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Influence of anaerobic and anoxic hydraulic retention time on biological nutrient removal in a membrane bioreactor

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To Marnie, thanks for your patience and everything you do,

and to my parents who always encouraged me

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

Regulation of the discharge of biological nutrients into the environment continues to increase in order to protect sensitive bodies of water. One promising new technology is the membrane bioreactor, which combines the activated sludge process with membrane filtration.

The focus of this study was to determine the best anaerobic and anoxic hydraulic retention time (HRT) for biological nitrogen and phosphorus removal. A randomized experimental design of fourteen different HRT runs was tested with the anaerobic HRT varying between 0.5 and 3 hours and the anoxic HRT varying between 1 and 5 hours. Essentially complete nitrification was achieved with an average ammonia removal of 98.8 ± 0.2%. Total nitrogen removal varied from a low of 76 ± 1.2% to 88.7 ± 0.3% and showed a positive correlation with increases in anoxic HRT from 1 to 4 hours. High anaerobic HRTs (3 hours) slightly decreased nitrogen removal. Phosphorus removal varied from 40.3 ± 2.2% to 81.7 ± 0.8% and showed strong positive correlation with increases in anaerobic HRT from 0.5 to 2 hours and a negative correlation with increases in anoxic HRT. In general, phosphorus removal appears to be more sensitive to changes in HRT than nitrogen removal. Optimization of the system requires balancing the conflicting needs of higher anoxic HRT for nitrogen removal but negative impact on phosphorus removal and higher

anaerobic HRT for phosphorus removal. A prediction model was developed to estimate nitrogen and phosphorus removal given the anaerobic and anoxic HRT.

In addition, a study was conducted to determine the influence of various SRTs on biomass phosphorus concentrations and bacterial floc sizes in an aerobic MBR system. Phosphorus uptake by the biomass increased with increased SRT from 10 to 50 days and decreased from 50 to 75 days. This finding has implications for the operation of aerobic MBR systems at high SRTs. A statistical analysis indicated that the bacterial floc diameters were statistically similar from 10 to 50 day SRT and significantly larger for 75 day SRT. The results did not follow the trend of decreasing floc size with increased SRT reported in other studies, although the floc sizes were generally similar to those reported in other studies.

1. INTRODUCTION AND OBJECTIVES

1.1 Introduction

Regulation of pollutant discharge into the environment has become steadily stringent over the past century, particularly in the past 30 years. Early pollution control efforts were directed towards relatively easily observed problems such as acutely toxic chemicals and biological oxygen demand. Efforts that are more recent have been directed towards problems less easily observed but certainly important such as endocrine disrupting compounds and biological nutrients. Consequently, the field of environmental engineering has grown rapidly in order to meet the increased demands for new technologies to meet the regulations.

The conventional treatment processes for municipal wastewater is the trickling filter or the activated sludge process. Despite improvements to these processes, conventional treatment is no longer sufficient to meet the increasingly strict effluent limitations. A recent development in wastewater treatment technology is the membrane bioreactor (MBR). The MBR combines the activated sludge process with membrane filtration to provide many improvements and increased flexibility of operation (Visvanathan et al., 2000). The membrane filter offers excellent solids removal and complete retention of biomass within the system, which allows biomass concentrations up to and above 20 g/L (Kraume et al., 2005). The ability to retain biomass in the system allows a MBR to achieve high solids retention times (SRT), which provides the ability to maintain adequate treatment even at low hydraulic retention times (HRT), while providing an effluent with essentially no suspended solids.

Despite the excellent treatment potential of MBRs, there remain issues to be overcome in order to realize their full effectiveness. Much of the new MBR technology has been developed faster than it can be carefully studied and understood. Design of MBRs remains to an extent, based on the traditional activated sludge process, the designer's previous experience or costly pilot-scale studies. There is a need to determine the operating envelope of the MBR in order to improve design and operation. Costs can be reduced by eliminating the need for excessively large safety factors in design. Improvements in design will also allow for confident application of MBRs as a solution to a wider range of treatment problems. In particular, studies are needed to capitalize on the unique aspects of the MBR process that may affect BNR, such as high biomass concentrations, high SRT, low HRT, and the differences in the microbial population that these unique operating parameters foster. The MBR has the potential for much greater nutrient removal compared to conventional treatment processes, although complete optimization of MBR processes will require further research. For example, the operation of a MBR at high biomass concentrations can increase nutrient removal efficiency, while a high SRT can aid in degradation of recalcitrant compounds. Operation at high SRTs also has implications for phosphorus removal due to changes in biomass phosphorus concentration at higher SRTs.

The goal of this study was to determine the influence of anaerobic and anoxic HRT on biological removal of nitrogen and phosphorus in a MBR. A 36 L lab-scale reactor was constructed to specifically:

1. Determine the relationship between changes in anaerobic and anoxic HRT on biological nitrogen and phosphorus removal.
2. Determine the optimal anaerobic and anoxic HRT to maximize both nitrogen and phosphorus removal.
3. Develop an empirical model to estimate nitrogen and phosphorus removal for a given anaerobic and anoxic HRT.
4. Determine the relationship between changes in SRT on phosphorus content of the sludge, phosphorus removal, and floc size in an aerobic MBR.

The results of this study, combined with previous and possibly future work can be utilized to develop a model that can be used for the design of nutrient removal MBR systems.

1.2 Thesis organization

This thesis is organized into 5 chapters with 3 appendices. Chapter 1 provides an introduction and objectives of the study. Chapter 2 is a literature review comprising information that is important in providing a fundamental understanding of the issues and a basis for the work undertaken in the study. Chapter 3 details the research project on biological nitrogen and phosphorus removal for varied anaerobic and anoxic hydraulic retention times in a membrane bioreactor. Chapter 3 also includes a statistical analysis to determine the optimal hydraulic retention time of the anaerobic and anoxic reactors for nitrogen and phosphorus removal. Chapter 4 details a short study of the influence of solids retention times on biomass phosphorus concentrations, phosphorus removal, and bacterial floc size in an aerobic MBR. Chapter 5 provides the conclusions of this study, and includes recommendations for future study. Appendix A is a summary of the raw data collected from the experiments detailed in Chapter 3. Appendix B provides the raw data collected from the experiments in Chapter 4, and Appendix C contains the images of bacterial flocs used in Chapter 4.

2. LITERATURE REVIEW

Abstract

Membrane bioreactors (MBRs) can be an effective technology capable of excellent treatment performance, although questions remain concerning the optimal operation of a MBR for biological nutrient removal (BNR) applications. Conventional activated sludge based BNR systems typically operate with solids retention times (SRT) less than 20 days and biomass concentrations of 2-4 g/L. The MBR allows for complete retention of the biomass independent of the hydraulic retention time (HRT), permitting greatly increased flexibility in operation (Visvanathan et al., 2000). MBR systems are capable of biomass concentrations of up to 20 g/L, and have successfully maintained treatment performance at SRTs as high as 75 days. The operation of a MBR for BNR at high solids retention times (SRT) above 30 days has not been fully investigated, despite the potential advantages of a high SRT such as high mixed liquor suspended solids (MLSS) and low sludge production. Most MBR systems use HRTs similar to those used for conventional systems, despite the potential of increased operational flexibility. To date, there has been relatively little research focused on optimizing the HRTs for BNR using membrane processes. Common HRTs are in the range of 0.5 to 3 hours for anaerobic reactors, 1 to 3 hours for anoxic, and 4 to 12 hours aerobic.

Many of the recent MBR studies focused on BNR have been small lab-scale studies using synthetic wastewater that can favor biological nutrient removal processes and does not always adequately represent full-scale conditions. In addition, the influent carbon:nitrogen:phosphorus (C:N:P) ratio is a potentially important factor for BNR, especially for phosphorus removal, where further research is needed. A C:P ratio of about 40:1 is recommended for maximum phosphorus removal (Randall et al., 1992; Xialian et al., 2006).

2.1 Introduction

Discharge of wastewater containing nitrogen and phosphorus can lead to eutrophication of receiving waters. In many areas, increasingly stringent nutrient discharge limitations require adoption of new treatment practices (Barnard and Steichen, 2006). Biological nutrient removal (BNR) processes have seen a steady increase in use in the past 10-20 years as an effective means of nutrient removal. Biological nutrient removal processes have proved to be a cost-effective, "green" technology compared to conventional chemical treatments (Muyima et al., 1997 as quoted in Mulkerrins et al., 2004). The majority of early BNR systems relied on conventional activated sludge and clarifier processes, which may have difficulty achieving future strict nutrient and solids discharge limitations.

Combining biological nutrient removal with membrane bioreactors (MBRs) offers a promising solution to meet strict nutrient discharge standards. The MBR combines a biological treatment process with micro or ultra membrane filtration and provides several advantages over conventional treatment such as high effluent quality, high treatment efficiency, flexible operation, and low sludge production. In the last 10-15 years, there has been a great deal of research on the feasibility of MBR treatment systems for municipal and industrial wastewater treatment. MBR systems are now at the point where they can be cost competitive and can be more effective than conventional treatment processes (Adham et al., 2001). Many of the published MBR studies have focused on feasibility or proof of concepts; there have been few studies investigating the optimization of a complete MBR system (Yang et al., 2006). In particular, there have been relatively few studies of biological nutrient removal in MBRs, especially those with a focus on combined nitrogen and phosphorus removal (Patel et al., 2005).

This paper will provide a brief background of the concepts of BNR, typical BNR processes, a review of recent research using MBRs for BNR, and the influence of wastewater composition on BNR processes.

2.2 Biological nutrient removal

BNR includes the removal of nitrogen and phosphorus that is in excess of that required for biomass production (Metcalf and Eddy, 2003). Complete nitrogen removal is the process of nitrification of ammonia to nitrate, which is then denitrified to nitrogen gas and removed from the treatment system. Phosphorus accumulating organisms (PAOs) are responsible for removal of excess phosphorus in a process termed enhanced phosphorus removal.

2.2.1 Nitrification

Nitrification is a two-step aerobic process in which microorganisms oxidize ammonia (NH_4) to nitrite (NO_2^-) that is then further oxidized to nitrate (NO_3^-). In recent years, several genera of microorganisms have been found to be capable of nitrification, although there are two principal and distinct groups of microorganisms responsible for nitrification. Ammonia oxidation is primarily conducted by the genera *Nitrosomonas*, while nitrite oxidation is primarily accomplished by the genera *Nitrobacter*. *Nitrosomonas* and *Nitrobacter* are chemoautotrophic, obligate aerobes that can utilize carbon dioxide as a carbon source and ammonia and nitrite as the respective energy sources (Bitton, 2005). The reactions involved are as follows: (adapted from Metcalf and Eddy, 2003):

Ammonia Oxidation

$$2NH_4^+ + 3O_2 \xrightarrow{Nitroso-bacteria} 2NO_2^- + 4H^+ + 2H_2O \qquad 2.1$$

Nitrite Oxidation

$$2NO_2^- + O_2 \xrightarrow{Nitro-bacteria} 2NO_3^- \qquad 2.2$$

Total Reaction:

$$NH_4^+ + 2O_2 \longrightarrow NO_3^- + 2H^+ + H_2O \quad 2.3$$

The rate of the total reaction (eq. 2.3) is limited by the rate of ammonia oxidation by *Nitrosomonas* (eq. 2.1). Nitrite is unstable in most water environments and is usually transformed rapidly into nitrate (Droste, 1997). If biomass synthesis is included, the complete nitrification reaction is as shown (eq. 2.4) (Crites and Tchobanoglous, 1998).

$$NH_4^+ + 1.863O_2 + 0.098CO_2 \longrightarrow 0.0196C_5H_7NO_2 + 0.98NO_3^- + 0.0941H_2O + 1.98H^+ \quad 2.4$$

Several parameters may affect nitrification performance including dissolved oxygen, pH, influent ammonia or nitrite concentrations, and carbon:nitrogen:phosphorus (C:N:P) ratios. A relatively large amount of oxygen (4.3 mg) is required to oxidize 1 mg of ammonia into nitrate (Metcalf and Eddy, 2003). In order to maintain a sufficient oxygen supply, a minimum dissolved oxygen concentration of 2 mg/L is recommended in the aeration reactor (Xiaolian et al., 2006). The optimum pH range is 7.5-8.5 with inhibition shown for pH of 6.0. Nitrification will also result in the consumption of 7.14 mg alkalinity per mg of ammonia oxidized, leading to a potential decrease in pH (Metcalf and Eddy, 2003).

2.2.2 Denitrification

Denitrification is the biological reduction of nitrate to nitrogen gas in the absence of dissolved oxygen. Denitrification occurs under anoxic conditions using nitrate as the electron acceptor. Denitrification involves several reduction steps from nitrate to nitrite and ultimately to nitrogen gas (2.5).

$$NO_3^- \longrightarrow NO_2^- \longrightarrow NO \longrightarrow N_2O \longrightarrow N_2 \qquad 2.5$$

Two common treatment methods using biological denitrification are preanoxic and postanoxic denitrification (Kraume et al., 2005) (Figure 2.1).

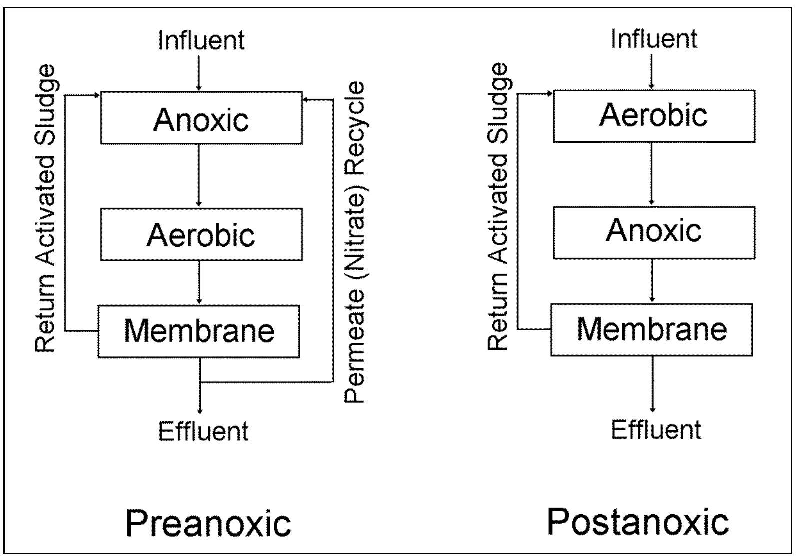

Figure 2.1 Common denitrification treatment processes (adapted from Kraume et al., 2005)

A pre-anoxic system uses an anoxic basin followed by an aerobic basin. Nitrate from the aerobic basin is recycled to the anoxic basin where denitrification occurs. The organic substrate in the anoxic basin can improve nitrification rates and the oxidation ability of nitrate offers some reduction in oxygen demand, which can decrease the size of the aeration basin (Kraume et al., 2005). Nitrogen removal is usually constrained to 75-90% in the pre-anoxic process due to limitations of the activated sludge recycle ratio to the anoxic basin. Typical recycle rates are 1 to 2 times the influent flowrate (Metcalf and Eddy, 2003). Nitrogen removal rates can also be limited by a low carbon:nitrogen (C:N) ratio, which may require a supplementary carbon source (Kraume et al., 2005). Xiaolian et al. (2006) reported increasing nitrogen removal with an increase in C:N from 3 to 7.7 and decreasing nitrogen removal with an increase in C:N from 7.7 to 12.

A post-anoxic system features the anoxic basin after the aerated basin. Denitrifying bacteria are heterotrophic and require an organic carbon source for their metabolism. In the pre-anoxic system, the wastewater supplies the required carbon source while the post-anoxic system relies on either slow endogenous respiration or a potentially costly supplemental carbon source (Kraume et al., 2005). Post-anoxic systems are not constrained by sludge recycle limitations and offer nitrogen removal rates of up to 90-96% (Adam et al., 2003). Typical HRTs for these systems are 0.5 to 2 hours anaerobic, and 1 to 4 hours anoxic (Metcalf and Eddy, 2003).

2.2.3 Biological phosphorus removal

Microorganisms can biologically remove phosphorus through assimilation; a process termed enhanced biological phosphorus removal (EBPR) allows certain microorganisms to assimilate and remove significant amounts of phosphorus (Bitton, 2005). Typical activated sludge microorganisms will assimilate approximately 1.5-

3% phosphorus (dry weight) to grow and maintain biomass, which equates to approximately 10-25% phosphorus removal through sludge wasting (Bitton, 2005; Metcalf and Eddy, 2003).

Enhanced biological phosphorus removal is a process designed to increase the assimilation of phosphorus into the biomass in excess of 3%, up to a practical maximum of about 7-8% when using municipal wastewater as a substrate (Droste, 1997). Enhanced biological phosphorus removal relies on microorganisms called phosphorus-accumulating organisms (PAOs), which have the ability to store excess phosphorus in polyphosphate granules. EBPR has been successfully used in full-scale treatment plants since the 1980s. While the general theory of EBPR is understood, there remain questions about optimization of the process (Bitton, 2005). There are many variations of the EBPR process, but all are based on an anaerobic phase followed by an aerobic phase, which promotes growth of PAOs, and is briefly described below and illustrated in Figure 2.2 (Bitton, 2005).

- In an anaerobic environment, PAOs use energy from polyphosphate hydrolysis to uptake fermentation products that are stored as polyhydroxyalkanoate (PHA) energy reserves. There is a release of inorganic phosphorus in this process. Fatty acids are also stored during this phase.

- In an aerobic environment, energy is derived from the stored PHA and inorganic phosphorus is assimilated into the cell and stored in polyphosphate granules. The PAOs will uptake more phosphorus during aerobic conditions than was released during anaerobic conditions, and the overall result is a net increase of phosphorus in the PAOs and a net decrease of phosphorus in the wastewater (Bitton, 2005).

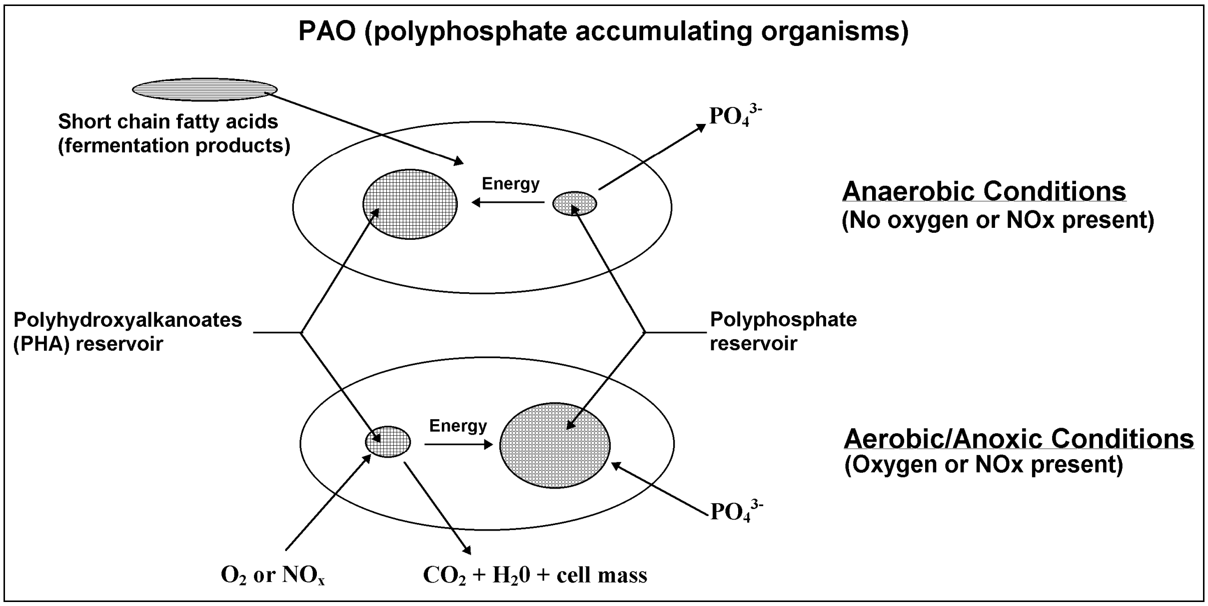

Figure 2.2 Enhanced biological phosphorus removal (adapted from Brenner, 2005)

A potential problem for biological phosphorus removal is competition from glycogen accumulating organisms (GAOs), which have a somewhat similar metabolism compared to PAOs. GAOs uptake fermentation byproducts in the anaerobic zone and store it as glycogen which can later be metabolized in an aerated zone (Oehmen et al., 2006). The competition between GAOs and PAOs is dependant on many environmental conditions and continues to be a source of interest for many researchers (Barnard and Steichen, 2006; Panswad et al., 2003; Chen et al., 2002). Research has shown that temperature, pH, amount and type of carbon source can significantly influence the balance between PAOs and GAOs (Barnard and Steichen, 2006). PAOs tend to dominate at temperatures below approximately 20^{O}C, while GAOs dominate between 25 and 32.5 ^{O}C (Panswad et al., 2003). Several recent studies have investigated the influence of influent carbon sources. One study reported the addition of simple sugars led to an increase in GAOs, while complex carbon sources favored PAOs (Maclean et al., 2002 as quoted in Barnard and Steichen, 2006). Similarly, Chen et al. (2002) found more stable operation of phosphorus removal when simultaneously feeding supplemental acetic and propionic acids than either alone. It should be emphasized that there remains much work to be done to fully understand GAO versus PAO competition.

Another potential problem for biological phosphorus removal is nitrate and or nitrite inhibition. In the past, it was thought that PAOs only used oxygen as an electron acceptor, although it has since been shown that some PAOs have the ability to also use nitrate as an electron acceptor (Kuba et al., 1994). Lee et al. (2001) reported that some PAOs will also utilize nitrite when nitrate levels are below 1 mg/L, but that nitrate is preferentially consumed. These unique PAOs have the ability to perform denitrification as well as enhanced biological phosphorus removal (Hu et al., 2002). When there is limited nitrate availability, ordinary heterotrophic organisms (OHOs) will out compete PAOs for nitrate and there will be a low impact to the enhanced biological phosphorus removal process. If the nitrate loading exceeds the denitrification potential of the OHOs, PAOs, are more likely to utilize the excess nitrate (Hu et al., 2002). When these denitrifying PAOs use nitrate as an electron acceptor, they will still uptake phosphorus, although anoxic phosphorus uptake is not as efficient as aerobic phosphorus uptake and will lead to a decrease in removal rates (Hu et al., 2002). Even in biological phosphorus removal systems without nitrate present, denitrifying PAOs will develop and can cause a rapid drop in phosphorus removal rates if nitrate is introduced into the system (Kuba et al., 1994). There is no strong consensus on the point where nitrate concentration where inhibition of phosphorus removal occurs. Kuba et al. (1996a) reported that nitrite concentration of 5-10 mg NO^-_2–N/L strongly inhibited phosphorus uptake. Lee et al. (2001) reported that if PAOs are continuously exposed to nitrite (up to 5 mg NO_{2j}^--N/L) acclimation to nitrate/nitrite is possible, and greatly reduces nitrate/nitrite inhibition of phosphorus uptake. The most practical method to control denitrifying PAOs from negatively impacting phosphorus removal is to limit the amount of nitrate introduced into the anoxic reactor to less than the denitrification potential of the OHOs (Hu et al., 2002).

2.3 Biological nutrient removal processes

In order to accomplish biological nutrient removal of nitrogen and phosphorus, nitrification, denitrification and EBPR must be combined into a system that allows each process to be efficiently accomplished with a minimum of interference. Combined biological nitrogen and phosphorus removal systems share three common traits (Figure 2.3) (Metcalf and Eddy, 2003):

- An anaerobic reactor(s) for selection of PAOs with a typical HRT of 0.5-2 hours.
- An anoxic reactor(s) for denitrification with a typical HRT of 1-4 hours and an aerobic reactor(s) for nitrification and enhanced phosphorus uptake by PAOs with a typical HRT of 4-12 hours.

The typical design parameters of common BNR processes found in textbooks are presented in Table 2.1. The performance of BNR systems is greatly influenced by site-specific constraints such as wastewater composition, effluent requirements, and possible limitations of other treatment plant processes (Xiaolian et al., 2006). The relative strengths and weaknesses of the above mentioned BNR processes are presented in Table 2.2 (Adapted from Metcalf and Eddy, 2003).

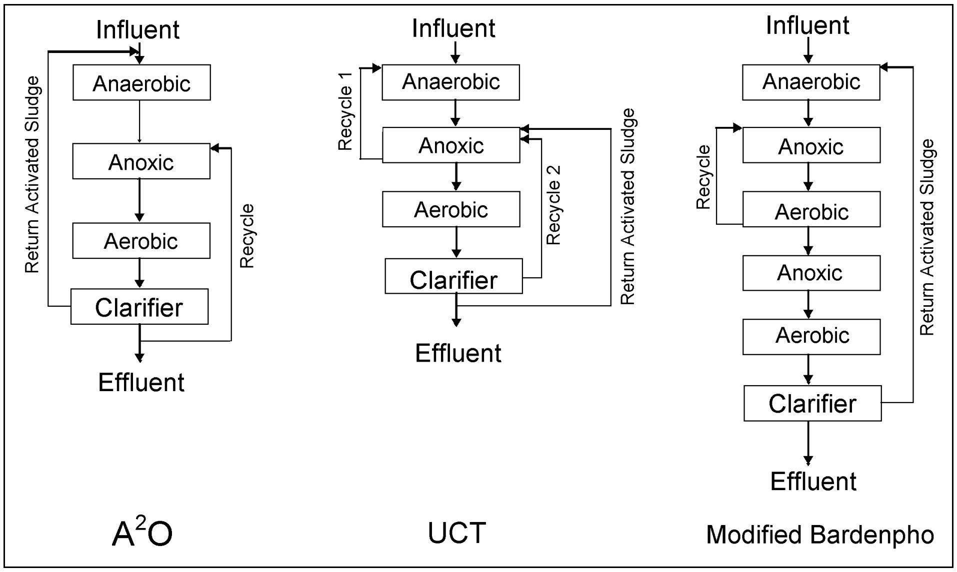

Figure 2.3 Three common biological nutrient removal processes

Table 2.1 Typical design parameters for common BNR processes (adapted from Metcalf and Eddy, 2003)

Process	Parameter					
	SRT (days)	HRT (hours)			Recycle Rate (% of influent)	
		Anaerobic	Anoxic	Aerobic	RAS	Internal
A^2O	5-25	0.5-1.5	0.5-1	4-8	25-100	100-400
UCT	10-25	1-2	2-4	4-12	80-100	200-400 (anoxic) 100-300 (aerobic)
VIP	5-10	1-2	1-2	4-6	80-100	100-200 (anoxic) 100-300 (aerobic)
Modified Bardenpho	10-20	0.5-1.5	1-3 (1^{st} stage) 2-4 2^{nd} stage)	4-12 (1^{st} stage) 0.5-1 (2^{nd} stage)	50-100	200-400

Table 2.2 Comparison of biological nutrient removal processes

Process	Advantages	Limitations
A^2O	Simple operation, capable of 5 mg/L effluent TN	Phosphorus removal may be limited by nitrate in return activated sludge
UCT / VIP	Capable of high nitrogen and phosphorus removal	Complex operation
Bardenpho (5-stage)	Effluent TN of 3-5 mg/L possible	Complex operation, multiple basins required

2.4 Biological nutrient removal using a membrane bioreactor

The majority of early BNR systems employed conventional activated sludge basins with sedimentation clarifiers. Increasingly stringent discharge standards will likely exceed the capabilities of conventional processes. Water quality criteria published by the U.S. Environmental Protection Agency in 2001 prescribed new effluent standards that can be equal or less than 3 mg/L total nitrogen (TN) and 0.03 – 0.07 mg/L total phosphorus (TP) in sensitive coastal areas (Barnard and Steichen, 2006). Many conventional treatment systems cannot achieve these strict discharge standards, and there is great interest in finding economical methods to meet the new and future standards.

Combining membrane filtration technology with BNR offers a promising solution to meeting strict new discharge limitations. Membrane bioreactors offer many advantages compared to conventional activated sludge systems, and are increasingly cost competitive. Membrane filtration offers superior solids separation compared to conventional clarifiers and provides complete retention of biomass, allowing for very high biomass concentrations of up to 20 g/L compared to 2-4 g/L for most conventional systems (Kraume et al., 2005).

The elimination of the clarifier also allows for operation of the system without regard to the settleability of the biomass and permits the HRT to be controlled completely independently of the SRT (Visvanathan et al., 2000). Many MBRs are operated at a relatively high SRT of 20-30 days, although it is possible to operate at very high

SRTs of up to 75 days and maintain satisfactory treatment performance (Ahn et al., 2003; Ersu, 2006; Zhang et al., 2006). Operation at high SRT lowers sludge production and reduces the associated costs for sludge disposal (Trussell et al., 2005). SRTs above 30 days have been shown to decrease the concentration of extra-cellular organic compounds, which improves effluent quality (Masse` et al., 2006). The high biomass concentrations and high SRTs typical in a MBR have also shown potential for the treatment of recalcitrant organic compounds and concentrated industrial wastewaters (Trussell et al., 2005). A consequence of the high biomass concentration and improved efficiency mentioned above is the ability to operate with a low HRT and therefore smaller reactor (Visvanathan et al., 2000). The elimination of secondary clarifiers by membrane filters also provides space and cost savings (VanDijk and Roncken, 1997 as quoted in Trussell et al., 2005). Overall, a MBR's footprint can be two to four times smaller than an equivalent conventional activated sludge system (Xing et al., 2001).

The clarifier, in a traditional system, acts as a selector for fast growing bacteria. In a MBR, slow growing bacteria such as nitrifiers and others that are adept at degrading complex compounds are encouraged to grow, which can improve system performance (Urbain et al., 1996). Research has demonstrated that the microbial population in a MBR contains a higher viable fraction of microbes, capable of degrading a wider range of carbon substances, and the membrane retains enzymes that improve metabolic rates compared to a conventional activated sludge system (Cicek et al., 1999).

MBRs do have some disadvantages compared to conventional activated sludge systems. MBRs have high capital and operating costs, although prices continue to become more competitive. Fouling of the membrane can be a problem that can decrease permeate flux and possibly lead to deterioration of the membrane. Routine chemical cleaning, using hypochlorous acid, sodium hppochlorite or proprietary cleaning solutions are often required to maintain stable operation (Visvanathan et al., 2000; Yoon et al., 2004).

Although the use of MBRs for wastewater treatment has increased substantially in the past 10 years, there remain many questions concerning their optimum operation. Early generation MBR systems were operated with process parameters similar to conventional activated sludge systems, and the design and operation of current MBRs remains influenced to an extent by conventional systems.

There have been relatively few studies on biological nutrient removal in MBRs, many of which have focused on either nitrogen or phosphorus removal individually, but not simultaneously (Patel et al., 2005). Furthermore, many of the published MBR studies have investigated issues of feasibility, but not process optimization (Yang et al., 2006). In recent years, there has been an interest in the incorporation of membrane filtration with sequencing batch reactors (SBR). Research has shown that membrane-SBRs are capable of satisfactory biological nutrient removal while providing the space and cost savings typically associated with an SBR system (Ahn et al., 2003; Zhang et al., 2006). Despite advances in SBR technology, multiple stage MBRs remain superior when very low effluent nitrogen and phosphorus is required (Patel et al., 2005). Details of individual studies of recently published BNR work using conventional and membrane processes are presented in Tables 2.3 and 2.4. A summary of current trends in BNR studies using conventional and membrane technology is presented in Tables 2.5 and 2.6.

Table 2.3 Summary of recent BNR research with non-membrane processes

Scheme	Scale	Wastewater	Influent Parameters (mg/L)			Hydraulic Retention Time (Hours)				SRT (d)	MLSS (g/L)	Removal %			Reference
			COD	TN	TP	Anaerobic	Anoxic	Aerobic	Total			COD	TN	TP	
A^{2}O	Lab	Synthetic brewery wastewater	375	50.8	8	2.2	1.8	5	9	12	3	71	75	92	Peng et al., 2006
			330	53.7	8.4	2.25	2.25	4.5	9	12	2.7	88	78	96	
			340	66	7	2	2	5	9	12	3.3	84	64	93	
			300	69.7	6.3	1.8	2.2	5	9	12	3.4	83	70	85	
UCT	Pilot	Municipal	~300	~33	~4.5	0.8 – 1.1	2 - 2.8	4.3 - 6.1	7-10	12	~6	92	65	95	Monti et al., 2006
$(AO)_4$-step feed	Pilot	Municipal	~250	~35	-*	-	-	-	9	20	2.5-5	92	65	-	Sheping et al., 2006
A^{2}O	Lab	Synthetic brewery wastewater	358	51.9	15.2	1.9	1.5	4.2	7.6	12	~3	89.9	77.2	62.9	Xiaolian et al., 2006
			346	52.6	10.1							89.8	78.6	96.9	
			364	56.6	8.5							92.2	79.9	97.1	
			373	51.9	6.9							92.4	77.8	93.4	
A^{2}O-BAF#	Pilot	Municipal	150	28	3.3	2	2	1	6	16	7.4	82.6	62	90.8	Lee et al., 2005
A^{2}O	Full	Municipal	-	22.4	2.8	1.5	6.1	9.4	17	-	-	-	75	79	Sakuma, 2005
			-	27.9	4.3	3.3	1.7	9.9	14.9	-	-	-	68	91	
			-	27.2	3.3	1.8	2.2	9.8	13.8	-	-	-	64	91	
			-	26	2.8	1.5	4.9	9.3	15.7	-	-	-	69	89	
			-	25.8	3.5	1.4	4.8	7.7	13.9	-	-	-	70	91	
			-	31.4	3.3	1.8	3.5	8.1	13.4	-	-	-	71	67	
			-	27	2.7	2.3	3.8	9.2	15.3	-	-	-	69	85	
SBR (AOA)	Lab	Synthetic Municipal	300	30	11.3	1.5	3.25	1.5	8	15-25	4-5.5	-	83	92	Tsuneda, et al., 2005
UCT-IFAS#	Lab	Municipal	605	72	34	4	2	6	12	10	3.5-5	95.1	~75	61.9	Sriwiriyarat and Randall, 2005
UCT											~3.3	94.8	~75	70.5	
SBR	Full	Municipal	-	36	9	N/A	2	2	4	18	5.6	-	92.5	94.4	Peters et al., 2004
			-	33	6	N/A	2	2	4	12	4.5	-	90.9	93.3	
$(AO)_2$-SBR	Lab	Synthetic Municipal	300	30	10	1.5	2.5	1	5	12	-	-	88	~99	Lee et al., 2001
A^{2}O	Lab	Synthetic Municipal	-	-	-	5	1.9	5.6	12.5	-	3.6	91.2	-	64	Mulkerrins et al., 2000

*Not reported; # BAF- Biological aerated filter; IFAS- Integrated fixed film activated sludge

Table 2.4 Summary of recent BNR research using MBRs

Scheme	Scale	Wastewater	Influent Parameters (mg/L)			Hydraulic Retention Time (Hours)				SRT (d)	MLSS (g/L)	Removal %			Reference
			COD	TN	TP	Anaerobic	Anoxic	Aerobic	Total			COD	TN	TP	
UCT	Pilot	Municipal	~300	~33	~4.5	0.8 – 1.1	2 - 2.8	4.3 - 6.1	7 – 10	12	~6	92	65	95	Monti et al., 2006
Sequencing AO with Aerobic	Lab	Synthetic Municipal	400	~20	1.3	-*	-	-	22	60	5.6	94.9	65	90	Zhang et al., 2006
A^2O	Lab	Synthetic Municipal	480	41	12	2	2	8	12	10	4.8	94	66	71	Ersu, 2006
										25	8.1	94	78	75	
										50	11.3	95	78	81	
										75	15.1	95	81	61	
A^2O	Lab	Synthetic Municipal	300	25	5	3	3	6	12	20	2.1-5.5	98	78	96	Patel et al., 2005
Single Stage with Low D.O. (0.7-1.0 mg/L)	Lab	Synthetic Municipal	315	~30	2	-	-	-	4	∞	23.1	97	55	97	Holakoo et al., 2005
			350	~30	2	-	-	-	6	∞	18.5	98	36	98	
Sequencing Anaerobic/Anoxic with Aerobic	Pilot	Municipal	122	23	2.6	0.8	2.1	3.5	6.4	80	6	94	71	69	Cho et al., 2005
			171	27	3.3	0.9	2.9	4.5	8.3	80	9	95	60	60	
Anoxic/anaerobic/ oxic/anoxic	Pilot	Municipal	96-1200	16-61	1-12.3	-	-	-	6	9-56	7-14	92-98	71-76	88-94	Yoon et al., 2004
Sequencing Anaerobic/Anoxic with Aerobic	Lab	Municipal	245	38	3.7	2.2	1	4.8	8	70	10.1	96	60	93	Ahn et al., 2003
UCT (Pre-Denitrification)	Pilot	Municipal	998	70	10.5	-	-	-	21	15	~12	96	82	99	Lesjean et al., 2003
UCT (Post-Denitrification)	Pilot	Municipal	740	61	9.1	-	-	-	18	26	~10	95	87-99	99	
Sequencing Anoxic/Oxic Ultrafiltration	Pilot	Municipal	~295	~43	~4	N/A	1.5	2.5		10	~3	~89	~73	~75	Innocenti et al., 2002
									14	190	~6	~86	~85	~90	
										>200	~8	~94	~69	~73	
Intermittent air aerobic MBR	Lab	Municipal	520	~49	15	-	-	-	8-24	30-100	1.9-14.5	~97	~93	~85	Hasar et al., 2001

*Not Reported

Table 2.5 Trends in recent BNR research using non-membrane processes

	Reported Hydraulic Retention Time (Hours)				Total SRT (d)	Aerobic MLSS (g/L)	Removal (%)		
	Anaerobic	Anoxic	Aerobic	Total			COD	TN	TP
Anaerobic/Anoxic/Oxic (A^2O) Processes									
Range	1.4-5	1.5-6.1	4.2-9.9	7.6-17	12-12	2.7-3.6	71-92.4	64-79.9	62.9-97.1
Average*	2.1 ± 0.9	2.9 ± 1.5	7.1 ± 2.3	12.3 ± 3.2	N/A	3.2 ± 0.3	86.8 ± 7	72.4 ± 5	85.8 ± 12
University Cape Town (UCT) Processes									
Range	0.8-5	1.9-2.8	4.3-6.1	7-12.5	10-12	3.3-6	91.2-95.1	65-75	61.9-95
Average*	2.7 ± 1.8	2.2 ± 0.4	5.5 ± 0.8	10.4 ± 2.5	10.7 ± 1.2	4.3 ± 1.2	93.3 ± 2	71.7 ± 6	72.9 ± 15
Sequencing Batch Reactor (SBR) Processes									
Range	1.5-1.5	2-3.25	1-2	4-12.5	12-25	4-5.6	-#	83-92.5	64-94.4
Average*	N/A	2.4 ± 0.6	1.6 ± 0.5	7.1 ± 4	17.5 ± 5.6	4.9 ± 0.8	-	88.6 ± 4	85.9 ± 15

*One standard deviation; # not reported

Table 2.6 Trends in recent BNR research using MBR processes

	Reported Hydraulic Retention Time (Hours)				Total SRT (d)	Aerobic MLSS (g/L)	Removal (%)		
	Anaerobic	Anoxic	Aerobic	Total			COD	TN	TP
Anaerobic/Anoxic/Oxic (A^2O) Processes									
Range	2-3	2-3	6-8	12	10-75	4.8-15.1	94-98	66-81	61-96
Average*	2.5 ± 0.7	2.5 ± 0.7	7.5 ± 0.7	12	36 ± 26	7.8 ± 4.7	95.2 ± 1.6	76 ± 5.8	76.8 ± 13
University Cape Town (UCT) Processes									
Range	0.8-1.1	2-2.8	4.3-6.1	7-21	12-26	6-12	94-96	65-99	95-99
Average*	0.95 ± 0.2	2.4 ± 0.6	5.2 ± 1.3	14 ± 6.6	17.7 ± 7	9.3 ± 3	94.3 ± 2	83.3 ± 14	97 ± 2.3
Sequencing Batch Reactor (SBR) Processes									
Range	0.8-2.2	1.5-2.9	2.5-4.8	4-24	10-190	1.9-14.5	86-97	60-93	60-93
Average*	1.3 ± 0.8	1.8 ± 0.8	3.8 ± 1	11.2 ± 7.2	77 ± 53	7.1 ± 3.8	93 ± 3.8	72 ± 11.7	79 ± 11.8

*One standard deviation

Several trends are noticed when studying differences in research between conventional and membrane based systems. Although there were some studies that used similar operational parameters, the membrane systems tended to use slightly lower HRTs, possibly due to improved efficiencies gained from operation at higher MLSS concentrations (~8-9 g/L compared to ~3-5 g/L). Membrane systems in many studies were operated at much higher SRTs (up to 190 days in one study) than conventional systems, which rarely were operated above 20 days SRT.

