

**Comparison of Aeration Strategies for  
Optimization of Nitrogen Removal in an Adsorption/Bio-oxidation Process  
with an Emphasis on Ammonia vs. NO<sub>x</sub> Control**

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**Thesis submitted to the faculty of the  
Virginia Polytechnic Institute and State University  
In partial fulfillment of the requirements for the degree of**

**Master of Science  
In  
Environmental Engineering**

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**November 6, 2015  
Blacksburg, Virginia**

**Keywords: AvN, ABAC, DO Control, AOB, NOB, NOB out-selection, Aeration control, Intermittent aeration, Nitrogen removal, Nitrification, Denitrification, Nitrite Shunt, Partial Nitritation, Mainstream Deammonification, Nitrite accumulation, Two-stage Activated Sludge, A/B Process, BNR, MLE**

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## Abstract

The Chesapeake Bay is a natural and economic resource to the states comprising its watershed. Over the past several decades population growth in the region has led to increased discharge of nitrogen and phosphorus. In excessive concentrations, these nutrients pose significant environmental threats to the Bay including eutrophication, oxygen depletion, and toxicity. Wastewater treatment plants (WWTPs), which comprise a significant percentage of the nutrient loading, are continuously working to implement cost effective strategies to perform greater amounts of removal from their waste streams.

In order to benefit this nutrient removal effort, research was conducted for the Hampton Roads Sanitation District at a pilot-scale WWTP (CE Pilot) operating an adsorption/bio-oxidation (A/B) process at 20°C. The A-Stage is a high-rate activated sludge process which aims to accomplish carbon capture for methane generation. The A-Stage was operated at low DO concentrations ( $\leq 0.5$  mg/L), an SRT of 6-12 hours, and an HRT of 30 minutes. The A-Stage is followed by a B-Stage process which performs biological nutrient removal. The B-Stage consists of 4 CSTRs (Total Volume = 606 L) operated at a 5 hour HRT followed by a secondary clarifier (Volume = 340 L). Secondary effluent passed through an Anammox moving bed biofilm reactor (MBBR) for tertiary treatment prior to discharge from the CE Pilot. Specialized sensors for the measurement of DO, pH, ammonium, nitrite and nitrate were installed in the B-Stage reactors. Coordination between the sensors and a programmable logic controller allowed for the operation of multiple aeration strategies.

The study compared B-Stage performance under the operation of three different aeration strategies: 1) DO Control, 2) Ammonia Based Aeration Control (ABAC), and 3) Ammonia vs. NO<sub>x</sub> (AvN) Control. Both DO Control and ABAC were operated as continuous aeration strategies with the B-Stage in a MLE configuration. AvN was operated as an intermittent aeration strategy in two separate configurations: 1) a configuration in which all CSTRs were intermittently aerated for the same interval and duration (fully-intermittent) and 2) a MLE configuration in which the first reactor was designated as an anoxic selector and downstream reactors were intermittently aerated for the same interval and duration. When in an MLE configuration the internal mixed liquor recycle was kept at 300% of the influent flow. The strategies were evaluated on the basis of nitrogen removal performance, COD utilization efficiency, and alkalinity consumption. The study also compared each aeration strategy with A-Stage effluent (ASE) or primary clarifier effluent (PCE), considering variable properties of the influent feed.

Nitrogen removal performance for AvN in both fully-intermittent and MLE configurations was shown to be comparable to DO Control and ABAC. The highest nitrogen removal performance was seen when

operating DO Control ( $81.4 \pm 1.2\%$ ) and ABAC ( $81.1 \pm 1.2\%$ ) with PCE. The difference in nitrogen removal performance for DO Control and ABAC when ammonia loading rate increased proved that the benefit of ABAC is only recognized if DO concentrations are kept low. Since most WWTPs operate at lower ammonia loading rates than those presented in this study, the results indicate a clear benefit for transitioning from a strategy like DO Control to one of ammonia-based control.

High nitrogen removal efficiency ( $77.5 \pm 6.1\%$ ) was also seen when fully-intermittent AvN operation was fed ASE containing a high particulate COD (pCOD) fraction. A high effluent nitrite accumulation ratio ( $\text{NAR} = \text{NO}_2^- / (\text{NO}_2^- + \text{NO}_3^-)$ ) was seen during this period ( $46 \pm 15\%$ ) accompanied by the out-selection of *Nitrospira*. The pCOD fraction was found to have significant correlation with the NAR ( $r = 0.807$ ). The increased pCOD fraction helped to maintain high oxygen uptake rates (OUR) encouraging heterotrophic competition for substrate ( $\text{O}_2$  and  $\text{NO}_2^-$ ) with nitrite oxidizing bacteria (NOB) during transition to non-aerated periods. Compared to fully-intermittent operation, AvN in a MLE configuration resulted in decreased NAR. Due to nitrite accumulation, the combination of AvN with the Anammox MBBR (AvN+) was found to yield better overall nitrogen removal performance compared to DO Control and ABAC. Effluent from DO Control and ABAC is not suitable for post treatment with Anammox bacteria due to substrate limitation in the MBBR.

Efficiency of COD use for denitrification was found to vary between operating modes based on the amount and type of influent COD. AvN in an MLE configuration was found to use COD more efficiently than fully-intermittent AvN. With regards to alkalinity AvN required less alkalinity addition than DO Control or ABAC.

By containing higher influent rbCOD concentrations, PCE leads to increased heterotrophic competition with nitrifiers for oxygen and space in the B-Stage. This results in lower nitrification activity rates and therefore requires a longer SRT or HRT. Feeding PCE resulted in improved nutrient removal performance over ASE due to increased COD loading; however the COD not used for nutrient removal is lost due to mineralization by heterotrophic activity. The ability of the A-Stage to operate in a manner that controls the influent C/N ratio avoids overloading a B-Stage with carbon. This increases efficiency of plant operation as carbon not needed in the B-Stage can be redirected for energy recovery.

## Acknowledgements

First and foremost I would like to thank my family for supporting me throughout this process. Without their continued support this thesis would have been a much more arduous task. I would like to thank my committee members Dr. Charles Bott, Dr. John Novak, and Dr. Gregory Boardman for their time spent and advice shared throughout the duration of this project. I would also like to thank Dr. Pusker Regmi for his helpful insight and constant willingness to answer all of my questions. He encouraged me to learn and develop my knowledge in the field of wastewater treatment. His guidance was paramount to my understanding and completion of this thesis. The same must also be said for Mark Miller who was a great mentor to me throughout my research at the CE Pilot. There is no question that Mark couldn't answer and he was always able to provide advice when I needed help.

During my time here I had the chance to meet and work with several other HRSD Special Projects Interns. Their names are listed as follows:

Amanda Kennedy	Claire Welling	Johnnie Godwin	Peter Buehlmann
Andrew DeVries	Dana Fredericks	Matt Elliot	Stephanie Klaus
Arba Williamson	Holly Anne Hillard	Maureen Kinyua	Tyler Brickles
Becky Holgate	John DeArmond	Peerawat Noon Charuwat	Warner Thomas

It has been a pleasure working with each of you. The camaraderie between the interns at HRSD is unlike any other place I have worked. This experience truly has been a rewarding one and I wish each of you continued success.

A big thank you must also be extended to electricians and instrumentation specialists Leonard Cressman, Dean DeCarlis, Leon Brzezowski, Joe Covey, and Dave Hughes for providing me with support during process upsets and programming changes on the PLC. Their willingness to support the crew at the CE Pilot is integral to our overall success. Lastly I would like to thank HRSD for providing the funding to make this research possible. Photos included in this thesis were taken by the author.

Very respectfully,  
Mike Sadowski

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## 1. Introduction

Water has the ability to dissolve more substances than any other liquid, and although it is considered “the great diluter” it should also be recognized for its ability to transport toxic chemicals, sediment, nutrients, and persistent organic pollutants around the globe. This means a great deal when we consider that water covers approximately 71% of Earth’s surface. There is little question as to the importance of water as a resource. Without it, life would cease to exist. In this modern age of growth and development, worldwide populations place increasing demand on the global fresh water supply. This strain is caused by pollution from point sources, including stormwater and wastewater treatment plant discharges, as well as non-point sources such as atmospheric deposition and agricultural and urban runoff. Water from these sources may contain contaminants such as organic matter (COD and volatile solids (VS)), nutrients (nitrogen and phosphorus), pathogens, and solids. When in excess these contaminants present harm to receiving waterways through their ability to threaten habitat and wildlife, diminish aesthetic appeal, and impair use of the waterway for recreation or as a source for drinking water.

Such is the case within the Chesapeake Bay watershed which spans approximately 64,000 square miles and incorporates parts of the following 6 states: Virginia, West Virginia, Maryland, Delaware, New York, and Pennsylvania. The Chesapeake Bay is the largest estuary in the United States. When settlers first landed in the region in the early 1600s, they discovered a Bay which contained healthy populations of oysters and fish thriving in pristine water conditions. At that time the watershed was composed of heavily wooded forests and an abundance of marine vegetation. Since then the environmental condition of the Bay has declined, and today a different picture remains. Between 1985 and 2012, the population in the Bay watershed increased 30 percent, from 13.5 million people to 17.7 million people. It is believed that this number will continue to rise, as experts predict the population will reach 20 million by year 2030 ("Population Growth," 2012). Physical properties of the Bay including its shallowness (average depth of 21 feet) and land to water ratio of 14:1 make it susceptible to the impact of urban sprawl ("Facts and Figures," 2012).

The Chesapeake Bay Foundation (CBF) is a governmental organization which publishes a recurring report titled the State of the Bay Report. This report is a comprehensive measure of the Bay's health and outlines goals for restoration efforts as well as progress towards those goals. It does this by evaluating indicators and assigning each with an index score, between 1 and 100, in addition to a letter grade. Scientists from the CBF compare historical information to current data in order to establish trends in the overall health of the Bay. The most recent report released in 2014 gave the Chesapeake Bay an overall score of 32 out of 100 showing improvement over previous years but also indicating that much more work remains if restoration is to succeed. In the report, “Pollution” is a specific category which comprises subsets such as water clarity, toxics, dissolved oxygen (DO), and nitrogen and phosphorus. Each of these subsets received scores of 37 or less out of 100 indicating that the Bay is still far from complete restoration ("State of the Bay Report," 2014).

A main area of concern within the Chesapeake Bay is nutrient pollution. Nutrients such as nitrogen and phosphorus accumulate in the Bay due to human activities in addition to natural processes.

Unfortunately environmental factors within the Bay such as wind and currents paired with physical factors like the Bay's shallowness create an ecosystem which is well adapted to retain nutrients. Due to the high residence time of nutrients within the Bay, concentrations steadily increase over time. The lack of mixing is noticed most in northern parts of the Bay where nutrient concentrations are highest, whereas the southernmost parts typically see less nutrient accumulation due to adequate flushing with ocean currents and tidal movement.

The main problem with nitrogen and phosphorus accumulating in a system like the Chesapeake Bay is that the high nutrient concentrations result in a process known as eutrophication. Eutrophication is the response by an ecosystem to excessive amounts of nutrients. Microorganisms, mainly algae and other phytoplankton, grow into large masses known as "blooms". These blooms occur when nutrients, sunlight, and temperature are favorable. The growth of these organisms presents an array of problems. First, the massive algal blooms blanket the surface of the water blocking sunlight penetration through the layers of the water column. This causes severe harm to submerged aquatic vegetation which needs sunlight to grow. Second the decay of phytoplankton depletes the water of DO leaving large areas of hypoxia (little or no DO) throughout the Chesapeake Bay. Third, these areas of hypoxic conditions may create dead zones where marine life is rendered uninhabitable resulting in massive fish kills.

Several regulations have lessened the environmental impact on the Bay. The most important of these is the Clean Water Act. The Clean Water Act was passed in 1972 and establishes the basic structure for regulating the discharge of pollutants into waters of the United States and regulating quality standards for surface waters. Sections 117, 303, 319, and 402 of the Act directly pertain to the Chesapeake Bay. They cover topics such as management of the Bay, establishment of water quality standards (WQS) and total maximum daily loads (TMDLs). The sections also address nonpoint source pollution and national pollutant discharge elimination system (NPDES) permits (Introduction to the Clean Water Act, 2006).

Discharge from wastewater treatment facilities is considered a point source because of the ability to directly identify a point of discharge and the concentrations of nutrients and solids in the effluent. Although agriculture is the largest contributor to nitrogen and phosphorus in the Chesapeake Bay, wastewater treatment facilities comprise the second largest percentage. In 2009 municipal wastewater treatment facilities contributed an estimated 17 percent of the total nitrogen and 16 percent of the total phosphorus loads delivered to Chesapeake Bay (Chesapeake Bay Tmdl Section 4, 2010). In order to combat this issue the Environmental Protection Agency (EPA) established a TMDL for the Chesapeake Bay on December 29, 2010. The purpose of a TMDL is to identify the maximum amount of a pollutant the waterway can receive and still meet water quality standards. This TMDL was prompted by insufficient progress and continued poor water quality in the Chesapeake Bay and its tidal tributaries. The TMDL sets Bay watershed limits of 185.9 million pounds of nitrogen, 12.5 million pounds of phosphorus and 6.45 billion pounds of solids per year. This equates to a 25 percent reduction in nitrogen, a 24 percent reduction in phosphorus and a 20 percent reduction in solids. The TMDL is

designed to ensure that all pollution control measures needed to fully restore the Bay and its tidal rivers are in place by 2025, with at least 60 percent of the actions completed by 2017 (Chesapeake Bay Tmdl Sections 1-3, 2010).

## 1.1 Project Motivation

The research conducted in this thesis was performed for the Hampton Roads Sanitation District (HRSD). HRSD is a wastewater treatment organization located in southeast Virginia. The utility performs wastewater treatment services for cities comprising Hampton Roads as well as those located on the peninsula and middle peninsula of the Chesapeake Bay. Shown in Figure 1, the organization has nine major treatment plants in addition to four smaller treatment plants servicing more isolated communities within the district. Currently HRSD is required to meet a total nitrogen (TN) limit of 6 million lbs/yr which applies to the total output of seven of its nine major plants which discharge into the James River Basin. By the year 2022 EPA-mandate will reduce this nitrogen limit to 3.4 million pounds annually.

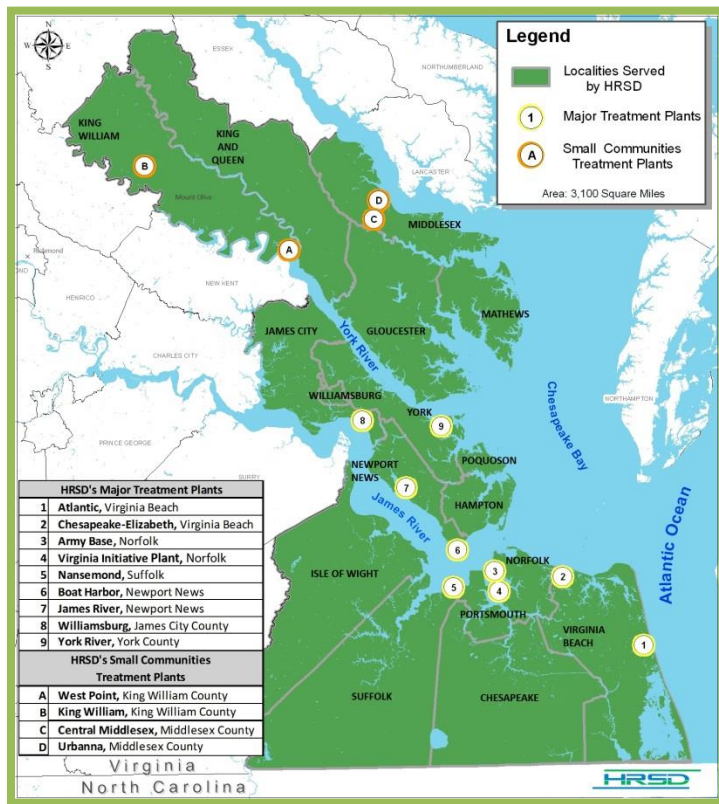


Figure 1 – HRSD Service Area. <http://www.hrsd.com/images/FastFactsServiceAreaMap2.jpg>. Used with permission of HRSD, 2015.

In order to meet this future TN requirement for the James River Bubble Permit, HRSD is looking to upgrade several of its existing wastewater treatment facilities. The first plant HRSD considered for this change was its Chesapeake Elizabeth (CE) wastewater treatment plant (WWTP) which is situated near the mouth of the Chesapeake Bay and indicated by the number 2 on Figure 1. A schematic of the facility is shown on Figure 2 and an aerial view of the facility is shown in Figure 3. The design capacity of the

facility is 24 MGD, while daily flow averages 15-20 MGD. The plant achieves some phosphorus removal through ferric addition to meet an annual total phosphorus (TP) limit of 2 mg-P/L. However, the CE WWTP does not perform nitrogen removal. It is operated at low SRT to remove COD while preventing nitrification.

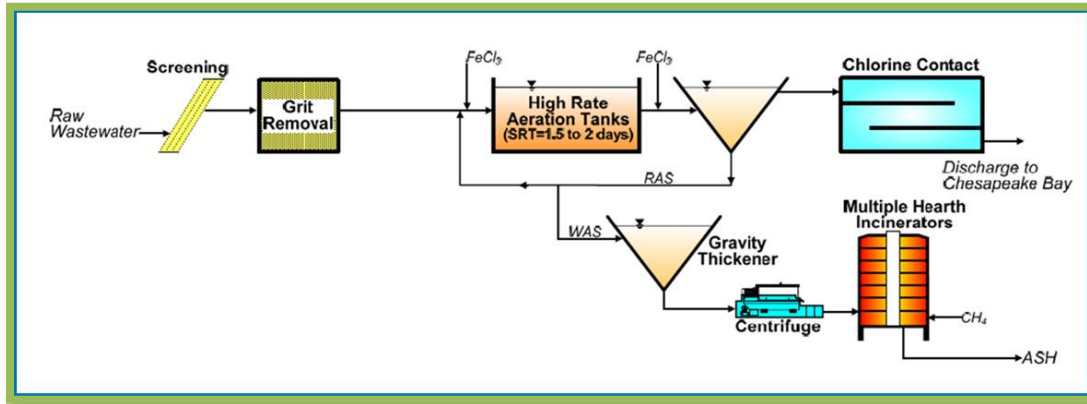


Figure 2 – Schematic of the Chesapeake Elizabeth Wastewater Treatment Facility

HRSD requested a cost estimate to upgrade the CE WWTP for nitrogen removal by December of 2021 to meet an average annual total nitrogen (TN) limit of 5 mg/L and comply with EPA’s mass load reduction. The capital cost was estimated at \$125-\$150 million. In addition operational costs would increase dramatically and there was limited land available for the necessary expansion.

A pilot-scale study was therefore developed at the CE WWTP with the goal of investigating appropriate nitrogen removal technologies applicable at the plant. The study was designed to examine full-scale implementation of the European-style A/B process at the CE WWTP. Although not currently used in the US, the A/B process is an attractive option due to its ability to treat large volumes of wastewater within a small volume and footprint. The A/B process is a two-sludge system accomplishing carbon capture and nitrogen removal. The A-Stage is a high rate process (HRT = 30 min) operated at low DO (<0.5 mg/L) and low SRT (<1 day) (Boehnke et al, 1997). It serves to increase carbon capture for biogas production, reduce aeration tank volume, and protect the B-Stage from shock loading. The A-Stage can also be operated to control the carbon to nitrogen (COD/ $NH_4^+-N$ ) ratio in effluent fed to the B-Stage for optimum nitrogen removal performance (Regmi et al, 2014). The B-Stage consists of a biological nutrient removal (BNR) process which aims to perform efficient nitrogen removal through optimized aeration and efficient use of influent carbon for denitrification.





Figure 3 – Aerial Photograph of the Chesapeake Elizabeth Wastewater Treatment Facility. <https://www.bing.com/mapspreview>. Produced from Bing Imagery, 2015. Used under fair use, 2015.

The CE pilot was constructed in 2011. The main goals of the project were to 1) develop an A-Stage which could be built additionally onsite at the CE WWTP, 2) design a B-Stage process that would fit into the existing aeration basins at the plant, and 3) study the A/B process. Future status of the CE WWTP changed as HRSD decided it would be converted into an off-line storm surge storage facility. Upon this change, flow will be diverted to the Atlantic plant. The CE pilot now serves as a treatment technology and process control development project working to support ongoing efforts to improve nitrogen removal, process intensification, chemical and energy efficiency, as well as sensor and control systems at HRSD's other treatment plants.

## 1.2 Research Objectives

Several aeration strategies have been developed for BNR processes. The major strategies include DO setpoint control (DO Control), ammonia-based aeration control (ABAC), and intermittent aeration (Batchelor, 1983; Åmand et al, 2013; Rieger et al, 2014). Previous research at HRSD has shown successful operation of a new intermittent aeration control strategy (Fredericks, 2014; Regmi et al, 2014). The process, known as Ammonia vs. NO<sub>x</sub> (NO<sub>2</sub><sup>-</sup> + NO<sub>3</sub><sup>-</sup>) or AvN for short, is performed through the use of sensors targeting ammonium, nitrite, and nitrate. The process uses high operational DO, residual ammonia, and strict control of the solids residence time (SRT) to perform out-selection of nitrite oxidizing bacteria (NOB) while encouraging growth of ammonia oxidizing bacteria (AOB) at maximum rates. AvN also allows for a high degree of nitrogen removal by maintaining a desired aerobic fraction and provides an effluent containing equal parts ammonia and NO<sub>x</sub> suitable for tertiary treatment through an anaerobic ammonium oxidation (Anammox) moving-bed biofilm reactor (MBBR).

The combination of separate sludge systems in the A/B process allows each to be optimized based on that particular system's operational objectives while at the same time achieving overall carbon and nitrogen reduction goals (Miller et al, 2012). Single-sludge systems operated with primary clarification may not allow for such optimization resulting in reduced carbon capture for biogas generation in comparison with the A-Stage and excessive organic carbon loading to the BNR process. Although previous authors have compared the performance of DO control and ABAC (Jimenez et al, 2013; Rieger et al, 2014) no studies have compared B-Stage performance under DO Control, ABAC, and AvN operation.

Therefore, the first objective of this research was to investigate the performance of different aeration strategies (DO Control, ABAC, and AvN) in terms of nitrogen removal, COD efficiency, and alkalinity consumption. To do this AvN was operated in the following two configurations: 1) a configuration in which all reactors were intermittently aerated for the same interval and duration (fully-intermittent) and 2) a Modified Ludzack-Ettinger (MLE) configuration in which the first reactor was designated as an anoxic selector and downstream reactors were intermittently aerated for the same interval and duration. Performance under AvN operation, in both fully-intermittent and MLE configurations, was then compared to performance under DO control and ABAC, each in a MLE configuration with continuous aeration.

The second objective was to determine the effect of influent feed characteristics on the performance of the B-Stage also in regards to nitrogen removal, COD efficiency, and alkalinity consumption. To do this feed from both a controlled high rate activated sludge (HRAS) A-Stage process and primary clarifier effluent (PCE) was used to operate the different aeration strategies. The hypothesis was that A-Stage effluent (ASE) would allow similar total nitrogen removal with advanced aeration strategies being used (i.e. ABAC and AvN), but result in carbon and alkalinity limitations as compared to feeding with PCE.

This study provides a good starting point for the full-scale application of an A/B process in the United States. An efficient BNR process is one which maximizes nutrient removal performance while minimizing supplemental alkalinity and COD requirements through reduced aeration. By providing a comparison of aeration strategies and influent feed-types (ASE and PCE), more efficient operation of BNR processes can be implemented at WWTPs.

## 2. Literature Review

### 2.1 Biological Nitrogen Removal

Effluent nitrogen from the biological treatment of wastewater exists predominantly in the form of ammonia (Bitton, 2011). However, the compound poses several environmental and public health hazards. Environmental factors include ammonia's toxicity, increased oxygen demand, and effect as a limiting nutrient in aquatic systems. Public health factors include the ability of ammonia to hinder disinfection in water and wastewater treatment facilities and its risk to drinking water safety when transformed into oxidized compounds.

When discharged into aquatic systems ammonia is toxic to marine life. Toxicity increases with pH and temperature, although pH is known to be the greater factor as it distinguishes the dissociation of ammonia between its ionized ( $\text{NH}_4^+$ ) and unionized ( $\text{NH}_3$ ) forms. Unionized ammonia, also termed free ammonia, exists in water as a dissolved gas and enters the gills of marine organisms during respiration. Inside the organisms, unionized ammonia is transformed into ionized ammonia, also known as ammonium. Elevated ammonium ions work to displace potassium ( $\text{K}^+$ ) ions in marine vertebrates which can cause severe damage to the central nervous system. Convulsions, coma, and even death may result (Randall et al, 2002).

Ammonia also presents an oxygen demand in the presence of nitrifying organisms. The metabolism of these organisms depletes water of 4.6 mg of oxygen for every 1 mg of ammonia. For waterbodies like the Chesapeake Bay, which contain a variety of aquatic species, DO is an essential part of water quality. Nitrogen in wastewater effluent may also impact a waterbody through its effect as a limiting nutrient. The discharge of nitrogenous compounds into receiving streams which are nitrogen deficient has the potential to stimulate excessive algal and aquatic plant growth. This growth can lead to eutrophication which can negatively impact the waterway's use as a resource for habitat, drinking water, and recreational activities.

Ammonia also hinders disinfection of wastewater by combining with chlorine to form chloramines which have less potency as a disinfectant than free chlorine. Therefore, if effective disinfection is desired greater amounts of chlorine, longer contact times, or alternative disinfectants must be used in order to remove pathogenic organisms. Nitrogen present in aquatic systems may also lead to the formation of nitrite and nitrate which can cause problems for drinking water plants striving to meet maximum contaminant levels (MCLs). Methemoglobinemia, also known as blue baby syndrome, is caused in young infants who drink water containing elevated nitrate levels. Nitrate conversion to nitrite in the gastrointestinal tract leads to the inability of oxygen to bind to hemoglobin in the blood leading to suffocation. Therefore nitrogen removal should also be performed in areas where wastewater effluent is used for groundwater recharge and other water reclamation activities (Bitton, 2011).

The importance of achieving effective nitrogen removal is clear. The nutrient can be removed from wastewater by chemical, physical, and biological methods. Chemical methods include ion exchange and

breakpoint chlorination. Physical removal may occur with ammonia stripping in packed towers at pH above 10. Biological removal methods tend to be the most cost effective and includes several different processes such as nitrification-denitrification, nitritation-denitritation, and deammonification. These nitrogen removal processes will be discussed in detail in the following sections.

## 2.2 Nitrification – Denitrification

The most common process used for nitrogen removal in the treatment of municipal wastewater is nitrification-denitrification. The process was first utilized in wastewater treatment in the early 1900s. Today the process is used where effluents are discharged into nutrient sensitive waterbodies some of which include areas like the Chesapeake Bay and the Great Lakes. The pathway is illustrated in Figure 4 and involves the conversion of nitrogen in the form of ammonia to nitrogen gas ( $N_2$ ). The process is achieved by alternating between aerobic and anoxic zones of an activated sludge process to achieve nitrification ( $NH_3 \rightarrow NO_3^-$ ) and denitrification ( $NO_3^- \rightarrow N_2$ ) respectively. The requirement for nitrogen removal is based on a wastewater treatment plant's discharge permit issued by state environmental agencies. Some plants are not required to remove nitrogen while others are only required to remove ammonia (through nitrification). For plants that are required to perform nitrogen removal, nitrification-denitrification is the most common approach.

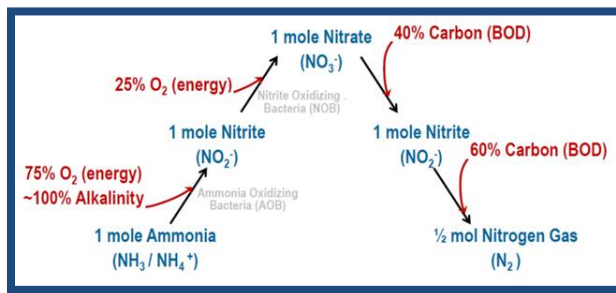


Figure 4 – Nitrification – Denitrification Pathway

### 2.2.1 Nitrification

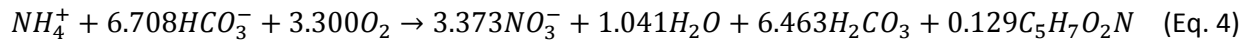
Nitrification is a two-step process by which ammonia ( $NH_3$ ) is converted to nitrite ( $NO_2^-$ ) and nitrite converted to nitrate ( $NO_3^-$ ). The first step in the nitrification process is the conversion of ammonia to nitrite ( $NH_3 \rightarrow NO_2^-$ ). This process, termed nitritation, is performed by a group of organisms known as ammonia oxidizing bacteria (AOB). The second step in the nitrification process, known as nitratation, is the conversion of nitrite to nitrate ( $NO_2^- \rightarrow NO_3^-$ ) by nitrite oxidizing bacteria (NOB). The stoichiometric reactions describing nitritation, nitratation, and the overall nitrification process are listed in Eqs. 1, 2, and 3 respectively.

#### Nitritation by AOB:



**Nitrataion by NOB:****Nitrification:**

Complete nitrification requires a large input of oxygen (4.57 g O<sub>2</sub>/g NH<sub>4</sub><sup>+</sup>-N oxidized). Of the two part reaction, conversion of ammonia to nitrite by AOB has a greater oxygen requirement (3.43 g O<sub>2</sub>/g NH<sub>4</sub><sup>+</sup>-N oxidized) compared to nitrataion. Although not shown in Eq. 1, hydroxylamine (NH<sub>2</sub>(OH)) is an intermediate in this anabolic pathway. Conversion of nitrite to nitrate by NOB uses considerably less oxygen (1.14 g O<sub>2</sub>/g NH<sub>4</sub><sup>+</sup>-N oxidized). When biomass growth is incorporated during nitrification, the overall process can be represented according to Eq. 4.

**Nitrification Considering Biomass Growth:**

In addition to oxygen consumption, the alkalinity demand for nitrification is high (7.14 g CaCO<sub>3</sub>/g NH<sub>4</sub><sup>+</sup>-N oxidized). A small amount of alkalinity is incorporated into cell material. However, during nitrification only a small amount of biomass is produced reflecting the low yields of autotrophic growth (0.166 mg biomass/mg NH<sub>4</sub><sup>+</sup>-N removed). The majority of alkalinity utilization is associated with the neutralization of hydrogen ions released during the oxidation of ammonia (Grady, 2011). If the wastewater alkalinity drops below the normal physiological range it can inhibit nitrifier activity.

