples ranged from 35.00 rand for 100% concentrated defoamer to 26.00 rand for 40% concentrated defoamer.

4.2.3 **Description of plant trial set up**

Each container bearing various 30kg defoamer samples was connected to a dedicated dosing pump for each set of plant trial. Foam height in the bio-reactor was measured using the existing foam level probe installed in the bio-reactor (see Figure 3.3). The monitoring of the foam height was done by two ways:

(1) Reading the foam level on the PLC display screen inside the panel at the defoamer dosing station and

(2) By occasional physical checks of the foam height in the bio-reactor to ascertain that the readings on the PLC display screen were consistent with the actual foam height in the bio-reactor.

The defoamer dosing pump was switched on and off manually when required using a start-stop approach. A stop watch was used to measure the rate of foam knock down (foam decay rate) and the foam stay-down periods (time taken for the foam to accumulate to a height that required dosing of defoamer). It must be noted that the air to the bio-reactor is supplied through a uniformly distributed pipe network on the sides of the bio-reactor and the assumption made was

that the foam growth rate for each tried concentration would grow at the same rate. A step by step procedure of the plant trials is presented in section 4.2.3 below.

4.2.4 **Procedure for plant trials**

The suction side of the defoamer dosing pump was connected to a container of water and the dosing line was flushed with water to remove all residual defoamer in the line before setting up for the plant trial was done. Using horse clamps, a horse pipe was connected to the suction side of the defoamer dosing pump and inserted inside a 30l container with 40% concentration of defoamer. The defoamer dosing pump was first primed to avert airlock and the defoamer dosing pump flow rate was set up at 1.5L/minute.

The foam height in the bio-basin was monitored using the PLC display screen and when the foam height got to 100% foam height, the defoamer dosing pump was switched on to run at a flow rate of 1.5L/min. With a stop watch, the time taken to knock-down the foam from 100% foam height to 70% foam height was measured. When the foam height in the bio-reactor got to 70%, the dosing pump was switched off. The time taken for the foam to be completely knocked down from 70% foam height to 0% was measured. Using the PLC display screen the time taken for the foam to build up from 0% height to 100% foam height was also measured. These procedures were repeated 3 times or until the 30l defoamer sample was finished, whichever came first. The same was repeated for the rest of the defoamer samples.

SECTION 5

RESULTS AND DISCUSSION

This chapter outlines the results and discussions of the batch laboratory experiments (using the adopted dynamic foam rise test method), and of the plant trials to show the foam knock-down and foam stay-down of each one of the defoamer samples employed in the two sets of experiments. This is followed by presenting the results and discussions of the economic evaluations performed of the various samples used in this work on both the batch experiments and the plant trials.

5.1 Batch laboratory experiment results

On observations of the foam growth curves across the full range of defoamer concentrations (0-100%) used in the batch experiments, it was clear that the foam behaved differently upon dosage of each of the defoamer concentrations employed. Graphs of foam behavior of the control experiment, with no defoamer (0% concentration graphs) and after dosing low defoamer concentrations (10%), showed no reduction in the foam height generated in the graduated measuring cylinder. (-see Fig 5.1). The foam height remained at maximum height after three dosing cycles of the 0% and 10% defoamer concentrations (the two graphs are superimposed on each other).

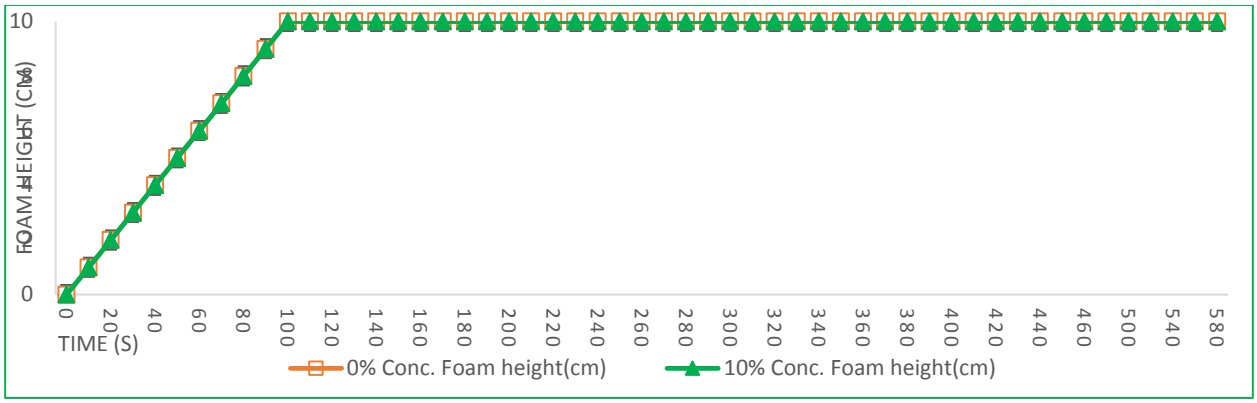


Figure 5 1: Graphs of 0% and 10% defoamer concentrations during batch experiments

Graphs of the foam behavior after dosing 20% and 30% defoamer concentrations showed minimum reduction in the foam height (14% and 42% foam height reduction, respectively), however, these two concentrations did not achieve the required 100% foam reduction in the graduated measuring cylinder after three defoamer dosing cycles (-see Fig 5.2) The foam stay-down times for these two defoamer concentrations were relatively very short(50sec for both 20% and 30%) resulting in short defoamer dosing cycles (130 sec and 150 sec, respectively).

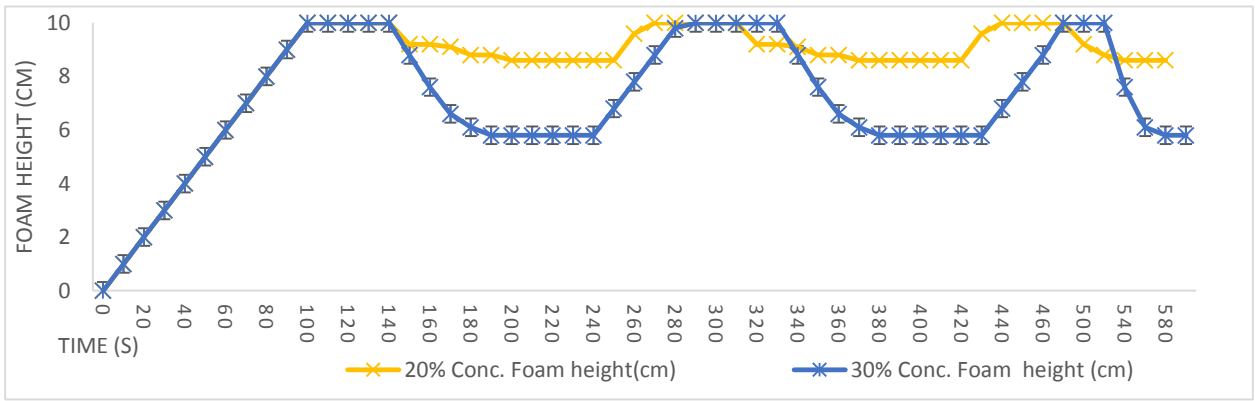


Figure 5 2: Graphs showing foam behavior after dosing 20% and 30% defoamer concentrations during batch experiments

The minimum defoamer concentration to achieve complete foam decay during the batch experiments was that of 40%. The average time taken for the 40% defoamer concentration to achieve complete foam decay was 58 seconds. Thereafter, the foam remained suppressed for 30 seconds, resulting in a mean defoamer dosing cycle of 88 seconds. When the behavior of the foam after dosing three cycles of defoamer concentrations of 40% was compared to those after dosing defoamer concentrations of 50% and 70% (see Figure 5.2), it appeared that the rate of foam decay and the foam suppression times increased with increase in defoamer concentrations. 60% concentration graphs were skipped in this comparison because there was minimum difference, (fractions of seconds apart) with the results of 50% concentration graphs. The magnitude of the defoamer dosing cycles also increased with each increase in defoamer concentration which was mainly attributed to lengthier foam suppression times. The mean foam knock down rate for 50% defoamer concentration was 47s and the mean foam suppression time was 57s. The total defoamer dosing cycle for 50% concentration was 104s. The mean foam decay rate for 70% defoamer concentration was 20s while the mean foam stay-down times 270s. The dosing cycle added up to 290s. For further information on the batch experiment results please refer to Appendices A1 and A2.