The trend of BNR research using MBRs in recent years is towards defining the limits of the MBR process and developing design methods based on the unique aspects of MBRs. Some of the important process parameters that remain to be fully understood include operation at high SRTs, the influence of varied HRTs, glycogen vs. phosphorus accumulation organism competition, influence of influent C:N:P ratios, and the microbial characteristics in a MBR.

2.4.1 Impact of SRT on BNR performance

The SRT of a MBR has the potential to greatly influence nutrient removal, particularly phosphorus (Mulkerrins et al., 2004). During enhanced biological phosphorus removal, phosphorus content in the biomass increases from 1.5-2.5% up to 6-8% (dry weight) (Kraume et al., 2005). The SRT and therefore the amount of sludge wasted can be seen to play an important role in phosphorus removal. Traditionally it was thought that high sludge ages (> 20 days) did not allow for EBPR due to bacterial cell lysis and subsequent phosphorus release, although that has since been shown not to be true (Adam et al., 2002). It is reasonable to assume that an optimum SRT exists for phosphorus removal, balancing the benefits of higher biomass concentrations against increased cell lysis and phosphorus release at high SRTs. Few studies have investigated SRTs above 25 days, although some studies have demonstrated promising results. Ahn et al. (2003) reported total nitrogen removal of 60% and total phosphorus removal of 93% at 70 days SRT. Ersu (2006) investigated SRTs from 10 to 75 days using synthetic municipal wastewater and reported optimum performance (78% TN, 81% TP removal) at an SRT of 50 days. Innocenti et al. (2002) reported promising MBR performance (85% TN, 89% TP removal) at an SRT of 190 days.

2.4.2 Influence of reactor HRT on BNR performance

In the past, many systems have been designed with the shortest HRT that provides acceptable results in order to reduce cost and space requirements. BNR systems with multiple reactors may benefit from optimization of the HRT to improve removal performance. It has been proposed that the reactor HRT may have a significant influence on biological nutrient removal (Mulkerrins et al., 2004). Conventional activated sludge systems are limited in the extent that the HRT can be varied, although the MBR process allows for much greater flexibility in selecting the HRT as the constraints imposed by a settling clarifier are removed. A search of the literature did not find any studies focused on quantifying the influence of HRT on biological nutrient removal in a MBR. Data from a recent study of seven full-scale conventional activated sludge (A^2O process) municipal wastewater treatment plants indicates a possible influence on nutrient removal due to differences in HRT (Sakuma, 2005) (See Figures 2.4 and 2.5, Table 2.3).

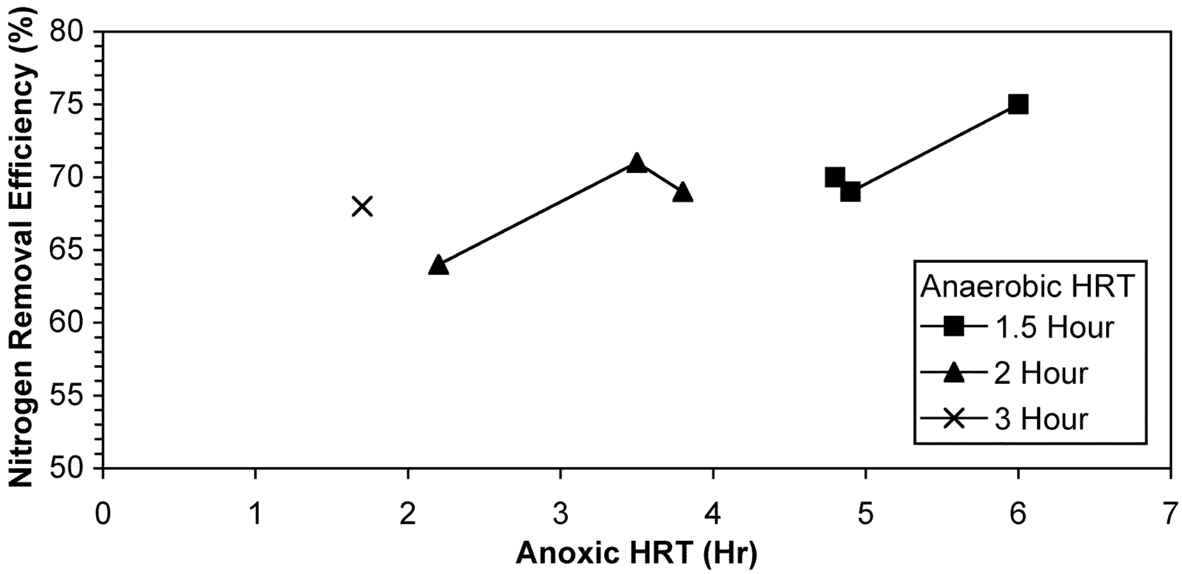

Figure 2.4 Influence of HRT on total nitrogen removal (data from Sakuma, 2005)

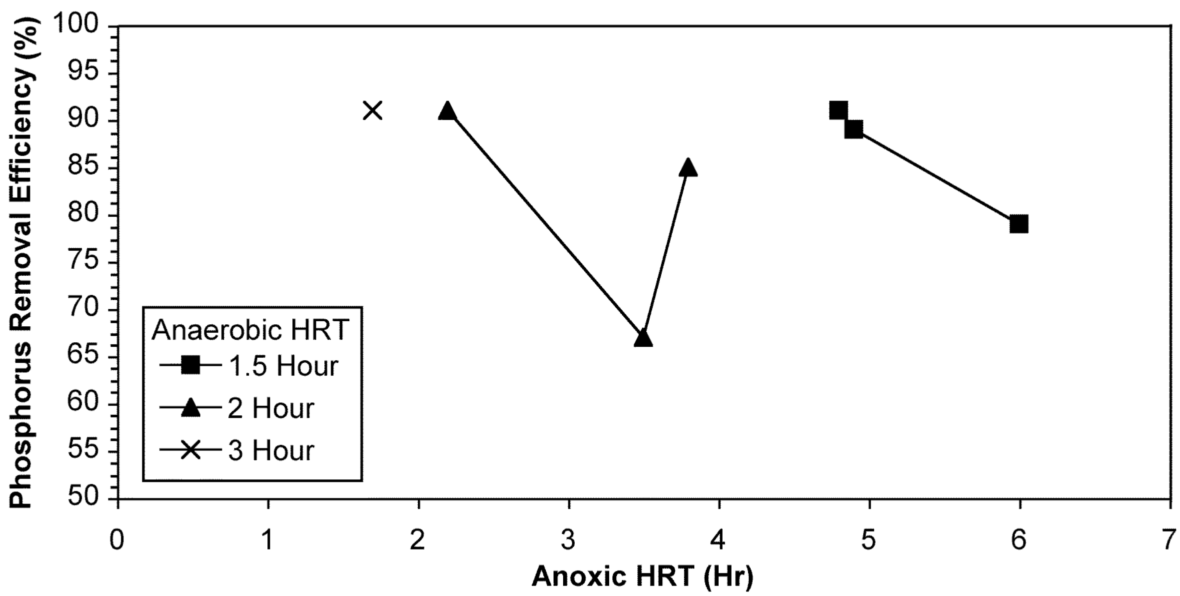

Figure 2.5 influence of HRT on total phosphorus removal (data from Sakuma, 2005)

The anaerobic HRT is important for phosphorus removal; the products of fermentation are stored by PAOs as polyhydroxyalkanoate (PHA) energy reserves for future use. Depending on the characteristics of the influent, if the anaerobic HRT is too short (roughly 0.5 hours or less), then the PAOs will not have sufficient energy reserves to perform enhanced phosphorus uptake in the aerobic zone. Increasing the anaerobic HRT will increase the availability of fatty acids for PAOs, although with too much time the energy supply for the PAOs will become depleted and lead to secondary release of phosphorus (Danesh and Oleszkiewicz, 1997). The secondary release of phosphorus can harm the EBPR process (Mulkerrins et al., 2004). The exact time for onset of secondary phosphorus release depends on the characteristics of the influent. Excessive anaerobic HRT can also harm nitrogen removal by limiting the available COD for denitrification later in the treatment process.

The HRT of the anoxic zone has implications for both nitrogen and phosphorus removal. If the anoxic HRT is short (typically less than 1 hour depending on reactor conditions and influent) incomplete denitrification is possible. Increasing the anoxic HRT to 3-4 hours will improve nitrogen removal, although HRTs past the point of complete denitrification will not further improve nitrogen removal and can negatively affect phosphorus removal. Several studies have suggested that PAOs are more efficient in enhanced phosphorus uptake in aerobic environments than anoxic, and phosphorus removal is harmed by excessive anoxic HRT (Patel et al., 2005).

The optimal HRT for biological nitrogen removal is not the same as for biological phosphorus removal. Biological nitrogen removal excels at low anaerobic HRT and high anoxic HRT, and the opposite is true for biological phosphorus removal, which prefers high anaerobic HRT and low anoxic HRT. By adjusting the anaerobic and anoxic HRT, there is potential to optimize a MBR system for nitrogen and/or phosphorus removal.

2.4.3 Composition of microbial population

The composition and characteristics of the microbial population in a MBR can be significantly different from a conventional activated sludge system, particularly with longer SRTs. One of the most obvious differences is the high biomass concentration typical of MBR systems, which can improve treatment efficiency and allows for smaller reactors. Most MBRs are operated at an MLSS of 8-20 g/L compared to a conventional system in the range of 1.5-3 g/L (Adham et al., 2001). Less obvious are changes in the concentration of microbial extracellular and other organic compounds in a MBR compared to a conventional system. In a conventional system as the SRT increases, concentrations of proteins, polysaccharides and sCOD in the effluent all increase (Masse` et al., 2006). This process is likely responsible for the deteriorating performance of a conventional system at higher SRTs (Masse` et al., 2006). In a MBR, the organic compounds decreased as SRT increased, and were lower that those of conventional systems at high sludge ages (37+ days) (Masse` et al., 2006). It is theorized that high sludge ages allows bacteria time to further degrade organics and promotes growth of slow growing bacteria which can metabolize some of the polysaccharides and proteins, and improves effluent quality (Masse` et al., 2006). This difference in the concentration of extracellular organic compounds marks a significant difference between conventional and MBR systems.

Several studies have documented differences in the size of microbial flocs, reporting that MBR flocs are generally smaller and settle poorly compared to conventional systems (Zhang et al., 1997). Zhang et al (1997) reported MBR median floc diameters ranged from 20-40 µm, while conventional activated sludge ranged from 80-300 µm (Zhang et al., 1997). The smaller MBR floc has been shown to improve oxygen transfer and increase nitrification activity from 0.95 to 2.28 g NH_4^+/kg MLSS-h, although there does not appear to be a significant influence on denitrification (Zhang et al., 1997). The differences observed in aerobic reactors would likely translate into differences in the anaerobic and anoxic reactors, although little research has been reported concerning differences in anaerobic and anoxic microbial populations between conventional and MBR systems.

2.4.4 Influence of wastewater composition on BNR

Biological nitrogen and phosphorus removal systems are complex systems that attempt to balance the requirements of multiple simultaneous removal processes as described earlier. A potential conflict occurs between PAOs and denitrifiers, which compete for the same carbon source to carry out their metabolism (Xiaolian et al., 2006). The role of influent C:N:P ratios on biological nutrient removal is not fully understood. Design of modern MBR systems for BNR considers the effect of the influent C:N:P ratio, although there remains a variation of opinions among researchers. An influent C:P ratio of at least 40:1 was recommended to maximize phosphorus removal (Randall et al., 1992 as quoted in Mulkerrins et al., 2004). A study of the A^2O process using a conventional activated sludge system reported a C:N ratio of 5:1-7.1:1 and C:P ratio of 42:1 for optimum combined nitrogen and phosphorus removal (Xialian et al., 2006). A similar study of the A^2O conventional activated sludge process reported 90-98% phosphorus removal for C:P ratios above 32:1 (Ma et al., 2005). It is possible that optimum C:N:P ratios in a MBR will be different from the values reported in the previously mentioned studies of conventional systems, especially at high SRTs, which can have different microbial characteristics. The C:N:P ratio may also affect competition between PAOs and GAOs.

The mass-loading rate is a design parameter for conventional systems. MBRs are not as sensitive as conventional systems and can be used satisfactorily with loading rates eight times as high as conventional systems (Xing et al., 2001). Sludge yields in MBRs are usually lower than conventional systems, particularly for SRTs above 30 days (See Table 2.7) (Stephenson et al., 2000).

Table 2.7 Sludge yield in MBR and conventional systems

SRT (days)	Sludge Yield, kg SS (kgCOD removed)$^{-1}$	
	MBR	Conventional Activated Sludge
12	0.22	0.28
24	0.18	0.26
102	0.02	0.07

Traditionally, most conventional activated sludge based BNR systems used a food:microorganism (F:M) ratio of 0.1 to 0.2 kg BOD/kg MLVSS/day as the main design criteria (Mulkerrins et al., 2004).

2.5 Further studies

Early investigations of BNR using the MBR process demonstrated the ability of effective individual biological nitrogen or phosphorus removal, but only recently has combined nitrogen and phosphorus removal been seriously investigated (Patel et al., 2005). Recent literature reports have demonstrated the ability for combined nitrogen and phosphorus removal, albeit often under carefully controlled operating conditions that may be impractical for full-scale implementation (Patel et al., 2005).

Although the use of MBRs is rapidly growing, several issues remain unresolved concerning the optimization of MBR technology when applied to biological nutrient removal. The majority of published studies have used relatively short to medium SRTs from 10 to 25 days. Recent research has shown superior removal performance at much higher SRTs of 50-75 days (Ersu, 2006; Ahn et al., 2003; Zhang et al., 2006). There is a need to determine the effect of high SRT on other operating parameters such as HRT, C:N:P ratios, and microbial populations. There has been little if any research focused on optimizing the HRT of a MBR system for BNR, despite the potential for improved performance and cost savings.

A search of the literature found few studies investigating influent C:N:P ratios in a BNR system, but none in a MBR system designed for BNR. Many recent MBR studies have used synthetic feeds with a high proportion of simple sugars designed to improve biological phosphorus removal (Patel et al., 2005). The use of tailored synthetic feeds may be acceptable for early feasibility studies, but research with influents designed to better simulate real-world conditions is needed to further the understanding of the limits of BNR in a MBR. The effect of hydraulic and nutrient shock loadings is another area of potential research. The results of studies investigating influent C:N:P ratios in conventional activated sludge systems may not hold true for MBRs, particularly at high SRTs, which have different microorganism characteristics than conventional systems.

The competition between PAOs and GAOs continues to be a source of interest for many researchers. Recent studies have discovered several parameters, such as temperature and influent composition that affect the competition between PAOs and GAOs, although it should be emphasized that there remain many more questions than answers concerning PAO versus GAO competition. If an understanding of the underlying processes that control PAO/GAO competition were developed, there is potential for much improved biological phosphorus removal systems.

There is a need for a comprehensive study to optimize BNR for MBRs. As stated earlier, many of the studies completed so far have focused on issues of feasibility and not on process optimization. Patel et al. (2005) noted that many recent BNR studies used operating parameters that may be impractical for full-scale applications, and it is important to focus future work on the implementation of MBRs for full-scale use.

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3. INFLUENCE OF ANOXIC AND ANAEROBIC HYDRAULIC RETENTION TIME ON NITROGEN AND PHOSPHORUS REMOVAL IN A MEMBRANE BIOREACTOR

Abstract

This study evaluated the influence of anaerobic and anoxic hydraulic retention times on biological nitrogen and phosphorus removal in a MBR treating a synthetic medium strength municipal wastewater. A 36 L lab-scale MBR consisting of anaerobic, anoxic, and aerobic reactors (A^2O system) was constructed for the study and operated for 258 days with 14 different runs. Return mixed liqour was recycled (100% of influent) from the aerobic to anaerobic reactor and membrane permeate was recycled (100% of influent) to the anoxic reactor. A randomized experimental design was created using JMP™ version 6.0 (SAS Institute Inc.). The anaerobic HRT was varied between 0.5 and 3 hours, while the anoxic HRT was varied between 1 and 5 hours. The aerobic HRT was maintained at 8 hours throughout the study. Removal rates ranged from 95-99% sCOD, 76-89% TN and 40-82% TP. TN and TP removal rates correlated well with increases in anoxic and anaerobic HRT, respectively, and there was evidence of anoxic phosphorus uptake. A conflict was observed between the anaerobic and anoxic HRT requirements for nitrogen and phosphorus removal. Increased anaerobic HRT increased phosphorus removal, and slightly decreased nitrogen removal. While increased anoxic HRT tended to decrease phosphorus removal and increase nitrogen removal. An empirical model was developed to predict nitrogen and phosphorus removal given anaerobic and

anoxic HRTs, and to determine optimal HRT conditions for nitrogen and phosphorus removal.

Keywords: hydraulic retention time, membrane bioreactor, nitrogen, phosphorus, PAO, phosphorus uptake, A^2O

3.1 Introduction and objectives

3.1.1 Introduction

In recent years, control of the discharge of nutrients into the environment has become the focus of increased attention and strict regulations. New treatment technologies are required in many cases to meet new nutrient discharge standards for municipal wastewater treatment systems. Conventional activated sludge systems have been developed which allow for BNR processes through the combination of various schemes of anaerobic, anoxic and aerobic reactors. These processes include the anaerobic/anoxic/oxic (A^2O), University Cape Town (UCT), Virginia Initiative Plant (VIP) and Bardenpho systems and typically include 3-5 separate reactors or reaction zones (excluding clarifiers) (Metcalf and Eddy, 2003). Processes with multiple reactor basins and clarifiers, as well as multiple sludge recirculations can be both large and costly. In the past 10 years, the use of membrane bioreactors (MBRs) has been demonstrated for biological nutrient removal. The MBR combines the activated sludge process with membrane filtration to provide many improvements as well as increased flexibility of operation (Visvanathan et al., 2000). MBRs offer several advantages over conventional activated sludge systems including excellent solids removal and complete retention of biomass within the system, which allows high biomass concentrations of up to 20 g/L, which can improve treatment efficiency (Kraume et al., 2005). The MBR process allows the solids retention time (SRT) to be operated independently of the hydraulic retention time (Visvanathan et al., 2000). This unique ability provides improved performance by operating with a high SRT and a low HRT, while maintaining treatment performance. The ability of a MBR to handle varying HRTs without solids carry over could promise significant optimization of BNR processes. The differing anaerobic and anoxic requirements for biological nitrogen and phosphorus removal will likely lead to a range of anaerobic and anoxic HRTs that provide the best conditions for BNR. A review of the literature found no studies focused on the influence of varied anaerobic or anoxic HRTs on BNR processes, although it has been proposed that the reactor HRT may have a significant influence on biological nutrient removal (Mulkerrins et al., 2004). Despite the treatment potential of MBRs for BNR, there remain issues to be overcome in order to realize their full effectiveness. Much of the new MBR technology has been developed faster than it can be carefully studied and understood. Design of MBRs for BNR remains based on the traditional activated sludge process to an extent, previous experience or costly pilot-scale studies. There is a need to determine the operating envelope of BNR processes in a MBR in order to improve design and operation. Costs can be reduced by eliminating the need for excessively large safety factors in design. Improvements in design will also allow for confident application of MBRs as a solution to a wider range of treatment problems. In particular, studies are needed on the unique aspects of the MBR process such as high biomass concentrations, high SRT, low HRT, and differences in the microbial population.

3.1.2 Project objectives

The goal of this study was to determine the influence of anaerobic and anoxic HRT on biological removal of nitrogen and phosphorus in a MBR. A 36 L lab-scale reactor was constructed to:

1. Determine the relationship (if any) between changes in anaerobic and anoxic HRT and changes in biological nitrogen and phosphorus removal,
2. Determine the optimal anaerobic and anoxic HRT to maximize both nitrogen and phosphorus removal,
3. Develop an empirical model to estimate nitrogen and phosphorus removal for a given anaerobic and anoxic HRT.

The results of this study, combined with previous and possibly future work can be utilized to develop a model that can be used for the design of biological nitrogen and phosphorus removal using MBRs.

3.2 Methods and materials

3.2.1 Membrane bioreactor experimental setup

All lab experiments were conducted in a bench-scale membrane bioreactor system with three separate reactors: anaerobic, anoxic, and aerobic (Figure 3.1). The reactor design was based on previous work by Ersu (2006) who found that one optimal recycle arrangement was membrane permeate recycled to the anoxic reactor and return mixed liqour recycled to the anaerobic reactor, both at 100% of influent flow rate and at a solids retention time of 50 days (Ersu, 2006). The anaerobic and anoxic reactors were both cylindrical shaped with a total volume of 12 L each and employed magnetic stirrers to provide complete mix conditions. The aerobic reactor was rectangular to accommodate the membrane filter with a maximum volume of 12 L. The membrane was a plate frame, double-sided filter with a cellulose membrane manufactured by Kubota Co., Japan (Table 3.1).

Sampling points will be referred to as follows:

- A – Feed
- B – Anaerobic Influent
- C – Anaerobic Effluent
- D – Anoxic Effluent
- E – Aerobic Mixed Liquor
- F – Membrane Permeate

Air was supplied from a filtered air compressor to a diffuser located in the bottom of the aerobic reactor, and was adjusted to provide a dissolved oxygen concentration of at least 2 mg/L. The air diffuser was centered beneath the membrane to provide air scouring of the membrane to reduce fouling.

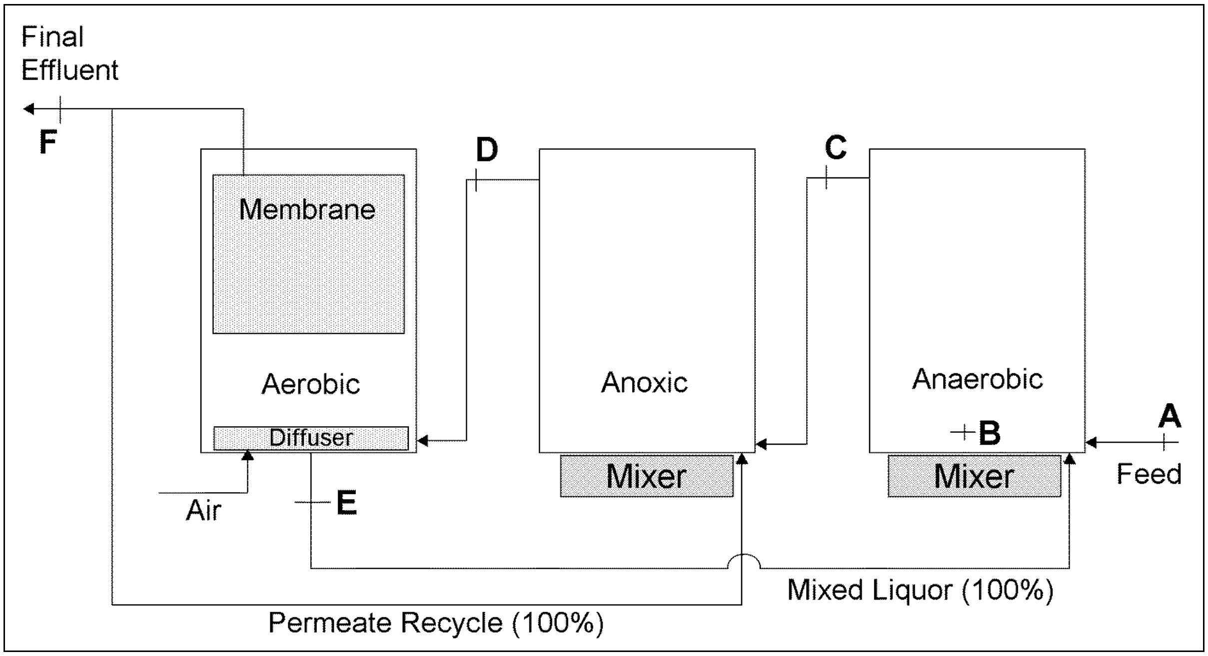

Figure 3.1 Biological nutrient removal MBR process diagram

Table 3.1 Membrane filter specifications

Parameter	**Specification**
Module Configuration	Plate-frame
Membrane Material	Cellulose
Pore Size	0.2 µm
Membrane Porosity	60% volume
Dimensions (Width x Thickness x Height)	23 cm x 1 cm x 31 cm
Total Filtration Area	0.15 m^2
pH Range	5.5 - 10
Maximum Temperature	80 ^{O}C
Maximum Pressure	25 kPa

The influent was stored in a 20 L plastic container that was refrigerated at approximately 4 to 5º C. The influent was fed into the anaerobic reactor with a Cole-Palmer (Model 7553-30) peristaltic pump. The effluent from the anaerobic reactor flowed by gravity to the anoxic reactor, which also used gravity to flow to the aerobic reactor. The permeate pump was a Cole-Palmer (Model 7532-20) that maintained an average flux of 13 ± 0.44 L/(hr-m^2). The membrane was operated in cycles of 4.5 minutes pumping and 0.5 minutes of idle to reduce membrane fouling and avoid the need for backwashing. Permeate and return mixed liquor was recycled to the anoxic and anaerobic zones, respectively, using Cole-Palmer (Model 7520-25) peristaltic pump. The pumps were controlled by a ChronTrol® computer timer. The SRT was controlled by manually wasting mixed liquor from the aerobic reactor each day. Two water level sensors in the aerobic reactor were used to prevent overflow of the system by shutting off influent and permeate recycle pumps. A synthetic wastewater designed to simulate medium strength municipal wastewater was used throughout the study (Table 3.2). The wastewater was stored at approximately 4 to 5º C.

Before beginning the experiments with biological nutrient removal, baseline data were collected in a MBR consisting of only the aerobic reactor (Figure 3.2). Sampling point notation is the same as in Figure 3.1. The single aerobic reactor configuration allowed for later comparison with the three-stage biological nutrient removal MBR. Of particular interest was comparison of phosphorus content in the biomass in the single stage system and the multi-stage system during enhanced biological phosphorus removal. The single stage experiments were conducted in the same 12 L aerobic reactor with the same synthetic wastewater used in the three stage MBR experiments. The aerobic MBR was operated for two weeks to ensure steady state results before proceeding.

Table 3.2 Synthetic wastewater composition and constituents

Ingredient	Concentration mg/L
Calcium Sulfate	40
Ferric Chloride	3
Isomil (Simulac™)	20 mL (1% by volume)
Magnesium Sulfate	4
Nutrient Broth	250
Potassium Chloride	5
Sodium Bicarbonate	63
Sodium Biphosphate Monobasic	60
Sodium Citrate	500
Composition	
Chemical Oxygen Demand (COD)	494 ± 4*
Total Nitrogen (TN)	45.9 ± 0.9
Ammonia Nitrogen (NH_3–N)	22.7 ± 0.8
Nitrate Nitrogen (NO_3^- -N)	0.38 ± 0.05
Nitrite Nitrogen (NO_2^- -N)	0.17 ± 0.03
Total Soluble Phosphorus (TP)	14.4 ± 0.3
Suspended Solids	27.3 ± 3.5
pH	7.2 ± 0.03

* Statistical α= 0.05, 95% CI

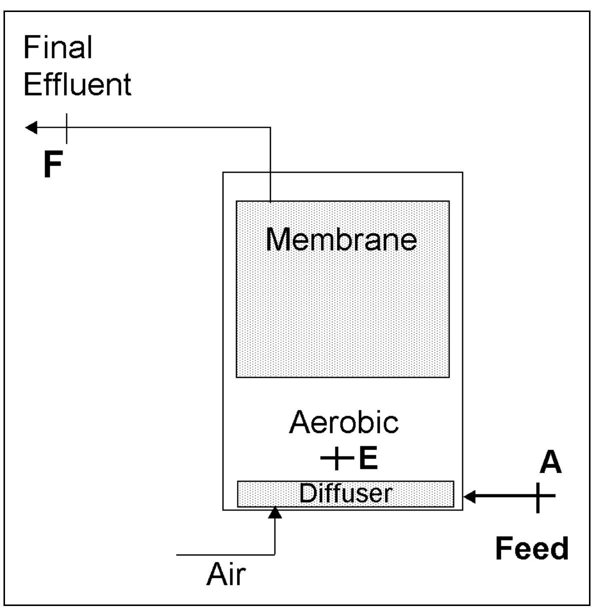

Figure 3.2 Single stage MBR process diagram

3.2.2 Acclimation of membrane bioreactor for BNR

The reactor was seeded using 5 gallons of activated sludge from the Boone wastewater treatment plant, Iowa with a total suspended solids concentration of 2-3 g/L. The system was initially operated in a 12-hour aerobic batch mode to improve acclimation of the microorganisms to the synthetic feed. After 6 cycles (72 hours), continuous mode was begun with 1 L/hr influent feed and 100% recycle of permeate and return mixed liqour. The HRT was fixed at 2 hours anaerobic, 3 hours anoxic, and 8 hours aerobic. No mixed liqour was wasted from the system for several days to increase the biomass concentration after which the SRT was gradually increased to 50 days over the period one week. From this point, the reactor was operated until steady state conditions developed at 66 days.

3.2.3 Biological nutrient removal experimental design

The statistical software package JMP™ version 6.0 (SAS Institute Inc., Cary, NC) was used to create the experimental design. Prior to creating the experimental design, trials using the computer modeling software Biowin® version 2.2 (Envirosim Inc., Ontario, Canada) and a review of current literature were carried out to narrow the range of hydraulic retention times to be tested.

A biological nutrient removal MBR model was constructed in Biowin® to simulate the lab-scale reactor as closely as possible. To model a MBR, Biowin® simulates the system as an aerated reactor with a filter belt dewatering system that returns all of the sludge to the aeration basin (Figure 3.3). The influent wastewater parameters used in the model were the same as those in the lab-scale study. Trials were run to calculate estimated total nitrogen and phosphorus removal for hydraulic retention times set to cover a range of potential values (Figures 3.4 and 3.5)

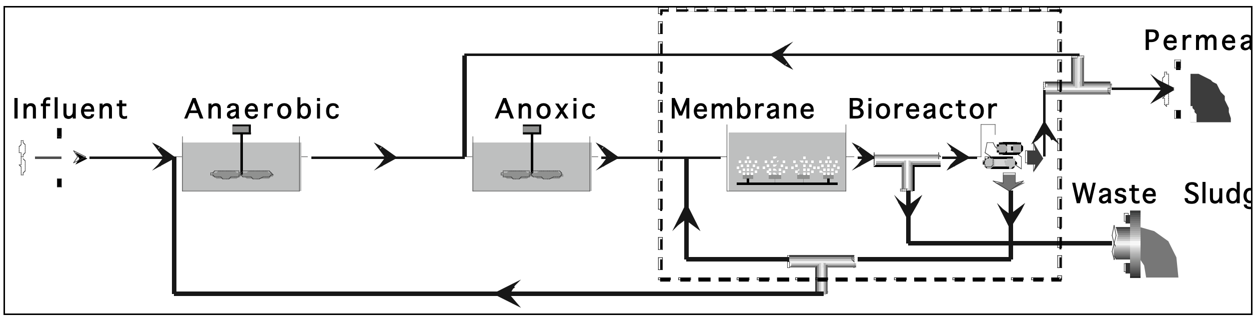

Figure 3.3 Biowin® process diagram

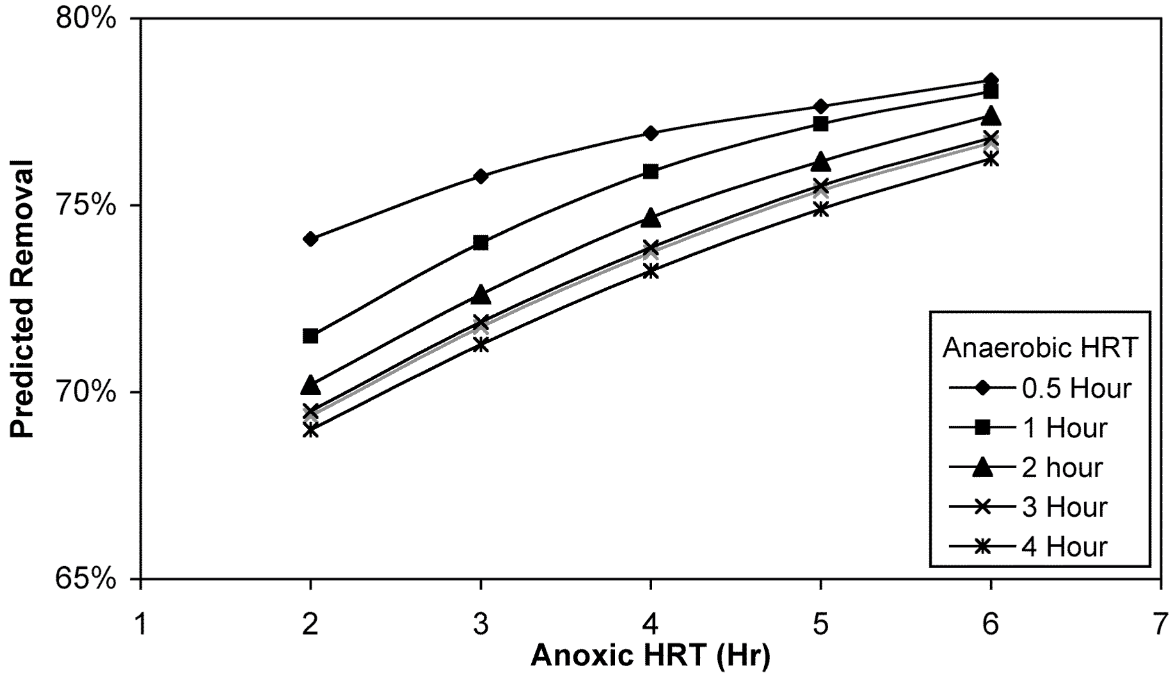

Figure 3.4 Total nitrogen removal using Biowin® model

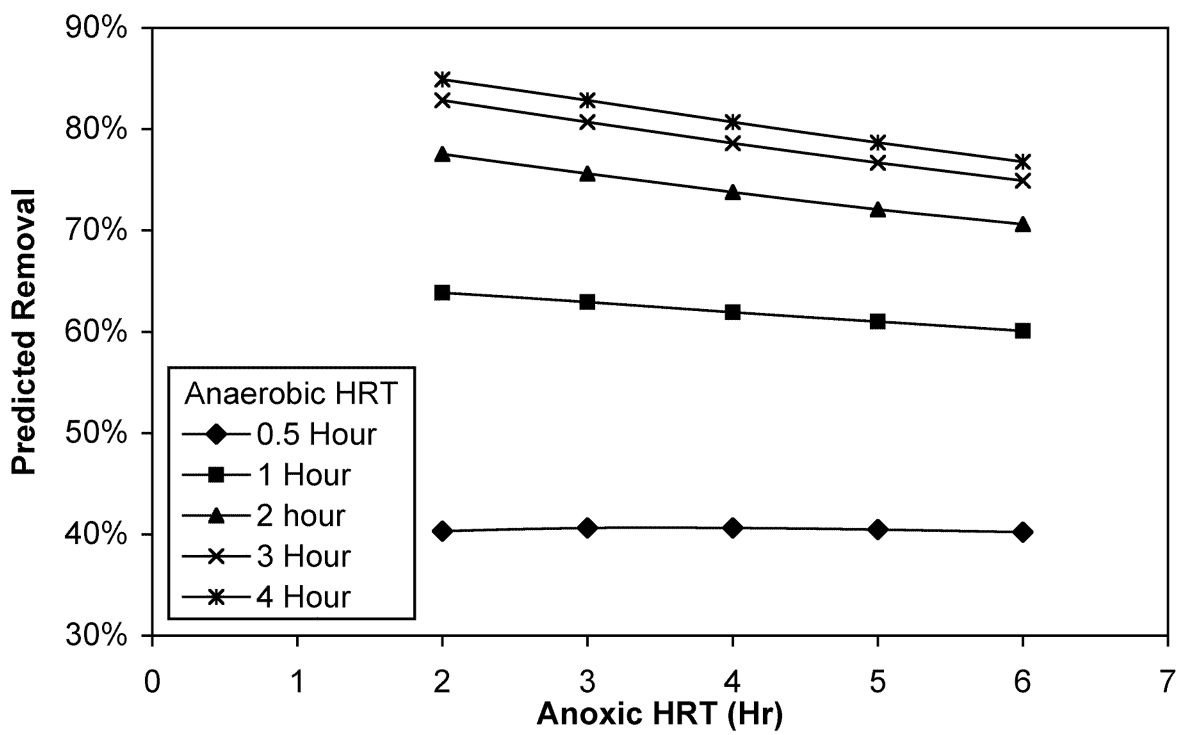

Figure 3.5 Total phosphorus removal using Biowin® model

Based on previous work, Biowin® (version 2.2) has been shown to not accurately predict the behavior of biological phosphorus removal in MBRs, particularly at high SRTs (Ersu, 2006), but must be properly calibrated before it can be used. Therefore, the results of this Biowin® analysis were considered to be rough estimates. The results of biological phosphorus removal modeling using Biowin® highlights the need for updated models, more accurate default kinetic parameters and the need for model calibration and verification for BNR in MBRs.