Successful nitrification performance is also pH dependent. Optimal rates occur at pH values in the range of 7.5-8.0; however nitrification rates decrease significantly at pH values less than 6.8 (Tchobanoglous et al, 2003). Since the process of nitrification releases hydrogen ions (H<sup>+</sup>), acidifying the mixed liquor; additional alkalinity may need to be provided. Typical chemicals used to raise the pH include lime (CaOH), soda ash (Na<sub>2</sub>CO<sub>3</sub>), sodium bicarbonate (NaHCO<sub>3</sub>), and magnesium hydroxide (MgOH).

The SRT controls the concentration of microorganisms in activated sludge systems. Typical BNR systems are operated at high SRT in order to retain the autotrophic bacteria necessary for nitrification. Operating SRT values will vary depending on temperature and wastewater characteristics but usually fall between 10-20 days at 10°C or 4-7 days at 20°C. Figure 5 shows that increased temperature allows for decreased SRT due to faster growth rates of nitrifying communities.

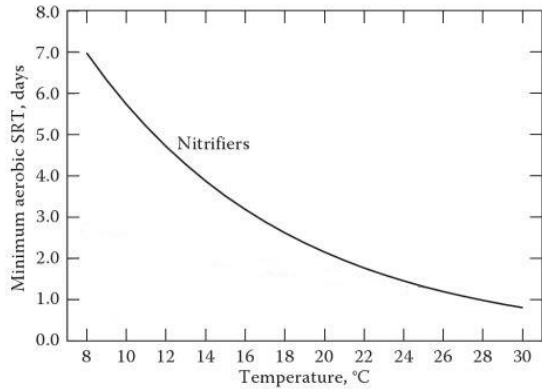


Figure 5 – SRT as a function of Temperature for the Growth of Nitrifying Bacteria. Grady, C. P. L. (2011). [Biological Wastewater Treatment](#). Boca Raton, FL, IWA Pub./CRC Press. Used with permission of Taylor and Francis Group LLC Books, 2015.

As autotrophic bacteria, AOB and NOB both derive cellular carbon from inorganic carbon in a process known as carbon fixation. This is the catabolic pathway for nitrifiers. To acquire energy for this process AOB and NOB use molecular oxygen to oxidize ammonia and nitrite respectively. This is the anabolic pathway for nitrifiers. Although the two groups of bacteria seem similar, they are in fact distinctly different. Genera of AOB include *Nitrosomonas*, *Nitrosococcus*, *Nitrospira*, *Nitrosolobus*, and *Nitrosorobrio* (Painter, 1970). It is widely accepted that *Nitrosomonas* predominate in most activated sludge systems. Genera of NOB include *Nitrobacter*, *Nitrococcus*, *Nitrospira*, *Nitrospina*, and *Nitroeystis*. Originally *Nitrobacter* was commonly accepted to be the predominant genera in most activated sludge systems until it was determined that that the genus *Nitrospira* was the more common dominant population (Daims et al, 2006; Kim et al, 2006).

Bacteria may be classified as R-strategists or K-strategists depending on their affinity for substrate. R-strategists grow quickly at higher substrate concentrations and slower at lower concentrations while K-strategists are the opposite, growing at faster rates when subjected to low substrate concentrations and slower at high concentrations. R-strategist nitrifiers include *Nitrosomonas europae* and *Nitrobacter* spp. while K-strategists include *Nitrospira* and *Nitrospina* (Schramm et al, 1999).

Growth of nitrifying bacteria is commonly modeled using Monod kinetics. The specific growth rates of AOB ( $\mu_{AOB}$ ) and NOB ( $\mu_{NOB}$ ) are the most important design parameters for BNR systems (Tchobanoglous et al, 2003). Their growth rates are functions of several parameters including the substrate concentrations, endogenous decay rate, and maximum specific growth rate. The Monod equations used to express AOB and NOB growth rates are listed in Eqs. 5 and 6 respectively.

**Monod equation for the growth rate of AOB:**

$$\mu_{AOB} = \mu_{max,AOB} * \left( \frac{S_{NH4}}{S_{NH4} + K_{NH4}} \right) * \left( \frac{S_{O2}}{S_{O2} + K_{O2,AOB}} \right) - b_{AOB} \quad (\text{Eq. 5})$$

**Monod equation for the growth rate of NOB:**

$$\mu_{NOB} = \mu_{max,NOB} * \left( \frac{S_{NO2}}{S_{NO2} + K_{NO2}} \right) * \left( \frac{S_{O2}}{S_{O2} + K_{O2,NOB}} \right) - b_{NOB} \quad (\text{Eq. 6})$$

Where:  $\mu_{\max}$  is the maximum growth rate ( $d^{-1}$ )  
 $S_{NH_4}$  is the concentration of ammonia (mg-N/L)  
 $S_{NO_2}$  is the concentration of nitrite (mg-N/L)  
 $S_{O_2}$  is the concentration of DO (mg/L)  
 $K_{NH_4}$  is the ammonia half-saturation constant (mg-N/L)  
 $K_{NO_2}$  is the nitrite half-saturation constant (mg-N/L)  
 $K_{O_2}$  is the oxygen half-saturation constant (mg/L)  
 $b$  is the decay rate ( $d^{-1}$ )

The maximum specific growth rates ( $\mu_{\max}$ ) of AOB and NOB are functions of temperature. At temperatures below 20°C Monod kinetics are dominated by AOB growth rates since, at these temperatures, nitrification becomes rate limited by the ammonia oxidation step. At higher temperatures (> 20°C) or at low DO concentrations (< 0.5 mg/L) kinetics of both AOB and NOB must be considered because these conditions are more favorable to AOB activity (Tchobanoglous et al, 2003). Half saturation values for AOB ( $K_{NH_4}$ ) and NOB ( $K_{NO_2}$ ) have been reported at 0.50 and 0.20 mg/L respectively (Nutrient Control Design Manual, 2010). Values reported for  $\mu_{\max, AOB}$  at 20°C range from 0.33 to 1.0  $d^{-1}$  (Sedlak, 1991; Randall, 1992) depending on the value selected for the specific decay rate coefficient ( $b_{AOB}$ ). Reported values for  $\mu_{\max, NOB}$  at 20°C are consistently higher than  $\mu_{\max, AOB}$ . Values of 1.33  $d^{-1}$  (Wett et al, 2003), 1.8  $d^{-1}$  (Sin et al, 2008), and 1.0  $d^{-1}$  (Kaelin et al, 2009) have been reported. The endogenous decay rate (0.15  $d^{-1}$ ) for AOB has been reported to be no different than that for NOB (Manser et al, 2006; Salem et al, 2006).

Nitrifiers need major and minor nutrients in order to perform cell synthesis and reproduction. The following trace elements have been known to stimulate nitrifying bacteria: Ca = 0.50, Cu = 0.01, Mg = 0.03, Mo = 0.001, Ni = 0.10, and Zn = 1.0 mg/L (Poduska, 1973). If insufficient concentrations exist, supplemental nutrients may need to be added to systems designed to nitrify. Inhibitors of nitrification include low temperatures, low DO concentrations, metals, toxic compounds (such as cyanide), free ammonia, free nitrous acid, and the abundance of organic carbon which increases heterotrophic competition for substrate and space.

### 2.2.2 Denitrification

Denitrification is the process by which oxidized forms of nitrogen such as nitrate and nitrite are reduced to gaseous forms by microorganisms. The denitrification pathway (Eq. 7) illustrates the reduce intermediaries which may form during the biological process.

#### Denitrification pathway:



The reduction of nitrate to nitrogen gas transforms nitrogen from an oxidation state of five to an oxidation state of zero. The oxidation states of the species listed above are as follows: nitrate (+5),

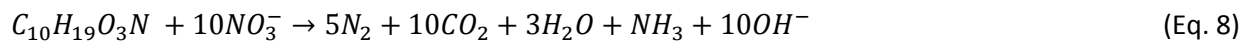
nitrite (+3), nitric oxide (+2), nitrous oxide (+1), and nitrogen gas (0). Organisms capable of denitrification may be classified as either true denitrifiers or partial denitrifiers. True denitrifiers contain enzymes capable of catalyzing the entire denitrification pathway shown above while partial denitrifiers are only able to catalyze one or a few steps (Gardner, 2008).

The process of denitrification requires an anoxic environment describing conditions of low oxygen where nitrate or nitrite exists in solution. This is because most denitrifying organisms are facultative aerobes, meaning they have the ability to use oxygen as well as nitrate or nitrite as their electron acceptor. Since oxygen is used preferentially, conditions of anoxia specifically target the reduction of nitrate and nitrite by triggering the release of specific reductase enzymes giving denitrifiers the ability to utilize oxidized nitrogenous compounds as electron acceptors instead of oxygen.

There are two forms of nitrate reduction: dissimilatory and assimilatory. Dissimilatory nitrate reduction has been discussed previously and occurs when nitrate or nitrite is used as the electron acceptor for the oxidation of organic or inorganic electron donors. For this to occur, ammonia has to be present in solution for incorporation into biomass. However, when no ammonia is present in solution a process known as assimilatory nitrate reduction may occur. This process describes the reduction of nitrate to ammonia for use in cell synthesis. Assimilatory nitrate reduction is independent of the DO concentration and results in a lower growth yield.

Heterotrophic and some autotrophic organisms are capable of performing denitrification. In wastewater treatment, heterotrophs comprise the majority of denitrifying populations of which *Pseudomonas* species are the most common and widely distributed (Payne, 1981). As heterotrophic bacteria, denitrifiers need organic matter to obtain carbon for cell synthesis and to obtain energy for the reduction of nitrogenous compounds. Biodegradable organic matter in wastewater is represented by the compound  $C_{10}H_{19}O_3N$ . In the best case scenario, organic matter present in wastewater would supply microorganisms with enough carbon to perform complete denitrification (Eq. 8).

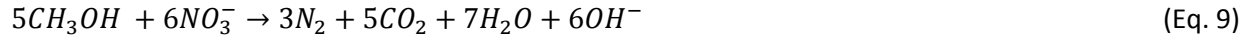
**Denitrification with Domestic Wastewater:**



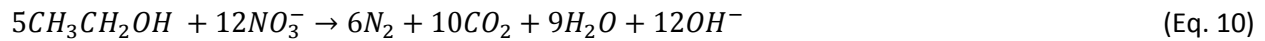
However, at many BNR plants, the influent wastewater does not contain a sufficient concentration of COD to perform full denitrification (van Dongen et al, 2001). In this scenario an external carbon source must be added to meet low effluent TN limits. Examples of supplemental carbon sources include alcohols like methanol, ethanol, glycerol, and organic acids such as acetate (Eqs. 9-12). Determination of the best carbon source is based on cost, availability, safety and handling, kinetics, and cell yield (External Carbon Sources for Nitrogen Removal, 2013). Due to the increased operational cost of external carbon addition it is highly important for facilities to be designed in a manner which uses internal carbon in the most efficient way possible. Reactor configurations and aeration strategies have the largest impact on carbon usage thus controlling the level of treatment.

**Denitrification with Methanol:**

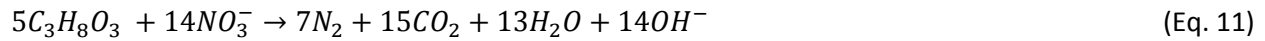




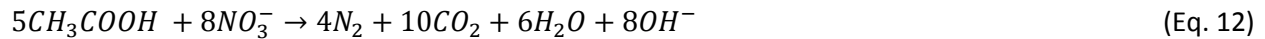
**Denitrification with Ethanol:**



**Denitrification with Glycerol:**



**Denitrification with Acetate:**



From equations 9-12 it is shown that denitrification produces alkalinity (3.57 g CaCO<sub>3</sub>/g NO<sub>3</sub><sup>-</sup>-N reduced). This amount remains constant no matter the type of organic carbon. Comparing this amount to that lost from nitrification (7.14 g CaCO<sub>3</sub>/g NH<sub>4</sub><sup>+</sup>-N oxidized) illustrates that denitrification recovers 50% of the alkalinity consumed during nitrification.

Glycerol and acetate are generally considered too expensive to be applied full-scale. To help reduce costs bio-diesel glycerol waste and an industrial waste alcohol were studied as possible sources (Uprety, 2013). Henze et al. (1989) compared the denitrification rates using several organic components and found that the rate with domestic wastewater was about one third of the value obtained with acetic acid or methanol (Henze, 1989). When comparing acetate, methanol, and glucose, Gerber et al. (1986) found that acetate produced the highest denitrification rates at 2.51 mg NO<sub>3</sub><sup>-</sup>-N/mg MLSS/hr, followed by ethanol (1.79 mg NO<sub>3</sub><sup>-</sup>-N/mg MLSS/hr), methanol (1.12 mg NO<sub>3</sub><sup>-</sup>-N/mg MLSS/hr), and glucose (0.92 mg NO<sub>3</sub><sup>-</sup>-N/mg MLSS/hr) (Gerber et al, 1986). In full-scale application methanol has been the most commonly used external carbon source based on cost, availability, favorable kinetics, and low cell yield.

Denitrification rates vary according to the type and amount of biodegradable COD available and the temperature of the anoxic reactor. Carbon must be in a form easily used by microorganisms. This form is measured as readily biodegradable chemical oxygen demand (rbCOD). For nitrification-denitrification processes the influent carbon to nitrogen ratio is strongly correlated to removal performance. The optimal ratio to support conventional biological denitrification was reported to be 6.0–8.0 mg COD/mg NO<sub>3</sub><sup>-</sup>-N (Chiu et al, 2003). Barnard 1992 found that complete denitrification could be achieved with an influent COD/TKN ratio of 7 (Barnard, 1992).

Maximum growth rates of heterotrophs (3.2 d<sup>-1</sup>) are significantly greater than that of nitrifiers (AOB = 0.9 d<sup>-1</sup> and NOB = 0.7 d<sup>-1</sup>) when treating domestic wastewater. Unlike nitrification, heterotrophic growth rates are less affected by changes in temperature and more dependent upon the type of COD present and concentration of electron acceptor. This is because many of the denitrifying species are adaptive to temperature changes. Denitrification may be performed in the range of 5-40°C (Halling-Sørensen et al, 1993). While rates at temperatures of 20°C and above are sufficient for most nitrogen removal facilities, at lower temperatures rates begin to significantly decline hindering overall removal efficiency (Sutton et al, 1975).

## 2.3 Simultaneous Nitrification/Denitrification

Traditionally nitrification and denitrification processes occur in separate tanks isolating respective aerobic and anoxic environments. A process known as simultaneous nitrification-denitrification (SND), describes a condition when both biological reactions proceed at the same time in the same reactor. SND was first documented at two full-scale oxidation ditches (Rittmann et al, 1985). Since then, the process has been studied for its ability to achieve nitrogen removal with reduced aeration, carbon, and alkalinity requirements. SND performance is determined by several parameters including bulk oxygen concentrations, mixing patterns within biological reactors, the size of flocs in suspension, presence of novel organisms, as well as influent COD/N ratios (Daigger et al, 2000; Jimenez et al, 2010).

SND is most commonly performed in continuously aerated systems at low DO concentrations. Determining the optimal DO concentration is paramount for maximized SND efficiency and typically results in equivalent nitrification and denitrification rates. Von Münch et al. (1996) determined this DO concentration to be around 0.5 mg/L (Münch et al, 1996).

It has been suggested that DO concentrations ranging from approximately 0.3 mg/L to 0.7 mg/L maximize removal via SND (Jimenez et al, 2010). This was confirmed in a study by Pochana et al. (1999) in which the influent C/N ratio was kept constant at 13.8 mg COD/mg NH<sub>4</sub><sup>+</sup>-N while the DO concentration was changed between 0.3, 0.5, and 0.8 mg/L. The SND efficiencies observed for each DO setpoint were approximately 100%, 80%, and 75% respectively (Pochana et al, 1999). Low DO operation reduces activity rates necessitating use of a sufficiently long HRT for SND systems (Third et al, 2003). If oxygen concentrations fall below 0.2 mg/L nitrification occurs at too slow a rate to provide benefit (Bliss et al, 1986).

Denitrification rates have been shown to increase in SND systems at DO concentrations up to 0.8 mg/L (Pochana et al, 1999). The occurrence of SND at higher DO concentrations ( $\geq 0.8$  mg/L) may be a result of faster denitrification rates due to an increased production of NO<sub>x</sub> or the presence of novel microorganisms. However operation at these DO concentrations has the potential to result in reduced denitrification ability and a subsequent loss in SND performance. This was shown in a study by Third et al. (2003) where increased DO concentrations significantly decreased SND performance from 78% at 0.5 mg/L to 61% at 1.0 mg/L to 55% at 1.5 mg/L. The DO levels suitable for SND will vary between WWTPs due to changes in the floc sizes, porosities, and respiration rates as a result of unique influent wastewater characteristics and operational conditions.

The occurrence of SND has also been shown to result from inadequate mixing in biological reactors. Although modeled as homogenous, full-scale bioreactors are many times unable to distribute COD, DO, and biomass uniformly across a reactor. This may stem from inadequate mixing devices such as mechanical aerators or improper diffuser arrangement which can lead to the establishment of different environmental conditions within a reactor. This may lead to sufficient oxygen transfer in one part of the

reactor while limited oxygen transfer occurs throughout another portion (Daigger et al, 2000). Therefore WWTPs may see evidence of SND due to physical limitations of unit processes.

SND performance is also directly related to the size of the flocculent particles in suspension (Pochana et al, 1999). DO concentration gradients occur within biological flocs. Outside layers contain organisms equipped to perform oxidation of ammonia while inner layers, protected from oxygen transfer, provide anoxic zones necessary for microbial activity to achieve denitrification via nitrate or nitrite which diffuses into the core as illustrated in Figure 6 (Münch et al, 1996). The flocs need to be sufficiently large to create an anoxic zone in their interior allowing for denitrification. Literature values of floc sizes vary from 10-110  $\mu\text{m}$  in diameter (Andreadakis, 1993; Pochana et al, 1999). If a system is unable to maintain floc size due to various factors, including filamentous bulking, DO is able to penetrate the interior of the floc structure causing SND performance to deteriorate (Daigger et al, 2007). Due to oxygen diffusion limitations, suspended systems with larger floc sizes are able to operate at higher DO concentrations. This is also the case with integrated fixed film systems (IFAS) where media allows for the adhesion and growth of microbial communities.

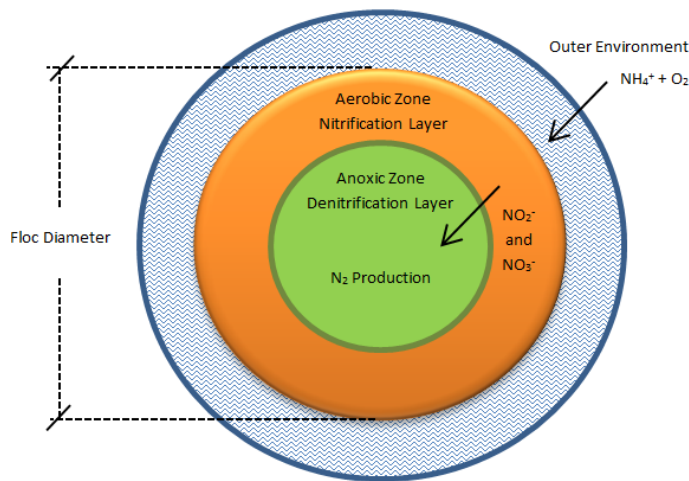


Figure 6 – Zones of a Floc Particle in a SND System

The influence of novel microorganisms has a strong influence on SND performance. Some species of heterotrophs have been shown to denitrify even when DO is present at high concentrations (Robertson et al, 1984). Other heterotrophs have the capability to oxidize ammonia to nitrite using a pathway similar to *Nitrosomonas* (Robertson et al, 1990). Heterotrophs also remove a large portion of ammonia when incorporating the compound into biomass. Although not considered removal via SND, assimilation is responsible for 25-30% of the nitrogen removal at ordinary WWTPs (Bitton, 2011).

It has also been demonstrated that AOB have the ability to denitrify when DO is not present. Using ammonia as an electron donor and nitrite as an electron acceptor the organisms can produce nitrous oxide (Bock et al, 1995; Kuai et al, 1998). In addition, some phosphorus-accumulating organisms (PAOs) are able to denitrify using nitrate as the terminal electron acceptor (Filipe et al, 1999). The ability of

microorganisms to perform dual-roles suggests that under conditions of low oxygen concentrations both nitrifying and denitrifying abilities may be enabled in these organisms.

Organic carbon available for denitrification is perhaps the most important contributor to SND activity (Pochana et al, 1999; Zhang et al, 2007; Jimenez et al, 2010). To ensure COD will not become limiting, high influent chemical oxygen demand to nitrogen (C/N) ratios must be fed to SND processes. Jimenez et al. (2010) indicated that for complete denitrification in conventional SND, an influent C/N ratio of at least 10.0 is required (Jimenez et al, 2013). In order to measure the efficiency of SND processes Third et al. (2003) proposed the following equation (Third et al, 2003).

$$\text{Efficiency SND} = \left(1 - \frac{\text{NO}_x \text{ remaining}}{\text{NH}_4^+ \text{ oxidized}}\right) * 100\% \quad (\text{Eq. 13})$$

In their experimentation, an SND efficiency of 78% was achieved at a DO concentration of 0.5 mg/L. Using synthetic wastewater, Chiu et al. (2007) examined the effect of the influent C/N ratio on the efficiency of SND processes. Dosage of sodium acetate was adjusted to test the effect of three different influent COD/NH<sub>4</sub><sup>+</sup>-N ratios (6.3, 11.1, and 19.7). DO concentrations were kept in the range of 0.64-0.68 mg/L. In the study, 11.1 was found to be the optimal C/N value yielding an SND efficiency of 98.7%. The ratio allowed the system to reach equilibrium between the nitrification and the denitrification reactions resulting in optimal removal of both nitrogen and organic carbon (Chiu et al, 2007).

If a high degree of the COD provided in the influent is in a readily biodegradable form it will be rapidly oxidized to carbon dioxide within the early stages of aeration. Therefore SND requires slowly degradable carbon substrate to provide lasting reduction potential across the reactor. Under carbon limited conditions, the rates of the nitrification and denitrification reactions are not balanced, resulting in an inefficient SND process. Appropriate control of the carbon source concentration can stimulate SND to optimize biological nutrient removal (Chiu et al, 2007).

Jimenez et al. (2013) used laboratory-scale SBRs to evaluate the following two aeration strategies and their effect on SND performance: 1) Constant low DO control, 2) Ammonia (NH<sub>4</sub><sup>+</sup>) based aeration control. The results showed that constant low DO aeration control provided higher SND removals than the NH<sub>4</sub><sup>+</sup> based aeration control at C/N ratios lower than 6. At higher C/N ratios, both strategies provided comparable SND removal (Jimenez et al, 2013). For application full-scale an important consideration is how these strategies operate under high loading situations. With low DO operation (0.5 mg/L) the downside lies in the fact that the control strategy cannot adapt to high loading situations. Therefore the nitrification capacity becomes limited due to the low DO concentration. During high ammonia loading, ABAC would increase the DO concentration to utilize the full nitrification capacity. However compared to constant low DO operation, the result of ABAC is a flexible system providing full aeration intensity at peak loading and minimal airflow at low load conditions.

Control of SND is a significant point of interest for designers and operators of wastewater treatment plants as it potentially has significant advantages over conventional nitrogen removal systems. Most

notably, since nitrification and denitrification occurs in a single tank, SND may eliminate the need to build isolated tanks. In addition, SND reduces carbon, oxygen, and alkalinity consumption in BNR facilities. However the low DO conditions required for SND may provide an environment which is more susceptible to sludge bulking. This hinders its applicability in plants with limited secondary clarification capacity. SND processes may also require large reactor volume due to the impact of low DO on nitrification rates, but many plants already operate under their designed flow. One of the most difficult aspects of SND process control is that the operator cannot make changes to important performance parameters such as floc size, internal storage of COD and the DO profile within the flocs (Jimenez et al, 2010). Because of this, SND has been perceived to be unpredictable and therefore has not typically been designed into full-scale wastewater treatment plants.

## 2.4 Nitritation-Denitritation

Although traditional biological nitrogen removal has been achieved through nitrification-denitrification, it has been discovered that the oxidation of nitrite to nitrate is an unnecessary step in the nitrogen removal pathway. Instead, the process of ammonia oxidation may be halted at nitrite and denitrification may proceed from nitrite to nitrogen gas. This process, shown in Figure 7, is termed nitritation-denitritation or “nitrite shunt”. Compared to nitrification-denitrification the nitrite shunt pathway has the ability to reduce oxygen demand by 25% and carbon demand by up to 40% (Turk et al, 1989; Pollice et al, 2002). Reduced carbon demand also results in an equivalent reduction in biomass.

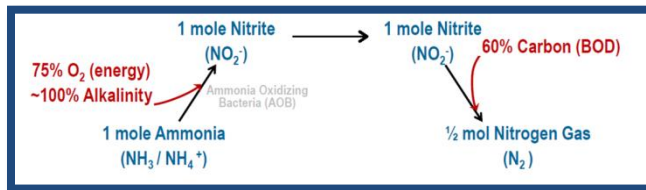
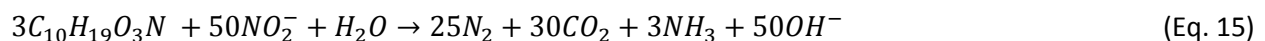


Figure 7 – Nitritation – Denitritation Pathway

### Nitritation:



### Denitritation with Domestic Wastewater as the Carbon Source:



The nitritation reaction ( $\text{NH}_3 \rightarrow \text{NO}_2^-$ ), shown in Equation 14, consumes 3.43 grams of oxygen per gram of nitrogen ( $\text{NH}_4^+\text{-N}$ ) compared to the 4.57 g  $\text{O}_2/\text{g NH}_4^+\text{-N}$  required for complete nitrification. The nitritation reaction requires 7.14 grams of alkalinity (as  $\text{CaCO}_3$ ) per gram of ammonia as nitrogen oxidized. The denitritation ( $\text{NO}_2^- \rightarrow \text{N}_2$ ) reaction produces 3.57 grams of alkalinity (as  $\text{CaCO}_3$ ) per gram of nitrite as nitrogen reduced. Therefore no significant alkalinity is saved with nitrite shunt compared to complete nitrification-denitrification.

Carbon supply is a limiting factor for denitrification. Because nitrite shunt requires a lower amount of carbon, it has the ability to achieve a greater amount of nitrogen removal when compared to conventional nitrification-denitrification in carbon-limited processes. This equates directly to cost savings through a reduction in external carbon addition. However, in order to benefit from the reduced aeration requirements of nitrite shunt, influent wastewater carbon must be diverted in a cost-effective way (Fredericks, 2014). If influent carbon is not properly controlled to a nitrite shunt process, the oxygen requirement imposed by excess carbon will negate the reduced oxygen demand. In this instance, savings would be lost due to carbon oxidation by heterotrophic bacteria. The implementation of an A-Stage process has the ability to control the effluent carbon to a nitrite shunt process while redirecting excess carbon to energy producing processes such as anaerobic digestion.

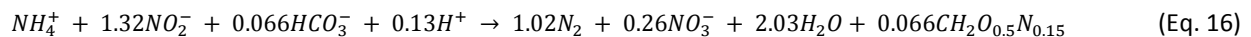
Implementation of the nitrification-denitrification pathway requires suppression of NOB. The difficulty in achieving NOB suppression is that, under most conditions, AOB growth is slower than NOB (Grady, 2011). Therefore, conditions favoring growth of AOB tend to also favor NOB growth. Suppression of NOB is commonly achieved in sidestream processes such as SHARON. Mainstream application is significantly more difficult. Several factors can contribute to suppression of NOB including DO concentration, temperature, pH, SRT, substrate concentration, influent C/N ratio, aeration patterns, and chemical inhibitors (Fadali et al, 2014).

## 2.5 Deammonification

In 1977 Austrian physicist, Broda, proposed the existence of a lithotrophic organism which could derive its energy for growth from the oxidation of ammonium coupled with the reduction of nitrite or nitrate and produce nitrogen gas (N<sub>2</sub>) as an end product (Broda, 1977). Although its existence had been proposed, the organism remained undiscovered until 1995 when Mulder revealed proof of its existence through experimentation in a denitrifying fluidized bed reactor (Mulder et al, 1995). Instead of utilizing oxygen as the electron acceptor, the newly discovered biological process converted ammonia to nitrogen gas using nitrite as the terminal electron acceptor. Since this process occurred under anaerobic conditions Mulder termed the process “Anammox”, for ANaerobic AMMONium OXidation.

The stoichiometric equation for Anammox bacteria was later discovered by Strous and is listed in Eq. 16 (Strous et al, 1998).

### Anammox Metabolism:



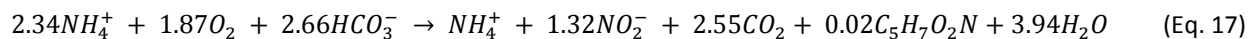
Ratios of the stoichiometric coefficients shown in Eq. 16 are commonly used to verify or prove Anammox activity (Arp et al, 2011). Anammox are autotrophic organisms, appear red in color, and belong to the phylum Planctomycetes. The bacteria are also obligate anaerobes, meaning their metabolism will only occur in the absence oxygen. Concentrations greater than 2 uM are considered inhibitory; however inhibition is reversible (Jetten et al, 2001). Anammox consume ammonium and

nitrite in order to produce nitrogen gas and a small amount of nitrate. In addition, the reaction generates a small amount of alkalinity. The optimum growth environment is a temperature of 37°C and pH of 8.0 respectively (Kuenen et al, 2001).

The use of Anammox bacteria in wastewater treatment processes requires the presence of nitrite. In order to produce nitrite ammonia is oxidized aerobically. Although not typically seen in practice it is also possible for nitrite to be produced from the reduction of nitrate. In fact, Anammox have the ability to oxidize organic acids such as formate, acetate, and propionate to carbon dioxide while using nitrite and nitrate as electron acceptors (Strous et al, 2005; Strous et al, 2007). This process, known as dissimilatory nitrate reduction, results in ammonium as the final end product which Anammox can then convert to nitrogen gas via the usual pathway (Kuenen 2008). The process of dissimilatory reduction may not be achieved with supplemental carbon sources such as methanol and ethanol as they irreversibly inhibit Anammox activity (Strous et al, 2005).

Since Anammox need both nitrite and ammonia it is unnecessary to completely oxidize all of the ammonia in the influent wastewater. Instead, half of the ammonia in solution is oxidized in a process termed partial nitritation (Eq. 17) which leaves equal parts nitrite and ammonia in the effluent. Suppression of NOB is important; therefore, strategies used in nitritation processes must be employed.

**Partial Nitritation:**



When partial nitritation is combined with the Anammox process, the overall reaction is termed partial nitritation-Anammox (PNA) or deammonification. The process of deammonification has great advantages over traditional nitrogen removal through nitrification-denitrification. The pathway, shown in Figure 8, decreases the need for organic carbon by 100%, reduces aeration requirements by about 60%, reduces alkalinity consumption by 50%, and reduces sludge production by approximately 90% (Siegrist et al, 2008).



