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Pilot assessment of Novel Membrane Bioreactor Processes - Improvements in Biological Nutrient Removal and Membrane Operation

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Pilot Assessment of Novel Membrane Bioreactor Processes – Improvements in Biological Nutrient Removal and Membrane Operation

by

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of the requirements for the degree of
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Dedication

I dedicate this thesis to my fiancé, Robert, who has given me endless support throughout the stressful and overwhelming times. It has been a long journey and along the way, you have always reassured me that I could do it. This thesis is the product of both our efforts. You have truly helped and guided me through this and I thank you.

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I thank my parents for always telling me to aspire for more and always guiding me in my endeavors. To my entire family – you have been nothing short of supportive. I especially thank everyone, as during the writing of my thesis I grieved the loss of my grandmother and great aunt. It was truly a time of emotional struggle and sadness.

Finally, I thank my peers who believed in me and also supported me every day of this challenge.

Table of Contents

List of Tables

List of Figures

Abstract

With increasing water reuse applications and upcoming stringent regulations for treated wastewater effluent discharge, wastewater plants need to consider alternative technologies beyond conventional treatment processes. The new regulations, Numeric Nutrient Criteria (NNC), may regulate discharge nitrogen and phosphorus concentrations to as low as 0.5 mg/L as N and 10 µg/L as P respectively. To meet these target requirements, system retrofitting to incorporate chemical or advanced nutrient removal systems possibly with membrane technology will most likely be required. Although microfiltration/ultrafiltration membranes coupled with biological processes, otherwise known as membrane bioreactors (MBR), remove contaminants and suspended solids, nutrient removal is minimal to none. This emphasizes the importance of the biological process in MBRs. This study evaluated and tested the improvement of biological nutrient removal (BNR) in an MBR system which can meet NNC regulations along with the optimization of membrane operation for the reduction of fouling and energy consumption.

A pilot study was conducted at the City of Tampa wastewater treatment plant and was divided into four phases of experimentation using two submerged MBR membranes operated with modified biological configurations. Laboratory analyses and data collection were conducted during the experiments and the performance evaluated for each configuration. System configurations were also optimized throughout each phase of testing for nutrient removal. Important factors used in the development of an appropriate configuration included isolation of the membrane tank from the biological reactors in the design, control of the dissolved oxygen (DO)

concentrations or specifically the oxidation reduction potential (ORP) during operation and appropriate internal recirculation rates between the reactors.

The results of this study provided information relevant for the assessment of both the BNR process and membrane performance. Membrane performance data indicated the importance and effect of air scouring (despite energy consumption) on membrane fouling for long-term stable flux operation as well as the cleaning frequency whether chemical enhanced backwash (CEB) or clean-in-place (CIP). This assessment also discussed how BNR systems can be enhanced through the incorporation of important design factors to eliminate the inhibiting factors of nitrogen and phosphorus removal such as dissolved oxygen. One of the biological processes tested in this study achieved effluent nitrogen and phosphorus concentrations below 5 mg/L and 1 mg/L respectively. Although the process tested did not meet NNC criteria, it can be applied with chemical precipitation. This, in turn, can reduce the operating and maintenance (O&M) costs associated with the chemical precipitation of phosphorus.

1. Introduction

1.1 Background

Growing water demands and increasing global water shortage are driving research towards sustainable water source alternatives. The alternatives include water reuse which can be used to meet non-potable water demands and perhaps be applied for direct or indirect potable reuse. Often water reuse systems incorporate membrane filtration such as in the tertiary treatment of wastewater. Recently, membrane applications in water reuse have increased and the market is projected to continue increasing [1-7]. Such applications usually combine biological processes with microfiltration (MF) or ultrafiltration (UF) membranes for the direct treatment of wastewater and has been termed membrane bioreactors (MBRs).

MBR systems for wastewater treatment typically meet the water quality standards required for reuse applications such as the California Department of Public Health (CDPH) Title 22 criteria [8]. Future regulations, specifically the numeric nutrient criteria, are expected to change the discharge requirements beyond the treatment limitations of conventional wastewater treatment [3, 9] and MBRs may be required. Although membrane bioreactors produce effluent water that meets the water reuse criteria, some disadvantages in MBR include fouling propensity and energy consumption. These are the main drivers in both academic and industrial research towards improving MBR operation and maintenance [10].

Membrane bioreactors can remove solids and soluble contaminants from wastewater once combined with the appropriate biological process. Previous research studies have evaluated MBRs with different biological processes – most commonly

Modified Ludzack Ettinger (MLE) and Anaerobic-Anoxic-Oxic (A^2O) (discussed in section 2.2) to improve nutrient removal etc. [11-14]. Specific studies into the improvement of phosphorus and nitrogen removal are becoming more prominent. These studies have focused on modifications to the A^2O and University of Cape Town (UCT) process with respect to operating parameters including hydraulic retention time (HRT), internal recirculation and sludge retention time (SRT) [12, 15, 16]. In this study these processes were re-evaluated and modified to test and optimize biological nutrient removal (BNR) with MBR for the application of water reuse that will meet future regulations.

1.2 Objectives

Given the upcoming regulations, the main purpose of this research study was to evaluate and modify biological nutrient removal process(es) with a membrane bioreactor for the enhancement of biological nitrogen and phosphorus removal. The biological processes were pilot-tested and assessed for their implementation to meet the numeric nutrient criteria especially for that of phosphorus. During pilot operation, BNR system performance was assessed and optimized. Also, membrane optimization assessments were completed to improve fouling and energy consumption.

1.3 Scope of Work

The pilot system was designed with 1) a modified A^2O-MBR, 2) a modified UCT-MBR biological process configurations and 3) a new biological process that uses components of both the A^2O and UCT in order to test and optimize nitrogen and phosphorus removal performance at high solids concentration and at a fixed HRT. Two polyvinylidene fluoride (PVDF) membranes were tested in this study and the flux, trans-membrane pressure (TMP) and the filtrate turbidity were monitored to evaluate the performance of each membrane. This study was divided into 4 phases of experimentation where the biological processes mentioned were tested among the two membranes. Nitrogen and phosphorus profiles were conducted frequently throughout all phases of testing to record nutrient removal performance and the effect of changing operating parameters. Data analysis was performed to evaluate membrane operational efficiency and to evaluate membrane fouling and its relation to MBR operating parameters.

2. Literature Review

2.1 Conventional Activated Sludge Process

Generally wastewater, after treatment, is discharged to the natural environment or can be used for water reuse. The level of treatment in wastewater treatment depends on the regulated discharge requirements to preserve the natural environment and to protect human health [17]. Wastewater can be treated using physical, chemical and biological processes. Some physical and chemical processes include the addition of chemicals such as polymers to the wastewater, settlement with a clarifier, and filtration with sand filters [18]. Biological processes utilize microorganisms to convert, take up or remove contaminants under the appropriate growth conditions. Microorganisms can utilize organics, inorganics, and suspended solids for the removal of regulated contaminants such as ammonia, biochemical oxygen demand (BOD), nitrogen, and phosphorus [19].

Wastewater treatment can be categorized according to treatment whether primary, secondary or tertiary (also considered 'advanced' wastewater treatment) [17, 18]. As wastewater enters the treatment plant, it is screened to remove large objects and a grit removal system isolates inert particles especially sand. Primary treatment removes settleable organic solids. Additionally, the chain-and-flight collector on some clarifiers help to additionally remove floatable inert and organic solids [20]. In secondary treatment, organics are removed whether colloidal or soluble [17, 21]. Tertiary treatment refers often to nitrogen or phosphorus removal, or both, whilst advanced wastewater treatment usually further refers to required disinfection and additional removal of solids often to be used for water reuse.

However, tertiary and advanced wastewater treatment have been considered to achieve the same treatment outcome [17].

Raw wastewater contains nutrients, suspended solids, organic and inorganic contaminants. Wastewater processes utilize suspended growth bacteria in reactors for the removal of target contaminants. The organic content of domestic wastewater has an oxygen demand, which if discharged to the environment causes depletion of the dissolved oxygen (hypoxia) in environmental waters which may cause eutrophication [22]. With aeration and in the presence of an appropriate bacterial species, organics are removed as they become oxidized to carbon dioxide. The microorganisms utilize the organics for growth and become aggregated to form what is described as microbial suspended 'flocs' (activated sludge). A clarifier is then used to settle solids, and the 'floc' returns microorganisms in the return activated sludge (RAS) for continued organic removal or nutrient removal from the incoming wastewater. This is important because effluent is produced because the flocs settle due to gravity and are not discharged to the environment. These flocs can be described according to their morphological properties such as pin floc and bulking floc. These terms are used to describe smaller (slower settling) floc formation and filamentous growth (non-settling) respectively [23]. For these reasons, settling properties are important in conventional treatment to prevent loss of microorganisms and to prevent total suspended solids (TSS) from being present in the effluent (at high concentrations).

Figure 2.1 shows a conventional advanced wastewater treatment process using a basic biological process with a clarifier. Conventional wastewater treatment includes screening (of large material), grit removal, primary clarification and a simple biological process for removal of organics specifically BOD. Usually, a clarifier and

disinfection is used prior to the final discharge to the environment to remove fecal coliforms. Wasted sludge or primary sludge is often treated by anaerobic digestion.

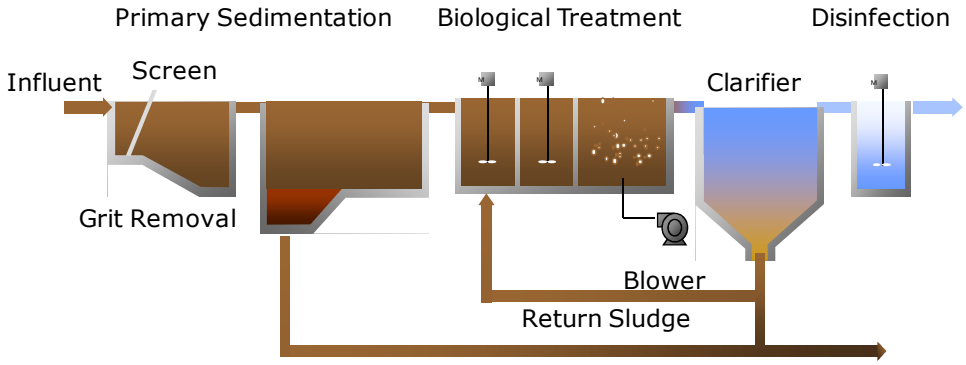


Figure 2.1 Conventional Activated Sludge (CAS) Treatment Process

2.2 Biological Nutrient Removal Process

Wastewater contains nutrients such as nitrogen and phosphorus. If untreated and discharged, these nutrients lead to hypoxia and eventually eutrophication. Because of nutrient loading to estuaries and rivers, a conventional wastewater treatment process requires removal of such nutrients to meet regulated discharge limits. Biological nutrient removal (BNR) processes are configured for the removal of both total nitrogen (TN) and total phosphorus (TP) from wastewater through the use of microorganisms under different environmental conditions in different reactor zones combined in a single process [24].

Total nitrogen in domestic wastewater comprises of ammonia, nitrite, nitrate and particulate and soluble organic nitrogen. Nitrogen in the form of ammonia can be removed using the biological nutrient removal (BNR) process of nitrification and denitrification in the wastewater treatment plant (WWTP) [25]. The nitrification process oxidizes ammonia (NH_3) initially to nitrite (NO_2) and is then subsequently further oxidized to nitrate (NO_3). *Nitrosomonas* and *Nitrobacter* are examples of

autotrophic bacterial species that can carry out such conversions [26]. The denitrification process reduces nitrate to nitric oxide (NO), nitrous oxide (N_2O), and lastly nitrogen (N_2) gas which is released to the atmosphere [18]. Heterotrophic and autotrophic bacterial species can perform denitrification [24, 26]. Because of the differing growth conditions required of each species, reactors are designed to maintain the specific growth conditions which in turn maintain the nitrification and denitrification rate of the process.

The process involved in nitrogen removal can be explained through the biochemical reactions occurring and described in the equations below. Nitrogen is removed through a series of redox reactions between electron donors and acceptors [22]. Equation 2.1 and equation 2.2 show the two step nitrification (oxidation) process while Equation 3 shows the overall nitrification process [22].

$$\frac{1}{6}\ NH_4^+ + \frac{1}{4}\ O_2 \rightarrow \frac{1}{6}\ NO_2^- + \frac{1}{3}\ H^+ + \frac{1}{6}\ H_2O \qquad 2.1$$

$$\frac{1}{2}\ NO_2^- + \frac{1}{4}\ O_2 \rightarrow \frac{1}{6}\ NO_2^- + \frac{1}{2}\ NO_3^- \qquad 2.2$$

$$NH_4^+ + 1.815\ O_2 + 0.1304 \rightarrow 0.0261\ C_5H_7O_2N + 0.973\ NO_3^- + 0.921\ H_2O + 1.973\ H^+ \qquad 2.3$$

Figure 2.2 shows the treatment of nitrogen as nitrifying bacteria undergo the nitrification reaction in the presence of oxygen in the aerobic reactor, and denitrifying microorganisms undergo the denitrification reaction in the absence of oxygen and in the presence of a carbon source in the anoxic reactor as shown in Figure 2.2 [25]. Also shown in Figure 2.2 is the influent total nitrogen (TN) for which Total Kjeldahl Nitrogen (TKN) can also be measured. TKN is a measure of organically bound nitrogen and ammonia/ammonium. If nitrate and nitrite are measured separately, they can be added to the TKN to obtain the TN. Reactor configurations are further discussed in section 2.2.

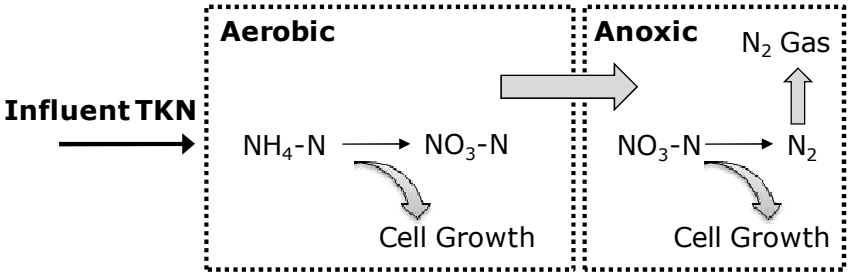


Figure 2.2 Biological Removal Mechanism for Nitrogen

Another nutrient found in wastewater is phosphorus which can be soluble or particulate in nature. Both the soluble and particulate phosphorus together incorporate total phosphorus (TP). Particulate phosphorus can be removed by physical treatment options such as filtration or settling. Soluble phosphorus, on the other hand, requires a biological or chemical process for removal. Chemical precipitation is one option with the use of aluminum or iron coagulants [17]. A biological phosphorus removal process utilizes bacterial capabilities for their capability to take up phosphorus as they grow in the system. This process is considered the enhanced biological phosphorus removal (EBPR). The bacteria responsible for this are categorized as phosphate-accumulating organisms (PAOs) [17, 18]. Phosphorus, which is now stored inside PAO cells (in mixed liquor), is then removed from the system through fixed and continued wasting of the mixed liquor. This wasting flow controls the sludge retention time (SRT) and is important. Since cells can release phosphorus and take up phosphorus, if the SRT is not carefully controlled, secondary phosphorus release may be possible and is not desired. Phosphorus can be taken up by PAOs in excess of cell requirement but only under specific biological cell requirements. In anaerobic conditions of low dissolved oxygen (DO) concentrations, PAOs convert readily available organic matter like volatile fatty acids (VFAs) to carbon compounds for storage which is considered as

polyhydroxybutyrate (PHB). This is further discussed later. The result of this is an initial release of phosphorus from the cells. In the aerobic zones of high DO concentrations, PAOs then utilize the stored carbon compounds for growth leading to an excessive uptake of the phosphorus which was previously released in the anaerobic zone [25]. For efficient phosphorus removal, it is very important to promote the growth of PAOs in the bioreactor which can be inhibited by denitrifiers or the presence of nitrate. Figure 2.3 below summarizes phosphorus removal.

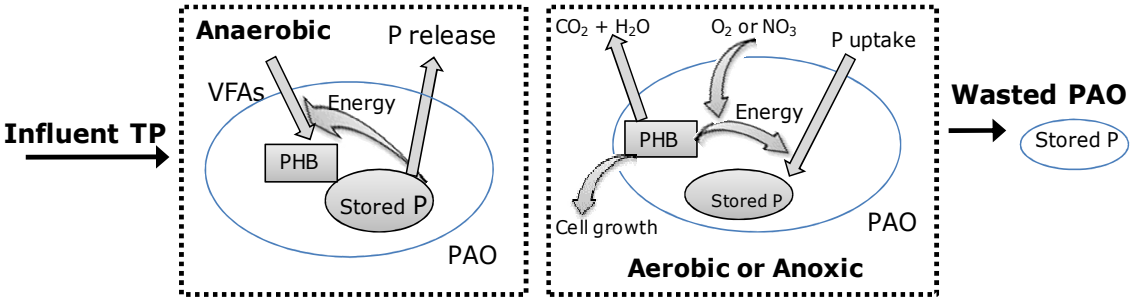


Figure 2.3 Biological Removal Mechanism for Phosphorus [25]

Removal of either nitrogen and phosphorus removal, or both, is achieved using different BNR configurations. Depending on the regulated effluent quality and influent wastewater quality, biological nutrient removal configurations vary based on the sequence and environmental conditions of the reactor zones including the aerobic, anaerobic, and anoxic reactors. Table 2.1 shows a comparison of BNR systems and their configurations for the removal of nitrogen and phosphorus. BNR systems like those described below can be applied to remove nutrients in wastewater treatment process or selectively remove phosphorus or nitrogen. Biological configurations are further discussed in section 2.2.

Table 2.1 Types of BNR Configurations [17, 18, 26]

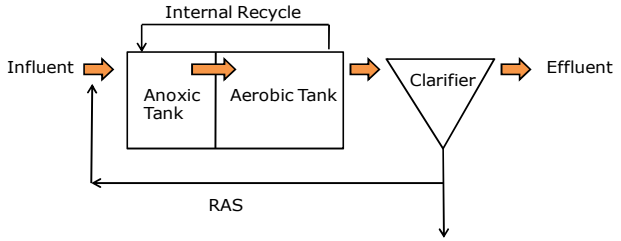
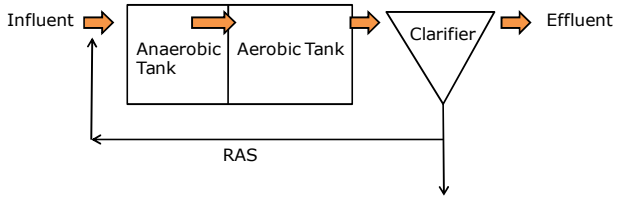
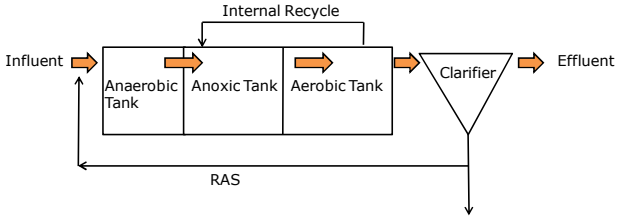
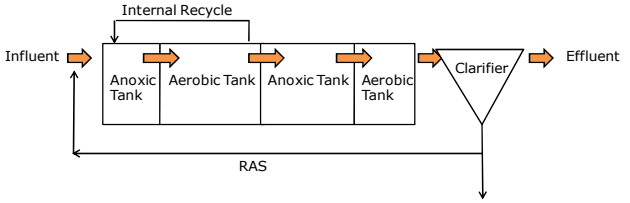
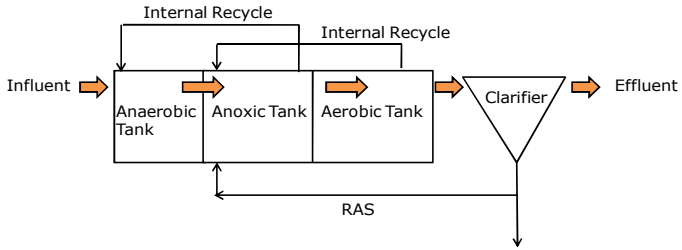
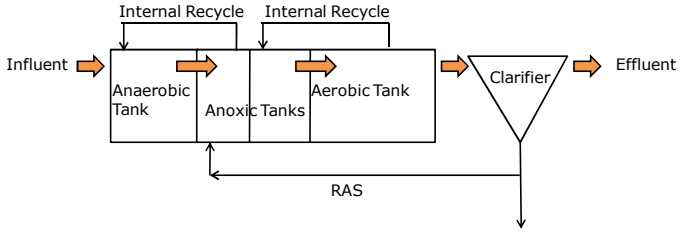
Process Configuration	Description	Process Layout
MLE (Modified Ludzack-Ettinger)	Basic activated sludge process using an anoxic and oxic tank followed by a clarifier. The oxic tank produces nitrate which when recycled to the anoxic can be converted to nitrogen gas. Phosphorus removal is minimal to none.	
Pho-redox A/O (Anaerobic – Oxic)	An anaerobic tank and oxic tank provide the conditions for PAO growth and phosphorus uptake. This is a simple process for phosphorus removal.	
A^2O (Anaerobic-Anoxic-Oxic)	This configuration combines the operation of MLE and A/O for growth of PAO, nitrifiers and denitrifiers with recirculation from the oxic to the anoxic and the RAS to the anaerobic. Nitrogen and phosphorus removal can be achieved.	
Bardenpho Process	This process utilizes sequenced anoxic-oxic configurations for nutrient removal. Improved phosphorus and nitrogen removal.	

Table 2.1 (Continued)

UCT (University of Cape Town)	This process maintains the same reactor configuration of A^2O with the addition of a recirculation line from the anoxic to the anaerobic reactor. Efficient removal of phosphorus and nitrogen.	
MUCT (Modified University of Cape Town)	This is an improved configuration of UCT with separated recirculation from specific reactor zones of the anoxic tank. Better nitrogen and phosphorus removal compared to UCT observed.	

In a BNR system, the percentage and content of mixed liquor recycle rate to the anoxic zone and the RAS recycle rate to the anaerobic zone are crucial factors for enhancing nitrogen and phosphorus removal efficiencies [27, 28]. This is because the recycled sludge provides active biomass and the biomass affects the nitrification and denitrification reaction. Optimizing the percentage and content of this recycle stream results in optimal TN removal. The RAS contains high DO or high nitrate content and may interfere with the phosphorus removal mechanism [28]. Therefore, optimized sludge recycle rate and the minimized RAS recycle rate need to be utilized for BNR systems [16, 29].