A review of the literature found relatively few papers investigating or reporting hydraulic retention times for biological nutrient removal, especially for MBRs. A summary of reported HRTs from recent BNR studies is presented in Table 3.3 (Summary of Tables 2.3 and 2.4).

Based on the above investigations, the range of hydraulic retention times selected for further lab-scale testing were as follows:

- Anaerobic: 0.5 to 3 hours
- Anoxic: 1 to 5 hours
- Aerobic: Fixed at 8 hours

The aerobic HRT was fixed at 8 hours in order to allow comparison of this study with data from previous work by Ersu (2006), who operated at an 8 hour aerobic HRT. Furthermore, a fixed aerobic HRT allows influences of the anaerobic and anoxic

HRTs on BNR to be isolated. The 8 hour aerobic HRT also ensures complete nitrification and meets the flux limitations of using a single membrane filter.

JMP™ was used to create an experimental protocol where two responses (nitrogen and phosphorus removal) were both maximized by varying two factors (anaerobic and anoxic HRT). Each factor was divided into discreet levels (Table 3.4). The software indicated a minimum of seven trials to statistically evaluate the desired HRT ranges. Based on the schedule of time available to conduct the experiments, nine trials were created and randomly ordered by the software, with an additional five randomly ordered trials added later in the study (Table 3.5). The additional five trials provided information that improved the confidence of the prediction model created with JMP™.

Table 3.3 Summary of HRTs from recent biological nutrient removal studies

	Hydraulic Retention Time (Hours)			
	Anaerobic	**Anoxic**	**Aerobic**	**Total**
Range	0.8-5	1-1.6	1-1.9	4-24
Average*	2.02 ± 0.4	2.6 ± 0.4	5.4 ± 0.96	10.8 ± 1.6

*95% confidence level

Table 3.4 Boundary conditions for experimental design

	Factor	
Level	**Anaerobic HRT (Hour)**	**Anoxic HRT (Hour)**
1	0.5	1
2	1	2
3	2	3
4	3	4
5	-	5

Table 3.5 Biological nutrient removal experiment design

Run	Anaerobic HRT (Hr)	Anoxic HRT (Hr)	Aerobic HRT (Hr)
1	2	3	8
2	0.5	5	8
3	2	1	8
4	0.5	4	8
5	1	5	8
6*	2	2	8
7	1	2	8
8	3	4	8
9	2	4	8
10	2	5	8
11	1	3	8
12	3	5	8
13	0.5	1	8
14	3	2	8

* Ersu, 2006

3.2.4 Laboratory analysis

Water quality and reactor performance parameters were frequently monitored to evaluate the performance of the MBR. All analyses were conducted in accordance to Standard Methods (APHA, AWWA and WEF, 1998). Analysis included measurements throughout the treatment process. Chemical constituents and reactor parameters were measured a minimum of twice per week and preferably three to four times per week during steady state conditions in order to collect sufficient data (Table 3.6).

3.3 Results and discussion

3.3.1 Membrane performance

The membrane module performed well for all test runs, with an average flux of 13.0 ± 0.44 L/(hr-m^2) and average transmembrane pressure of 0.47 ± 0.06 bar (6.8 ± 0.87 psi) (Figure 3.6). Transmembrane pressure slowly rose until about day 45 of the study where it stabilized at about 0.5 bar (7.25 psi). Flux was relatively constant, with occasional increases due to fouling of the membrane. The membrane was cleaned with a brush approximately every ten days to maintain a sufficient flux. This cleaning schedule is reasonable compared to a full-scale membrane application that requires regular chemical cleaning using citric acid, sodium hypochlorite or proprietary cleaning solutions to maintain stable operation (Visvanathan et al., 2000; Yoon et al., 2004).

Table 3.6 Laboratory analysis plan

Constituent	Sampling Locations	Physical Parameter	Sampling Locations
Chemical Oxygen Demand	A, B, C, D, E, F	Dissolved Oxygen	B, C, D, E
Total Nitrogen	A, B, C, D, E, F	pH	A, B, C, D, E, F
Ammonia-nitrogen	A, B, C, D, E, F	Suspended Solids	A, B, C, D, E, F
Nitrate-nitrogen	A, B, C, D, E, F	Oxidation Reduction Potential	A, C, D, E
Nitrite-nitrogen	A, B, C, D, E, F	Temperature	A, B, C, D, E
Total Soluble Phosphorus	A, B, C, D, E, F	Membrane Flux	F
Total Phosphorus (solids)	B, C, D, E	Transmembrane Pressure	F

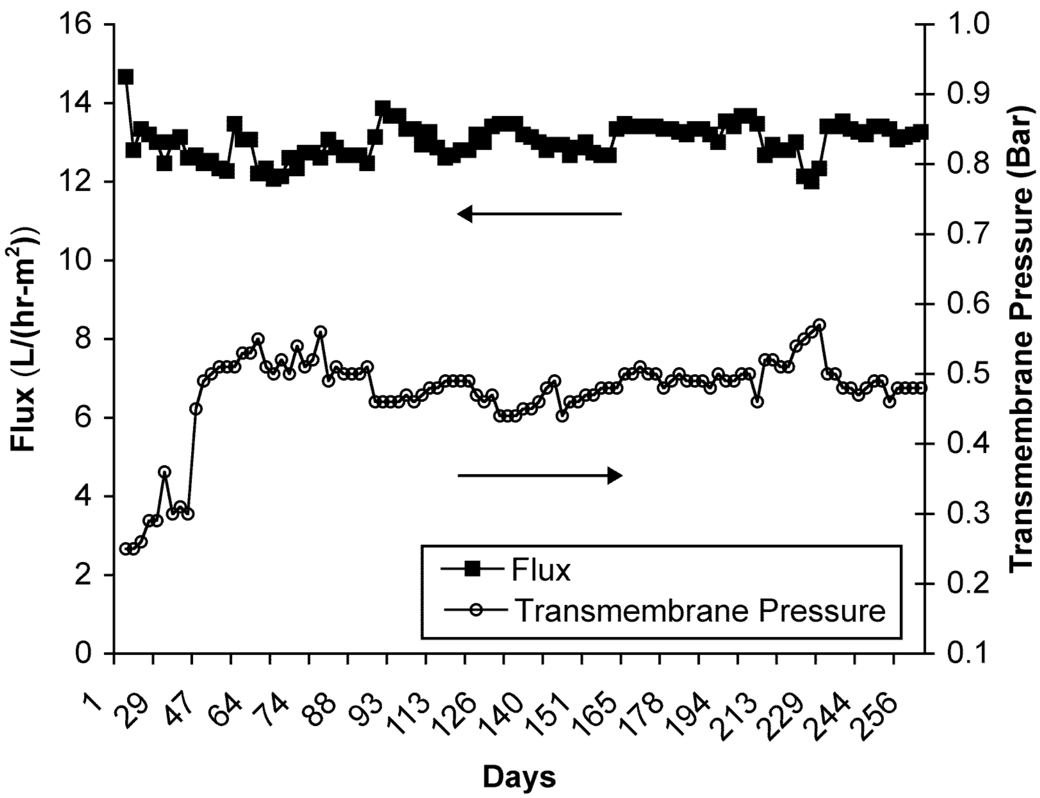

Figure 3.6 Membrane performance

3.3.2 Observation of suspended solids, dissolved oxygen, pH, and oxidation reduction potential

The average steady-state results for SS, DO, pH, and ORP for each run are presented in Figure 3.7. Over the entire study, the total suspended solids concentrations averaged 5,026 ± 104 mg/L in the anaerobic reactor, 4,147 ± 184 mg/L in the anoxic reactor, and 7,093 ± 212 mg/L in the aerobic reactor. Dissolved oxygen was maintained below 0.2 mg/L in the anaerobic and anoxic reactors and above 2 mg/L in the aerobic reactor. pH was very stable throughout the study, and no pH adjustments were necessary. ORP was stable with averages of -250 ± 10 mV anaerobic, -160 ± 8 mV anoxic, and 158 ± 3 mV aerobic. ORP measurements confirmed distinct differences between anaerobic, anoxic, and aerobic reactors.

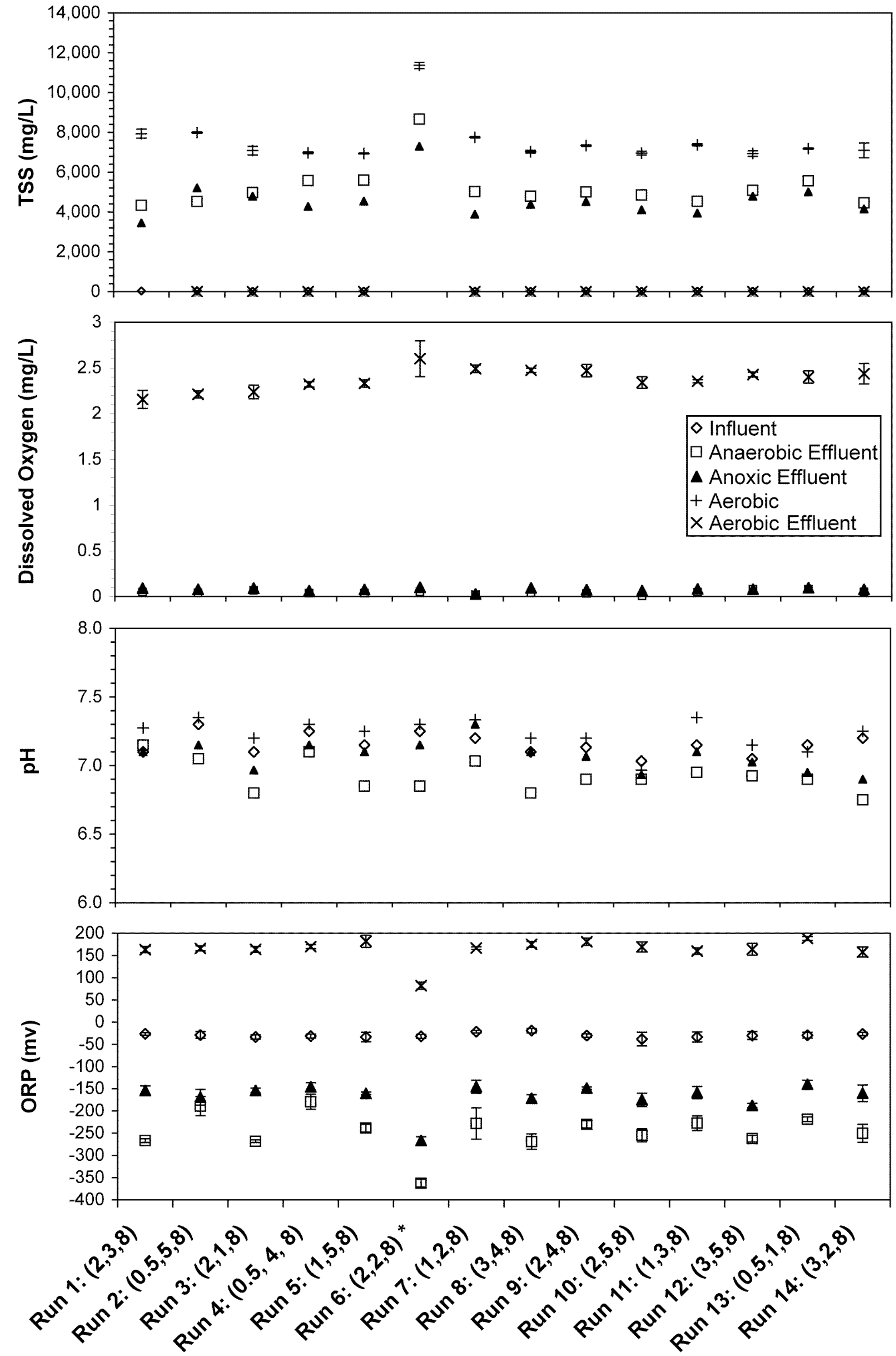

Figure 3.7 Steady-state results for SS, DO, pH, and ORP (95% confidence level); *Ersu, 2006

3.3.3 Biological nutrient removal performance for varied anaerobic and anoxic hydraulic retention times

A summary of the average steady-state removal rates for each run is presented in Table 3.7. Figure 3.8 illustrates the average steady-state concentrations for sCOD, TN, and TP for each run. Effluent soluble COD was steady for all runs, with an average steady-state value of 27.4 ± 2.8 mg/L. Several factors supported the steady, high COD removal rates. The influent COD was consistent, averaging 494 ± 4 mg/L with no large deviations. The high MLSS concentrations in the MBR system allowed for low mass and hydraulic loadings of approximately 0.15 kg COD/kg MLSS/d and 0.75 to 1.2 kg COD/m^3/d respectively. The loading rates from the MBR are lower than most conventional systems, which operate with typical mass loading rates of 0.3 to 0.6 kg COD/kg MLSS/d and hydraulic loading rates of 0.8 to 2 kg COD/m^3/d (Metcalf and Eddy, 2003). The low loading rates from the MBR allow it to operate more efficiently and to handle higher COD loadings than a conventional system.

Table 3.7 Summary of steady-state reactor performance

Run	Hydraulic Retention Time			Removal (%)[#]			
	Anaerobic	Anoxic	Aerobic	TN	TP	sCOD	Ammonia
Baseline	0	0	8	27.7 ± 2.5	16.6 ± 1.8	90.5 ± 0.9	98.8 ± 0.05
1	2	3	8	81.1 ± 0.9	72 ± 2.7	95.6 ± 2.9	99.3 ± 0.3
2	0.5	5	8	83.6 ± 0.7	40.3 ± 1.5	96 ± 0.5	99.2 ± 0.1
3	2	1	8	77.8 ± 1.2	81.7 ± 0.8	96.2 ± 0.5	99.5 ± 0.1
4	0.5	4	8	86.4 ± 1.2	56.7 ± 1.1	98.8 ± 0.4	98.7 ± 0.6
5	1	5	8	88.7 ± 0.3	63.4 ± 0.8	97.2 ± 0.1	98.2 ± 0.5
6*	2	2	8	78.2 ± 2.8	81.4 ± 0.9	94.5 ± 0.8	98.5 ± 0.5
7	1	2	8	82.5 ± 0.7	68.9 ± 1.2	97.8 ± 0.5	98.3 ± 0.5
8	3	4	8	81.8 ± 0.4	62.1 ± 2.6	98.6 ± 0.1	99.1 ± 0.2
9	2	4	8	87.7 ± 0.6	71.3 ± 1.2	98.8 ± 0.1	98.8 ± 0.1
10	2	5	8	85.5 ± 1.4	68.4 ± 2.6	97.7 ± 0.3	98.5 ± 0.1
11	1	3	8	84.9 ± 2.1	70.3 ± 1.1	98.6 ± 0.4	98.8 ± 0.5
12	3	5	8	78.1 ± 1	58 ± 3.8	97.3± 1.8	99.2 ± 0.3
13	0.5	1	8	76 ± 1.2	63.4 ± 2.9	95.6 ± 0.5	98.3 ± 0.2
14	3	2	8	83.6 ± 2	70.9 ± 1.7	94.8 ± 1.6	99.1 ± 0.4

[#]Statistical α = 0.05, 95% confidence interval; *Ersu, 2006

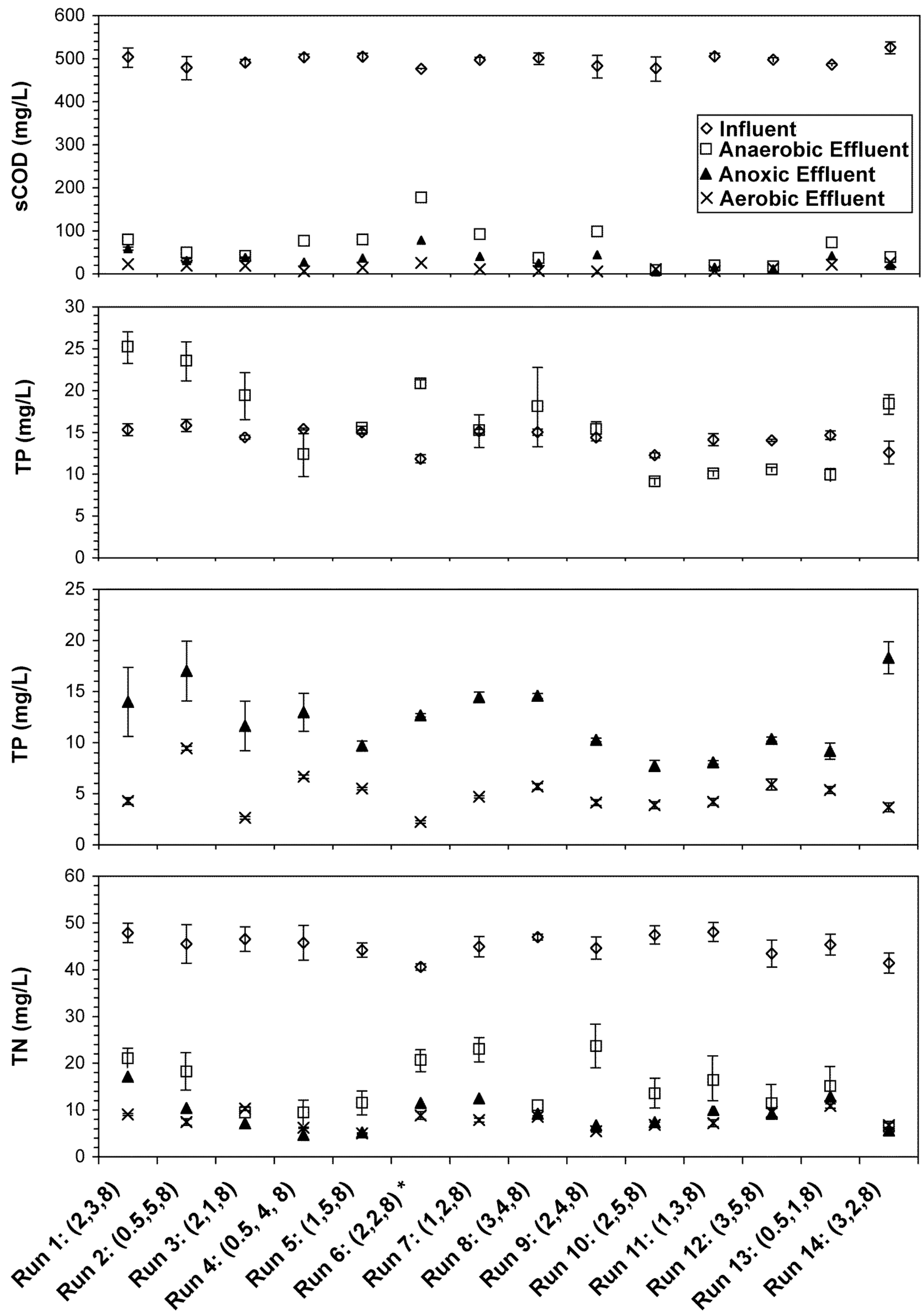

Figure 3.8 Summary of steady-state results for sCOD, TN, and TP (95% confidence level); *Ersu, 2006

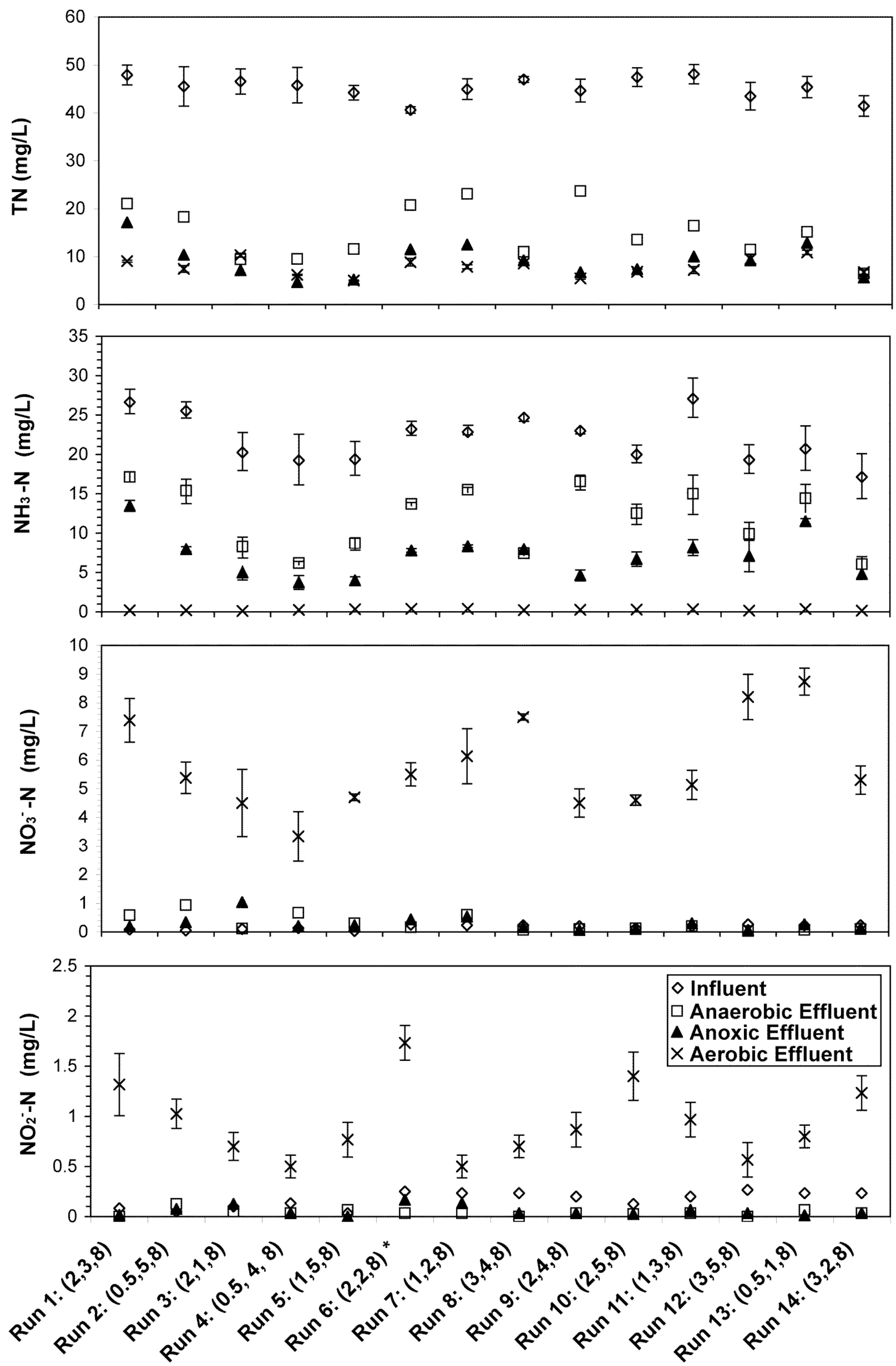

Figure 3.9 Summary of steady-state results for nitrogen compounds (95% confidence level); *Ersu, 2006

The effluent total nitrogen showed considerable variation between different runs (Figure 3.9). Average steady-state effluent total nitrogen ranged from 5.0 to 10.9 mg/L, with removal rates increasing with increasing anoxic HRT from 1 to 4 hours and decreasing from 4 to 5 hours (Figure 3.10). Effluent ammonia was stable throughout the study with an average concentration of 0.15 ± 0.04 mg/L. The eight-hour aerobic HRT was sufficient for essentially complete nitrification.

Total phosphorus removal rates also showed considerable variations throughout the study (Figure 3.11). Total phosphorus removal increased with an increase in anaerobic HRT from 0.5 to 2 hours, but showed a decrease for anaerobic HRT above 2 hours indicating a possible secondary phosphorus release.
All of the runs demonstrated enhanced biological phosphorus removal (EBPR), with the phosphorus content of the aerobic sludge increasing with an increase in phosphorus removal (Figure 3.12). Enhanced phosphorus removal is indicated by the phosphorus content of the sludge being greater than approximately 2.5-3% dry weight (Bitton, 2005; Metcalf and Eddy, 2003). EBPR is also indicated by the observing the cyclic release and uptake of phosphorus throughout the treatment process. Figure 3.13 illustrates the anaerobic release of phosphorus, the subsequent phosphorus uptake (with some dilution) in the anoxic reactor, and the large aerobic phosphorus uptake during run 3 (HRT: 2,1,8 hours).

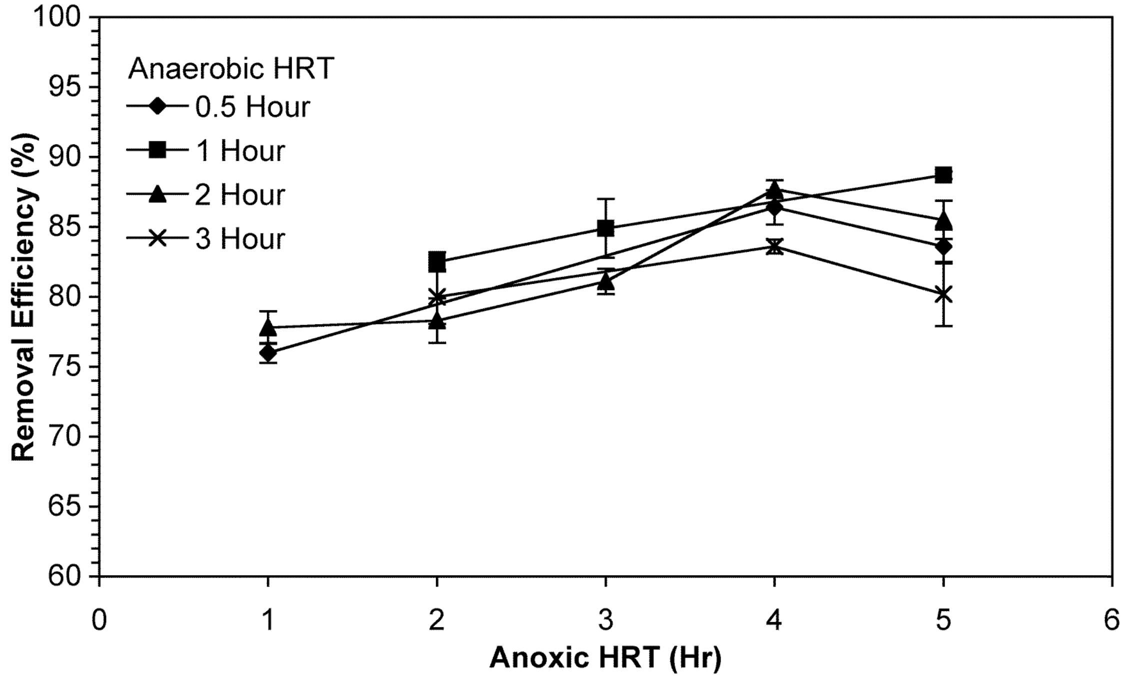

Figure 3.10 Total nitrogen removal for varied anoxic HRT

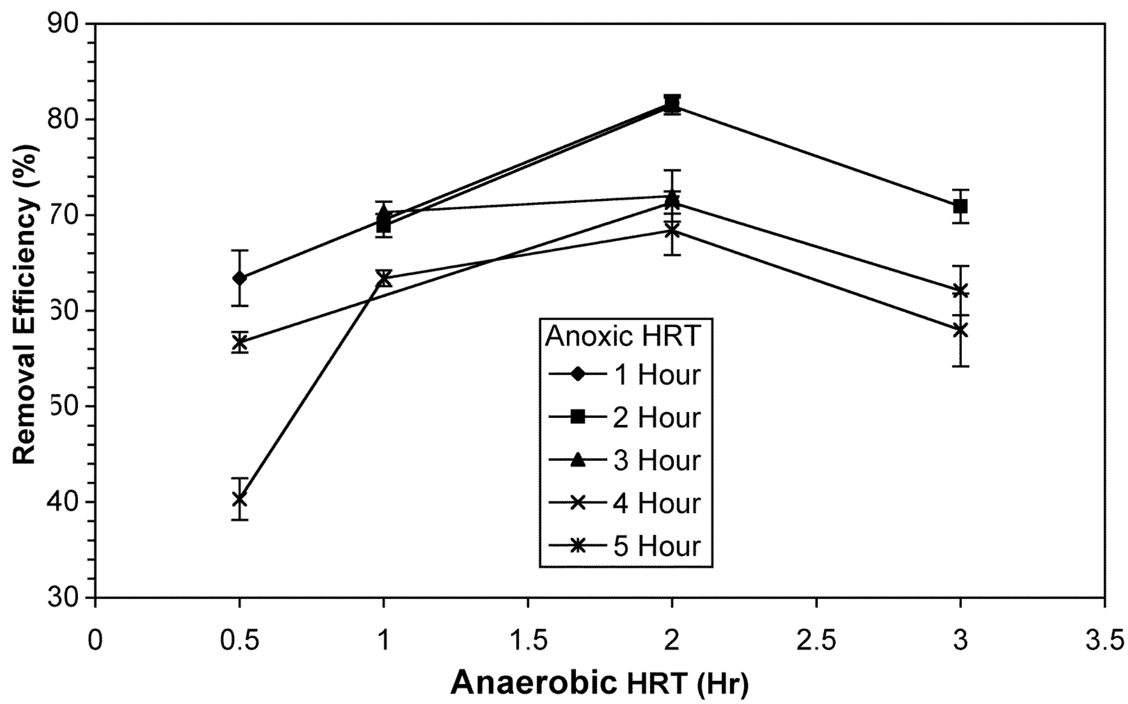

Figure 3.11 Total phosphorus removal for varied anaerobic HRT

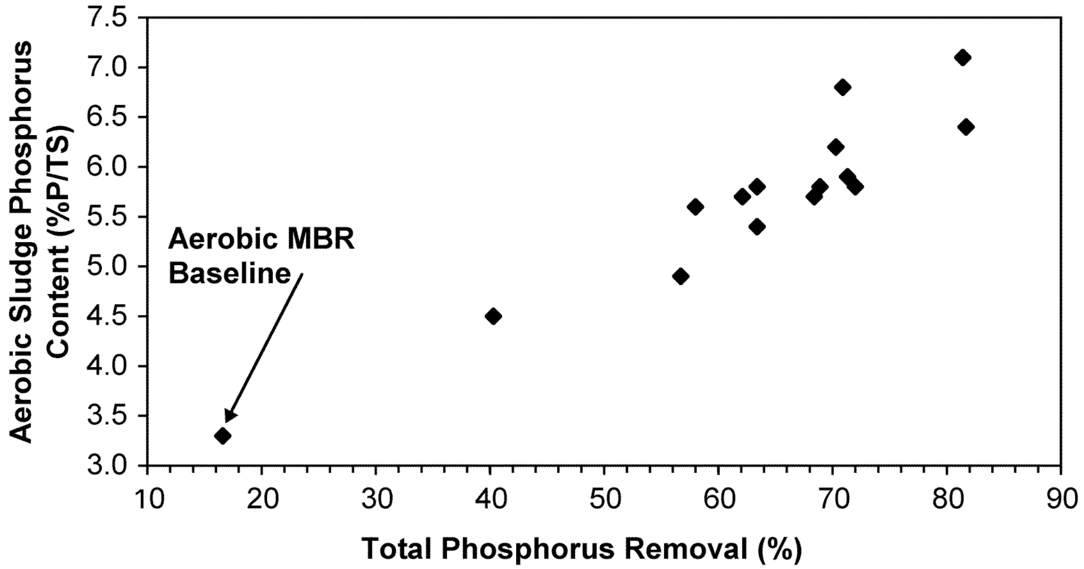

Figure 3.12 Aerobic sludge phosphorus content

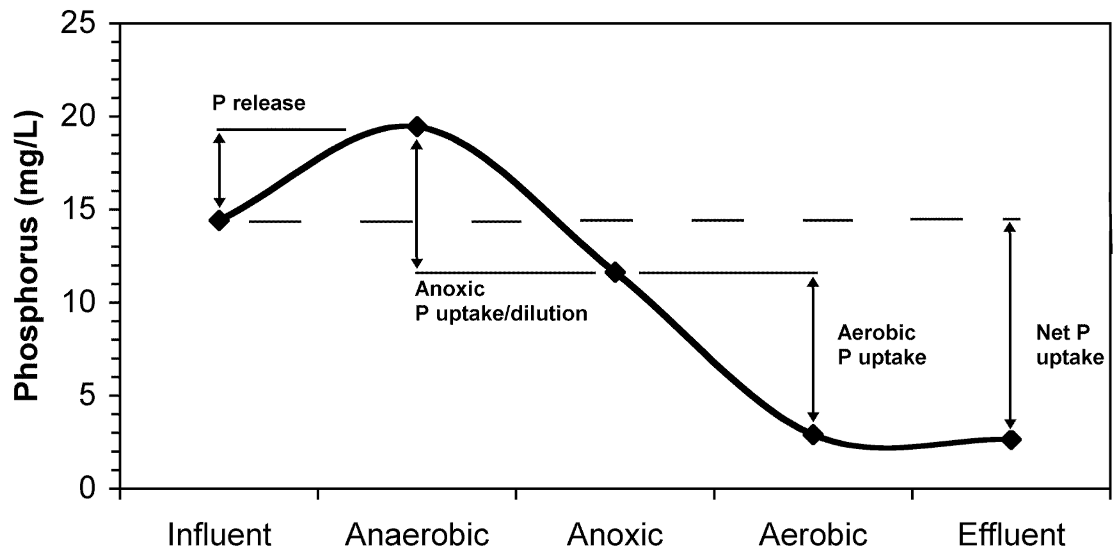

Figure 3.13 Phosphorus profile for run 3 (HRT: 2,1,8 hours)

3.3.4 Influence of anaerobic and anoxic HRT on biological phosphorus removal

A statistical analysis was conducted using JMP™ to determine the significance of varied anaerobic and anoxic HRTs for total phosphorus removal. A standard least squares model was employed that used phosphorus removal as the model variable and the anaerobic and anoxic HRT as the model effects. A least squares fit prediction equation was determined from the model to predict phosphorus removal given anaerobic and anoxic HRTs (eq 3.1). A graphical representation of the prediction expression was also generated using Microsoft Excel® to better illustrate the results (Figures 3.14).

$$TP_{rem} = 66.2 - 9.96 \bullet HRT^{3}_{ana.} + 38.8 \bullet HRT^{2}_{ana.} - 27.7 \bullet HRT_{ana.} - 0.076 \bullet HRT^{3}_{anox.} - 3.39 \bullet HRT^{2}_{anox} + 10.99 \bullet HRT_{anox.} \quad 3.1$$

The phosphorus removal model demonstrated a moderately good fit with an R^2 value of 0.8 (Figure 3.15). Prediction of phosphorus removal at 5 hours anoxic HRT was noticeably less accurate than for the other HRT conditions. The R^2 value rises to 0.92 when the 5 hour anoxic HRTs are excluded. The modeling and prediction equation includes the 5 hour anoxic HRTs. An analysis of variance test confirmed that the model was statistically significant at a 95% level of confidence, and indicated that at least one of the model effects was statistically significant (Table 3.8). In order to determine if only one or both of the model effects (anaerobic and anoxic HRT) were statistically significant, an effects test was conducted (Table 3.9).

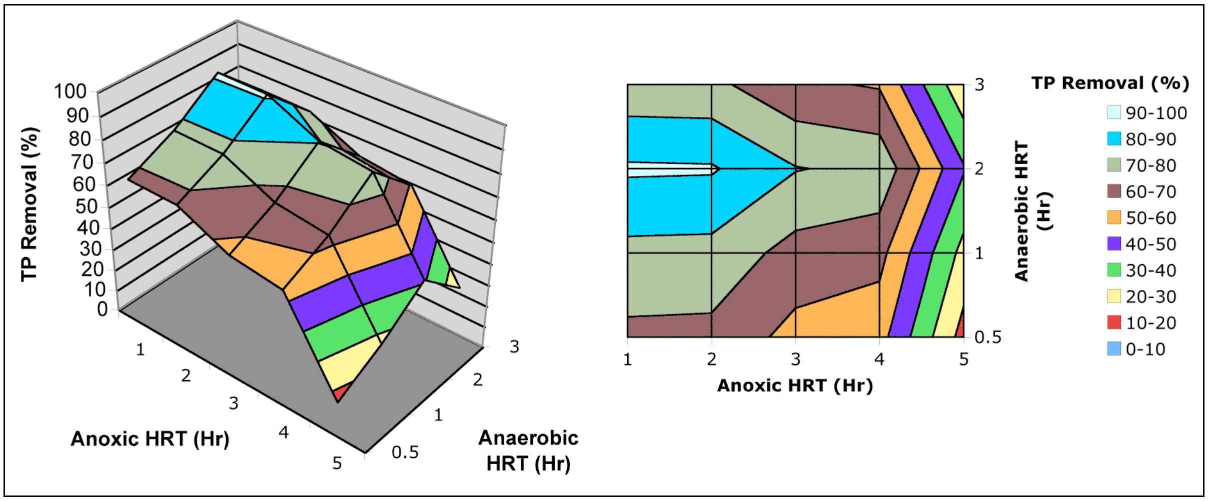

Figure 3.14 Total phosphorus removal prediction

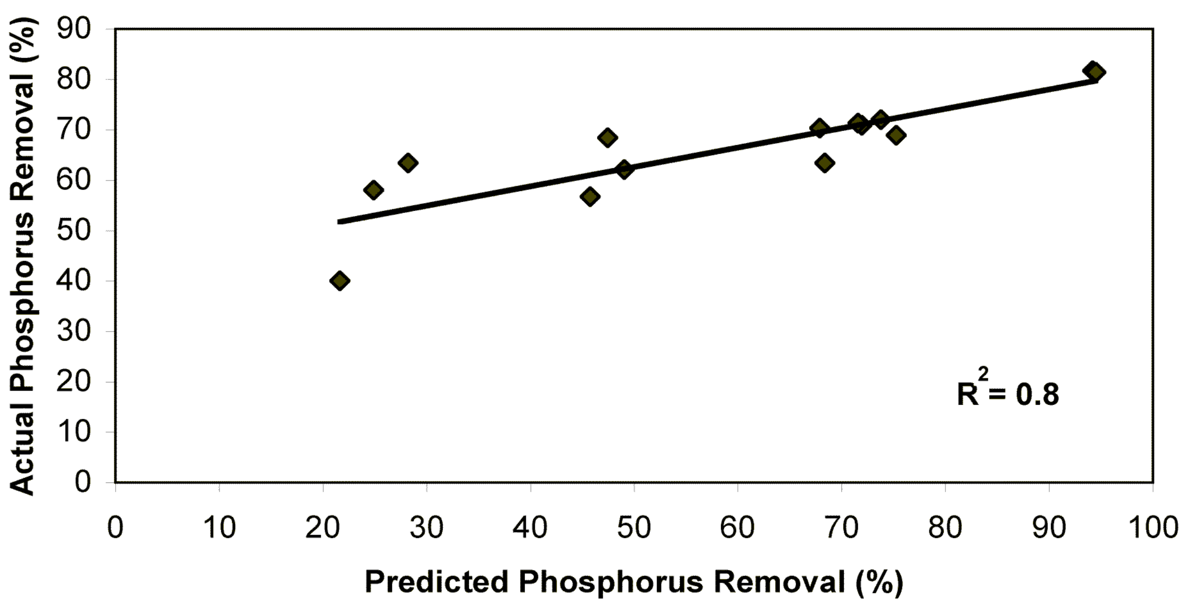

Figure 3.15 Phosphorus removal prediction equation summary of fit

The low p-values for both anaerobic and anoxic HRT indicated that both were statistically significant for phosphorus removal (Devore, 2004).