Figure 8 – Partial Nitritation – Anammox Pathway

Both one-reactor and two-reactor combinations exist for deammonification processes. For one-reactor configurations, two main approaches exist. The first is continuous operation in which oxygen levels vary across a gradient. In these types of systems biofilm or granule formation allows oxygen to be consumed on the outer layer while inner anoxic layers consume the produced nitrite. The second method is

through time dependent aeration in which oxygen levels vary with time. This method, also known as intermittent aeration, takes place through defined periods of aeration and anoxia in the same reactor. Two-reactor configurations involve reactors with separate microbial communities. The first reactor encourages growth of AOB, while the second reactor cultivates Anammox bacteria. Physical transport is required between each of the reactors. With more full-scale experiences, focus has shifted to one-reactor systems based on the lower investment costs (Arp et al, 2011).

The slow growth rate of Anammox bacteria ( $0.05$  to  $0.2\text{ d}^{-1}$ ), approximately one tenth that of nitrifying bacteria ( $1$  to  $1.2\text{ d}^{-1}$ ), presents a challenge for designers (Arp et al, 2011). For this reason it is important to use processes which are able to easily retain biomass such as sequencing batch reactors (SBRs) and MBBRs. Currently SBR technology is the most commonly applied reactor type comprising more than 50% of all deammonification systems (Lackner et al, 2014). It's followed in number by granular systems and MBBRs.

The vast majority of Anammox systems are designed as sidestream options for the treatment of anaerobically digested sludge liquor. Several technologies exist, but the major focus includes the SHARON/ANAMMOX, DEMON, ANITAMox, and Paques ANAMMOX processes. Deammonification mainstream is more challenging. Low biomass growth rates, as a result of lower operating temperatures and nitrogen concentrations, may not lead to significant accumulation of Anammox communities within the system. There is also great difficulty in retaining the bacteria in mainstream operation as high flowrates increase the threat of biomass wash-out. Bioaugmentation, granule formation, and selective wasting processes can help retain bacteria within mainstream processes.

## 2.6 Biological Nutrient Removal Processes

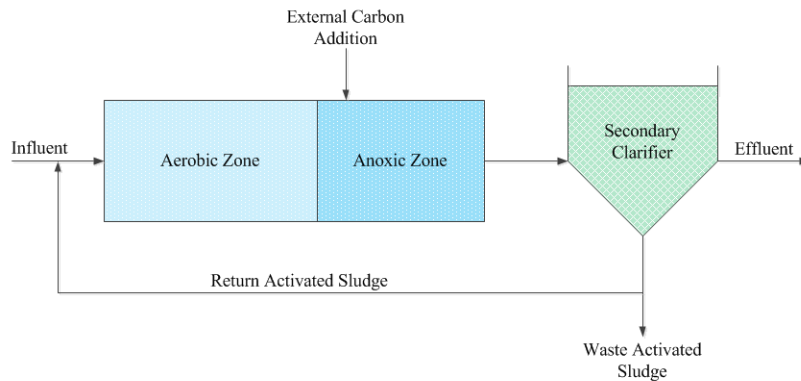
The activated-sludge process is an overall term encompassing three basic concepts: 1) an aerated reactor in which microorganisms are kept in suspension, 2) a liquid-solids separation process, and 3) a recycle stream for the return of solids, captured in the separation process, back to the reactor. It's the most commonly used process for the biological treatment of wastewater. Originally activated sludge processes were designed to remove only biological oxygen demand (BOD) and suspended solids from the wastewater. As time progressed it was realized that process configurations could be established to achieve BNR. Reactor combinations for nitrogen removal may exist as one or two-sludge systems. One-sludge systems have one recycle stream for microorganisms throughout the entire process. They comprise the majority of activated sludge systems. Two-sludge systems have two recycle streams independent of one another and, therefore, contain distinct microbial communities. The following sections highlight reactor configurations for achieving biological nitrogen removal at wastewater treatment facilities.

### 2.6.1 Post-Anoxic Denitrification

The post-anoxic process was developed by Wuhrmann in 1964. In this process nitrification occurs in the aerobic zone while denitrification occurs in the sequential anoxic zone. The process is notorious for an



inefficient use of carbon. This is because heterotrophic activity during the aerobic phase converts organic carbon present in the influent wastewater to carbon dioxide. In doing so, this process removes all or most of the readily biodegradable COD (rbCOD) which leads to carbon limitation in the anoxic zone. Therefore, supplemental carbon sources are commonly added to this configuration to achieve high nitrogen removal efficiency (Christensson et al, 1994). Aeration demand in the aerobic tank is often substantial due to high COD loading. In addition poor settling may result in the secondary clarifier due to a lack of post aeration leading to entrapment of nitrogen gas within the solids (Burton et al, 2013).



**Figure 9 – Post Anoxic Denitrification Configuration**

### 2.6.2 Pre-Anoxic Denitrification

The pre-anoxic denitrification process was developed by Ludzack and Ettinger in 1962. In this process, influent wastewater is first fed into an anoxic basin followed by an aerobic zone. This process is more efficient than the post-anoxic process because it uses carbon present in the influent wastewater to help drive denitrification. In the anoxic selector rbCOD present in the influent water is consumed by heterotrophic microorganisms performing denitrification. This process reduces the need for external carbon addition and also adds alkalinity which provides buffering capacity for nitrification in the aerobic zone. The configuration's ability to remove COD present in the influent before the aerobic zone also reduces aeration demand. The drawback to this setup is that it relies on nitrate being returned to the anoxic zone via the return activated sludge (RAS) line from the secondary clarifier. Nitrogen removal becomes limited in this type of configuration based on the RAS recycle ratio. Increased RAS rates also aid in settlability of solids in this configuration. Plants which have problems of sludge settlability in secondary clarifiers due to denitrification are reverting to this type of configuration (Burton et al, 2013).

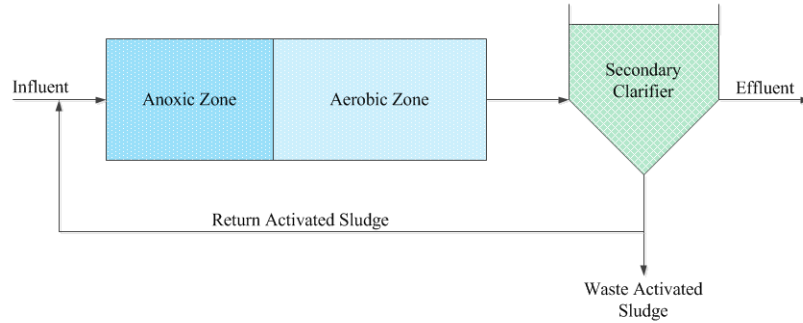


Figure 10 – Pre Anoxic Denitrification Configuration

### 2.6.3 Modified Ludzack-Ettinger

The pre denitrification process was improved by Barnard in 1973. This new process termed Modified Ludzack-Ettinger (MLE) incorporated an internal nitrate recycle. This recycle known as internal mixed liquor recycle (IMLR) or nitrate recycle (NRCY) transports wastewater from the aerobic tank to the head of the anoxic tank via mechanical pumping. Nitrate and nitrite present in the recycle stream provide electron acceptors for denitrification. If DO levels are high in the recycle stream, control may need to be implemented in order to lower the concentration so that nitrate and nitrite are the targeted electron acceptors. Internal recycle flows generally range from 2-4 times that of the influent flow. The MLE process increases denitrification rates and therefore improves the overall nitrogen removal efficiency. Nitrogen removal is a function of the internal recycle ratio and the type of influent COD. The MLE configuration allows rbCOD, present in the influent stream, to be consumed in the anoxic zone whereas in a post-anoxic process, rbCOD is converted to CO<sub>2</sub> in the aerobic zone and never has the chance to benefit the anoxic basin. The MLE process can meet effluent standards of less than 10 mg/L (5-8 mg/L on average) total nitrogen (TN) and is adaptable to existing activated sludge facilities (Burton et al, 2013).

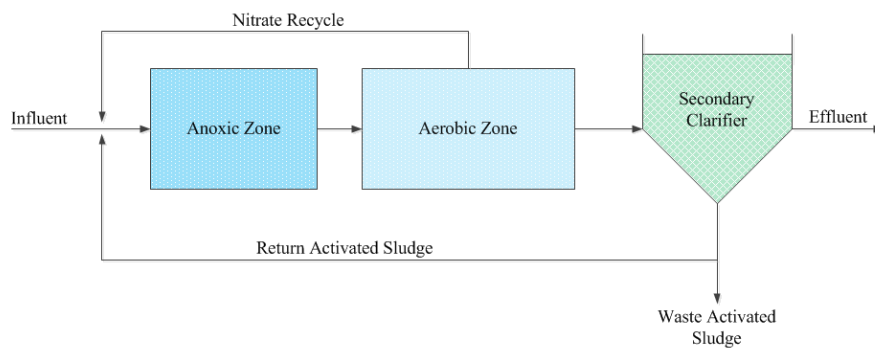


Figure 11 – Modified Ludzack-Ettinger Configuration

### 2.6.4 Four Stage Bardenpho

The Bardenpho process was invented by Barnard in 1974 and has the ability to simultaneously remove nitrogen and phosphorus. The process adds post anoxic and aerobic reactors to the MLE configuration. The pre-anoxic zone achieves the largest amount of nitrate reduction whereas the post-anoxic zone is generally used as a polishing step for further nitrogen removal. The detention time of the post-anoxic zone is about the same as or larger than that used for the pre-anoxic zone. Since the post-anoxic process depends on endogenous respiration to provide electron donor for nitrate consumption, denitrification rates can be slow. This is usually overcome through the addition of an external carbon source. Effluent nitrogen levels less than 3 mg/L are possible with the use of supplemental carbon. If biological phosphorus removal is desired a 5-Stage Bardenpho may be implemented through the addition of an anaerobic selector to the 4-Stage process (Burton et al, 2013).

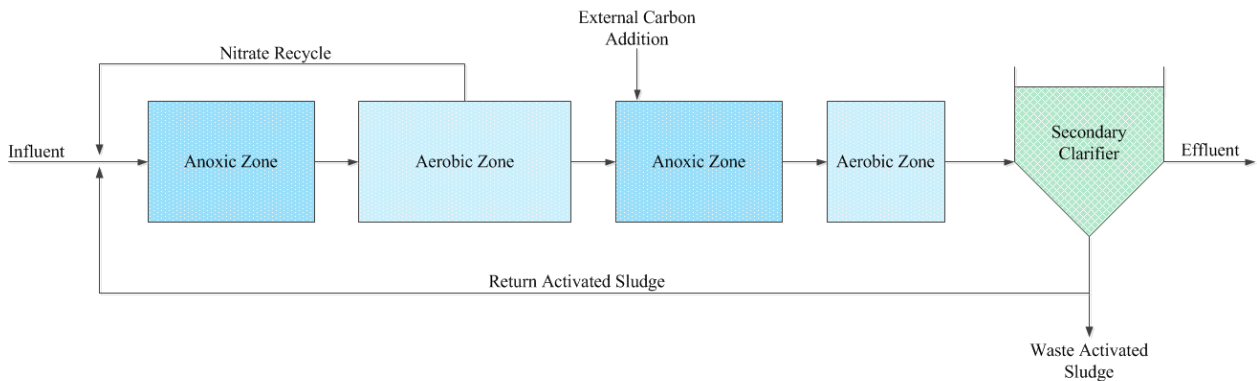


Figure 12 – Four Stage Bardenpho Configuration

### 2.6.5 Step Feed

The step feed BNR process consists of a series of alternating anoxic and aerobic basins. Volumes of these basins are usually equivalent and several alternations may exist within a system. Flow into this system is split amongst the multiple anoxic zones and may be divided symmetrically or asymmetrically. The percentages of influent flow that each anoxic basin receives will determine the overall nitrogen removal capability. Therefore an accurate measure of the deviation of flow is necessary. Since the aerobic and anoxic tanks are sequential there is a chance for carryover of oxygen from the aerobic to the anoxic basin. This transfer must be minimized for maximum nitrogen removal efficiency. This also leads to important control of DO concentrations.

This process is more complex than an MLE and has the ability to achieve effluent nitrogen concentrations of less than 10 mg/L. Activity in the last anoxic zone is highly important to the overall performance of the system. The final flow portion to the last anoxic zone is critical because the nitrate produced in that zone will not be reduced and will be incorporated into the final TN concentration. In order to increase nitrogen removal, external carbon may be added to the final anoxic zone. This addition may be necessary anyway due to insufficient amounts of readily degradable organic matter. In addition,

an internal mixed liquor recycle from the last aerobic zone to the last anoxic zone has the potential to yield nitrogen concentrations less than 5 mg/L (Burton et al, 2013).

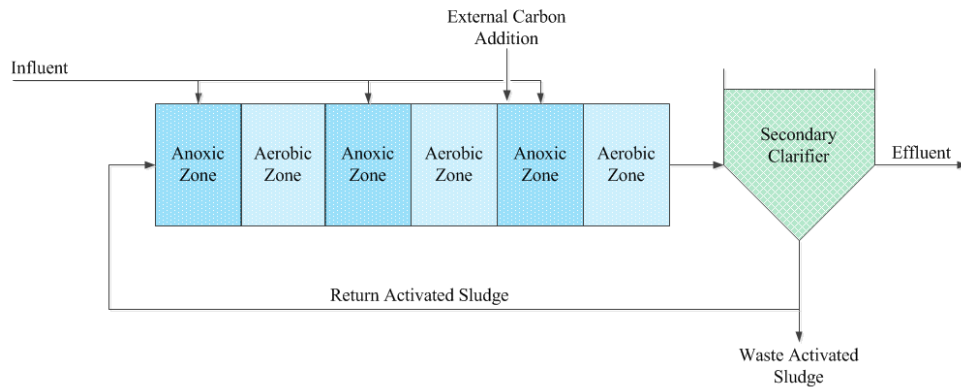


Figure 13 – Step Feed Configuration

### 2.6.6 Adsorption/Bio-oxidation Process

The Adsorption/Bio-oxidation (A/B) process is not a nitrogen removal configuration. Rather it is a two-sludge process which focuses on carbon capture in the A-Stage and incorporates one of the above or similar configurations in the B-Stage to achieve nutrient removal. In this regard the A/B process is unlike the single-sludge processes mentioned in the above sections. Instead the A/B process has two distinct microbial ecosystems at work which are used to treat different characteristics of the wastewater.

As shown in Figure 14, the A/B process is composed of an A-Stage which is a HRAS process that provides minimal aeration. Effluent from the A-Stage enters an intermediate clarifier from which excess solids and return sludge is withdrawn. The general objectives of an A-Stage are to produce large amounts of waste sludge that can be converted to biogas by anaerobic digestion and reduce the organic load on the subsequent BNR process (Schulze-Rettmer et al, 1998). Supernatant from the process passes to the B-Stage where biological processes are incorporated for nutrient removal.

The A/B process was first researched at the municipal treatment plant of Krefeld in western Germany (Boehnke et al, 1998). Since more than half of plant flow originated from various industrial processes, influent was characterized by large fluctuations in COD, pH, and toxic compounds. This was causing inhibition of nitrification processes. Since the extreme conditions of the wastewater made traditional biological treatment unfeasible, engineers had to devise a new method of treatment. The result was the invention of the A/B process. The process was found to provide cost-effective treatment and reduce the need for chemical addition. Soon after experimental work the process was installed full-scale. Once expansion was completed in 1993, operation of the AB process at the Krefeld plant achieved excellent removal efficiencies of COD (96.2%), Total Nitrogen (93%), and Total Phosphorus (97%) (Boehnke et al, 1998).

The A-Stage stage treats the influent wastewater through processes such as adsorption, flocculation, and coagulation. It is a very high rate process with a HRT of 30 minutes or less and a SRT of 3-12 hours (Boehnke et al, 1998). Operation is performed at a very high food-to-microorganism (F:M) ratio in which conditions mimic that of a sanitary sewer collection system. Aeration is supplied to prevent fermentation; however, oxygen concentrations are maintained close to zero ( $\leq 0.5$  mg/L). These factors result in a group of bacteria that is fast growing, adaptive, and most suited to treat influent wastewater. It is also thought that because the SRT is only a few hours, biomass in the A-Stage consists almost entirely of bacteria (Boehnke et al, 1997). The high metabolism rate of bacteria ensures fast reduction of organic pollutants. And because bacteria reproduce so quickly, there is a high likelihood of the formation of mutations that can disintegrate various pollutants and resist adverse conditions. Therefore the A-Stage proves resistant to shock loads which may occur in the collection system protecting the sensitive bacteria from toxic compounds in the subsequent BNR process (Boehnke et al, 1997).

Because of the high food to microorganism (F:M) ratio and short retention time, the A-Stage is able to achieve high COD removal efficiencies at small treatment volumes. It has been stated that the A-Stage has the ability to remove up to 80% of the influent BOD and COD; although full-scale experimentation has shown an even higher degree of removal efficiency (Boehnke et al, 1997). Soluble rbCOD is removed by intracellular storage and conversion to biomass, while particulate and colloidal COD are generally thought to be removed by enmeshment (Miller et al, 2012). Enmeshment occurs due to the bacterial production of extracellular polymeric substances (EPS) which aid in the formation of microbial aggregates. These aggregates entrap and settle COD. The ability of the A-Stage to remove COD allows more organic material to be fed to anaerobic digestion processes for increased methane production as well as a reduction in the aeration capacity and tank volumes needed for operation of the B-Stage.

Carbon removal in the A-Stage process can lead to COD limitation in the B-Stage and consequently reduced denitrification performance. Therefore the B-Stage should take advantage of SND, nitrite shunt, or deammonification style processes in order to achieve low effluent TN concentrations (Brandt et al, 2012). A study by Miller et al. (2013) showed that the A-Stage can inadvertently control the COD output through control of SRT (Miller et al, 2013). In the study, effluent COD concentrations were determined by the concentration of microorganisms within the system measured by the mixed liquor suspended solids (MLSS) and volatile suspended solids (VSS). Higher mixed liquor concentrations equated to greater COD removal and vice versa. One of the most critical parameters for denitrification in the B-Stage is the type and concentration of carbon substrate. Because the A-Stage has the ability to selectively remove refractory substances, it provides easily biodegradable COD to the B-Stage. Also, because organic compounds leaving the A-Stage have been converted to simpler molecules, they are more easily metabolized in the B-Stage. This reduces the organic load and provides a more consistent influent to the BNR process.

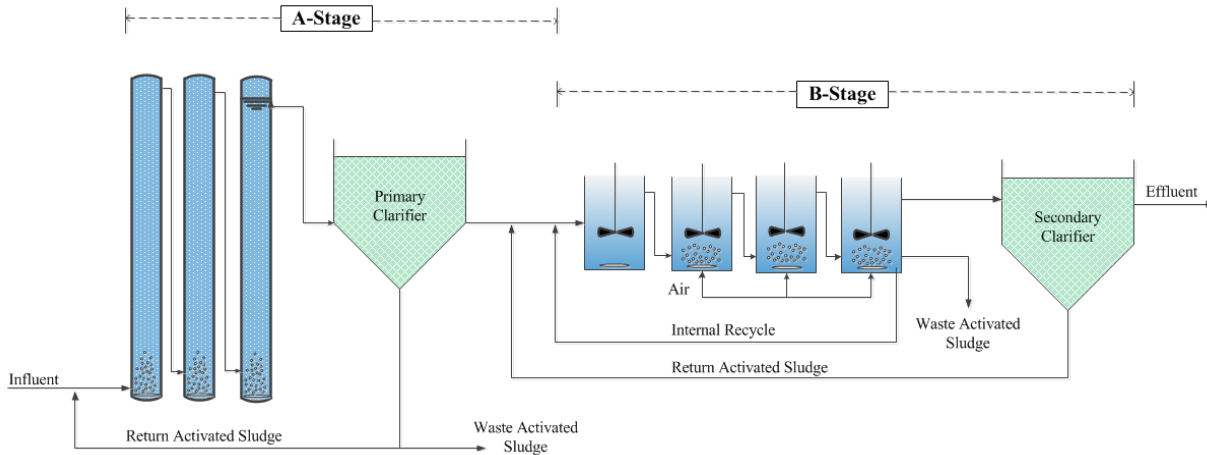


Figure 14 – Adsorption Bio-oxidation Process

## 2.7 Sidestream NOB Suppression

The dewatering of anaerobically digested solids produces two end products: cake solids and liquid centrate. The cake solids are typically handled through incineration, land application, or disposal via landfill. In most cases the centrate is returned to the activated sludge process or the head of the plant. This return flow, termed “sidestream”, is small compared to the total plant inflow (< 5% by volume). However it contains very high nutrient concentrations (800 – 3000 mg/L  $\text{NH}_4^+\text{-N}$ ) (Stinson et al, 2013). In fact, side-stream flows typically constitute 15 to 20% of the total nitrogen load to wastewater treatment plants (Fux et al, 2002). Some say it may comprise a wider range: 10-30% (van Loosdrecht et al, 2006). By invoking separate treatment of these sidestreams prior to returning the water to mainstream processes bulk concentrations of nitrogen may be removed. This acts to significantly reduce plant loading and improve overall water quality.

Four primary mechanisms enable out-selection of NOB within sidestream processes: 1) continuous or intermittent aeration at low DO concentrations, 2) inhibition due to high concentrations of free ammonia (FA), 3) inhibition due to accumulation of free nitrous acid (FNA), and 4) operation at low aerobic SRT to wash-out NOB (Burton et al, 2013). In most cases a combination of the above mechanisms is used in order to accomplish NOB out-selection while at the same time increased temperatures (> 20°C) and ammonia concentrations within sidestream processes encourage the growth of AOB. The effects of the two inhibitory substances (FA and FNA) are dependent upon reactor pH, ammonia and nitrite concentrations, and temperature.

### 2.7.1 Temperature and SRT Control

Temperature significantly influences the specific growth rates of AOB and NOB. High temperatures are known to favor the growth of AOB over NOB (Kim et al, 2008). This is advantageous to the treatment of sidestreams since elevated temperatures (30-35°C) are easily achieved as a result of anaerobic digestion. The plot of nitrifier growth rates, shown in Figure 15a, indicates that a shift in the growth

rates of AOB and NOB occurs at a temperature of 20°C. Above this temperature AOB growth rates are faster than NOB, while the opposite holds true below 20°C. Because of temperature, AOB growth rates are already significantly higher than NOB growth rates within sidestream treatment processes.

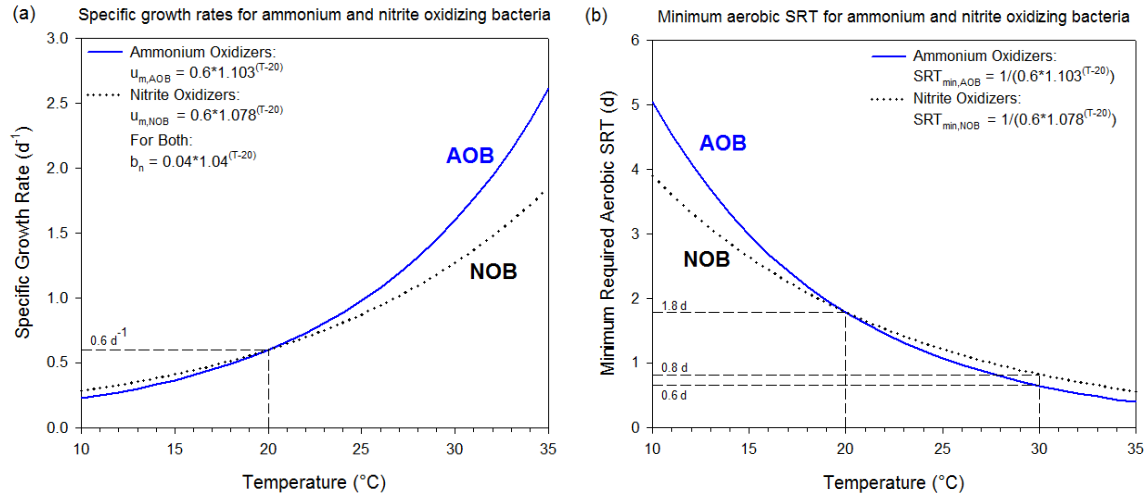
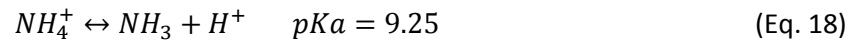


Figure 15 – a) Maximum specific growth rate of nitrifying organisms vs. temperature b) Aerobic  $SRT_{min}$  vs. temperature. van Dongen, L. G. J. M., S. M. Jetten, M. C. M. van Loosdrecht and C. M. van Loosdrecht (2001). *The Combined Sharon/Anammox Process: A Sustainable Method for N-Removal from Sludge Water*, IWA Publishing. Used under fair use, 2015.

Higher growth rates of AOB at elevated temperature allow NOB to be removed from the system while AOB are retained. Removal of NOB from the system, known as wash-out, occurs through strict control of the SRT. Wash-out of NOB is achieved by controlling the SRT at or less than the minimum required aerobic SRT for NOB but greater than the minimum required aerobic SRT for AOB (Aerobic  $SRT_{min}$  for AOB  $\leq$  SRT of Reactor  $\leq$  Aerobic  $SRT_{min}$  for NOB). Therefore NOB are physically unable to reproduce quickly enough in order to remain in the system. Figure 15b estimates that at a temperature of 30°C the minimum aerobic sludge age is 0.6 days for AOB and 0.8 days for NOB. Higher temperature will increase this differential allowing for more successful wash-out of NOB at reduced aerobic SRT. However temperature of a sidestream reactor should not exceed 40°C due to a sharp decline in the activity rates of AOB above this threshold (Hellings et al, 1998).

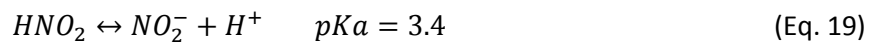
### 2.7.2 Free Ammonia and Free Nitrous Acid

High ammonia concentrations within sidestream processes can encourage the suppression of NOB activity. Ammonia in solution exists as ammonium ( $NH_4^+$ ) or free ammonia ( $NH_3$ ). The concentration of these two is dependent on both pH and temperature; however, pH has the greatest influence on the dissociation. At 25°C and pH of 9.25 the concentrations of ammonium and free ammonia are equal (Eq. 18). If the pH drops below 9.25 concentrations of ammonium increase while free ammonia decreases. The opposite holds true above a pH of 9.25. Free ammonia also increases with temperature. For example, the free ammonia concentration at 30°C is about twice as much as it is at 20°C for the same pH and total ammonia nitrogen concentration.



Free ammonia, not ammonium, is considered substrate for AOB. Although considered substrate it has been shown that elevated concentrations of the compound can inhibit both AOB and NOB. Inhibition of nitrifiers to free ammonia is disproportionate, as inhibitory concentrations for AOB are typically greater than those for NOB. The range of inhibitory concentrations for *Nitrosomonas* was found to be 10-150 mg/L whereas the range for *Nitrobacter* was shown to be 0.1-1.0 (Anthonisen et al, 1976). Another report shows higher inhibitory concentrations as free ammonia inhibited *Nitrosomonas* at concentrations above 16 mg/L and *Nitrobacter* at concentrations above 6 mg/L (Vadivelu et al, 2007). In a continuous flow experiment free ammonia concentrations greater than 0.3 mg/L resulted in nitrite accumulation, but once levels were brought down to less than 0.2 mg/L nitrite oxidation began to reemerge (Anthonisen et al, 1976). This highlights that free ammonia inhibition is temporary, and once levels drop below the threshold of inhibition, nitrite oxidation may resume. This difference in inhibitory levels can be used to achieve NOB suppression. Sole suppression of NOB using free ammonia is difficult to achieve long-term. This may be due to acclimation of nitrifiers to the compound (Turk et al, 1989).

Like free ammonia, free nitrous acid ( $HNO_2$ ) also exerts an inhibitory effect on nitrifiers. As nitrite accumulates inside sidestream reactors, free nitrous acid concentrations will also increase. At 25°C and a pH of 3.4 the concentrations of nitrite and free nitrous acid are equal (Eq. 19) (Grady, 2011). When pH increases the concentration of free nitrous acid decreases while the concentration of nitrite increases. The opposite is seen at pH values below the pKa value. Free nitrous acid was shown to affect nitrifying organisms at concentrations between 0.22 and 2.8 mg/L (Anthonisen et al, 1976). Just as seen with inhibition to free ammonia, it takes higher concentrations of free nitrous acid to inhibit AOB than NOB. This is shown through inhibition of *Nitrosomonas* at 0.40 mg/L while *Nitrobacter* was inhibited at 0.02 mg/L (Vadivelu et al, 2007).



Several factors account for the variation in inhibitory effects of free ammonia and free nitrous acid including acclimation of nitrifiers to the compounds, temperature of solution, and number of active nitrifying organisms. However, the presence of one or both compounds can lead to successful NOB out-selection within sidestream processes.

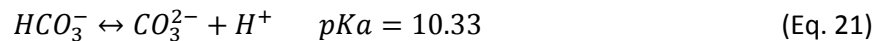
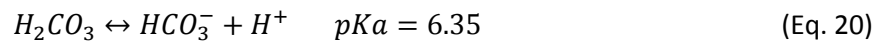
### 2.7.3 Effect of Inorganic Carbon

Within biological systems Anammox, AOB, and NOB all compete for inorganic carbon as their preferred assimilative carbon source. Although carbon dioxide is thought of as the carbon source for these autotrophic organisms, bicarbonate is the true substrate. A deficit in the inorganic carbon concentration will therefore result in decreased activity rates of autotrophic organisms. In both mainstream and sidestream processes, inorganic carbon can become limiting. In the mainstream, inorganic carbon limitation has often been neglected, as it is usually present in abundance. This is because mainstream wastewater contains a large amount of organic carbon per unit of ammonia. During aeration, the



aerobic degradation of organic matter by heterotrophic organisms produces CO<sub>2</sub> which is utilized by autotrophic organisms for growth (Guisasola et al, 2007). However in sidestream processes which are fed with centrate containing very low C/N ratios, inorganic carbon may become limiting.

The oxidation of high concentrations of ammonia in sidestream processes results in the stripping of carbon dioxide from the wastewater and the continuous removal of inorganic carbon from the system. This occurs due to the low partial pressure of CO<sub>2</sub> in air. Rising air bubbles caused by aeration strip more carbon dioxide than they can transfer into the water according to Henry's law (Wett et al, 2003). Ammonia oxidation also acts to remove alkalinity by adding hydrogen ions into solution. This reduction in pH reduces the amount of bicarbonate in solution.