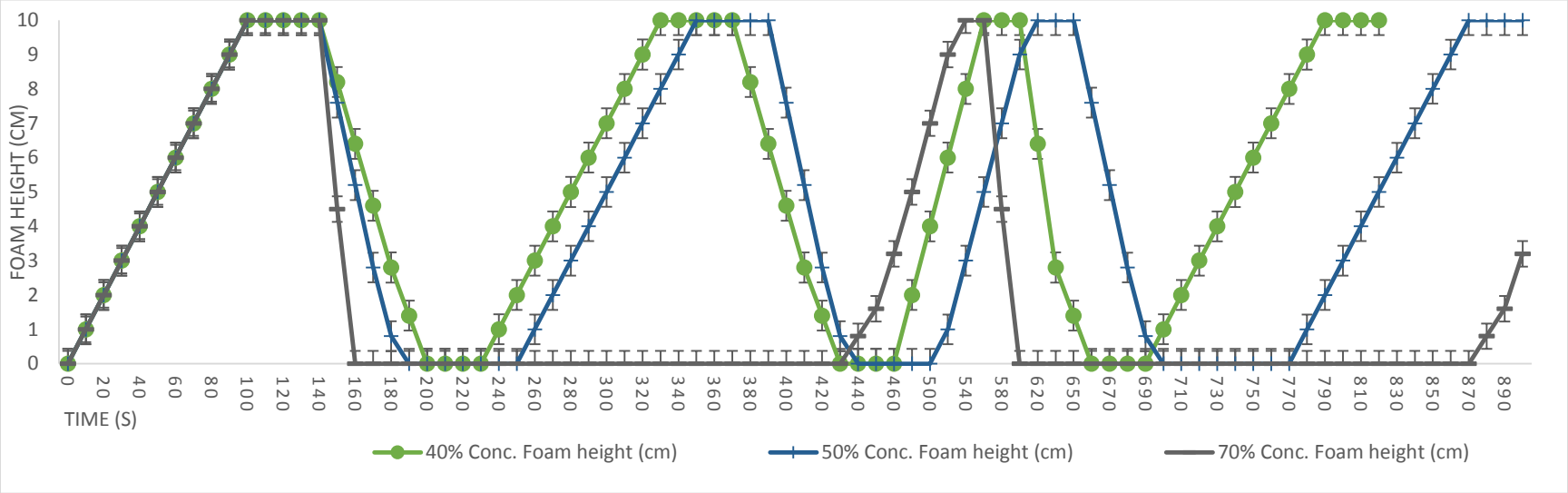


Figure 5 3: Graphs showing foam behavior after dosing defoamer concentrations of 40%, 50% and 70% during batch experiments

When it appeared evident that the increase in defoamer concentration were directly proportional to the foam knock down rates and the foam stay-down times, the last graphs to be compared against one another were those of the upper-end concentrations (80%-100%, see **Figure 5.4**). The same relationship observed in previous cases (of increase in concentration having direct proportion with increase in foam knock-down rates and foam stay down times) was still evident. The mean foam knock down rate for 80% defoamer concentration was 16s and the mean foam suppression time was 290s. The total defoamer dosing cycle for 80% concentration was 306s. The mean foam knock down rate for 90% defoamer concentration was 5s and the mean foam suppression time was 320s. The total defoamer dosing cycle for 90% concentration was 325s. The mean foam knock down rate for 100% defoamer concentration was 6s and the mean foam suppression time was 330s. The total defoamer dosing cycle for 50% concentration was 336s. This showed that as the defoamer concentration increased towards maximum, the difference between the behaviors of foam were very minimal, 320sec and 330sec, in the case of 90% and 100% respectively.

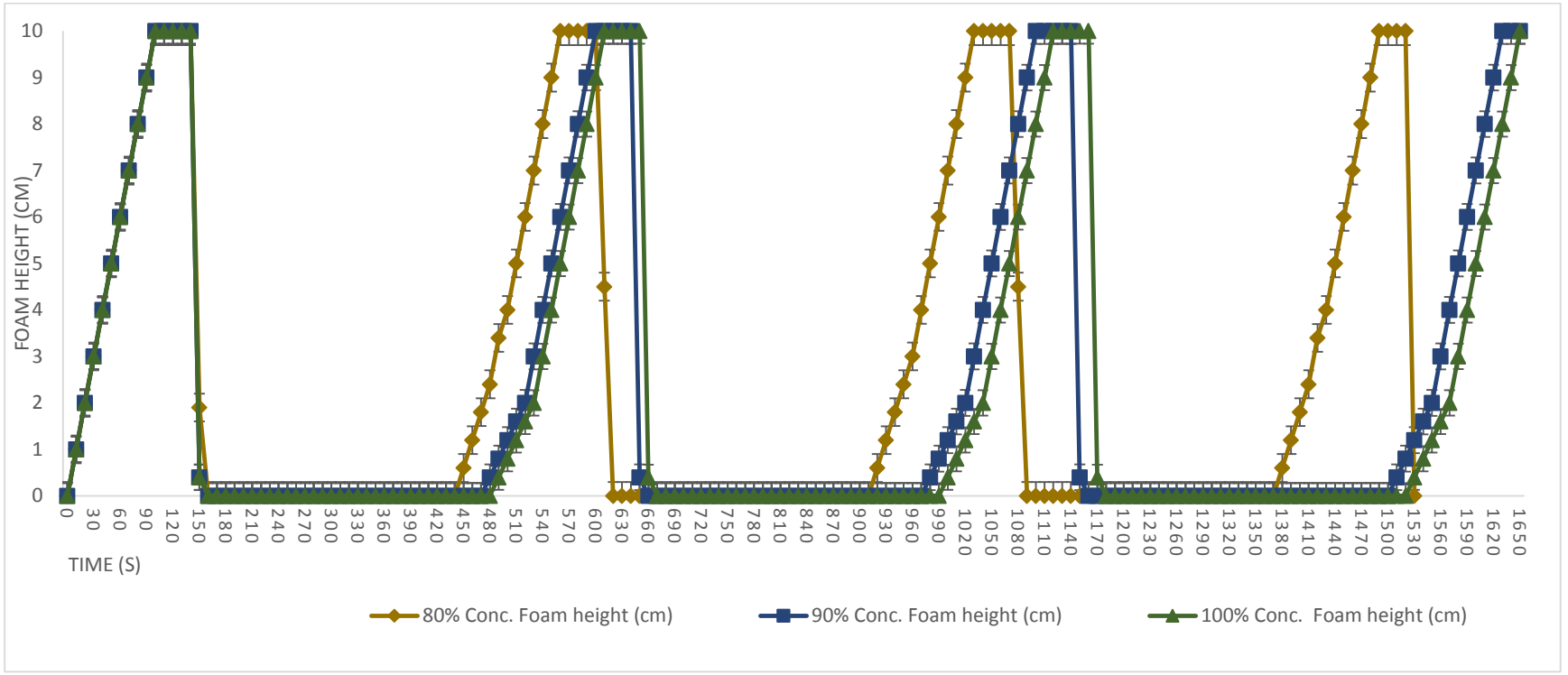


Figure 5 4: Graphs showing foam behavior after dosing defoamer concentrations of 80%, 90% and 100%

To summarize the results observed on the batch experiments, it was apparent that there was a threshold below which the concentration of defoamer were ineffective in controlling foam (30% concentration and below in this case). That is, of 30% and below were not effective enough in controlling foam.