Nitrifying bacteria, otherwise known as ammonia oxidizing bacteria (AOB) and nitrite oxidizing bacteria (NOB), require carbon dioxide and an inorganic substrate whether ammonia or nitrite [17]. During nitrification, carbon dioxide is consumed which in turn reduces the alkalinity in the system. This is further discussed in 2.2.1. Oxygen concentrations above 2 mg/L are most important as well as a pH above 7.0 [17]. Denitrifiers are facultatative aerobes which use nitrate or nitrite to oxidize organic substrates. Oxygen is most preferable as an electron acceptor but nitrate can also be used if oxygen is not available. The end product in nitrogen removal is the production of gaseous nitrogen which is released to the environment.

Phosphorus removal is less understood at the biological and biochemical level. Theoretical models for phosphorus removal as previously mentioned above have been developed over the years and continue to be studied since the dominant species responsible for phosphorus removal has not been identified although *Acinetobacter* spp. has been tentatively identified to contribute to EBPR [30, 31]. The most common theory for phosphorus removal is shown in Figure 2.3. The PAOs use a carbon source, VFAs, to release phosphorus followed by an uptake as cell growth enables a larger uptake than that released in the anaerobic reactor [17, 30, 32].

In the anaerobic reactor, PAOs hydrolyze poly-P which supplements energy in order for carbon sources from the influent to be taken up. The hydrolysis of poly-P causes the release of orthophosphate. The carbon becomes stored in the form of polyhydroxyalkanoates (PHA) specifically polyhydroxybutyrate (PHB) [30, 32, 33]. Liu et. al [33] have also studied the effect of competing glycogen accumulating organisms (GAOs) for VFA uptake in biological proceses. GAOs can take up acetate, also producing PHA, but lack the ability to remove phosphorus and can have an effect on EBPR if they become dominant in the anaerobic reactor which has been identified to undergo favorable growth with pH below 7.2. [33]. In the aerobic reactor, PAOs grow aerobically where the cells use orthophosphate previously released to recover poly-P as the stored PHA is utilized [30]. It has also been suggested that phosphorus uptake can be observed in the anoxic since PHB is used for respiration. Importantly, since phosphorus is stored in the bacterial cells, phosphorus becomes removed as the sludge (mixed liquor) is wasted at fixed design rates and appropriate retention times to prevent secondary release (due to cell death) which would inhibit phosphorus removal.

2.2.1 Modified Ludzack-Ettinger (MLE) Process

If we consider the most conventional process for nitrogen removal, the MLE process is utilized. Although phosphorus removal is minimal, nitrogen and BOD are removed efficiently with the appropriate operating parameters. If we review the nitrification and denitrification process as previously discussed, nitrification will utilize oxygen as an electron acceptor. A side product produced during the process is hydrogen ions which will react and consume alkalinity in the water. This is equivalent to the molar fraction in Equation 3. Nitrifiers, which are autotrophs, also have a very slow growth rate which explains the requirement of a longer SRT [22]. By placing an

un-aerated and mixed reactor before the aerobic reactor as shown in Figure 2.4, influent BOD is utilized for denitrification. The BOD serves as an electron donor. In the aerobic reactor, BOD not utilized for denitrification is oxidized and TKN/TN is converted to nitrate. The nitrate is returned through the internal recycle to be denitrified. The ratio of recirculation flow rate compared to the feed flow rate, Q, is important since nitrate and water not recycled will leave the system as the effluent. The additional benefit to this process is the reduction in oxygen requirement for BOD removal since nitrate becomes an electron acceptor and organic carbon is the electron donor in denitrification. Since denitrifiers are heterotrophs, they can shift between oxygen or nitrogen respiration [22]. During the biochemical reactions, alkalinity becomes consumed or generated as a side product of the reaction which is the case in nitrification and denitrification respectively.

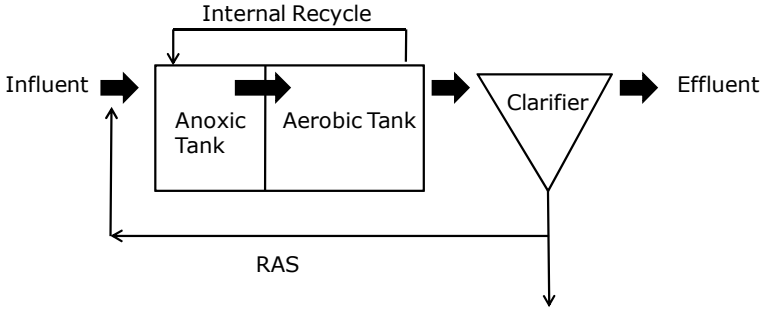


Figure 2.4 MLE-CAS Process Flow Configuration

2.2.2 Anaerobic-Anoxic-Oxic (A^2O) Process

Unlike the MLE process, the A^2O process includes an additional reactor, anaerobic reactor. The addition of this reactor helps in the removal of phosphorus. Bacterial cells contains 2-3% P in its dry weight [22]. Based on biomass growth in the system, phosphorus can be removed which is proportional to the available BOD for biomass production and now emphasizes the importance of SRT and BOD removal. On the other hand some bacteria can take up higher concentrations of phosphorus compared to their cell weight and usually concentrations. This can be 4 to 15% of its cell dry weight [22]. Unlike the MLE, the A^2O requires the initial reactor to be free of oxygen and nitrate in order for simple organic molecules to be taken up and internal polyphosphate (poly P) is hydrolyzed for energy. For this reason the additional anaerobic reactor is placed before the anoxic reactor and the result is that phosphorus becomes released. In the aerobic reactor, since oxygen and nitrate are present, they can be utilized as an electron acceptor in respiration for the additional uptake of phosphorus as adenosine triphosphophate (ATP) is generated and poly P is also restored. Like mentioned before, the main desired operating parameter is to maintain the anaerobic reactor free of oxygen and exposed to low concentrations of nitrate from the internal recirculation flows.

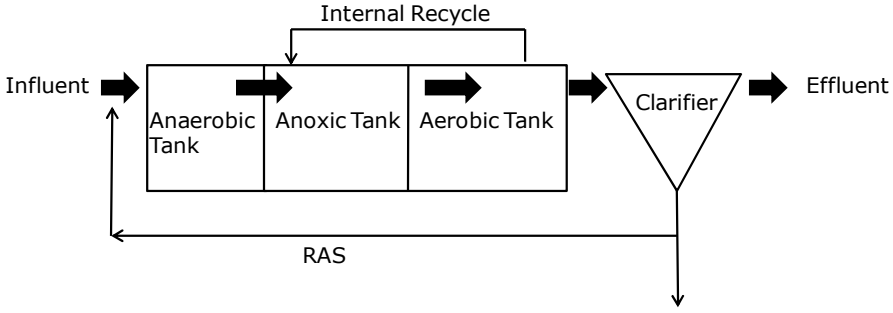


Figure 2.5 A^2O-CAS Process Flow Configuration

2.2.3 University of Cape Town (UCT) Process

The UCT process is an upgrade to the A^2O process for an increased efficiency in the removal of phosphorus – enhanced biological phosphorus removal (EBPR). The basis for the process includes elimination of oxygen and nitrate exposure to the anaerobic reactor. Three reactors are used just as in A^2O with the exception of the return activated sludge (RAS) being returned to the anoxic reactor rather than the anaerobic reactor to prevent the inhibition of nitrate on phosphorus release. The internal recirculation from the anoxic reactor to the anaerobic reactor serves to recirculate biomass to the anaerobic reactor.

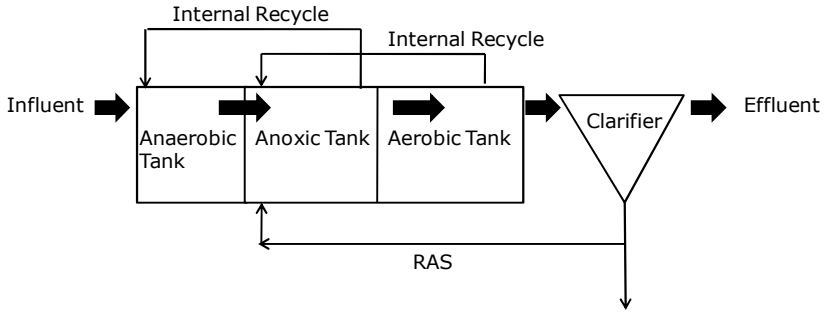


Figure 2.6 UCT-CAS Process Flow Configuration

2.3 Membrane Bioreactor (MBR) Process

The MBR process utilizes biological treatment processes similar to an activated sludge process and couples low pressure microfiltration (MF) or ultrafiltration (UF) membranes as a physical barrier for a complete solid-liquid separation in place of a clarifier. Because of this, secondary and tertiary wastewater treatment can be achieved within a single BNR-MBR process since bacteria (coliforms), suspended solids, nutrient and organics are removed [3]. A comparison of the conventional configuration with the BNR-MBR process is shown in Figure 2.7. Because MBR is coupled with biological treatment, there are several BNR processes

that can be operated for improved removal of nutrients which demonstrates the flexibility of MBR.

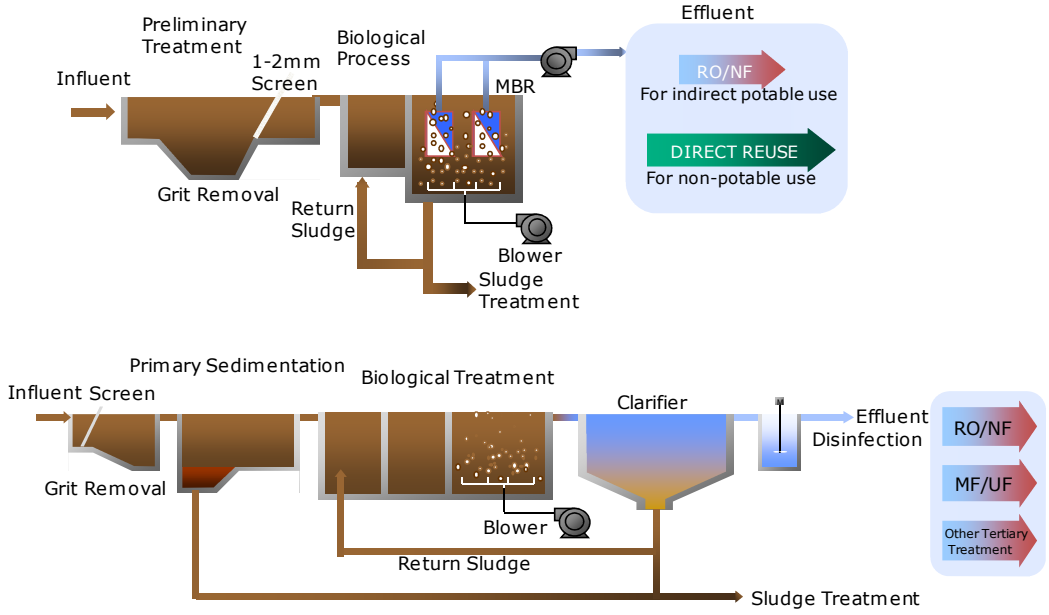


Figure 2.7 MBR (Top) and CAS (Bottom) General Process Schematic

The UF and MF can be either submerged or operated externally of a bioreactor as seen in Figure 2.8. Submerged membranes can be installed in the aerobic (oxic) bioreactor or within a separate membrane tank also shown in Figure 2.8. Submerged membranes can operate with dead end filtration while external membranes operate with a cross flow filtration mechanism which is further discussed in section 2.3.2.

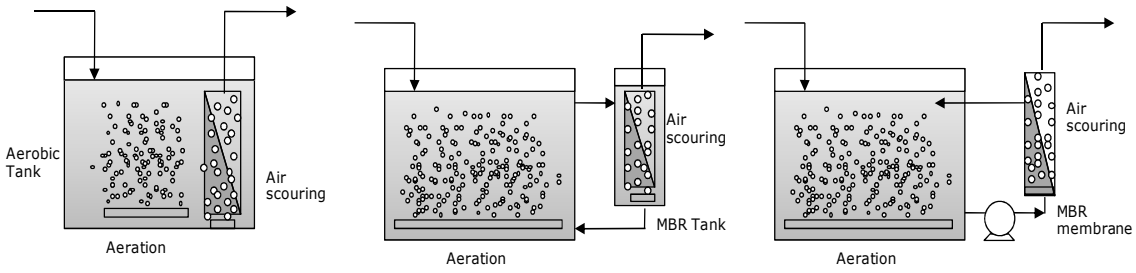


Figure 2.8 Submerged and External Membrane Operating Schemes

Membranes can be characteristically different when comparing membranes from different manufacturers and their operational design. There are several types of MBR membrane designs including flat sheet, hollow fiber and tubular membranes [34]. Flat sheet (FS) membranes and hollow fiber (HF) membranes are generally used in submerged membrane designs. Hollow fibers are most common in applications in the US market and globally while flat sheet membrane applications can be found in the Asian market especially in Japan [3, 35]. Flat sheet membranes have been used in plants since the 1980s and 1990s but are now considered less attractive due to the footprint required compared to the submerged HF units [3, 4, 35]. External membrane applications are generally found in Europe where they are also generally manufactured and these operate using an inside-out configuration while hollow fiber membranes usually operate with an outside-in mechanism. This is discussed further in section 2.3.2. Cross flow operation in external membranes require a higher velocity and recirculation flow rate for water (effluent) production. Advantages of external membranes include the absence of membrane tanks and the benefit of cleaning in place rather than the requirement to remove the membranes (HF) from the MBR tanks for maintenance and cleaning. Additionally, extra tankage is not required with external membranes for clean in place (CIP) recovery cleaning which are discussed in 2.4.4.

Advantages of an MBR system compared to the conventional activated sludge process include the direct production of tertiary effluent or better with the treatment of domestic wastewater. Another reason for growing interests in MBR for water reuse or recycle includes the smaller footprint occupied compared to clarifiers or sedimentation tanks. For example the expansion of a conventional plant to double its capacity is possible within the same footprint with the use of MBR technology. Such technology is not limited to domestic wastewater but can also be applied to industrial

wastewater for reuse. Even more attractive is the lower sludge production rate due to a much higher SRT of 15-20 days compared to 5-6 days. Also the MLSS concentrations are much higher at 8-12 g/L compared to conventional treatment for improved nutrient removal and lower hydraulic retention time (HRT). Because the membrane acts as a barrier for solid liquid separation, an MBR system eliminates some of the general issues associated with clarification. The system is unaffected by low settling due to filamentous growth (sludge bulking), pinpoint 'floc' or dispersed growth sludge properties and as such reduces some of the operational maintenance that would otherwise be required with a clarifier.

Operation of the MBR process includes careful design and pretreatment of the membranes to prevent mechanical or permanent damage as well as exposure to abrasive materials. Screening is important to prevent hair becoming trapped within the membrane module as well as other solids greater than 2 mm. For this reason 1.0 to 2.0 mm screens are used. Internally fed rotary drum screens, externally fed rotary drum screens and travelling band screens are some of the types of screens commonly used in MBR applications but rotary drum screens are becoming of greater preference. Also, 1.0 mm or even less is considered ideal for MBR rather than 2.0 mm screens because some applications have experienced materials bypassing.

Air scouring is of utmost importance in MBR operation to prevent severe fouling of the membranes. Optimum air scouring allows for higher flux operation without rapid and permanent fouling and especially cake layer buildup. Given the higher MLSS concentrations for which MBR systems operate, frequent maintenance cleanings and out of tank cleanings are also important to maintain membrane integrity in terms of fouling and permeability. These design precautions, once taken into account with MBR operation, decreases operational maintenance. Research is ongoing in order to improve air scouring, fouling, permeability (flux operation) with

the goal to reduce energy consumption in MBR systems which is considerably higher than conventional activated sludge systems [36].

2.3.1 Membrane Material

Physical and chemical properties are important in the material selection for UF and MF membrane production for wastewater treatment. Some of the important membrane characteristics include pore size, mechanical strength, braid reinforcement, surface area, packing density, contact angle, chemical resistance and crystallinity [37, 38]. UF and MF are generally distinguished by the pore size with UF membranes ranging in pore sizes <0.1 μm while MF membranes have pores sizes ≥0.1 μm. Membrane manufacturers produce various MF/UF membranes using one of two manufacturing methods – a phase inversion or stretching process/drying spinning method [34]. Phase inversion is used in production of UF membranes while MF membranes can be produced using either method. There are two types of phase inversion methods known as the temperature induced phase separation (TIPS) or non-solvent induced phase separation (NIPS) process [39, 40]. The TIPS process melts the resin and use temperature control for membrane solidification and manufacture while the NIPS process adds the resin to a non-solvent to form a sheet or hollow fiber that can be supported on a non-woven sheet or braid for additional mechanical support [40]. Hence, membrane properties are attributed to membrane material and the manufacturing method.

Various materials can be used to manufacture membranes which attribute to the mechanical strength and chemical resistance. Common membrane materials used in UF/MF production are listed in Table 2.2 which also shows the comparison of chemical and physical properties of each membrane material.

Table 2.2 Comparison of Membrane Materials [34, 41-43]

Membrane materials	Characteristics
Polypropylene (PP)	- Limited pH resistance and low chemical resistibility - Good mechanical strength and permeability - Low oxidant tolerance such as chloramines (up to 0.5ppm)
Polyethylene (PE)	- Hydrophobic and difficult to chemically modify - Used for MF membranes and susceptible to oxidation
Polyethersulfone (PES)	- Highly oxidant tolerant and wide pH range (1-12) - Exhibit resistance to oils and grease - Ease of modification for hydrophilic properties - Weak to organic solvent - Best for UF rating and for polymer blending
Polysulfone	- Exhibit resistance to wide pH range (1-13) and oxidants - High mechanical strength and high temperature limit (typically 75 ºC) - Hydrophobic with low resistance to fouling
Polyvinyldenefluoride (PVDF)	- Highly oxidant tolerant and moderate pH range (2-10.5) - Moderate temperature limit (typically 40 ºC) - Good mechanical strength and flexibility
Cellulosic derivatives (CD)	- Hydrophilic and includes cellulose acetate (CA) - Exhibit narrow pH range (4-8.5) and low temperature limit (<35 ºC) - Moderate oxidant tolerance - Easily attached by bacteria - Lower chemical resistance and mechanical strength than PVDF and PS
Polyacrylnitrile (PAN)	- Moderate tolerance to oxidant, acids and caustic - Hydrophilic for low membrane fouling - Moderate temperature limit (40ºC) and moderate pH ranges (2-10) - Good mechanical strength but weaker than PVDF membrane

Because of the mechanical strength and chemical resistance of PVDF membrane, this is the most common membrane material for UF/MF manufacturer for

MBR applications. As mentioned in Table 2.2, PVDF membranes are hydrophobic and require chemical treatment to hydrophilicize the membrane. This chemical treatment contributes to the contact angle of the membrane which is used to evaluate hydrophobicity of the membrane. Other manufacturers have also increased chemical resistance and mechanical strength using reinforced mechanical support.

2.3.2 Membrane Configuration

Configurations of UF/MF membranes for MBR systems can generally be classified as submerged or external membranes. Submerged membranes are installed within the bioreactor while external membranes are operated outside of the bioreactor tanks. Submerged membranes include hollow fiber (HF) and flat sheet (FS) membranes while external membranes use multi-tubular (MT) membranes. Figure 2.9 shows examples of these membranes. Hollow fiber membranes are the most commonly applied configuration in UF/MF membrane because of the favored high surface area to volume and footprint ratios.

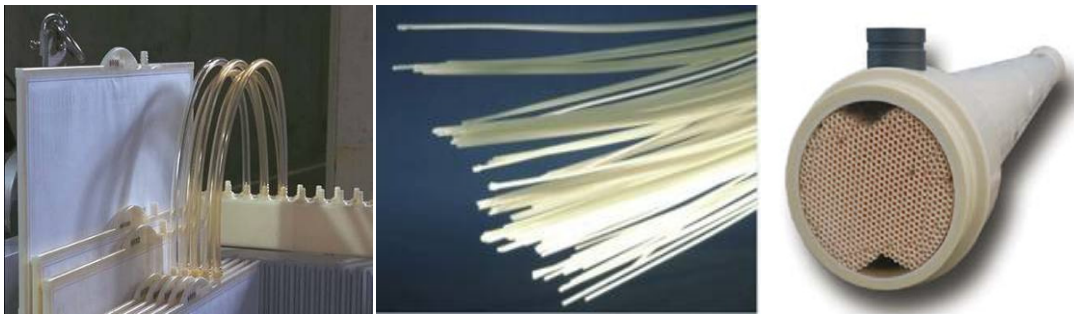


Figure 2.9 Flat Sheet, Hollow Fiber and Multi-Tubular Membranes [44-46]

Submerged membranes are operated with filtration modes from the outside to the inside of the membrane (fiber) or from the inside of the membrane to the outside as is common with MT membranes as shown in Figure 2.10. There are

several advantages to submerged and external configurations as is discussed in Table 2.3.

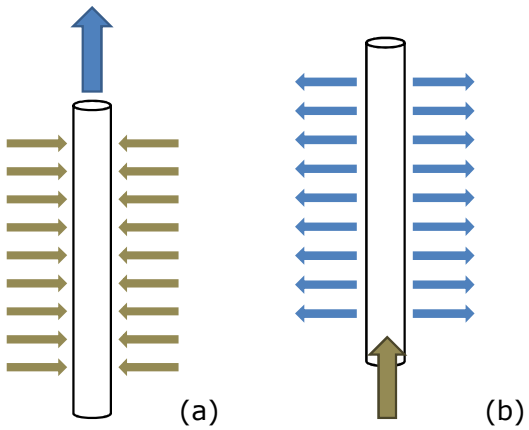


Figure 2.10 Membrane Filtration Operating Mechanisms
(a) Submerged and (b) External [21]

Table 2.3 Comparison of Submerged and External Membranes [3]

Submerged Membranes	**External Membrane system with high recycling rate and high velocity**
Aeration cost high (~90%)	Aeration cost low (~20%)
Very low pumping costs (higher if suction pump is used (~28%)	High pumping costs
Lower flux (large footprint)	Higher flux (smaller footprint)
Less frequent cleaning required	More frequent cleaning required
Lower Operating Costs	Higher operating costs
Higher Capital Costs	Lower capital costs

2.4 MBR Operation and Maintenance

2.4.1 Membrane Filtration

MBR membranes operate with specific cycle of filtration and backwash or relaxation and at low pressure. Suction on the permeate header allows water to move from the outside of the membrane to the lumen of the fiber. The MLSS

concentrations in MBR systems range between 8-12 g/L and are the limiting factor in membrane filtration. Importantly, air scouring prevents permanent attachment of solids on the surface which also is considered in the operational design of filtration cycle. Commonly observed in MBR systems is a filtration and backwash or relaxation cycle of 9 min: 1 min. Some membrane manufacturers can operate at higher filtration times but may require more backwash or relaxation time.