Wastewater deficient in inorganic carbon directly affects the activity of AOB. Experimental results obtained by Guisasola et al. (2007) show that AOB activity was limited at total inorganic carbon (TIC) concentrations lower than 3mmol C/L. At the same time, no carbon source limitation for NOB was observed. NOB were limited by TIC concentrations lower than 0.1mmol C/L (Guisasola et al, 2007). This indicates that AOB are more sensitive to inorganic carbon limitation than NOB. Therefore, systems which aim to maximize activity of AOB should maintain concentrations of inorganic carbon which are non-limiting to their growth.

For systems performing deammonification, inorganic carbon limitation is even more important. Ma et al. (2015) observed a decrease in overall nitrogen removal in a biofilm nitritation-Anammox process from 78 ± 2.0% before inorganic carbon limitation to 46 ± 2.9% during limitation. The study showed that Anammox were far more vulnerable than AOB and NOB to the effects of limitation. Inorganic carbon limitation also led to increased production of NO and N<sub>2</sub>O within the system (Ma et al, 2015). Providing sufficient inorganic carbon ensures the stability of deammonification processes and reduces the production of greenhouse gases.

#### 2.7.4 Sidestream Treatment Methods

Sidestream wastewaters often contain little organic matter (e.g. Fux et al. 2002) with an ammonium nitrogen concentration 1, 2 or 4 times higher than the chemical oxygen demand (COD) (e.g. Carrera et al., 2003 or Lai et al., 2004). Low C/N ratios and limited alkalinity make conventional nitrification-denitrification extremely inefficient for sidestream application. If process design enabled efficient nitrogen removal from these concentrated waste streams the energy required to treat mainstream flows could be greatly reduced. Recently, several cost-effective alternatives have emerged to treat these sidestreams.

### 2.7.4.1 SHARON Process

SHARON (Single reactor High activity Ammonia Removal Over Nitrite) is a process that was first researched in the Netherlands at the Delft University of Technology. The goal of the process was to reduce the nitrogen load to the B-Stage at Dokhaven WWTP in Rotterdam. An evaluation at the plant showed that an 85% reduction in ammonia in the recycle stream could reduce total nitrogen in the effluent by 25% and shift operation of the B-Stage from oxygen limited to ammonium limited (Hellinga et al, 1998).

The SHARON process performs nitrification-denitrification through intermittent aeration in a single continuously stirred tank reactor (CSTR). Since the process treats centrate from anaerobically digested solids at an operating temperature between 30-40°C with design temperature being 35°C. Temperature control equipment is not usually needed for these reactors because the nitrification reaction is exothermic. A 10°C temperature increase results from each gram of ammonia oxidized (Mooij, 2010). Lab-scale testing at Delft revealed the optimum temperature of operation to be 40°C with a corresponding growth rate of 2.1 d<sup>-1</sup> (Hellinga et al, 1998). At greater temperatures cellular deterioration takes place and the growth rate decreases. This is shown in Figure 16 below.

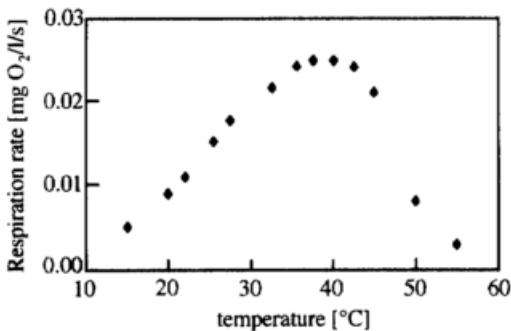


Figure 16 – Nitrifier oxygen uptake rate vs. Temperature. Hellinga, C., A. Schellen, J. W. Mulder, M. C. M. van Loosdrecht and J. J. Heijnen (1998). "The Sharon Process: An Innovative Method for Nitrogen Removal from Ammonium-Rich Waste Water." *WATER SCIENCE AND TECHNOLOGY* 37(9): 135-142. Used under fair use, 2015.

The SHARON reactor is operated without retention of biomass (HRT=SRT). Therefore growth rate of AOB is measured as 1/SRT. Because the reactor is operated without solids retention the HRT may be adjusted to achieve wash-out of NOB. Typical aerobic HRT for the Sharon process is approximately 1 day. Higher aerobic retention times result in a greater amount of ammonia conversion but may also lead to NOB growth.

Although digester centrate contains an elevated pH, the high level of substrate and increased AOB activity quickly reduces pH inside the reactor. In order to prevent loss of nitrification the pH must be controlled. This is usually done through CO<sub>2</sub> stripping, denitrification, or caustic addition. Denitrification is commonly used and usually driven with the addition of methanol. For SHARON processes which don't

regulate pH with denitrification, the effluent nitrate and nitrite produced is reduced when mixed with raw influent at the head of the plant. In order to maintain AOB activity over NOB, a higher pH is desired. A range between 6.5 and 8.5 has been specified to prevent the effects of free nitrous acid (HNO<sub>2</sub>) and free ammonia (NH<sub>3</sub>) respectively (Hellings et al, 1998; Haandel et al, 2012).

When studied at Delft, the SHARON process was operated at 35°C in a lab-scale reactor with a 1.5 day total HRT. The reactor was intermittently aerated (80 minutes aerobic/40 minutes anoxic) and achieved an average ammonium conversion of 85%. This holds true with today's full-scale SHARON installations which are able to achieve 80-95% ammonia removal efficiency (Haandel et al, 2012). The first full-scale installation of the SHARON process occurred at Utrecht in the Netherlands in 1997. The first and only installation in the United States is located at the Wards Island treatment plant in New York City. Below is a list of additional full-scale installations that have been constructed since.

**Table 1 – Global SHARON Installations accompanied by their respective Loading Rates. Data from (Mooij, 2010).**

WWTP	Loading Rate (kg NH <sub>4</sub> <sup>+</sup> /day)	Year of Operation
<b>Utrecht (Netherlands)</b>	900	1997
<b>Rotterdam (Netherlands)</b>	850	1999
<b>Zwolle (Netherlands)</b>	410	2003
<b>Beverwijk (Netherlands)</b>	1200	2003
<b>Groningen (Netherlands)</b>	2500	2005
<b>Den Haag (Netherlands)</b>	1200	2005
<b>New York City (United States)</b>	5000	2009
<b>Linköping (Sweden)</b>	500	2009
<b>Geneva (Switzerland)</b>	1700	2010
<b>MVPC Shell Green (United Kingdom)</b>	1600	2010
<b>Whitlingham (United Kingdom)</b>	1500	2010
<b>Seine Grésillons (France)</b>	3500	2012

#### **2.7.4.2 STRASS Process**

Due to the importance of pH regulation in sidestream treatment processes an operational strategy using pH-controlled aeration was developed. In the mid 1990's the Strass WWTP in Austria had need for ammonium conversion in a sidestream process. Research was performed onsite with a 640 m<sup>3</sup> SBR which was intermittently aerated to treat the reject water. Influent to the SBR was fed from an equalization basin. The process which was developed established a maximum ratio of aerobic to anoxic periods of 2:1 and allowed for online measurement of pH to control aeration. The pH setpoint was allowed to fluctuate between a minimum of 7.2 and a maximum of 7.6. When the maximum setpoint was reached aeration commenced at a DO setpoint of 2 mg/L. Once nitrification lowered the pH to its minimum setpoint aeration was terminated. Denitrification then recovers pH until the maximum setpoint of 7.6 was again reached. Primary sludge from the A-Stage of an A/B process was fed to the reactor in order to provide a carbon source for denitrification. The SRT of the SBR was very high (≈ 50

days). The process ran until all available alkalinity was consumed. Then supernatant was sent to mix with influent plant flow and new reject water was fed (Wett et al, 1998).

Nitrogen removal performance in the SBR is a factor of the concentrations of ammonia and alkalinity present in the reject water and the alkalinity produced during denitrification. TKN removal rates of 80% were achieved. High free ammonia levels (1 mg/L) and elevated temperature (20-25°C) in the reactor kept the oxidation of nitrite to nitrate to 30% on average. Overall the STRASS process was shown to balance alkalinity, reduce CO<sub>2</sub> stripping, and eliminate the need for nutrient specific (ammonia, nitrite, and nitrate) probes. This process was implemented full-scale from 1997 to 2004. In 2004 the process was converted to a DEMON installation.

#### **2.7.4.3 SHARON/ANAMMOX**

The two-stage SHARON/ANAMMOX process operates off continuous flow and was one of the first processes developed for sidestream deammonification. The first reactor consists of a CSTR operated at a temperature above 30°C and an SRT of approximately 1.5 day. The SRT may be adjusted to a minimum level (approximately 1 day) in order to achieve selective wash-out of NOB in the suspended biomass system (van Loosdrecht et al, 2006). Although the SHARON reactor is not typically supplied with additional alkalinity, reactor pH should be maintained around 6.6 to 7.0 to provide high ammonia removal rates. No supplemental organic carbon is added to this reactor.

From the SHARON reactor, the partially nitrified wastewater flows into a second stage ANAMMOX reactor operated in an upflow configuration. Under high upflow velocity the reactor selects for Anammox bacteria which form dense granules with high settling velocities. This allows for the development of a sludge blanket at the bottom of the reactor. Due to the high upflow velocity flocculated particles with lower densities and settling velocities are washed out. Internal mixing is provided in order to remove nitrogen gas produced by the sludge bed. De-gassed mixed liquor is then returned to the bottom of the tank. Between the two reactors a clarifier is sometimes provided to prevent the accumulation of denser inert solids in the ANAMMOX reactor (Burton et al, 2013).

#### **2.7.4.4 DEMON**

DEMON (derived from the term DEaMmONification) is the most popular configuration for sidestream deammonification comprising more than 80% of all SBR systems (Lackner et al, 2014). This process was first implemented at the Strass WWTP where reject water was originally treated in a nitrification-denitrification SBR with a pH-based control. The DEMON SBR is a suspended growth reactor which is intermittently aerated based on pH or time-based control. The SBR operates to achieve partial nitrification during aerobic periods and nitrogen removal through Anammox during the anoxic phases. Peak oxygen concentration in the reactor is established at approximately 0.3 mg/L to provide pressure against NOB growth as well as rapid transition to the anoxic environment. Cycle duration is typically controlled through pH setpoints. Operating pH is typically controlled in order to prevent the loss of

inorganic carbon thus maintaining nitrification rates. When time-based cycle duration is applied aerated periods are generally kept at 10-15 minutes with anoxic periods on the order of 5-10 minutes in duration (Burton et al, 2013). The duration of the anoxic period is designed to completely reduce nitrite in the reactor. High nitrite concentrations ( $\geq 100$  mg-N/L) are not desired in the reactor as Anammox have shown complete inhibition at these concentrations (Strous et al, 1999).

The use of hydrocyclones in the waste stream allow for separate adjustment of SRT for AOB and Anammox bacteria. This is achieved through differences in density between the two bacteria. Anammox bacteria are capable of forming dense granules which settle quickly compared to lighter flocs of AOB, NOB, and heterotrophs. Within the hydrocyclone heavy Anammox-rich granules are separated into the underflow, while lighter AOB-rich flocs are separated into the overflow and wasted (Nifong, 2013). Anammox populations are retained with SRTs on the order of 40-50 days whereas AOB populations are retained with an SRT of approximately 10 days (Wett et al, 2010).

#### **2.7.4.5 ANITAMox**

ANITAMox is a single-stage moving bed biofilm reactor for deammonification. The reactor is continuously aerated with a variable DO setpoint (0.5 to 1.5 mg/L). Adjustment of the DO setpoint is required to minimize nitrate production while providing stable ammonium removal. Mechanical mixing is generally not required due to adequate mixing from continuous aeration. However during startup and periods of low ammonia loading, mixing may aid in removal performance (Burton et al, 2013).

Plastic media retain microorganisms within the reactor. The media within the reactor is designed to provide a high surface area to volume ratio for Anammox to grow, thus preventing wash-out. Volume of media within the reactor should not exceed 50% of the total volume. This is done to prevent insufficient mixing and allow for media movement throughout the reactor. Biofilms which develop on the media contain stratified groups of microorganisms. The exterior of the biofilm contains AOB and NOB while the inner layer of the biofilm contains Anammox.

#### **2.7.4.6 Paques ANAMMOX**

This process was developed off the principle of the SHARON/ANAMMOX concept. However, instead of separate reactors treatment occurs in a single reactor. The Paques process consists of a continuously fed reactor containing granular biomass. Aeration is provided for rapid mixing of the influent with the reactor content. The intense contact between the wastewater, biomass, and oxygen drives conversion of nitrogen. Ammonia is oxidized to nitrite on the outer layers of the granules while inner layers, impenetrable to oxygen, contain Anammox which perform the conversion to nitrogen gas.

Treated wastewater leaves the reactor by passing a patented biomass retention system at the top of the reactor. The system separates the granular biomass from the cleaned wastewater, assuring high

biomass content in the reactor. The large concentration of biomass provides for high conversion rates minimizing the necessary reactor volume (Paques).

## 2.8 Mainstream NOB Suppression

Unlike sidestreams, mainstream wastewaters are much less concentrated (30-40 mg-N/L) and exhibit greater variability in flow. Typical concentrations associated with mainstream conditions are shown in table 2.

Table 2 – Typical Medium-Strength Wastewater Characterization in the US. Tchobanoglous, G., F. L. Burton, H. D. Stensel, Metcalf and Eddy (2003). Wastewater Engineering: Treatment and Reuse. Boston, McGraw-Hill. Used under fair use, 2015.

Component	Concentration (mg/L)
COD	430
BOD	190
TSS	210
VSS	160
TKN	40
NH <sub>4</sub> <sup>+</sup> -N	25
NO <sub>3</sub> <sup>-</sup> -N	0
TP	7
Alkalinity	200 (as CaCO <sub>3</sub> )

Because nutrient concentrations in the bulk liquid are so low relative to sidestream conditions there is a lack of inhibitory pressure from free ammonia on NOB in mainstream operation. In addition, low effluent ammonia requirements associated with mainstream processes further reduce the ability of AOB to maintain a competitive advantage over NOB. This occurs as low substrate availability favors NOB activity over AOB.

Unlike sidestream wastewater, mainstream wastewater contains carbon in high concentrations (COD:NH<sub>4</sub><sup>+</sup>-N = 10-14) (Henze, 2008). The influent COD:NH<sub>4</sub><sup>+</sup>-N ratio is important in shifting nitrogen removal towards the pathway of nitrite shunt, especially in domestic wastewaters containing lower amounts of carbon per unit ammonia. This is because high amounts of carbon can lead to competition between AOB and heterotrophic bacteria thus decreasing AOB activity and making nitrogen removal via nitrite difficult to achieve.

Temperatures of mainstream processes fluctuate throughout the year. Seasonal variations in the influent water temperature at HRSD's facilities range between 12 and 30°C. As temperatures fall below 20°C the growth of AOB is not favored. Raising the temperature of the water to improve the growth rate of AOB would be cost prohibitive and therefore is not a considerable option.

In the natural environment AOB and NOB tend to coexist. This is because AOB provide substrate for NOB. Due to this, nitrite rarely accumulates in the environment. Limiting factors of mainstream conditions create challenges in maintaining sustainable nitrogen removal via the nitrite pathway.

Therefore specific operational strategies must be considered to suppress growth of NOB. Strategies for achieving NOB out-selection mainstream include transient anoxia, terminating aeration prior to ammonium oxidation, supplementing AOB through bioaugmentation, and introducing chemical inhibitors. Once NOB suppression is achieved, usually through a combination of these methods, aggressive SRT control allows for selective wash-out of NOB.

### 2.8.1 Transient Anoxia

Transitions between the anoxic and aerobic environments, termed “transient anoxia” may lead to nitrite accumulation within activated sludge systems. This is because transient anoxia works to create a differential in the response of NOB activity compared with that of AOB. This may be attributed to enzymatic lag or substrate limitation during transition to the aerobic phase, production of inhibitory compounds during the anoxic phase, or competition for substrate during transition to the anoxic phase.

AOB have been shown to recover more quickly than NOB after periods of starvation. Tappe and Leavermen induced feast/famine conditions on pure cultures of *Nitrosomonas* and *Nitrobacter* (Tappe et al, 1999). They found that the starvation recovery differed between the two species and that, when subjected to longer periods of starvation (up to 3 months), both AOB and NOB experienced a decrease in their spontaneous respiratory activity. The lag in spontaneous activity was directly proportional to the length of starvation. In each test, activity of *Nitrosomonas* was found to resume significantly faster than that of *Nitrobacter*. This observation was attributed to an inactivation of the nitrite oxidoreductase enzyme by *Nitrobacter* during periods of low substrate concentrations. AOB, however, have the ability to maintain a high ammonia-oxidizing capacity during periods of starvation. They have adapted this trait from regular exposure to long periods of starvation in the natural environment (Gerards et al, 1998). This may explain the accumulation of nitrite after periods of starvation.

Similarly Kornaros (2010) modeled the behavior of nitrifying bacteria during the transition from anoxic to aerobic conditions. This study was performed with anoxic periods on the order of 1.5-12 hours. The model assumed deactivation of the nitrite oxidoreductase enzyme by NOB during anoxic conditions. Mixed culture experiments highlighted that AOB did not exhibit any impact in their performance following anoxic disturbances; however NOB were inhibited. This inhibition was indicated by a period of reduced growth rate, which was proportional to the duration of the anoxic disturbance (Kornaros et al, 2010).

Although the previous studies examined the effects of longer anoxic durations, short anoxic disturbances may also induce a lag in NOB activity. Gilbert et al. (2014) found that intermittent aeration with short anoxic periods (15–20 min) followed by aerobic periods that do not exceed the specific lag phase, might be sufficient for suppressing NOB. In this study the length of the observed lag in NOB activity varied between 5 and 15 minutes. A distinctive increase in the specific lag phase was shown to occur between anoxic periods of 5 and 20 min. This indicates that NOB need exposure to some minimum anoxic duration before deactivating metabolic enzymes. Once deactivation occurs a lag phase may be observed in the following aerobic period. An important finding of this study was that the length of the lag phase was found to be biomass specific. The duration of the lag phase for NOB adapted to

high DO concentrations was shown to be longer than that of biomass adapted to low DO. The length of the lag phase was also found to be uninfluenced by temperature and, unlike other studies, duration of the anoxic period had no noticeable effect on the NOB lag time (Gilbert et al, 2014).

Transient or intermittently aerated systems may also achieve NOB out-selection from heterotrophic competition. Fast transitions from the aerobic to the anoxic environment encourage competition between NOB and heterotrophic denitrifiers for oxygen and nitrite. Over many cycles in intermittently aerated systems NOB activity is expected to gradually decrease due to this competition, accompanied by increased nitrite accumulation (Lemaire et al, 2008). This has also been cited for systems containing Anammox which have the ability to compete against NOB for nitrite at low free ammonia, low free nitrous acid, and high DO levels (De Clippeleir et al, 2013).

Rapid transition to the anoxic environment allows for the lag in NOB growth to be exploited in intermittently aerated systems. The key for successful implementation of rapid transient anoxia is to maintain high oxygen uptake rates (OUR) (Regmi et al, 2014). Several approaches exist to increase a system's OUR. The first approach is to operate at higher mixed liquor suspended solids (MLSS) concentrations. This maintains more microorganisms within the same volume. A second approach is to feed influent wastewater at the end of the aerobic phase to provide COD for fast consumption of oxygen during the anoxic period. A step-feed configuration would be appropriate for this approach allowing for a high OUR to be maintained across the entire length of a reactor. The third approach would be to increase the temperature and therefore the growth rates of all organisms in the system; although, this option may not be economically feasible (Regmi et al, 2014).

As mentioned previously it is commonly seen that the length of anoxic duration is directly related to the lag in NOB activity. Chandran and Smets found the NOB lag-time to be a result of full denitrification during the anoxic phase, resulting in nitrite limitation in the aerobic phase (Chandran et al, 2000). Nitrite reduction during the anoxic period removes available substrate for the NOB population during the aerobic period. Since growth of NOB cannot occur until the AOB generate nitrite, accumulation may result. This condition of substrate availability, or lack thereof, may limit growth of NOB while maintaining high AOB growth rates. Malovanyy et al. (2014) proposed that the absence of DO and nitrite, and not the anoxic phase length, was the only mechanism affecting the activity of NOB (Malovanyy et al, 2014). In theory this means systems with better nitrite reduction performance can operate at shorter cycle durations. Simulation runs showed that an optimum aeration frequency can be effective in out-selecting NOBs. This is achieved by an aeration phase short enough to limit nitrite conversion to nitrate via NOB, followed by an anoxic phase length which allows for removal of nitrite via Anammox and/or OHO (Al-Omari et al, 2013).

### 2.8.2 DO Concentration

DO (DO) can be easily controlled through manipulation of air supply to the activated sludge process. Its concentration plays a significant role in the activity rates of microorganisms, especially those involved in nitrification kinetics. Oxygen half-saturation ( $K_o$ ) values represent the DO concentration at which the



activity rate of microorganisms is half of their maximum rate. Separate values exist for AOB ( $K_{O,AOB}$ ) and NOB ( $K_{O,NOB}$ ).

Originally these values were taken from literature rather than estimated for the wastewater in question. However the values hold a great deal of importance, especially when modeling BNR systems. Oxygen affinity values are specific to community structure. Therefore the values may vary between WWTPs or the type of wastewater nitrification system (biofilm, granular, or activated sludge). Because of this,  $K_{O,AOB}$  and  $K_{O,NOB}$  values should be determined for optimization of nitrogen removal processes. These values are typically estimated through the use of Monod kinetics and describe microorganism activity as a function of the DO concentration.

Guisasola et al. (2005) developed a rigorous procedure for the calculation of oxygen affinity constants. The procedure is based on monitoring the oxygen uptake in the reactor when external aeration is stopped and biomass is consuming without substrate (ammonium or nitrite) limitations. This methodology considers the oxygen transfer from the atmosphere, the response time of the DO probe, and the inhibition of the nitrification step with sodium azide when estimating  $K_{O,AOB}$  (Guisasola et al, 2005). Oxygen affinity values are then estimated from plots of OUR similar to how Wisemann derived values in Biological Nitrogen Removal from Wastewater (Wiesmann, 1994).

In literature it has been widely accepted that operation at low DO levels leads to nitrite accumulation (Jayamohan et al, 1988; Sin et al, 2008). Blackburne et al. (2008) operated a continuous process containing enriched AOB and NOB cultures at low DO concentrations (0.4 mg/L). The process was operated without sludge retention to elicit the nitrification process. Nitrification was achieved through wash-out of *Nitrobacter* and nitrite accumulation ratio (NAR),  $NO_2^- / (NO_2^- + NO_3^-)$ , was found to be up to 90% (Blackburne et al, 2008).

Accumulation of nitrite at low oxygen concentrations is due to AOB's affinity over NOB for oxygen. This is shown through the plot in Figure 17.

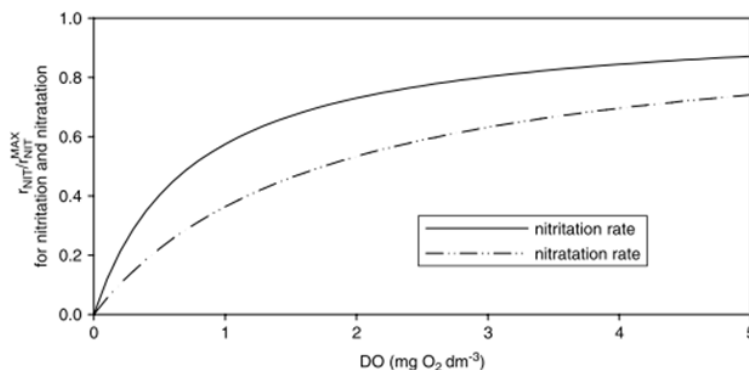


Figure 17 – Simulation of the nitritation and nitrification rates as a function of DO concentration  $K_{O,AOB} = 0.74$  mg O<sub>2</sub>/L and  $K_{O,NOB} = 1.75$  mg O<sub>2</sub>/L. Guisasola, A., I. Jubany, J. A. Baeza, J. Carrera and J. Lafuente (2005). "Respirometric Estimation of the Oxygen Affinity Constants for Biological Ammonium and Nitrite Oxidation." Journal of Chemical Technology & Biotechnology 80(4): 388-396. Used with permission of John Wiley and Sons, 2015.

When DO is the sole limiting substrate, competition between AOB and NOB will occur. This is due to the fact that both organisms use oxygen as an electron acceptor. Figure 17 shows that at lower oxygen concentrations the rate of ammonia oxidation (nitrification rate) is considerably greater than the rate of nitrite oxidation (nitrification rate). This may also be inferred from the  $K_{O,AOB}$  and  $K_{O,NOB}$  values. A smaller value indicates greater affinity for oxygen. Therefore systems which accumulate nitrite at low DO concentrations commonly yield  $K_{O,AOB} < K_{O,NOB}$ . It is important to recognize that continuous operation at DO levels below  $K_{O,AOB}$  may lead to wash-out of AOB and NOB and subsequent failure of process performance.

A negative associated with operation at low DO is that the specific substrate utilization rate is reduced. Therefore, in order for systems to achieve effective treatment high HRTs and SRTs are desired. One report has stated that although activity rates are reduced, the growth yield of ammonia oxidizers increases (Hanaki et al, 1990). Elevated growth yields enable a large presence of AOB biomass in suspended growth reactors which may help compensate for the reduced ammonia oxidation rate per unit of biomass. Decreases in the ammonia oxidation rate may also be compensated with the use of a biofilm reactor. Nitrite accumulation was shown in the operation of a biofilm reactor at low DO concentrations (0.5 mg/L) where NAR in the effluent reached greater than 90% (Dangcong et al, 2001). In addition, constant operation at low DO concentrations may lead to excessive growth of filamentous bacteria (Olsson et al, 2005).

Many of the systems which successfully achieve nitrite accumulation at low DO contain *Nitrobacter* as the dominant NOB genera. It has been seen in several studies that operation at high DO concentrations can also lead to nitrite accumulation (Manser et al, 2005; Lemaire et al, 2008; Ge et al, 2014; Regmi et al, 2014). High DO operation is favored when *Nitrospira* is the dominant NOB species. This difference in DO operation may be explained by the theorem of R-strategists vs. K-strategists. R-strategists have higher specific growth rates and low substrate affinity, whereas K-strategists have lower specific growth rates and higher substrate affinity. Therefore *Nitrobacter*, which functions as an R-strategist, may not have the ability to compete with AOB at low DO concentrations which is why operation at low DO could lead to nitrite accumulation. *Nitrospira*, which functions as a K-strategist may be able to outcompete AOB for oxygen at low DO. Therefore systems which contain *Nitrospira* as the dominant NOB may need to operate at higher DO to provide a competitive advantage for AOB over NOB.

This was observed in a study by Regmi et al. (2014) which showed that operation at high DO (> 1.5 mg/L) in a system enriched with *Nitrospira* could aid in achieving nitrite accumulation. Oxygen affinity values were determined for this system and may be seen in Figure 18. The figure illustrates that low DO gives favor to NOB activity over AOB; therefore high DO operation was chosen (Regmi et al, 2014). Peng et al. (2004) studied nitrite accumulation in a continuous plug-flow step-feed process where *Nitrospira* was the dominant bacteria. They observed no nitrite accumulation under low DO conditions (0.3 – 0.7 mg/L); however stable nitrite accumulation was obtained under much higher DO conditions (1.5 – 2.0 mg/L). Nitrite in the effluent accumulated to over 81.5% (Peng et al, 2004). Similar results were seen at Strass WWTP in that NOB repression could not successfully be achieved as long as low DO-operation (0.5–0.9 mg/L) was applied. Once operation was switched to a higher DO level (1.5 mg/L) for the same process

scheme, NOB-repression took effect (Wett et al, 2013). Although it is unclear as to the dominant species of NOB,  $K_o$  values for combined AOB and NOB were found to be more than double those of NOB.

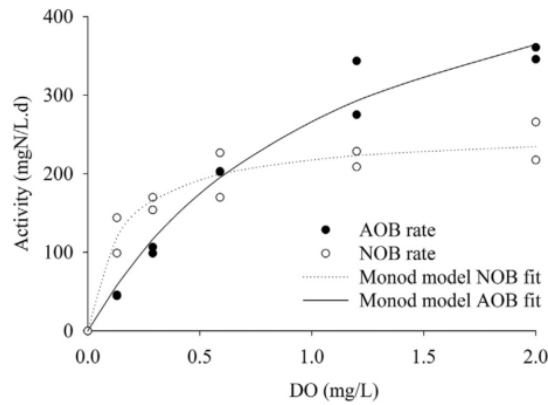


Figure 18 – *In situ* nitrification and nitrification rates as a function of DO concentration  $K_{O, AOB} = 1.16 \text{ mg O}_2/\text{L}$  and  $K_{O, NOB} = 0.16 \text{ mg O}_2/\text{L}$ . Regmi, P., M. W. Miller, B. Holgate, R. Bunce, H. Park, K. Chandran, B. Wett, S. Murthy and C. B. Bott (2014). "Control of Aeration, Aerobic Srt and Cod Input for Mainstream Nitrification/Denitrification." *Water research* 57: 162-171. Used with permission of Elsevier, 2015.

Table 3 lists oxygen affinity constants for AOB and NOB from several studies. The majority of studies illustrate a greater oxygen affinity of AOB at low DO concentrations. This is commonly understood. However studies previously mentioned which indicate the opposite trend are listed at the bottom of the table.

Table 3 – Oxygen Affinity Values for AOB and NOB from Literature

Reference	$K_{O, AOB}$ (mg/L)	$K_{O, NOB}$ (mg/L)	pH	Temperature (°C)
(Blackburne et al, 2008)	$0.033 \pm 0.003$	$0.43 \pm 0.08$	7.6	19-23
(Jayamohan et al, 1988)	.63	1.32	N/A	20
(Hanaki et al, 1990)	0.32	N/A	7.3-7.8	25
(Wiesmann, 1994)	0.3	1.1	8	20
(Guisasola et al, 2005)	$0.74 \pm 0.02$	$1.75 \pm 0.01$	7.5	25
(Henze et al, 2000)	0.4	N/A	N/A	25 and 10
(Laanbroek et al, 1994)	0.22-0.56	0.17-4.33	7.5	25
(Laanbroek et al, 1993)	0.04-0.48	0.7-5.3	7.5	25
(Regmi et al, 2014)	1.16	0.16	N/A	25
(Wett et al, 2013)	0.40	0.06	N/A	15
(Manser et al, 2005)	$0.79 \pm 0.08$	$0.47 \pm 0.04$	7.5	15
(Daebel et al, 2007)	0.65	0.23	7.2	20

### 2.8.3 Effect of Organic Carbon

It has also been shown that organic loading has a large effect on competition for oxygen within activated sludge systems. This is because readily biodegradable organic matter supports the growth of heterotrophic bacteria which compete with nitrifiers for oxygen, nutrients, and space (Sharma et al,

1977). Heterotrophic bacteria typically have a maximum growth rate of five times and yields of two to three times that of nitrifiers (Grady et al, 1980). Nitrifying bacteria also have relatively high half-saturation constants for oxygen compared to heterotrophs ( $K_{O,HET} = 0.1 \text{ mg/L}$ ) (Arp et al, 2011). For these reasons nitrifying bacteria are usually outcompeted by the heterotrophs in the presence of organic carbon which can lead to deterioration or failure of nitrification performance (Okabe et al, 1995; Satoh et al, 2000).