It was observed that from concentrations of 40% to 100%, the time taken to achieve a complete foam decay was getting shorter with each increase in defoamer concentration. The foam suppression times were also observed to have been increasing with each increase in defoamer concentration with the exception of 90% and 100% concentration where the foam decay rate and the foam suppression times were nearly the same. This observation was consistent with the results of literature reviewed (Pelton, 1996)

5.2 **Plant trial results**

All the defoamer samples used for the plant trials managed to achieve complete foam decay and resulted in foam suppression in the bio-reactor although the foam knock-down rates and foam suppression duration varied from one defoamer concentration to another (see Table 5.1). Defoamer concentrations of 40% achieved complete foam knock-down with a mean foam knock-down time of 19 minutes. The mean foam stay-down time was 41 minutes (for 40% defoamer concentration). The 50% defoamer concentration sample achieved a mean foam knock-down time of 15 minutes and a mean foam stay-down time of 45 minutes. The defoamer concentration that achieved the quickest foam knock down of all the defoamer samples used was the one with 90% concentration, however the foam stay-down time (for the 90% concentration) was the second shortest (43 minutes). The defoamer concentration to result in

the lengthiest foam stay-down time was the 80%. On observing the frequency of dosage of all the defoamer concentrations used, it was apparent that the concentration that had the highest dosing frequency (shortest defoamer dosing cycles) was that with 40% concentration and the defoamer concentration with the least dosing frequency per hour (lengthiest dosing cycles) was the 80% concentration. Calculations of the mean hourly defoamer usages in kg presented in the last column of Table 5.1 were found by multiplying the mean volume of defoamer used on each trial by the specific gravity of each of the samples (formula not presented because SG values of the samples could not be disclosed). The mean hourly defoamer usages show that 40% defoamer concentration had the highest usage and that 90% concentration had the least mean hourly defoamer usages.

Perhaps the most interesting observation is that although the knock-down times of foam in the bio-reactor seemed to be concentration dependent on the day the plant trials were performed(the higher the concentration the shorter the foam knock-down rate), the foam stay-down times were not dependent on defoamer concentration. Probably, this might be contributed to variances in the amount of air being supplied to the bottom of the bio-reactor by the blowers indicating some inefficiencies in the equipment operation. This observation is based on the fact that, from literature reviewed, (Pelton, 1996) from the dynamic foam rise experiments which predicted that without antifoam and at low antifoam concentrations, a linear increase in foam volume at the same rate as the gas flow rate is observed. Pelton (1996) further observed that lower antifoam concentrations got depleted faster than higher concentrations and as a result had lesser foam suppression times. Further investigations on site revealed that there were no flow meters

to measure the volume of air being supplied to each individual bio-reactor. For detailed results of the plant trial data, refer to Appendix E.

Analysis of historical data of the plant defoamer usages done (Appendix D) showed that it was very common to have big variances in the volumes of defoamer consumed from day to day for the 100% defoamer concentration. Further investigations on the historical scada screen graphs (Appendix D2) further reviewed that the variances in defoamer concentrations were attributed to the foaming propensity of the foam in the bio-reactors at any given time. Also evident was that although all the five bio-reactors received same volumes of effluent continuously, the daily defoamer usages of the five bio-reactors were never similar. This further suggested that the foaming propensity in each reactor was determined by many operating parameters such as reactor pH, sludge age, F/M Ratio, MLSS and others (Reyes et al., 1998)

Table 5 1: Foam knock-down times, foam stay-down times and defoamer dosing cycles of the plant trials

Defoamer Concentration	Mean foam knock-down times(min)	Mean foam Stay-down (min).	Mean dosing frequencies per hour	Mean hourly defoamer usages (kg)
100% defoamer concentration	10	43	1.40	17.5
90% defoamer concentration	7	43	1.40	12.2
80% defoamer concentration	9.5	50.5	1.19	15.7
70% defoamer concentration	11	49	1.22	18.2
60% defoamer concentration	13	47	1.28	20.3
50% defoamer concentration	15	45	1.33	23.2
40% defoamer concentration	19	41	1.46	29.3

5.3 Economic Evaluation of plant trial results

The results of the economic evaluations of all the defoamer concentrations employed in the plant trials showed that the least concentrated defoamer sample (40% concentration), resulted in the most costly plant trial(-see Table 5.2). The trend shown was that cost of plant trials of concentrations between 40% and 90% got lower with increase in defoamer concentrations. The exception to this trend was with the plant trial cost of the100% defoamer concentration which had the third most costly (ZAR612.5/hr.), compared to the rest. The plant trial with the least cost was that of 90% defoamer concentration (ZAR408/hr.).

Table 5 2: Cost of plant trials of defoamer concentration ranges between 40%-100%

Concentration of Defoamer sample	Mean hourly defoamer usages (kg)	Cost of defoamer sample (ZARkg)	Cost of trial (ZAR/hr)
100% defoamer sample	17.5	35.0	612.5
90% defoamer sample	12.2	33.5	408.7
80% defoamer sample	15.7	32.0	502.4
70% defoamer sample	18.2	30.5	555.1
60% defoamer sample	20.3	29.0	588.7
50% defoamer sample	23.2	27.5	638
40% defoamer sample	29.3	26.0	761.8

The investigative work of this research culminated at identifying the most optimal concentration of defoamer that could control foam in a bio-reactor taking into cognizance that concentrations below optimal would be ineffective in controlling foam in activated sludge reactors and that when defoamer concentrations were above optimal, the solid particles in the defoamer would act as foam stabilizers prompting to further accumulation of foam (Denkov et al., 2014b; Karakashev and Grozdanova, 2012; Soddell et al., 1993). Majority of process controllers in bio-plants have been observed (author's personal experience) to react to problems of excessive foaming in bio-reactors by increasing the defoamer dosing pump output to maximum.

The effects of increasing the output of the defoamer dosing pump for prolonged periods in reaction to a scenario where the defoamer concentration would be lower than the optimal leads to a significant spike in the cost of treatment irrespective of whether the foam may end up getting controlled or not. And the effect of the same reaction to a scenario where the concentration of defoamer is above optimum is disastrous, leads to accelerated accumulation of foam which more often results in foam getting out of control coupled with the burden of significant increases in the cost of foam treatment.

5.4 **Discussion of batch experiment results**

During the batch experiments, foam decay rates of different defoamer concentrations were determined in order to evaluate the foam reduction efficiency of each of the defoamer concentrations. The average foam decay rates depicted that the higher the defoamer

concentration, the faster the foam decay rate, and, that the higher the defoamer concentration the longer the foam suppression times.

These results are in accordance with previous study reporting that 500mg/L, 300mg/L, 100mg/L and 50mg/L of antifoam suppressed foam in the corresponding descending order (Pelton, 1996). As was expected, the control sample, without defoamer in it did not manage to reduce the foam. Similarly, very low concentrations, 10%, 20% and 30% also failed to completely knock-down the foam.