To determine which of the individual anaerobic HRTs were statistically significantly different from one another, the Tukey test was conducted using JMP™ (Table 3.10). The results of the test revealed that there were three separate groups of statistically different anaerobic HRTs:

i. 0.5 hours anaerobic HRT
ii. 1 and 2 hours anaerobic HRT
iii. 1 and 3 hours anaerobic HRT

The interpretation of these groups is that 0.5 hours was significantly different from all other anaerobic HRTs. 1 and 2 hours anaerobic HRT were similar, but different from 0.5 and 3 hours. Likewise, 1 and 3 hours were similar in percent removal, but significantly different from 0.5 and 2 hours anaerobic HRT.

A Tukey test was also conducted to determine which individual anoxic HRTs were statistically different from one another (Table 3.11). Three significantly different groups of anoxic HRTs were identified:

i. 1, 2, and 3 hours anoxic HRT
ii. 2, 3, and 4 hours anoxic HRT
iii. 3, 4, and 5 hours anoxic HRT

HRT values in each group are statistically similar to one another, but are significantly different from the values in the other groups.

Table 3.8 Analysis of variance for phosphorus removal response

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F Ratio
Model	7	1339.9	191.4	11.2
Errors	6	102.6	17.1	
Total	13	1442.5	209.2	
Probability > F : 0.0045; *F* Distribution: $F_{\alpha,I-1,I(J-1)}$, $F_{0.05,7,6} \approx 4.21$				

Table 3.9 Phosphorus removal effects tests

Source	Number of Parameters	Degrees of Freedom	Sum of Squares	F Ratio	Probability > F
Anaerobic HRT	3	3	715.1	13.94	0.0041*
Anoxic HRT	4	4	445.5	6.51	0.0226*

*Indicates source is statistically significant

Table 3.10 Tukey test for significance of anaerobic HRT for phosphorus removal

Levels: Anaerobic HRT	Significance*			Mean	Least Square Mean
2	A			74.9	74.96
1	A	B		67.5	69.61
3		B		63.7	65.93
0.5			C	53.5	54.27

*Levels connected by the same letter are not significantly different (95% confidence)

Table 3.11 Tukey test for significance of anoxic HRT on phosphorus removal

Levels: Anoxic HRT	Significance*			Mean	Least Square Mean
1	A			72.6	74.1
2	A	B		73.7	69.8
3	A	B	C	71.2	65.1
4		B	C	63.4	64.5
5			C	57.3	57.5

*Levels connected by the same letter are not significantly different (95% confidence)

The prediction equation for total phosphorus removal indicates increased removal with increasing anaerobic HRT from 0.5 to 2 hours and decreases from 2 to 3 hours. Increasing the anaerobic HRT increases the concentration of fermentation by-products available to PAOs that leads to increased anaerobic phosphorus release and ultimately increases enhanced phosphorus removal rates (Bitton, 2005). Decreased phosphorus removal at 3 hours anaerobic HRT may indicate excessive phosphorus release that decreased overall removal rates. Figure 3.16 illustrates the trend observed in the lab studies of decreased anaerobic biomass phosphorus content with increases in anaerobic HRT. Phosphorus removal decreased moderately with increasing anoxic HRT from 1 to about 3-4 hours and then decreased sharply from 3-4 to 5 hours. Increasing anoxic HRT increases the potential for anoxic phosphorus uptake by PAOs, which is less efficient than aerobic phosphorus uptake (Hu et al., 2002). Evidence of anoxic phosphorus uptake was supported by increased anoxic sludge phosphorus content with increases in anoxic HRT (Figure 3.17). These data would explain decreased phosphorus removal rates with increased anoxic HRTs.

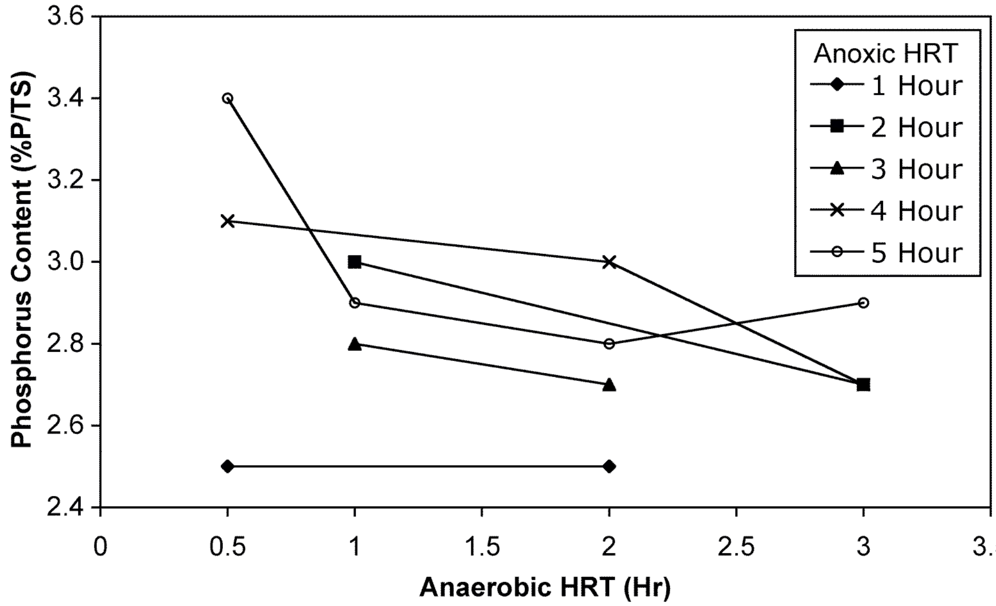

Figure 3.16 Phosphorus content of anaerobic sludge

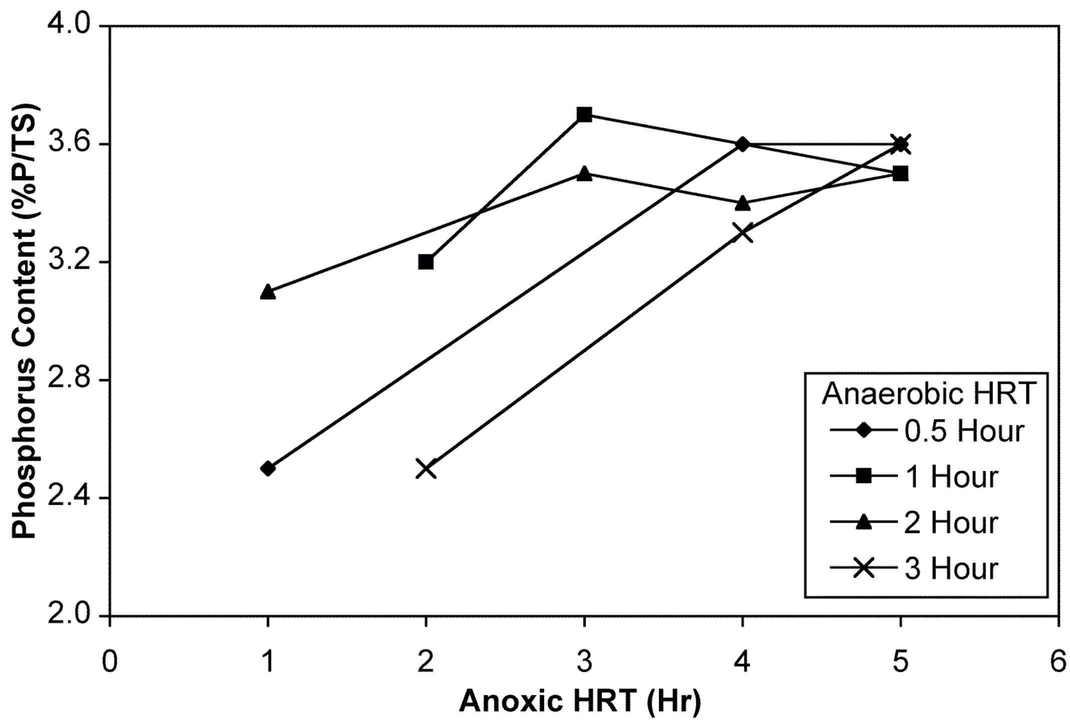

Figure 3.17 Phosphorus content of anoxic sludge

3.3.5 Influence of anaerobic and anoxic HRT on biological nitrogen removal

A statistical analysis was also conducted using JMP™ to determine the significance of varied anaerobic and anoxic HRTs for total nitrogen removal. A standard least squares model was employed that used nitrogen removal as the model variable and the anaerobic and anoxic HRT as the model effects to determine a prediction model for nitrogen removal. A least squares fit prediction equation was determined from the model to predict nitrogen removal given anaerobic and anoxic HRTs (eq. 3.2). A graphical representation of the prediction expression was also generated using Microsoft Excel® to better illustrate the results (Figure 3.18).

$$TN_{rem} = 69.3 + 3.3 \bullet HRT^{3}_{ana.} - 19.7 \bullet HRT^{2}_{ana.} + 32.4 \bullet HRT_{ana.} - 0.54 \bullet HRT^{3}_{anox.} + 5.4 \bullet HRT^{2}_{anox.} - 8.3 \bullet HRT_{anox.} \qquad 3.2$$

The nitrogen removal prediction equation indicated a R^2 value of 0.68 (Figure 3.19). The prediction equation indicates a strong increase in nitrogen removal with increasing anoxic HRTs from 1 to 4 hours and steady removal rates from 4 to 5 hours. Increasing anoxic HRT from 1 to 4 hours increased the time possible for denitrification, leading to increased nitrogen removal rates. Nitrogen removal appeared to be less sensitive to the anaerobic HRT, being relatively steady from 0.5 to 2 hours with a moderate decrease from 2 to 3 hours.

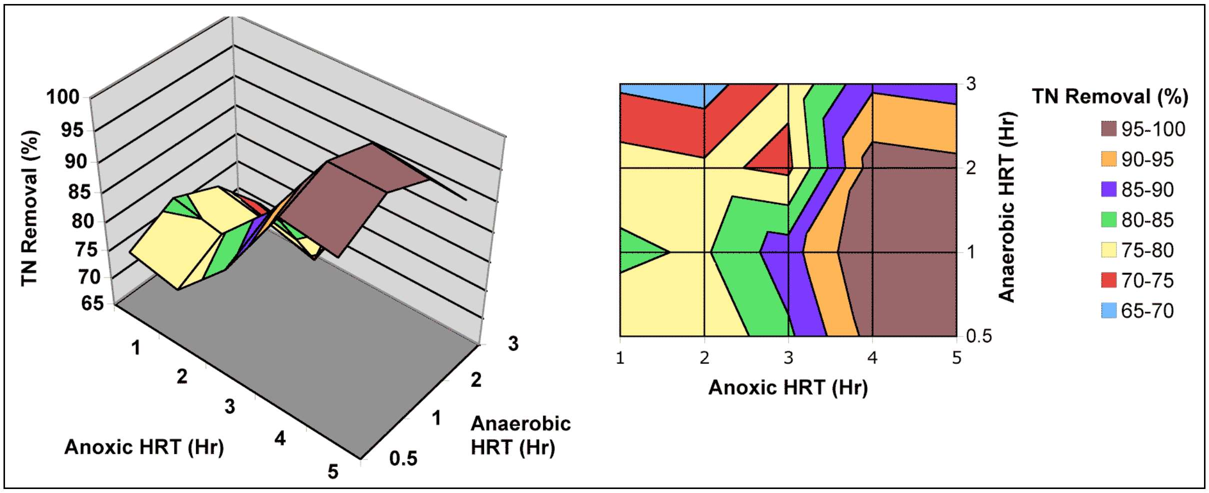

Figure 3.18 Total nitrogen removal prediction

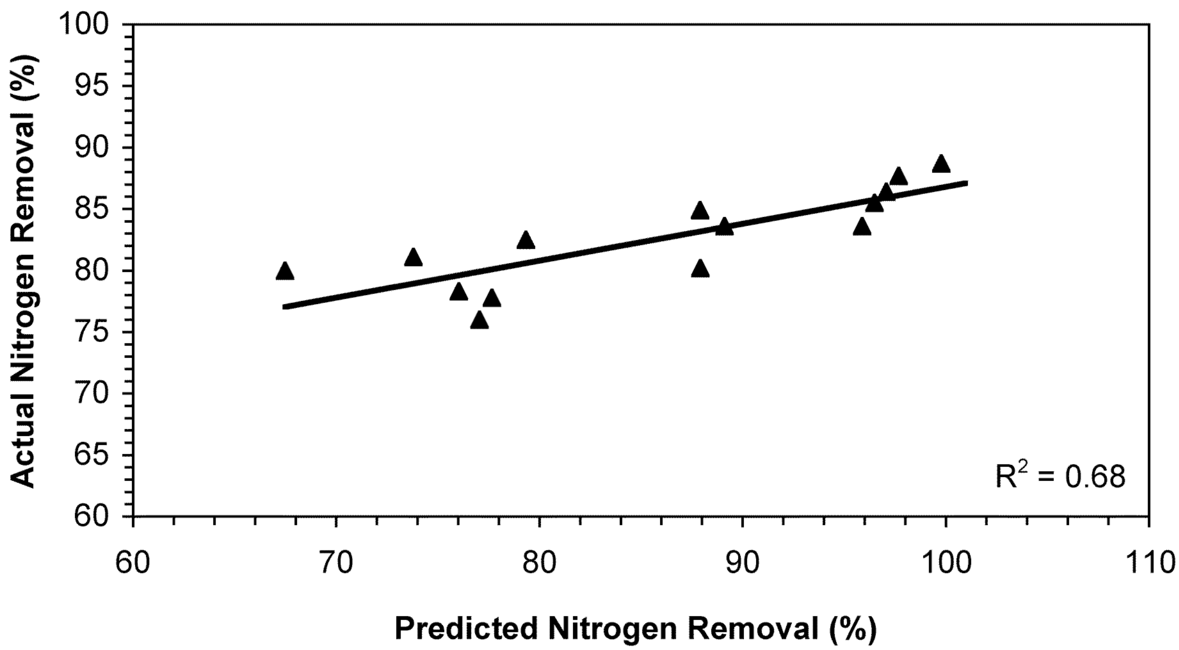

Figure 3.19 Nitrogen removal prediction equation summary of fit

An analysis of variance test indicated that the model effects (anaerobic and anoxic HRTs) were statistically significant at a 95% confidence level (Table 3.12). In order to determine if only one or both of the model effects were statistically significant to changes in nitrogen removal, an effects test was completed (Table 3.13). The results of the effects test indicated that anaerobic HRT was significant at a 95% confidence level and anoxic HRT was significant at a 98% confidence level.

To determine if any of the individual anaerobic HRTs were statistically different from one another, the Tukey test was conducted using JMP™. The results of the Tukey test show that there are two groups of significantly different anaerobic HRTs at a 95% confidence level (Table 3.14). A plot of total nitrogen removal for varied anaerobic HRT illustrates the lack of strong significant differences (Figure 3.20). There is a mild trend of decreasing nitrogen removal with increased anaerobic HRT, possibly due to decreased COD availability in the anoxic reactor for denitrification. A Tukey test was also conducted to determine which, if any, of the individual anoxic HRTs were statistically different from one another. The result of the test revealed that there were statistically significant differences at a 95% confidence level (Table 3.15).

Table 3.12 Analysis of variance for nitrogen removal response

Source of Variation	**Degrees of Freedom**	**Sum of Squares**	**Mean Square**	**F Ratio**
Model	7	174.5	24.92	8.37
Errors	6	17.9	2.97	
Total	13	192.4		

Probability > F : 0.0097; *F* Distribution: $F_{\alpha,I-1,I(J-1)}$, $F_{0.05,7,6} \approx 3$

Table 3.13 Nitrogen removal effects tests

Source	**Number of Parameters**	**Degrees of Freedom**	**Sum of Squares**	**F Ratio**	**Probability > F**
Anaerobic HRT	3	3	49.6	5.55	0.036
Anoxic HRT	4	4	142.1	11.93	0.0051

Table 3.14 Tukey test for significance of anaerobic HRT for nitrogen removal

Levels: Anaerobic HRT	**Significance***	**Mean**	**Least Square Mean**
1	A	82.36	85.44
2	B	85.08	82.08
0.5	B	82.00	81.08
3	B	82.07	79.25

*Levels connected by the same letter are not significantly different (95% confidence)

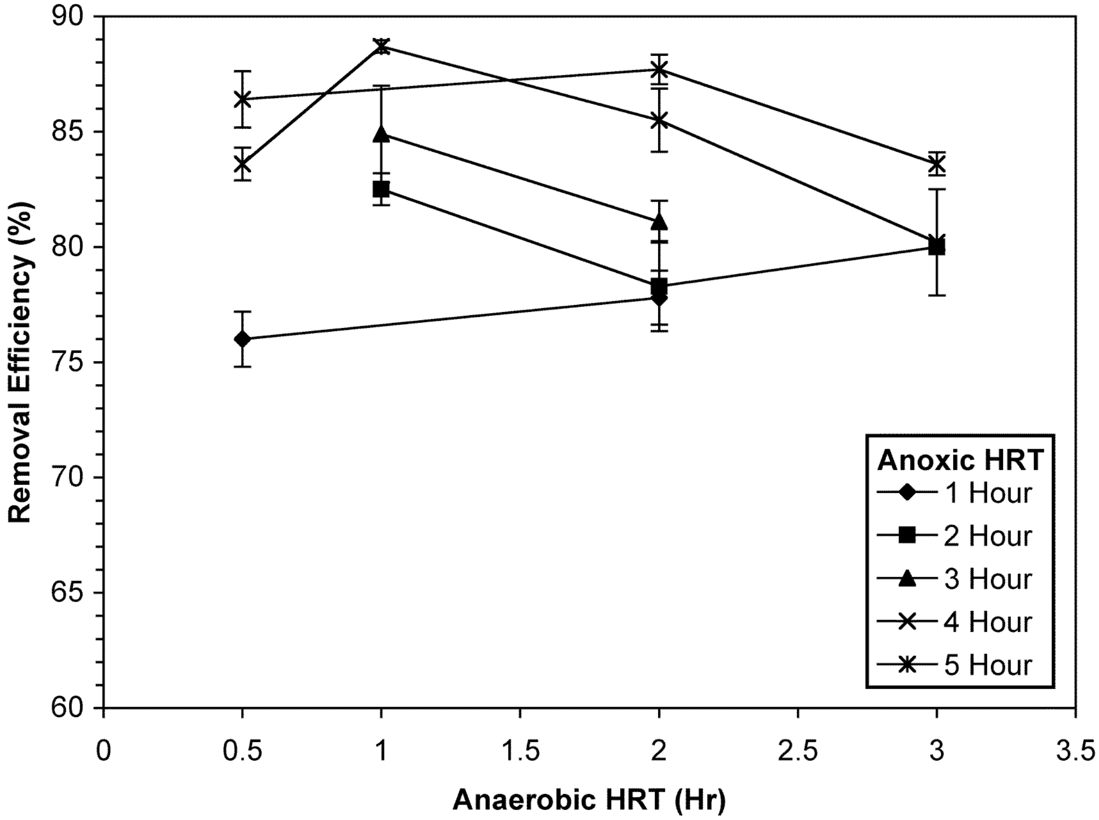

Figure 3.20 Total nitrogen removal for varied anaerobic HRT

Table 3.15 Tukey test for significance of anoxic HRT on nitrogen removal

Levels: Anoxic HRT	**Significance***			**Mean**	**Least Square Mean**
4	A			85.7	86.86
5	A	B		84.5	84.50
3		B	C	83.0	81.20
2			C	80.3	79.97
1			C	76.9	77.28

*Levels connected by the same letter are not significantly different (95% confidence)

3.3.6 Determination of optimum anaerobic and anoxic HRT for biological nitrogen and phosphorus removal

The prediction equations described in the two previous sections were brought together to form an expected combined nitrogen and phosphorus removal prediction (Figure 3.21). Using the product of total phosphorus and total nitrogen percent removal for the Y-axis, the graph shows two distinct peaks, at approximately 2 hours anaerobic, 2 hours anoxic and 2 hours anaerobic, 4 hours anoxic, representing the high points of combined phosphorus and nitrogen removal, respectively.

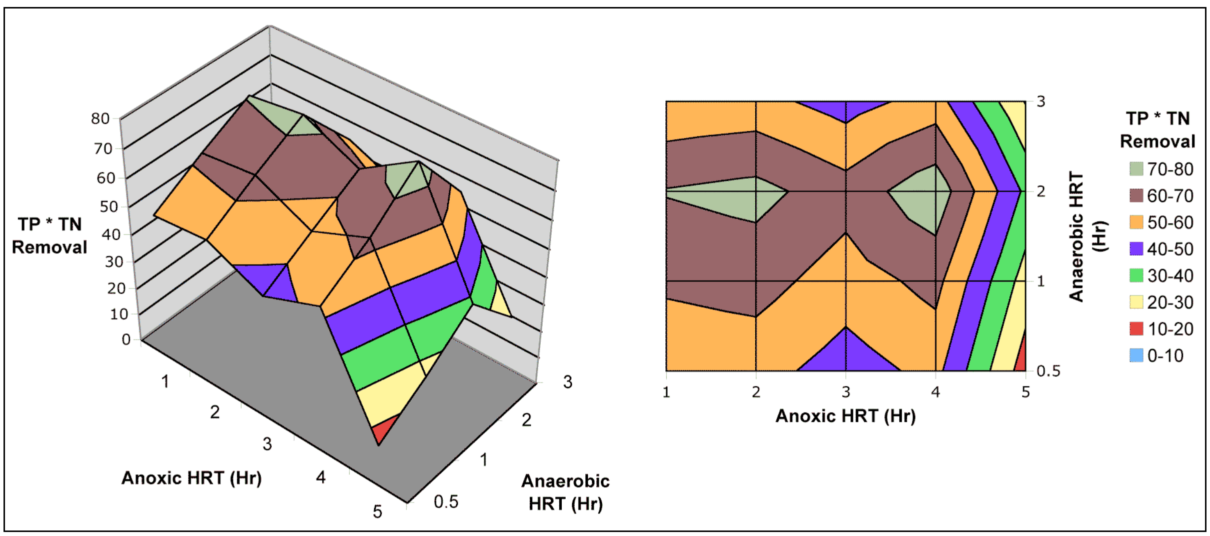

Figure 3.21 Prediction for combined total nitrogen and phosphorus removal

If there is a desire to focus on either nitrogen or phosphorus removal, the prediction expressions described in sections 3.5.5-6 may be utilized to optimize the anaerobic and anoxic HRTs. If there is a desire to simultaneously maximize nitrogen and phosphorus removal, care must be taken to balance the sometimes conflicting requirements of biological nitrogen and phosphorus removal, illustrated by the double peak in Figure 3.24. In general, phosphorus removal greatly benefited from increased anaerobic HRTs, and was harmed by increased anoxic HRTs. Contradictorily, nitrogen removal improved with increased anoxic HRTs, and showed slight decreases with increased anaerobic HRT.

Increasing anaerobic HRT from 0.5 to 2 hours greatly improved phosphorus removal and had little effect upon nitrogen removal. Therefore, it is recommended that anaerobic HRT be increased when possible to 2 hours. The exact anaerobic HRT could shift slightly depending on the wastewater characteristics, although the trends observed in this study would remain. The issue of the influence of wastewater characteristics will be the focus of future research and will be briefly discussed section 5.2.

Selecting the optimal anoxic HRT is more difficult than the anaerobic HRT, because both nitrogen and phosphorus removal are sensitive to the anoxic HRT. Nitrogen removal rapidly increases with increased anoxic HRT from 1 to about 4 hours, while phosphorus removal is steady from 1 to 2 hours, and decreases from 2 to 5 hours.

The recommended anoxic HRT is approximately 4 hours to optimize both nitrogen and phosphorus removal.

The prediction profiler feature of JMP™ indicated the best conditions for maximum nitrogen and phosphorus removal of 86.4 ± 5.5% and 73 ± 7.3%, respectively, would be expected at 2 hours anaerobic and 4 hours anoxic HRT. Note that the study was conducted with 100% recycle of mixed liquor and 100% recycle of permeate. With higher recycle of the activated sludge and permeate, higher nitrogen and phosphorus removal were observed by others (Ersu, 2006).

3.4 Conclusions

Experiments investigating the influence of anaerobic and anoxic HRT on biological nitrogen and phosphorus removal were conducted in a lab-scale membrane bioreactor. The experimental design consisted of 14 runs that varied the anaerobic HRT from 0.5-3 hours, anoxic HRT from 1-5 hours and fixed the aerobic HRT at 8 hours. Recycle of the mixed liqour and permeate were kept constant at 100% of influent. Excellent average COD and ammonia removals of 94.7 ± 1.6% and 99.1 ± 0.4% respectively, were observed throughout the study. Average steady-state total nitrogen removal varied between 76 ± 0.3% and 88.7 ± 2.1%, while total phosphorus removal varied between 40.3 ± 0.3 and 81.7 ± 3.8%.

The results revealed a conflict between the anaerobic and anoxic HRT requirements for nitrogen and phosphorus removal. In general, increasing anaerobic HRT improved phosphorus removal and slightly decreased nitrogen removal, while increased anoxic HRT decreased phosphorus removal and increased nitrogen removal. The trends in phosphorus removal were supported by observation of the biomass phosphorus concentrations. Increased anaerobic HRT decreased the phosphorus content of the sludge, indicating phosphorus release as part of enhanced biological phosphorus removal. Increased anoxic HRT increased the phosphorus content of the biomass, indicating anoxic uptake of phosphorus, decreasing overall phosphorus removal from the system. Nitrogen removal decreased at high anaerobic and anoxic HRTs, possibly due to decreased availability of COD for denitrification.

There is currently limited research investigating the influence of varied HRTs for BNR, and current software models such as Biowin® (version 2.2) have been shown to be inaccurate for modeling biological phosphorus removal in MBRs without calibration of kinetic parameters (Ersu, 2006). The conflicting nature of anaerobic and anoxic HRTs for nitrogen and phosphorus removal led to a desire to determine the conditions that would best balance the competing requirements for optimized nitrogen and phosphorus removal. A least squares prediction model for both nitrogen and phosphorus removal was developed using the JMP™ software. The model indicated that optimal nitrogen and phosphorus removal would be expected at 2 hours anaerobic HRT and 4 hours anoxic HRT.

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4. INFLUENCE OF SOLIDS RETENTION TIME ON NUTRIENT REMOVAL AND BACTERIAL FLOC SIZE IN A AEROBIC MEMBRANE BIOREACTOR

Abstract

This study evaluated the influence of various SRTs on the biomass phosphorus content and bacterial floc size in an aerobic MBR treating a synthetic medium strength municipal wastewater. Of particular interest was determining the change in phosphorus content of the biomass for varying SRTs. A 12 L lab-scale MBR was constructed for the study and operated in 4 randomly ordered SRT runs of 10, 25, 50 and 75 days.

Excellent average COD and ammonia removals of 93.9 ± 1.2% and 98.8 ± 0.1%, respectively, were measured during the study. Average steady-state total nitrogen removal varied between 20.9 ± 1.9% and 31 ± 1.7%, while total phosphorus removal varied between 4.4 ± 1.5% and 19.9 ± 0.6%. COD and total nitrogen did not show a clear trend in changing removal rates for changes in SRT. However, there was a clear trend of increased phosphorus content in the sludge with increased SRT from 10 to 50 days and a decrease from 50 to 75 days. Phosphorus removal increased from 10 to 25 days SRT and was steady from 25 to 75 days SRT. A statistical analysis indicated that the average bacterial floc diameters (32.4 ± 3.4 to 49.3 ± 5 microns) are consistent with the results of similar studies on floc sizes in MBRs, but did not follow the expected trend of decreased floc size with increased SRT.

4.1 Introduction and objectives

4.1.1 Introduction

Membrane bioreactors continue to gain acceptance as a means for advanced wastewater treatment. MBRs have the ability to operate with very high SRTs, low HRTs and high biomass concentrations, while maintaining high treatment performance. Despite the increased operational flexibility that MBRs offer, many systems are designed based to an extent on traditional activated sludge processes. There is a need to determine the operational parameters for MBR systems that will permit the most efficient operation. While conventional systems are typically limited to SRTs of 25 days or less, MBRs have been successfully operated at 75 and even 190 days SRT (Ahn et al., 2003; Innocenti et al., 2002). Operation at high SRTs increases treatment performance and reduces sludge production, which in turn reduces sludge disposal costs. In multistage BNR systems, the SRT has been shown to influence phosphorus removal (Mulkerrins et al., 2004). Traditionally it was thought that high sludge ages did not allow for biological phosphorus removal due to bacterial cell lysis and subsequent phosphorus release, although that has since been shown not to be true in BNR MBR systems (Adam et al., 2002). There is a question if operation at high SRTs in an aerobic MBR will have an influence on phosphorus removal, particularly if there is a point at which phosphorus release occurs at a high SRT. It is reasonable to assume that an optimum SRT exists for phosphorus removal, balancing the benefits of higher biomass concentrations against potential increased cell lysis and potential phosphorus release at high SRTs.

The characteristics of the biomass in a MBR can be significantly different from a conventional system, especially at higher SRTs. Masse` et al. (2006) reported that extracellular products in the effluent decreased in MBR systems as the SRT increased, and were lower than conventional systems above 37 days SRT. Several studies have reported decreased bacterial floc size with increased SRT in MBRs (Masse et al., 2006; Sperandio et al., 2005). Smaller MBR flocs have been shown to improve oxygen transfer and increase nitrification activity compared to conventional systems (from 0.95 to 2.28 g NH_4^+/kg MLSS-h) (Zhang et al., 1997). Zhang et al (1997) reported MBR median floc diameters ranged from 20-40 μm, while conventional activated sludge ranged from 80-300 μm.

With additional research applied to the design of MBR systems, there is opportunity for increased removal efficiencies, decreased costs, and potential application to a wider range of treatment problems.

4.1.2 Project objectives

The goals of this study were to determine the influence of long SRTs on phosphorus and nitrogen removal and bacterial floc size in an aerobic MBR. The objectives are:

1. To study the influence of long SRTs on the phosphorus content sludge, phosphorus removal and nitrogen removal in an aerobic MBR.
2. To investigate the changes in SRT and changes in bacterial floc sizes in an aerobic MBR for long SRTs.

4.2 Methods and materials

4.2.1 Membrane bioreactor experimental setup

All lab experiments were conducted two identical bench-scale, single-stage aerobic membrane bioreactors (Figure 4.1). The identical reactors were 12 L in volume, and rectangular to accommodate the membrane filter. The membranes were plate frame, double-sided filters with a cellulose membrane manufactured by Kubota Co., Japan (Table 4.1)

Sampling points will be referred to as follows:

- A – Feed
- B – Aerobic Mixed Liquor
- C – Membrane Permeate

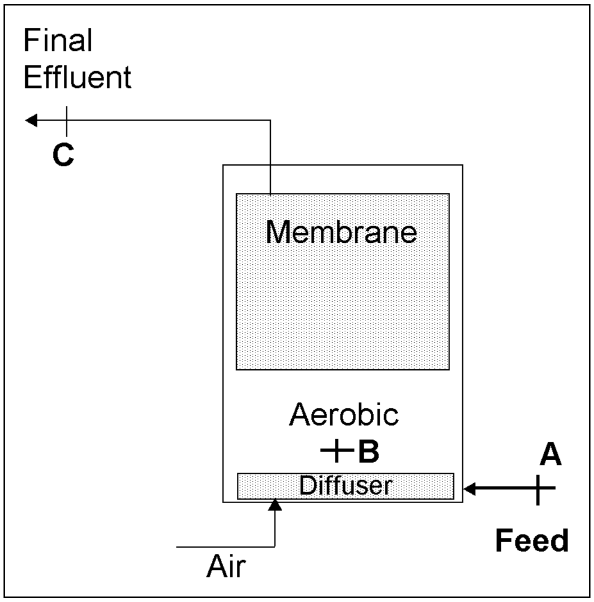

Figure 4.1 Single stage membrane bioreactor

Table 4.1 Membrane filter specifications

Parameter	Specification
Module Configuration	Plate-frame
Membrane Material	Cellulose
Pore Size	0.2 μm
Membrane Porosity	60% volume
Dimensions (Width x Thickness x Height)	23 cm x 1 cm x 31 cm
Total Filtration Area	0.15 m^2
pH Range	5.5 - 10
Maximum Temperature	80 ^{O}C
Maximum Pressure	25 kPa

Air was supplied from a filtered air compressor to a diffuser located in the bottom of the aerobic reactor, and was adjusted to provide a dissolved oxygen concentration of at least two mg/L. The air diffuser was centered beneath the membrane to provide air scouring of the membrane to reduce fouling. The influent was stored in a 20 L plastic container that was refrigerated at approximately 4 to 5º C. The influent was fed into the reactors with a Cole-Palmer (Model 7553-30) peristaltic pump. The permeate pump was a Cole-Palmer (Model 7532-20) that maintained an average flux of 6.4 ± 0.1 L/(hr-m^2) throughout the study. The membrane was operated in cycles of nine minutes pumping and one minute of idle to reduce membrane fouling and avoid the need for backwashing. The pump timing was controlled by a ChronTrol® computer timer. The SRT was controlled by manually wasting sludge from the aerobic reactor each day. A water level sensor was used to prevent overflow of the system by shutting off the influent pump. A synthetic influent designed to simulate medium strength municipal wastewater was used throughout the study (Table 4.2).

Table 4.2 Synthetic wastewater composition and constituents

Ingredient	Concentration mg/L*
Calcium Sulfate	40
Ferric Chloride	3
Isomil (Simulac™)	20 mL (1% by volume)
Magnesium Sulfate	4
Nutrient Broth	250
Potassium Chloride	5
Sodium Bicarbonate	63
Sodium Biphosphate Monobasic	60
Sodium Citrate	500
Composition	
Chemical Oxygen Demand (COD)	489 ± 10.4
Total Nitrogen (TN)	52.1 ± 3.1
Ammonia Nitrogen (NH_3–N)	21.5 ± 1.6
Nitrate Nitrogen (NO_3^--N)	1.4 ± 0.5
Nitrite Nitrogen (NO_2^--N)	0.5 ± 0.3
Total Soluble Phosphorus (TP)	14.2 ± 0.3
Suspended Solids	27.4 ± 8.2
pH	7.1 ± 0.03

* Statistical α = 0.05, 95% CI

The reactors were operated for approximately two to three weeks to ensure steady-state operation. The four runs were randomly ordered as follows:

1. Run One: 25 Day SRT
2. Run Two: 50 Day SRT
3. Run Three: 10 Day SRT
4. Run Four: 75 Day SRT

Runs 1, 2, and 4 were operated in the same reactor, while run 3 was operated in the second reactor. Two reactors were used to finish the experiments quickly.

4.2.2 Laboratory analysis

Water quality and reactor performance parameters were frequently monitored to evaluate the performance of the MBR. All analyses were conducted in accordance to Standard Methods (APHA, AWWA and WEF, 1998). Analysis included measurements throughout the treatment process. Chemical constituents and reactor parameters were measured a minimum of twice per week and preferably three to four times per week during steady state conditions in order to collect sufficient data (Table 4.3).

Table 4.3 Laboratory analysis plan

Constituent	**Sampling Locations**	**Physical Parameter**	**Sampling Locations**
Chemical Oxygen Demand	A, B, C	Dissolved Oxygen	B
Total Nitrogen	A, B, C	pH	A, B, C
Ammonia-nitrogen	A, B, C	Suspended Solids	A, B, C
Nitrate-nitrogen	A, B, C	Microscopic Observation	B
Nitrite-nitrogen	A, B, C	Temperature	A, B, C
Total Soluble Phosphorus	A, B, C	Membrane Flux	C
Total Phosphorus (solids)	B	Transmembrane Pressure	C

Microscopic observation of the biomass was done approximately every two to three weeks to determine the bacterial floc size and observe changes in the biomass characteristics. The microscopic observations were made using a color digital video camera (JVC Model TK-870U) mounted to a light microscope (Olympus Model CH-2) capable of magnifications from 40 to 1000x. The digital still images were viewed on a Sony color lab monitor (Model PVM-1342Q) and captured onto a desktop computer using Adobe Premiere™ software at a resolution of 720 x 480 pixels.

4.3 Results and discussion

4.3.1 Membrane performance

The membrane modules performed well for all runs, with an average flux of 6.43 ± 0.1 L/(hr-m^2) and average transmembrane pressure of 0.32 ± 0.03 bar (4.64 ± 0.44 psi) (Figure 4.2). The membranes used in the study had previously been used in an earlier MBR study and did not require a break-in period to obtain stable flux. Transmembrane pressure and flux were both relatively constant, with occasional fluctuations due to slight fouling of the membrane. The membrane was cleaned with a brush approximately every seven to ten days to maintain sufficient flux. This cleaning schedule is reasonable compared to a full-scale membrane application that requires regular chemical cleaning using citric acid, sodium hypochlorite or proprietary cleaning solutions to maintain stable operation (Visvanathan et al., 2000; Yoon et al., 2004).