The backwash or relaxation cycle is determined according to membrane manufacturer specification. Whilst relaxation and increased air scouring can remove particulates building at the surface layer, a backwash with air scouring can remove foulants blocking pores and the surface. The membranes tested in this study used both methods – relaxation in Membrane A and backwash in Membrane B.

Membrane filtration control is important in the control of flux operation. Continued wastewater treatment is expected despite backwash or relaxation cycles. Flux operation is important to establish the required permeate filtrate flow per train in the plant during filtration cycles, backwash/idling cycles, maintenance cleaning cycles and CIP cleaning. For such reason, redundancy in membrane design is used for the option of future expansion or for the removal of membrane trains for cleaning.

2.4.2 Membrane Air Scouring

Air scouring of the membrane is essential in the design and operation of MBR process because the supplied air for air scouring in the membrane tank is used to keep solids from accumulating on the membrane wall. In an MBR system, aeration is important for both microbial growth and mixing at the membrane surface. Membrane aeration contributes to about 30-50% of energy demands in the operation of an MBR process [2]. It was reported that total energy demands for biological

process air blowers and membrane aeration was more than 70% of the total energy demands of the entire process operation [47]. In most cases of submerged membrane tank operation, air scouring produces shear forces on the membrane which will help to remove the fouling layer. Air scouring methods, especially aeration intensity and aeration mode, will affect the reduction of particle depositions[38].

Generally, oxygen consumption is closely related to donor substrate utilization and biomass endogenous decay in the biological process. The amount of air required for biological nutrient removal can be calculated using theoretical and empirical data for design and as such limit optimization of aeration. MBR suppliers and researchers have been studying the optimization of air scouring in their product design. The process configurations and hydrodynamic conditions can contribute to the performance of the membrane system. A two phase (air and liquid) cross-flow was proven to enhance the system performance compared to a single-phase (liquid) cross flow because air scouring can produce higher levels of turbulence and surface contact to remove solids in an MBR system [48].

Development of various air scouring designs over the past 10 years has decreased air scour energy consumption in an MBR system. Air scouring rates observed a drop by 75% from 1.2 m^3-air/m^3-filtered to 0.3 m^3-air/m^3-filtered [49]. With respect to the operational scheme, two methods of air scouring have been widely used - intermittent air scouring and continuous air scouring. While Zenon MBR systems use intermittent air scouring with the option for 10 seconds on and then 10 seconds off mode, most other membranes are using continuous air scouring with different air scouring header and diffuser designs. The advantage of the patented intermittent air scouring method by GE Zenon is less energy consumption with the same air scouring efficiency as shown in Figure 2.11 [50].

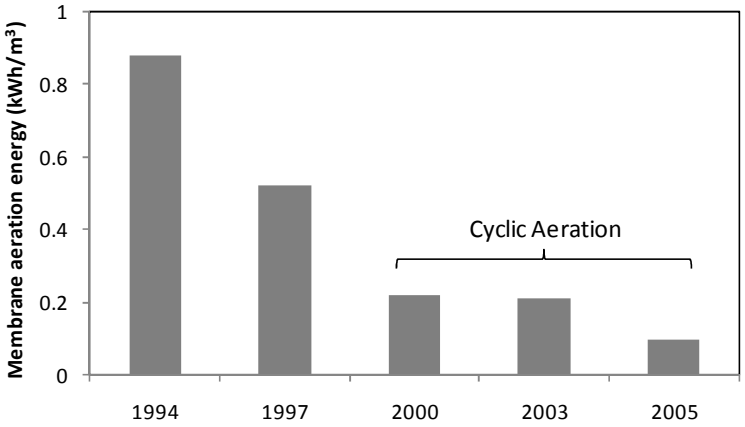


Figure 2.11 Reduction of Air Scouring and Energy

Table 2.4 Comparison of European MBR Plants and Aeration Demand [51]

Parameter	**Location B**	**Location D**	**Location E**	**Location F**	**Location G**	**Location J**
Membrane	Hollow Fiber	Hollow Fiber	Flat Sheet	Flat Sheet	Hollow Fiber	Hollow Fiber
SADm (m/h)	0.38	0.5-1.25	0.86	0.33	0.4	0.3-0.6
SADp (m3/m3)	16	25-70	52	20.6	17	N/A

Membrane aeration is often evaluated using specific air demand per membrane area (SAD_m) or specific air demand per cubic meter of water produced ($SAD_{p)}$. SAD_p values can average between 10 – 50 and some applications average at or below 5 [2]. Both values can be used to evaluate membrane performance and optimization. While SAD_m values can be compared and shows improved air scouring per module, SAD_p shows the relation of air scouring to water production and also to the number of membrane modules required for such production. Generally, a higher SAD_p correlates to a higher SAD_m but the overall air demand can be affected by the membrane packing density.

2.4.3 Membrane Backwash/Relaxation

Membrane bioreactors operate by filtration and relaxation cycles. Since the membrane filters mixed liquor at high concentrations over a period ranging from 7-9 minutes, a backwash or relaxation is necessary to help prevent build up of solids on the surface of the membrane as well as to flush the membrane pores with water. Flat sheet MBR membranes cannot be backwashed and undergo filtration-relaxation cycles whilst hollow fiber MBR membranes can be backwashed or relaxed. The backwash or relaxation cycle can last between 30 seconds to 60 seconds. During this period, the membrane is air scoured without filtration as the membrane relaxes or is backwashed. Some membrane manufacturers' recommend a backwash at a rate of 1.5 – 2Q for a better clean and to recover the TMP when filtration begins again. External membranes (tubular) require backwash every 10-12 minutes but differs with submerged membranes because the backwash period is usually 5-10 seconds at a high backwash flux rate for appropriate cleaning of the membrane. Previously membrane manufacturers' also recommended higher air scouring during the relaxation period if a backwash was not conducted. However, the concerns for energy consumption became even greater and membrane manufacturers are consistently trying to improve energy consumption due to air scouring.

2.4.4 Membrane Chemical Cleaning

The MBR process requires maintenance cleaning to prevent irreversible fouling despite efficient air scouring. Particulates and biofilm can accumulate at the membrane surface blocking the pores. Generally, a manual clean can be done to remove the layer deposited on the membrane fibers with the use of a hose. For maintenance cleaning, chemical enhanced backwash (CEB) serves to remove foulants which have blocked or plugged the membrane pores and have decreased

filterability/permeability. Maintenance cleaning can also be scheduled based on membrane TMP trending and pressure limits according to the membrane manufacturer. This backwash uses a reverse filtration method (inside-out) with sodium hypochlorite at a rather low concentration for oxidation of organics and removal of organics plugging the pores which is enhanced by soaking. CEB is important to maintain membrane permeability and prevent irreversible fouling of the membrane and is conducted 1-2 times a week in the membrane tank depending on the manufacturer specifications. For a complete recovery clean when CEB does not improve membrane performance, higher concentrations of sodium hypochlorite and citric acid are used. The membranes are removed and soaked in another tank into the solutions consecutively for hours prior to placing them back in operation (CIP). The soak time for CEB can span between 30-90 minutes while CIP can span from 4-6 hrs for each chemical soak. Table 2.5 shows cleaning protocols for some manufacturers where CIA is cleaning in air in the MBR tank with removal of mixed liquor and CIP is clean in place without membrane removal or draining of the MBR tank.

Table 2.5 Examples of Chemical Cleaning Methods [3]

Membrane	**Cleaning method**	**Chemical**	**Concentration (%)**	**Protocol**
Mitsubishi	CIP	NaOCl	0.3	Backflow through membrane (2 hr) and soak (2 hr)
Zenon	CIA	Citric Acid and NaOCl	0.2 0.2	Backpulse and recirculate
Memcor	CIA	Citric Acid and NaOCl	0.2-0.3 0.01	Recirculate through lumen, mixed liquor, and air manifold
Kubota	CIP	Citric Acid NaOCl Oxalic Acid	0.2 0.5 1	Backflow and soaking for 2 hr

2.5 Membrane Fouling

Although membrane bioreactors can extract water from biomass, they are susceptible to fouling. This is one disadvantage of membrane bioreactors because membrane performance is important for continuous operation. Membrane fouling occurs where solute or particles deposit onto a membrane surface or into membrane pores decreasing water permeability. Membrane fouling is a major problem that can cause membrane performance degradation with flux decline and filtered water quality exacerbation. Accordingly, fouling can increase operational costs. Factors affecting fouling rate in membrane operation include i) characteristics of solutes and solvents in water, ii) membrane properties such as materials, pore size, and surface characteristics, and iii) hydrodynamics in the membrane reactor [52]. Major foulants have been classified as colloids, organics such as macromolecules, inorganics such calcium and metal hydroxides, and particulates. Colloidal particles can form a fouling layer, and macromolecules can create gel or cake layer on membranes. Precipitation of salts and hydroxides can be formed on the membrane due to changes of pH or concentration (saturation). Since fouling mechanisms are closely related to the active pore size of the membrane, there are four major fouling mechanisms – complete pore blocking, internal pore blocking, partial pore block blocking, and cake filtration (Figure 2.12) [42, 52].

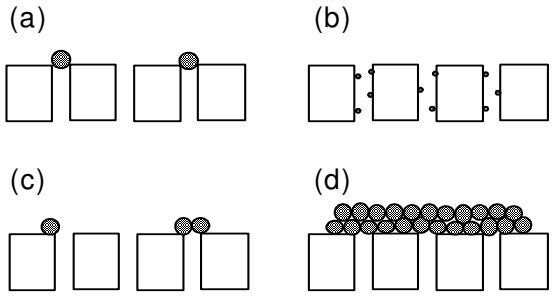


Figure 2.12 MBR Membrane Fouling Mechanisms
(a) complete (b) internal (c) partial pore blocking and (d) cake filtration

Complete pore blocking occurs and blocks pores of membranes completely when particles are bigger than the membrane pore size. This reduces the active membrane surface area available for filtration and permeability. Internal pore blocking will restrict membrane filtrate flow when particles are smaller than membrane pore size and are adsorbed or deposited inside the membrane pores. The pore size reduction due to internal pore blocking increases membrane resistance. Partial pore blocking happens when particles at the surface of membrane block a pore partially or bridge a pore. This will cause the reduction of membrane area. Particles can form a cake on the surface of the membrane without entering the pore or sealing the pores [42].

Approaches to preventing fouling begin with the identification and characterization of foulants. Research studies have been conducted to determine the causes and characteristics of foulants [53]. Some have determined that a shift in operating parameters can have an effect on fouling such as having intermittent feed flow, changes in SRT, and sudden shift in dissolved oxygen while others have focused on characterization of foulants including extracellular polymeric substances (EPS) and soluble microbial products (SMP) [54-56]. Based on this research, fouling can be prevented or mitigated through membrane design, biological process design and through efficient air scouring concepts/designs.

MBR membrane manufacturers suggest customers to use their respective membrane module or cage which was designed to prevent sludge bulking (Figure 2.13). Each manufacturer specifies design and operating parameters for optimum membrane performance. Among these include various air scouring methods, weekly maintenance using chemical enhanced backwash (CEB), manual cleanings, chemical recovery cleaning, and cleaning in place (CIP) methods which are applied to most MBR membrane systems.

Figure 2.13 Examples of MBR Membrane Fouling

2.6 MBR Energy Consumption

Energy consumption as previously mentioned is of greatest concern with membrane bioreactors. According to Wallis-Lage and Levesque, over 76% of energy demand, as shown in Table 2.6, is aeration of the bioreactor and for air scouring of the membrane while pumping energy consumption follows at 14%. Energy consumption can average 0.3 kWh/m^3 in conventional activated systems [57]. Additional air scouring for the MBR membranes explain why compared to conventional systems energy consumption in MBR systems is generally 0.2 KWh/m^3 higher but can be comparable when energy demands of CAS and tertiary treatment are combined [58, 59]. Small to medium MBR plants (<5 MGD) have been observed to operate at or above 1 kWh/m^3 but larger plants (5-10 MGD) with optimization can operate < 1 kWh/m^3 [59]. Previous energy consumption evaluations have observed submerged MBRs with power consumption between the ranges of 0.2 – 0.4 kWh/m^3 but more commonly less than 1 kWh/m^3 whilst side stream external MBRs have been evaluated with energy consumption between 2 – 10 kWh/m^3 with some examples between 0.2 – 2.4 kWh/m^3 [60-63].

Table 2.6 Energy Consumption in MBR Plant [47]

Process	**Fraction Energy Consumption (%)**
Bio process aeration	42%
Membrane aeration	34%
RAS pumping	10%
Permeate pumping	4%
Anoxic mixing	9%
Miscellaneous	1%

If additional treatment processes are used to treat the MBR effluent such as with RO/NF membranes and required disinfection, the total energy costs are further increased [64]. For water reuse including indirect potable reuse, this treatment process is growing in application. To maintain competitive advantage, membrane manufacturers are exploring new strategies for reduced air scouring demand and improved flux operation.

3. Methods and Materials

3.1 Experimental Setup

The MBR pilot system was located at the City of Tampa Wastewater Treatment Plant otherwise known as the Howard F. Curren Advanced WWTP. The plant has a capacity of 96 million gallons per day (MGD) and operates at an average of 57 MGD. The plant uses a multistage biological process beginning with a carbonaceous BOD removal reactor with the use of high purity oxygen generated onsite (for BOD removal), followed by nitrification (aeration reactor) and lastly, post-denitrification (anoxic) using methanol as a carbon source. The MBR pilot system was installed near the primary clarifier after grit removal. Wastewater was withdrawn at the influent of the clarifier and pumped to the pilot system as influent. The pilot was also seeded with mixed liquor from the aerobic and denitrification processes of the plant. Wasted sludge and filtrate were returned back to the primary clarifier during pilot operation for a side-stream closed-loop process. Figure 3.1 shows the location of the pilot at the wastewater plant.

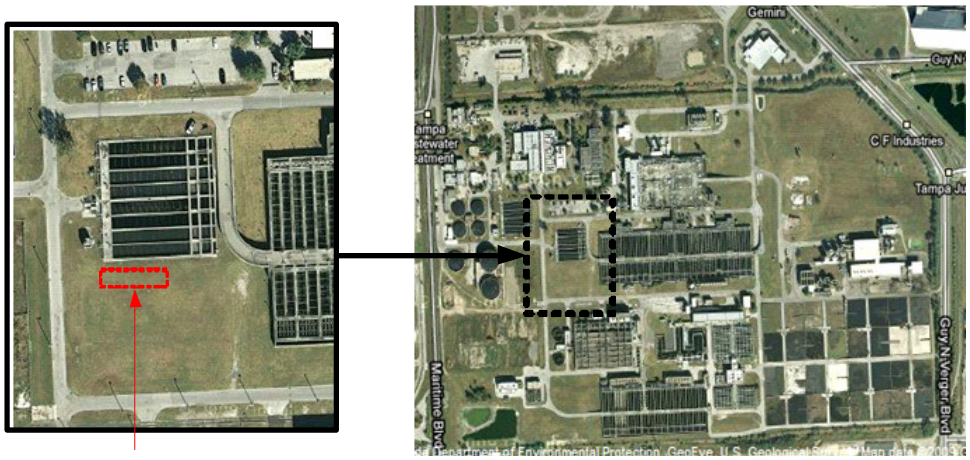


Figure 3.1 Location of the MBR Pilot Plant at the Howard F. Curren WWTP [65]

The MBR pilot was operated with two membranes, denoted as membrane A and B, which were tested at fixed and varying flux rates. Membrane performance evaluation and biological nutrient removal were observed and optimized through alterations of operating parameters based on the data acquisition from online sensors and laboratory analyses. The system was operated with the two membrane system optimization where necessary such as with flux operation and air scouring. These are separated as different phases of experimentation. Membrane A was tested first followed by Membrane B testing which operated over a longer operational period. The proposed biological configurations were tested with Membrane B for the comparison of the performance of the enhanced biological phosphorus removal process in conjunction with nitrogen removal in each. The target effluent parameters in this study are shown in Table 3.1.

Table 3.1 Treatment Target Effluent Quality for this Study

Parameter	**Target**
TSS (mg /L)	<1
BOD_5 (mg/L)	<5
TN (mg N/L)	<5
TP (mg P/L)	<1
NH_4^+ (mg N/L)	<0.1

3.2 Pilot Plant Design and Equipment

The pilot system was designed for the operation of advanced nutrient removal processes and consisted of an intake system, fine screen, biological reactors, and a membrane tank as shown in the process flow diagram in Figure 3.3. The biological reactors were divided into three zones including the anaerobic, anoxic, and oxic (aerobic) zones of 240 gallons, 480 gallons and 960 gallons of working volume respectively. An additional denitrification reactor was also designed with a variable water volume for adjustment of the hydraulic retention time (HRT). These reactors were designed for flexibility to operate the A^2O BNR system with both MBR membranes as well as the UCT configuration. All reactors contained mixers and the oxic tank contained additional fine diffusers. The anoxic and oxic tanks were designed as plug flow reactors (PFR) with baffles and mixers installed while the anaerobic and denitrification tanks were designed as complete mixed flow reactors (CMFR) as shown in Figure 3.2 which also shows the location for recirculation (UCT). Overflows from one reactor to another occurred through submerged weirs. The membrane tank was designed for feeding mixed liquor from the oxic tank and the overflow and RAS return from the membrane tank was designed to return to the aerobic and denitrification reactor. During the operation in UCT configuration, the overflow from the membrane tank was returned completely to the oxic tank with subsequent internal recirculation from the oxic to the anoxic tank and the anoxic to the anaerobic tank as shown below.

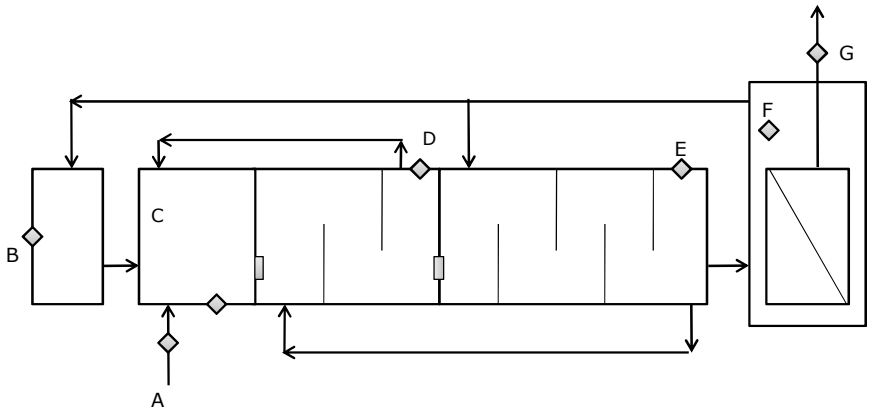


Figure 3.2 Diagram Showing the Reactor Design and Sampling Points
A:Influent B:Deoxygenation C:Anaerobic D:Anoxic E:Oxic F:MBR G:Effluent

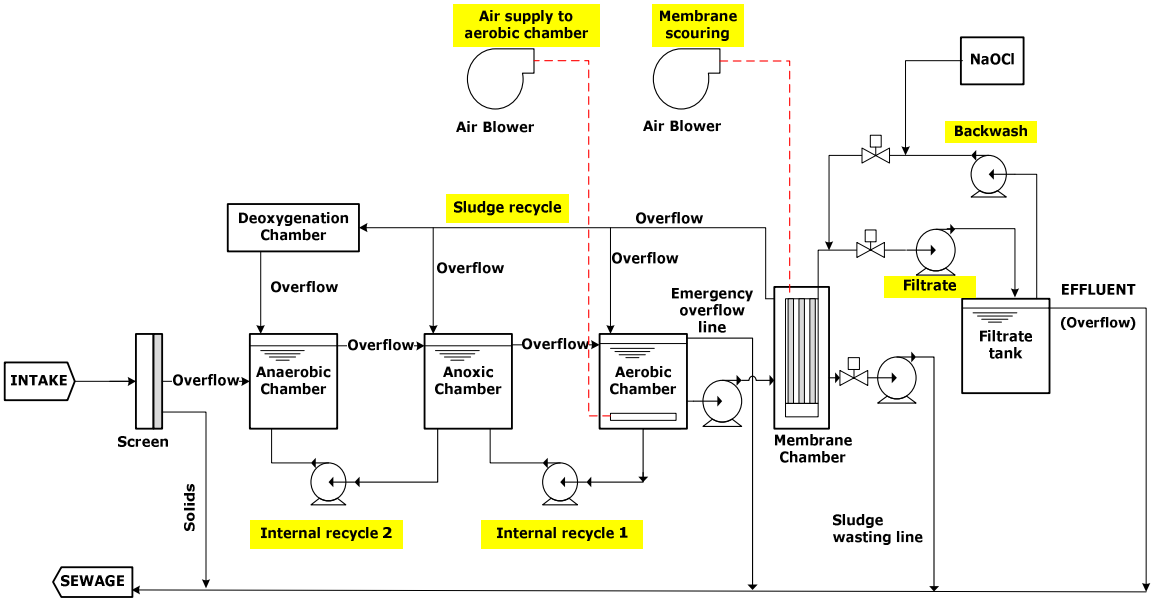


Figure 3.3 Process Flow Diagram of A^2O/UCT-MBR Pilot System

The equipment used in pilot testing were sized for the operating ranges that are compatible for the operation and testing of both PVDF membranes. Additional equipment required for membrane operation, air scouring, and internal recirculation include self-priming centrifugal pumps for the feed and effluent, rotary lobe blowers for aeration and air scouring, and rotary lobe pumps for internal recirculation of mixed liquor. A self-priming centrifugal pump with suspended solids tolerance was

selected for the intake system to prevent the loss of suction between start and stop operations. The rotary lobe pumps were selected because of the tolerance of solids – up to 2% solids. Pilot system installation is shown in Figure 3.4 and Figure 3.5 with the installed membrane tanks appropriate to the membrane manufacturers' specification. The MBR tank for Membrane A was constructed of carbon steel while that of Membrane B was constructed with stainless steel 316L which also served as a CIP cleaning tank and is further discussed in section 3.1.2 below.