This might imply that the minimum threshold concentration required to have a complete knock-down effect of foam was above 30% defoamer concentration. This observation was consistent with literature reviewed from work done by (Karakashev and Grozdanova, 2012; Pelton, 1996), where foam was observed to grow at a rate directly proportional to air flow rate in the presence of low antifoam concentrations. This disqualified lower defoamer concentrations than 30% for use on the full plant trials.

The observation that defoamer concentration of 40% managed to achieve 100% foam knock down and substantial foam suppression times lead to the assumption that defoamer concentrations between 40% and 100% could be applied for the plant trials. It was also assumed that this concentration was within the range of the minimum threshold concentration required for foam control in the bio-reactor.

The batch experiments results further showed an increase in both the foam decay rate and the foam suppression times with each increase in defoamer concentration with the exception of concentrations of 90% and 100% where the differences in foam decay rate and foam suppression times were not following the same trajectory. This was consistent with results observed from literature reviewed (Pelton, 1996, 1996; Soddell et al., 1993).

In summary the results of the batch experiments using the dynamic foam rise method showed that increase in foam knock down rates and foam suppression durations were generally, directly proportional to increase in defoamer concentrations. This observation was consistent with previous work done by Pelton, (1996) on foam growth in the presence of antifoam emulsions. The batch experiment results assisted in identifying a cut-off on minimum concentration required for the samples prepared for the plant trials.

5.5 **Discussion of plant trial results**

The literature reviewed had shown that perhaps the most critical part in the use of defoamers for foam control was to establish the optimal concentration for treating the particular type of foam because lower concentrations than optimal would not be effective and higher concentrations than optimal would lead to adverse effects because solids in the defoamer would end up acting as foam stabilizers resulting in increase of foam among other undesired effects (Karakashev and Grozdanova, 2012). Other than just focusing on the foam knock-down rate, that is, the time taken for the foam to decay after defoamer is applied, and the duration of foam suppression times (the time taken for foam to start accumulating again), the most essential factor was the cost of treatment. Therefore, cost evaluation of the different defoamer concentrations used in this work had to be

determined if the most optimal defoamer concentration suitable for treatment of existing foam type was to be identified. Perhaps, justifiably so because the cost of treatment in any context is probably the most valued factor in decision making when operating most businesses.

As has been mentioned in previous sections, concentrations of 10%-30% were not trialed in the plant since they had already been eliminated after failing to reduce foam during the batch experiments.

SECTION 6

CONCLUSION AND RECOMMENDATIONS

The main conclusions of this work can be summarized as follows:

- The foaming conditions in an activated sludge reactor are very dynamic and require to be closely monitored especially when the foam control method being used is the use of defoamers. Foam suppression times in the bio-reactor were not dependent on defoamer concentration used alone but on the foaming propensity of the foam present in the bio-reactor at each given time.
- Cost effective use of defoamers in controlling foam requires establishing the most optimal concentration for that particular foam type given the dynamic nature of foaming conditions in bio-reactors. This means that use of a single defoamer concentration to control different types of foam in a bio-reactor may be both costly and unreliable.
- Performing an economic evaluation of each defoamer concentration together with measuring the foam knock-down capacity and foam suppression times is valuable in identifying the most optimal defoamer concentration.
- 90% defoamer concentration was the most optimal defoamer concentration for the foam type present in the bio-reactor during the plant trials and was also the least costly (ZAR408.7/hr.).

Some of the limitations of this work are that the quantity and quality of the constituents of the stripped gas liquor streams that contributed to the overall foaming propensity of the mixed liquor in the bio-rector is dependent on the source of the coal that was in use at the time this work was performed. Coal from different mines or even different depths of the seam of coal

being mined at any given time leads to a variance in the quality of coal and subsequently in the quantity and types of the pollutants received in the bio-reactors. The nature and quantities of pollutants subsequently affect the health of the microorganisms in the bio-reactor leading to changes in the foam type present and the specific requirement of defoamer concentration needed to treat that particular foam type. This makes the repeatability of this work rather difficult to achieve.

We recommend that future studies should focus on conducting longer plant trials during periods of different foaming conditions to be able to develop a model that predicts the most cost effective defoamer concentration for each particular foam type. We also do recommend that microbiological tests be conducted each time there is excessive foam growth in the bio-reactors to determine the specific type of microorganisms present in the foam at each given time. This will assist in applying the most appropriate approach to reduce the growth rate of that particular type of microorganism in order to contain excessive foaming. It is also recommended that some form of online measuring device be installed to measure the exact flowrate of air being supplied to each bio-reactor at any given time so that inefficiencies in the blower operations can be picked up on time.

REFERENCES

Awong, J., Bitton, G., Koopman, B., 1985. ATP, oxygen uptake rate and INT-dehydrogenase activity of actinomycete foams. Water Research 19, 917–921. doi:10.1016/0043-1354(85)90151-4

Barnard, J.L., 1976. A review of biological phosphorus removal in the activated sludge process. *Water Sa*, *2*(3), pp.136-144.

Bikerman, J.J., 1973. FUNDAMENTAL LIMITATION OF REPLICA METHOD. *Microscope*, *21*(JUL), pp.183-184.

Blackall, L.L., Harbers, A.E., Greenfield, P.F., Hayward, A.C., 1991. Foaming in activated sludge plants: A survey in Queensland, Australia and an evaluation of some control strategies. Water Research 25, 313–317. doi:10.1016/0043-1354(91)90011-E

BLACKALL, L.L., PARLETT, J.H., HAYWARD, A.C., MINNIKIN, D.E., GREENFIELD, P.F., HARBERS, A.E., 1989. Nocardia pinensis sp. nov., an Actinomycete Found in Activated Sludge Foams in Australia. Microbiology 135, 1547–1558. doi:10.1099/00221287-135-6-1547

Blackall, L.L., Seviour, E.M., Cunningham, M.A., Seviour, R.J. and Hugenholtz, P., 1995. "Microthrix parvicella" is a novel, deep branching member of the actinomycetes subphylum. *Systematic and applied microbiology*, *17*(4), pp.513-518.

Brown, A.K., Isbell, C., Gallagher, S., Dodd, P.W., Varley, J., 2001. An Improved Method for Controlling Foams Produced Within Bioreactors. Food and Bioproducts Processing 79, 114–121. doi:10.1205/096030801750286276

Chambers, B. and Tomlinson, E.J., 1982. *Bulking of activated sludge: preventive and remedial methods*. Ellis Horwood.

Chang, W.C., Jou, S.J., Chien, C.C. and He, J.A., 2004. Effect of chlorination bulking control on water quality and phosphate release/uptake in an anaerobic-oxic activated sludge system. *Water Science and Technology*, *50*(8), pp.177-183.

Davenport, R.J., Curtis, T.P., 2002. Are filamentous mycolata important in foaming? Water Science and Technology 46, 529–533.

de los Reyes, F. L., Rothauszky, D., & Raskin, L. (2002). Microbial community structures in foaming and nonfoaming full-scale wastewater treatment plants. *Water environment research: a research publication of the Water Environment Federation*, *74*(5), 437-449.

Denkov, N.D., Marinova, K.G., Tcholakova, S.S., 2014a. Mechanistic understanding of the modes of action of foam control agents. Advances in Colloid and Interface Science, Manuel G. Velarde 206, 57–67. doi:10.1016/j.cis.2013.08.004

Denkov, N.D., Marinova, K.G., Tcholakova, S.S., 2014b. Mechanistic understanding of the modes of action of foam control agents. Advances in Colloid and Interface Science, Manuel G. Velarde 206, 57–67. doi:10.1016/j.cis.2013.08.004

Dhaliwal, B.S., 1979. Nocardia amarae and Activated Sludge Foaming. Journal (Water Pollution Control Federation) 51, 344–350.