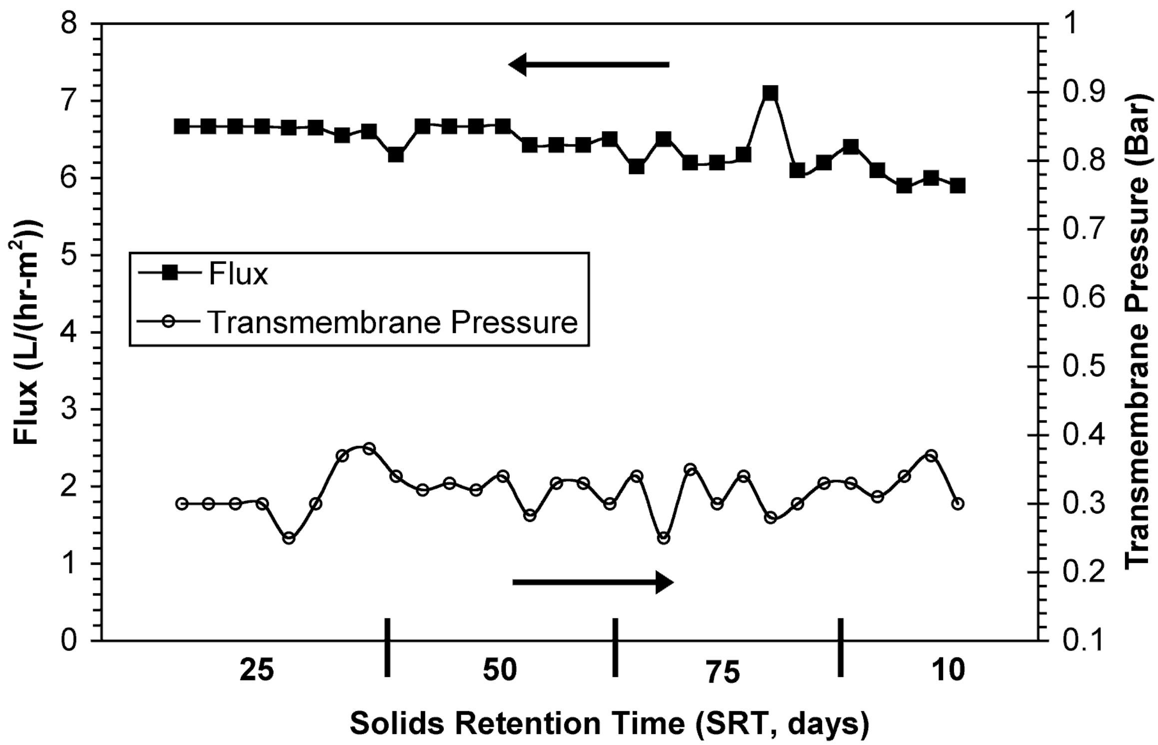

Figure 4.2 Membrane performance

4.3.2 Biological nutrient removal performance

A summary of the steady-state results for each run is presented in Table 4.4.

Table 4.4 Summary of steady-state reactor performance

Run	SRT (days)	Suspended Solids (mg/L)*	Removal (%)*			
			TN	TP	sCOD	Ammonia
1	25	8,465 ± 284	27.7 ± 1.7	19.5 ± 0.6	97.4 ± 1.4	98.5 ± 0.03
2	50	7,848 ± 141	24.5 ± 2.5	16.9 ± 1.8	90.7 ± 0.9	98.9 ± 0.05
3	10	3,455 ± 134	20.9 ± 1.9	4.4 ± 1.6	91.1 ± 2.9	99.2 ± 0.01
4	75	9,095 ± 200	31 ± 1.7	19.9 ± 0.6	93.8 ± 2.3	99.1 ± 0.1

* Statistical α= 0.05, 95% confidence level

Figure 4.3 illustrates the average steady-state concentrations for sCOD, TN, and TP for each run. Effluent sCOD removal was relatively high, ranging from 90.7 ± 0.9% to 97.4 ± 1.4% with an average of 93.9 ± 1.2%. Ammonia removal rates were high for all runs, with an average steady-state value of 98.8 ± 0.1%, respectively. There was no clear trend in nitrogen removal for varied SRTs (Figure 4.4). The high COD removal rates were supported by a consistent influent COD, averaging 489 ± 10.4 mg/L. The high MLSS concentrations of up to 9,000 mg/L allowed for COD mass loading rates from approximately 0.16 to 0.4 kg COD/kg MLSS/d, lower than the typical values (0.3 to 0.6 kg COD/kg MLSS/d) used in many conventional systems (Metcalf and Eddy, 2003). The low loading rates in the MBR allow it to operate more efficiently and to handle higher COD loadings than many conventional systems.

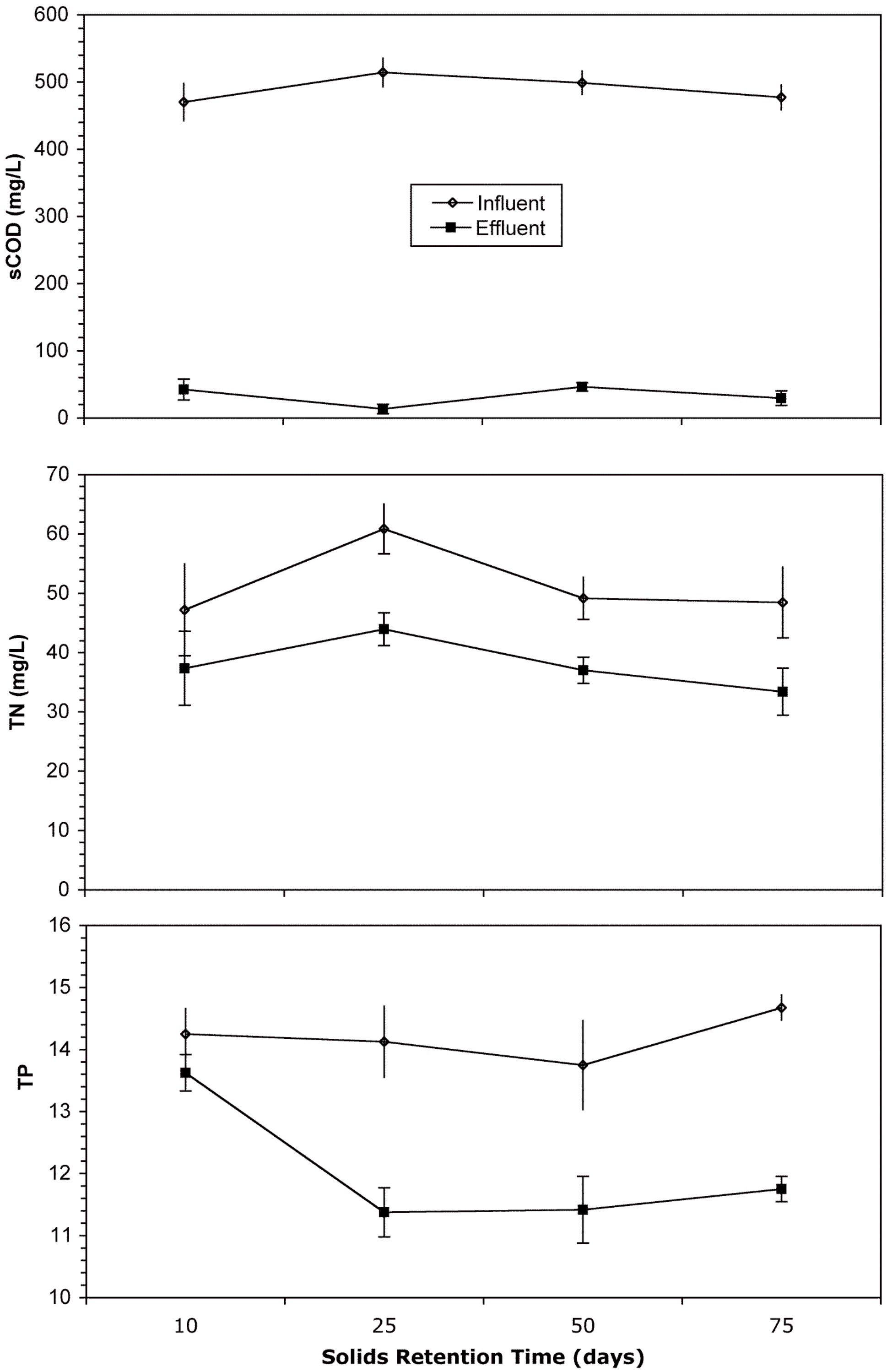

Figure 4.3 Summary of steady-state results for sCOD, TN, and TP (95% confidence level)

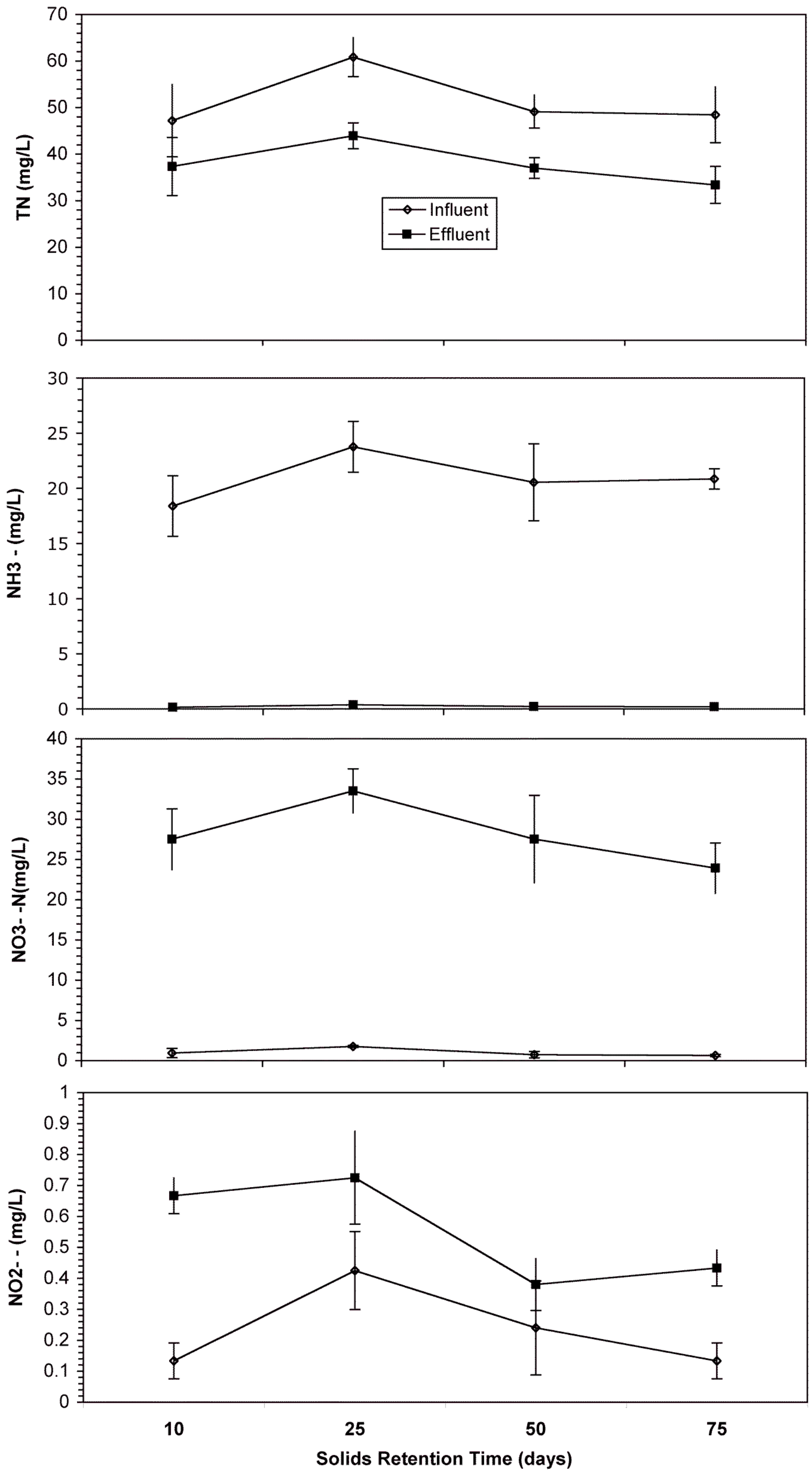

Figure 4.4 Summary of steady-state results for nitrogen compounds (95% confidence level)

Perhaps most interestingly, there were significant differences in the phosphorus content of the sludge with the different SRTs (Figure 4.5). Phosphorus content in the sludge increased from 10 to 25 days, was steady from 25 to 50, and decreased from 50 to 75 days SRT. The increased biomass concentrations at 75 days might be responsible for the lower phosphorus concentrations, but there is also the possibility that some phosphorus release might have occurred as well. Effluent phosphorus concentrations decreased from 10 to 25 days SRT, and were relatively steady from 25 to 75 days SRT. This finding indicates that any potential phosphorus release was either minor at the SRT ranges tested, or was obscured by increased biomass concentrations at higher SRTs. It is possible that differences in the bacterial flocs observed at 75 days SRT may be responsible for the differences in phosphorus characteristics observed. These results show that operation of aerobic MBRs at SRTs up to 75 days may not lead to a significant increase in effluent phosphorus. The decreased phosphorus content of the sludge at 75 days SRT may enable additional land application of sludge when limited by phosphorus application rates. The varied phosphorus content of the sludge and its affect on phosphorus removal rates is not adequately addressed by modeling software such as Biowin® (version 2.2). Incorporation of this information has potential to improve the design of aerobic MBRs and phosphorus removal systems. Additional research is needed to determine if a significant effluent phosphorus release occurs at SRTs above 75 days.

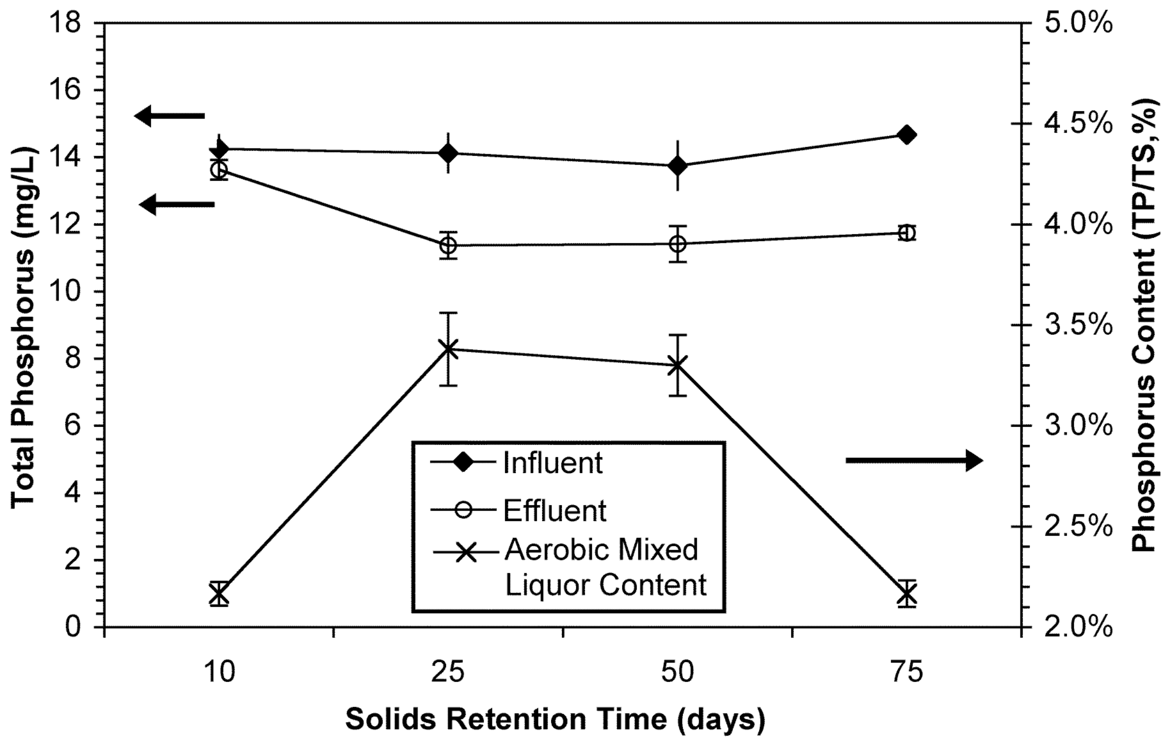

Figure 4.5 Steady-state phosphorus results (95% confidence level)

4.3.3 Bacterial floc size

Numerous images were taken of mixed liquor samples for each test run similar to those shown in Figures 4.6 to 4.9. The images were taken at magnifications from 40 to 400x and indicated the presence of protozoa, filamentous, suspended or floc forming bacteria. Samples taken at 75 days SRT, showed slightly more filamentous bacteria than the other runs. There were no noticeable differences in the number of protozoa between the different SRT runs. For each test run, images from several sludge samples were used to estimate the diameter of bacterial flocs present. An effort was made to carefully measure floc sizes, although there is the potential for measuring error. The methods used in this study for measuring floc sizes are admittedly susceptible to error are intended only for a rudimentary analysis of the general trends in floc sizes. Large sample sizes were used to minimize the influence of individual errors. The results of the floc measurements are presented in Figure 4.10.

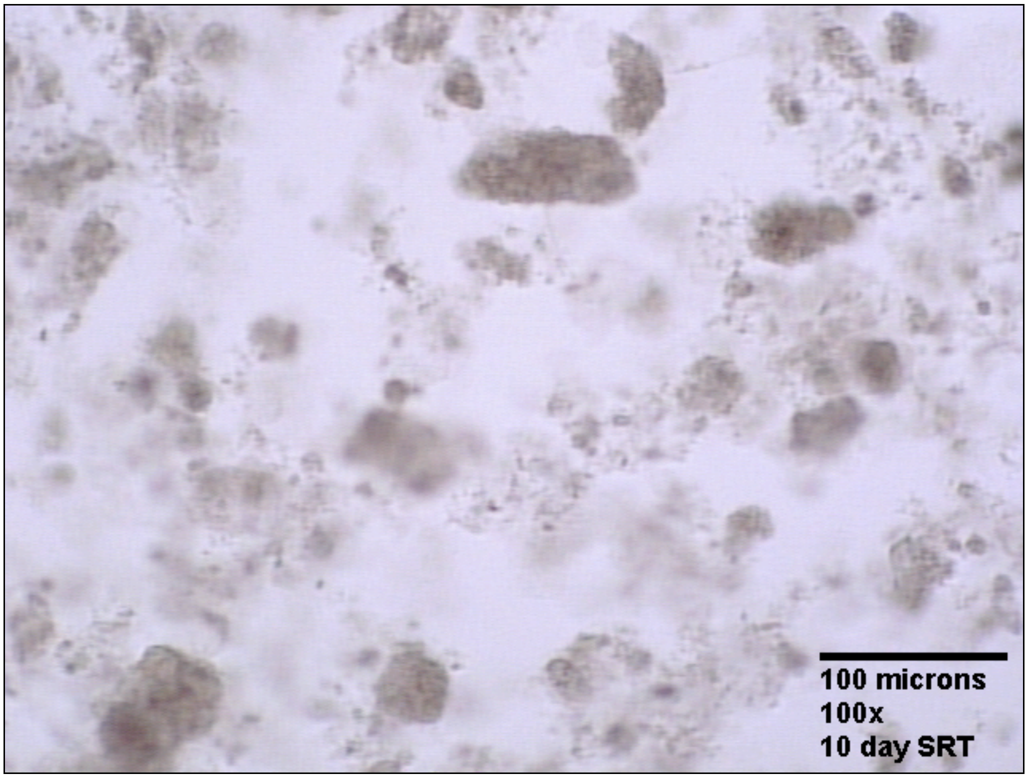

Figure 4.6 Example of microscope image of sludge sample, 10 day SRT

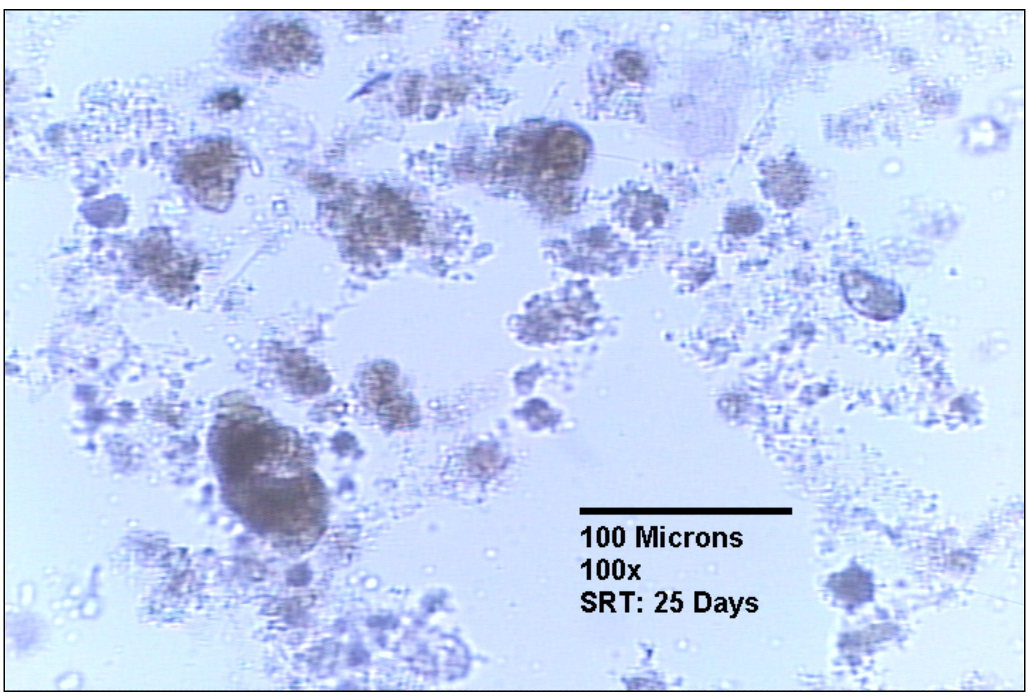

Figure 4.7 Example of microscope image of sludge sample, 25 day SRT

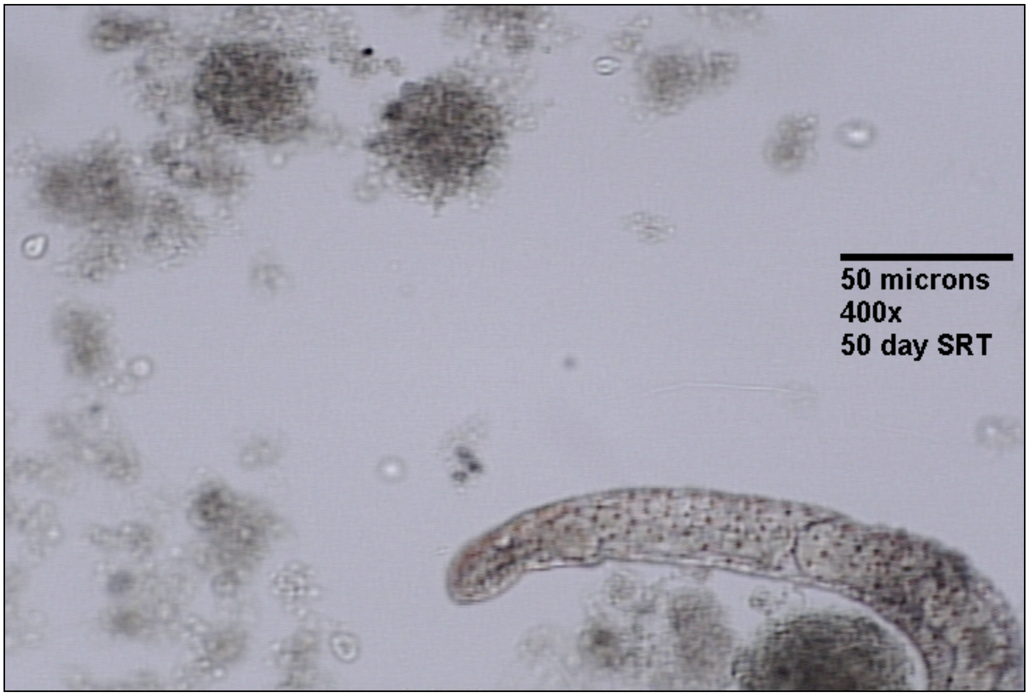

Figure 4.8 Example of microscope image of sludge sample, 50 day SRT

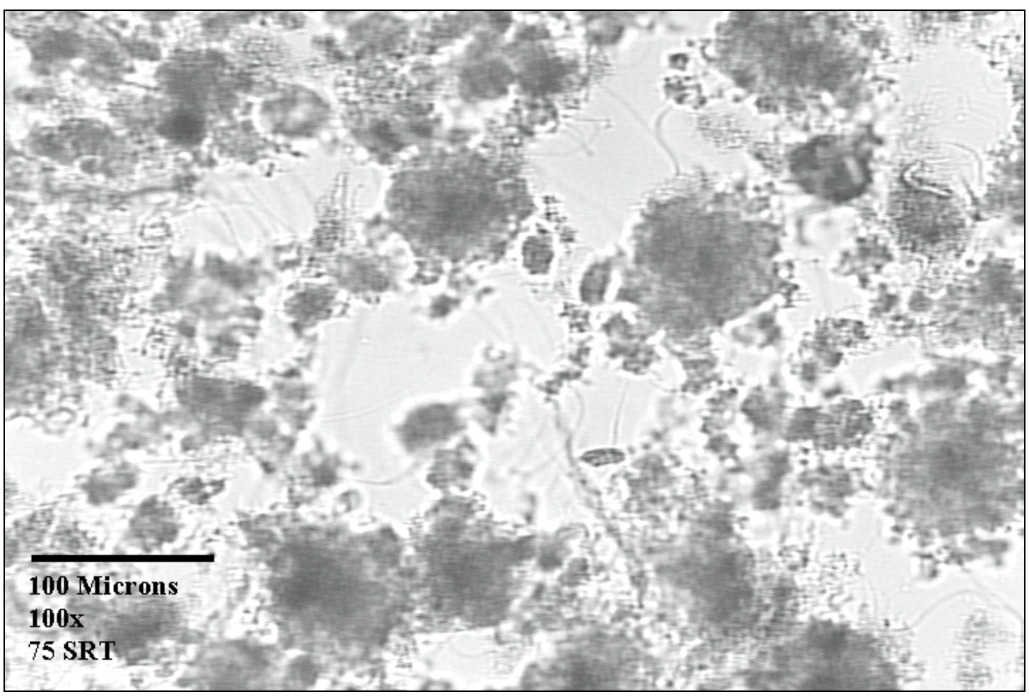

Figure 4.9 Example of microscope image of sludge sample, 75 day SRT

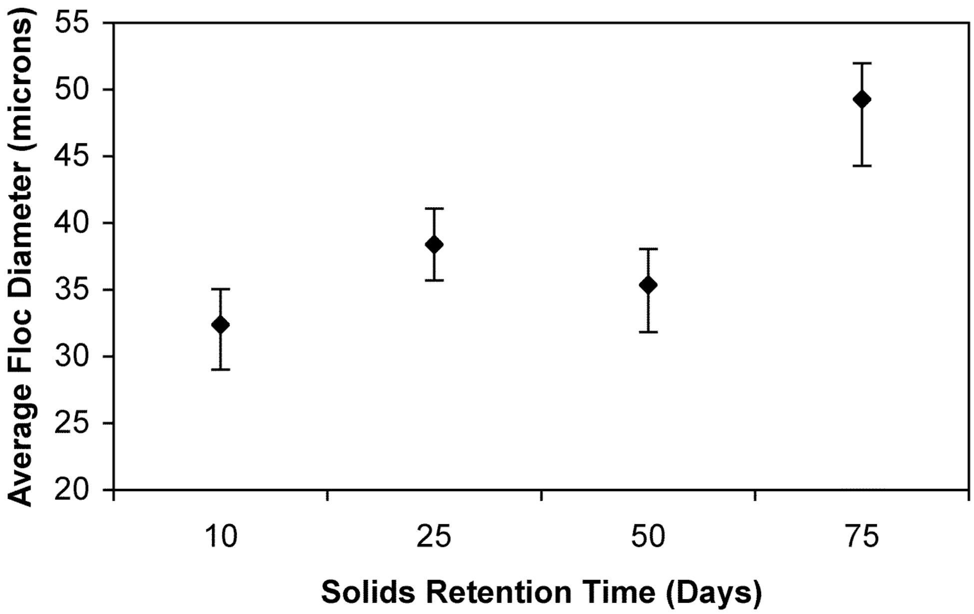

Figure 4.10 Bacterial floc size for varied SRT (95% confidence interval)

A statistical analysis was conducted to determine if the SRT had a statistically significant effect on bacterial floc diameter. The first step was to determine if there were significant differences in floc diameter for each SRT. An analysis of variance test was conducted that indicated that at least two of the floc diameters were significantly different (Devore, 2004). A Tukey test was used to determine which of the floc diameters were statistically different from one another (See Table 4.5) (Devore, 2004). The results of the Tukey test verified that the floc diameters for SRTs of 10, 25 and 50 days were statistically similar, and that the flocs at 75 days SRT were significantly different.

Table 4.5 Tukey results for floc size

Levels: SRT	Significance*		Mean floc diameter (microns)
10 days	A		32.4
25 days	A		35.4
50 days	A		38.4
75 days		B	49.3

*Levels connected by the same letter are not significantly different (95% confidence)

The average floc diameters ranged from 32-49 microns, similar to work by Zhang et al. (1997), who reported average MBR floc diameters of 10-40 microns. The results do not follow the expected trend of decreasing floc size with increases in SRT, however (Sperandio et al., 2005). Several variables contribute to the floc diameter, including wastewater characteristics, and hydrodynamic conditions in the reactor (Kim et al., 2001 as quoted in Sperandio et al., 2005). Masse et al. (2006) reported that MBR floc diameter decreased from 120-220 to 70-100 microns with an increase in SRT from 10 to 30 days and was stable at 80 ± 20 microns above 30 days. Another study reported a decrease in average floc size from 240 to 70 microns with an increase in SRT from 9 to 106 days (Sperandio et al., 2005). While the observed trend in floc sizes did not follow the expected trends, the floc sizes were similar to values reported for MBR systems (Masse et al., 2006).

4.4 Conclusions

The results of this study revealed several interesting trends, particularly concerning phosphorus removal. There was no clear trend in COD or total nitrogen removal rates based on changes in SRT. Excellent average COD and ammonia removals of 93.9 ± 1.2% and 98.8 ± 0.1%, respectively, were measured during the study.

However, there was a clear trend of increased phosphorus content in the sludge with increased SRT from 10 to 50 days and a decrease from 50 to 75 days. Effluent phosphorus concentrations decreased from 10 to 25 days and remained steady from 25 to 75 days indicating that there was no significant phosphorus release at high SRT conditions. Total phosphorus removal varied between 4.4-± 1.5% and 19.9 ± 0.6%.

The average floc diameters (32.4 ± 3.4 to 49.3 ± 5 microns) were consistent with the results of similar studies on floc sizes in MBRs. The results did not follow the trend of decreasing floc size with increased SRT reported in other studies (Sperandio et al., 2005). Statistical tests revealed that floc sizes from 10-50 days SRT were not significantly different at a high confidence level, although floc sizes at 75 day SRT were statistically significantly larger. While the floc size measurements did not follow the expected trends, the trend observed in the phosphorus content of the sludge is interesting and an area of potential further research.

4.5 References

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5. CONCLUSIONS

5.1 Conclusions

In order to control eutrophication of receiving waters, many areas have enacted or plan to enact stringent effluent nitrogen and phosphorus limitations. Conventional municipal treatment processes are no longer sufficient to meet the increasingly strict effluent nutrient limitations. Despite improvements to conventional systems to employ biological nutrient removal (BNR) processes, future nutrient limitations will require adoption of new treatment practices. The use of MBRs has become an increasingly attractive technology in the last 10 years for the treatment of municipal wastewaters. Combining BNR with MBRs offers a promising solution to meet strict nutrient discharge standards. There have been relatively few published studies investigating the optimization of a complete MBR system. In particular, there is a need to improve the modeling and optimize the design of MBRs for combined nitrogen and phosphorus removal.

In Chapter 3, it was determined that varied anaerobic and anoxic HRTs have an influence on nitrogen and phosphorus removal. Average steady-state total nitrogen removal varied between 76 ± 0.3 and 88.7 ± 2.1%, while total phosphorus removal varied between 40.3 ± 0.3 and 81.7 ± 3.8% for 100% recycle of the activated sludge and permeate. Total phosphorus removal increased rapidly with increasing anaerobic HRT from 0.5 to 2 hours and decreased with increasing anoxic HRT from about 2 to 5 hours. Total nitrogen removal decreased slightly with increased anaerobic HRT, and increased with increased anoxic HRTs from 1 to 4 hours.

The results indicated a conflict between the anaerobic and anoxic HRT requirements for nitrogen and phosphorus removal. In general, increasing anaerobic HRT improved phosphorus removal and slightly decreased nitrogen removal, while increasing anoxic HRT decreased phosphorus removal and increased nitrogen removal. Increased anaerobic HRT appeared to increase release of phosphorus by the biomass, which improved subsequent enhanced phosphorus removal. Excessive anaerobic HRT (3 hours) led to decreased nitrogen and phosphorus removal, possibly due to a lack of available COD, and secondary phosphorus release. Increased anoxic HRT led to increased anoxic uptake of phosphorus by the biomass, which decreased overall phosphorus removal. Contradictory, increased anoxic HRT increased nitrogen removal by increasing the time available for denitrification. Excessive anoxic HRT (5 hours) led to decreased nitrogen removal by a possible lack of available COD and decreased phosphorus removal due to excessive anoxic phosphorus uptake by the biomass.

A prediction model was created to estimate nitrogen and phosphorus removal given the anaerobic and anoxic HRT. The maximum total nitrogen removal of 86.% was predicted for an anaerobic HRT of 1 hour and anoxic HRT of 4 hours, while the maximum phosphorus removal of 94.5% is predicted at an anaerobic HRT of 2 hours and anoxic HRT of 1 hour. The conditions for maximum combined nitrogen and phosphorus removal of 83% and 71%, respectively, would be expected at 2 hours anaerobic and 4 hours anoxic HRT.

In Chapter 4, the SRT in an aerobic MBR was varied to observe changes in biomass phosphorus content and removal, and bacterial floc sizes. There were significant differences in phosphorus characteristics with varying SRTs. Phosphorus uptake by the biomass increased with increased SRT from 10 to 50 days and decreased from 50 to 75 days, possibly due to cell lysis at high SRTs. Effluent phosphorus concentrations decreased from 10 to 25 days SRT and were relatively steady from 25 to 75 days SRT, despite the changes in biomass phosphorus content possibly due to increasing biomass concentrations at higher SRTs. These findings support operation of aerobic MBRs at high SRTs, which was traditionally thought to increase effluent phosphorus concentrations caused by increased phosphorus release at high SRTs.

A statistical analysis indicated that the bacterial floc diameters were statistically similar from 10 to 50 days SRT and significantly larger for 75 day SRT. The results did not follow the trend of decreasing floc size with increased SRT reported in other studies, although the floc sizes were generally similar to those reported in other studies.

5.2 Recommendations for future research

There is currently limited research investigating the influences of varied HRTs for BNR. Current software models such as Biowin® (version 2.2) have been shown to be inaccurate for modeling BNR in MBRs (Ersu, 2006).

The influence of varied C:N:P ratios is an area that has received relatively little attention. A search of the literature found few studies investigating influent C:N:P ratios in a BNR system, but none in a MBR system designed for BNR. Many recent MBR studies have also used synthetic feeds with a high proportion of simple sugars designed to improve biological phosphorus removal (Patel et al., 2005). The use of tailored synthetic feeds may be acceptable for early feasibility studies, but research with influents designed to better simulate real-world conditions is needed to further the understanding of the limits of BNR in a MBR.
The influent wastewater characteristics could have an impact on the optimal HRTs determined in this study. The general trends observed in this study, would likely remain similar regardless of C:N:P ratio, but the removal trends would possibly shift either up or down depending on the influent C:N:P. The results of a study of varied C:N:P could be incorporated with the data presented here into an improved model. The effect of hydraulic and nutrient shock loadings is another area of potential research that has yet to be fully studied.

The competition between phosphorus accumulating organisms (PAOs) and (glycogen accumulating organisms) GAOs in phosphorus removal systems continues to be a source of interest for many researchers. Recent studies have discovered several parameters, such as temperature and influent composition that effect the competition between PAOs and GAOs, although it should be emphasized that there remain many more questions than answers concerning PAO versus GAO competition. If an understanding of the underlying processes that control PAO/GAO competition were developed, there is potential for much improved biological nutrient removal systems. There is a need for a comprehensive study to optimize BNR for MBRs. As stated earlier, many of the studies completed so far have focused on issues of feasibility and not on process optimization. Patel et al. (2005) noted that many recent BNR studies used operating parameters that may be impractical for full-scale applications, and it is important to focus future work on the implementation of MBRs for full-scale use.