Figure 3.4 MBR Pilot System with Membrane A MBR Tank

Figure 3.5 MBR Pilot System with Membrane B MBR Tank

3.3 Comparison of PVDF Membranes – Membranes A and B

Two PVDF submerged microfiltration membranes with pore size of 0.1 μm were selected for pilot testing and are identified as membrane A and membrane B. One of the unique characteristics of membrane A is the 'u-turn' configurations for improved air scouring of the membrane hollow fibers in each module with a dual permeate outlet for top and bottom filtration [44]. Membrane B is manufactured with high crystalline PVDF and is designed uniquely with uniform fiber distribution in the bottom potting while fibers are bundled at the top of the module for even air scouring in a circular module. Opposite of membrane A, membrane filtration occurs through a single permeate outlet at the top of the module. Table 3.2 shows a detail comparison of membrane A and membrane B membrane and module specifications. This comparison identifies the differences in membrane element design, module design, air scouring design, and permeate header design.

Table 3.2 Membrane and Module Specifications of Membrane A and B

Parameter	**Membrane A**	**Membrane B**
Membrane Material	PVDF	PVDF
Pore size (μm)	< 0.1	0.1
Fiber ID/OD/ inches(mm)	0.024/0.047 (0.6/1.2)	0.028/0.047
Membrane length (m)	1.5	2.0
Filtration mode	Outside/in	Outside/in
Filtrate collection	Dual port	Single port
Air scouring (SCFM/module)	1-3	3-6
Effective membrane area per module/ ft^2 (m2)	215.3 (20)	269.1 (25)
Operating pressure/ psi (KPa)	1.7 – 7. (10 – 50)	1.0 – 6.0 (10- 30)
Operating Temperature/ °F(°C)	41 – 113 (5 – 45)	41 – 104 (5 – 40)
Module dimension/ (inches) (LxWxH) or (DxH)	22.5 x 1.8 x 60.4 (rectangular)	6D x 78.7H (circular)

3.4 System Operation and Control

The BNR-MBR pilot operated 24/7 with feed and effluent production to prevent overflow and low level events. System operation was automated and controlled by a programmer logic controller (PLC) based on a complex control philosophy for automated remote operation and data acquisition. This control was set up according to the required operation of the biological system and membrane operation of both Membranes A and B. Alarms were also built into the program for control of equipment should certain events such as an overflow or low level detection, which if it occurred, would cause possible membrane exposure in the membrane tank.

Pump operations were controlled with the use of variable frequency drives (VFDs) for fixed flow operation based on flow meter control feedback (Proportional-Integral-Derivative (PID) loop). Actuated valves helped to control the filtration and backwash/relaxation cycles in membrane operation. The water level in the biological system and membrane tank was monitored by an ultrasonic level sensor which lowered feed flow rate to prevent overflow and increased feed flow rate to prevent low water level in the biological tank. RAS flow rates were controlled by careful ball valve manipulation to split and manipulate flows returning to the oxic and denitrification reactors. A timer controlled sludge wasting as the sludge wasting pump was connected with a flow meter to fix the wasting rate per day (PID loop). Aeration flow in the oxic (aerobic) tank was based on a feedback mechanism of the DO probe installed in the aerobic tank for operation at a fixed DO concentration whilst air scouring was fixed according to membrane specification. Table 3.3 shows the operating parameters of the biological process.

Table 3.3 BNR Operating Parameters for A^2O Operation

Parameter	**Membrane A**	**Membrane B**
Aeration flow rate	Maximum 30 (cu.ft/min)	Maximum 30 (cu.ft/min)
Internal recirculation (oxic to anoxic)	5Q (20 gal/min)	5Q (20 gal/min)
Return activated sludge	1Q (4 gal/min)	1Q (4 gal/min)
Recirculation to Oxic tank	3Q (12 gal/min)	3Q (12 gal/min)
Recirculation to denitrification tank	Q (4 gal/min)	Q (4 gal/min)
Sludge wasting	20 (gal/min)	20 (gal/min)
MLSS	Min 6 g/L	Min 6 g/L
HRT	7 hrs (1:2:4 in each reactor)	7 hrs (1:2:4 in each reactor)
Denitrification HRT	30 min	30 min
DO concentration in the aerobic	2 mg/L	2 mg/L

Membrane operation control was based on membrane manufacturer specifications and the operation and maintenance manual. The MBR system operated with four basic operational steps including filtration, idling or backwash, CEB and CIP. Idling or backwash was controlled based on set points placed in the program by the user regarding filtration time. Maintenance cleaning with sodium hypochlorite (NaOCl) was performed once a week according to the operation and maintenance manual using a filtration-idle/backwash cycle counter or based on a trans-membrane pressure (TMP) trigger. The filtrate pump was controlled based on a VFD on a feedback control from the flow meter for fixed flow operation to match feed flow rates and to maintain the HRT. CIP cleaning was triggered based on TMP measurements and conducted manually. Table 3.4 describes the operating

parameters of both the MBR membrane systems during this study which were within the presented ranges during phase testing.

Table 3.4 MBR Membrane Operating Parameters for UCT

Parameter	**Membrane A**	**Membrane B**
Filtrate flow rate	4-5 gpm	4-6 gpm
Filtrate flux	25 L/m^2.hr	23-27 L/m^2.hr
Air scouring flow rate	2 -2.5 SCFM	2-6 SCFM
Membrane feed flow rate	5Q (20 gal/min)	5Q (20 gal/min)
Recirculation to Oxic and Anaerobic tank	5Q (20 gal/min)	5Q (20 gal/min)
MLSS	6 g/L	6 -10 g/L
HRT	7 hrs (1:2:4)	7 hrs (1:2:4)
Filtration:Idling/Backwash	9 min: 1 min (idle)	9 min: 1 min (backwash)
CEB	1 per week (Manual)	1000 cycles

System startup was completed by seeding the system with mixed liquor from the carbonaceous reactor RAS and nitrification reactor RAS in a 3:2 ratio for a total addition of 500 gallons of mixed liquor at about 4 g/L. The mixed liquor was also treated using a coarse screen to remove debris and large particles to prevent physical damage to the membranes. Conservative operating parameters were used in the first few days of operation in order to confirm the precise stability of the PID loops controlled by the PLC program. This confirmed the stable and fixed operation as well as remote control and data acquisition. Each sensor is read and recorded every 10 seconds. An excel file is generated each hour with the saved values from each sensor on the pilot skid.

3.5 Analytical Methods

The pilot system was monitored through online sensors and through laboratory analyses. Online sensors included Hach pH sensors model DPD1P1 (Loveland, CO), Hach ORP sensors model DRD1P5 (Loveland, CO), Hach DO sensors model LDO 57900 (Loveland, CO) and Hach online turbidity sensor model Ultraturb SC (Loveland, CO). The pH, ORP and DO sensors were installed in each reactor to monitor the water quality and to control the DO concentration in the oxic tank. A DO sensor was also installed in the denitrification tank to observe the DO concentration from the RAS. A portable multi-probe sensor, WTW Multi 300i (Germany), was used for system monitoring and for online sensor verification. The portable multi-probe sensor included a WTW Conox DO probe and Sentix 41-3 pH/temperature probe (Germany).

Weekly sampling and analyses were conducted for evaluation of nutrient removal and membrane performance based on the schedule described in Table 3.5. Standard methods and Hach test n' tube plus kits (Hach TNTplus) with the Hach UV-visible spectrophotometer model DR5000 (Loveland, CO) were used for analyses [66]. Hach test kits were used for detection of total nitrogen, total phosphorus, COD, alkalinity, and ammonia. Of these tests, all are considered USEPA equivalent except for total nitrogen and total alkalinity. These USEPA methods include Methods 365.1, 365.3, 410.4, and 350.1 respectively excluding total nitrogen and alkalinity. Nitrate, nitrite, and phosphate concentrations were measured using Dionex ion chromatography model ICS-2100 (Sunnyvale, CA) based on the standard method SM4110B. Total organic carbon (TOC) was analyzed by a high temperature combustion type TOC analyzer (Shimadzu TOC V-CPH) which uses the Standard Method 5310B. Turbidity of the filtrate was also verified using the Standard Method, SM2130B using the portable and online sensor. Lastly BOD_5 is measured on the feed

and effluent using the Hach DO sensor model LDO 57900 (Loveland, CO) based on the AWWA Standard Method (SM 5210B). Mixed liquor suspended solids (MLSS) and mixed liquor volatile suspended solids (MLVSS) were also measured using AWWA Standard Methods (SM2540D and SM2540E respectively).

Table 3.5 Sampling Schedule and Laboratory Analyses

Sample	**Analyses – Three times/week**			
	Standard Method	**Hach TNT Kit**	**Ion Chromatograph**	**Daily Field Test**
Intake (Wastewater)	Total COD BOD_5 Total Nitrogen Total Phosphorus	Soluble COD Soluble BOD Ammonia Alkalinity	Nitrate Nitrite Phosphate	pH
After Screen	SS VSS COD TN TP	NA	NA	NA
Denitrification	MLSS MLVSS	Soluble COD Ammonia	Nitrate Nitrite Phosphate	pH DO
Anaerobic	MLSS MLVSS	Soluble COD Ammonia	Nitrate Nitrite Phosphate	pH DO
Anoxic	MLSS MLVSS	Soluble COD Ammonia	Nitrate Nitrite Phosphate	pH DO
Oxic	MLSS MLVSS	Soluble COD Ammonia	Nitrate Nitrite Phosphate	pH DO
MBR	MLSS MLVSS	Soluble COD Ammonia	Nitrate Nitrite Phosphate	pH DO Temperature
Filtrate (Effluent)	Total COD BOD_5 Total Nitrogen Total Phosphorus	Soluble COD Soluble BOD Ammonia	Nitrate Nitrite Phosphate	pH DO Turbidity

3.6 Experimental Phases

During the course of this project, several phases of experiments were conducted. Table 3.6 provides an overview of each phase of testing. Two submerged MBR membranes from two different manufacturers were used during the pilot test. The proposed biological configuration with MBR was tested with both membranes under differing operating conditions appropriate to the manufacturers' specifications. Nutrient removal was closely observed by profiling each reactor on a weekly basis. Membrane performance was also closely observed during pilot operation and was used to make the required adjustments to improve overall membrane performance as well as test the membrane's potential.

Table 3.6 Phases of Experiments with Biological Processes with MBR

Phase	Experiment			
	Membrane	**BNR Configuration**	**Flux (LMH)**	**Air scour (SCFM)**
Phase 1	Membrane A	Modified A^2O	25	1 – 2.5
Phase 2	Membrane B	Proposed BNR	25-27	6
Phase 3	Membrane B	Modified A^2O	25-27	6
Phase 4	Membrane B	Modified UCT	19 -25	2 - 6

Phase 1 of testing was conducted with the modified A^2O biological process with membrane A. Testing included average flux operation of 25 LMH (Liter/meter^2.hour) and at lower air scouring rates. During this phase, membrane performance was further observed at a higher flux and air scour rate to improve membrane performance and reduce fouling potential.

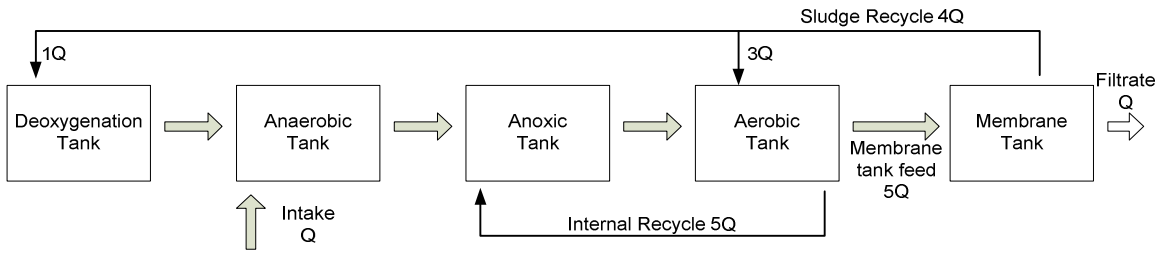


Figure 3.6 Phase 1 and 3 Modified A^2O-MBR Process Schematic

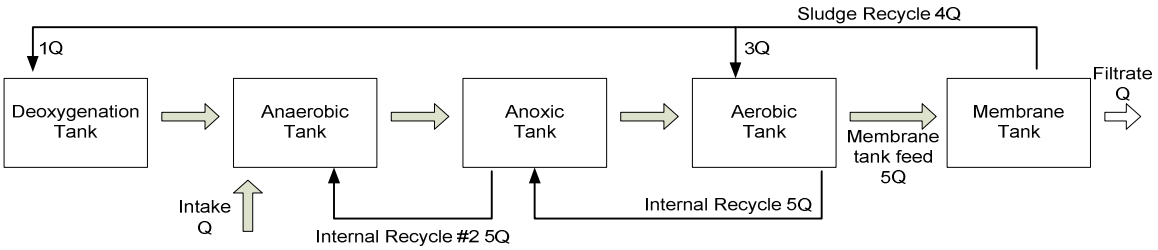


Figure 3.7 Phase 2 Proposed BNR-MBR Process Schematic with Deoxygenation Tank

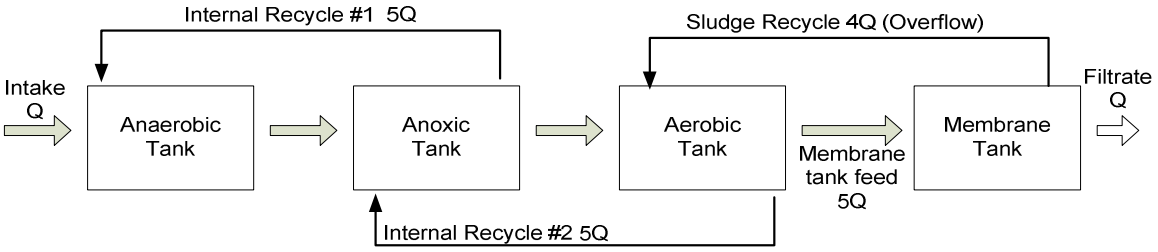


Figure 3.8 Phase 4 Modified UCT-MBR Process without Deoxygenation Tank

Phases 2 to 4 were conducted with membrane B. The system was operated with the modified A^2O, the proposed biological process as well as the modified UCT process in these phases as shown in Figure 3.6 and 3.7. Membrane operation differed with each phase in lower and higher flux operation as well as air scour rates to reduce energy consumption but maintain stable TMP operation and to control the fouling potential of the membrane.

4. Results and Discussion

BNR system operation startup used seeded sludge from the clarifier RAS of the wastewater plant at a starting MLSS concentration of 4 g/L. The seeded sludge contained bacteria from nitrification and denitrification processes and was seeded at 3:2 volume ratio. This provided the appropriate bacterial species and helped shorten the acclimation period to nitrogen and phosphorus removal. During pilot operation, data were collected from online sensors with daily laboratory analyses conducted during the first 2-3 weeks of either membrane operation. Pilot operation was conducted during the summer and winter periods for an observed performance of both the BNR and membranes. Feed water characteristics variation was observed to be minimal during each test phase but temperature variations were directly observed and were more evident during membrane B testing.

The hydraulic retention time was fixed at 7 hrs and the DO was controlled and fixed at 2 mg/L in the aerobic tank throughout testing. Wasting was not conducted during the first 30 days of operation despite MBR membrane operation. This was done in order to increase the MLSS concentrations to about 8 g/L. Membrane A operated during the acclimation period with the modified A^2O process while membrane B testing was conducted with the same mixed liquor and after system acclimation with the modified A^2O process, the proposed biological process and the modified UCT process. The pilot was operated for about 250 days. During the first 50 days, the system was operated with membrane A and the remainder of the test period with membrane B. The results are provided and discussed below for each phase of testing.

4.1 Phase 1 Membrane A Test with Modified A^2O-MBR Process

Phase 1 of testing included commissioning and sludge acclimation with Membrane A. The pilot system was commissioned and operated with a modified A^2O process. This process was designed for the return of mixed liquor to both the anaerobic and oxic tanks by means of gravity with an additional anoxic reactor (deoxygenation reactor) which served to reduce the dissolved oxygen content in the return activated sludge (RAS) to the anaerobic reactor. By controlling the dissolved oxygen and nitrate content being returned to the anaerobic tank, VFAs are available to aid the PAOs in the release of phosphorous. A higher phosphorus release improves the uptake in the oxic tank under high DO conditions which helps to improve and stabilize the removal of phosphorus whilst maintaining nitrogen removal above 90%.

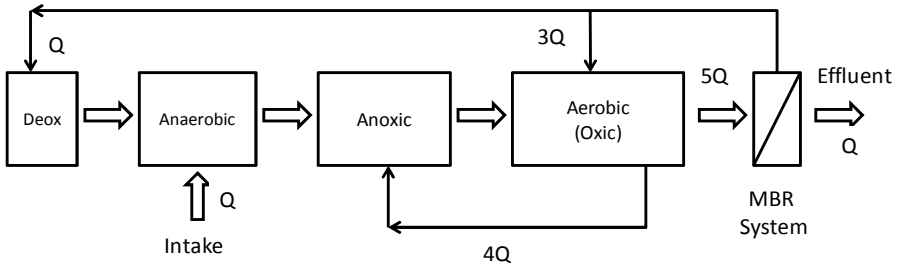


Figure 4.1 Phase 1 Modified A^2O-MBR Process with Deoxygenation Tank

Phase 1 operation was unique with mixed liquor being returned to the deoxygenation tank and the aerobic tank by gravity at a 3:1 ratio as shown in Figure 4.1. The sludge return was controlled with the use of a PVC tee and ball valve to control the flow to the aerobic and to the deoxygenation tanks at 3Q and Q respectively. The internal recirculation from the aerobic tank to the anoxic tank was operated at 5Q due to a limitation on pump control preventing a lower recirculation flow rate. Since the mixed liquor return was controlled by gravity, the flow rate to the deoxygenation tank was frequently measured to confirm a 3:1 ratio.

The primary influent wastewater was collected every week and analyzed. The wastewater characteristics tested are listed in Table 4.1 which also lists the annual averages as tested by the wastewater plant. Grab samples were taken prior to the drum screen and after the drum screen to observe screen efficiency. Analyses were completed from grab samples taken from the biological tanks every other day to determine the biological system performance. The concentration of nitrogen and phosphorus was monitored in all reactor tanks as well as the MLSS and MLVSS concentrations.

Table 4.1 Characteristics of Raw Wastewater During Pilot Operation

Parameter	**Annual Average**	**Membrane A**
BOD (mg/L)	182	156.1(±38.1)
COD (mg/L)	452	477.5 (±111.2)
Total alkalinity (mg/L as $CaCO_3$)	340	303.6 (±36)
Nitrate (mg as N/L)	0.29	0.4 (±0.3)
Ammonia (mg as N/L)	27	23.0 (±4.0)
Total nitrogen (mg as N/L)	28.05	31.9 (±4.9)
Total phosphorus (mg as P/L)	5.6	4.9 (±1.28)
TSS	190	126 (±85)

MLSS concentrations in the BNR system at the start of Phase 1 were 2-3 g/L. This increased during Phase 1 operation to a maximum value of 7-8 g/L and 8-9 g/L in the aerobic and MBR tanks respectively. Anaerobic MLSS concentration did not increase above 6 g/L since the influent at Q diluted the mixed liquor recirculating from the membrane tank. The MLSS in the aerobic and membrane tank averaged at about 5 g/L and 6 g/L respectively as can be seen in Table 4.2. Figure 4.2 shows the trend in MLSS concentration increasing over the first 40 days of Phase 1 testing with

the modified A^2O testing since wasting was not conducted. However, CIP clean was conducted on day 35 which may have contributed to the observed fluctuation in MLSS concentrations for all tanks. Manual wasting was then conducted during the last 8 days of experimentation at a fixed wasting rate.

Table 4.2 MLSS Concentrations During Phase 1 Testing

Biological Tank	**MLSS(mg/L)**	**MLVSS(mg/L)**
Anaerobic Tank	6290	3980
Anoxic Tank	4775	4538
Aerobic Tank	5388	4598
MBR Tank	5463	5331
Denitrification Tank	6395	5263

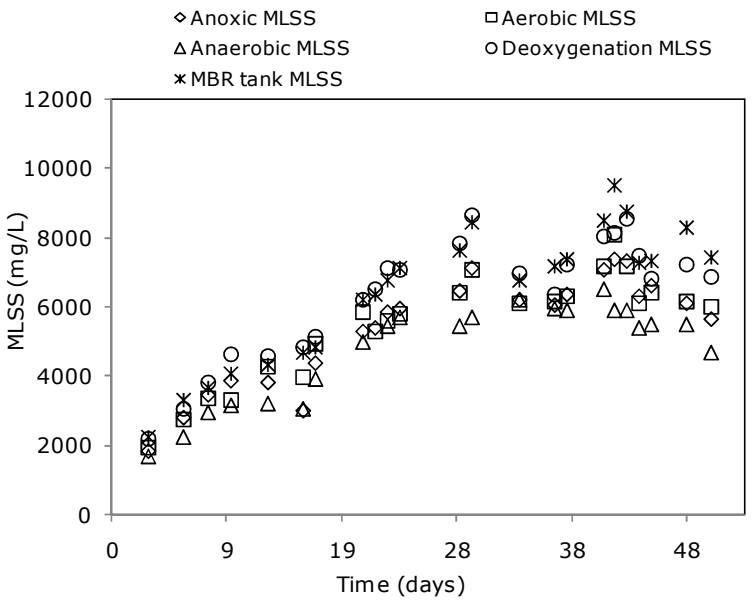


Figure 4.2 Phase 1 MLSS Trend with Membrane A

Based on Table 4.1, the average TCOD:TN value was 15 to 1 which is ideal for the removal of both COD and nitrogen. During Phase 1 of testing, the COD removal

efficiency in membrane A was about 99% and the average effluent BOD was observed to be less than 1 mg/L which can be seen in Figure 4.3 showing the removal efficiency for BOD and COD. COD removal was consistent during testing but BOD removal efficiency fluctuated slightly during the first 30 days possibly since this was during the acclimation period. A more stabilized removal trend was observed after day 36.