Dhaliwal, B.S., Pitt, P.A., Jenkins, D., 1991. Discussion of: Causes and Control of Nocardia in Activated Sludge. Research Journal of the Water Pollution Control Federation 63, 184–186.

Ekama, G.A., South Africa, University of Cape Town (Eds.), 1999. Causes and control of low F/M filament bulking in nutrientremoval activated sludge systems, WRC report. Water

Research Commission, Pretoria.
Garrett, P.R., 2015a. Defoaming: Antifoams and mechanical methods. Current Opinion in Colloid & Interface Science 20, 81–91. doi:10.1016/j.cocis.2015.03.007
Garrett, P.R., 2015b. Defoaming: Antifoams and mechanical methods. Current Opinion in Colloid & Interface Science 20, 81–91. doi:10.1016/j.cocis.2015.03.007
Garrett, P.R., 1993a. Recent developments in the understanding of foam generation and stability. Chemical engineering science 48, 367–392.
Garrett, P.R., 1993b. The mode of action of antifoams. Surfactant Science Series 1–1.
Gerardi, M.H., 2002. Wiley: Nitrification and Denitrification in the Activated Sludge Process - Michael H. Gerardi [WWW Document]. URL http://www.wiley.com/WileyCDA/WileyTitle/productCd-0471065080.html (accessed 2.28.17).
Heard, J., Harvey, E., Johnson, B.B., Wells, J.D., Angove, M.J., 2008a. The effect of filamentous bacteria on foam production and stability. Colloids and Surfaces B: Biointerfaces 63, 21–26. doi:10.1016/j.colsurfb.2007.10.011
Heard, J., Harvey, E., Johnson, B.B., Wells, J.D., Angove, M.J., 2008b. The effect of filamentous bacteria on foam production and stability. Colloids and Surfaces B: Biointerfaces 63, 21–26. doi:10.1016/j.colsurfb.2007.10.011
Jenkins, D., Richard, M.G. and Daigger, G.T., 1993. Manual on the causes and control of activated sludge bulking and foaming. 2. In *Manual on the causes and control of activated sludge bulking and foaming. 2. ed*. Lewis.
Jenkins, D., Richard, M.G. and Daigger, G.T., 2003. Manual on Solving Activated Sludge Bulking, Foaming, and Other Solids Separation Problems. *Lewis Publishers, London UK*.
Jenkins, D., Richard, M.G., Daigger, G.T., 2004. Manual on the Causes and Control of Activated Sludge Bulking, Foaming, and Other Solids Separation Problems, 3rd Edition. CRC Press, Boca Raton, Fla.
Karakashev, S.I., Grozdanova, M.V., 2012. Foams and antifoams. Advances in Colloid and Interface Science 176–177, 1–17. doi:10.1016/j.cis.2012.04.001
Kougias, P.G., Boe, K., Tsapekos, P. and Angelidaki, I., 2014. Foam suppression in overloaded manure-based biogas reactors using antifoaming agents. *Bioresource technology*, *153*, pp.198-205.
Lechevalier, H., 1975. Actinomycetes of sewage-treatment plants.
Sezgin, M., Lechevalier, M.P. and Karr, P.R., 1988. Isolation and identification of actinomycetes present in activated sludge scum. *Water science and technology*, *20*(11-12), pp.257-263.
Leja, J., 1982. Flotation Surfactants, in: Surface Chemistry of Froth Flotation. Springer US, pp. 205–339. doi:10.1007/978-1-4615-7975-5_5
Lemmer, H., 1986. The ecology of scum causing actinomycetes in sewage treatment plants. Water Research 20, 531–535. doi:10.1016/0043-1354(86)90204-6
Mamais, D., Kalaitzi, E., Andreadakis, A., 2011. Foaming control in activated sludge treatment plants by coagulants addition. Global Nest Journal 13, 237–245.
Masters, G.M. and Ela, W., 2008. *Introduction to environmental engineering and science* (Vol. 3). Englewood Cliffs, NJ: Prentice Hall.
Myers, D., Surfactant Science and Technology, VCH, New York, 1988. *There is no corresponding record for this reference*, pp.118-119.
Nikolov, A.D. and Wasan, D.T., 1992. Dispersion stability due to structural contributions to the particle interaction as probed by thin liquid film dynamics. *Langmuir*, *8*(12), pp.2985-

2994.
Pagilla, K.R., Jenkins, D., Kido, W.H., 1996. Nocardia control in activated sludge by classifying selectors. Water Environment Research 68, 235–239. doi:10.2175/106143096X127677
Painter, H.A. and King, E.F., 1978. The effect of phosphate and temperature on growth of activated sludge and on biodegradation of surfactants. *Water Research*, *12*(11), pp.909-915.
Pantano, J.F., Watts, M.W., 1984. Techniques for Nocardia sp. control in activated sludge. WATER POLLUT. CONTROL ASSOC. PA MAG. 17, 32–38.
Pelton, R., 1996. A model of foam growth in the presence of antifoam emulsion. Chemical Engineering Science 51, 4437–4442. doi:10.1016/0009-2509(96)81675-7
Pipes, W.O., 1978. Actinomycete scum production in activated sludge processes. Journal (Water Pollution Control Federation) 628–634.
Pitt, P., Jenkins, D., 1990. Causes and control of Nocardia in activated sludge. Research Journal of the Water Pollution Control Federation 143–150.
Pretorius, W.A., Laubscher, C.J.P., 1987. Control of Biological Scum in Activated Sludge Plants by Means of Selective Flotation. Water Science and Technology 19, 1003–1011.
Ramothokang, T.R., Drysdale, G.D., Bux, F., 2003. Isolation and cultivation of filamentous bacteria implicated in activated sludge bulking. Water SA 29, 405–410. doi:10.4314/wsa.v29i4.5045
Richards, T., Nungesser, P., Jones, C., 1990. Solution of Nocardia foaming problems. Research journal of the water pollution control federation 915–919.
Ross, S. and Suzin, Y., 1985. Measurement of dynamic foam stability. *Langmuir*, *1*(1), pp.145-149.
Saayman, G.B., Van Leeuwen, J., Schutte, C.F., 1997. Full-scale chemical control of sludge bulking, WRC report. Water Research Commission, Pretoria.
Sezgin, M., Karr, P.R., 1986. Control of actinomycete scum on aeration basins and clarifiers. Journal (Water Pollution Control Federation) 972–977.
Soddell, J.A. and Seviour, R.J., 1990. Microbiology of foaming in activated sludge plants. *Journal of Applied Microbiology*, *69*(2), pp.145-176.
Soddell, J.A. and Seviour, R.J., 1994. A comparison of methods for determining the fractal dimensions of colonies of filamentous bacteria. *Binary-Computing in Microbiology*, *6*(1), pp.21-31.
Soddell, J.A., Seviour, R.J., 1995. Relationship between temperature and growth of organisms causing Nocardia foams in activated sludge plants. Water Research 29, 1555–1558. doi:10.1016/0043-1354(94)00222-S
Soddell, J.A., Seviour, R.J., Seviour, E.M., Stratton, H.M., 1993. Foaming and foam control in activated sludge systems. Prevention and Control of Bulking Activated Sludge 115–132.
Stainsby, F.M., Soddell, J., Seviour, R., Upton, J., Goodfellow, M., 2002. Dispelling the "Nocardia amarae" myth: a phylogenetic and phenotypic study of mycolic acid-containing actinomycetes isolated from activated sludge foam. Water Science and Technology 46, 81–90.
Tchobanoglous, G., Burton, F.L., Stensel, H.D., Metcalf & Eddy (Eds.), 2003. Wastewater engineering: treatment and reuse, International ed. ed, McGraw-Hill series in civil and environmental engineering. McGraw-Hill, Boston : London.
Tsang, Y.F., Sin, S.N., Chua, H., 2008. Nocardia foaming control in activated sludge process treating domestic wastewater. Bioresource Technology 99, 3381–3388.

doi:10.1016/j.biortech.2007.08.012
van Haandel, A. and van der Lubbe, J., 2007. *Handbook Biological Waste Water Treatment-Design and Optimisation of Activated Sludge Systems*. Webshop Wastewater Handbook.
Vardar-Sukan, F., 1998. Foaming: consequences, prevention and destruction. *Biotechnology advances*, *16*(5-6), pp.913-948.
Wanner, J., 1994. *Activated sludge: bulking and foaming control*. CRC Press.