Table A.1 Influent Characteristics

Run	Date	Day	Influent Characteristics (mg/L where applicable) COD	TN	NO_3^--N	NO_2^--N	NH_3-N	TP (soluble)	TSS	pH	ORP, mV
Baseline (Aerobic MBR)	3-16-06		498	54				13.5			
	3-17-06		476	53.1	1	0.5	24.8	12.8	17.8	6.9	
	3-18-06		512					13.7			
	3-19-06		536	52.8	1.2	0.6	21.9	14.8	28.8		
	3-23-06		495	49.9				14.7		7	
	3-24-06		488	44.4	0.5	0.2	17.1	12.7	27.5	7.1	
	3-29-06		487	45.5	0.2	0.1	18.4	13.8		7	
Acclimation with Run 1: 2,3,8	3-22-06	5	492	39.4	0.2	0.3	13.6	14.1			
	4-3-06	17						15		7.4	
	4-6-06	20	489	33.6	0.3		9.8	15			
	4-11-06	25		48				12.8	59.2		
	4-13-06	27	437	43.2	0.7			13.1		7.2	
	4-15-06	29		77.2		0.2	38.9	12.5			-31
	4-18-06	32		59	0.5			13.6		7.1	
	4-20-06	34	479	50.8				13.5	65.2		
	4-24-06	38			0.3			15.2			
	4-29-06	43	483	39.6				14.8			-28
	5-1-06	45		43.5	0.4	0.1	24.9	14.6			
	5-3-06	47		45.2				15.8		7.3	
	5-5-06	49	549	52.8				15.3	49.2		
	5-9-06	53		47	0.4	0.2	27.4	13.2			
	5-11-06	55	507	49				12.5		7.1	-18
	5-14-06	58	503	48.6	0.5	0.1	26.3	12.4			
	5-16-06	60	498	56				18	23.2	7.1	-25
	5-20-06	65	494					17			
Run 1: 2,3,8	5-22-06	66	522	48	0.6	0	25.6	17		7	-30
	5-23-06	67		46.5	0.5	0.1	24.9	15.4	49.5		
	5-25-06	69	476	48	0.6	0	27.9	15.1			-25
	5-27-06	71		43.8	0.7	0.1	24.5	14.9	35.2	7.1	
	5-28-06	72	519	49.8	0.7	0.2	28.1	14.4	21.4		-23
	5-30-06	74	500	51.2	0.6	0.1	28.8	15.2	28.4	7.2	-28

Table A.1 (Continued) Influent Characteristics

Run	Date	Day	Influent Characteristics (mg/L where applicable)								
			COD	TN	NO_3^--N	NO_2^--N	NH_3-N	TP (soluble)	TSS	pH	ORP, mV
	6-2-06	78			0.6						
	6-5-06	81	509	44.8				14.8	22.8		-31
	6-9-06	85	480	57.3	0.7	0.1	31.3			7.5	-27
	6-11-06	87	476	43.8				17.9	11.9		
Run 2: 0.5,5,8	6-13-06	89	483	44.9	0	0.1	27.4	15.3		7.2	-23
	6-14-06	90	432	42.4	0.3	0	25.9	14.7	72.4		
	6-15-06	91	508	53.7	1.1			16.8		7.4	-25
	6-16-06	92	489	44.2			24.6	16.5	28.9		
	6-17-06	93	478	42.5	0.9	0.1		15.7		7.2	
	6-18-06	94	491	44.8			26.1	15.5	24.3		-33
	6-25-06	100	488	57.2				15.7	25.8		
	6-26-06	101	505	58	0.1	0.1	22.3	15.5		7.1	-29
	6-28-06	103	503	55.1	0.2			15.2	17.9		
Run 3: 2,1,8	6-30-06	105	498	45.1	0.1	0.1	19.8	14.6		7.1	
	7-3-06	108	494	45.9	0.1	0.2	21.4	14.8	39		-38
	7-8-06	113	484	47.5	0.2			14.2	12.5	7	
	7-9-06	114	481	44.5	0.1	0	17.2	14.3			-30
	7-10-06	115	498	51.2	0.1	0.1	22.6	14.2	13.8	7.2	-32
	7-14-06	119	494	47.5	0.2	0.1	17.4	14.9	34.2	6.9	-27
	7-17-06	122	450	48.2	0.3	0.2		15.2	11.3		
Run 4: 0.5,4,8	7-21-06	126	510	48.8	0.4	0.2	16.4	15.4	18.9	7.3	-34
	7-23-06	128	496	42.3	0.2	0.1	19.4	15.5	23.4		
	7-25-06	130	503	46.2	0.2	0.1	21.9	15.3	39.8	7.2	-29
	7-29-06	134	501	43.5	0.1	0		15.3	34.9	7.1	-31
	8-1-06	137	498	46.8	0.4	0.1	20.6	15.2	29.4		
Run 5: 1,5,8	8-4-06	140	510	42.7	0.2	0	17.3	14.8	15.3	7.3	-39
	8-6-06	142	507	44.6	0.1	0	20.5	15.2	12.5		
	8-8-06	144	496	45.3	0.3	0.1	20.3	15.1	26.8	7	-28

Table A.1 (Continued) Influent Characteristics

Run	Date	Day	Influent Characteristics (mg/L where applicable)								
			COD	TN	NO_3^- -N	NO_2^- -N	NH_3-N	TP (soluble)	TSS	pH	ORP, mV
Run 6*: 2,2,8	12-13-05		482	39.3	0.5	0.3	21.9	11.8	No Data	7.3	
	12-17-05									7.2	
	12-20-05		475	38.7	0.6	0.2	21.6	12.2		7.1	
	12-24-05									7.3	-32
	12-27-05		463	40.2	0.5	0.3	23.3	11.5		7.3	
	12-31-05									7.2	-28
	1-3-06		483	38.7	0.6	0.4	23.6	11.8		7.1	
	1-7-06									7.3	-36
	1-10-06		476	41.3	0.4	0.3	22.8	12.1		7.2	-32
	1-14-06									7.3	
	1-17-06		477	40.3	0.5	0.2	23.6	11.6		7.2	-28
Run 7: 1,2,8	8-11-06	147	484	45.2	21.4	0.3	0.5	15.1	24.3	7.2	-18
	8-13-06	149	499	44.7				14.8			
	8-15-06	151	503	42.9	22.5	0.2	0.2	15.2	31.2	7.1	-23
	8-20-06	156	493	46.7	22.9	0.2	0.3	15.3		7.3	
	8-22-06	158	496	45.2	23.1	0.3	0.3	14.9	17.2	7.2	-20
Run 8: 3,4,8	8-25-06	161	487	48	0.3	0.1	20.4	14	25.3		-28
	8-27-06	163	503	48.5	0.4	0.3	19.4	14.7		7	
	8-29-06	165	504	47.5	0.2	0.1	24.3	15.4	17.3		-15
	9-2-06	169	510	47.3	0.5	0.4	25.1	14.9		7.1	-19
	9-4-06	171	490	47.2	0.4	0.2	24.6	14.8	14.8		-24
Run 9: 2,4,8	9-7-06	174	479	44.5	0.4	0	24.3	14.3	27.4	7.2	-25
	9-9-06	176	471	49.5	0.2	0.1	25.3	14.2			-21
	9-11-06	178	461	44.5	0.4	0.1	23.4	14.8	59.9	7.1	-34
	9-16-06	183	504	42.6	0.3	0.3	22.9	14.1	15.3	7.1	-27
	9-18-06	185	485	46.8	0.2	0.2	22.7	14.3	21.6	7.2	-30
Run 10: 2,5,8	9-21-06	188	495	45.2	0.2	0	21.9	12.3	17.2	7.1	-35
	9-24-06	191	485	44.7	0.1	0.1	19.4	12.2			
	9-27-06	194	439	48.6	0.3	0.2	20.3	12.6	29.4	7	-43
	9-30-06	197	484	49.2	0.2	0.1	18.9	11.9		6.9	-49
	10-4-06	201	502	47.3	0.2	0.1	21.3	12.4	19.4	7.2	-23

* Ersu, 2006

Table A.1 (Continued) Influent Characteristics

Run	Date	Day	Influent Characteristics (mg/L where applicable)								
			COD	TN	NO_3^- -N	NO_2^- -N	NH_3-N	TP (soluble)	TSS	pH	ORP, mV
Run 11: 1,3,8	10-8-06	205	506	46.3	0.6	0.3	28.5	13.5		7.1	-23
	10-10-06	207	490	39.4				14.2	25.3		-25
	10-12-06	209	512	46.1	0.4	0.2	29.4	13.4		7.2	-39
	10-16-06	213	500	48.5	0.5	0.1	26.4	14.6	25.4		-40
	10-20-06	217	504	49.6	0.3	0.3	25.4	14.4	19.4	7.1	-22
Run 12: 3,5,8	10-24-06	221	490	42.9	0.5	0.3	22.6	13.4	11.2	7.1	-35
	10-27-06	224	495	44.5				14.2		7	-24
	10-30-06	227	492	39.8	0.2	0.3	19.3	14	45.3	7	-39
	11-1-06	229	499	46.8	0.4	0.2	20.8	14.1	19.4	7.1	-37
	11-3-06	231	504	42.8	0.5	0.3	17.8	13.9	23.4	7.1	-21
Run 13: 0.5,1,8	11-6-06	234	504	48.4	0.7	0.3	22.5	13.8	22.4	7.3	-33
	11-9-06	237	508	40.3				14.3			
	11-13-06	241	486	47.6	0.4	0.2	23.2	15.1	31.2	7.2	-36
	11-16-06	244	489	44.6	0.6	0.3	20.5	14.2	15.9		-27
	11-17-06	245	484	43.9	0.3	0.2	18.4	14.7	19.3	7.1	-25
Run 14: 3,2,8	11-20-06	248	524	47.3	0.3	0.4	24.9	14.4	28.9	7.1	-25
	11-23-06	251	538	44.6	0.2	0.4	21.2	14.1			-34
	11-26-06	254	539	40.3	0.5	0.2	19.3	13.7	39.5	7.3	-30
	11-28-06	256	520	39.6	0.6	0.3	14.5	11.3	39.8		-24
	11-30-06	258	519	40.2	0.5	0.2	17.6	12.8	14.6	7.1	-26

Table A.2 Anaerobic Characteristics

Run	Date	Day	Anaerobic Characteristics (mg/L where applicable)									
			sCOD	TN	NO_3^- -N	NO_2^- -N	NH_3-N	TP (soluble)	Biomass P, %	TSS	DO	pH
Acclimation with Run 1: 2,3,8	3-22-06	5									0.08	
	4-3-06	17								2,000	0.09	7.4
	4-6-06	20										
	4-11-06	25		23.9				10.2		1,980		
	4-13-06	27	119					11.4				
	4-15-06	29		30.6		0.1		10.9	2.9	2,420	0.05	7.2
	4-18-06	32		26.4				13.5				
	4-20-06	34	122					13.4	3.7	2,680	0.03	7.1
	4-24-06	38						15.5				
	4-29-06	43		29.3					3.3	2,840	0.04	
	5-1-06	45		25.3		0.1	17.6	15.2				
	5-3-06	47		20.4							0.04	7.3
	5-5-06	49	122	24.5				18.6	3.1	2,960		
	5-9-06	53		24.6	2.8	0	17	18.3				
	5-11-06	55	117	25.5				16.7	2.7	3,320	0.03	7.1
	5-14-06	58	108	21.6	2.1	0.1	15.5					
	5-16-06	60	119					19.3		3,800	0.02	7.1
	5-20-06	64	103					21.2				
Run 1: 2,3,8	5-22-06	66	104	24.7	2.1	0	17.6	20.3	3.4	4,140	0.02	7
	5-23-06	67		25.3	1.5	0	17.4	23.8	3.5	4,340		
	5-25-06	69	109	22.8	1.9	0	16.5	20.8	3.1	4,520	0.08	
	5-27-06	71		25.2	4.1	0		21.7		4,520	0.03	7.1
	5-28-06	72	97	22.4	2.3	0.2	16.4	26.1	2.7	4,680	0.04	
	5-30-06	74	102	26.4	2.7	0	18.1	24.2	3.1	4,540	0.03	7.2

Table A.2 (Continued) Anaerobic Characteristics

Run	Date	Day	Anaerobic Characteristics									
			sCOD	TN	NO_3^- -N	NO_2^- -N	NH_3-N	TP (soluble)	Biomass P, %	TSS	DO	pH
Run 2: 0.5,5,8	6-2-06	78										
	6-5-06	81							3.1	4,840	0.08	
	6-9-06	85		29.6	2	0.2	18.3				0.09	7.4
	6-11-06	87	67.7	17.4				29.9	4.0	5,260		
	6-13-06	89		18.2	2.8	0.2	19.2	27.3			<.1	7.3
	6-14-06	90	51.7	16.2	2.1	0.1	16.9	11.4	3.9	4,520		
	6-15-06	91	50.3	27.5	1.3			23.5			0.05	7.2
	6-16-06	92	49.3	18.2	1.7	0.2	15.2	21.3	3.9	4,700		
	6-17-06	93	48.2	16.9	1.4	0.1		20.5	4.2	4,600		7.1
	6-18-06	94	51.3	18.9	1.6	0.1	14.2	21.4	3.7	4,680	0.03	
Run 3: 2,1,8	6-25-06	100	47.1					28.5	3.7	5,560		
	6-26-06	101		16.4	2.8	0.1	10.7				0.08	
	6-28-06	103	50.5	13.3	1.2			24.9	3.2	5,600		
	6-30-06	105		12.6	0.4	0.1	9.4					
	7-3-06	108	47.1	11.5	0	0.2	8.2	28.2	3	5,480	0.07	
	7-8-06	113	41.6	7.8	0.6			11.9	2.4	5,380		
	7-9-06	114	33.4	10.1	0.3	0	9.1	17.2	2.7	5,220	0.10	
	7-10-06	115	35.2	7.9	0.5	0.1	6.8	14.3	3	5,020	0.08	
Run 4: 0.5,4,8	7-14-06	119	45.3	6.6	0.6	0	7	16.2	3.3	5,120	0.05	
	7-17-06	122	74.2	8.3	0.8	0.1		8.3	2.9	5,560	0.05	
	7-21-06	126	70.3	10	1	0.1	6.4	9.4	3.1	5,640	0.05	
	7-23-06	128	78.3	9.4	0.9	0.1	6.4	12.6	2.9	5,680	0.04	
	7-25-06	130	104.2	9.3	0.7	0	6.3	11.8	3.1	5,660	0.04	
Run 5: 1,5,8	7-29-06	134	63.5	13.4		0		12.5	2.9	5,680	0.03	
	8-1-06	137	78.5	13.2	1.2	0.1	9.4	14.1	2.7	5,720	0.05	
	8-4-06	140	84.3	12.4	1.1	0.1	8.3	15.2	3	5,640	0.04	
	8-6-06	142	88.5	11.9	0.9	0.1	9.3	15.1	3	5,600	0.03	
	8-8-06	144	82.5	12.5	1.3	0.1	9	15.2	3.1	5,620	0.03	

Table A.2 (Continued) Anaerobic Characteristics

Run	Date	Day	Anaerobic Characteristics									
			sCOD	**TN**	**NO_3^--N**	**NO_2^--N**	**NH_3-N**	**TP (soluble)**	**Biomass P, %**	**TSS**	**DO**	**pH**
Run 7: 1,2,8	8-11-06	147	100	16.2	0.5	0.1	13	16.4	3.1	5,540	0.04	7.2
	8-13-06	149	90	21.9				15.4		5,400		
	8-15-06	151	95	23.8	0.2	0	15.3	14.3	3.2	5,120	0.04	7.1
	8-20-06	156	90	23.7	0.3	0.1	15.6	14.3	3.5	5,080	0.04	7.3
	8-22-06	158	96	23.2	0.3	0	15.7	14.5	3.2	5,100	0.03	7.2
Run 8: 3,4,8	8-25-06	161	43	10.4	0.1	0	7.5	14.3	3.2	5,000	0.05	
	8-27-06	163	49	13.7	0.2	0.2	8.3	19.4				6.9
	8-29-06	165	44	14.7	0	0	7.5	16.5	3.2	4,840	0.04	
	9-2-06	169	51	13.5	0.1	0.1	8	14.3	3.2	4,940	0.05	7
	9-4-06	171	47	14.7	0.2	0	7.6	17.3	2.9	4,900	0.03	
Run 9: 2,4,8	9-7-06	174	121	21.6	0.2	0.1	14.7	15.4	3.6	4,880	0.04	7
	9-9-06	176	109	23.7	0.3	0.1	15.6	12.9				
	9-11-06	178	85	20.6	0.1	0.2	17	14.3	3.3	5,020	0.02	7
	9-16-06	183	113	25.9	0.2	0	17.7	15.6	3.1	5,120	0.04	6.9
	9-18-06	185	120	25	0.1	0.1	15.4	15.5	3.1	5,040	0.04	7.1
Run 10: 2,5,8	9-21-06	188	16	18.5	0.3	0.1	14	10.3	3.0	4,920	0.03	7
	9-24-06	191	9	14.6	0.2	0	13.9	9.7	3.1	4,860		
	9-27-06	194	8	13.4	0.4	0.1	13.4	9	3.0	4,740	0.03	7
	9-30-06	197	10	14.2	0.2	0.1	12.8	8.9	2.9	4,800	0.01	6.9
	10-4-06	201	11	12.9	0.1	0	11.2	9.2	2.6	4,880	0.02	7.1

Table A.2 (Continued) Anaerobic Characteristics

Run	Date	Day	Anaerobic Characteristics									
			sCOD	TN	NO_3^--N	NO_2^--N	NH_3-N	TP (soluble)	Biomass P, %	TSS	DO	pH
Run 11: 1,3,8	10-8-06	205	19.4	14.6	0.2	0	13.5	10.2	2.8	4,620	0.04	7
	10-10-06	207	24.5	16.3				10.4		4,620	0.06	
	10-12-06	209	28.6	17.2	0.3	0.1	17.4	9.5	3.2	4,400	0.08	7
	10-16-06	213	23.6	14.8	0	0.1	13	10.1	2.8	4,600	0.1	
	10-20-06	217	27.1	16.8	0.4	0.1	14.6	10.3	2.8	4,640	0.09	7
Run 12: 3,5,8	10-24-06	221	19.7	12.5	0.1	0	12.3	9.3	3.8	5,180	0.05	7
	10-27-06	224	19.4	13.7				10		5,080	0.08	7
	10-30-06	227	25.6	12.5	0.2	0	11.2	10.3	3.6	5,140	0.09	6.9
	11-1-06	229	23.3	10.2	0.2	0	9.5	11.2	3.4	4,980	0.09	7
	11-3-06	231	17.9	9.8	0.3	0	9.3	10	3.8	5,100	0.09	7
Run 13: 0.5,1,8	11-6-06	234	51.4	10.4	0.2	0.2	9.2	7.6	2.9	5,340	0.08	7.3
	11-9-06	237	67.3	12.5				10.3		5,500		
	11-13-06	241	74.3	13.5	0.3	0.1	13.2	9.1	2.8	5,480	0.09	7.1
	11-16-06	244	79.4	15.7	0.1	0.3	14.4	9	2.4	5,580	0.08	
	11-17-06	245	80.2	16.4	0.2	0.2	16.3	10	2.7	5,620	0.05	7
Run 14: 3,2,8	11-20-06	248	48.6	8	0.3	0	7.5	12.4	3.1	4,480	0.04	7
	11-23-06	251	44.3	7.4	0.2	0	7.4	16.5		4,400	0.06	
	11-26-06	254	48.5	6.5	0.4	0	6.3	18.6	3.1	4,300	0.07	7.2
	11-28-06	256	49.8	6.3	0.3	0	5	15.3	3.2	4,560	0.05	
	11-30-06	258	38.7	7	0.2	0	6.7	14.5	3	4,620	0.05	6.9

Table A.3 Anaerobic Effluent Characteristics

Run	Date	Day	Anaerobic Effluent Characteristics										
			sCOD	TN	NO_3^- -N	NO_2^- -N	NH_3-N	TP (soluble)	Biomass P, %	TSS	DO	pH	ORP, mV
Acclimation with Run 1: 2,3,8	3-22-06	5											
	4-3-06	17											
	4-6-06	20											
	4-11-06	25		19.5						1,920			
	4-13-06	27	95					12.4					
	4-15-06	29		24.6		0.1		11.3	2.8	2,400		7.2	-177
	4-18-06	32		24.5				13.9					
	4-20-06	34	94					13.9	3.5	2,540	0.04	7.3	
	4-24-06	38						15.9					
	4-29-06	43		22.9						2,680			-239
	5-1-06	45		21.5	0.3	0	17.5	16.4					
	5-3-06	47		17.3							0.04	6.9	
	5-5-06	49	73	19.4				19.6	3.1	2,940			
	5-9-06	53		20.8	1.4	0	17.1	20.2					
	5-11-06	55	94	24.5				17.8	2.4	3,040	0.04	6.8	-258
	5-14-06	58	90	19.5	0.9	0	15.4						
	5-16-06	60	88					19.9		3,660	0.03	7	-266
	5-20-06	64	83					23.4				7.1	
Run 1: 2,3,8	5-22-06	66	80	22.8	1.1	0	17.5	21.5	3.1	3,960	0.05	7	-271
	5-23-06	67		24.6	0.3	0	17.3	25.4	2.7	4,220			
	5-25-06	69	79	19.3	0.5	0	16.4	22.6	2.5	4,460	0.06	7.1	-264
	5-27-06	71		20.8	1.1	0		24.5		4,340		7.2	
	5-28-06	72	77	18.2	0.8	0	16.4	28.7	2.5	4,580	0.04		-270
	5-30-06	74	82	20.6	1.1	0	18.1	26.8	2.6	4,460	0.04	7.3	-262

Table A.3 (Continued) Anaerobic Effluent Characteristics

Run	Date	Day	Anaerobic Effluent Characteristics										
			sCOD	TN	NO_3^--N	NO_2^--N	NH_3-N	TP (soluble)	Biomass P, %	TSS	DO	pH	ORP
Run 2: 0.5,5,8	6-2-06	78											
	6-5-06	81									0.05		-206
	6-9-06	85			2.3	0.2	16.2				0.05	7.4	-212
	6-11-06	87	61	18.2				33.6	3.6	5,080			
	6-13-06	89		17.6	2.1	0.2	14.3				<0.1	7.3	-209
	6-14-06	90	51	16	1.8	0.1	16.8	12.2	3.5	4,340			
	6-15-06	91	49	25.3	1.2			27.3			0.04	7.2	-178
	6-16-06	92	49	17.4	1.3	0.2	15.1	22.4	3.2	4,440			
	6-17-06	93	48	15.3	1.1	0.1		23.6	3.6	4,520		7.1	
	6-18-06	94	51	17.3	1.2	0.1	14.3	24.3	3.4	4,420	0.04		-200
Run 3: 2,1,8	6-25-06	100	43					31.5	3.4	5,020			
	6-26-06	101		14.5	0.7	0	10				0.06		-259
	6-28-06	103	48	11.5	0.2			29.8	3.2	5,100			
	6-30-06	105		11.8	0.3	0.1	9.4						
	7-3-06	108	46	10.4	0	0	8	29.5	2.9	5,040	0.05		-266
	7-8-06	113	41	7.5	0.1			16.8	2.8	4,980			
	7-9-06	114	38	9.8	0.1	0	9.1	19.1	2.9	5,040	0.09		-271
	7-10-06	115	41	7.7	0.1	0.1	6.7	18.6	2.8	4,860	0.06		-267
Run 4: 0.5,4,8	7-14-06	119	40	6.2	0.6	0	6.9	17.2	3.2	4,960	0.04		-201
	7-17-06	122	70	8.1	0.6	0.1		8.9	3.0	5,140	0.05		
	7-21-06	126	68	9.9	1.2	0.1	6.3	10.4	3.1	5,440	0.03		-178
	7-23-06	128	64	9.3	0.5	0	6.3	14.7	2.9	5,600	0.04		-195
	7-25-06	130	98	9.3	0.3	0	6	12.1	3.2	5,580	0.04		-165
Run 5: 1,5,8	7-29-06	134	59	11.2	1	0		13.8	2.9	5,600	0.04		-241
	8-1-06	137	70	12.3	0.9	0	9.1	14.8	3.1	5,680	0.05		
	8-4-06	140	79	11.5	0.8	0.1	8	15.4	3.1	5,580	0.04		-234
	8-6-06	142	81	10.9	1.2	0	9.2	15.6	2.7	5,640	0.04		
	8-8-06	144	80	12.3	1.5	0.1	8.9	15.7	2.8	5,580	0.03		-243

Table A.3 (Continued) Anaerobic Effluent Characteristics

Run	Date	Day	Anaerobic Effluent Characteristics										
			sCOD	TN	NO_3^--N	NO_2^--N	NH_3-N	TP (soluble)	Biomass P, %	TSS	DO	pH	ORP
Run 6*: 2,2,8	12-13-05	N/A	266	23.4	1.6	0.7	12.7	8.5	Not Reported	5,290	0.3	7.1	-275
	12-17-05												
	12-20-05		232	22.7	1.1	0.4	13.4	10.2		6,820	0.2	7	-310
	12-24-05												
	12-27-05		218	22.3	0.7	0.1	13.5	14.1		7,960	0.2	6.9	-349
	12-31-05												
	1-3-06		184	21.9	0.4	0	14.2	18.3		8,630	0.1	6.9	-334
	1-7-06												
	1-10-06		182	21.2	0.2	0	13.8	20.6		8,590	0.1	6.8	-367
	1-14-06		171	20.7	0.2	0.1		20.7					
	1-17-06		179	20.3	0.1	0	13.6	21.3		8,750	0	6.9	-358
Run 7: 1,2,8	8-11-06	147	98	16	0.4	0.1	13.1	18.4	2.9	5,400	0.04	7	-233
	8-13-06	149	85	21.9				19.5		5,320			
	8-15-06	151	94	23.7	0.4	0	15.2	16.4	3.0	5,080	0.03	7	-210
	8-20-06	156	86	22.5	0.9	0.1	15.7	13.4	3.0	4,920	0.02	7.1	
	8-22-06	158	95	23	0.5	0	15.6	16	2.9	4,960	0.01	7	-246
Run 8: 3,4,8	8-25-06	161	39	10.3	0.1	0	7.5	16.6	2.7	4,860	0.04		-238
	8-27-06	163	36	10.6	0.2	0.1	8	21.8				6.9	
	8-29-06	165	39	11.1	0.1	0	7.3	20.7	2.9	4,700	0.04		-284
	9-2-06	169	36	11.2	0	0	7.7	13.4	2.6	4,820	0.04	6.8	-253
	9-4-06	171	36	10.8	0.1	0	7.3	20.3	2.6	4,760	0.04		-270
Run 9: 2,4,8	9-7-06	174	112	21.4	0.1	0	14.6	16.4	3.0	4,800	0.02	7	-224
	9-9-06	176	97	23.6	0.3	0.1	15.3	13.6					-243
	9-11-06	178	78	20.6	0.1	0	16.5	14.5	3.2	4,960	0.03	6.9	-238
	9-16-06	183	106	25.7	0	0	17.3	15.8	2.9	5,020	0.04	6.9	-228
	9-18-06	185	111	24.8	0.2	0.1	15.9	15.9	2.9	4,940	0.03	6.9	-224
Run 10: 2,5,8	9-21-06	188		18.4	0.3	0	13.9	10	2.9	4,900	0.03	6.9	-231
	9-24-06	191		14.3	0.1	0	13.8	9.6	2.8	4,880			
	9-27-06	194	8	13.1	0.2	0	13	8.8	2.9	4,840	0.01	6.8	-242
	9-30-06	197	9	14	0.2	0.1	12.3	8.9	2.5	4,880	0	6.8	-268
	10-4-06	201	10	12.8	0	0	11	9.3	3.0	4,840	0.01	7.1	-254

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Table A.3 (Continued) Anaerobic Effluent Characteristics

Run	Date	Day	Anaerobic Effluent Characteristics										
			sCOD	TN	NO_3^--N	NO_2^--N	NH_3-N	TP (soluble)	Biomass P, %	TSS	DO	pH	ORP
Run 11: 1,3,8	10-8-06	205	14.6	14.5	0.1	0.1	13.8	13.5	2.8	4,580	0.05	7	-218
	10-10-06	207	17.4	16.4				14.2		4,600	0.04		-220
	10-12-06	209	20.3	18.3	0.2	0	17.3	13.4	2.9	4,440	0.05	7	-239
	10-16-06	213	19.3	14.7	0.1	0.1	13.2	14.6	2.7	4,560	0.06		-211
	10-20-06	217	18.7	16.3	0.3	0	14.5	14.4	2.6	4,620	0.03	6.9	-232
Run 12: 3,5,8	10-24-06	221	14.5	12.4	0.1	0	12.1	13.4	3.3	5,240	0.05	7	-265
	10-27-06	224	13.4	13.4				14.2		5,040	0.09	6.9	-256
	10-30-06	227	21.1	12.2	0	0	11.4	14	3	5,180	0.07	6.9	-270
	11-1-06	229	19.7	10.4	0.1	0	9.2	14.1	2.7	5,000	0.08	6.9	-255
	11-3-06	231	15.2	9.8	0	0	9.1	13.9	2.9	5,120	0.08	7	-268
Run 13: 0.5,1,8	11-6-06	234	41.3	10.5	0.1	0.1	9.1	13.8	2.8	5,320	0.09	7.2	-209
	11-9-06	237	63.6	12.6				14.3		4,480			
	11-13-06	241	70.4	13.6	0.1	0	13	15.1	2.5	5,500	0.1	7	-223
	11-16-06	244	73.5	15.6	0	0.1	14.2	14.2	2.3	5,600	0.08		-219
	11-17-06	245	74.9	16.2	0.1	0.1	16.1	14.7	2.6	5,600	0.06	6.8	-214
Run 14: 3,2,8	11-20-06	248	42.6	7.9	0.1	0.1	7.6	14.4	2.9	4,460	0.03	6.9	-248
	11-23-06	251	39.3	7.2	0	0.1	7.2	14.1		4,360	0.05		-238
	11-26-06	254	40.2	6.4	0.1	0	6.1	13.7	2.6	4,280	0.06	6.8	-230
	11-28-06	256	44.8	5.8	0.1	0.1	5.2	11.3	2.6	4,560	0.04		-258
	11-30-06	258	32.2	7.2	0.1	0	6.9	12.8	2.7	4,540	0.05	6.7	-263

Table A.4 Anoxic Effluent Characteristics

Run	Date	Day	Anoxic Effluent Characteristics										
			sCOD	TN	NO_3^--N	NO_2^--N	NH_3-N	TP (soluble)	Biomass P, %	TSS	DO	pH	ORP
Acclimation with Run 1: 2,3,8	3-22-06	5											
	4-3-06	17									0.14	7.1	
	4-6-06	20											
	4-11-06	25		17.5									
	4-13-06	27	74					9.9					
	4-15-06	29		22.5		0.1		9.5	2.9	2,580	0.08	7.1	-130
	4-18-06	32		19.4				9.6					
	4-20-06	34	79					9.8	3.8	2,740	0.09	7.2	
	4-24-06	38						11.5					
	4-29-06	43		18.3					3.4	2,860	0.08		-132
	5-1-06	45		19.4		0	13.3	12.8					
	5-3-06	47		15.9							0.08	7.1	
	5-5-06	49	54	17.3				14.5	3.2	3,020			
	5-9-06	53		17.5	0	0	12.3						
	5-11-06	55	71	19.4				15.2	3.4	3,080	0.09	7.1	-146
	5-14-06	58	62	14.9	0.2	0	11.2						
	5-16-06	60	60					17.2	4	3,520	0.08	7	-159
	5-20-06	64	59					15.4					
Run 1: 2,3,8	5-22-06	66	54	19.4	0.3	0	13.2	9.5	3.2	3,460	0.12	7	-141
	5-23-06	67		23.5	0.1	0.1	16.3	9.7	3.5	3,360			
	5-25-06	69	63	17.4	0.1	0	12.4	12.5	3.2	3,540	0.07		-154
	5-27-06	71		13.4	0.3	0		18.3	4.2	3,120		7.2	
	5-28-06	72	57	14.2	0.2	0	12.5	19.4	3.4	3,640	0.08		-167
	5-30-06	74	59	14.9	0.1	0	12.9	14.5	3.3	3,580	0.09		-153

Table A.4 (Continued) Anoxic Effluent Characteristics

Run	Date	Day	Anoxic Effluent Characteristics										
			sCOD	TN	NO_3^- -N	NO_2^- -N	NH_3-N	TP (soluble)	Biomass P, %	TSS	DO	pH	ORP
Run 2: 0.5,5,8	6-2-06	78											
	6-5-06	81								4,080	0.07		-166
	6-9-06	85			2.3	0.2	9.8				0.07	7	-174
	6-11-06	87	45	14.6				17.6	3.9	4,420			
	6-13-06	89		13.4	0.9	0.3	8.2	16.9			0.08	7.1	-162
	6-14-06	90	36	10.6	0.2	0.1	7.3	12.9	3.5	5,220			
	6-15-06	91	29	12.5	0.5			17			0.08	7.2	-178
	6-16-06	92	25	10.9	0.3	0	8.5	22.2	3.6	5,140			
	6-17-06	93	34	8.3	0.4	0.1		16.7	3.7	5,280		7.1	
	6-18-06	94	32	9.6	0.3	0.1	8.1	16.2	3.6	5,200	0.08		-160
Run 3: 2,1,8	6-25-06	100	40					19.5	3.8	3,980		6.9	
	6-26-06	101		8	1.2	0.6	5.7				0.09		-139
	6-28-06	103	41	6.9	1.2			17.8	3.5	4,480		6.9	
	6-30-06	105		7.9	1.1	0.1	5.1						
	7-3-06	108	38	7.4	0.4	0.1	5.4	11.5	3.1	4,760	0.08	6.9	-154
	7-8-06	113	38	7.2	1.1			14.9	3	4,880			
	7-9-06	114	36	6.8	1.4	0.2	4.8	8.9	3	4,800	0.1	7.1	-158
	7-10-06	115	39	6.5	1.2	0.1	4.7	11.2	3.2	4,720	0.09		-149
Run 4: 0.5,4,8	7-14-06	119	18	6.8	0.3	0	3.9	9.2	4	4,380	0.06	7	-180
	7-17-06	122	31	6.7	0.4	0.1		10.2	3.9	4,300	0.09		
	7-21-06	126	24	4.9	0.1	0.1	2.9	11.1	3.7	4,320	0.06	7.1	-155
	7-23-06	128	22	4.3	0.3	0	3.7	14.2	3.5	4,220	0.07		-140
	7-25-06	130	36	4.8	0.2	0	4.6	13.6	3.6	4,280	0.06	7.2	-142
Run 5: 1,5,8	7-29-06	134	25	5.9	0.6	0		10.3	3.2	4,620	0.06	7.1	-152
	8-1-06	137	32	5.7	0.8	0.1	4.2	11.2	3.7	4,560	0.07		
	8-4-06	140	38	4.4	0.1	0	3.1	9.3	3.6	4,540	0.06	7.3	-159
	8-6-06	142	36	5.3	0.3	0	4.4	10.1	3.4	4,480	0.09		
	8-8-06	144	35	5.9	0.3	0	4.5	9.7	3.4	4,620	0.08	6.9	-162

Table A.4 (Continued) Anoxic Effluent Characteristics

Run	Date	Day	Anoxic Effluent Characteristics										
			sCOD	TN	NO_3^--N	NO_2^--N	NH_3-N	TP (soluble)	Biomass P, %	TSS	DO	pH	ORP
	12-13-05		164	14.9	2.5	1.5	8.9	6.2		4,860	0.5	7.2	-210
	12-17-05												
	12-20-05		147	14.4	1.9	1.3	8.2	8.6		5,910	0.3	7.3	-245
	12-24-05												
	12-27-05		118	14.1	1.4	0.9	8.5	11.2		6,420	0.3	7.1	-238
Run 6*: 2,2,8	12-31-05	N/A							Not Reported				
	1-3-06		102	13.2	1.1	0.6	7.9	12.4		7,270	0.2	7.2	-256
	1-7-06												
	1-10-06		84	12.7	0.5	0.3	8.2	12.8		7,180	0.1	7.2	-262
	1-14-06		77	11.1	0.5	0.1	7.4	12.7					
	1-17-06		73	10.7	0.3	0.1	7.8	12.5		7,420	0.1	7.1	-271
	8-11-06	147	49	8.4	0.3	0.1	9	16.5	3.3	4,020	0.03	7.2	-145
	8-13-06	149	45	14.1				15.4		3,900			
Run 7: 1,2,8	8-15-06	151	40	13.5	0.5	0.1	8.4	14.9	3.2	3,860	0.03	7.3	-138
	8-20-06	156	41	11.7	0.7	0.2	8.1	14	3.2	3,900	0.01	7.4	
	8-22-06	158	42	12.2	0.4	0.1	8.5	14.4	3.2	3,880	0.04	7.2	-153
	8-25-06	161	27	8.7	0.3	0	5.3	16.9	3.5	4,240	0.06		-162
	8-27-06	163	23	8.9	0.1	0.2	6.8	13.4				7.1	
Run 8: 3,4,8	8-29-06	165	27	9.3	0.2	0	8	14.8	3.3	4,340	0.12		-172
	9-2-06	169	25	9.1	0.1	0	7.8	14.5	3.3	4,400	0.08	7.1	-179
	9-4-06	171	24	9.2	0.2	0.1	8.1	14.4	3.4	4,380	0.08		-164
	9-7-06	174	43	11.3	0.2	0.1	9.4	12.3	3.4	4,440	0.06	7.1	-160
	9-9-06	176	46	7.5	0	0	6.4	11.5					-153
Run 9: 2,4,8	9-11-06	178	32	7.2	0.1	0	4.5	10.4	3.4	4,580	0.1	7	-149
	9-16-06	183	50	6.1	0.1	0.1	4.6	10.3	3.3	4,480	0.07	7.1	-146
	9-18-06	185	52	6.9	0	0	4.8	10.1	3.5	4,500	0.05	7.1	-151
	9-21-06	188		7.3	0.1	0	6.4	9.4	3.5	4,460	0.04	7	-161
	9-24-06	191		6.3	0	0	5.8	8.2	3.4	4,200			
Run 10: 2,5,8	9-27-06	194	5	8.1	0.1	0	7.4	7.3	3.3	4,120	0.08	6.9	-189
	9-30-06	197	5	7.2	0.1	0.1	6.5	7.2	3.9	4,020	0.05	6.9	-163
	10-4-06	201	5	7.9	0	0	7.1	8.2	3.2	4,100	0.06	7	-173

*Ersu, 2006

Table A.4 (Continued) Anoxic Effluent Characteristics

Run	Date	Day	Anoxic Effluent Characteristics										
			sCOD	TN	NO_3^- -N	NO_2^- -N	NH_3-N	TP (soluble)	Biomass P, %	TSS	DO	pH	ORP
Run 11	10-8-06	205	5.3	9.1	0.3	0.2	8	7.9	3.8	4,000	0.05	7.1	-153
	10-10-06	207	12.5	10.2				8.4		3,980	0.06		-162
	10-12-06	209	16.3	10.4	0.3	0.1	9.1	8.1	3.7	4,020	0.09	7.2	-148
	10-16-06	213	14.3	9.9	0.2	0	7.8	7.9	3.5	3,920	0.08		-172
	10-20-06	217	15.7	9.7	0.4	0.1	7.6	8.2	3.9	3,900	0.08	7	-156
Run 12	10-24-06	221	9.8	8	0.1	0	5.6	9.6	3.8	4,340	0.07	7	-170
	10-27-06	224	8.5	10.9				10.1		4,640	0.09	7	-184
	10-30-06	227	14.6	9.8	0	0.1	8.1	10.4	4.1	4,880	0.08	6.9	-183
	11-1-06	229	12.8	8.7	0.1	0	6.4	10.6	3.3	4,840	0.08	7	-190
	11-3-06	231	10.2	7.4	0.1	0	6.8	10.3	3.5	4,820	0.07	7.2	-193
Run 13	11-6-06	234	30.4	9.1	0.2	0.2	8	9.3	2.9	4,900	0.1	7.2	-134
	11-9-06	237	37.9	10.5				9.1		5,020			
	11-13-06	241	40.2	11	0.3	0.1	9.5	9.8	2.6	4,980	0.09	6.9	-148
	11-16-06	244	42.6	13.5	0.3	0.2	12.2	8.4	2.3	5,040	0.1		-140
	11-17-06	245	42.7	14.1	0.2	0.1	12.8	9.3	2.8	5,000	0.1	7	-132
Run 14	11-20-06	248	25.2	7.4	0.1	0.1	5.7	18.5	2.9	4,320	0.1	6.9	-159
	11-23-06	251	19.2	6.7	0.3	0.1	6			4,120	0.09		-149
	11-26-06	254	18.5	5.7	0.2	0	4.8	19.1	2.5	3,880	0.08	6.9	-141
	11-28-06	256	22	5	0	0.1	4.5	17.5	2.4	4,240	0.07		-168
	11-30-06	258	17.9	6.2	0.2	0	5.1	19.2	2.5	4,320	0.08	6.9	-171