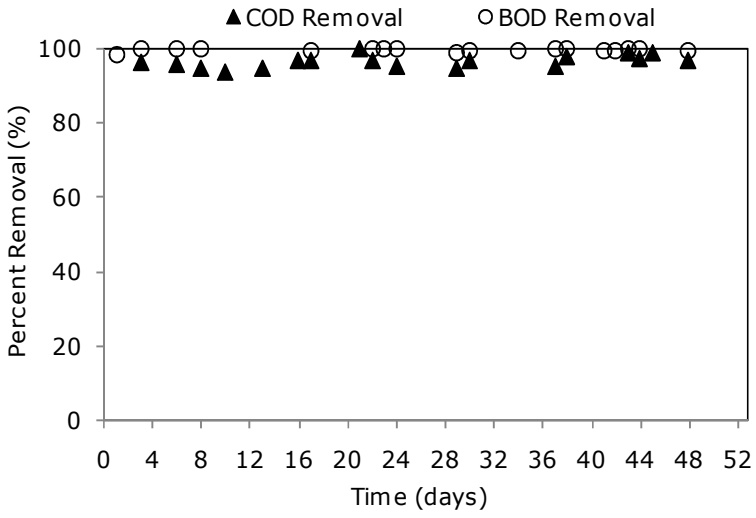


Figure 4.3 Phase 1 COD and BOD Removal During Membrane A Testing

Nutrient removal fluctuated during the acclimation period with nitrogen removal averaging initially around 80% while TP removal was observed initially in the first 40 days to be minimal with fluctuating and unstable phosphorus removal performance. The CIP clean on day 35 may have also contributed to the unstable phosphorus removal since during CIP cleaning the membrane is not in operation for a period of about 2 hours. During this time, feed is not introduced into the biological tanks to prevent possible overflow. A few days after (approximately day 40), the TP removal efficiency was observed to increase in trend with some fluctuations towards approximately 78%. The dissolved oxygen in the anaerobic tank importantly had an effect on the removal efficiency of phosphorus as well as sludge wasting in the last

few days of operation. Sludge was wasted from the membrane tank daily at a fixed rate corresponding to an SRT of 15 days.

The HRT in the deoxygenation tank was fixed at 30 minutes in order to control the DO at an average of less than 0.5 mg/L in this reactor. This was important to prevent oxygen from the MBR tank entering the anaerobic tank. This can directly be observed as during days 32 – 41, the air scouring rate for membrane A was increased to prevent further TMP increases and since a CIP clean was required. This is further discussed later. The increase in air scouring increased the DO content in the MBR tank during this period and can be observed in Figure 4.4. This may have directly inhibited phosphorus removal. After day 42, the average DO concentrations returned below 0.5 mg/L for which phosphorus removal improved.

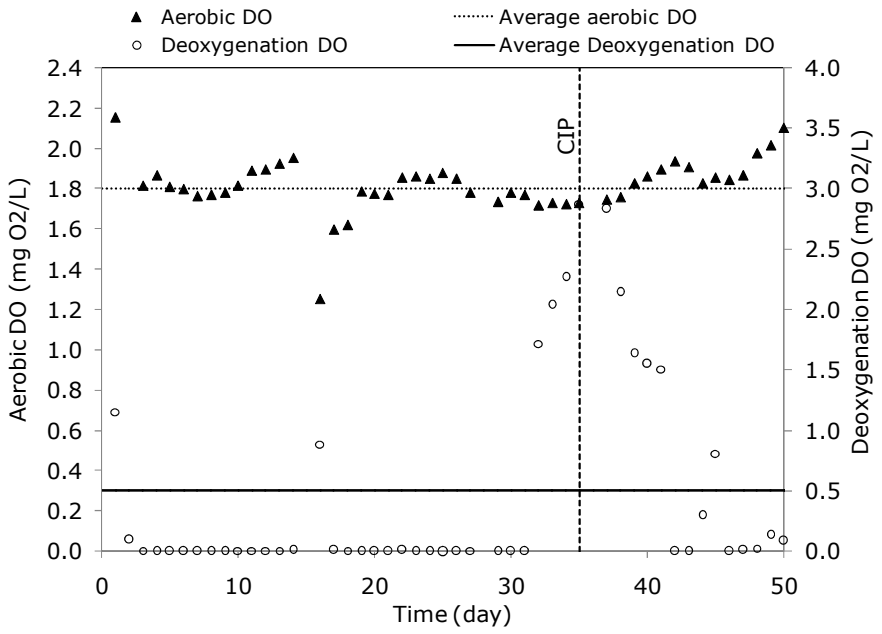


Figure 4.4 Phase 1 DO Concentrations in the Biological System

The average nitrate and phosphorus profiles in the reactors can be observed in Table 4.3 and the effluent TP and TN concentration are also shown in Figure 4.6. The results of the profile indicate that the PAO have not acclimated during Phase 1 since the release and uptake of phosphorus was not significant and explains the lack

of removal of phosphorus. This was especially observed during day 32-41 where the inhibiting oxygen content introduced into the deoxygenation and anaerobic tank completely prevented phosphorus removal. This was despite the low concentration of nitrate in the anaerobic tank. Nitrogen removal was unaffected by the increase in oxygen content in the membrane tank as well as the deoxygenation and anaerobic tanks. Since this period was during the acclimation period, there may have been competition between denitrifiers and PAO for the carbon source explaining the high COD and BOD removal.

Table 4.3 Phase 1 Nitrate and Phosphorus Concentration Profiles

Biological Tank	**Nitrate (mg N/L)**	**Phosphorus (mg P/L)**
Influent	0.4	4.9
Anaerobic	1.51	4.39
Anoxic	4.16	3.13
Aerobic	4.08	3.25
MBR	5.02	3.05
Deoxygenation	2.71	5.00

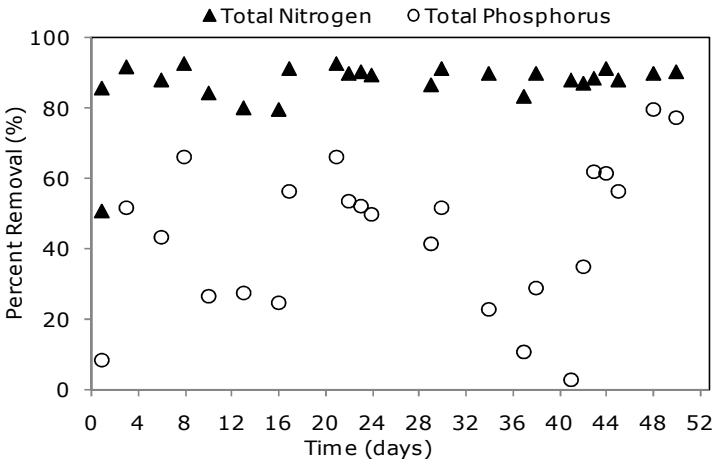


Figure 4.5 Phase 1 Nutrient Removal During Membrane A Testing

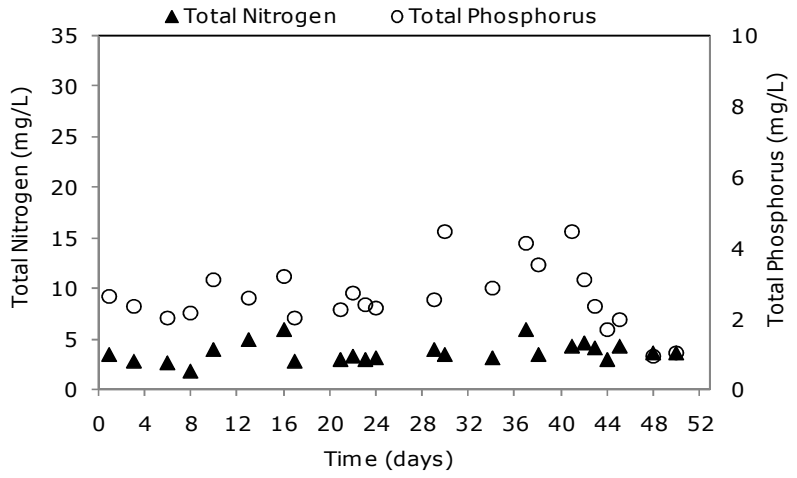


Figure 4.6 Phase 1 Effluent Phosphorus and Nitrogen Concentration

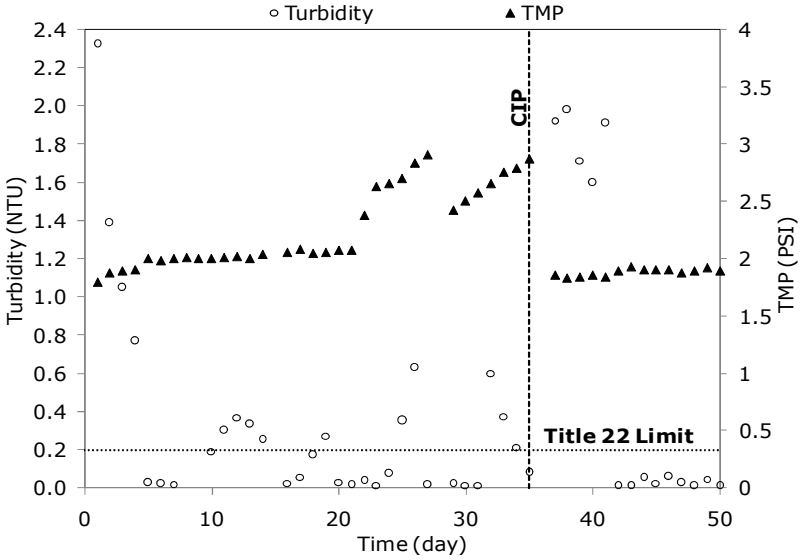


Figure 4.7 Phase 1 Effluent Turbidity and TMP Trend

Particulate contaminants can be removed by the 1 mm fine screen and the MBR membrane. Because the pore size of the filter for suspended solids (SS) measurement is larger than the UF membrane being tested during Phase 1, the membrane effluent could not be tested for SS and was undetectable. The effluent quality was then evaluated using turbidity. Since SS removal efficiency of UF membrane can be more than 99%, turbidity values have been observed less than 1

NTU. In the case of water reuse applications, the turbidity of the effluent should be less than 0.2 NTU based on the Title 22 requirement. During Phase 1 of testing, the turbidity was observed to be higher than 0.2 NTU in membrane A as shown in Figure 4.7. During CIP cleaning, broken fibers were observed and after reinserting the membrane for operation, the turbidity values were observed to spike above 3 NTU. This explains the fluctuating turbidity values observed during testing. Plugging of the broken fibers contribute to lower turbidity values observed after day 42. Membrane performance and optimization is discussed in detail for both membranes tested in section 4.5 and 4.6.

4.2 Phase 2 Membrane B Test with Modified BNR-MBR Process

Since fiber breakage was observed in membrane A during Phase 1 of testing and turbidity of the effluent did not meet Title 22 requirements, membrane B was installed for continued membrane performance evaluation in conjunction with BNR testing using the same mixed liquor (sludge) from Phase 1. Phase 2 testing was conducted over 48 days with one additional change to pilot operation. Phase 2 included an additional recirculation line from the anoxic reactor to the anaerobic reactor as shown in Figure 4.8. This biological process schematic was the result of the combination of an A^2O and UCT process. The additional recirculation line was operated at 5Q and utilized to improve the MLSS concentration in the anaerobic tank since the RAS from the MBR tank was diluted in a 1:1 ratio by the influent and was evident in the MLSS trend of the anaerobic tank in Phase 1. All other operating and controlled parameters remained the same as in Phase 1 except for membrane operation which was operated according to the membrane manufacturer specifications in terms of air scouring and cleaning protocols. Phase 2 testing with membrane B required the use of a different membrane tank to accommodate the

membrane frame/cage. Notably, Phase 2 testing was conducted during the end of the summer and beginning of the winter time.

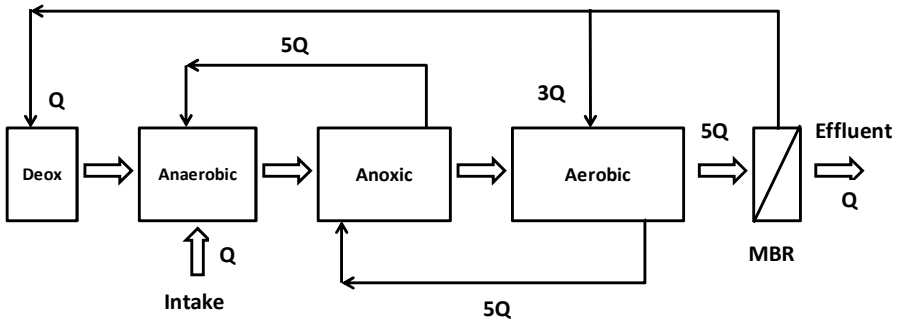


Figure 4.8 Phase 2 Process Schematic with Deoxygenation Tank

During Phase 2 operation, like in Phase 1, wasting was not conducted during the first days of operation in order to increase the MLSS to the desired value at or above 8 g/L. After 14 days of operation for which the MLSS concentrations were increasing rapidly, automated wasting began to fix the SRT at 15 days. Wasting was controlled by the sludge wasting pump at a fixed flow rate with a timer to specifically control the total volume of sludge wasted per day. Wasting contributed to the somewhat fluctuating MLSS observed during Phase 2 testing and was done three times a day. During this time, filtration and influent flows are stopped. Figure 4.9 shows the trend of MLSS concentrations during Phase 2 testing including the temperature trend. The gap observed between days 34-40 was due to the Thanskgiving holiday for which grab samples was not collected for MLSS and water quality analyses. The aerobic and MBR tank MLSS concentrations did not increase above 7 and 10 g/L respectively and the anaerobic tank MLSS remained at or below 6 g/L despite the increased recirculation from the anoxic tank. The lower MLSS concentration may have been contributed by the lower temperature which lowers bacterial activity and possibly due to a short SRT at 15 days. Temperatures observed

were averaging around 29-30°C but towards the end of Phase 2 fluctuated with the lowest temperature recorded at 22°C. Table 4.4 shows the average values during pilot testing.

Table 4.4 Phase 1 Average MLSS and MLVSS During Membrane A Testing

Biological Tank MLSS (mg/L)	**MLSS**	**MLVSS**
Anaerobic Tank	4816	4230
Anoxic Tank	5541	4813
Aerobic Tank	5531	4787
MBR Tank	6445	5534
Denitrification Tank	5689	4915

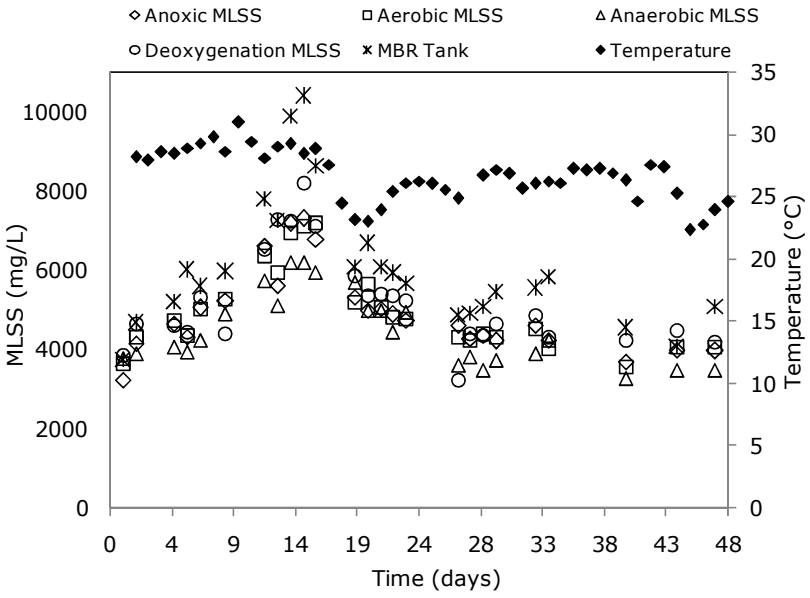


Figure 4.9 Phase 2 MLSS Concentration During Testing

Biological system performance was analyzed based on COD, BOD and nutrient removal. Over the testing period, COD and BOD removal was observed at or above 97% and are shown in Figure 4.10. Fluctuations were not observed during Phase 2 for COD and BOD removal despite the temperature and MLSS fluctuations.

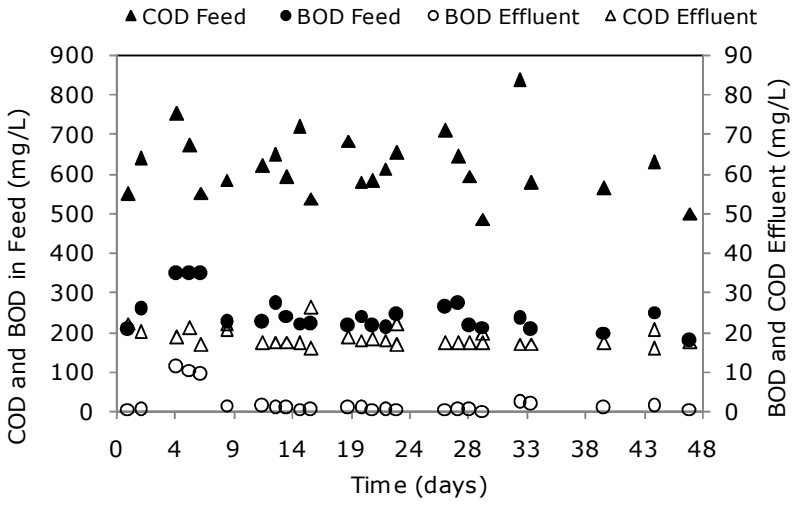


Figure 4.10 Phase 2 COD and BOD Removal During Membrane B Testing

Similar to Phase 2, the nitrogen and phosphorus content of each reactor was analyzed and measured. The average nitrate and phosphorus concentration profiles can be found in Table 4.5. The results seem to show that the additional recirculation to the anaerobic reactor improved the phosphorus removal with additional phosphorus release being observed in the deoxygenation tank. However, this seemed to have affected the denitrification process as nitrate concentrations were observed above the effluent target and accumulating in all reactor tanks. Nitrate concentrations were observed much higher in Phase 2 testing than Phase 1 testing. Given the improved phosphorus removal, there remained a possible competition between denitrifiers and PAOs. Nutrient removal during Phase 2 was averaged at 87% and 52% for nitrogen and phosphorus respectively. The nutrient removal trend over the Phase 2 testing period is shown in Figure 4.12.

Table 4.5 Phase 2 Nitrate and Phosphorus Concentration Profiles

Biological Tank	Nitrate (mg N/L)	Phosphorus (mg P/L)
Influent	0.4	4.9
Anaerobic	5.65	4.29
Anoxic	13.05	2.20
Aerobic	12.12	3.36
MBR	16.07	2.34
Deoxygenation	5.79	6.71

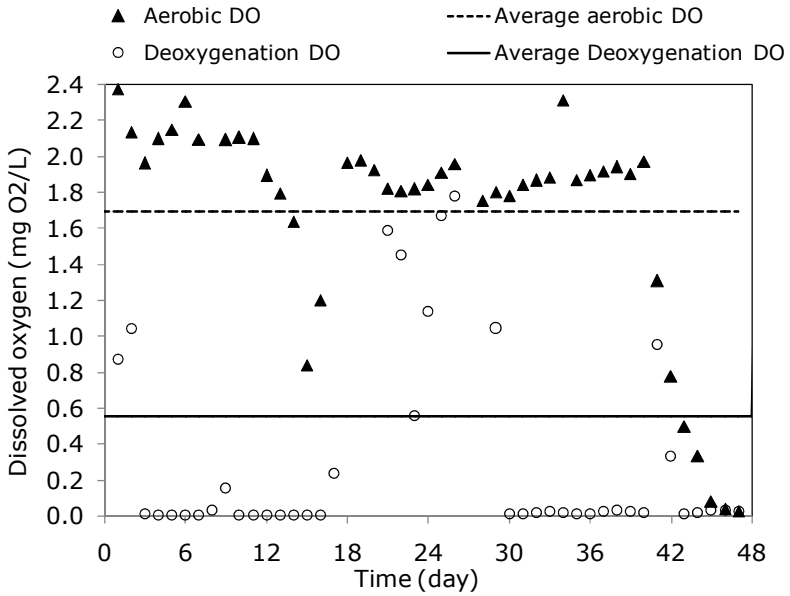


Figure 4.11 DO Concentrations in Biological System

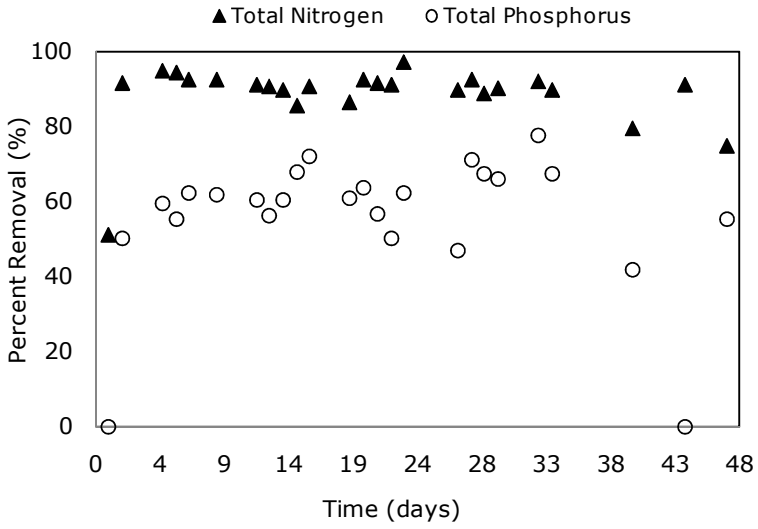


Figure 4.12 Phase 2 Nutrient Removal During Membrane B Testing

Similar to the nutrient removal trending, Figure 4.13 shows the trend for total phosphorus and total nitrogen in the effluent. Although phosphorus removal was improved, the effluent phosphorus content was observed to be similar to that in Phase 1. Nitrogen in the effluent on the other hand was compromised and was observed to be less stable than that observed in Phase 1.