APPENDIX A

Table A 1: Data of batch experiments for defoamer concentrations between 0%-50%

0% Conc. Foam height(cm)	10% Conc. Foam height(cm)	20% Conc. Foam height(cm)	30% Conc. Foam height (cm)	40% Conc. Foam height (cm)	50% Conc. Foam height (cm)
0	0	0	0	0	0
1	1	1	1	1	1
2	2	2	2	2	2
3	3	3	3	3	3
4	4	4	4	4	4
5	5	5	5	5	5
6	6	6	6	6	6
7	7	7	7	7	7
8	8	8	8	8	8
9	9	9	9	9	9
10	10	10	10	10	10
10	10	10	10	10	10
10	10	10	10	10	10
10	10	10	10	10	10
10	10	10	10	10	10
10	10	9.2	8.8	8.2	7.6
10	10	9.2	7.6	6.4	5.2
10	10	9.1	6.6	4.6	2.8
10	10	8.8	6.1	2.8	0.8
10	10	8.8	5.8	1.4	0
10	10	8.6	5.8	0	0
10	10	8.6	5.8	0	0
10	10	8.6	5.8	0	0
10	10	8.6	5.8	0	0
10	10	8.6	5.8	1	0
10	10	8.6	6.8	2	0
10	10	9.6	7.8	3	1
10	10	10	8.8	4	2
10	10	10	9.8	5	3

0% Conc. Foam height(cm)	10% Conc. Foam height(cm)	20% Conc. Foam height(cm)	30% Conc. Foam height (cm)	40% Conc. Foam height (cm)	50% Conc. Foam height (cm)
10	10	10	10	6	4
10	10	10	10	7	5
10	10	10	10	8	6
10	10	9.2	10	9	7
10	10	9.2	10	10	8
10	10	9.1	8.8	10	9
10	10	8.8	7.6	10	10
10	10	8.8	6.6	10	10
10	10	8.6	6.1	10	10
10	10	8.6	5.8	8.2	10
10	10	8.6	5.8	6.4	10
10	10	8.6	5.8	4.6	7.6
10	10	8.6	5.8	2.8	5.2
10	10	8.6	5.8	1.4	2.8
10	10	9.6	5.8	0	0.8
10	10	10	6.8	0	0
10	10	10	7.8	0	0
10	10	10	8.8	0	0
10	10	10	9.8	1	0
10	10	10	10	2	0
10	10	9.2	10	3	0
10	10	9.2	10	4	0
10	10	9.1	10	5	0
10	10	8.8	10	6	1
10	10	8.8	8.8	7	2
10	10	8.6	7.6	8	3
10	10	8.6	6.6	9	4
10	10	8.6	6.1	10	5
10	10	8.6	5.8	10	6
10	10	8.6	5.8	10	7
10	10	8.6	5.8	10	8
End	End	End	5.8	10	9
			5.8	8.2	10
			5.8	6.4	10
			End	4.6	10
				2.8	10
				1.4	10

0% Conc. Foam height(cm)	10% Conc. Foam height(cm)	20% Conc. Foam height(cm)	30% Conc. Foam height (cm)	40% Conc. Foam height (cm)	50% Conc. Foam height (cm)
				0	7.6
				0	5.2
				0	2.8
				0	0.8
				1	0
				2	0
				3	0
				4	0
				5	0
				6	0
				7	0
				8	0
				9	1
				10	2
				10	3
				10	4
				10	5
				End	6
					7
					8
					9
					10
					10
					10
					10
					10
					End

APPENDIX A2

Table A 2: Data of batch experiments of defoamer concentrations of 60%-100%

60% Conc. Foam height (cm)	70% Conc. Foam height (cm)	80% Conc. Foam height (cm)	90% Conc. Foam height (cm)	100% Conc. Foam height (cm)
0	0	0	0	0
1	1	1	1	1
2	2	2	2	2
3	3	3	3	3
4	4	4	4	4
5	5	5	5	5
6	6	6	6	6
7	7	7	7	7
8	8	8	8	8
9	9	9	9	9
10	10	10	10	10
10	10	10	10	10
10	10	10	10	10
10	10	10	10	10
10	10	10	10	10
6.5	4.5	1.9	0.4	0.4
3	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
1	0	0	0	0

Key	
(dark blue)	Stop Air flow
(yellow)	Dose antifoam
(light blue)	Start air flow
(black)	End exp.

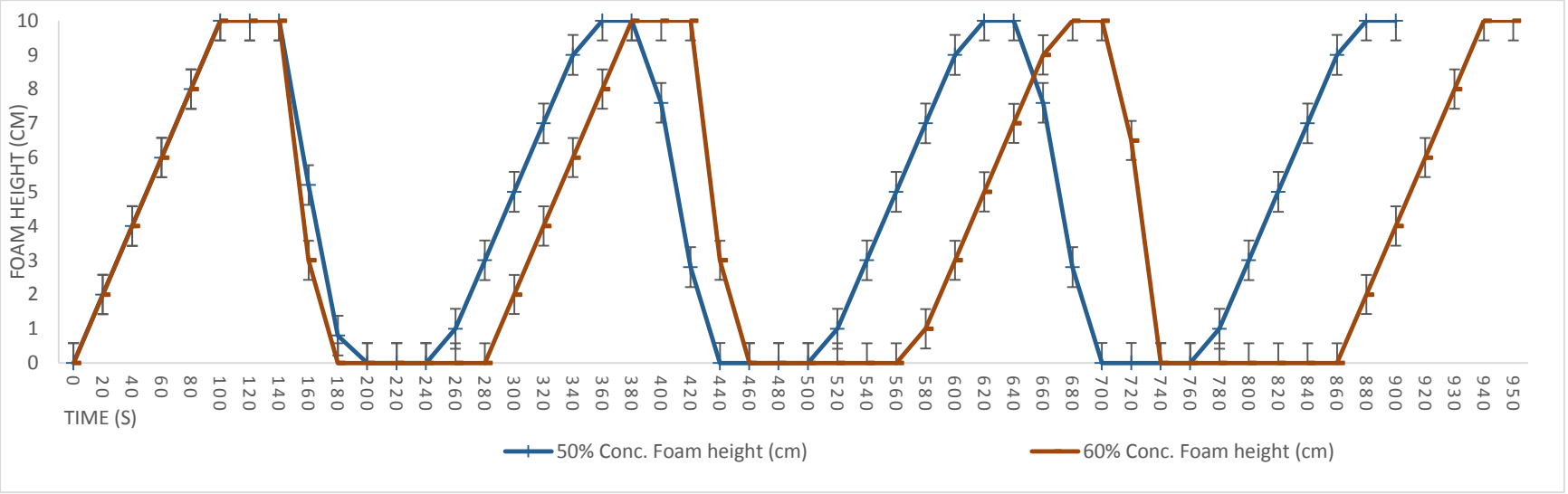
60% Conc. Foam height (cm)	70% Conc. Foam height (cm)	80% Conc. Foam height (cm)	90% Conc. Foam height (cm)	100% Conc. Foam height (cm)
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	0	0	0	0
10	0	0	0	0
10	0	0	0	0
10	0	0	0	0
10	0	0	0	0
6.5	0	0	0	0
3	0.8	0	0	0
0	1.6	0.6	0	0
0	3.2	1.2	0	0
0	4	1.8	0	0
0	5	2.4	0.4	0
0	6	3.4	0.8	0.4
0	7	4	1.2	0.8
0	8	5	1.6	1.2
0	9	6	2	1.6
0	10	7	3	2
0	10	8	4	3
0	10	9	5	4
0	10	10	6	5
0	10	10	7	6
1	4.5	10	8	7
2	0	10	9	8
3	0	10	10	9
4	0	4.5	10	10
5	0	0	10	10
6	0	0	10	10
7	0	0	10	10
8	0	0	0.4	10
9	0	0	0	0.4