In a study by Hanaki et al. (1990) the combination of low DO with organic loading (addition of glucose) led to competition between AOB and heterotrophic organisms for DO resulting in decreased ammonia oxidation rates and increased effluent ammonia concentrations (Hanaki et al, 1990). Bovendeur et al. (1990) observed a significant decrease in the nitrification rate for decreased levels of DO (DO) and/or increased organic loading rate (Bovendeur et al, 1990). Ohashi et al. (1995) found that the percentage of ammonia-oxidizers and nitrite-oxidizers decreased with an increasing substrate carbon to nitrogen (C/N) ratio, and the heterotrophs became more dominant as the C/N ratio increased (Ohashi et al, 1995). Heterotrophic bacteria also compete with Anammox bacteria for substrate. It has been reported that when COD/N was approximately 10 the Anammox were outcompeted by heterotrophic activity (Ahn et al, 2004). Therefore mainstream deammonification systems must also carefully consider the effect of high COD loading on process performance in order to prevent heterotrophs from outcompeting Anammox. Due to competition by heterotrophic bacteria on both AOB and Anammox it is advantageous to have control over the amount of COD fed to nitrification systems.

#### 2.8.4 Residual Ammonia

A study by Stinson et al. (2013) cited that as ammonia concentrations begin to decrease below 1.5 mg-N/L the specific growth rate of AOB decline at a faster rate than that of NOB for an equivalent substrate concentration. This is shown in Figure 19. Therefore in order to maintain the condition of AOB rates greater than NOB rates it is necessary to maintain an ammonia residual (preferably on the order of 1.5 – 2.0 mg-N/L). Although higher DO concentrations could help compensate for the low AOB growth rate at low substrate concentrations, it would serve to enhance the growth of NOB more which would be counterproductive (Stinson et al, 2013). Since many wastewater treatment plants require removal of ammonia to a lower threshold, a polishing step may be necessary, possibly through the use of Anammox bacteria.

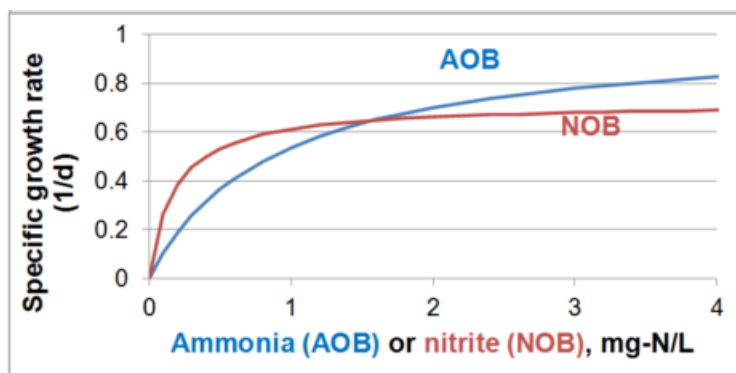


Figure 19 – Specific Growth Rates of AOB and NOB at low concentrations of ammonia and nitrite respectively. Chandran, K. and B. F. Smets (2005). "Optimizing Experimental Design to Estimate Ammonia and Nitrite Oxidation Biokinetic Parameters from Batch Respirograms." *Water research* 39(20): 4969-4978. Used with permission of Elsevier, 2015.

Maintaining an ammonium residual is essential for NOB out-selection (Knowles et al, 1965; Chandran et al, 2000). By providing residual substrate for AOB, it is ensured that ammonia oxidation will always limit the availability of oxygen to NOB. Studies have demonstrated that terminating aeration prior to or immediately after the completion of ammonium oxidation can lead to sustainable partial nitrification to nitrite (Peng et al, 2004; Yang et al, 2007; Lemaire et al, 2008). This process, known as aeration phase length control, uses probes to terminate aeration based on real-time data signaling completion of ammonia oxidation. The idea behind real-time control is that aeration may be supplied long enough for effective ammonia oxidation, but inadequate for nitrite to be further oxidized. In theory this process should lead to the gradual accumulation of nitrite (Yang et al, 2007).

A continuous pre-denitrification plug flow bioreactor was operated using domestic wastewater from a sewer line at the Beijing University of Technology. The wastewater comprised a COD/NH<sub>4</sub><sup>+</sup>-N ratio of 3. Aerobic zones of the reactor were operated at low DO (approximately 0.6 mg/L). Reactor temperature was controlled at 21±1°C. High NARs of 96.5, 94.7, and 97.0% were seen. Residual ammonia was maintained in each of the three stages with effluent concentrations averaging 3.8, 0.8, and 1.3 mg/L respectively. Maintaining ammonium throughout the aerobic zones was found to be beneficial for the establishment of the nitrite pathway. While the exact reason was not confirmed, it is likely that ammonia oxidation limits the availability of O<sub>2</sub> to NOB (Ma et al, 2009).

Yang et al. (2007) operated a pilot-scale SBR with a working volume of 54 m<sup>3</sup> in order to investigate nitrogen removal via nitrite. The SBR was step-fed with municipal wastewater (NH<sub>4</sub><sup>+</sup>-N = 60.05 mg/L) and operated at temperatures ranging from 11.9 - 26.5°C at high DO (≥ 2.5 mg/L). Fixed-time control showed low nitrite accumulation due to excessive aeration. When switched to real-time control, using pH, the SBR displayed consistently excellent nitrite accumulation. Successful nitrogen removal via nitrite was achieved for 180 days with average NAR above 95%. This indicated that real-time control was not only the critical condition for achieving partial nitrification via nitrite but also saved in aeration costs. At the end of each aerobic/anoxic phase, ammonia concentrations remained under 2.5 mg/L. Nitritation was maintained at the coldest operating temperature (11.9°C) even though NOB growth rates are much greater than that of AOB at this temperature (Yang et al, 2007).

Gao et al. (2009) operated a 38 L SBR treating diluted wastewater from a soybean mill ( $\text{NH}_4^+ = 60 \text{ mg-N/L}$ ). It was discovered that by using pH and ORP as real-time control parameters they could avoid or reduce the occurrence of excess aeration in order to prevent the conversion of nitrite to nitrate. In the study over-aeration was observed to convert nitrogen removal via nitrite to that of full nitrification. The results showed that after excess aeration for 13 cycles, a shortcut nitrification with an NAR of 96% converted to full nitrification with an NAR ratio of 29%. In the study stable removal via nitrite was achieved for two months at room temperature ( $25 \pm 0.5^\circ\text{C}$ ), with ORP and pH as real-time control parameters. Process effluent comprises an ammonium concentration of 6.8 mg-N/L while nitrite and nitrate were below detection level. This good stability demonstrated that real-time control could not only avoid the negative impact of excess aeration, but also maintain shortcut nitrification (Gao et al, 2009).

Regmi et al. (2014) operated a pilot-scale CSTR treating domestic wastewater ( $\text{NH}_4^+\text{-N} = 29.7 \text{ mg/L}$ ) at  $25^\circ\text{C}$ . The CSTR had an HRT of 3 hours and was intermittently aerated at high operational DO (1.6 mg/L) in order to achieve equal parts ammonia and  $\text{NO}_x$  in the effluent. After secondary settling, the effluent was fed to an Anammox MBBR for polishing. Cycle time for the CSTR varied between 24-12 minutes while the aerobic fraction was maintained at approximately 50% via control of the wastage rates. The AvN aeration controller allowed maintenance of residual ammonia ( $7.3 \pm 4.4 \text{ mg-N/L}$ ) throughout the study allowing AOB growth rates to remain close to maximum (Regmi et al, 2014). AOB rates were greater than NOB rates throughout the entire study which produced an average effluent NAR of  $36 \pm 27\%$ . It was surmised that the combination of heterotrophic denitrification pressure, high DO, intermittent aeration, and residual ammonia provided unfavorable conditions for NOB, without adversely affecting the AOB population. The ability of the system to be operated at aggressive SRTs then allowed for the out-selection of NOB over AOB.

The Changi Water Reclamation Plant in Singapore claims to be the first full-scale mainstream deammonification facility. Anammox activity was confirmed through the reduction of nitrite coupled with ammonia removal in the anoxic zones. The facility operates a step-feed BNR process with an HRT of 5.8 hours and an SRT of 5 days. DO in the aerated basins is maintained in the range of 1.4-1.8 mg/L. Influent ammonia from the primary clarifier is 30 mg-N/L with an influent COD/ $\text{NH}_4^+\text{-N}$  of 10.2. Final effluent concentrations of ammonia, nitrite, and nitrate are 1.7, 1.1, and 0.8 mg-N/L respectively. Average NAR in the aerobic zones was shown to be 80.1%. Partial nitritation was credited to the short aerobic SRT (2.5 days), high operating temperature ( $28^\circ\text{C}$ – $32^\circ\text{C}$ ), and alternating aerobic/anoxic environment (Cao et al, 2013).

### 2.8.5 Bioaugmentation

The process of bioaugmentation refers to the transfer of microbial communities from one system to another in order to enhance the ability of the seeded population to respond to process fluctuations. With regard to wastewater treatment, bioaugmentation is commonly associated with the transfer of nitrifiers from sidestream treatment processes to mainstream processes for enhancement of

nitrification performance. This tactic is used at WWTPs located in cold climates where wastewater temperatures drop below 15°C. At those temperatures, SRT values on the order of 15 days are typically necessary in order to compensate for the reduced microbial activity. Bioaugmentation, allows for operation at a decreased SRT by supplementing the necessary microorganisms to maintain performance at cold temperatures.

The effect of bioaugmentation is more pronounced if the seeded reactors are operated at higher ammonia loading rates. This is due to a low affinity for ammonia of seeded AOB which are accustomed to elevated concentrations in sidestream processes (Munz et al, 2012). Bioaugmentation is also more successful when the seeded reactor is operated near the minimum required SRT for nitrification. The process helps to overcome reduced growth rates of nitrifiers, preventing wash-out and allowing for seeded populations to provide the additional activity needed to maintain nitrification. Perhaps the largest factor in the success of bioaugmentation is the temperature difference between the seeded (low temperature) and source (high temperature) reactors. When this temperature difference is minimized, nitrifiers are subjected to less thermal shock enhancing the effectiveness of bioaugmentation (Munz et al, 2012).

The ability of microorganisms to respond to fast changes in temperature is a very important consideration for design and implementation of bioaugmentation processes. While direct temperature shock appears to be reversible, the initial reaction of nitrifiers is much more pronounced than after a few days of acclimation (Hwang et al, 2007) due to a lag period caused by the temperature difference (Lee et al, 2011). Average decreases in nitrification rates were shown to be 58%, 71%, and 82% for biomass cooled to 10°C after the biomass had previously been acclimated to 20°C, 25°C, and 30°C respectively (Head et al, 2004).

Two prominent bioaugmentation processes for the enhancement of nitrification are InNitri and BABE. With InNitri (Inexpensive Nitrification), warm dewatering liquid containing a high ammonia load is mixed with a small portion of effluent from the primary clarifier and nitrified in the side-stream nitrification aeration tank. The mixing of PCE with reject water serves to adjust temperature, provide COD, and provide sufficient substrate for AOB. A portion of the resulting biological sludge, which contains a high percentage of nitrifiers, is continuously or periodically discharged into the main aeration tank providing supplemental nitrifiers to the activated sludge process (Kos et al, 2000). BABE (Bio-Augmentation Batch Enhanced) is a process consisting of a nitrification reactor in the RAS line. An SBR is fed with reject water containing high concentrations of nitrogen at elevated temperature and RAS containing nitrifiers at low temperature. The mixing of these two streams lowers the temperature of the BABE reactor to approximately 25°C such that adaptability and survivability of the bioaugmented nitrifying biomass is increased in the mainstream (Salem et al, 2003).

Bioaugmentation may also aid in performing repression of NOB mainstream. Unlike the previously mentioned processes which bioaugment both AOB and NOB to mainstream processes, it is thought that bioaugmentation of sidestream nitrification-denitrification or deammonification processes may help increase populations of AOB and or Anammox to compete with NOB for substrate (oxygen and nitrite

respectively) and space. Continuous seeding of biomass from the sidestream DEMON process coupled with selective sludge wasting via mainstream cyclones led to a visible enrichment of Anammox granules in the aeration tanks at Strass WWTP (Wett et al, 2013). During mainstream deammonification testing at Strass WWTP, higher NOB out-selection was observed during late December 2011 when tourism more than doubled plant flow. During this period, high ammonia loading increased effluent ammonia concentrations to 2.5 mg N/L compared to the normal operational setpoint of 1.5 mg N/L. The observed NOB out-selection was indicated by an NAR greater than 50% even though operation was performed at low temperatures. Simulation results accompanying the study demonstrated that NOB can hardly be repressed at typical maximum NOB growth rates, even at high bioaugmentation rates for AOB and AMX. Therefore, NOB growth-rates must also be reduced by specific process conditions.

### 2.8.6 NO and N<sub>2</sub>O Production

In recent years, interest in wastewater treatment has shifted towards understanding and quantifying the emission of greenhouse gases (GHG) such as carbon dioxide, methane, and nitrous oxide (Kampschreur et al, 2009). The most potent of these is nitrous oxide which is considered to be 300 times more harmful than carbon dioxide as a GHG. Nitrous oxide is produced in the biological treatment of wastewater from the reduction of nitric oxide (Carr et al, 1990), a compound which should also be considered for its ability to readily form nitrogen dioxide (NO<sub>2</sub>) in the atmosphere which increases formation of smog. In order to assess sustainability and efficiency of nitrogen removal processes, wastewater treatment plants have begun to consider the release of gaseous products not only for determining their environmental impact but also for assessment of overall system performance.

The majority of nitric and nitrous oxide production at WWTPs occurs in the activated sludge process, emitted during aeration due to gas stripping. Both compounds can be produced by AOB and heterotrophic organisms though it remains unclear as to whether nitrifying or denitrifying microorganisms are the main source of production. AOB produce nitric and nitrous oxide by two different pathways (Figure 20), hydroxylamine oxidation or nitrifier denitrification. Hydroxylamine oxidation takes place under aerobic conditions. It involves the conversion of hydroxylamine (NH<sub>2</sub>OH) to NO by hydroxylamine oxidoreductase (HAO) and the subsequent reduction to N<sub>2</sub>O through nitric oxide reductase (NOR) (Arp et al, 2011).

Under anoxic conditions, NO and N<sub>2</sub>O production by AOB stems from a process known as nitrifier denitrification. This process involves the sequential reduction of nitrite to NO and N<sub>2</sub>O via the nitrite reductase (NirK) and nitric oxide reductase (NorB) enzymes respectively (Chandran et al, 2011). Nitrifier denitrification does not require an organic carbon source to serve as the electron donor.



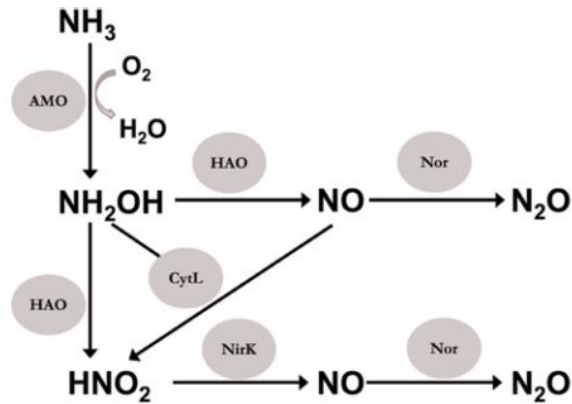


Figure 20 – Pathway of NO and N<sub>2</sub>O production in AOB. Chandran, K., L. Y. Stein, M. G. Klotz and M. C. M. van Loosdrecht (2011). "Nitrous Oxide Production by Lithotrophic Ammonia-Oxidizing Bacteria and Implications for Engineered Nitrogen-Removal Systems." *Biochemical Society transactions* 39(6): 1832-1837. Used with permission of the Biochemical Society, 2015.

Heterotrophic denitrification, which requires an organ carbon source, can also result in the production of nitric and nitrous oxide through the typical pathway. However, unlike AOB, heterotrophs have the ability to further reduce N<sub>2</sub>O to N<sub>2</sub>. Concentrations of NO and N<sub>2</sub>O has been noted to increase in systems operating at low DO concentrations, high nitrite concentrations, high ammonia loading, or low influent COD/N ratios (Kampschreur et al, 2009).

Nitrifier denitrification occurs under conditions of low DO but also under aerobic conditions during ammonia oxidation (Goreau et al, 1980; Lipschultz et al, 1981). Coupled with the contribution from increased heterotrophic denitrification, operation at low DO can result in higher emissions. At concentrations between 0.1 and 2 mg/L O<sub>2</sub>, production of N<sub>2</sub>O from nitrifier denitrification was shown to dominate that of heterotrophic denitrification. The percentage of heterotrophic denitrification was also shown to decrease from 42% to 17% when the oxygen concentration increased from 0.1 to 2mg/L (Tallec et al, 2006). Therefore operation at higher DO concentrations can minimize the production of NO/N<sub>2</sub>O in the aerobic zone of an activated sludge process. Goreau et al. (1980) studied how oxygen concentration impacted N<sub>2</sub>O production. It was found that at oxygen concentrations below 1 mg/L N<sub>2</sub>O production can correspond to 10% of the nitrogen load to a WWTP (Goreau et al, 1980).

It has been found that insufficient carbon may lead to incomplete heterotrophic denitrification and consequently, the production of gaseous intermediates (NO/N<sub>2</sub>O). Limited availability of biodegradable organic carbon is known to increase N<sub>2</sub>O emission during denitrification (Schulthess et al, 1996; Chung et al, 2000). Hanaki et al. (1992) investigated the impact of various COD/N ratios (1.5, 2.5, 3.5 and 4.5) and observed that up to 10% of the nitrogen load was emitted as N<sub>2</sub>O at the lowest COD/N ratio studied (Hanaki et al, 1992). It should also be noted that COD/N ratios higher than 10 could lead to enrichment of aerobically denitrifying microorganisms, with possibly an associated increase of N<sub>2</sub>O emission (Van Niel et al, 1993).

Increased nitrous oxide production by AOB may occur with higher specific ammonium oxidation rates, which occurs with increasing ammonia loading and DO concentration (Yu et al, 2010). The emissions were clearly linked to the ammonium oxidation. The N<sub>2</sub>O emissions increased with anoxic time and decreased when the ammonium oxidation rate was decreased. The NO emissions also increased with ammonium oxidation.

Under steady operating conditions, the nitrous oxide reduction rate is almost four times faster than the nitrate and nitrite reduction rates and thus little if any nitrous oxide would be present (Wicht, 1996). However, transient conditions can cause nitric and nitrous oxide to accumulate because the induction of nitrous oxide reductase is slower than that for the upstream reductase enzymes in addition to an over-expression of the nitrite reductase gene (Holtan-Hartwig et al, 2000; Yu et al, 2010). This has also been suggested by Wett et al. (2013) who stated that intermittent aeration may repress NOB growth by interrupting metabolic conversions which may then lead to the formation of inhibitory intermediate products such as nitric oxide (Wett et al, 2013).

Nitrite accumulation often results in increased nitrous oxide (N<sub>2</sub>O) and nitric oxide (NO) emissions (Star et al, 2009; Chandran et al, 2011; De Clippeleir et al, 2012). The similarity in conditions allowing for an AOB/NOB activity differential and NO/N<sub>2</sub>O emissions are remarkable (De Clippeleir et al, 2013) and raised the question if the emissions are a mere result of the nitrite accumulation after establishment of NOB out-selection or if the emissions can play a role in the NOB out-selection itself. Nitric oxide has been found quite toxic to most bacteria including NOB (Mancinelli et al, 1983). However, because NO is an intermediate product for AOB metabolism, high concentrations of the gas do not detrimentally impact AOB activity (Kartal et al, 2010). Therefore, in conditions of elevated NO concentrations, AOB could have a competitive advantage over NOB.

It is known that nitric oxide can suppress nitrite-dependent oxygen consumption rates in *Nitrobacter winogradskyi* (Starkenburger et al, 2008). The addition of 2  $\mu$ M NO, severely inhibited nitrite-dependent oxygen uptake. After the addition of 3.5  $\mu$ M NO to cells respiring NO<sub>2</sub><sup>-</sup>, uptake was inhibited for over 3 min. After NO was completely consumed, oxygen uptake was immediately restored close to initial rates highlighting that inhibition is reversible. The same is true for long-term exposure. Even after contact with NO at 125 mM for 90 min, *N. winogradskyi* remained viable and nitrite could be oxidized after removal of NO. The halt of nitrite-dependent oxygen uptake may be the result of nitric oxide's ability to bind to cytochrome oxidase (Carr et al, 1990).

Courtens et al. (2015) studied the direct effect of NO on the NOB activity in different types of nitrifying sludge with different *Nitrobacter/Nitrospira* ratios (Courtens et al, 2015). Nitrifying communities dominated by *Nitrospira*, having a high affinity for nitrite and lower maximum specific growth rate (K-strategist) were strongly inhibited by NO. Even at very low NO concentrations in the liquid phase (2  $\mu$ g-N/L), significant effects on the NOB activity in the nitrifying sludge were obtained. This indicates that the AOB/NOB activity differential needed in the novel mainstream nitrification technologies can potentially be enhanced by a certain level of *in situ* NO production. Further research is needed to elucidate the

mechanism of NO inhibition and the minimum level of NO needed in the system (within flocs/biofilms/granules) to enhance NOB out-selection.

Experiments in serum bottles showed that the production of nitric oxide can also cause severe inhibition of the denitrification pathway (Schulthess et al, 1995). In this study denitrification with nitrate as the first electron acceptor produced insignificant amounts of NO and N<sub>2</sub>O. However, pulse feeding nitrite to organisms already saturated with nitrate and acetate was shown to cause accumulation of NO and N<sub>2</sub>O. Heterotrophic sensitivity to nitrite is relatively large. Artificial nitrite pulses of 10 mg/L led to a four-to-eightfold increase in N<sub>2</sub>O emission during nitrification, depending on the oxygen concentration (Tallec et al, 2008). Response of denitrifying sludge to a nitrite pulse is accumulation of NO/N<sub>2</sub>O due to inhibition of the NO reductase enzyme. Following accumulation of NO, inhibition of the nitrite and nitrous oxide reductase enzymes will occur.

Experiments with pure cultures and with purified enzymes confirm this (Dhesi et al, 1984; Frunzke et al, 1986) and explain why buildup of NO can also lead to accumulation of N<sub>2</sub>O. Nitric oxide's high affinity to metal ions located in the active site of enzymes may be the cause of its inhibitory nature. The inhibitory effects of NO on denitrification may be reduced by gas stripping (Schulthess et al, 1995). Although the *in situ* production of NO may lead to nitrogen removal via nitrite, the tendency of WWTPs to decrease their energy consumption by decreasing aeration could be adverse towards the greenhouse effect (Kampschreur et al, 2009).

## 2.9 Aeration Control

Without the consideration of influent pumping, blowers operated to provide aeration are the single largest user of energy at treatment plants, motivating appropriate aeration control (Åmand et al, 2013). Aeration energy is commonly responsible for around half of the total plant power usage (WEF 2009) but numbers up to 75% have been reported (Rosso et al, 2008; Courtney, 2011). Control of aeration systems becomes even more important as modern treatment plants face more stringent discharge limits and push further towards more efficient operation. Because of the energy intensiveness of blower operation, the stoichiometric oxygen demand is an important parameter in the cost evaluation of operating a conventional nitrification process. The oxygen demand also provides a baseline for comparing alternative ammonia oxidation processes (Tchobanoglous et al, 2003).

### 2.9.1 Automated Control

Previously, analogue controllers were used to control wastewater unit processes. The industry was dominated by manual control of plant processes through physical changes made by operators. Today, operators still play a large role in overall performance of the plant, but their roles are moving more towards that of maintenance as WWTPs are becoming increasingly automated with the development of new technology. Digital Programmable Logic Controllers (PLC), as well as advanced computerized systems such as Supervisory Control and Data Acquisition (SCADA) and Distributed Control Systems

(DCS), in large part, have replaced analogue controllers and are revolutionizing the ease, efficiency, and complexity of wastewater treatment.

A PLC is a computer which controls and co-ordinates all functions of an outstation including acquisition of measurement data, smoothing, filtering, checks for status, function, and limits, temporary data storage, calculation of control action, and receive and report data to and from the central station. In the control rooms of WWTPs, supervisory control and data acquisition systems manage all incoming and outgoing data. Alarms are generated here, and operators monitor and control the processes through the change of setpoints (Schütze et al, 2004).

PLCs work to provide control as desired by the user. There are several methods of control including feed-back, feed-forward, and feed-back/feed-forward. Feed-back loop control commands are actuated depending on the measured deviation of the controlled process from a user-defined setpoint. Unless there is a deviation, a feed-back controller is not activated. A feed-forward controller anticipates the immediate future values of these deviations using a model of the process. Then it activates controls ahead of time to avoid the deviations. A feed-back/feed-forward controller is a combination of these two types.

How a controller responds to process fluctuations is dictated by the response of individual PID (proportional–integral–derivative) control loops working inside a PLC. PID control is used as a method to vary the response of an actuator as a function of the difference between a measured variable and a user-established setpoint. The controller can either be used with all its parts or with only the P, PI or PD terms. The proportional part reacts to the present control errors, the integral part sums up previous control errors, and the derivative part predicts future control errors by using the derivative of the control error (Åström et al, 1995). PI (proportional–integral) control or variations thereof were the most common strategies in full-scale at the turn of the last century. PID control is joined under the name “rule-based” control where *if-then* statements are used to determine a desired response based on feed-forward or feed-back signals mentioned above. The PID values must be calibrated unless the controller is equipped with an auto-tuning facility. If the controller does not have auto-tuning capabilities, manual tuning must be performed. For simple control where one PID loop controls a reaction this is not overly difficult. However, for process control with nested PID loop structures, tuning may become overwhelming, necessitating the need for an auto-tuner which, if not included with the controller, can be an expensive investment for WWTPs.

### 2.9.2 Nutrient Sensors

In the words of Ingildsen, “A major change in paradigm is taking place in the operation of wastewater treatment plants as automatic process control is becoming increasingly feasible.” His research concluded that *in situ* nutrient measurements, in combination with simple control strategies, can significantly improve full-scale plant performance (Ingildsen, 2002). Several different types of sensors have been employed for wastewater treatment applications. Fast advancement of technology within the industry has led to more accurate nutrient detection ability within activated sludge systems. Within

these BNR processes, commonly recorded concentrations include oxygen, ammonia, nitrate, nitrite, phosphate, and suspended solids. The detection of these parameters has allowed for the development of more stringent process control strategies which are able to perform more efficient nutrient removal with reduced aeration and external carbon requirements.

The DO concentration is a key component to the operation of nutrient removal processes for its ability to instigate activity of microorganisms. DO concentrations may be measured in two main ways: 1) electrochemical sensors (galvanic or polarographic) or 2) optical sensors with luminescent or fluorescent techniques.

Galvanic and polarographic cells were previously the dominating technology for measuring DO in wastewater treatment facilities. These sensors operate through the use of an anode and a cathode contained in an electrolyte and isolated from the process medium by an oxygen-permeable membrane. Due to their delicate membrane and contamination of the electrolyte, these sensors require regular maintenance. The process of frequent cleaning can lead to frustration among operators and, if not done with care, can cause inaccuracies in the proceeding measurements. Recently, optical probes for the measurement of DO have developed a rapid increase in popularity due to their ease of use, low maintenance requirement, and lower drift in measurement accuracy over time. Optical probes may use either luminescent (LDO) or fluorescent (FDO) techniques to determine oxygen concentrations.

With luminescent technology DO diffuses through a paint layer on the sensor cap, quenches both the lifetime and intensity of the luminescence associated with certain chemical dyes. Measurement of the DO is performed by emitting a blue light of proper wavelength causing a dye in the sensing element to luminesce. Meanwhile, the sensor also emits a red light that is reflected by the dye layer back to a photodiode in the sensor. The sensor measures the reflected light and uses that reading as the reference value. The lifetime of the luminescence from excitation by the blue light is compared to that of the reference value (red light) and a stable DO concentration is calculated. When there is no oxygen present, the lifetime and intensity of the signal are at their maximum. As oxygen is introduced to the sensing element, both the lifetime and intensity of the luminescence decrease (YSI, 2010).

With fluorescent technology the system takes measurements by producing a specific energy wavelength (475 nm) within the sensor. This wavelength is then transmitted to a ruthenium (a metal in the platinum group) compound that is immobilized in a sol-gel matrix. It absorbs the energy produced, exciting electrons in the ruthenium complex. In a process of fluorescence, the electron then collapses back into its original energy state, emitting energy at a wavelength of approximately 609nm. When oxygen molecules are present, the amount of fluoresce is reduced. This is called “fluorescence quenching”. By measuring the amount of quenching, it is possible to determine the oxygen concentration in contact with the sensing element (Davis, 2009).

In the nutrient removal process, there is an option to measure specific ions with automated wet chemistry techniques through the use of *in situ* ion-selective electrodes (ISE) (Vanrolleghem et al, 2003). These probes are known to have a short response time, as well as high accuracy, less maintenance and

high tolerance to harsh conditions. Ion selective electrodes work by converting the activity of a specific ion dissolved in solution into an electrical potential, which can then be measured by a voltmeter. Some of the ions which can be measured using ISE probes include  $\text{PO}_4^{3-}$ ,  $\text{NH}_4^+$ ,  $\text{NO}_3^-$ ,  $\text{NO}_2^-$ ,  $\text{Cl}^-$ ,  $\text{Ca}^{2+}$ ,  $\text{Na}^+$ ,  $\text{H}^+$ , and  $\text{K}^+$ . Ion selective electrodes have one of three membrane types: solid, liquid, or composite.

The targeted ions in question pass through the membrane generating an electromotive force between an ion selective electrode and a reference electrode, placed in the sample solution. In a perfect world only the targeted ions would penetrate the membrane; however in many cases multiple ions are able to penetrate the membrane. For this reason the potential is governed mainly by the activity of the target ion and also by the activity of interfering ions. The influence of interfering species in a sample solution is taken into consideration within the probe measurements. Important considerations to be aware of when selecting an ion selective electrode include the sensor's selectivity, range of linear response, detection limit, and response time. ISE sensors are known to have faster response times since no sample pretreatment such as filtering is required. They have also recently experienced a renaissance in nitrate measurement based on the lower purchase prices.