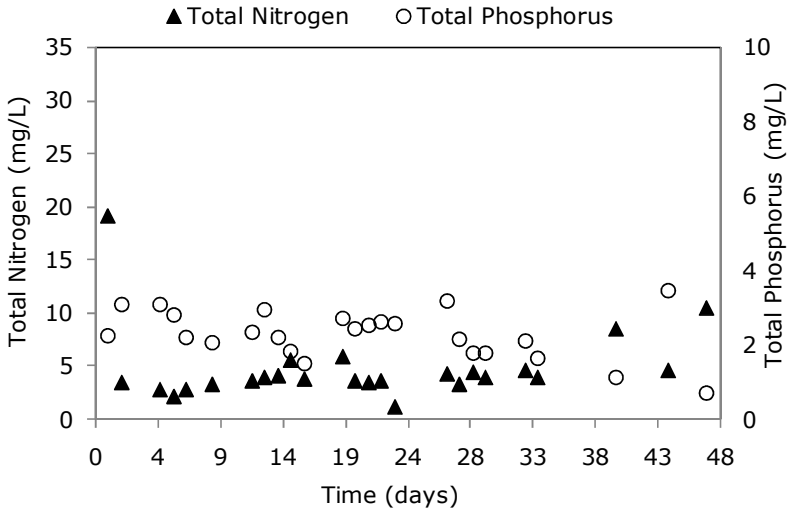


Figure 4.13 Phase 2 Effluent Phosphorus and Nitrogen Concentration

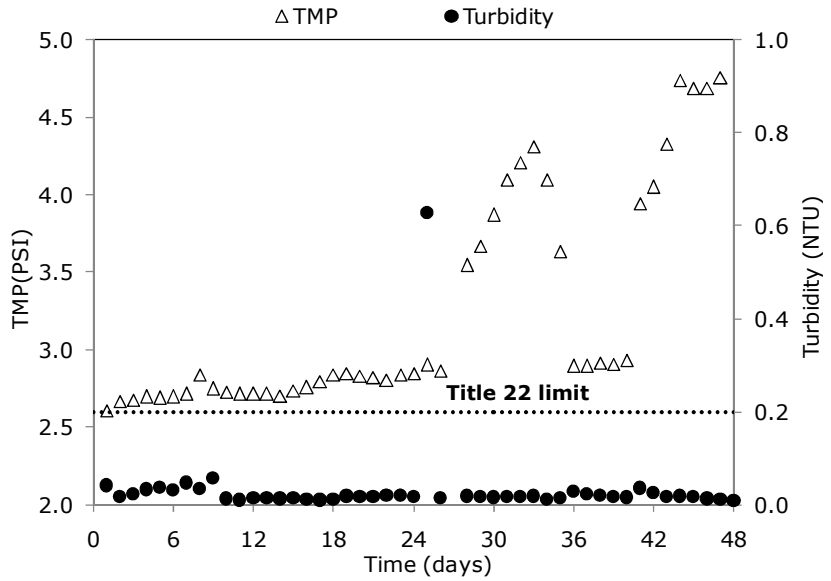


Figure 4.14 Phase 2 Effluent Turbidity and TMP Trend During Membrane B Testing

In comparison the membrane A, membrane B exhibited consistent turbidity values as can be observed in Figure 4.14. The single point at 4 NTU was due to the data recorded during the maintenance of the turbidity sensor and does not reflect the membrane performance. Unlike membrane A, membrane B exhibited consistent effluent turbidity values as can be Title 22 certified. This is despite membrane TMP and fouling performance. This indicates higher membrane integrity including the module design compared to membrane B.

4.3 Phase 3 Membrane B Test with Modified A^2O-MBR Process

Since Phase 2 was conducted with a proposed biological process that combines UCT and A^2O, the modified A^2O which performed better was then tested with membrane B for confirmation of Phase 1 testing. Phase 3 started directly after Phase 2 testing by turning off the recirculation pump which returns mixed liquor from the anoxic to the anaerobic tank. Phase 3 testing was conducted for 37 days with

fixed parameters similar to Phase 1 testing except for the internal recirculation to the deoxygenation tank. This change was made since the MLSS results in Phase 1 and 2 showed a lower MLSS concentration in the anaerobic tank compared to the membrane tank and aerobic tank. This may have contributed to the performance of phosphorus. The overflow from the membrane tank was returned to the deoxygenation and aerobic tank in the ratio of 1:1 at 2Q for an even distribution of the mixed liquor. Membrane operation was also fixed except for air scouring that was lowered to observe membrane performance.

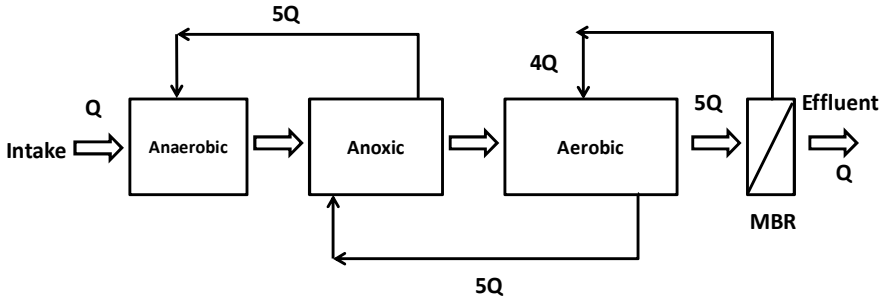


Figure 4.15 Phase 3 Process Schematic of UCT Process

Phase 3 was conducted during the winter period where temperatures dropped as low as 10°C. Sampling was not conducted between days 67 and 76 for water quality analyses due to the Christmas holiday. Remote monitoring however was continued which logged membrane performance and sensor information such as pH, DO and temperature.

During Phase 3 testing the MLSS trend as averaged in Table 4.6 was observed to be stable around 4 g/L and remained below the target minimum concentration of 6 g/L. The trend can be seen in Figure 4.16 which also shows the temperature trend over the testing period. Such low temperatures may have contributed to the observed MLSS concentrations since, like in Phase 2, automated wasting was conducted to fix the SRT at 15 days and microbial activities are affected by

temperature. The low temperatures observed may have prevented the MLSS from increasing above 4 g/L.

Table 4.6 Phase 3 Average MLSS and MLVSS During Membrane B Testing

Biological Tank MLSS (mg/L)	**MLSS**	**MLVSS**
Anaerobic Tank	4416	3913
Anoxic Tank	4270	3797
Aerobic Tank	4183	3746
MBR Tank	4752	4209
Deoxygenation Tank	4883	4293

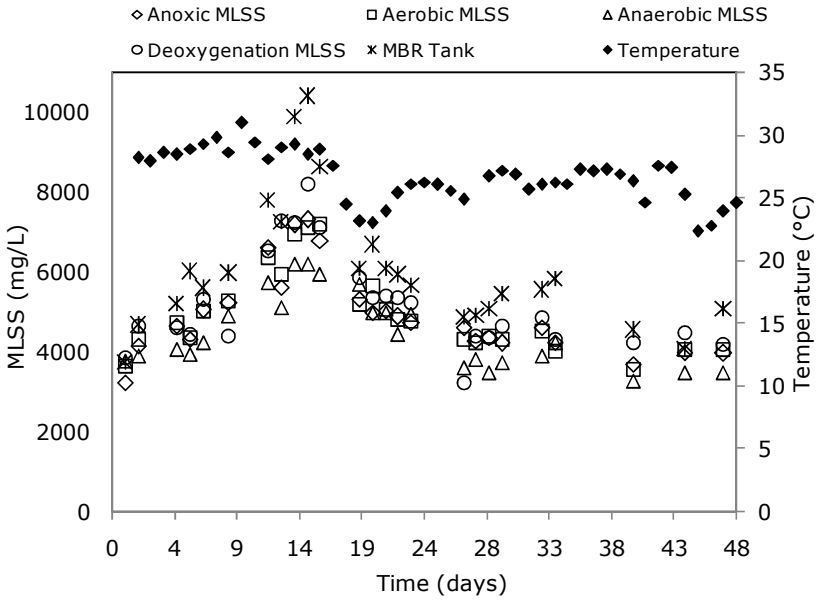


Figure 4.16 Phase 3 MLSS Concentration During Membrane B Testing

In observation of COD and BOD removal as shown in Figure 4.17, temperature did not seem to affect the removal efficiencies. As previously mentioned, the operating parameters remained the same for Phase 3 except for the membrane recirculation ratio to the aerobic and deoxygenation tank. The dissolved oxygen was maintained at 2 mg/L and averaged 2.7 mg/L in the aerobic tank and

4.3 in the deoxygenation tank as can be observed in Figure 4.18. This directly affected BOD and COD removal since the supply of oxygen was sufficient for the removal of both contaminants greater than 97%. The DO trend observed is also directly caused due to the increased air scouring rate which may have increased the DO in the membrane tank above 5 mg/L with the recirculation the aerobic tank kept at 2 mg/L. The DO observed above 6 mg/L during the period where sampling was not conducted, the level may have fluctuated to expose the DO probe to the atmosphere explaining the high DO concentrations.

Phase 3 showed a high DO in the deoxygenation which was recirculated from the membrane tank and remained for 30 minutes prior to entering the anaerobic tank. The deoxygenation tank averaged above 4 mg/L during Phase 3 and may have impacted the PAO as well as the denitrifiers.

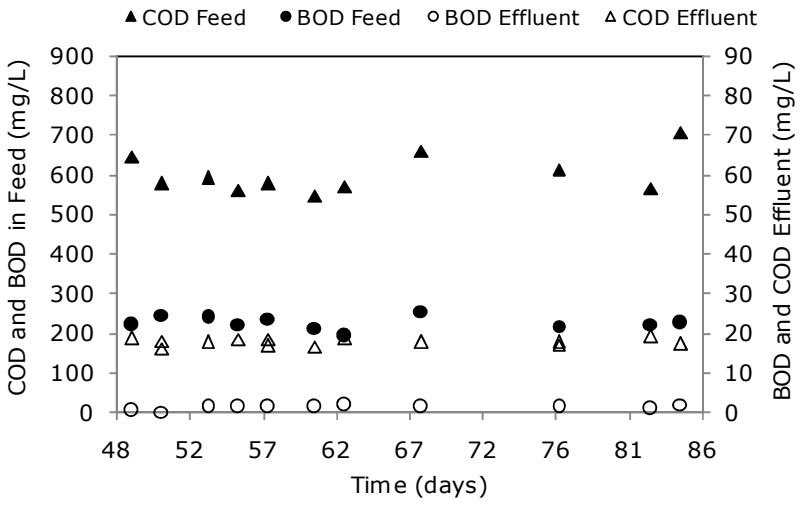


Figure 4.17 Phase 3 COD and BOD Removal During Membrane B Testing

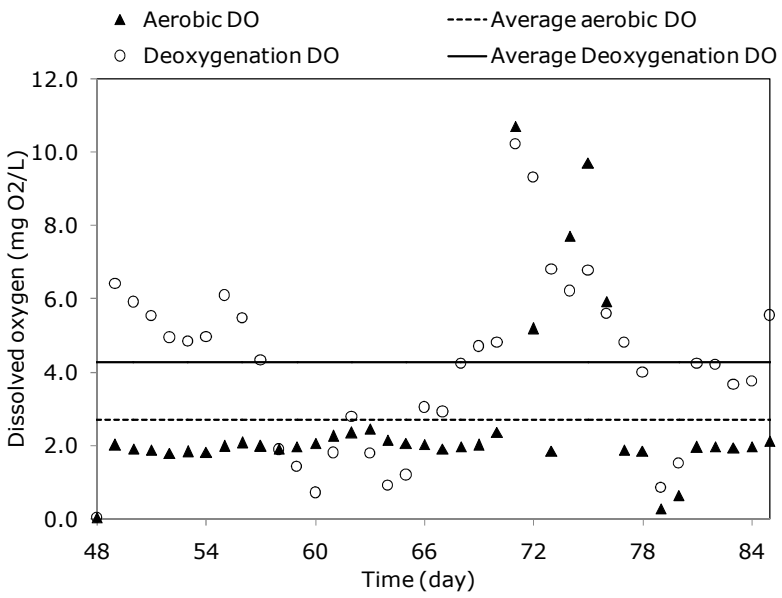


Figure 4.18 Phase 3 DO Concentration in the Biological System

As previously mentioned, the DO content during Phase 3 testing was unusually high due to the membrane operation additionally adding oxygen to the wastewater. The nutrient removal was observed during this period carefully except for the days noted when sampling was not conducted. The average nitrate concentration observed during Phase 3 in the effluent was 11 mg/L and the average phosphorus concentration was 2 mg/L. Table 4.7 shows the concentration profiles for nitrogen and phosphorus indicating an accumulation of nitrate within the system confirming the effect of temperature on the denitrifiers preventing complete denitrification despite the recirculation of 2Q to the deoxygenation which will return to the anoxic tank. Phosphorus removal on the other hand shows additional phosphorus release in the deoxygenation tank which contributed to some uptake of phosphorus in the aerobic tank. This corresponds with the decreasing oxygen concentration in the deoxygenation tank in Figure 4.19 as phosphorus removal increased during the first 14 days of operation of Phase 3. Figure 4.20 also confirms this with the decreasing phosphorus and nitrogen during the early stages of Phase 3.

The effluent fluctuations can be correlated with the temperature fluctuations observed during the winter emphasizing the effect of temperature on denitrification. Towards the end of Phase 3, phosphorus and nitrogen removal was not observed to be consistent and stable but the performance was improved when compared to Phase 1.

Table 4.7 Phase 3 Nitrate and Phosphorus Concentration Profiles

Biological Tank	**Nitrate (mg N/L)**	**Phosphorus (mg P/L)**
Influent	0.15	4.6
Anaerobic	3.95	4.29
Anoxic	13.05	2.20
Aerobic	12.12	3.36
MBR	16.07	2.34
Deoxygenation	5.79	6.7

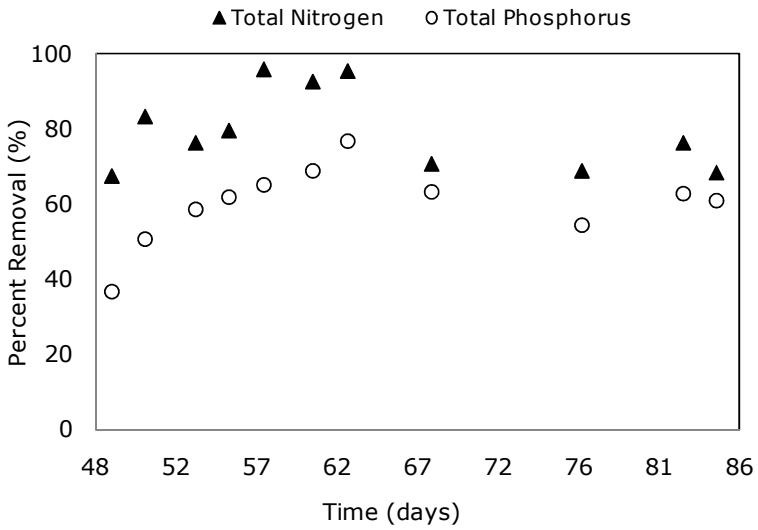


Figure 4.19 Phase 3 Nutrient Removal of Nitrogen and Phosphorus

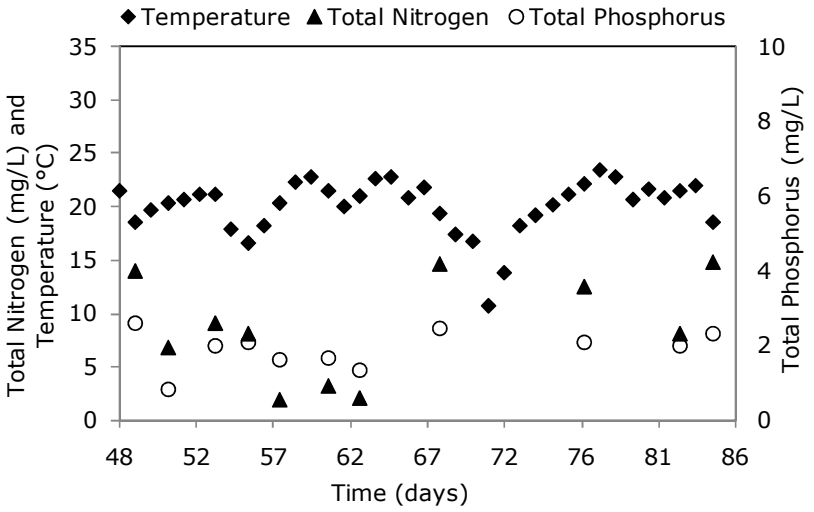


Figure 4.20 Phase 3 Effluent Phosphorus and Nitrogen Concentration

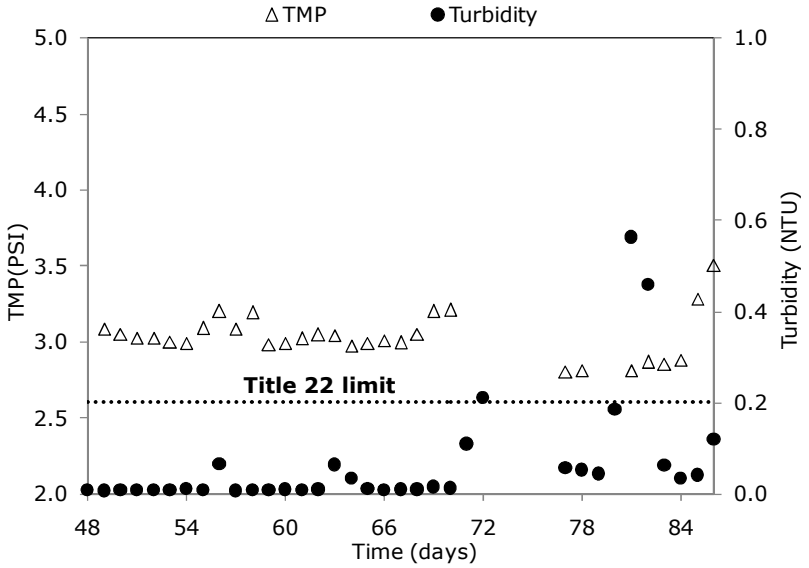


Figure 4.21 Phase 3 Effluent Turbidity and TMP Trend During Membrane B Testing

Turbidity was continued to be monitored alongside TMP to observe membrane integrity similar to Phases 1 and 2. The turbidity of the effluent from membrane B remained below 0.2 NTU. The points observed above 0.2 NTU were due to interference by air bubbles introduced during maintenance cleaning and calibration.

4.4 Phase 4 Membrane B Test with Modified UCT-MBR Process

Lastly, Phase 4 of testing was conducted to operate the modified UCT process as shown below in Figure 4.22 given the unstable performance of the previously mentioned biological processes. One idea that also may have contributed to the unstable and lower BNR performance is the SRT. The previous test phases operated with an SRT of 15 days. In order to improve MLSS concentrations and optimize the BNR, the SRT was changed to 24 days during Phase 4. This was important to operate the BNR and MBR at the desired higher MLSS concentrations.

Phase 4 of testing was also conducted with membrane B which was continuous of Phase 3 testing. In this phase, the overflow recirculation from the membrane tank was completely recirculated at 4Q to the aerobic tank with also an additional recirculation from the anoxic to the anaerobic reactor. The deoxygenation reactor was not utilized during Phase 4 of testing and was isolated by closing the overflow ball valve that was connected on the piping where the tee had previously split the flow of wastewater to the aerobic and deoxygenation tank. Membrane operation was kept constant at the same operating parameters as that in Phase 3 testing.

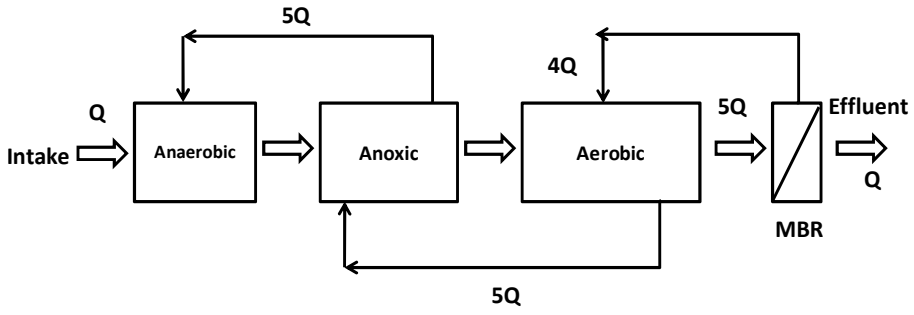


Figure 4.22 Phase 4 Modified UCT-MBR Process Schematic

System monitoring was conducted with the same analyses and data logging as the previous phases. Phase 4 of testing was conducted over 108 days to increase the MLSS concentrations above the minimum desired concentration of 6 g/L and to

confirm the observed membrane and BNR performance. Phase 4 testing ended when the CIP clean of membrane B was required as per the manufacturer's specifications as well as based on the observed TMP. MLSS and MLVSS concentrations were monitored and are averaged in Table 4.8. Due to the length of testing, the MLSS trend was recovered to 6 g/L and above as can be observed in Figure 4.23.

Table 4.8 Phase 4 Average MLSS and MLVSS during Membrane B Testing

Biological Tank	**MLSS (mg/L)**	**MLVSS (mg/L)**
Anaerobic Tank	5090	4465
Anoxic Tank	6216	5363
Aerobic Tank	6205	5322
MBR Tank	7105	6039

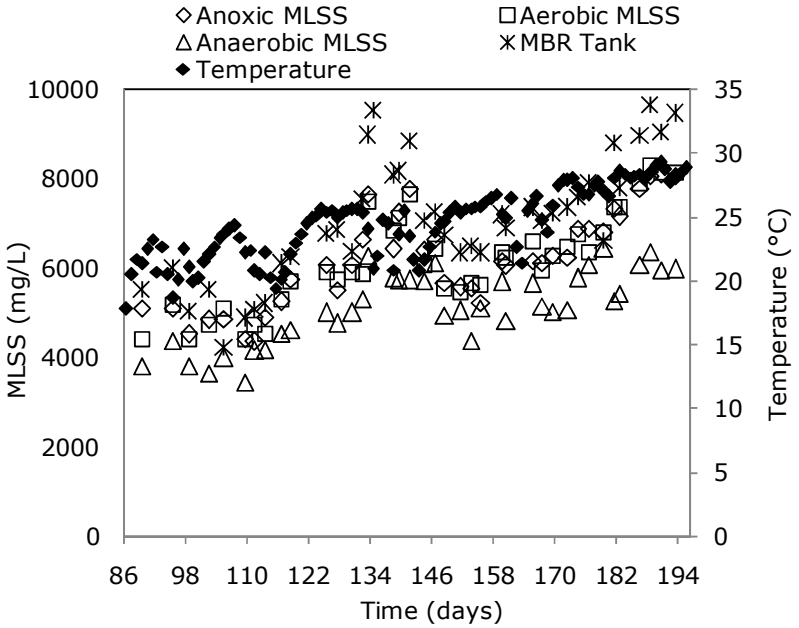


Figure 4.23 Phase 4 MLSS Concentrations During Membrane B Testing

The COD and BOD removal trend is presented in Figure 4.24 which showed some fluctuations in removal as compared to the previous testing phases. An explanation for this result is directly related to the DO control in the aerobic reactor.