60% Conc. Foam height (cm)	70% Conc. Foam height (cm)	80% Conc. Foam height (cm)	90% Conc. Foam height (cm)	100% Conc. Foam height (cm)
10	0	0	0	0
10	0	0	0	0
10	0	0	0	0
10	0	0	0	0
10	0	0	0	0
6.5	0	0	0	0
3	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
1	0	0	0	0
2	0.8	0	0	0
3	1.6	0	0	0
4	3.2	0	0	0
5	4	0	0	0
6	5	0.6	0	0
7	6	1.2	0	0
8	7	1.8	0	0
9	8	2.4	0	0
10	9	3	0	0
10	10	4	0	0
10	10	5	0.4	0
10	10	6	0.8	0
End	10	7	1.2	0.4
	10	8	1.6	0.8
	4.5	9	2	1.2
	0	10	3	1.6

60% Conc. Foam height (cm)	70% Conc. Foam height (cm)	80% Conc. Foam height (cm)	90% Conc. Foam height (cm)	100% Conc. Foam height (cm)
	0	10	4	2
	0	10	5	3
	0	10	6	4
	0	10	7	5
	0	4.5	8	6
	0	0	9	7
	0	0	10	8
	0	0	10	9
	0	0	10	10
	0	0	10	10
	0	0	10	10
	0	0	0.4	10
	0	0	0	10
	0	0	0	0.4
	0	0	0	0
	0	0	0	0
	0	0	0	0
	0	0	0	0
	0	0	0	0
	0	0	0	0
	0	0	0	0
	0	0	0	0
	0	0	0	0
	0	0	0	0
	0	0	0	0
	0	0	0	0
	0	0	0	0
	0	0	0	0
	0	0	0	0
	0.8	0	0	0
	1.6	0	0	0
	3.2	0	0	0
	4	0	0	0
	5	0	0	0
	6	0.6	0	0
	7	1.2	0	0
	8	1.8	0	0

60% Conc. Foam height (cm)	70% Conc. Foam height (cm)	80% Conc. Foam height (cm)	90% Conc. Foam height (cm)	100% Conc. Foam height (cm)
	9	2.4	0	0
	10	3.4	0	0
	10	4	0	0
	10	5	0	0
	10	6	0	0
	End	7	0	0
		8	0	0
		9	0	0
		10	0	0
		10	0	0
		10	0.4	0
		10	0.8	0
		End	1.2	0.4
			1.6	0.8
			2	1.2
			3	1.6
			4	2
			5	3
			6	4
			7	5
			8	6
			9	7
			10	8
			10	9
			10	10

APPENDIX B



Appendix B 1: Batch experiment graphs for 50% and 60% defoamer concentration.

APPENDIX C

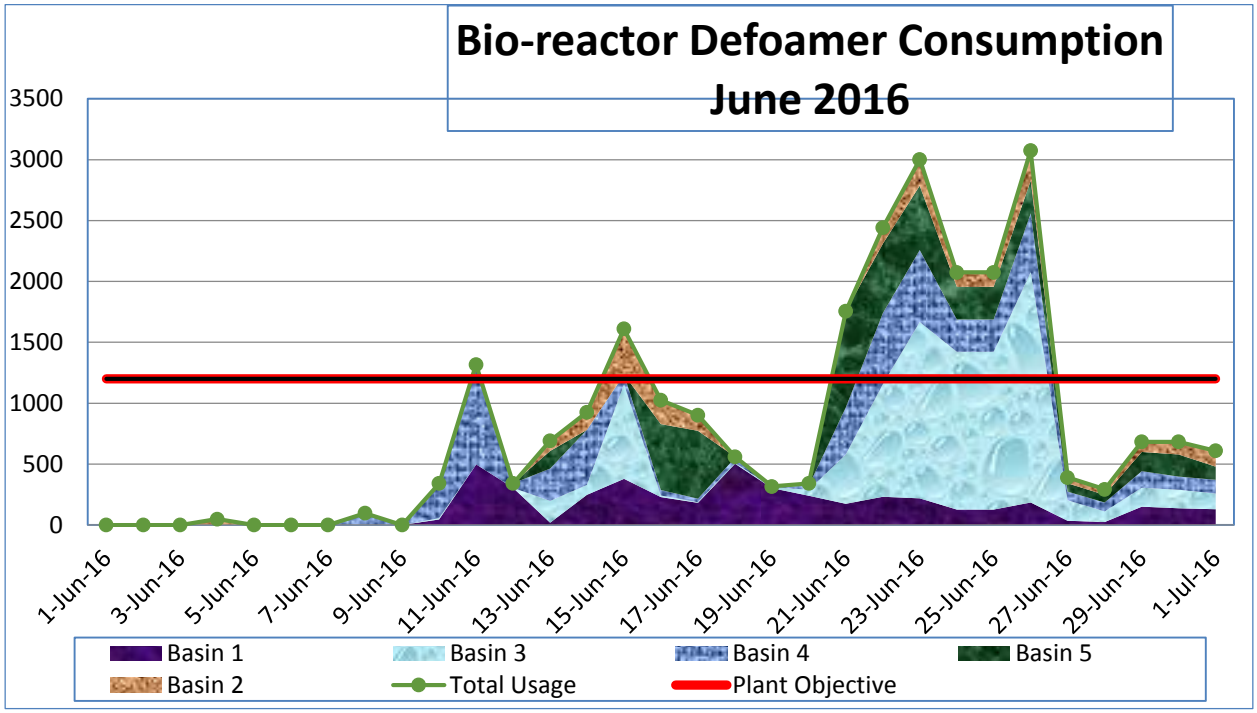
Appendix C 1: National Water Act waste discharge standards DWA 2010 Guidelines