In order to make accurate measurements of nitrate and or nitrite many are turning to the use of spectral sensors. These sensors operate off the principal that the absorbance of different compounds changes according to the wavelength of light emitted. This property is illustrated in Figure 21.

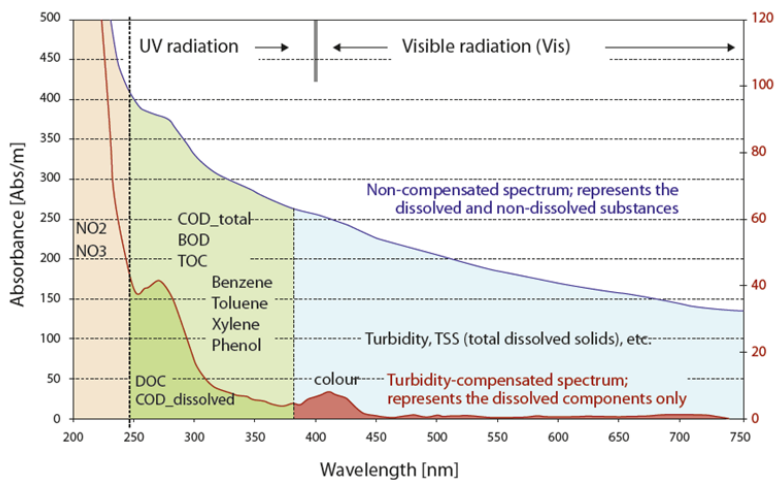


Figure 21 – Absorbance of compounds within a spectrum range of 200 to 750 nm. van den Broeke, J., G. Langergraber and A. Weingartner (2006). "On-Line and in-Situ Uv/Vis Spectroscopy for Multi-Parameter Measurements: A Brief Review." *Spectroscopy Europe* 18(4): 15-18. Used under fair use, 2015.

The sensors record the complete absorbance spectrum, encompassing both UV and Visible radiation. Operation is performed by directing a beam of light, produced from a xenon lamp, across a comparison pathway known as the pathlength. This is the area where the sensor is exposed to the process liquid. For wastewater applications appropriate pathlengths are in the range of 0.5-1.0 mm (S::CAN). Sensors placed in process effluent can have larger pathlengths due to low suspended solids concentrations. Substances present in the medium located in between the measuring windows adsorb visible and UV light. Internally a second light beam is guided across a comparison pathway. This two beam setup allows

for compensation with every measurement therefore reducing instrumental effects that could influence the quality of the measurement (e.g. ageing of the light source). The sensor outputs the absorbance spectrum for the process liquid which is used to monitor multiple parameters simultaneously while also compensating for possible cross-sensitivities. Turbidity, due to suspended substances, causes light scattering and shading, thus influencing the absorption over the entire spectra (van den Broeke et al, 2006). Internal algorithms compensate for these influences in order to obtain reliable and reproducible output readings.

Several varieties of sensors are available for wastewater application; however, when using a sensor for operation of process control, it is important to keep in mind that a sensor with a faulty signal can seriously hamper overall system performance. Measurements are often prone to be noisy, therefore signals should be filtered. Fast sampling may allow for averaging or more sophisticated filtering such as exponential filters. Many sensors have implemented an internal filter to combat these issues. In addition, sensor maintenance is a crucial factor to achieve good performance. This is especially true when sensors are placed in influent waste streams which constitute a more hostile environment for *in situ* measurements than secondary settler effluents.

The sensor location will impact the need for maintenance and the degree of system performance especially in systems which may not have adequate mixing throughout. The cost for maintenance work should be included in any cost-benefit analysis when a new control strategy is considered. For mainstream processes, *in situ* ISE sensors have been reported to require around 2 hours of maintenance per week and sensor to remove dirt around the electrode and biofilm formation on the membrane (Kaelin et al, 2008). As mixed liquor concentrations increase, the frequency and duration of cleaning may also increase.

### 2.9.3 Control Strategies

Aeration is provided to stimulate biological removal of several constituents including COD, nitrogen, and phosphorus. Aeration also aids in the ability to achieve good solid/liquid separation in clarification processes to achieve an effluent low in suspended solids. With regards to the nitrogen removal pathways, the type of nitrogen removal can be controlled through how aeration is supplied (Ge et al, 2014). Aeration control strategies may vary between WWTPs based on the cost of implementation and effluent requirements. However, in control it has been said that one should always keep the strategy as simple as possible.

Aeration in activated sludge basins is provided by the operation of diffusers, of which there are several types. Diffusers may be categorized as porous or fine porous diffusers, non-porous equipment, or other devices, including jet aerators (Tchobanoglous et al, 2003). Another way to categorize diffusers is by the bubble size they produce: coarse bubbles and fine bubbles. Of which, coarse bubble aeration has proven to yield a lower oxygen transfer efficiency (OTE) than fine bubble aeration (Groves et al, 1992). Oxygen transfer efficiency decreases at increasing air flow rates, therefore unnecessary high air flow rates and oxygen concentrations should be avoided (Olsson et al, 2005)

The earliest form of aeration control involved setting a constant airflow rate. However, this airflow setting made no adjustment in response to influent variables and therefore resulted in unnecessarily high airflow rates and oxygen concentrations. This operational scheme led to over-aeration thus severely limiting a WWTP's operational efficiency. In this scenario high oxygen demand at the head of the basin, formed from increased organic and ammonia loading, would necessitate higher airflow rates than that at the end of the tank. For this reason tapered aeration was and still is used in many plant designs. In tapered aeration the arrangement of diffusers is such that more are placed at the head of the basin while fewer are placed at the tail end to match the oxygen demand along the length of the basin. Tapered aeration decreases the diffuser density along the tank, but does not satisfactorily compensate for load variations. A design which lends more flexibility in operation is to divide the aeration basin into zones and control the airflow rate to the individual zones. This allows compensation for spatial and temporal load variations and has paved the way for the design and control of more modern aeration strategies.

### *DO Setpoint Control*

By the early 1970s the use of on-line DO sensors was well established in many WWTPs, making DO setpoint control possible. Today, most wastewater treatment plants have means to control the DO setpoint, by on/off, PI or cascaded PI controllers. In this control scheme aeration is provided to meet a setpoint concentration. A controller compares the DO setpoint to that of an online DO sensor reading. Based on the difference between the two values the controller adjusts the airflow rate by opening or closing valves attached to lines of compressed air. For plants operating DO setpoint control increased DO concentrations can lead to reduced process efficiency. In addition, DO concentrations greater than 2.0 mg/L are reported to have very little effect on nitrifier growth rates (Stenstrom et al, 1980). Plants aiming to achieve complete ammonia removal should carefully choose their DO setpoint as to avoid over aeration. Compared to manual control of airflow rates DO setpoint control provides greater energy efficiency because it allows for automated control of the DO concentration preventing unnecessary aeration. For WWTPs where any type of DO control is implemented, blowers should be supplied with variable frequency drives (VFD) to allow turndown of the aeration capacity (Åmand et al, 2013).

### *ABAC*

Keeping the DO levels constant as the ammonium concentration approaches zero could cause unnecessary aeration. This can be alleviated with use of ABAC. ABAC (ABAC) is applied at WWTPs to either reduce aeration costs, reduce peaks in the effluent ammonia concentration, or both. There are two types of ABAC structures: feed-back and feed-forward. In ammonium feed-back control a controller compares a user-defined effluent ammonium concentration to the measured value taken from a sensor in the process liquid. The degree of difference in these values initiates a response from the controller to increase or decrease the DO concentration in order to maintain the desired effluent ammonia. Feed-back control is based on the measured output of the process and therefore a possible criticism is that an error must exist before a control action can be taken (Rieger et al, 2014).



More attention is being paid to feed-forward based control for its ability to anticipate the impact of sudden load changes. A feed-forward controller measures a process disturbance, such as the influent ammonia load, and uses a model to predict the behavior of the controlled system. The objective is still to maintain effluent ammonia at a setpoint concentration; however, the controlled variable is not directly measured. The intent of the feed-forward controller is to use a time advantage to react more quickly to an influent disturbance by raising the bioreactor DO concentration. In doing so the controller provides buffering capacity to handle high load conditions which may otherwise exceed the capacity of the plant, resulting in violation of effluent ammonia discharge limits. Success of a feed-forward controller is therefore measured in terms of its ability to accommodate disturbances and reduce impacts on effluent quality. When compared to feed-back control, feed-forward control concepts generally need more sensors, are more complex, need increased maintenance/controller tuning, and place an additional burden on operators. For these reasons feed-back control structures are preferable in most situations (Åmand et al, 2013; Rieger et al, 2014).

Under operation of ABAC, oxidation of ammonia is constrained by maintaining approximately 1-2 mg-N/L ammonia in the effluent. Because of this, plant performance has been known to stabilize. In nitrifying plants, there is often a sudden drop in the oxygen demand at the point in the bioreactor where ammonia removal by nitrification is complete. Aerating beyond this point may lead to over-aeration of the downstream sections, even if diffuser tapering partly accounts for the oxygen demand profile. When using ammonia control, nitrification is never completely achieved, and therefore, this problem is avoided. However, over-aeration during daily peaks in ammonia loading is a potential issue. For this reason, ammonia controllers typically should be used in conjunction with DO limits. This prevents the controller from increasing or decreasing the DO passed a concentration which will provide benefit to the system. The ammonia controller will again resume control authority when the peak load has passed. Instead of increasing the DO concentration to a maximum value, some systems have the ability to switch aeration on or off in a swing zone during periods of high loading. This approach will have an immediate impact on nitrification performance by increasing the aerobic fraction. However, this could have a negative impact on denitrification performance.

There are several additional benefits to ABAC operation. Although ABAC reduces aeration, the process does not negatively impact removal of BOD or COD as the requirements will be satisfied if ammonia is reduced to low concentrations. The ability of ABAC to operate at lower DO concentrations allows for increased denitrification via SND therefore reducing the need for external carbon and alkalinity addition. The process of providing residual ammonia throughout the system maintains high AOB activity rates which have been shown to significantly decline at concentrations lower than 2 mg  $\text{NH}_4^+$ -N/L. ABAC's ability to limit aeration may also improve biological phosphorus removal performance. Because ABAC is not a constant low DO process there is little evidence from ABAC studies to suggest that sludge bulking and foaming are significant issues (Rieger et al, 2014).

Ingildsen (2002) compared four different aeration controllers at the Källby wastewater treatment plant. The four strategies were as follows: 1) a feed-forward controller based on an ammonium sensor located in the head end of the aerobic zone, 2) a slow floating feed-back controller from an ammonium analyzer located in the effluent from the secondary settler, 3) a combination of strategies 1 and 2, and 4) a PI

feed-back controller based on an *in situ* ammonium sensor located in the outlet from the last zone. The *in situ* controller (strategy 4) demonstrated the best performance of the four proposed controllers in terms of adjusting the DO setpoints to obtain a certain effluent ammonium setpoint. The experiment during the first period (ammonium setpoint of 1.5 mg/L  $\text{NH}_4^+\text{-N}$ ) demonstrated that, by removing the periods when the effluent ammonium concentration from the last aerobic zone is close to zero, the energy consumption can be significantly reduced (compared to a constant DO profile). It might also be possible to achieve a slight improvement by adding a derivative term to the *in situ* controller (Ingildsen, 2002).

Three aeration controllers were tested at a pilot plant located in the Dom-zale-Kamnik WWTP by Vrecko et al. (2006). In the pilot plant MBBR technology was tested with the intention of upgrading the full-scale plant for nitrification and denitrification. The three controllers tested were an oxygen cascade PI controller, an ammonia cascade PI controller, and an ammonia feed-forward cascade PI controller. During operation of the ABAC strategies the ammonia setpoint was selected as 1 mg/L. Experiments showed that with the ammonia cascade PI controller, sufficient removal of ammonia was obtained and airflow consumption was reduced by 23% compared to the oxygen cascade PI controller. The ammonia feed-forward cascade PI controller resulted in significant reduction of effluent ammonia peaks and required up to 45% less airflow per kilogram of ammonia removed than was needed with the oxygen cascade PI controller (Vrecko et al, 2006).

Rieger et al. (2012) conducted a simulation for HRSD's 30 MGD Nansemond WWTP in order to evaluate the savings potentials for different aeration control strategies. The evaluation compared the baseline strategy of DO setpoint control to two different feed-back ABAC strategies as well as one feed-forward ABAC strategy. Performance of each of the four aeration strategies was evaluated at temperatures of 12, 20, and 30°C by simulating plant operation when subject to typical influent flow and load variations over one week. Strategy 1 included DO control to fixed setpoints in three aeration zones. Strategy 2 was a feed-back ABAC strategy where the DO was varied, based on PID control, between min and max constraints to meet the effluent ammonia setpoint. Strategy 3 was also a feed-back ABAC strategy where aeration was switched on or off at established DO values in order to meet the setpoint ammonia concentration. Strategy 4 consisted of feed-forward/feed-back ammonium aeration intensity control changing the DO setpoints.

Strategy 1 (DO control) resulted in improved DO levels; however, at higher temperatures the scenario showed over-aeration in the rear reactors due to rapid removal of ammonia upstream. Compared to DO control, ABAC (control strategies 2-4) resulted in significant savings in aeration and methanol dosage requirements. The best scenarios showed a reduction in methanol use of over 50% due to ABAC's ability to provide larger anoxic zones enhancing denitrification using influent COD. Simulation results showed a reduction in aeration energy of approximately 5% at 12°C, 20% at 20°C, and over 30% at 30°C. Out of the ABAC strategies, Strategy 4 failed to significantly reduce peak loading more than the others. It was also marked by high investment and O&M costs, and therefore was not selected for full-scale implementation. Control strategy 3b (ammonia on-off control at DO setpoints of 0/2 mg/L) was deemed optimal. Because of hardship operation of the strategy may cause on the equipment (e.g. start-stop of blowers, valve positioning), control strategy 2b (ammonia PID control at DO setpoints of 0-2 mg/L) may

be the preferred option with only slightly reduced performance (Rieger et al, 2012). Since switching from DO Control to ABAC, Nansemond WWTP has produced equivalent nitrogen and phosphorus removal at significantly reduced aeration and carbon demand (Uprety, 2015).

### *Intermittent Aeration Control*

The overwhelming majority of aeration control at WWTPs is performed via continuous aeration where air is constantly supplied to basins aiming to achieve removal of ammonia. To the contrary intermittent aeration may also be used to achieve not only nitrification, but also denitrification in systems receiving a constant inflow. Batchelor was one of the first to investigate this process (Batchelor, 1983). The study simulated operation of a CSTR with an HRT of 4.3 hours, SRT of 10 days, and an influent feed containing 200 mg/L BOD and 30 mg/L ammonia-N. The bioreactor was operated with a cycle time of 30 minutes while the aerobic fraction was varied. After stable operation was achieved, average concentrations of ammonia-N, nitrate-N, and total nitrogen were calculated. Aerobic fractions too low produced an effluent high in ammonia due to insufficient growth of nitrifying bacteria. Aerobic fractions too high produce greater nitrate concentrations due to insufficient anoxic time for the reduction of nitrate. However there exists an optimum where effluent total nitrogen is minimized shown by the intersection in Figure 22. In the case of Batchelor's experiments, an aerobic fraction (Af) of 0.47 was deemed optimal.

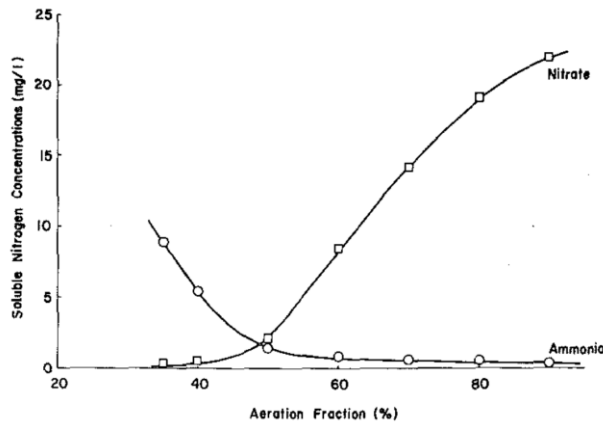


Figure 22 – Effect of the aerobic fraction on effluent nitrate and ammonia concentrations. Batchelor, B. (1983). "Simulation of Single-Sludge Nitrogen Removal." *Journal of Environmental Engineering* 109(1): 1-16. Used with permission of ASCE, 2015.

The optimal aerobic fraction was determined to vary according to system SRT. As SRT is increased the optimal aerobic fraction decreases. However, the range of optimal aerobic fraction also broadens as SRT increases. This suggests that longer SRTs provide more latitude in operation of the bioreactor to achieve optimum nitrogen removal. Intermittent aeration also offers an approach to control the aerobic SRT, a value which is highly important to the design and operation of intermittently aerated systems due to its significance to nitrifier growth. Although a 30 minute cycle time was used in Batchelor's experiment, the cycle time also has a large impact on the degree of nitrogen removal in intermittent systems. Longer cycle times increase the amplitude of the cycle because there will be longer durations for both reactions. Since effluent concentration is characterized by the daily average concentration, longer cycle

times result in higher average nitrogen concentrations. If too short a cycle time is chosen a point will be reached where it is difficult for biomass to switch rapidly enough from anoxic to aerobic metabolism and vice versa. Consequently, there is an optimum cycle time associated with each SRT and aerobic fraction. The cycle time may be significantly influenced by the nature of the wastewater (Grady, 2011).

It has been said that long cycle durations should be chosen for the removal of COD and nitrogen (Habermeier et al, 2005). However studies have proven that short cycle durations on the order of 12-24 minutes can achieve sufficient removal of both constituents (Pollice et al, 2002; Regmi et al, 2014). Inomae et al. (1987) studied performance of an oxidation ditch at a Japanese WWTP. Cycle times of 20 and 45 minutes proved to provide better nitrogen removal performance than the 60 minute cycle time. The cycle time of 45 minutes operated with an aerobic fraction of 0.42 produced the best nitrogen removal (81%) without the need for alkalinity or external carbon addition (Inomae et al, 1987).

In intermittently aerated systems removal efficiency depends on the available COD during the anoxic phase. Insufficiencies in carbon will hinder denitrification performance restricting the nitrogen removal rate. Carbon must be supplied at the appropriate concentration to intermittently aerated systems. Since aerated phases consume COD through heterotrophic activity, too long of aerated periods can result in COD limitation. Therefore higher influent COD concentrations ( $COD/NH_4^+-N > 10$ ) are necessary to achieve sufficient nitrogen removal. Optimum performance is achieved when the nitrification rate is equal to the denitrification rate. Therefore values of the aerobic fraction should be based off of both rates of activity (Inomae et al, 1987). In a study by Lim et al. (2007) the specific nitrification rate was found to be approximately equal to that of the specific denitrification rate when operating at an aerobic fraction of 0.42 (Lim et al, 2007).

Recent development of a new intermittent aeration strategy termed AvN has led to feasible mainstream deammonification in a two-stage system. The AvN strategy operates to control the aerobic fraction based on a ratio of the effluent ammonia concentration to a sum of nitrite and nitrate concentrations, each measured in real time. Typically, the aerobic fraction is controlled to maintain the  $NH_4^+-N:NOx-N$  ratio near 1. This provides optimum aerated and unaerated volume for nitrification and denitrification, optimum alkalinity for AOB growth, and residual ammonium to support higher AOB growth rates. The effluent ratio also provides substrate for nutrient polishing with Anammox bacteria (Regmi et al, 2014).

Nested PID loops allow for additional control. The aerobic fraction is maintained at a desired setpoint, usually around 0.50, through the use of PID-controlled wasting rates. If the current aerobic fraction is greater than the setpoint, wasting is decreased to increase SRT. The opposite condition holds true if the current aerobic fraction is less than the user-defined setpoint. An additional PID loop acts to control the total cycle time (sum of aerated and non-aerated periods). The loop is active during periods of low effluent ammonia. As the effluent ammonia approaches a user-defined value the PID loop acts to reduce the total cycle time. The cycle time is then increased as the effluent ammonia increases.

The AvN controller can be operated in both plug-flow and continuously stirred reactors. In a study by Regmi et al. (2014) the AvN process was fed effluent from a high rate A-Stage process. The study

examined the ability of AvN to be used as a shortcut nitrogen removal strategy through the achievement of NOB out-selection. By employing a combination of intermittent aeration, high DO (>1.5 mg/L), residual effluent  $\text{NH}_4^+$  (>2 mg-N/L), and aggressive SRT (< 5 days at 23-25°C) and HRT (< 4hr), NOB out-selection was achieved in a continuous-flow activated sludge process. The AOB activity was greater than NOB activity (AOB: 391±124 mg-N/L/d, NOB: 233±151 mg-N/L/d,  $p < 0.001$ ) during the entire study. This was attributed to heterotrophic denitrification pressure, high DO, and intermittent aeration providing unfavorable conditions for NOB without adversely affecting the AOB population. NOB were then removed from the system through strict SRT control. Under AvN operation an average TIN removal efficiency of 82±5% was achieved at an influent COD/ $\text{NH}_4^+$ -N ratio of 10.5±1. Effluent from the AvN process was fed to an Anammox MBBR for tertiary treatment where an additional 8±2% removal was achieved corresponding to a combined TIN removal of 91±4% (Regmi, 2014).

In a related study, Fredericks et al. (2014) compared operation of AvN in fully-intermittent and MLE configurations. It was found that the NAR was best under fully-intermittent aeration (where all reactors were intermittently aerated), achieving 0.43±0.10 at a 3 hour HRT and influent COD/ $\text{NH}_4^+$ -N ratio of 7.9±1.4. The NAR significantly decreased when the configuration was switched to a MLE aeration and was found to decrease with increasing internal mixed liquor return. At IMLR rates of 200%, 325% and 450% (with respect to the influent flowrate) the NAR was found to be 20%, 17%, and 14% respectively. The MLE configuration did improve the overall TIN removal efficiency compared to fully-intermittent operation. The TIN removal efficiency increased as the IMLR and influent COD/ $\text{NH}_4^+$ -N increased. When the IMLR was 200%, 325% and 450%, average TIN removal efficiencies were 76.4%, 80.2%, and 86.3%, respectively, corresponding to influent COD/ $\text{NH}_4^+$ -N ratios and HRTs of 9.2±0.8 and 4 hr, 9.8±0.4 and 6 hr, and 10.3±1.2 and 6 hr, respectively. Operating under different influent substrate concentrations and process configurations did not affect settling. AvN operation exhibited good settling characteristics with an average sludge volume index (SVI) of 128.3±36.3 mL/g (Fredericks, 2014).

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## 3. Methodology

### 3.1 Pilot Setup

Research was conducted at a pilot wastewater treatment facility located onsite at the CE WWTP operated by the HRSD. The CE pilot is a continuous flow process treating domestic wastewater with a HRAS A-Stage designed for carbon capture followed by a BNR process in the B-Stage. The addition of an Anammox MBBR after the B-Stage allows for additional polishing prior to discharge of final effluent. Effluent from the pilot is returned to the headworks of the CE WWTP. An overview of the pilot facility is shown in Figure 23.

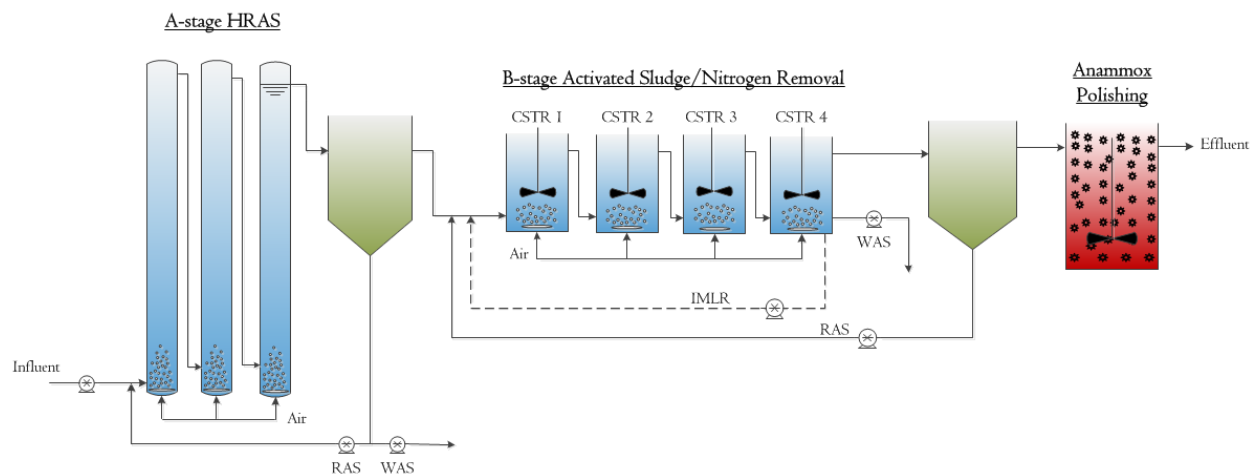


Figure 23 – CE Pilot Schematic

#### 3.1.1 Preliminary Treatment

Using a submersible pump (Tsurumi, Osaka, JP), raw wastewater influent (RWI) for the pilot process was pumped from the effluent channel of the preliminary treatment facility (PTF) at Chesapeake Elizabeth WWTP. The PTF includes fine screens and forced vortex grit removal as shown on Figure 2 in the introduction of this thesis. Due to inefficiencies of the PTF, the pumped RWI was first passed through a 568 L drum equipped with a variable-speed mixer (Grovhac Inc, Brookfield, WI) that was operated at a speed which allowed grit to settle but kept particulate and colloidal organic matter in suspension. Accumulated grit was removed weekly by draining and cleaning out the tank. Floatable material, such as oil and grease, was continuously removed by allowing the tank to overflow to a floor drain.

From the grit and scum removal tank, the RWI was pumped by a progressive cavity pump (Seepex, Somerset, UK) through basket screens with 2.4 mm openings into a temperature control tank. The temperature control tank contained submersible heaters (Process Technology, Mentor, Ohio) and a finned-tube coil for respective heating or cooling of the wastewater. The combination of a chiller (Aqua



Logic, San Diego, CA) and centrifugal pump (AMT, Mansfield, Ohio) maintained temperature of the water circulated through the coil. A PLC (Allen Bradley, Milwaukee, WI) controlled power to the heater and chiller pump based on a signal from a thermocouple in the temperature control tank and a user-defined temperature setpoint. This setup provided the capability to maintain a constant influent wastewater temperature, from 15 to 25°C, regardless of the temperature of the RWI. The temperature control tank also contained a constant-speed mixer (Grovhac Inc, Brookfield, WI). These processes were only necessary for the CE pilot and not intended for the full-scale process.

### 3.1.2 A-Stage Process

After temperature control, wastewater was pumped to the first of three HRAS reactors in the A-Stage. These reactors were constructed from PVC pipes and supported vertically on one end. The total operating volume of the three reactors was 511 L with a side water depth of 3.4 meters (11 feet). The HRAS process provided an HRT of 30 minutes with an influent flowrate of approximately 17 L/min. Aeration was provided using compressed air and a 17.7 cm membrane disc diffuser (EDI, Columbia, MO). DO was monitored by an FDO probe (Insite, Slidell, LA) positioned inside the last reactor. The desired DO setpoint (0.5 mg/L) was maintained by a single-loop PID controller regulating a mechanically operated valve (MOV) (Emerson Process Management, Shakopee, MN) on the compressed air line. The HRAS reactors were mixed through the release of a large bubble every two minutes.

The final A-Stage reactor overflowed by gravity into a cone-bottom clarifier outfitted with a scraper mechanism that rotated at 0.25 rpm directing settled solids to the bottom of the clarifier cone. The clarifier had a submerged vertical inlet inside of a center well which helped dissipate the influent hydraulic energy and allowed additional bioflocculation to occur before solids separation. The diameter of the clarifier was 1.4 m (4.5 feet) with a surface area of 1.48 m<sup>2</sup> (15.9 ft<sup>2</sup>). The clarifier was fed at a flowrate of 17 L/min (4.5 gpm). The surface overflow rate (SOR) of the clarifier was estimated at 16.6 m<sup>3</sup>/m<sup>2</sup>/day (407 gal/ft<sup>2</sup>/day) with an HRT of 1.7 hours.

A progressive cavity pump (Seepex, Somerset, UK) returned settled biomass in the clarifier to the first A-Stage aeration tank via the RAS line. The SRT of the HRAS process was controlled by wasting solids from the underflow of the clarifier using a programmable digital peristaltic pump (Cole-Parmer, Vernon Hills, IL). Manual wastage setpoints were established until installation of a sensor measuring MLSS (S::CAN, Vienna, AT) in the second A-Stage reactor automated SRT control. SRT in the A-Stage was maintained on the order of 6 to 12 hours. Effluent from the clarifier overflowed to a 208 L (55 gallon) drum that served as a flow-through feed-storage tank for the B-Stage. Effluent suspended solids (ESS), nutrients (NH<sub>4</sub><sup>+</sup>-N and Orthophosphate), COD, temperature, and pH were monitored in this tank. Mixing was maintained using a constant speed mixer. A-Stage effluent was pumped from the feed storage tank to the B-Stage with a progressive cavity pump (Seepex, Somerset, UK).

Results from optimization of the A-Stage control and operation studies are ongoing and can be accessed at DeArmond (2015) and Miller et al. (2013) (Miller et al, 2013; DeArmond, 2015).

### 3.1.3 Primary Clarifier

A clarifier, separate from the one used in the A-Stage HRAS process, was operated when the B-Stage was fed primary clarifier effluent. Primary clarification was performed in a cone bottom clarifier with a volume of 1170 L (310 gallons). The diameter of the clarifier was 0.9 m (3 feet) with a surface area of 0.66 m<sup>2</sup> (7.1 ft<sup>2</sup>). The clarifier was fed RWI at a flowrate of 15.1 L/min (4 gpm). The SOR was estimated at 33.2 m<sup>3</sup>/m<sup>2</sup>/day (815 gal/ft<sup>2</sup>/day) with an HRT of 1.3 hours.

The clarifier was outfitted with a scraper mechanism that rotated at 0.25 rpm directing settled solids to the bottom of the clarifier cone. The clarifier contained a submerged vertical inlet inside a center well which helped to dissipate the influent hydraulic energy allowing additional bioflocculation to occur before solids separation. Waste solids are continuously wasted from the bottom of the clarifier directly to a floor drain with a peristaltic pump (Cole-Parmer, Vernon Hills, IL). Since the clarifier was oversized the waste pump was operated at a flow that prevented the accumulation of a sludge blanket. The solids wasting rate was set at 1.9 L/min (0.5 gpm).