As the MLSS was increasing in Phase 4, the DO control was fluctuating since the transfer of oxygen decreased as the MLSS concentrations increased. Figure 4.25 shows the fluctuations in DO in the aerobic reactor which averaged at 1.4 mg/L during Phase 4. These fluctuations will have some impact on nutrient removal as well.

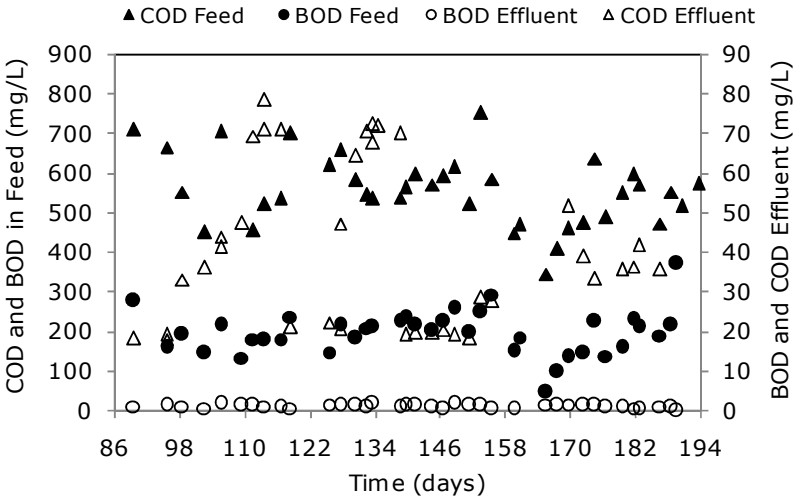


Figure 4.24 Phase 4 COD and BOD Removal During Membrane B Testing

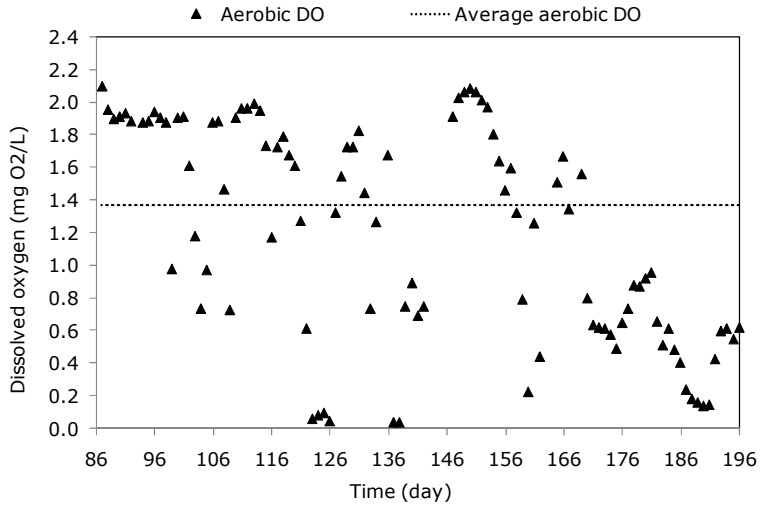


Figure 4.25 Phase 4 DO Concentrations During Membrane B Testing

The results of Phase 4 in terms of nutrient removal can be seen in Figure 4.26 and Figure 4.27 below. The nutrient removal averaged at approximately 90% for nitrogen and 79% for phosphorus. The phosphorus removal efficiencies below 60% were due to some shut down alarms which turned off the system temporarily until the alarm was cleared. This indicated the effect of system upsets on phosphorus removal. However, the system recovered a few days after in each occasion. The average removal efficiency of phosphorus excluding alarm events was 90%. Phosphorus removal is usually unforgiving of system upsets but the pilot system recovered in nutrient removal upon restarting the system after alarm or shut off events.

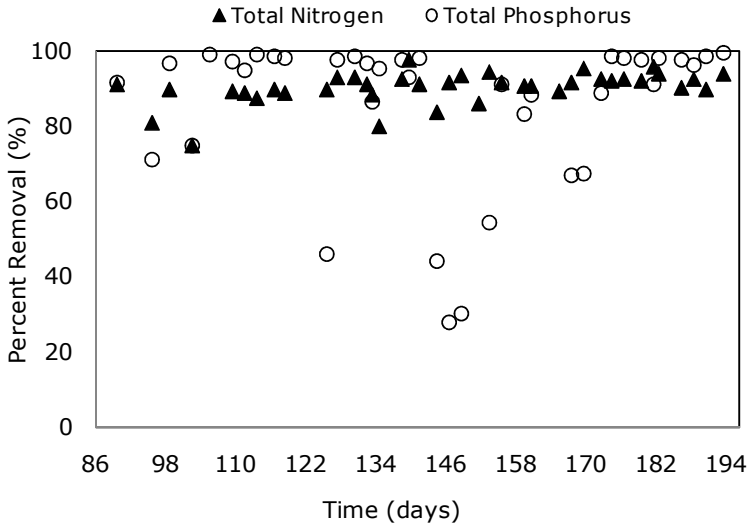


Figure 4.26 Phase 4 Nutrient Removal During Membrane B Testing

Specifically evaluating the effluent water quality, Figure 4.27 shows the effluent concentrations of nitrogen and phosphorus with the UCT-MBR process. Unlike the previous phases, both nitrogen and phosphorus was achieved at concentrations below 5 mg/L in the effluent and even more so below 1 mg/L for phosphorus. The data consistently showed phosphorus removal below 1 mg/L during this test phase. Nitrogen removal was first inhibited by phosphorus but later was

stabilized. The temperature also shown in Figure 4.27 shows the temperature increasing since the testing period extended into spring. Some temperature fluctuations were observed to have some effect on nitrogen removal but appeared minimal compared to the previous testing phases.

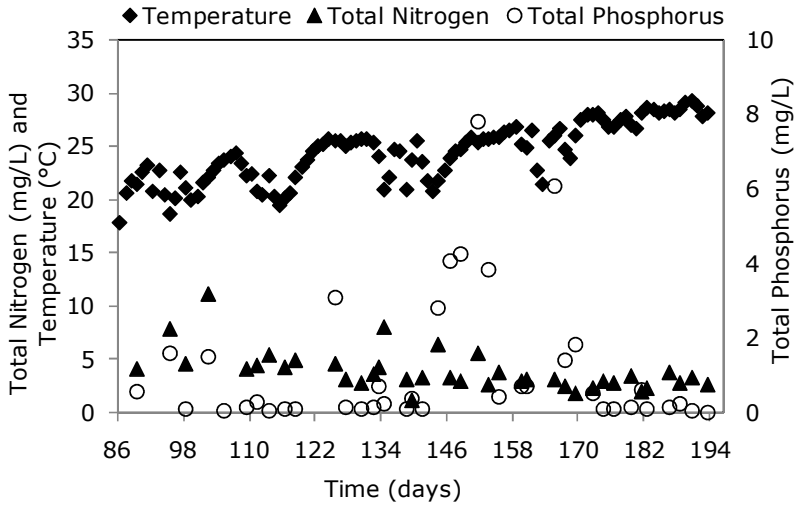


Figure 4.27 Phase 4 Effluent Phosphorus and Nitrogen Concentration

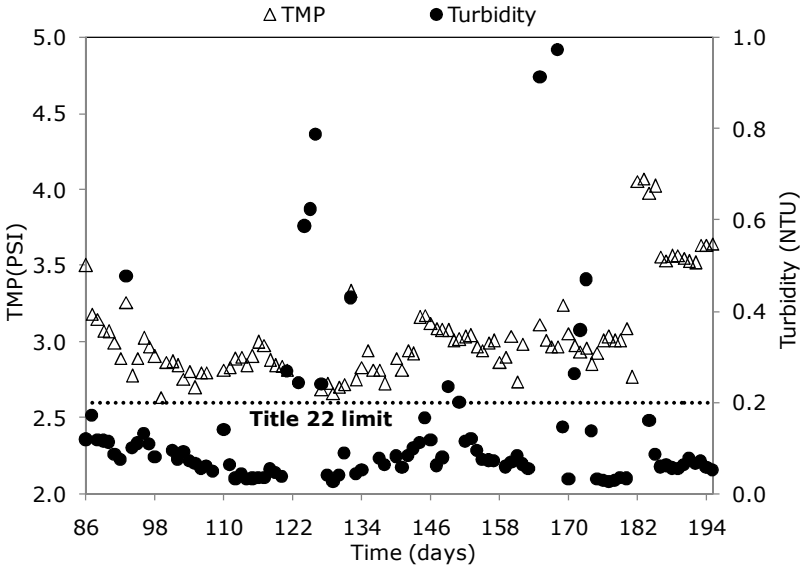


Figure 4.28 Phase 4 Effluent Turbidity and TMP Trend During Membrane B Testing

The turbidity of observed during Phase 4 remained below 0.2 NTU with fluctuating values due to algae growth and air bubbles from maintenance. The TMP confirms the membrane integrity since a higher TMP did not seem to show a high turbidity value above the limitation. The TMP observed during the end of the phase, indicated fouling of the membrane which required CIP cleaning.

4.5 BNR Configuration Comparisons

If we compare the BNR configurations in terms of phosphorus removal and correlate this with the data collected, a specific trend can be observed. Towards the end of experimentation with the UCT-MBR process configuration, phosphorus removal was observed to be more stable and removed from the system with nitrogen. This is further confirmed in Figure 4.29 and Figure 4.30 which show a lower ORP (more negative) in the anaerobic reactor and slightly higher ORP in the anoxic/oxic which provide the appropriate conditions for the take up of phosphorus. This is very important since Figure 4.30 shows the indirect relationship of the ORP in the anaerobic and oxic reactor to phosphorus removal. Also, the lower the DO concentration in the anoxic tank and the higher the DO concentration in the aerobic tank, the more efficiently phosphorus is removed. However, this is not true for the anaerobic reactor. If the DO concentration goes over 0-0.5 mg/L, phosphorus removal becomes inhibited based on the trend in Figure 4.30. Also the literature review discussed the importance of anoxic conditions for denitrification and anaerobic conditions for phosphorus release. For this reason, a DO concentration above 0.5 mg/L was sufficient to inhibit phosphorus activity (release). Figure 4.33 further shows the feed and effluent concentrations observed throughout the study with low concentrations of phosphorus and nitrogen obtained in the effluent with the UCT configuration and lower DO and ORP conditions.

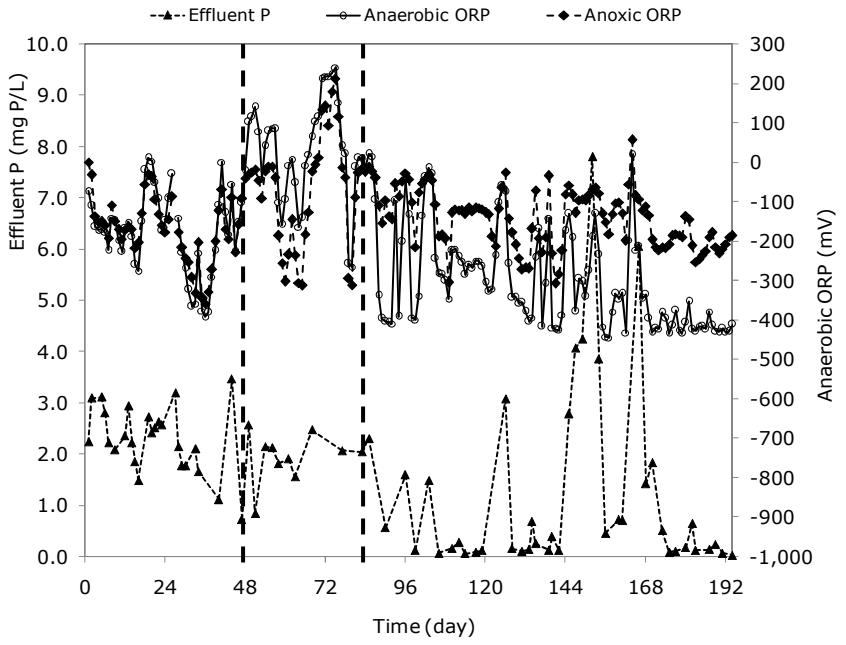


Figure 4.29 Anaerobic ORP and its Effect on Effluent Phosphorus Concentration

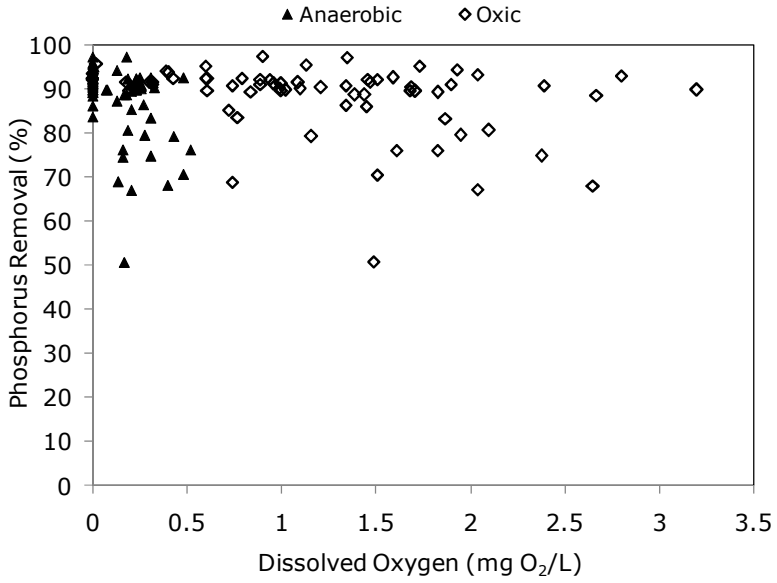


Figure 4.30 Correlation of Dissolved Oxygen and Phosphorus Removal

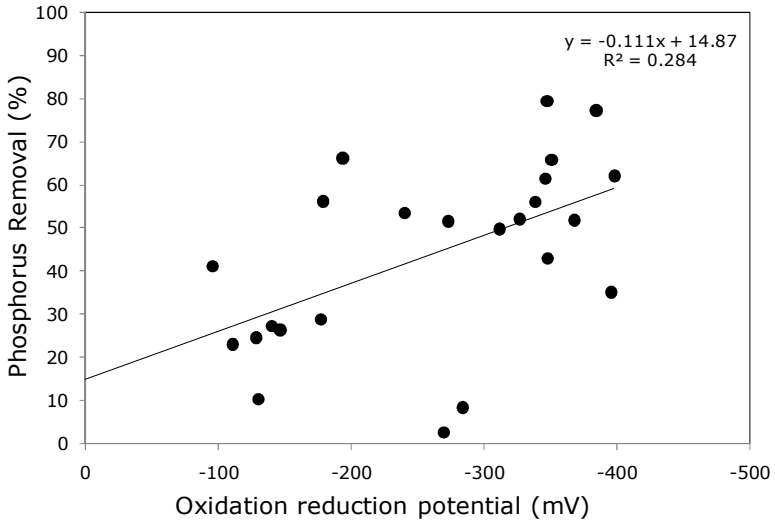


Figure 4.31 Correlation of Anaerobic ORP and Phosphorus Removal (Membrane A)

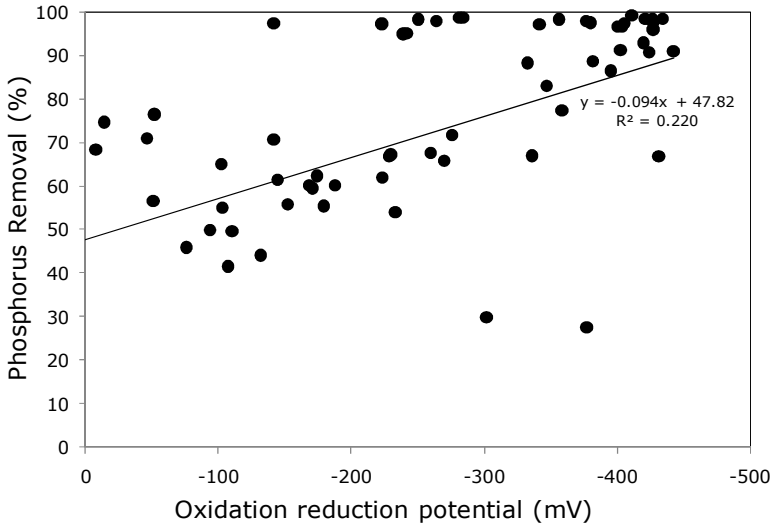


Figure 4.32 Correlation of Anaerobic ORP and Phosphorus Removal (Membrane B)

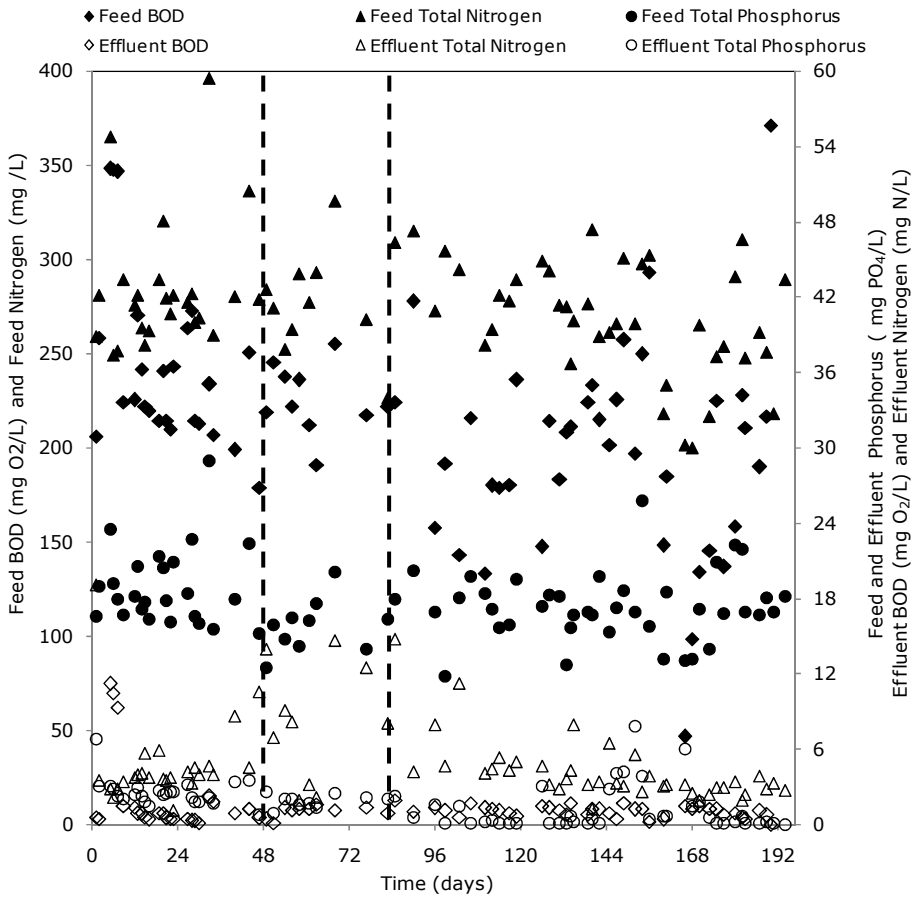


Figure 4.33 Feed and Effluent Phosphorus, Nitrogen and BOD Concentration

If we look at Figure 4.31 and Figure 4.32, which shows a correlation of the ORP value in the anaerobic reactor, there is a distinct trend dictating the effect of ORP in the anaerobic reactor on phosphorus removal. This is probably based on the principle of phosphorus release for which phosphorus is taken up by cells in the aerobic reactor. This trend provides a clearer relationship and the overall effect of ORP on in the anaerobic reactor on phosphorus removal. We can interpret from Figure 4.32 that for phosphorus removal above 90%, ORP values less than -350 mV is required. Phosphorus removal less than 50% were observed with ORP values greater than -200 mV. This was also observed in Figure 4.32.

4.6 MBR Membrane Performance and Optimization

Membrane A and B were tested over a period greater than 200 days under different BNR and membrane operating conditions. The design filtration flow rate of the pilot system as previously mentioned was 4 gpm but after startup of both membranes, the filtrate flow was observed above 4 gpm. Investigation into this led to the conclusion that the water level in the membrane tank contributed to the higher flow. Both membranes were operated in membrane tanks that were about 11-13 ft high. The filtrate plumbing was directly plumbed to the bottom of the filtrate tank which created a water head which was noticeable in the pressure transmitter (also installed on the bottom of the piping that is connected to the bottom of the filtrate tank) which read a positive pressure when the membranes were not in operation. The average pressure due to the water level of the tank was calculated using Equation 4.1 where A is the MBR tank water height and B is the filtrate tank water height in feet.

$$(A - B/2)\ \text{ft} = \text{Water Head (psi)} \qquad 4.1$$

Since the water head needs to be factored into the TMP trends, TMP was calculated by deducting the pressure transmitter reading at the filtrate line from the pressure due to the water head calculated in Equation 4.1. This was done for both membrane A and B. Membrane A was calculated to have a water head of 4.2 psi while membrane B was calculated to have a water head of 4.4 psi. Membrane operating flux and TMP were analyzed for both membrane A and B. Because data was collected every 10 seconds during testing, the daily averages of hourly average values were calculated which are plotted in Figure 4.34, Figure 4.35, Figure 4.36 and Figure 4.37 respective of the phases of testing. Also shown is the TMP and permeability of both membranes and their respective flux operating rates.

The performance of membrane A during Phase 1 of testing can be observed in Figure 4.34. Flux operation was uncontrolled due to the siphon effect of the water head. This prevented the operation of the operation of the filtrate pump. For this reason, flux rates were observed above the design flux of 20 LMH. As observed during Phase 1, the TMP trend began to increase after day 20 for which a system shut down occurred due to power failure. Although the TMP shows recovery of the membrane fouling continued as the TMP continued to climb near 4 psi. A CIP was then required on day 35 for which sodium hypochlorite at a concentration of 2-3 g/L was used. Also observed is the air scouring flow rate which was fixed at 1 SCFM during the first 7 days of operation and required 2 SCFM according to the membrane manufacturer. Despite the increase in air scouring TMP fouling was observed. Even more so at the same flux operation, the TMP continued to increase rapidly after air scouring was increased to 2.5 SCFM. Based on this performance, the CIP was required to recover the membrane since CEB was not recovering the TMP. After CIP, the membrane completely recovered to the original operating parameters with stable TMP operation. However, since membrane fiber breakages were evident after removal of the membrane out of the membrane tank and inspection, membrane B testing was conducted.