Table A.5 Aerobic Characteristics

Run	Date	Day	Aerobic Characteristics (mg/L where applicable)										
			COD	TN	NO_3^- -N	NO_2^- -N	NH_3-N	TP (soluble)	Biomass P, %	TSS	DO	pH	ORP
Baseline (Aerobic MBR)	3-16-06		70	39				11.9					Not Reported
	3-17-06		58	42.4	35.4	0.6	0.31	9.7	3.2	8,060	2.8	7.1	
	3-18-06		79					12			3.4		
	3-19-06		97	40.5	34.2	0.8	0.28	13.4	3.6	7,960			
	3-23-06		89					14	3.3	7,820	3.2	6.9	
	3-24-06		92	38.4	26.4	0.1	0.26	12.1	3.2	7,680	3.12	6.9	
	3-29-06		95	36.3	28.4	0.2	0.23	12	3.2	7,720	3.15	6.9	
Acclimation with Run 1: 2,3,8	3-22-06	5					0.4						
	4-3-06	17							2.1	2,400	1.78	7.7	
	4-6-06	20					0.44				2.44		
	4-11-06	25		25.1					2	3,160			
	4-13-06	27	21	16.9				10.3					
	4-15-06	29		19.4		1.4	0.26	9.9	3.1	4,220	2.35	7.6	205
	4-18-06	32		17.3				10.5					
	4-20-06	34	18					10.1	3.9	4,600	2.4	7.4	
	4-24-06	38						12.5			2.15		
	4-29-06	43		15.6					4.1	4,880	2.38		193
	5-1-06	45		15.9	12.8	1.2	0.24	12.9					
	5-3-06	47		12.7							2.35	7.3	
	5-5-06	49	12	14.9				11.2	4.7	5,160			
	5-9-06	53		13.9	9	1.4	0.28						
	5-11-06	55	36	15.1				8.4	5.3	5,480	2.24	7.2	181
	5-14-06	58	36	12.4	8.2	1.1	0.31			6,900	2.14		
	5-16-06	60	32	11.7				6.1	5.4	7,120	1.98	7.2	173
	5-20-06	65	30					4.7			1.93		
Run 1: 2,3,8	5-22-06	66	23	9	7.2	0.9	0.22	4.2	5.7	7,640	2.1	7.1	169
	5-23-06	67		9.8	7.1	1	0.23	4	5.9	7,940	2.27		
	5-25-06	69	77	9.3	8.4	1.1	0.27	5.3	5.6	8,120	1.95	7.2	153
	5-27-06	71		9.1	9.4	1.8		6.1	6.1	7,560	2.18	7.3	
	5-28-06	72	85	9	6	2.5	0.38	4.7	5.7	8,260	2.28		166
	5-30-06	74	31	9.4	7.6	1.5	0.28	5.1	5.9	8,080	2.15	7.5	165

Table A.5 (Continued) Aerobic Characteristics

Run	Date	Day	Aerobic Characteristics (mg/L where applicable)										
			sCOD	TN	NO_3^- -N	NO_2^- -N	NH_3-N	TP (soluble)	Biomass P, %	TSS	DO	pH	ORP
Run 2: 0.5,5,8	6-2-06	78			7.9								
	6-5-06	81							4.9	7,740	2.23		178
	6-9-06	85			6.5	1.5	0.4				2.15	7.5	156
	6-11-06	87	72	7				10.5	4	7,740			
	6-13-06	89		8	6.5	1	0.22		3.9	7,840	2.05	7.3	150
	6-14-06	90	30	8.3	5.9	1.4	0.26	10.3	4.3	7,960			
	6-15-06	91	25	9.2	7.2			9.9	4.6	7,980	2.19	7.4	163
	6-16-06	92	21	7.4	5.3	1.1	0.26	10.5	4.6	7,960			
	6-17-06	93	18	7.3	5.1	1.1		10.1	4.4	8,040		7.3	
	6-18-06	94	25	7.1	5.3	1	0.25	10.3	4.5	8,020	2.23		169
Run 3: 2,1,8	6-25-06	100	47	8.9				7.2	5.2	6,840			
	6-26-06	101		10.8	7.4	0.8	0.12				2.15		163
	6-28-06	103	23	9.8	7.1			4.2	5.9	7,140			
	6-30-06	105		10.7	6.8	0.7	0.14						
	7-3-06	108	36	10.4	2.4	0.8	0.13	2.9	6.2	7,340	2.17		170
	7-8-06	113	28	10.7	8.4			3.1	6.5	7,180			
	7-9-06	114	29	9.6	3.9	0.9	0.12	2.7	6.5	6,840	2.30		159
	7-10-06	115	36	10.7	7	0.6	0.17	2.9	6.3	6,980	2.24		163
Run 4: 0.5,5,8	7-14-06	119	15	8.8	3.6	0.9	0.28	6.1	5.3	6,820	2.28		162
	7-17-06	122	21	8.7	3.5	0.6		7	5.1	6,780	2.29		
	7-21-06	126	17	6.2	2.7	0.6	0.35	8.8	4.9	6,960	2.35		174
	7-23-06	128	11	6.4	3.8	0.4	0.28	7.2	4.8	7,020	2.3		170
	7-25-06	130	13	6.5	4.2	0.7	0.26	8.9	5.0	6,940	2.31		166
Run 5: 1,5,8	7-29-06	134	11	6.2	4.8	0.8		6.9	5.2	7,020	2.32		182
	8-1-06	137	15	5.2	4	0.9	0.4	7.2	5.2	7,100	2.34		
	8-4-06	140	19	5.4	4.7	1.2	0.46	6.1	5.4	6,940	2.35		189
	8-6-06	142	19	5.5	4.8	0.9	0.38	6.2	5.4	6,960	2.35		
	8-8-06	144	19	5.3	4.8	1	0.42	5.9	5.5	6,920	2.29		175

Table A.5 (Continued) Aerobic Characteristics

Run	Date	Day	Aerobic Characteristics (mg/L where applicable)										
			sCOD	TN	NO_3^- -N	NO_2^- -N	NH_3-N	TP (soluble)	Biomass P, %	TSS	DO	pH	ORP
Run 6*: 2,2,8	12-13-05									8,240	2.4		74
	12-17-05												
	12-20-05									9,160	2.6		82
	12-24-05												
	12-27-05								6.1	10,260	2.2		68
	12-31-05	Not Reported										Not Reported	
	1-3-06								6.5	10,420	3.1		94
	1-7-06												
	1-10-06								7	11,280	2.5		78
	1-14-06												
	1-17-06								7.2	11,450	2.7		86
Run 7: 1,2,8	8-11-06	147	15	5.6	5.2	0.5	0.3	5.8	5.7	7,180	2.53	7.2	174
	8-13-06	149	16	6.3				6.2		7,440			
	8-15-06	151	13	7.7	5.8	0.4	0.5	7.1	5.6	7,580	2.5	7.3	168
	8-20-06	156	11	8.3	7	0.5	0.4	9.7	5.8	7,560	2.52	7.4	
	8-22-06	158	15	7.8	5.5	0.6	0.4	6.7	5.8	7,520	2.45	7.3	165
Run 8: 3,4,8	8-25-06	161	22	9	6.5	1	0.18	11.5	5.7	6,020	2.35		162
	8-27-06	163	18	8.5	7	0.9	0.25	8.4				7.2	
	8-29-06	165	16	9.1	7.7	0.8	0.3	6.2	5.7	6,960	2.45		171
	9-2-06	169	14	9	7.9	0.9	0.25	5.7	5.7	7,080	2.49	7.2	172
	9-4-06	171	14	9	7.7	0.9	0.22	5.8	5.6	7,040	2.48		182
Run 9: 2,4,8	9-7-06	174		7	4.7	1.3	0.25	5.7	5.8	7,180	2.43	7.2	174
	9-9-06	176	5	5.6	5.3	0.9	0.3	5.4		7,240			179
	9-11-06	178	7	5.5	4.8	0.8	0.29	4.8	5.7	7,340	2.53	7.1	181
	9-16-06	183	7	5.4	4.8	1.4	0.31	4.3	6.1	7,300	2.47	7.2	174
	9-18-06	185	9	5.8	4.3	1.2	0.33	4.4	5.9	7,360	2.41	7.3	188
Run 10: 2,5,8	9-21-06	188	24	6.1	4.2	1.6	0.34	4.5	6.1	7,200	2.37	7.1	164
	9-24-06	191	14	6.9	5	1.5	0.3	5.4	5.8	7,080			
	9-27-06	194	9	7.4	4.6	1.8	0.28	3.3	5.7	6,980	2.35	6.9	159
	9-30-06	197	13	6.1	4.8	0.9	0.33	3.6	5.7	6,860	2.28	7	179
	10-4-06	201	12	7	4.9	1.6	0.34	4.1	5.7	6,920	2.39	7	170

*Ersu, 2006

Table A.5 (Continued) Aerobic Characteristics

Run	Date	Day	Aerobic Characteristics (mg/L where applicable)										
			sCOD	TN	NO_3^--N	NO_2^--N	NH_3-N	TP (soluble)	Biomass P, %	TSS	DO	pH	ORP
Run 11: 1,3,8	10-8-06	205	4.1	6.8	3.5	1.4	0.6	6	5.8	7,320	2.34	7.3	174
	10-10-06	207	5.7	8				4.1		7,460	2.4		198
	10-12-06	209	8.5	8.4	6	1	0.55	4.2	6	7,320	2.34	7.4	159
	10-16-06	213	7.4	8.3	5.6	0.9	0.34	4.5	6.1	7,420	2.37		167
	10-20-06	217	6.3	7.1	5.2	1.2	0.43	4.4	6.4	7,380	2.35	7.3	154
Run 12: 3,5,8	10-24-06	221	5.5	7.5	6.5	0.7	0.32	4.9	5.6	7,180	2.5	7.1	160
	10-27-06	224	5.1	10.5				6.3		7,080	2.4	7.1	156
	10-30-06	227	5.8	9.4	8.5	0.8	0.24	5.4	5.6	6,980	2.44	7	164
	11-1-06	229	6	8.6	10.2	0.5	0.27	6.7	5.6	6,740	2.46	7.2	153
	11-3-06	231	4.8	9.7	8.3	0.9	0.25	6.4	5.5	6,940	2.41	7.3	183
Run 13: 0.5,1,8	11-6-06	234	15.8	8.9	7.3	1.1	0.38	7.1	5.8	7,020	2.44	7.3	189
	11-9-06	237	28.5	10.3				6.4		7,140			
	11-13-06	241	31.7	11.5	10	0.6	0.35	5	5.7	7,180	2.4	7	193
	11-16-06	244	30.4	11.6	10.2	1.7	0.42	5.8	5.9	7,220	2.34		185
	11-17-06	245	29.5	10.8	8.3	0.6	0.36	6.2	5.7	7,160	2.46	7.2	187
Run 14: 3,2,8	11-20-06	248	26.4	7.1	7.3	1.1	0.26	7	5.9	6,980	2.43	7.2	153
	11-23-06	251	14.5	6.9		1.5	0.3	4.1		6,880	2.5		132
	11-26-06	254	30.4	7.3	10	1	0.23	4.5	6.5	6,720	2.55	7.2	148
	11-28-06	256	38.6	8.8	9.3	1.6	0.15	4.8	7.7	7,240	2.39		157
	11-30-06	258	22.3	7.1	8.7	1.5	0.12	4.9	6.2	7,320	2.37	7.3	168

Table A.6 Aerobic Effluent Characteristics

Run	Date	Day	Aerobic Effluent Characteristics (mg/L where applicable)							
			sCOD	TN	NO_3^- -N	NO_2^- -N	NH_3-N	TP	TSS	pH
Baseline (Aerobic MBR)	3-16-06		46	37				11.6		
	3-17-06		39.2	40.2	33.7	0.3	0.26	11.1	3.6	7.2
	3-18-06		47					11.5		
	3-19-06	N/A	60.6	38.4	33.1	0.4	0.24	12.4	1.2	
	3-23-06		49	36.2	24	0.3		11.9		6.9
	3-24-06		40.2	35.2	22.3	0.4	0.2	10.5	2.1	6.9
	3-29-06		42.5	35.1	24.6	0.5	0.2	11.1		6.9
Acclimation with Run 1: 2,3,8	3-22-06	5	54.8	22		1.4	0.3	12.7		
	4-3-06	17						13.8		7.6
	4-6-06	20	10	13.2	5.8		0.4	13.9		
	4-11-06	25		24				11.6	2.2	
	4-13-06	27	18	16.2	5.4			11.5		
	4-15-06	29		18.2		1.3	0.2	9.4		7.6
	4-18-06	32		16.8	5.7			10.3		
	4-20-06	34	16	15.7				10	1.2	7.4
	4-24-06	38						11.2		
	4-29-06	43	17	15.4				12.7		
	5-1-06	45		16	11.1	1.1	0.15	11.5		
	5-3-06	47		11.4				11.2		7.3
	5-5-06	49	11	14.5				9	<1	
	5-9-06	53	34	13.4	9	1	0.19	8.7		
	5-11-06	55	34	14.7				7.1		7.2
	5-14-06	58	37	12	8.3	0.9	0.21	6.8		
	5-16-06	60	30	11				5.9	1.1	7.2
	5-20-06	65	29					4.3		
Run 1: 2,3,8	5-22-06	66	20	8.9	7	0.8	0.14	4.1		7.1
	5-23-06	67		9.4	6.9	0.8	0.18	3.7	<1	
	5-25-06	69	17	9.1	8	0.9	0.24	4.8	1.1	
	5-27-06	71		8.9	9	1.3		4.6		7.3
	5-28-06	72	45	8.7	6	2.4	0.31	4	<1	
	5-30-06	74	9	9.3	7.5	1.2	0.21	4.5	<1	7.5

Table A.5 (Continued) Aerobic Effluent Characteristics

Run	Date	Day	Anaerobic Effluent Characteristics							
			sCOD	TN	NO_3^--N	NO_2^--N	NH_3-N	TP	TSS	pH
Run 2: 0.5,5,8	6-2-06	78			7.6					
	6-5-06	81	29	11.3				7.3	1.1	
	6-9-06	85	24	10.1	6.3	1.4	0.2			7.6
	6-11-06	87	25	6.4				10		
	6-13-06	89	18	7.8	6.2	1.1	0.32	11.6		7.4
	6-14-06	90	18	7.5	5.6	1.2	0.21	9.3	<1	
	6-15-06	91	20	8.8	6.3			9.5		7.4
	6-16-06	92	18	7	5.2	0.9	0.18	9.8		
	6-17-06	93	16	6.9	4.6	1.1		9.2		7.3
	6-18-06	94	24	7	5.2	0.9	0.22	9.4	<1	
Run 3: 2,1,8	6-25-06	100	29	7.2				5.7	1.1	
	6-26-06	101	21	7.9	7.1	0.8	0.1	4		7.1
	6-28-06	103	20	9	6.7			3	<1	
	6-30-06	105	22	10.6	6.4	0.6	0.09	2.8		7.2
	7-3-06	108	21	10.5	2.4	0.7	0.11	2.7	<1	
	7-8-06	113	15	10.4	8.1			2.7	<1	7.1
	7-9-06	114	17	9.5	3.9	0.9	0.1	2.4		
	7-10-06	115	18	10.5	6.8	0.6	0.13	2.6	1.1	7.2
Run 4: 0.5,4,8	7-14-06	119	11	8.7	3.4	0.7	0.24	5.4	<1	7.2
	7-17-06	122	2	8.6	3.2	0.5		5.8		
	7-21-06	126	8	6.1	2.5	0.5	0.31	6.5	<1	7.3
	7-23-06	128	4	6.2	3.5	0.4	0.23	6.8	1.2	
	7-25-06	130	6	6.3	4	0.6	0.19	6.7	<1	7.3
Run 5: 1,5,8	7-29-06	134	9	5.8	4.5	0.6		6.2	<1	7.2
	8-1-06	137	13	4.8	3.9	0.8	0.36	6		
	8-4-06	140	15	4.9	4.6	0.9	0.39	5.5	<1	7.4
	8-6-06	142	14	5.1	4.8	0.6	0.28	5.6	1	
	8-8-06	144	15	5	4.7	0.8	0.27	5.4	<1	7.2

Table A.5 (Continued) Aerobic Effluent Characteristics

Run	Date	Day	Aerobic Effluent Characteristics							
			sCOD	**TN**	**NO_3^--N**	**NO_2^--N**	**NH_3-N**	**TP**	**TSS**	**pH**
	12-13-05		78	13.7	6.1	2.4	1.1	4.9		7.3
	12-17-05									
	12-20-05		64	13.4	6.4	2.1	0.9	4.2		7.2
	12-24-05									
	12-27-05		42	12.8	6.8	2.5	0.7	3.5		7.4
Run 6*: 2,2,8	12-31-05	N/A							Not Reported	
	1-3-06		34	11.5	6.5	2.2	0.6	2.9		7.3
	1-7-06									
	1-10-06		28	9.6	5.9	1.9	0.4	2.3		7.3
	1-14-06		25	8.7	5.4	1.6	0.5	2.3		
	1-17-06		24	8.2	5.2	1.7	0.3	2.1		7.3
	8-11-06	147	13	5.5	4.4	0.5	0.3	5.3	<1	7.2
	8-13-06	149	11	6.1				5		
Run 7: 1,2,8	8-15-06	151	11	7.7	5.7	0.4	0.5	4.7	1.4	7.3
	8-20-06	156	10	8.3	7.1	0.5	0.3	4.6		7.4
	8-22-06	158	13	7.6	5.4	0.6	0.4	4.8	<1	7.3
	8-25-06	161	4	8.7	6.2		0.12	7.7	<1	
	8-27-06	163	11	8.5	5.1	0.9	0.22	6.5		7.2
Run 8: 3,4,8	8-29-06	165	7	8.0	4.7	0.7	0.27	5.6	<1	
	9-2-06	169	7	7.6	4.8	0.6	0.24	5.5		7.2
	9-4-06	171	7	7.7	4	0.8	0.19	6	<1	
	9-7-06	174	7	6.8	4.6	0.9	0.25	5	<1	7.2
	9-9-06	176	4	5.4	5.1	0.6	0.29	5		
Run 9: 2,4,8	9-11-06	178	6	5.3	4.7	0.7	0.26	4.4	<1	7.1
	9-16-06	183	6	5.5	4.8	1.1	0.28	3.9		7.1
	9-18-06	185	5	5.6	4	0.9	0.3	4.1	1.5	7.2
	9-21-06	188	23	6.1	4	1.6	0.3	4.3	<1	7.1
	9-24-06	191	13	6.9	4.8	1.4	0.29	4		
Run 10: 2,5,8	9-27-06	194	9	7.4	4.5	1.7	0.27	3.7	1.1	6.9
	9-30-06	197	10	6.1	4.4	1	0.31	3.5		7
	10-4-06	201	11	7	4.7	1.4	0.34	4.3	<1	7

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Table A.5 (Continued) Aerobic Effluent Characteristics

Run	Date	Day	Aerobic Effluent Characteristics (mg/L where applicable)							
			sCOD	TN	NO_3^--N	NO_2^--N	NH_3-N	TP	TSS	pH
Run 11: 1,3,8	10-8-06	205	3.9	6.1	3.2	1.3	0.51	5.6	1.2	7.3
	10-10-06	207	5.1	6.9				3.5		
	10-12-06	209	8.1	7.8	5.6	1.1	0.46	3.9	<1	7.4
	10-16-06	213	7.6	7.3	5.1	0.8	0.21	4.5	<1	
	10-20-06	217	5	6.5	4.7	1	0.35	4.2	1.1	7.2
Run 12: 3,5,8	10-24-06	221	4.3	7.3	6.1	0.5	0.21	4	<1	7.1
	10-27-06	224	3.2	9.9				5.8		7.1
	10-30-06	227	8.3	8.1	7.7	0.6	0.16	5.2	<1	7
	11-1-06	229	19.7	8.4	9	0.4	0.13	6.5	<1	7.2
	11-3-06	231	22	9.2	7.9	0.7	0.19	6.1	<1	7.2
Run 13: 0.5,1,8	11-6-06	234	16.5	8.4	7	0.9	0.34	6.8	1.3	7.3
	11-9-06	237	20.5	10.3				6.1		
	11-13-06	241	23.6	11	9.2	0.7	0.44	5.1	1.1	7
	11-16-06	244	20.4	11.2	8.6	0.9	0.36	5.3		
	11-17-06	245	19.5	10.4	8.4	0.8	0.29	5.7	<1	7.2
Run 14: 3,2,8	11-20-06	248	24.8	7	5.4	1.1	0.24	6.7	1.2	7.2
	11-23-06	251	8.5	6.5	5.1	1.3	0.2	3.7		
	11-26-06	254	28.4	7.2	5.8	1.1	0.15	4.1	1.3	7.3
	11-28-06	256	34.2	8.7	5.1	1.4	0.19	3.4	<1	
	11-30-06	258	19.5	8.1	5	1.2	0.11	3.5	1.2	7.3

Table B.1 Influent Characteristics

Run	Date	Influent Characteristics (mg/L where applicable)							
		COD	TN	NO_3^- -N	NO_2^- -N	NH_3-N	TP	TSS	pH
Run 1: 25 day SRT	12-14-05								
	12-18-05	530	49.6	4.2	1	>35	15.4	72	7.1
	12-21-05	534	44.2	2.6	1.2	28	12	15.6	7.1
	12-23-05	508	43.1	1.8	0.4		13.5		
	12-27-05	508	50.2	1.9	0.6	26	13.8	11.7	7
	12-30-06	545	49	1.6	0.3	23.9	14.4	22.9	7.1
	1-5-06	495	48.6	1.8	0.4	21.4	11.8		7.1
Run 2: 50 day SRT	3-10-06								
	3-16-06	498	54				13.5		
	3-17-06	476	53.1	1	0.5	24.8	12.8	17.8	6.9
	3-18-06	512					13.7		
	3-19-06	536	52.8	1.2	0.2	21.9	14.8	28.8	
	3-23-06	495	49.9	0.8	0.2		14.7		7
	3-24-06	488	44.4	0.5	0.2	17.1	12.7	27.5	7.1
	3-29-06	487	45.5	0.2	0.1	18.4	13.8		7
Run 3: 10 day SRT	3-31-06								
	4-4-06	479	47.3				14.3		
	4-5-06	451	55.6	0.8	0.1	23.2	15.8	11.2	7.1
	4-7-06	486	49				13.8		
	4-8-06	496	37.8	1.7	0.2	17.4	14	41.3	7.1
	4-10-06	480	52	1.1			13.8		
	4-12-06	430	55.2	0.6	0.1	21.5	14.5	19.3	7
	4-20-06	475	43.8	0.4	0.1	16.3	14.7		7.1
Run 4: 75 day SRT	3-30-06								
	4-4-06	442	51.4				14.6	35.4	
	4-5-06	451	55.6	0.8	0.1	23.2	15.8		7.1
	4-7-06	491	49				13.8		
	4-8-06	496	37.8	1.7	0.2	18.5	14.5	17.7	7
	4-10-06	480	52	0.8			14.5		
	4-12-06	450	55.2	0.6	0.1	21.5	14.5	29.3	7
	4-18-06	486	42.8	0.7	0.2		14.9		
	4-20-06	493	43.8	0.5	0.1	20.2	14.8	32.8	7.2

Table B.2 Aerobic Characteristics

Run	Date	Aerobic Characteristics (mg/L where applicable)									
		sCOD	TN	NO_3^- -N	NO_2^- -N	NH_3-N	TP (soluble)	Biomass P, %	TSS	PH	DO
Run 1: 25 day SRT	12-14-05										
	12-18-05	42	49.6	53	6.9	0.52	15.6	3.6	8,060	7.5	3.9
	12-21-05	40	44.2	34.1	0.8	0.48	12.9	3.4	8,560	7.3	3.6
	12-23-05	37	43.1	31.7			11.2	3.2	8,740		3.6
	12-27-05	20	50.2	38.5	1.2	0.44	8.6	3.3	8,680	6.9	3.6
	12-30-06	62	49	39.8	0.8	0.41	11.4	3.6	8,200	7	3.7
	1-5-06	65	48.6	37.9	0.2	0.35	11.8	3.5	8,240	7	3.62
Run 2: 50 day SRT	3-10-06										
	3-16-06	70	39				11.9				
	3-17-06	58	42.4	35.4	0.6	0.31	9.7	3.2	8,060	7.1	2.8
	3-18-06	79					12				3.4
	3-19-06	97	40.5	34.2	0.8	0.28	13.4	3.6	7,960		
	3-23-06	89					13	3.3	7,820	6.9	3.2
	3-24-06	92	38.4	26.4	0.1	0.26	12.1	3.2	7,680	6.9	3.12
	3-29-06	95	36.3	28.6	0.2	0.23	12	3.2	7,720	6.9	3.15
Run 3: 10 day SRT	3-31-06										
	4-4-06	56	34.2				13.8				
	4-5-06	67	38.6	23.3	0.9	0.38	15.7	3.5	2,680	6.8	2.3
	4-7-06	51	33.8				14.8				
	4-8-06	79	32.6	30.6	0.8	0.29	15.5	2.5	2,760	6.7	2.6
	4-10-06	48	45.8				14.5	2.1	3,660		2.8
	4-12-06	46	49.6	31.9	0.8	0.22	15.9	2.2	3,760	6.7	2
	4-20-06	51	41.7	24.2	0.7	0.18	13.9	2.1	3,540	6.8	1.92
Run 4: 75 day SRT	3-30-06										
	4-4-06	34	40.2				14.2		7,640		2.8
	4-5-06	47	38.8	24.5	0.7	0.31	14.9	2.6		6.8	
	4-7-06	52	41.8				12.9		8,460		2
	4-8-06	35	41.2	34.1	0.8	0.19	14.6	2.6	8,640	6.7	
	4-10-06	24	37.9				13.8		9,400		1.9
	4-12-06	45	36.5	27.8	0.6	0.23	12.1	2.1	8,980	6.9	2.06
	4-18-06	46	31.4				12.8	2.2	9,020		2.1
	4-20-06	46	33.8	21.2	0.6	0.22	11.8	2.2	8,980	7	2.05

Table B.3 Aerobic Effluent Characteristics

Run	Date	Aerobic Effluent Characteristics (mg/L where applicable)							
		sCOD	TN	NO_3^--N	NO_2^--N	NH_3-N	TP	TSS	pH
Run 1: 25 day SRT	12-14-05								
	12-18-05	20	54.4	57	6.5	0.41	14	1.1	7.5
	12-21-05	21	41.5	29.8	0.4	0.39	11.3		7.2
	12-23-05	22	44.5	30.6	0.8		10.9		
	12-27-05	4.5	47.5	31.8	0.9	0.4	11.2	1	6.9
	12-30-06	12	47.6	35.8	0.6	0.37	11.6		7
	1-5-06	15	42.2	35.9	0.6	0.34	11.8	1	7
Run 2: 50 day SRT	3-10-06								
	3-16-06	46	37				11.6		
	3-17-06	39	40.2	33.7	0.3	0.26	11.1	3.6	7.2
	3-18-06	47					11.5		
	3-19-06	61	38.4	33.1	0.4	0.24	12.4	1.2	
	3-23-06	49	36.2	24	0.3		11.9		6.9
	3-24-06	40	35.2	22.3	0.4	0.2	10.5	2.1	6.9
	3-29-06	43	35.1	24.6	0.5	0.2	11.1		6.9
Run 3: 10 day SRT	3-31-06								
	4-4-06	11	29.8				12.1		
	4-5-06	16	37.4	23	0.8	0.32	15.4	<1	6.8
	4-7-06	33	32.1				13.4		
	4-8-06	66	29.9	28.8	0.7	0.16	13.7	1.1	6.7
	4-10-06	38	42.5	28.4			13.2		
	4-12-06	31	42.5	30.8	0.6	0.18	13.7	1.1	6.7
	4-20-06	36	34.5	22.1	0.7	0.14	13.9		6.8
Run 4: 75 day SRT	3-30-06	3.9							
	4-4-06	21	37.8				12.8	1.2	
	4-5-06	24	36.9	23.5	0.5	0.29	14		6.8
	4-7-06	15	38.8				12.7		
	4-8-06		33.6	32	0.5	0.16	13.5	1	6.7
	4-10-06	13	36.7	25.3			11.5		
	4-12-06	35	36.9	26.5	0.4	0.19	11.7	<1	6.9
	4-18-06	35	29.3	24.5	0.5		12		
	4-20-06	35	30.7	19.4	0.4	0.2	11.8	<1	7