Temperature control was not performed prior to clarification. Effluent from the clarifier overflowed to a 208 L (55 gallon) tank, identical to the HRAS temperature control tank, which provided temperature control and served as a flow-through feed-storage tank for the B-Stage. Effluent suspended solids (ESS), nutrients (NH<sub>4</sub><sup>+</sup>-N and Orthophosphate), COD, temperature, and pH were monitored in this tank. Mixing was maintained by a constant speed mixer. PCE was then pumped to the B-Stage with a progressive cavity pump.

### 3.1.4 B-Stage Process

The B-Stage consists of four CSTRs in series followed by a secondary clarifier. The combination of multiple CSTRs provides a plug-flow design throughout the B-Stage which correlates with the flow patterns of most wastewater treatment facilities. Each CSTR is rectangular in shape and holds a volume of 151 L (Total Volume of 606 L). The system was maintained at a 5 hour HRT with an influent flowrate of 2 L/min (0.53 gpm). Flow rates were verified with magnetic flow meters (Emerson Process Management, Shakopee, MN). Effluent from the CSTRs flows into a center-fed, 340 L secondary clarifier. The clarifier was fitted with a scraper mechanism that rotated at 0.25 rpm directing settled solids to the bottom of the clarifier cone.

A programmable digital peristaltic pump (Cole-Parmer, Vernon Hills, IL) pumped RAS from the secondary clarifier to the first B-Stage CSTR at a flowrate of 2 L/min (100% of Influent Flow). Aeration capacity in all 4 tanks allowed the system to be operated with or without a defined anoxic zone. When operating in MLE configuration, an internal mixed liquor recycle (IMLR or NRCY for "Nitrate Recycle") line returned nitrified mixed liquor from the last CSTR to the anoxic reactor using a peristaltic pump (Cole-Parmer, Vernon Hills, IL) at a rate of 6 L/min (300% of Influent Flow). When IMLR was used the first tank was not aerated. For control of SRT, wasting occurred directly from the last reactor using a peristaltic pump (Cole-Parmer, Vernon Hills, IL). The PLC controlled on/off duration for this pump based on the user-

defined wastage rate. The process of wasting mixed liquor for SRT control instead of settled solids is termed the Garrett method (Tchobanoglous et al, 2003). Sodium Bicarbonate was fed via a peristaltic pump into the third CSTR for the purposes of maintaining an effluent pH setpoint of 6.8 and monitoring alkalinity requirements. Operating temperature of the B-Stage was maintained at 20°C for the duration of this study.

Each B-Stage CSTR was stirred using a variable speed mixer (Caframo, Ontario, CA) at  $G = 163 \text{ s}^{-1}$  to maintain complete-mix conditions. In addition, each tank contains a 17.7 cm membrane disc diffuser (EDI, Columbia, MO) which uses fine bubble aeration to disperse air into the water. Air was supplied via independent mechanically operated valves (ETI Systems, Carlsbad, CA) attached to a single compressed air line. Probes measuring DO were placed in each tank in order to monitor DO concentrations. Additional sensors were installed in the B-Stage CSTRs to monitor ammonium, pH, nitrate and nitrite. Details on the sensors installed in the B-Stage, including the type of probe, manufacturer, and their placement in the B-Stage are listed in Table 4. The location of these probes can be seen in Figure 24.

**Table 4 – Sensors used for process control in the B-Stage**

Sensor Name	Measurement	Type	Probe Function	Location	Manufacturer	Origin
<b>Foxboro pH</b>	pH	ISE	Bicarbonate Feed Control	3 <sup>rd</sup> CSTR	Invensys	London, United Kingdom
<b>LDO</b>	DO	Optical	Process Control during DO Control, ABAC, and AvN	All CSTRs	HACH	Loveland, USA
<b>Spectro::lyser</b>	NO <sub>2</sub> <sup>-</sup> -N, NO <sub>3</sub> <sup>-</sup> -N	Optical	Process Control during AvN	4 <sup>th</sup> CSTR	S::CAN	Vienna, Austria
<b>VARIION</b>	NH <sub>4</sub> <sup>+</sup> -N	ISE	Measurement of the Ammonium concentration	1 <sup>st</sup> CSTR	WTW (YSI)	Weilheim, Germany
<b>AmmoLyte</b>	NH <sub>4</sub> <sup>+</sup> -N	ISE	Process Control during ABAC and AvN	4 <sup>th</sup> CSTR	WTW (YSI)	Weilheim, Germany
<b>Robust N<sub>2</sub>O</b>	N <sub>2</sub> O-N		Measurement of the dissolved Nitrous Oxide concentration	1 <sup>st</sup> /3 <sup>rd</sup> CSTRs	Unisense	Aarhus, Denmark

The coordination between the aforementioned probes, a PLC, and independently controlled MOVs allow for the operation of different aeration strategies within the B-Stage reactors. The PLC receives output values from select sensors in the B-Stage and inputs those values into control loops which determine desired outputs for aeration control.

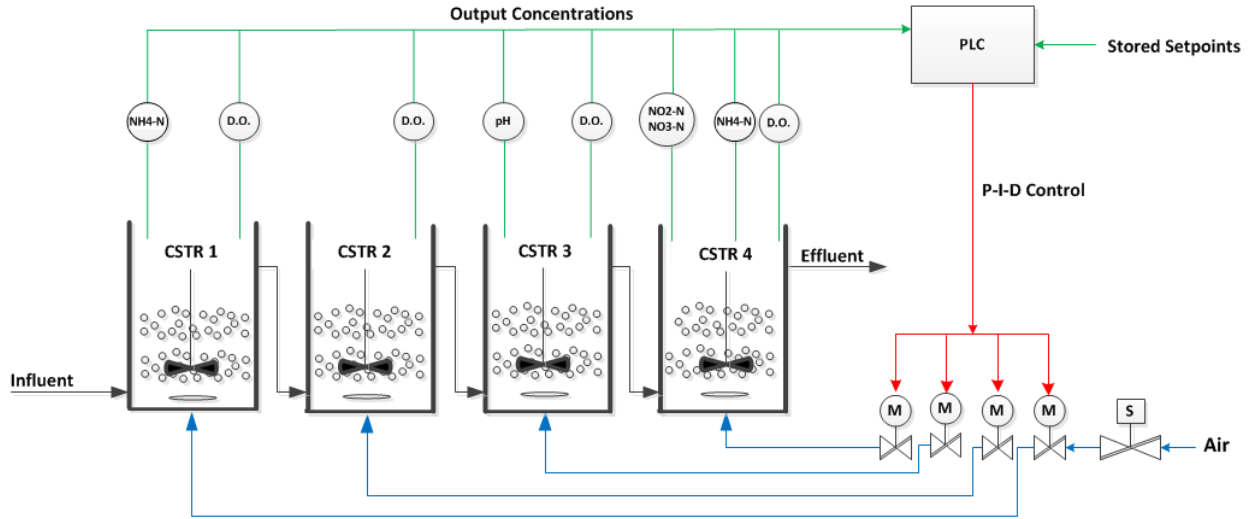


Figure 24 – Sensor and Controller locations within the B-Stage CSTRs

### 3.2 Aeration Strategies

In this study the following three aeration strategies were compared: 1) DO Control, 2) ABAC, and 3) AvN Control. Both DO Control and ABAC were operated as continuous aeration strategies where the B-Stage was placed in a MLE configuration. AvN was operated in the following two configurations: 1) a configuration in which all reactors were intermittently aerated for the same interval and duration (fully-intermittent) and 2) a MLE configuration in which the first reactor was designated as an anoxic selector and downstream reactors were intermittently aerated for the same interval and duration.

Table 5 – Modes of Operation in the B-Stage

Aeration Strategy	Configuration	Influent Feed	Code	Operation Period (days)
DO Control	MLE	ASE	DO_MLE_ASE	26
ABAC	MLE	ASE	ABAC_MLE_ASE	33
AvN	MLE	ASE	AvN_MLE_ASE	46
AvN	Fully Intermittent	ASE (Low COD/NH <sub>4</sub> <sup>+</sup> -N)	AvN_FI_ASE Low	31
AvN	Fully Intermittent	ASE (High COD/NH <sub>4</sub> <sup>+</sup> -N)	AvN_FI_ASE High	46
DO Control	MLE	PCE	DO_MLE_PCE	20
ABAC	MLE	PCE	ABAC_MLE_PCE	13
AvN	MLE	PCE	AvN_MLE_PCE	38
AvN	Fully Intermittent	PCE	AvN_FI_PCE	25

Shown in Table 5 above, the study compared each aeration strategy with both ASE and PCE. A code was developed for each combination of aeration strategy, configuration, and influent feed type. The aeration strategies covered in this experiment are designed to provide a general comparison for the optimization of an A/B process. Various control structures were used to perform each of the methods of aeration. The following sections highlight operation of the compared strategies.

### 3.2.1 DO Setpoint Control

The objective with this control strategy was to maintain a constant DO setpoint (2.0 mg/L) in the aerated reactors. Configuration of the B-Stage for operation of DO Control is shown in Figure 25. Performance of this strategy aimed to achieve complete ammonia oxidation so that the effluent TIN concentration was void of ammonia. By achieving complete removal of ammonia this strategy simulates operation for many of today's WWTPs performing nitrogen removal under DO Control.

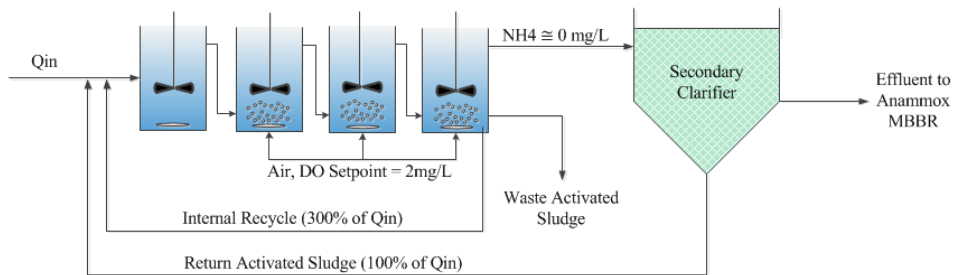


Figure 25 – DO Control Configuration

### 3.2.2 ABAC

Two control strategies were devised in order to maintain effluent ammonia within a desired concentration. The first strategy was achieved via feed-back control where the *in situ* ammonia concentration determined a response from the controller to increase or decrease the DO concentration. Physical configuration of this strategy is shown in Figure 26. During the second ABAC strategy the DO setpoint concentration was set to be equivalent to the effluent ammonia concentration. The physical configuration for this strategy is shown in Figure 27. This controller did not require proportional-integral-derivative (PID) control resulting in instantaneous response of the DO setpoint to effluent ammonia fluctuations. By establishing a set ammonia concentration in the effluent, ABAC aims to avoid over-aeration.

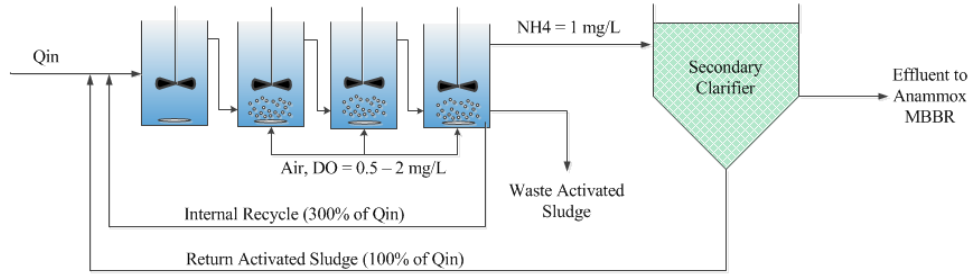


Figure 26 – Feed-back ABAC Configuration

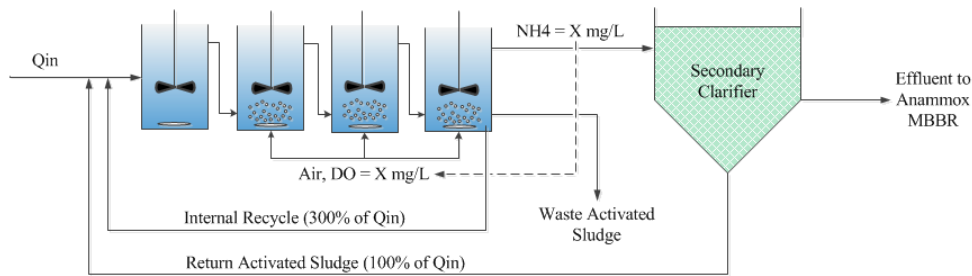


Figure 27 – Ammonia = DO ABAC Configuration

### 3.2.3 Ammonia vs. NO<sub>x</sub> Aeration Control

AvN in fully-intermittent and intermittent MLE configurations are shown in Figure 28 and 29, respectively. The controller achieves an effluent with equal parts ammonia and NO<sub>x</sub> by varying the aerobic fraction. This maintains optimum aerated and unaerated volume for nitrification and denitrification respectively as well as sufficient alkalinity for AOB growth. Since the controller maintains residual ammonia and high DO during aerated periods, AOB activity rates may remain high due to non-limiting conditions.

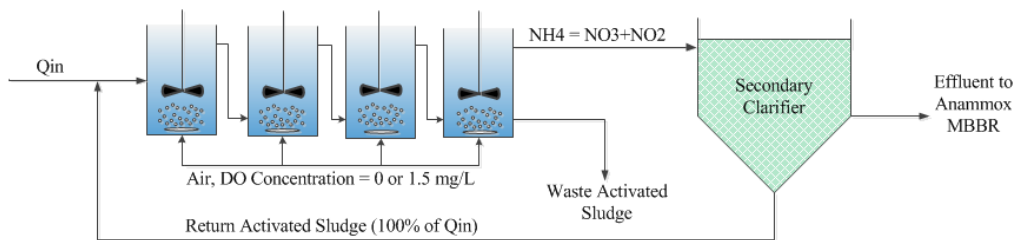


Figure 28 – Fully-Intermittent AvN Control Configuration

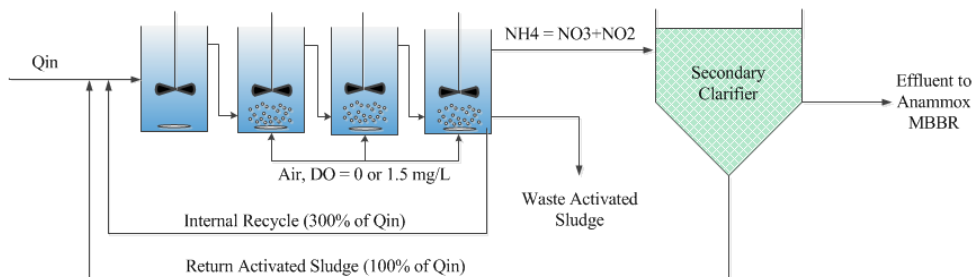


Figure 29 – AvN MLE Control Configuration

### 3.3 Influent/Effluent Monitoring

#### 3.3.1 Determination of Wastewater Composition

Process performance of the CE Pilot was monitored through the collection of 24-hour composite samples using automated samplers (ISCO, Lincoln, NE). The samplers extracted 250 mL at one hour intervals allowing average daily influent and effluent characteristics to be measured. Composite samples from the B-Stage were analyzed for TSS, VSS, total and soluble COD, TKN, TP, OP,  $\text{NO}_3^-$ -N,  $\text{NO}_2^-$ -N,  $\text{NH}_4^+$ -N and alkalinity. Relevant analytical methods performed at the CE Pilot for solids and liquids are presented in Table 6.

Table 6 – Analytical Measurements performed at the CE Pilot

Parameter	Reference Method	Description
<b>TSS</b>	SM <sup>a</sup> 20 <sup>th</sup> 2540D	Total Suspended Solids Dried at 103-105°C
<b>VSS</b>	SM <sup>a</sup> 18 <sup>th</sup> 2540E	Fixed and Volatile Solids Ignited at 550°C
<b>COD</b>	Hach 8000	- COD TNTplus HR (20 to 1500 mg/L COD) - COD TNTplus LR (3 to 150 mg/L COD) - COD TNTplus ULR (1 to 60 mg/L COD) *Sample for total COD was blended to homogeneity *Sample for soluble COD was denoted by filtration through 1.5µm glass fiber filter
<b>OP</b>	Hach 8048	Reactive Phosphorus TNT LR (0.6 to 5.00 mg/L $\text{PO}_4^{3-}$ )
<b><math>\text{NO}_3^-</math>-N</b>	Hach 10206	-Nitrate TNTplus LR (0.23 to 13.5 mg/L $\text{NO}_3^-$ -N) -Nitrate TNTplus HR (5 to 35 mg/L $\text{NO}_3^-$ -N)
<b><math>\text{NO}_2^-</math>-N</b>	Hach 10019	-Nitrite TNTplus LR (0.015 to 0.600 mg/L $\text{NO}_2^-$ -N) -Nitrite TNTplus HR (0.6 to 6.0 mg/L $\text{NO}_2^-$ -N)
<b><math>\text{NH}_3</math>-N</b>	Hach 10205	-Ammonia TNTplus ULR (0.015 to 2.00 mg/L $\text{NH}_3$ -N) -Ammonia TNTplus LR (1 to 12 mg/L $\text{NH}_3$ -N) -Ammonia TNTplus HR (2 to 47 mg/L $\text{NH}_3$ -N)
<b>SVI</b>	SM <sup>a</sup> 18 <sup>th</sup> 2710C	Settled Sludge Volume

<sup>a</sup> SM – Standard Methods (APHA, 2012)

In addition composite samples were sent twice a week for measurements performed by HRSD’s Central Environmental Lab (CEL). Relevant analytical methods performed in the analysis by the CEL are shown in Table 7.

Table 7 – Analytical Measurements performed by HRSD’s CEL

Parameter	Reference Method	Description
<b>TSS</b>	SM 20 <sup>th</sup> 2540D	Total Suspended Solids Dried at 103-105°C
<b>TVSS</b>	SM 18 <sup>th</sup> 2540E	Fixed and Volatile Solids Ignited at 550°C
<b>TKN</b>	EPA 351.2 Lachat 10-107-06-2-I	Determination of Total Kjeldahl Nitrogen by Flow Injection Analysis Colorimetry (Block Digestion)
<b>NH<sub>3</sub>-N</b>	EPA 350.1 Lachat 10-107-06-1-C	Determination of Ammonia by Flow Injection Analysis Colorimetry
<b>TP</b>	EPA 365.1 Lachat 10-115-01-1-E	Determination of Total Phosphorus by Flow Injection Analysis Colorimetry (Acid Persulfate Digestion)
<b>COD</b>	Hach 8000	Chemical Oxygen Demand, Reactor Digestion Method
<b>Alkalinity</b>	EPA 310.2 Lachat 10-303-31-1-A	Determination of Alkalinity by Flow Injection Analysis Colorimetry

Daily pH and temperature readings of the reactors were recorded using a handheld meter (Beckman Coulter, Brea, CA). Readings for DO were also recorded with a handheld LDO sensor (HACH Loveland, CO). In addition to solid and liquid testing, weekly batch testing and microbial quantification was performed in the B-Stage as described below.

### 3.3.2 AOB and NOB Activity Measurements

To measure maximum AOB and NOB activity, a 4 L sample was collected from B-Stage CSTR 4 (Figure 23). The sample was aerated for 30 minutes to oxidize excess COD in order to prevent heterotrophic competition for oxygen. A dissolved solution of ammonium chloride was added to the mixture supplying an initial concentration of 20-30 mg-N/L. At the same time a dissolved solution of sodium nitrite was also added to the mixture supplying an initial concentration of 2-4 mg-N/L. The addition of these compounds prevented substrate limitation to both AOB and NOB, respectively. Temperature was controlled during AOB and NOB activity measurements by submersing the batch reactor in a water bath (Fisher Scientific, Pittsburgh, PA). Air flow was diffused through a porous aeration stone. The sample was mixed and aerated to maintain a DO concentration between 2.5-4.0 mg/L. pH was maintained at approximately 7.5 by adding sodium bicarbonate. The batch reactor was operated for 1 hour and samples were collected at 15-minute intervals. All collected samples were filtered through 0.45 µm nylon filters and analyzed for NO<sub>3</sub><sup>-</sup>-N, NO<sub>2</sub><sup>-</sup>-N, and NH<sub>4</sub><sup>+</sup>-N as described above. The AOB rates (mgNO<sub>x</sub>-N/hr) were calculated as the slope of the NO<sub>x</sub>-N production versus time and NOB rates (mgNO<sub>3</sub><sup>-</sup>-N/hr) were calculated as the slope of the NO<sub>3</sub><sup>-</sup>-N production versus time.

### 3.3.3 Denitrifier Activity Measurements



Denitrification rate testing was performed by mixing 2 L of RAS from the B-Stage secondary clarifier with 2 L of effluent from the A-Stage process. Effluent from the A-Stage provided the internal carbon source for denitrification. During operational modes when the B-Stage was fed effluent from the primary clarifier, 2L of PCE was used as the internal carbon source instead of ASE. The DO concentration was allowed to drop to 0.10 mg/L before spiking the sample with 20-30 mg-N/L from a dissolved potassium nitrate solution and 1-3 mg-N/L from a dissolved sodium nitrite solution. The batch reactor was operated for 1 hour and samples were collected at 15 minute intervals. All collected samples were filtered through 1.5  $\mu\text{m}$  glass fiber filters and analyzed for  $\text{NO}_3^-$ -N,  $\text{NO}_2^-$ -N,  $\text{NH}_4^+$ -N, and sCOD. During the denitrification activity measurement, the sample was continuously mixed through use of a magnetic stir plate (Corning, Corning, NY). Temperature was controlled by submersing the batch reactor in a water bath. The 4L container was covered with a styrofoam lid to prevent oxygen transfer. In instances when high initial nitrite concentrations (5-10 mg-N/L) were necessary to prevent limitation, nitrogen gas was diffused into the solution through a porous aeration stone. This prevented the effects of nitric oxide accumulation. The pH was maintained between 7.0 and 7.5 with the addition of diluted hydrochloric acid or sodium bicarbonate. Denitrification rates were calculated based on the slope of the  $\text{NO}_x$ -N concentration versus time.

### 3.3.4 Oxygen Uptake Rate

To measure the OUR, samples were taken from each of the 4 B-Stage CSTRs. The samples were placed in 4L test vessels that were continuously mixed and aerated. A DO probe was also placed in each of the 4 test vessels. Samples were initially aerated until the DO concentration reached 4 mg/L, aeration was then turned off. DO measurements were then taken every 10 seconds until the DO concentration fell below 1 mg/L. The OUR test was carried out in triplicate. The OUR (mg/L/hr) was calculated as the average slope of DO concentration versus time.

### 3.3.5 Microbial Quantification

Sample preparation began by collecting a grab sample from the last CSTR in the B-Stage. From the grab sample 1.5 mL was placed into each of three labeled centrifuge vials. The vials were centrifuged at 13,000 rpm for 3 minutes at 0°C. The supernatant was decanted and 1.5 mL of RNA protect (Qiagen, Venlo, NL) was added. Each of the vials were then mixed by vortexing and incubated at room temperature for 5 minutes. Then the vials were centrifuged again for 3 minutes at 13,000 rpm and 0°C.

Supernatant was again decanted and pellet was stored in a freezer at -80°C. Frozen samples were shipped to Columbia University Department of Earth and Environmental Engineering Dr. Kartik Chandran's laboratory for analysis. The frozen sample was homogenized by use of a grinder, then 1 ml of TE buffer solution was added. The sample was resuspended by vortex mixing and either 0.1 ml (10 fold dilution) or 0.2 ml (5 fold dilution) resuspended sample was used for DNA extraction.

The abundance of AOB and NOB was quantified using TaqMan quantitative polymerase chain reaction (qPCR). AOB were targeted using the  $\text{NH}_4\text{p}$  mono-oxygenase subunit A (*amoA*) gene (Rotthauwe et al,

1997) while NOB were targeted using the *Nitrobacter* 16S rRNA gene (Graham et al, 2007) and *Nitrospira* 16S rRNA gene (Kindaichi et al, 2007). Total bacterial abundance was quantified using eubacterial 16S rRNA gene targeted primers (Ferris et al, 1996). qPCR assays were conducted on a iQ5 real-time PCR thermal cycler (BioRad Laboratories, Hercules, CA). Standard curves for qPCR were generated via serial decimal dilutions of plasmid DNA containing specific target gene inserts. qPCR for standard plasmid DNA and sample DNA were conducted with duplication and triplication, respectively. DNA-grade deionized distilled water (Fisher Scientific, MA) was used for non-template control. Primer specificity and the absence of primer-dimers were confirmed via melt curve analysis of each and every qPCR profile (Ma et al, 2015; Park et al, 2015).

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## 4. Manuscript 1: Comparison of Aeration Strategies for Optimization of Nitrogen Removal in an A/B Process: DO, ABAC, and AvN Control

### Abstract

Research was performed at a pilot-scale wastewater treatment plant operating an adsorption/bio-oxidation (A/B) process at 20°C. The study compared B-Stage performance under DO Control, Ammonia Based Aeration Control (ABAC), and Ammonia vs. NO<sub>x</sub> (AvN) control. AvN in 1) fully-intermittent and 2) intermittently-aerated MLE configurations was compared to DO Control and ABAC, each with continuous aeration, in an MLE configuration. The study also examined operation of each aeration strategy with two different feed types: A-Stage effluent (ASE) and primary clarifier effluent (PCE). Operating modes were compared on the basis of nitrogen removal performance, COD utilization efficiency for denitrification, and alkalinity consumption.

AvN was found to provide comparable nitrogen removal performance to DO Control and ABAC. The highest nitrogen removal performance was seen when operating DO Control ( $81.4 \pm 1.2\%$ ) and ABAC ( $81.1 \pm 1.2\%$ ) with PCE. High nitrogen removal efficiency ( $77.5 \pm 6.1\%$ ) was seen when fully-intermittent AvN operation was fed ASE containing a high particulate COD fraction. A high effluent nitrite accumulation ratio ( $\text{NAR} = \text{NO}_2^- / (\text{NO}_2^- + \text{NO}_3^-)$ ) was seen during this period ( $46 \pm 15\%$ ) accompanied by the out-selection of *Nitrospira*. Feeding effluent from AvN control to an Anammox MBBR improved removal efficiency.

Increased soluble COD loading resulted in greater nitrogen removal with strategies operating in an MLE configuration while particulate COD was found to be important for processes where removal was designed to occur in downstream reactors. Efficiency of COD for denitrification was found to vary based on the amount and type of influent COD; however AvN in an MLE configuration was found to use COD more efficiently than fully-intermittent AvN. In either configuration, AvN required less alkalinity addition than DO Control or ABAC. High sCOD concentrations in PCE led to increased nutrient removal as compared to ASE but increased heterotrophic growth and mixed liquor concentrations in the B-Stage making the A-Stage an attractive option for its ability to control the C/N ratio fed to BNR processes.

### 4.1 Introduction

Although the adsorption/bio-oxidation (A/B) process is not currently used in the US for domestic wastewater treatment it is a well-established wastewater treatment process in Europe. Unlike the single-sludge processes most commonly used, the A/B process is a two-sludge system where each stage is optimized for its specific set of goals. The A-Stage is a high-rate activated sludge (HRAS) process

operated at a low hydraulic retention time (HRT) of about 30 minutes, a low dissolved oxygen (DO) concentration of less or equal to 0.5 mg/L and a low solids retention time (SRT) of less than 1 day (Boehnke et al, 1997). The goals of the A-Stage are carbon capture for energy recovery through biogas production, reduced downstream aeration tank volume, and to protect the B-Stage from shock loadings. The B-Stage consists of a biological nutrient removal (BNR) process which aims to perform efficient nitrogen removal through optimized aeration and efficient use of influent carbon from the A-Stage for denitrification. One unique benefit of the upstream A-Stage is that it may be operated to control the carbon to nitrogen (COD/NH<sub>4</sub><sup>+</sup>-N) ratio in the influent fed to the B-Stage (A-Stage effluent) for optimum nutrient removal performance (Regmi et al, 2014).

The method for aerating wastewater greatly impacts nutrient removal performance and plant efficiency, as blower operation is the single largest user of energy at water resource recovery facilities (WRRF) (Ingildsen, 2002; Åmand et al, 2013). Today's WRRFs are becoming increasingly automated with the development of new technology. This shift is taking place in order to improve process stability and removal performance. Advanced computerized systems such as Supervisory Control and Data Acquisition (SCADA) as well as Distributed Control Systems (DCS) are revolutionizing the ease, efficiency, and complexity of wastewater treatment. When these automated systems are paired with advanced sensors such as optical probes for the measurement of DO, and ion-selective electrodes or spectral probes for the *in situ* measurements of nutrients, WRRFs gain a greater amount of control over BNR processes. This allows for operation of specific aeration strategies, three of which include conventional DO Control, ammonia-based aeration control (ABAC), and ammonia vs. NO<sub>x</sub> (AvN) control.

The earliest form of aeration control involved setting a constant airflow rate; however, this airflow setting made no adjustment in response to influent variability. This resulted in unnecessarily high airflow rates and DO concentrations. By the early 1970s the use of on-line DO sensors was well established in many WRRFs, making DO Control possible (Åmand et al, 2013). Compared to manual control of airflow rates, DO Control achieved greater efficiency by preventing unnecessary aeration. However, because this strategy did not perform real-time monitoring of effluent ammonia, it resulted in over-aeration towards the end of the reactor.

This was alleviated with the development of ABAC. This strategy is applied at WRRFs to either reduce aeration costs, reduce peaks in the effluent ammonia concentration, or both (Rieger et al, 2014). Feed-back ABAC involves establishing a setpoint effluent ammonia concentration (usually 1-2 mg-N/L) and allowing a controller to vary the DO in response to that setpoint. Because the process operates at lower DO concentrations it can increase denitrification performance via simultaneous nitrification-denitrification (SND) therefore reducing the need for external carbon and alkalinity addition (Jimenez et al, 2013).

Recently more interest has been placed on the development and implementation of strategies able to achieve suppression of nitrite oxidizing bacteria (NOB) due to savings in aeration energy and carbon demand. Out-selection of NOB is routinely achieved in sidestream processes treating anaerobic digester dewatering liquor (van Dongen et al, 2001). Under these conditions NOB may be suppressed by the

following mechanisms: 1) continuous or intermittent aeration at low DO concentrations, 2) inhibition due to high concentrations of free ammonia (FA), 3) inhibition due to accumulation of free nitrous acid (FNA), and 4) operation at low aerobic SRT to wash-out NOB (Burton et al, 2013). Anaerobic digester dewatering liquor is also favorable to ammonia oxidizing bacteria (AOB) due to warm temperature (30-40°C) and high ammonia concentrations (1000 mgNH<sub>4</sub><sup>+</sup>-N/L) (Stinson et al, 2013).