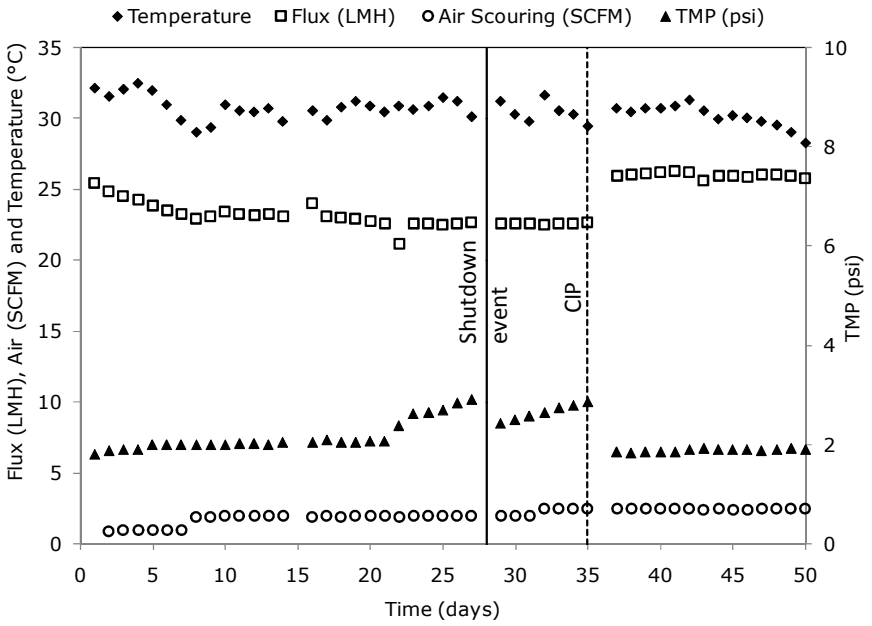


Figure 4.34 Membrane A Performance with A^2O

Membrane B testing in Phase 2 operated similar to membrane A with the siphon effect and inactive filtration pump. The air scouring rate operated in Phase 2 was fixed at 6 SCFM. Peak flux testing was conducted at 27 LMH which showed TMP increase above 4 psi. The flux rate was lowered to the original settings since this was during Thanksgiving. The flux was then returned to 27 LMH where the continued increasing trend in TMP was observed up to 5 psi. This ended the second experimental phase since the biological process configuration was changed.

Membrane B was then operated in Phase 3 at a flux rate of 18 LMH where the siphon effect was observed. The TMP remained at 3 psi at the start and during Phase 3 and the air scour rate was initially fixed at 8 SCFM to observe the effect on recovery of membrane operation in terms of TMP. The membrane remained at a TMP of 3 psi for 9 days. At this point, the air scour rate was then lowered since the TMP was stable. The air scour rate was lowered to 2 SCFM in order to observe energy

conservation given the higher air scouring requirement compared to membrane A. The TMP was not observed to increase and remained stable at 18 LMH with 2 SCFM.

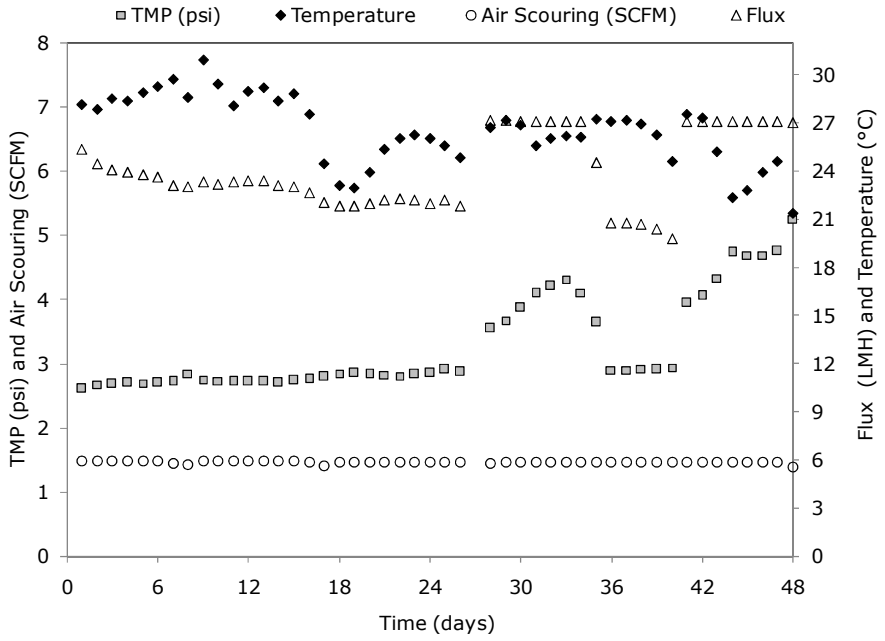


Figure 4.35 Phase 2 Membrane Performance with Membrane B

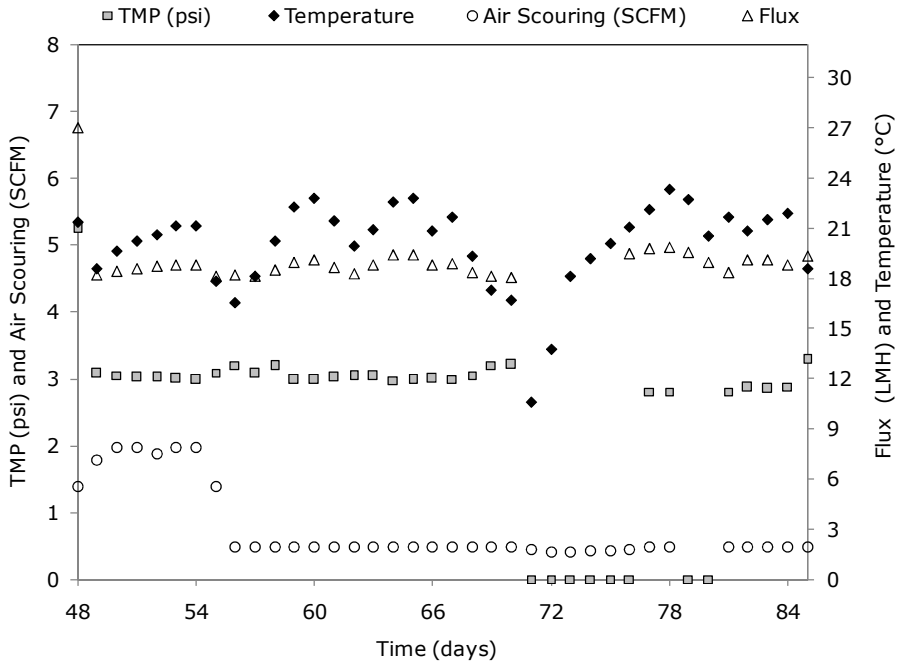


Figure 4.36 Phase 3 Membrane Performance with Membrane B

Figure 4.37 shows the operating and fouling trend of membrane B in the last phase of experimentation. The flux rate remained at 18 LMH in order to eliminate variables that may affect the BNR such as the air scouring rate which was remained at 2 SCFM. Although 2 SCFM is below membrane B manufacturer's specification, the membrane operated at a stable TMP with the automated required CEB cycles once every 1000 filtration cycles. Peak flux testing was then tested for 3-4 days at 25 LMH where the TMP was observed to increase and required a higher air scour rate at 4 SCFM but the TMP did not appear to lower below 4 psi. Flux operation was then restored to a lower peak flux at 21 LMH where at 4 SCFM, stable operation was observed in the last 10 days of operation. This concluded Phase 4 testing.

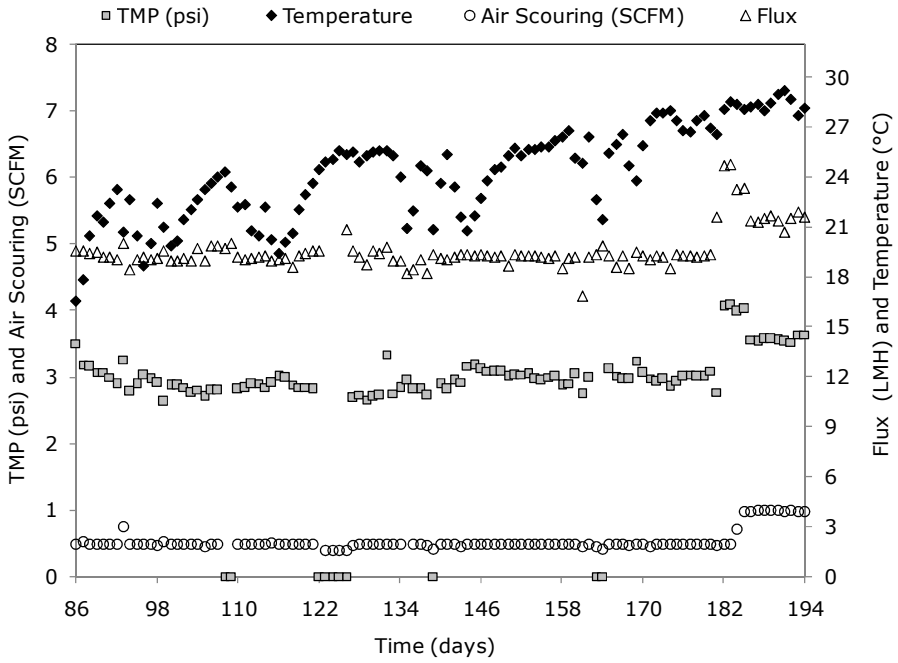


Figure 4.37 Phase 4 Membrane Performance with Membrane B

An overall evaluation of membrane A and B in terms of flux operation and permeability is shown in Figure 4.38, Figure 4.39, and Figure 4.40. Although membrane A provided stable TMP trending, the turbidity of the product did not meet Title 22 criteria. Membrane B, on the other hand, met the Title 22 criteria but

different fouling trends were observed as the TMP was observed to increase depending on the flux operation, air scouring rate and MLSS concentration in the membrane tank. This is confirmed with the data collected from Phase 3 where the MLSS concentrations were observed above 6 g/L up to 8 g/L.

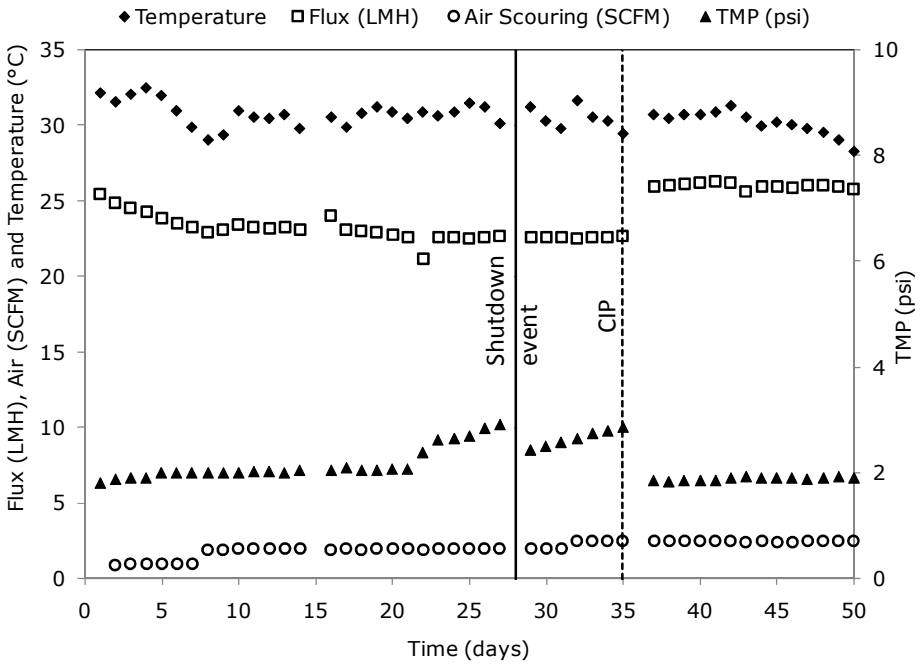


Figure 4.38 Overall Performance of Membrane A Operation

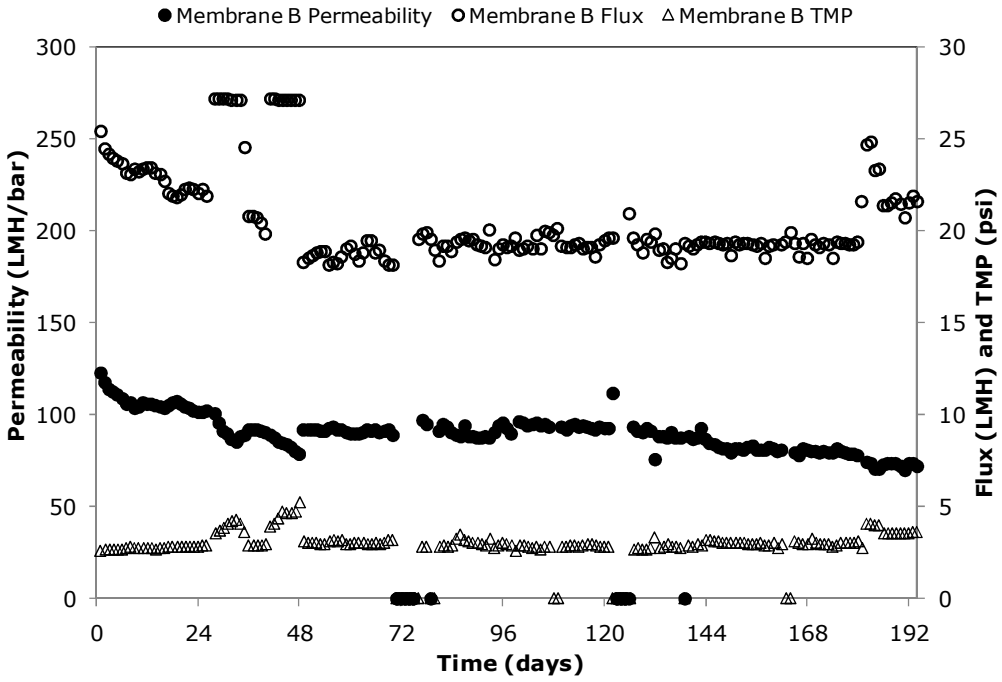


Figure 4.39 Overall Performance of Membrane B Operation

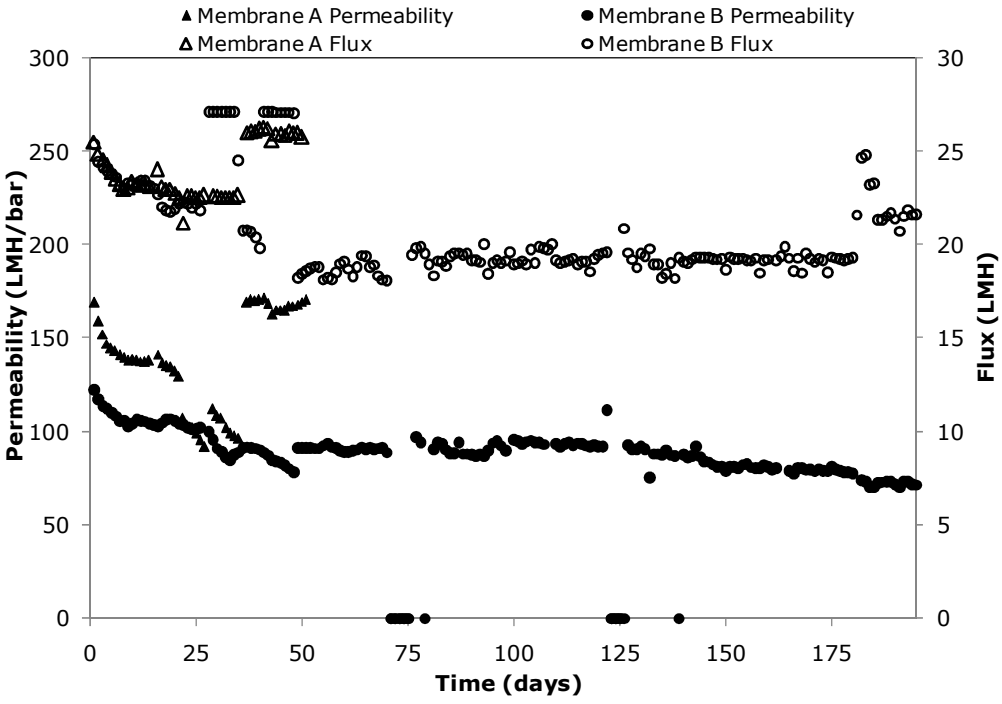


Figure 4.40 Comparison of Permeability and Flux in Membranes A and B

Even though the planned initial operating flux was 10 LMH, a much higher flux (20LMH) was observed without filtration pump operation. This implies that filtration process was performed not by the filtration pump but by a siphon effect because the membranes were new. The siphon effect disappeared after some days and filtration was controlled by the filtrate pump operating at normal conditions. The average pressure that was applied to the membrane A was 3.7 psi and the membrane TMP was lower than 3 psi. Because of this hydraulic configuration, the membrane system produced water without filtration pump operation. The flux was maintained at 24-25 LMH and the TMP at 2 psi. When the MLSS of the membrane tank increased above 6,000 mg/L, the TMP was increased. When the MLSS of the membrane tank reached about 8,000 mg/L, the TMP of the membrane was 2.8 psi.

Since the TMP did not recover to initial start-up conditions (3.7 psi) in 10 days despite a CEB clean, a CIP clean was conducted. After CIP, the TMP was lowered to 1.9 psi and the flux was increased to 20 LMH showing membrane recovery. The operation continued for 2 additional weeks and the membrane and membrane tank was replaced with membrane B.

Membrane B filtration flow rate was 5.2 gpm at start up without filtration pump operation. This is equivalent to an operating flux of 23 LMH. After 28 days of stable operation with this flux condition, the flux was increased up to 27 LMH for a filtration flow rate of 6 gpm. When the flux was increased, it was observed that the filtration pump was operational.

Membrane B was tested for 194 days. The filtrate flow rate was set at 4 gpm but because of the hydraulic pressure in the membrane tank (the average pressure to the membrane was 4.6 psi), the flux was maintained at 24 LMH and decreased to 22 LMH with time. During this time, the filtrate pump was not in operation. Instead of relaxation time of the membrane A, a backwash/backpulse was used in membrane

B operation. CEB maintenance cleaning was done on a weekly basis as recommended by the membrane manufacturer. After 4 weeks of operation, the flux was increased to 27 LMH and filtration pump operation was required to maintain the flux operation. The sludge wasting logic was added after 2 weeks of operation because the MLSS increased above 8g/L. The SRT was maintained at 15 days and the MLSS was maintained at about 4800 mg/L. The low MLSS is a possible reason for the constant flux. When the flux increased to 27 LMH, the TMP increased sharply.

5. Conclusion and Recommendation

An MBR pilot system was designed and operated to test two membranes from different manufacturers alongside different BNR processes. Membrane A was operated for 50 days followed by membrane B being operated over 194 days under the same conditions except for the MLSS concentrations which fluctuated during some of the experiments. The BNR configurations tested included a modified A^2O, a proposed biological process, and a modified UCT process. The flux rate observed for membrane A operation without rapid fouling and high TMP observation was 20 LMH. The maximum tested flux rate in membrane A was 26 LMH. On the other hand, membrane B operated with a stable TMP at 20 LMH and peaked at 27 LMH where TMP increases were observed despite increased air scouring rates. The height of the water in the membrane tanks of both membranes allowed for an initial siphon of filtrate (after the initial production using the suction of the filtrate pump). After the flux rate was increased, the TMP increased but remained stable especially with efficient CEB cleaning. Air scouring flow rate for both membranes differed two-fold. The minimum air scouring rate as recommended by membrane A and B were 1 and 3 scfm/module respectively.

The MBR pilot system operated achieved similar removal efficiencies of BOD and COD (around 99%) in all phases of testing. The nutrient removal efficiencies differed in each phase with the highest nutrient removal observed during Phase 4 of testing. Nitrogen removal averaged 90% and phosphorus removal was observed 85 to greater than 90% during testing with fluctuated values during alarm events such as low level, power outages and so forth. Effluent concentrations were less than 5

and 1 mg/L for nitrogen and phosphorus respectively. Sludge wasting (SRT) was an important factor to regulate effluent phosphorus concentration as well as the control of dissolved oxygen in the anaerobic and anoxic tanks despite the high DO concentrations observed in the MBR tank. The ORP value of the anaerobic reactor was also a very important factor in the removal of phosphorus and explains the results observed in this study. However, further evaluation and investigation of the effect of ORP on biological phosphorus removal in all reactors is recommended. This will help to clarify the mechanism of biological phosphorus removal in A^2O and UCT.

Since submerged membranes were testing during this phase, external membranes are recommended to be tested with the same biological configuration to observe the nutrient removal efficiency. One additional benefit to an isolated membrane tank for submerged membranes includes added retention in high DO conditions which may have contributed to further uptake of phosphorus prior to filtration. Consistent MLSS concentration during testing is important as well as the accurate control of membrane operation. This removes interfering variables such as membrane fouling, frequent cleanings, and required changing air scouring rates. Although two submerged membranes were tested in this study, comparative studies may be important for additional membrane optimization to reduce energy consumption. Also a longer term study will be required to confirm the combined nitrogen and phosphorus removal efficiencies observed above 95%.

The water quality produced by membrane B was consistent but membrane A did not produce consistent water quality during Phase 1 of testing since the membrane mechanical strength is questionable given the observation of broken fibers. Membrane B consistently produced effluent water quality which meets the Title 22 criteria for water reuse. The high phosphorus removal efficiency observed in

the UCT process provide an advantage to improve operating costs due to coagulants required to achieve phosphorus at or below 0.1 mg/L.

In conclusion, stable enhanced biological phosphorus and nitrogen removal can be achieved with MBR which when combined with a small addition of coagulant, effluent concentration as low as 0.05 mg/L and possibly even lower can potentially be achieved. This will allow the limit stated in the NNC criteria to be met. Membrane operation can also be optimized on a case by case situation in terms of membrane air scouring and flux operation. Air scouring may be reduced during stable low TMP operation and increased where TMP increases are expected for a significant cost savings. The chemical precipitation combined with EBPR may require confirmation to observe whether cost savings is achieved. Also, the energy consumption that may be required for the modified UCT-MBR tested in this study is significant and can be further studied for the improvement of its energy consumption.

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