APPENDIX C. BACTERIAL FLOC IMAGES FROM CHAPTER FOUR

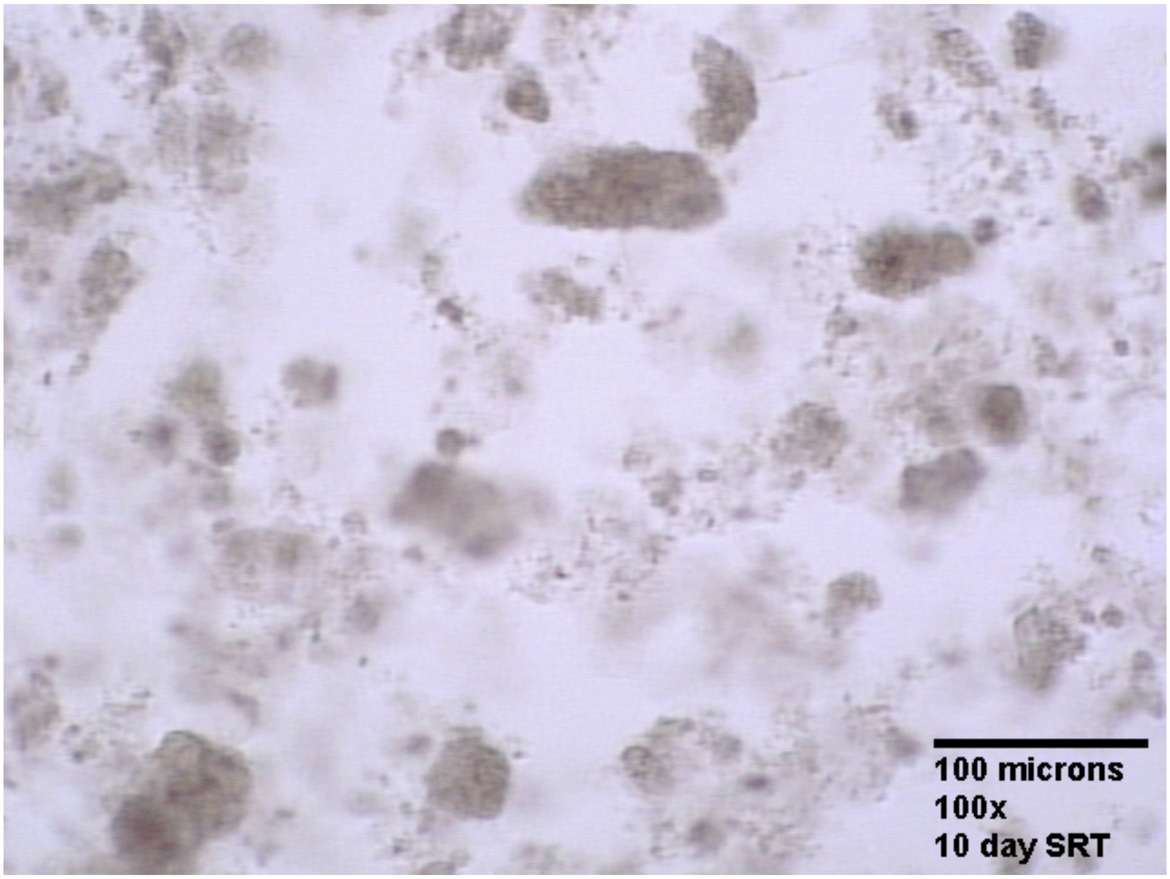

Figure C.1 Bacterial Floc Size Sample, 10 day SRT

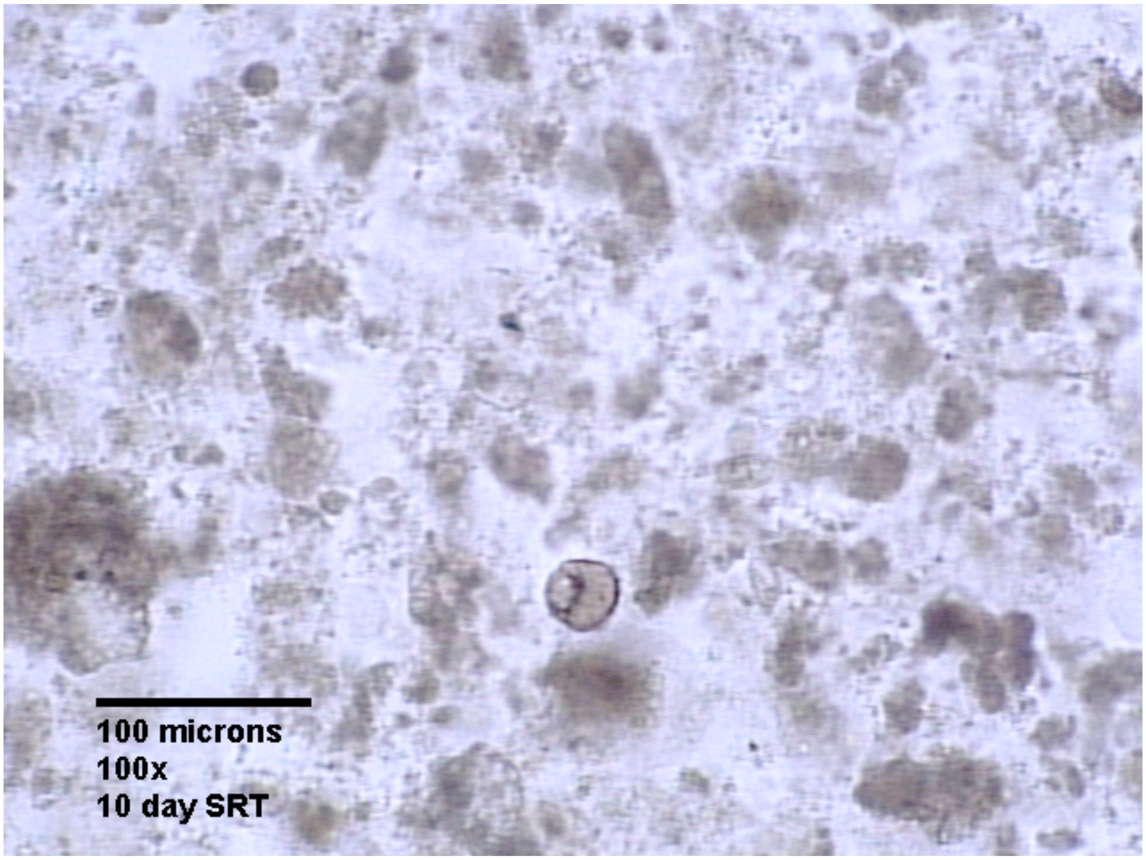

Figure C.2 Bacterial Floc Size Sample, 10 day SRT

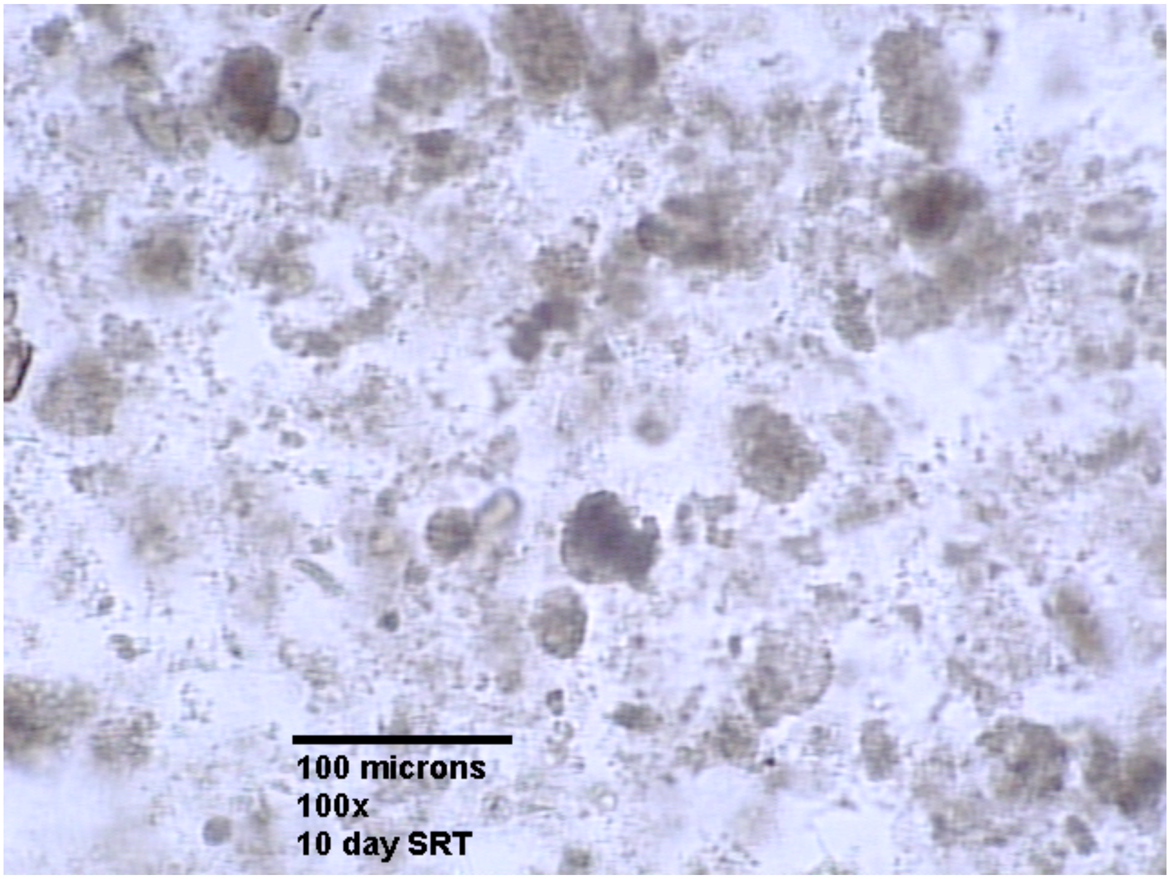

Figure C.3 Bacterial Floc Size Sample, 10 day SRT

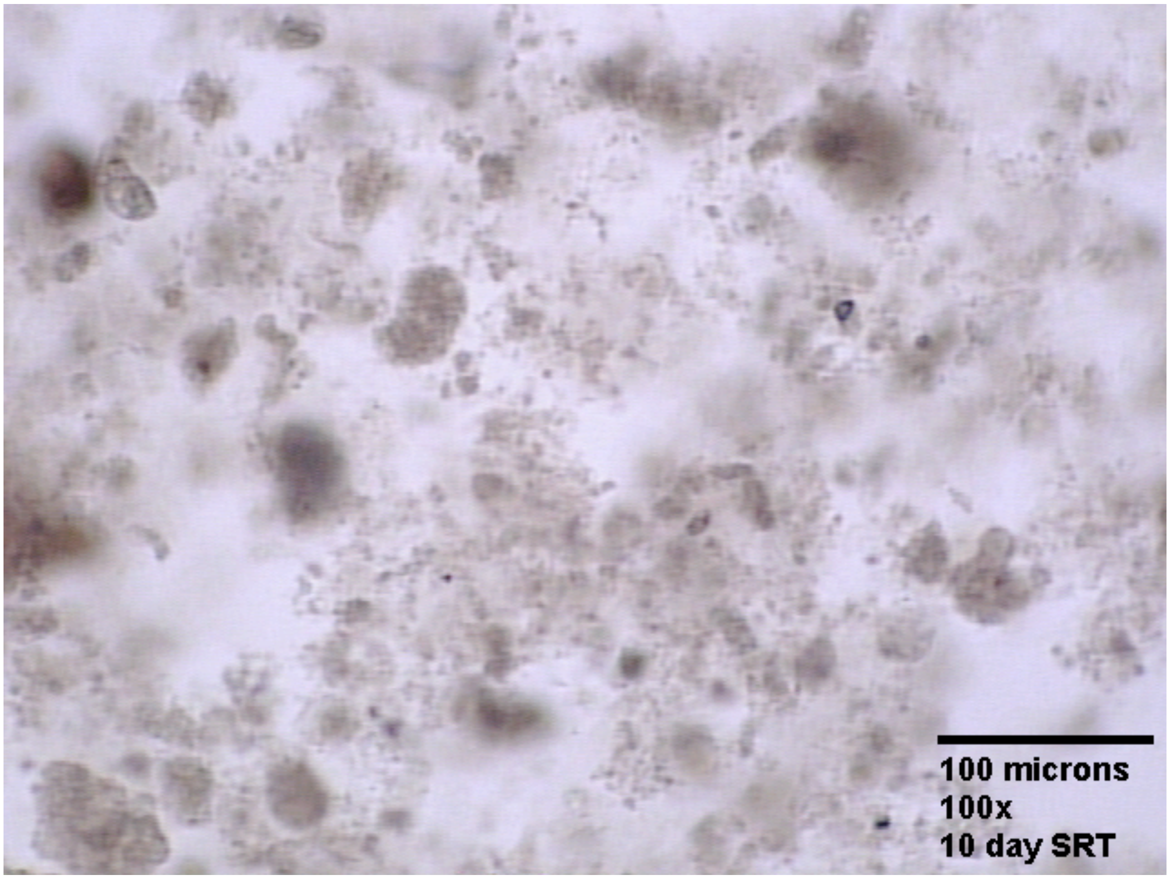

Figure C.4 Bacterial Floc Size Sample, 10 day SRT

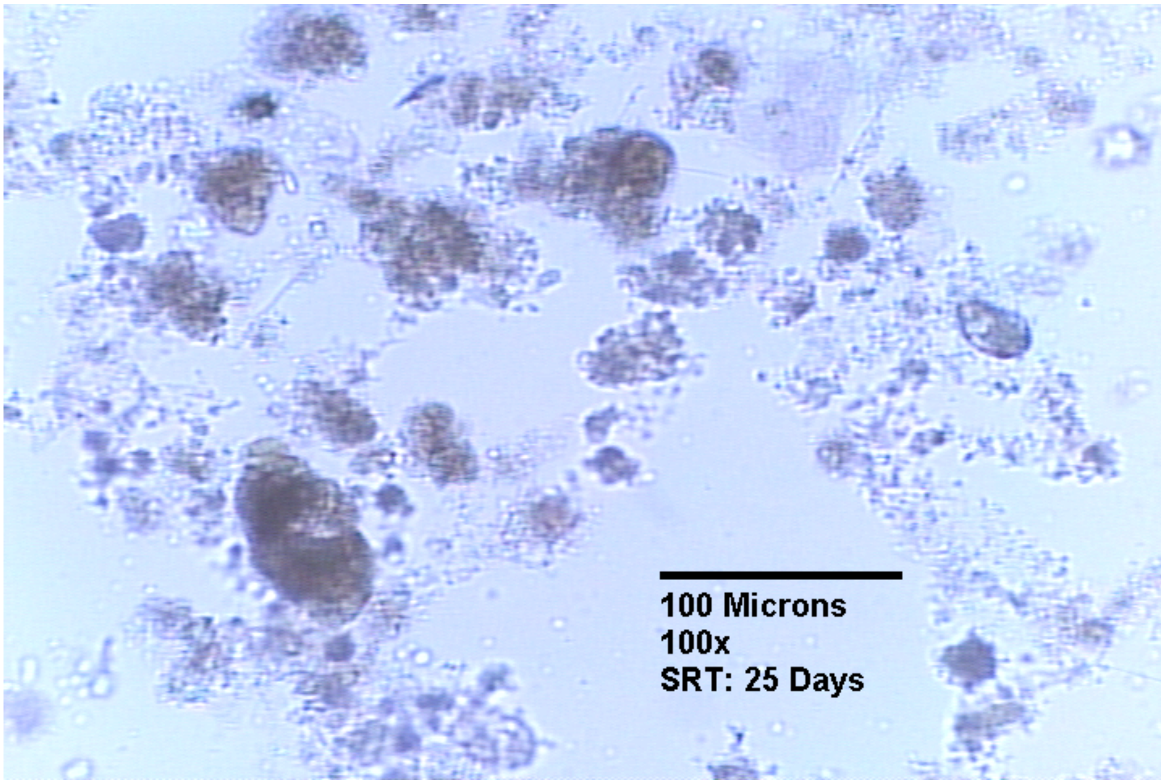

Figure C.5 Bacterial Floc Size Sample, 25 day SRT

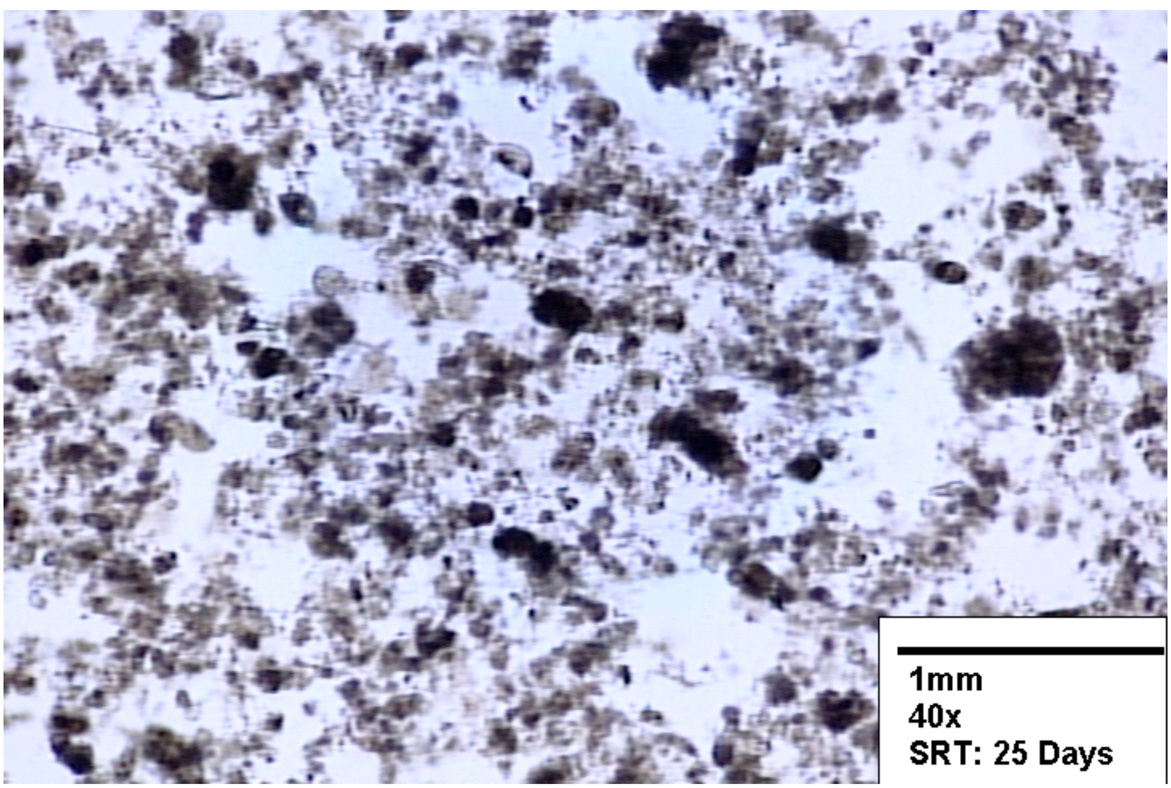

Figure C.6 Bacterial Floc Size Sample, 25 day SRT

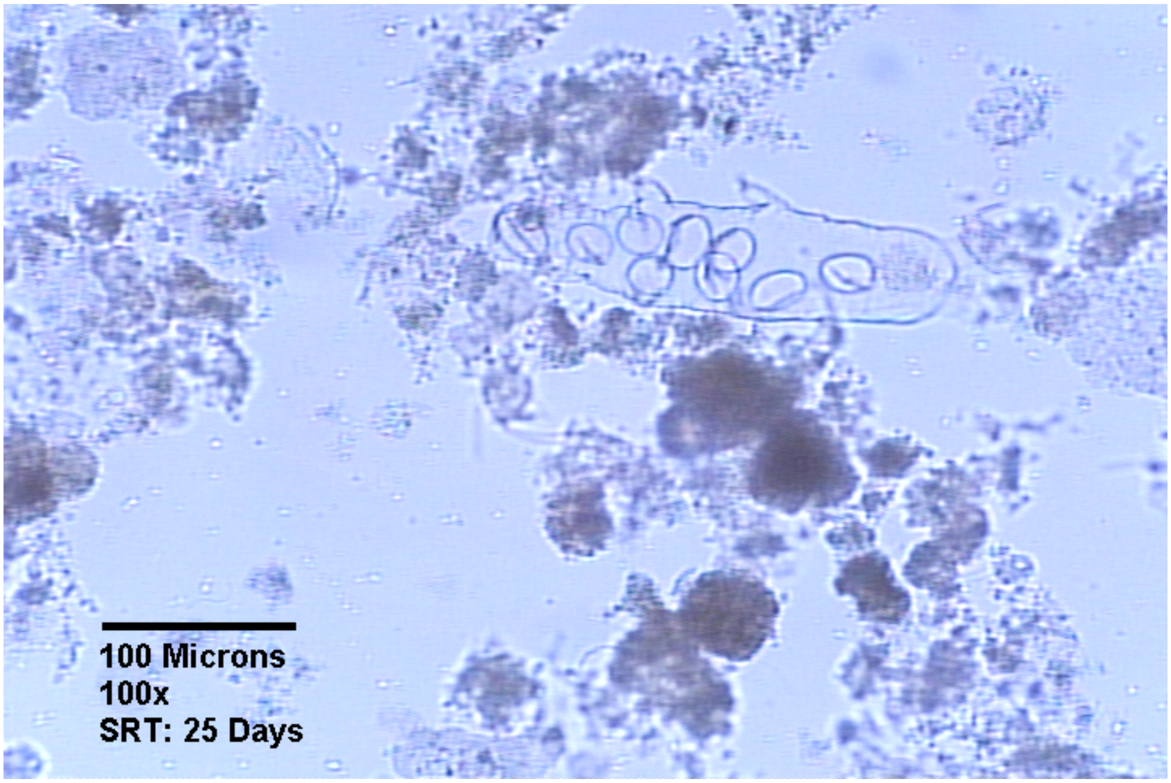

Figure C.7 Bacterial Floc Size Sample, 25 day SRT

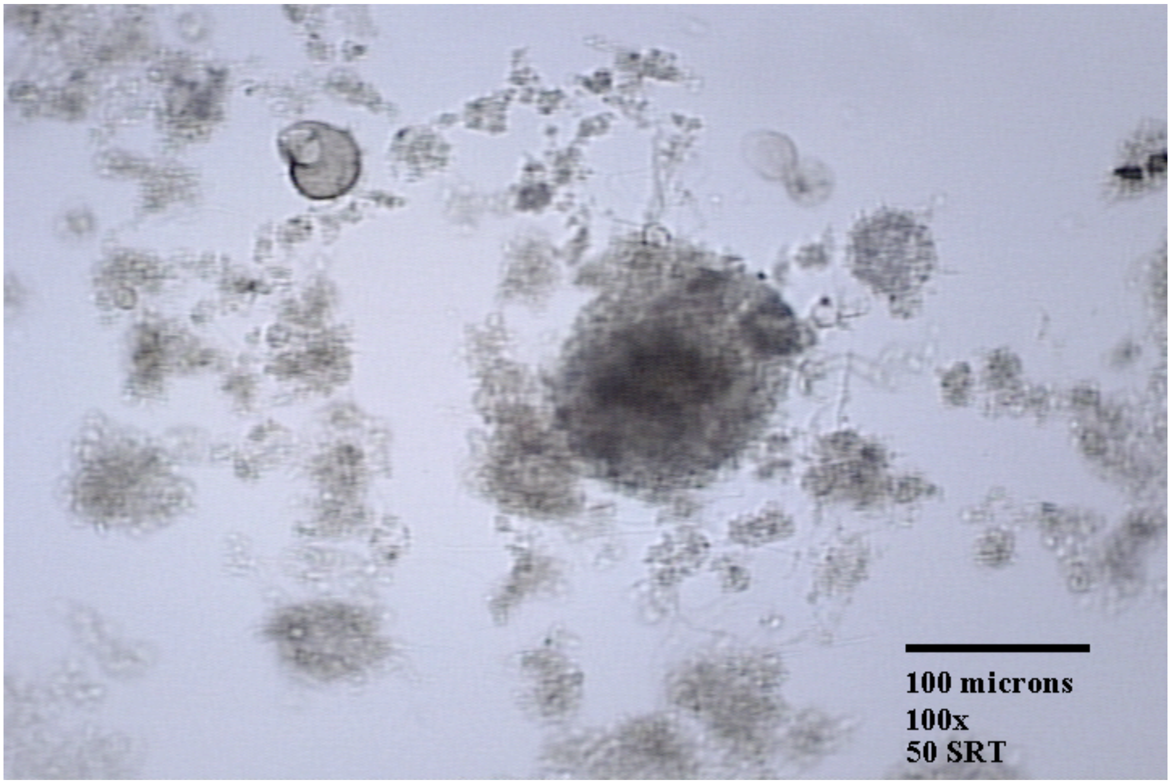

Figure C.8 Bacterial Floc Size Sample, 50 day SRT

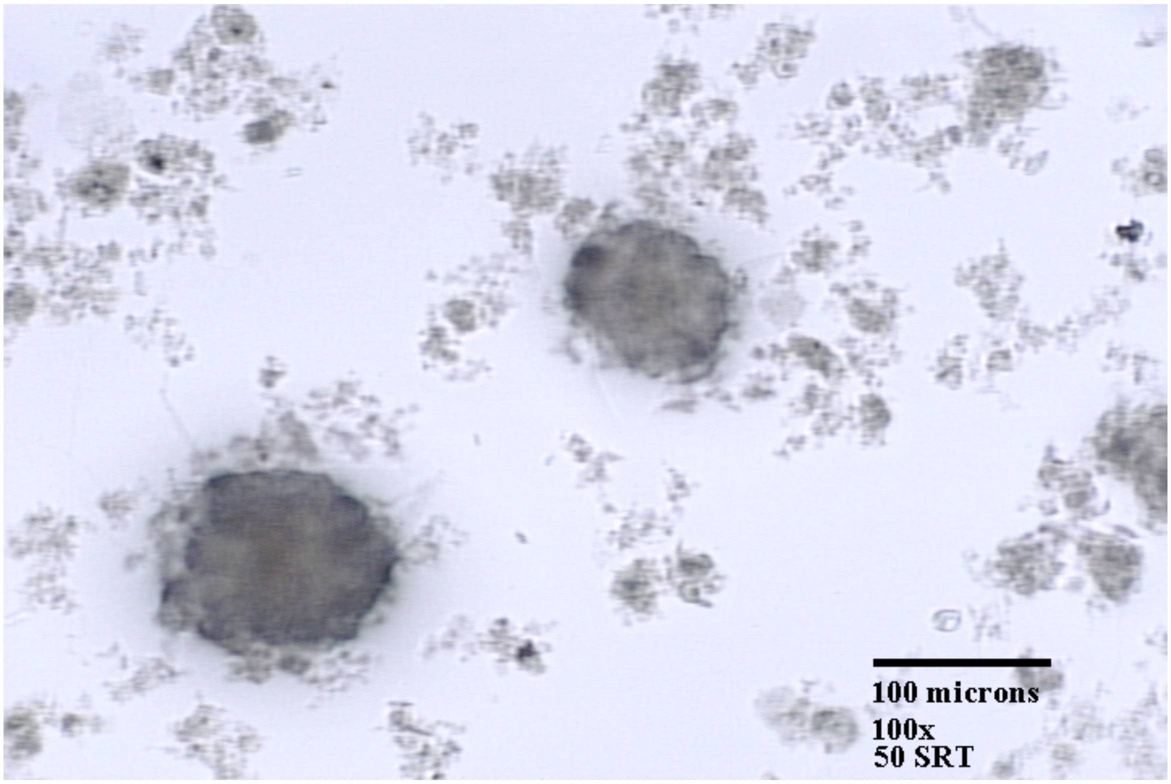

Figure C.9 Bacterial Floc Size Sample, 50 day SRT

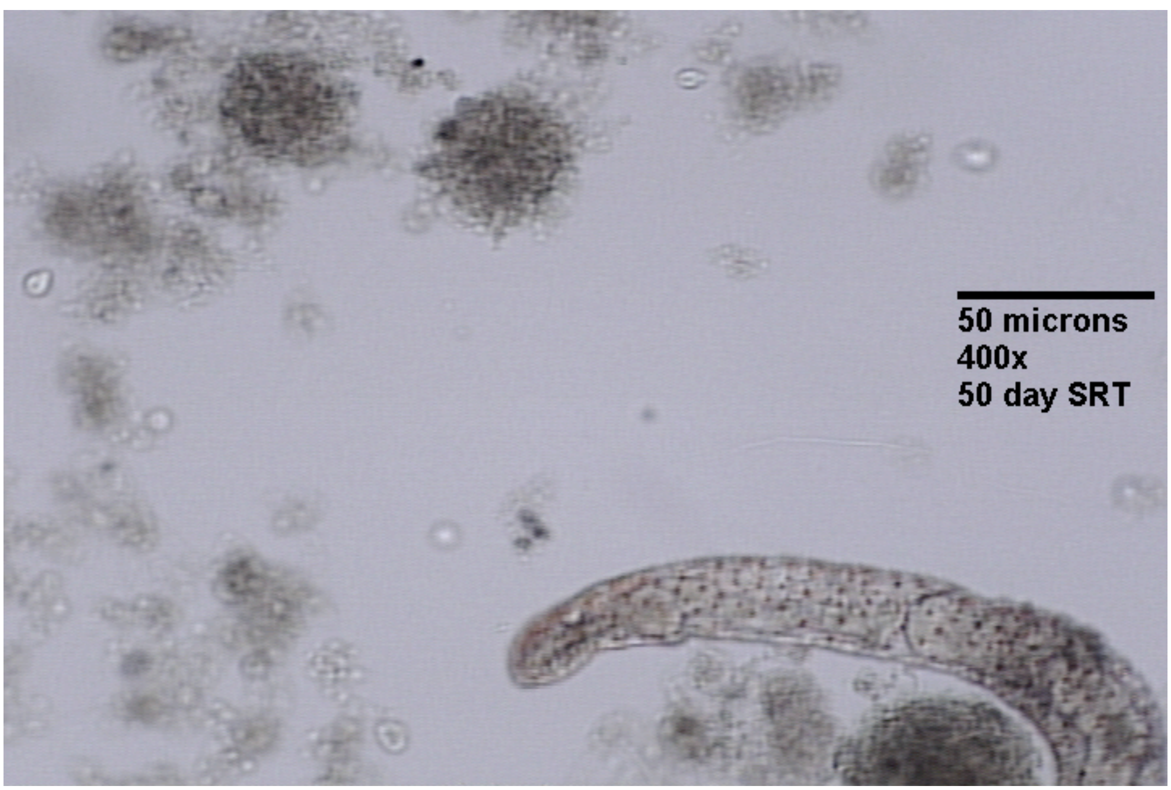

Figure C.10 Bacterial Floc Size Sample, 50 day SRT

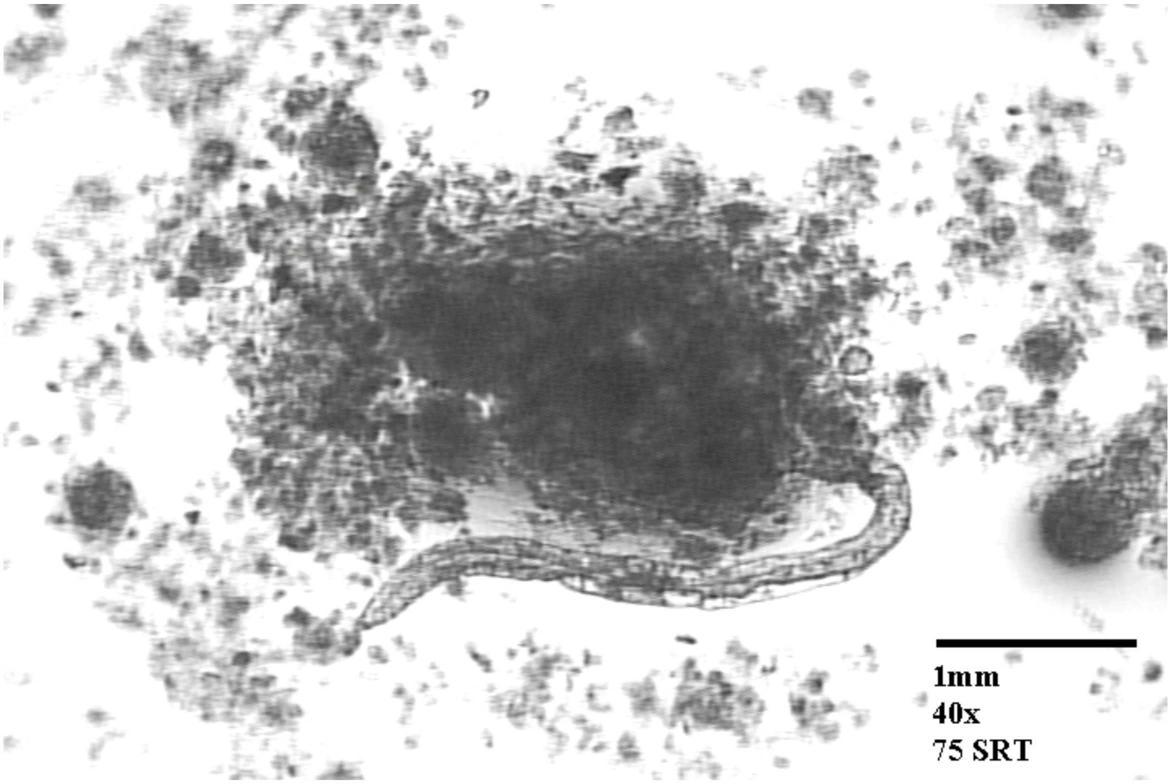

Figure C. 11 Bacterial Floc Size Sample, 75 day SRT

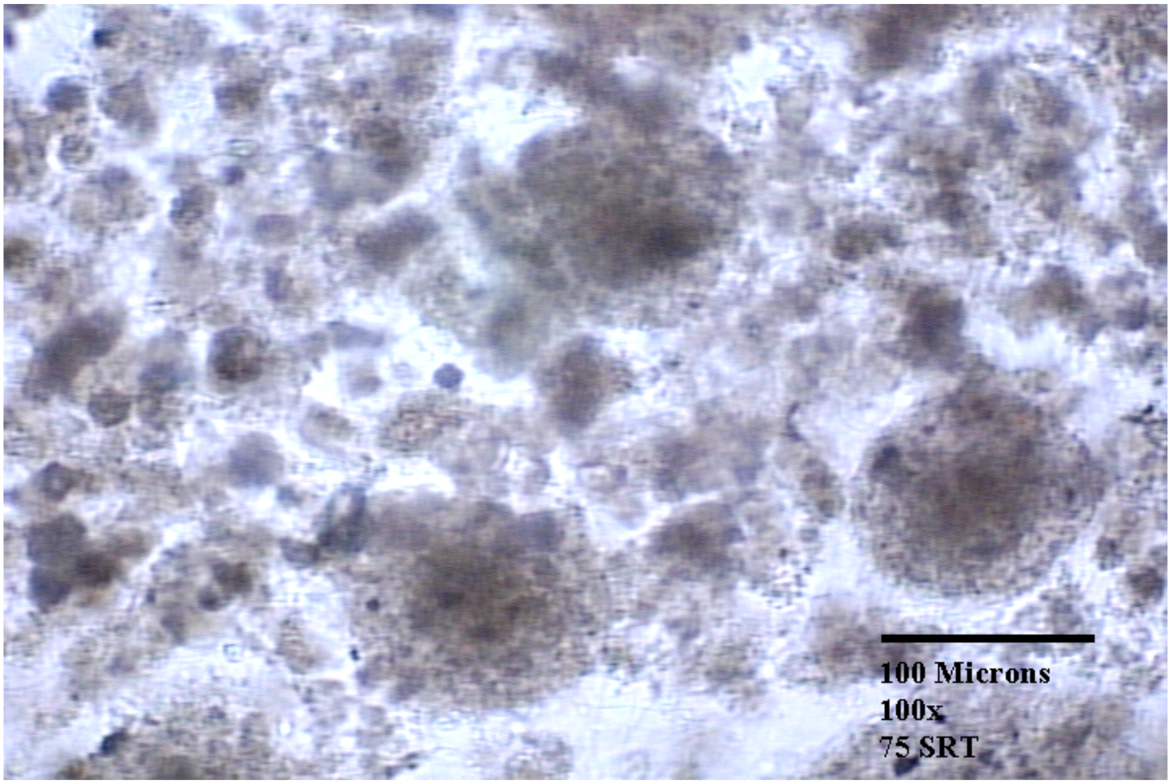

Figure C.12 Bacterial Floc Size Sample, 75 day SRT

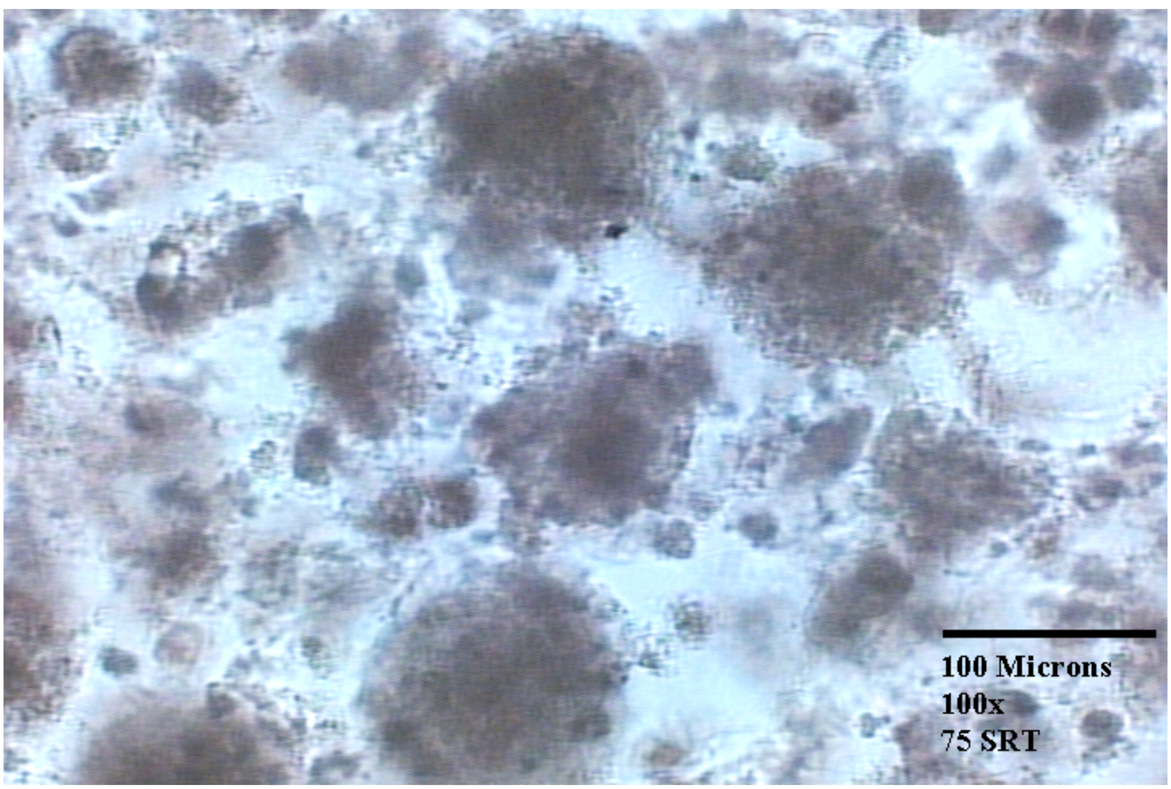

Figure C.13 Bacterial Floc Size Sample, 75 day SRT

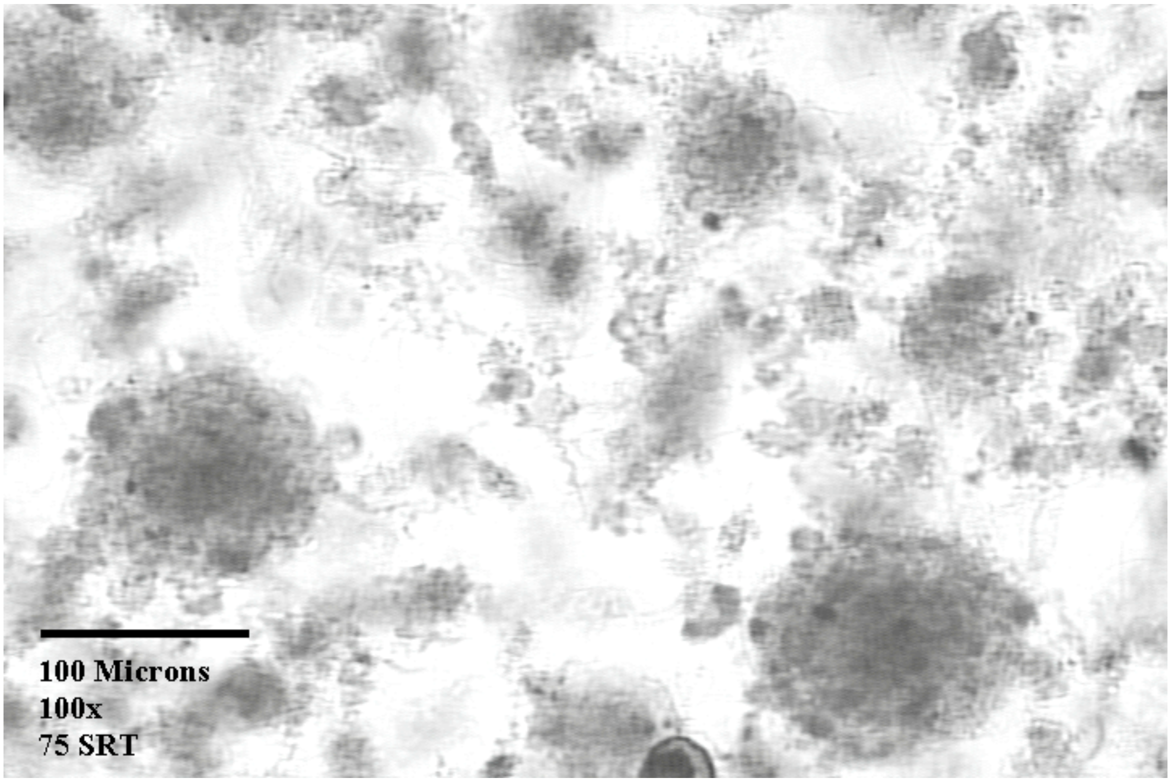

Figure C.14 Bacterial Floc Size Sample, 75 day SRT

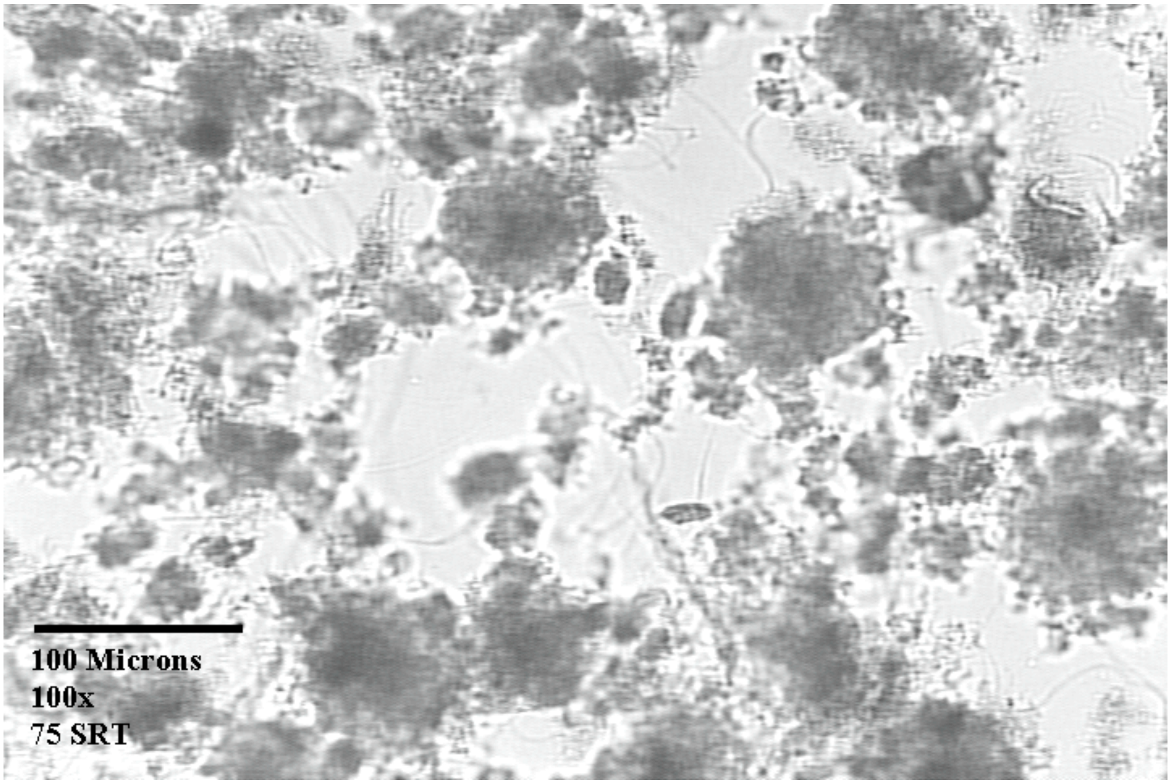

Figure C.15 Bacterial Floc Size Sample, 75 day SRT

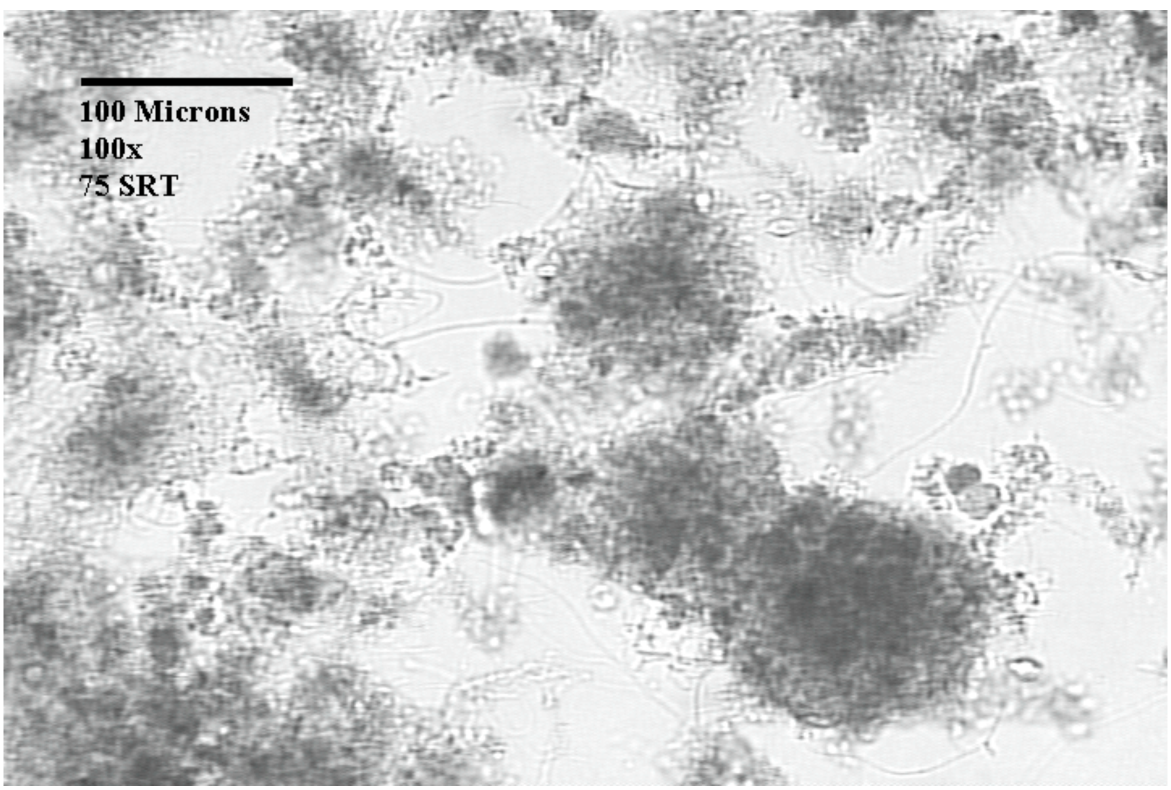

Figure C.16 Bacterial Floc Size Sample, 75 day SRT

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