National WATER ACT waste discharge standards DWA 2010 guidelines

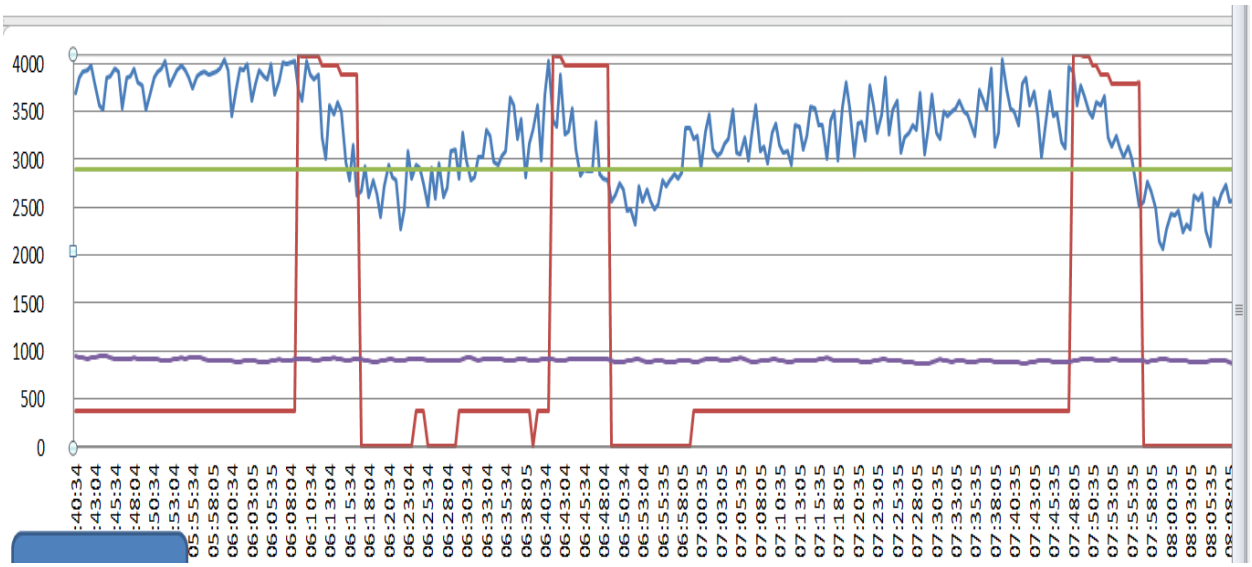
Wastewater limit values applicable to discharge of wastewater into a water resource

Variables and substances	Existing General Standards	Future all discharges
Chemical oxygen demand	75 mg/l	65 mg/l
Colour, odour or taste	No substance capable of producing the variables listed	No substance capable of producing the variables listed
Ionised and unionised ammonia (free and saline ammonia) (as N)	3,0 mg/l	1,0 mg/l
Nitrate (as N)	15	15 mg/l
pH	Between 5,5 and 9,5	Between 5,5 and 7,5
Phenol index	0,1 mg/l	0,01 mg/l
Residual chlorine (as Cl)	0.25 mg/l	0,014 mg/l
Suspended solids	25 mg/l	18 mg/l
Total aluminium (as Al)	-	0,03 mg/l
Total cyanide (as Cn)	0,02 mg/l	0,006 mg/l
Total arsenic (as As)	0,02 mg/l	0,01 mg/l
Total boron (as B)	1,0 mg/l	0,5 mg/l
Total cadmium (as Cd)	0,005 mg/l	0,001 mg/l
Total chromium III (as CrIII)	-	0,11 mg/l
Total chromium VI (as CrVI)	0,05 mg/l	0,02 mg/l
Total copper (as Cu)	0.01 mg/l	0,002 mg/l
Total iron (as Fe)	0.3 mg/l	0,3 mg/l
Total lead (as Pb)	0,01 mg/l	0,009 mg/l
Total mercury (as Hg)	0,005 mg/l	0,001 mg/l
Total selenium (as Se)	0,02 mg/l	0,008 mg/l
Total zinc (as Zn)	0.1 mg/l	0,05 mg/l
Faecal coliforms per 100 ml	1000 mg/l	1000 mg/l

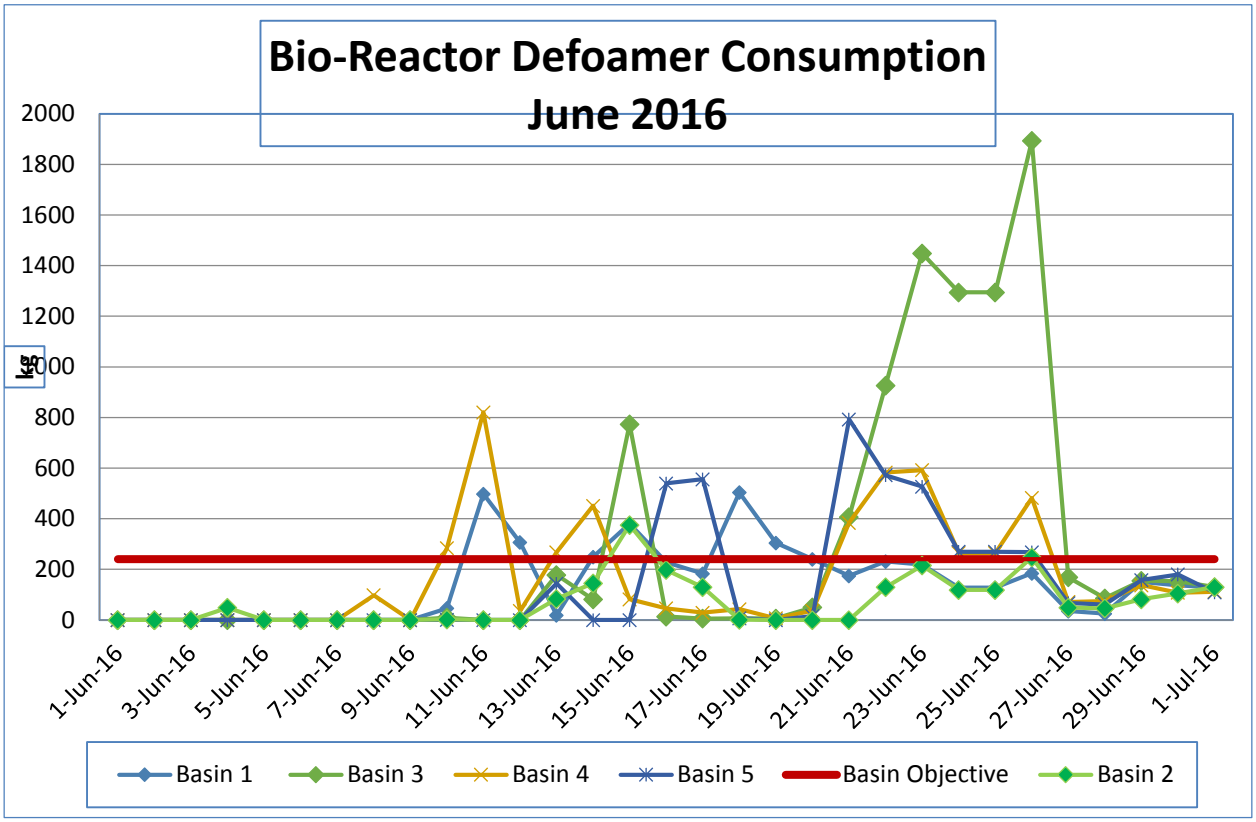
APPENDIX D



Appendix D 1: Bio-reactor Defoamer Consumption June 2016



Appendix D 2: Historical Scada Dump: Defoamer dosing pump output vs foam height in a Bio-reactor



Appendix D 3: Bio-Reactor Defoamer Consumption June 2016

APPENDIX E

Appendix E 1: Data for plant trials, 40%-100% defoamer concentration

Defoamer Conc. (%)	Time (s) 1st dose	Time (s) 2nd dose	Time (s) 3rd dose	Ave. Time(s)
40%	50	48	46	48
50%	40	36	34	37
60%	20	20	20	20
70%	20	20	20	20
80%	14	12	12	13
90%	10	10	10	10
100%	10	10	10	10