Although NOB out-selection is promising, implementation of nitrite shunt or deammonification processes in the mainstream is challenging. Mainstream wastewater is characterized by lower temperatures (15-25°C), dilute concentrations of ammonia (30-40 mgNH<sub>4</sub><sup>+</sup>-N/L), and high influent C/N ratios (Henze 2008). These conditions favor the growth of NOB and heterotrophic bacteria which compete with AOB for substrate and space within the reactor. Therefore, in order to increase AOB activity relative to NOB, specific operational conditions must be employed.

The AvN aeration strategy can be used for this. AvN is a partial nitrification strategy which was developed for mainstream deammonification processes. The aeration strategy was tested in a pilot study by Regmi et al. (2014). The treatment process consisted of a HRAS A-Stage whose effluent was fed into an intermittently aerated continuously stirred tank reactor (CSTR) in the B-Stage. Intermittent aeration was performed in the CSTR using AvN control which varied the aerobic fraction to maintain equal parts ammonia and NO<sub>x</sub> (NO<sub>2</sub><sup>-</sup> + NO<sub>3</sub><sup>-</sup>) in the effluent. The process generated significant nitrite accumulation at 25°C with a nitrite accumulation ratio (NAR) up to 90%. The process achieved NOB suppression through a combination of intermittent aeration, high DO concentration (>1.5 mg/L), and aggressive SRT control (aerobic SRT of 3.2 days). The system's ability to maintain residual ammonia (> 1.5 mg NH<sub>4</sub><sup>+</sup>-N/L) kept AOB activity high. Effluent from the B-Stage CSTR underwent secondary clarification before flowing through an Anammox moving bed biofilm reactor (MBBR) for final effluent polishing. In the MBBR, residual nitrite and ammonia were converted to nitrogen gas in addition to a small amount of nitrate through Anammox activity (Regmi et al, 2014).

Although a few studies have compared the performance of DO control and ABAC (Jimenez et al, 2013; Rieger et al, 2014), no studies have compared B-Stage performance under DO Control, ABAC, and AvN operation. Therefore, to bridge this research gap and build upon the study by Regmi et al. (2014), the first objective of this work was to investigate the performance of different aeration strategies (DO Control, ABAC, and AvN) and evaluate each in terms of nitrogen removal, COD utilization efficiency, and alkalinity consumption. The second objective was to determine the effect of influent feed characteristics on the performance of the B-Stage also in regards to nitrogen removal, COD utilization efficiency, and alkalinity consumption. To study this, each aeration strategy was fed effluent from a controlled A-Stage process or primary clarifier effluent (PCE) to evaluate performance with each influent feed. This study is beneficial because it provides validation for the selection of an aeration strategy based on performance results and influent feed type.

## 4.2 Materials and Methods

### 4.2.1 Pilot Setup

Research was conducted at a pilot wastewater treatment facility located onsite at the Chesapeake Elizabeth (CE) WRRF operated by the Hampton Roads Sanitation District (HRSD). The CE pilot is a continuous flow process treating domestic wastewater with a HRAS A-Stage designed for carbon capture followed by a BNR process in the B-Stage. The addition of an Anammox MBBR after the B-Stage allows for additional polishing prior to discharge of final effluent. An overview of the pilot facility is shown in Figure 1.

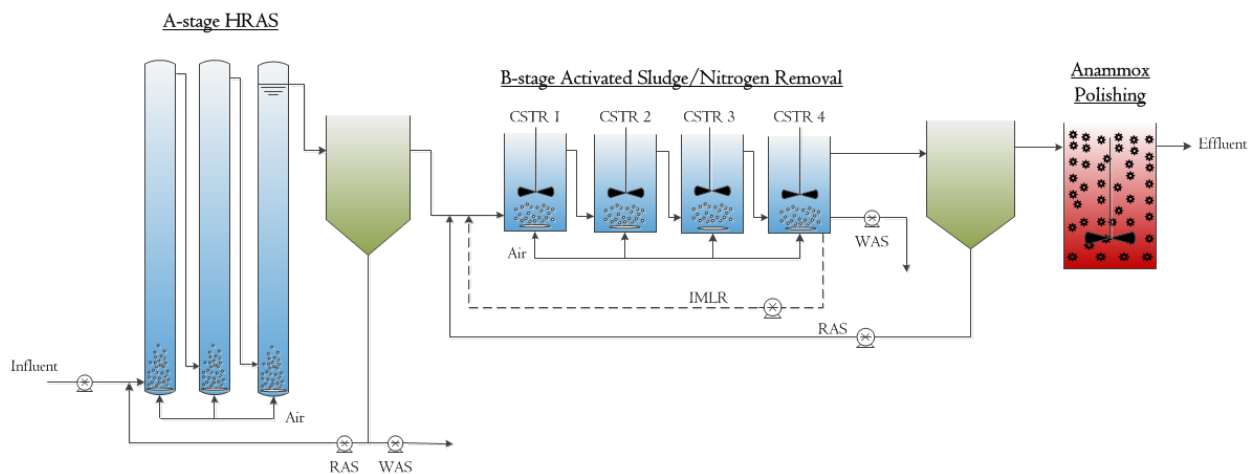


Figure 1 – Chesapeake Elizabeth (CE) Pilot Schematic

Influent water was subject to grit removal, screening, and temperature control before treatment in the CE pilot. Temperature was maintained at 20°C for the duration of the study. The A-Stage was operated at low DO concentrations ( $\leq 0.5$  mg/L), an SRT of 6-12 hours, and an HRT of 30 minutes. Aeration was supplied with motorized valves and membrane disc diffusers. Effluent from the A-Stage was fed into an intermediate clarifier. The clarified effluent provided influent for B-Stage operation. The effluent C/N ratio from the A-Stage was controlled through manual adjustment of wastage rates.

A clarifier, separate from the one used in the A-Stage process, was operated when the B-Stage was fed PCE. Primary clarification was performed in a cone bottom clarifier with a volume of 1170 L. Waste solids were continuously wasted from the bottom of the clarifier at a rate of 1.9 L/min. The surface overflow rate (SOR) was estimated at 1.38 m/hr with an HRT of 1.3 hours. Temperature control was not performed prior to primary clarification. Effluent from the clarifier passed into a tank serving as both temperature control, provided via a chiller coil and pump or submersible heater, and flow-through feed-storage for the B-Stage.

The B-Stage consisted of four CSTRs in series followed by a secondary clarifier. The system was maintained at a 5 hour HRT. Return activated sludge (RAS) from the clarifier and internal mixed liquor recycle (IMLR) from the last CSTR were fed using peristaltic pumps. For control of SRT, wasting occurred directly from the last reactor using a programmable peristaltic pump. A stock solution of sodium bicarbonate was fed to the third CSTR in order to maintain effluent pH at 6.8 and monitor alkalinity requirements.

Each CSTR was stirred by variable speed mixers and contained fine-bubble EPDM membrane disc diffusers supplying air from independent mechanically operated valves (MOVs). Sensors were installed in the B-Stage to monitor DO (HACH, LDO Model 1), pH (Foxboro), ammonium (YSI, AmmoLyt Plus 700), nitrate and nitrite (S::CAN, Spectro::lyser) concentrations. The coordination between a programmable logic controller (PLC), MOVs, and specialized sensors allowed for operation of different aeration strategies in the B-Stage.

#### 4.2.2 Modes of Operation

In this study the following three aeration strategies were compared: DO Setpoint Control, ABAC, and AvN. For DO Control and ABAC the B-Stage was placed in a MLE configuration. AvN was operated in the following two configurations: 1) a configuration in which all CSTRs were intermittently aerated for the same interval and duration (fully-intermittent) and 2) a MLE configuration in which the first reactor was designated as an anoxic selector and downstream reactors were intermittently aerated for the same interval and duration. The study compared each aeration strategy with both A-Stage effluent (ASE) and PCE. A code was developed for each combination of aeration strategy, configuration, and influent feed type as shown in Table 1 and will be referred to in the following sections.

Table 1 - Modes of Operation in the B-Stage

Aeration Strategy	Configuration	Influent Feed	Code	Operation Period (days)
<b>DO Control</b>	MLE	ASE	DO_MLE_ASE	26
<b>ABAC</b>	MLE	ASE	ABAC_MLE_ASE	33
<b>AvN</b>	MLE	ASE	AvN_MLE_ASE	46
<b>AvN</b>	Fully Intermittent	ASE (Low COD/NH <sub>4</sub> <sup>+</sup> -N)	AvN_FI_ASE Low	31
<b>AvN</b>	Fully Intermittent	ASE (High COD/NH <sub>4</sub> <sup>+</sup> -N)	AvN_FI_ASE High	46
<b>DO Control</b>	MLE	PCE	DO_MLE_PCE	20
<b>ABAC</b>	MLE	PCE	ABAC_MLE_PCE	13
<b>AvN</b>	MLE	PCE	AvN_MLE_PCE	38
<b>AvN</b>	Fully Intermittent	PCE	AvN_FI_PCE	25



### 4.2.3 Aeration Control Strategies

The aeration strategies covered in this experiment were designed to provide a general comparison for the optimization of an A/B process. Various control structures were used to perform each of the methods of aeration. The following sections highlight operation of the compared strategies.

#### 4.2.3.1 DO Setpoint Control

The objective with this control strategy was to maintain a constant DO setpoint (2.0 mg/L) in the aerated reactors. Configuration of the B-Stage for operation of DO Control is shown in Figure 2a. Performance of this strategy aimed to achieve complete ammonia oxidation so that the effluent TIN concentration was void of ammonia. By achieving complete removal of ammonia this strategy simulates operation for many of today's WRRFs performing nitrogen removal under DO Control.

#### 4.2.3.2 Ammonia Based Aeration Control

Two control strategies were devised in order to maintain effluent ammonia within a desired concentration. The first strategy was achieved via feed-back control where the *in situ* ammonia concentration determined a response from the controller to increase or decrease the DO concentration. Physical configuration of this strategy is shown in Figure 2b. During the second ABAC strategy the DO setpoint concentration was set to be equivalent to the effluent ammonia concentration. The physical configuration for this strategy is shown in Figure 2c. This controller did not require proportional-integral-derivative (PID) control resulting in instantaneous response of the DO setpoint to effluent ammonia fluctuations. By establishing a set ammonia concentration in the effluent, ABAC aims to avoid over-aeration.

#### 4.2.3.3 Ammonia vs. NO<sub>x</sub> Aeration Control

AvN in fully-intermittent and intermittent MLE configurations are shown in Figure 2d and e, respectively. The controller achieves an effluent with equal parts ammonia and NO<sub>x</sub> by varying the aerobic fraction. This maintains optimum aerated and unaerated volume for nitrification and denitrification respectively as well as sufficient alkalinity for AOB growth. Since the controller maintains residual ammonia and high DO during aerated periods, AOB activity rates may remain high due to non-limiting conditions.

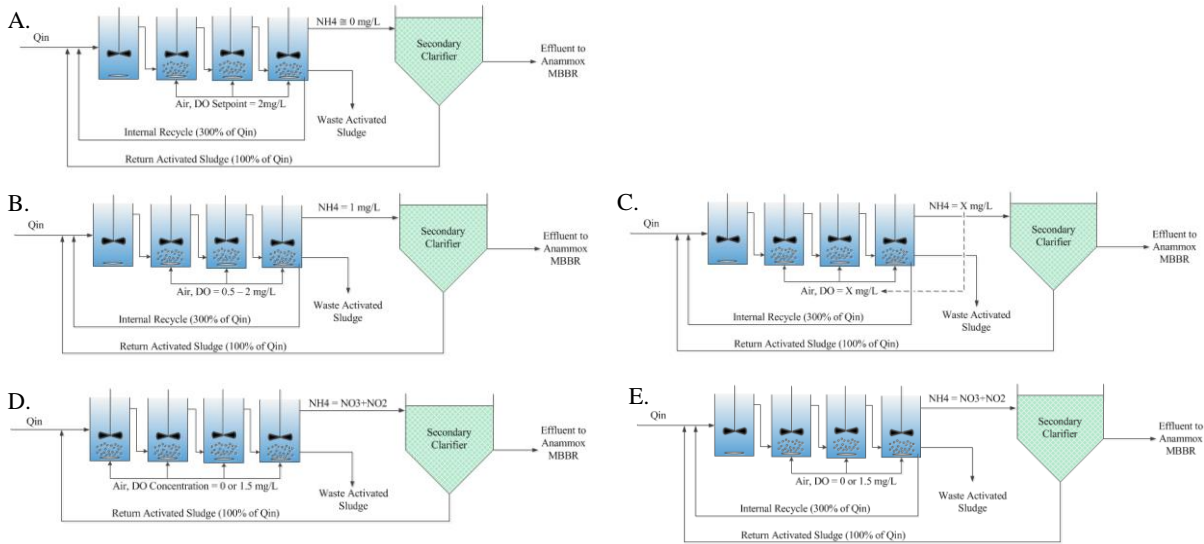


Figure 2 – B-Stage Configurations a) DO Control b) Feed-back ABAC c) Ammonia = DO ABAC d) Fully-Intermittent AvN Control e) AvN MLE Control

#### 4.2.4 AOB and NOB Activity Measurements

To measure maximum AOB and NOB activity, a 4 L sample was collected from the 4<sup>th</sup> CSTR and aerated for 30 minutes to oxidize excess COD. The sample was then spiked with 10 mL of a 10 g-N/L  $\text{NH}_4\text{Cl}$  solution and 1 mL of a 10 g-N/L  $\text{NaNO}_2$  solution so that initial concentrations were 20-30  $\text{mgNH}_4^+\text{-N/L}$  and 2-4  $\text{mgNO}_2^-\text{-N/L}$  respectively. Temperature was controlled via submersion in a water bath. Mixing was provided by a magnetic stir bar. The DO concentration was maintained between 2.5 and 4 mg/L. pH was maintained at approximately 7.5 through the addition of sodium bicarbonate. The batch reactor was sampled continuously for 1 h at 15-minute intervals. All collected samples were analyzed for  $\text{NH}_4^+\text{-N}$ ,  $\text{NO}_2^-\text{-N}$ , and  $\text{NO}_3^-\text{-N}$  as described below. The AOB rates were calculated as the slope of the  $\text{NO}_x\text{-N}$  production and NOB rates were calculated as the slope of the  $\text{NO}_3^-\text{-N}$  production.

#### 4.2.5 Denitrification Rate Measurements

To measure the denitrification rate, batch testing was performed by mixing 2L of RAS from the B-Stage secondary clarifier with 2L of ASE which provided the internal carbon source for denitrification. During operational modes when the B-Stage was fed PCE, 2L of PCE was used as the internal carbon source instead of ASE. When the DO concentration reached 0.10 mg/L the mixture was spiked with 20-30 mg-N/L from a dissolved potassium nitrate solution and 1-3 mg-N/L from a dissolved sodium nitrite solution. The batch reactor was operated for 1 hour and samples were collected at 15 minute intervals. All collected samples were filtered through 1.5  $\mu\text{m}$  glass fiber filters and analyzed for  $\text{NO}_3^-\text{-N}$ ,  $\text{NO}_2^-\text{-N}$ ,  $\text{NH}_4^+\text{-N}$ , and sCOD. The batch reactor was continuously mixed through use of a magnetic stir plate (Corning, Corning, NY). Temperature was controlled by submersion in a water bath. The reactor was covered with a styrofoam lid to prevent oxygen transfer. In instances when high initial nitrite concentrations (5-10

mg-N/L) were necessary to prevent limitation, nitrogen gas was diffused into the solution through a porous aeration stone. This prevented the effects of nitric oxide accumulation. The pH was maintained between 7.0 and 7.5 with the addition of diluted hydrochloric acid or sodium bicarbonate. Denitrification rates were calculated based on the slope of the NO<sub>x</sub>-N concentration versus time.

#### 4.2.6 Microbial Quantification

The abundance of AOB and NOB was quantified using TaqMan quantitative polymerase chain reaction (qPCR). AOB were targeted using the NH<sub>4</sub>p mono-oxygenase subunit A (*amoA*) gene (Rotthauwe et al, 1997) while NOB were targeted using the *Nitrobacter* 16S rRNA gene (Graham et al, 2007) and *Nitrospira* 16S rRNA gene (Kindaichi et al, 2007). Total bacterial abundance was quantified using eubacterial 16S rRNA gene targeted primers (Ferris et al, 1996). qPCR assays were conducted on a iQ5 real-time PCR thermal cycler (BioRad Laboratories, Hercules, CA). Standard curves for qPCR were generated via serial decimal dilutions of plasmid DNA containing specific target gene inserts. qPCR for standard plasmid DNA and sample DNA were conducted with duplication and triplication, respectively. DNA-grade deionized distilled water (Fisher Scientific, MA) was used for non-template control. Primer specificity and the absence of primer-dimers were confirmed via melt curve analysis of each and every qPCR profile (Ma et al, 2015; Park et al, 2015).

#### 4.2.7 Analytical Monitoring

Performance of the CE Pilot was monitored through the collection of 24-hour composite samples using automated samplers. The samplers extracted 250 mL aliquots at one-hour intervals allowing average daily influent and effluent characteristics to be measured. Total and volatile suspended solids (TSS and VSS) were analyzed using standard methods 2540D and 2540E respectively. Total and soluble COD, OP, NH<sub>4</sub><sup>+</sup>-N, NO<sub>2</sub><sup>-</sup>-N, and NO<sub>3</sub><sup>-</sup>-N were measured with HACH TNTplus kits and a HACH DR2800 spectrophotometer (HACH Loveland, CO). Composite samples were sent twice a week for TKN (EPA 351.2), TP (EPA 365.1), and alkalinity (EPA 310.2) measurements. The sludge volume index (SVI) for B-Stage mixed liquor was tested daily according to standard methods 2710C. Daily pH and temperature readings of the reactors were recorded using a Beckman Coulter handheld pH and temperature meter (Beckman Coulter, Brea, CA). Readings for DO were also recorded with using a HACH handheld luminescent DO sensor (HACH Loveland, CO).

### 4.3 Results and Discussion

#### 4.3.1 Influent and Effluent Characteristics

Influent wastewater composition to the B-Stage for each mode of operation is listed in Table 2. Loading conditions, removal rates, and effluent nutrient concentrations for each scenario are depicted in Figure 3.

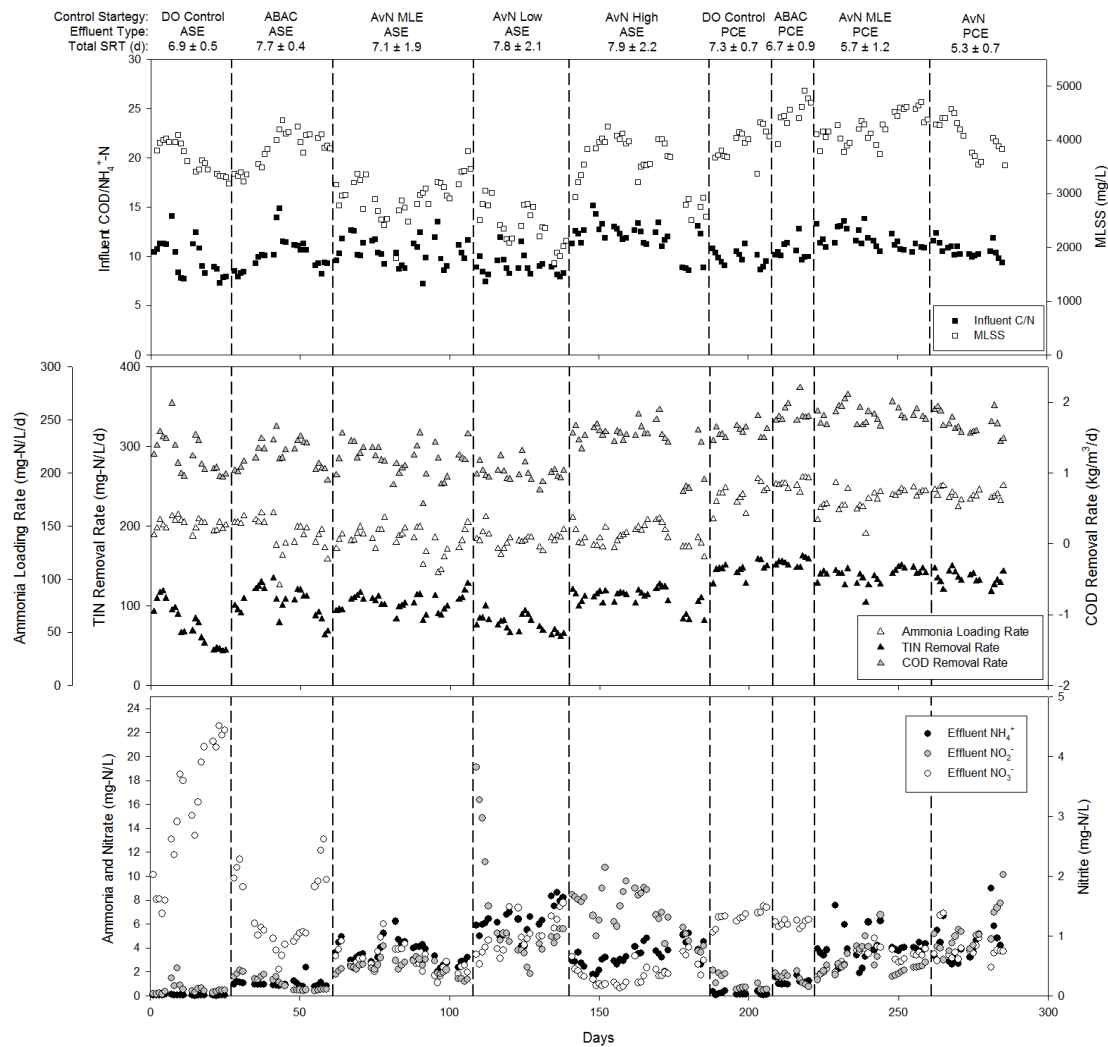
Table 2 – Influent Properties

Feed Type	A-Stage Effluent (ASE)					Primary Effluent (PCE)			
Control Strategy	DO Control	ABAC	AvN MLE	AvN Low	AvN High	DO Control	ABAC	AvN MLE	AvN
COD (mg/L)	311 ± 61	303 ± 40	303 ± 47	260 ± 23	356 ± 52	370 ± 18	424 ± 28	429 ± 28	401 ± 32
sCOD (mg/L)	146 ± 18	134 ± 22	138 ± 21	147 ± 17	169 ± 29	207 ± 21	223 ± 13	204 ± 20	210 ± 36
pCOD (mg/L)	166 ± 47	169 ± 25	165 ± 37	114 ± 17	186 ± 40	163 ± 23	198 ± 34	225 ± 29	192 ± 35
BOD (mg/L)	124 ± 30	109 ± 27	114 ± 21	115 ± 45	148 ± 50	159 ± 21	182 ± 4	202 ± 13	210 ± 29
TSS (mg/L)	103 ± 19	104 ± 14	109 ± 30	68 ± 13	107 ± 21	99 ± 8	104 ± 12	120 ± 18	107 ± 11
VSS (mg/L)	86 ± 17	86 ± 12	95 ± 29	62 ± 12	96 ± 18	84 ± 8	92 ± 13	103 ± 15	91 ± 12
TKN (mg-N/L)	39.6 ± 2.9	36.3 ± 4.7	38.4 ± 4.0	36.1 ± 4.0	34.6 ± 5.5	43.0 ± 3.1	43.8 ± 1.4	42.8 ± 1.5	44.4 ± 1.9
TAN (mg-N/L)	31.7 ± 1.2	30.0 ± 3.4	28.8 ± 2.6	28.8 ± 1.6	29.6 ± 2.0	37.7 ± 2.5	39.9 ± 1.0	36.7 ± 2.2	37.6 ± 1.1
TP (mg-P/L)	4.3 ± 0.4	4.0 ± 0.7	4.7 ± 0.7	4.0 ± 0.4	5.8 ± 3.2	5.5 ± 0.2	5.9 ± 0.6	5.7 ± 0.6	5.6 ± 0.3
OP (mg-P/L)	2.0 ± 0.6	2.3 ± 0.4	2.9 ± 1.0	2.9 ± 0.6	3.9 ± 0.6	3.8 ± 0.5	4.1 ± 0.5	3.7 ± 1.0	3.9 ± 0.3
Alkalinity (mg/L as CaCO <sub>3</sub> )	158 ± 5	151 ± 25	179 ± 13	164 ± 7	171 ± 14	202 ± 6	209 ± 5	200 ± 7	203 ± 8

DO Control achieved complete nitrification producing the lowest effluent ammonia and nitrite concentrations. Nitrate comprised the majority of effluent total inorganic nitrogen (TIN). Effluent nitrate concentrations were highest during DO\_MLE\_ASE at  $15.5 \pm 5.38$  mgNO<sub>3</sub><sup>-</sup>-N/L but much lower during DO\_MLE\_PCE at  $6.57 \pm 0.62$  mgNO<sub>3</sub><sup>-</sup>-N/L. This clearly demonstrates that a change in the influent feed type had a dramatic effect on the performance of the aeration strategy. The difference in nitrate concentrations suggests that there was a much greater amount of denitrification in the 1<sup>st</sup> CSTR when operating with PCE vs. ASE.

During operation of ABAC, effluent ammonia concentrations were maintained at  $1.01 \pm 0.33$  and  $1.19 \pm 0.26$  mg-N/L for ABAC\_MLE\_ASE and ABAC\_MLE\_PCE, respectively. During ABAC operation, lower effluent nitrate concentrations were observed when compared to DO Control. There was no sign of nitrite accumulation during operation of ABAC.

Operation of AvN in an MLE configuration produced a slight increase in the effluent nitrite concentration over DO Control and ABAC. Still, the average NAR during AvN\_MLE\_ASE and AvN\_MLE\_PCE was low at  $14 \pm 4\%$  and  $15 \pm 4\%$  respectively. AvN in the fully intermittent configuration produced the greatest nitrite accumulation with NARs of  $21 \pm 14\%$ ,  $22 \pm 7\%$ , and  $46 \pm 15\%$  for AvN\_FI\_ASE Low, AvN\_FI\_PCE, and AvN\_FI\_ASE High, respectively. AvN\_FI\_ASE Low, AvN\_FI\_PCE, and AvN\_FI\_ASE High produced effluent nitrite concentrations of  $1.30 \pm 0.92$ ,  $1.06 \pm 0.35$ , and  $1.41 \pm 0.38$  mg-N/L respectively. Out of the three phases of fully-intermittent operation of AvN, AvN\_FI\_ASE High had the lowest effluent TIN and best NOB out-selection.



**Figure 3 – A) Influent COD/NH<sub>4</sub><sup>+</sup>-N, MLSS B) Influent NH<sub>4</sub><sup>+</sup>-N Loading, TIN Removal Rate, and COD Removal Rate C) Effluent NH<sub>4</sub><sup>+</sup>-N, NO<sub>2</sub><sup>-</sup>-N, and NO<sub>3</sub><sup>-</sup>-N Concentrations**

During the entirety of AvN operation, average ammonia to NO<sub>x</sub> ratios were maintained near the setpoint value of 1.0. Due to this AvN maintained a greater ammonia residual than DO Control or ABAC. By controlling the waste rate, the average aerobic fraction was able to be maintained near 0.50 for operation of AvN in both fully-intermittent and MLE configurations. Since the 1<sup>st</sup> CSTR in the MLE configuration was an anoxic selector, the aerobic fraction was higher in the last three CSTRs to maintain the total aerobic fraction near 0.50. It was desired to keep the aerobic fraction near this value based off results from Batchelor’s work which deemed an aerobic fraction of 0.47 optimal for TN removal in an intermittently aerated system (Batchelor, 1983). Refer to Table 3 for a more comprehensive list of average effluent composition values.

Table 3 – Effluent Properties

Feed Type	A-Stage Effluent (ASE)					Primary Effluent (PCE)			
Control Strategy	DO Control	ABAC	AvN MLE	AvN Low	AvN High	DO Control	ABAC	AvN MLE	AvN
NH <sub>4</sub> <sup>+</sup> (mg-N/L)	0.06 ± 0.03	1.01 ± 0.33	3.58 ± 0.97	6.31 ± 1.27	3.35 ± 0.93	0.19 ± 0.12	1.19 ± 0.26	4.03 ± 1.24	4.40 ± 1.61
NO <sub>2</sub> <sup>-</sup> (mg-N/L)	0.11 ± 0.10	0.21 ± 0.12	0.48 ± 0.13	1.30 ± 0.92	1.41 ± 0.38	0.21 ± 0.12	0.30 ± 0.09	0.56 ± 0.24	1.06 ± 0.35
NO <sub>3</sub> <sup>-</sup> (mg-N/L)	15.5 ± 5.38	6.98 ± 3.12	3.01 ± 1.07	5.10 ± 1.51	1.86 ± 0.95	6.57 ± 0.62	6.04 ± 0.27	3.20 ± 0.81	3.94 ± 1.16
NAR (NO <sub>2</sub> <sup>-</sup> /NOx) (%)	N/A	N/A	14 ± 4	21 ± 14	46 ± 15	N/A	N/A	15 ± 4	22 ± 7
NOx/Ammonia Ratio	N/A	N/A	0.98 ± 0.18	1.02 ± 0.16	1.00 ± 0.24	N/A	N/A	1.03 ± 0.45	1.23 ± 0.34
OP (mg-P/L)	1.73 ± 0.35	1.74 ± 0.24	2.29 ± 0.75	2.39 ± 0.68	2.17 ± 0.67	2.11 ± 0.45	1.21 ± 0.41	0.31 ± 0.72	0.85 ± 0.95
TIN (mg-N/L)	15.7 ± 5.37	8.21 ± 3.13	7.07 ± 1.99	12.7 ± 2.41	6.62 ± 1.68	6.97 ± 0.58	7.53 ± 0.48	7.79 ± 1.52	9.40 ± 2.06
TN (mg-N/L)	20.3 ± 7.23	10.2 ± 3.30	10.9 ± 2.69	15.0 ± 2.45	9.40 ± 2.30	9.55 ± 0.74	9.17 ± 0.30	10.1 ± 1.77	12.0 ± 1.10
SVI 30 (mL/g)	85 ± 17	129 ± 9	149 ± 23	107 ± 23	157 ± 25	182 ± 23	186 ± 17	157 ± 20	164 ± 15
TSS (mg/L)	29 ± 6	20 ± 3	29 ± 6	26 ± 8	25 ± 11	18 ± 8	17 ± 7	22 ± 7	28 ± 16

### 4.3.2 Nitrogen Removal

Nitrogen removal performance for AvN in both fully-intermittent and MLE configurations was shown to be comparable to DO Control and ABAC in MLE configurations. Figure 4 illustrates that TIN removal was directly correlated with the influent COD/NH<sub>4</sub><sup>+</sup>-N (C/N) ratio. Feeding PCE resulted in greater nitrogen removal efficiency and more stability in performance than ASE. This is because PCE contained high influent COD concentrations saturating the BNR processes with substrate for denitrification.

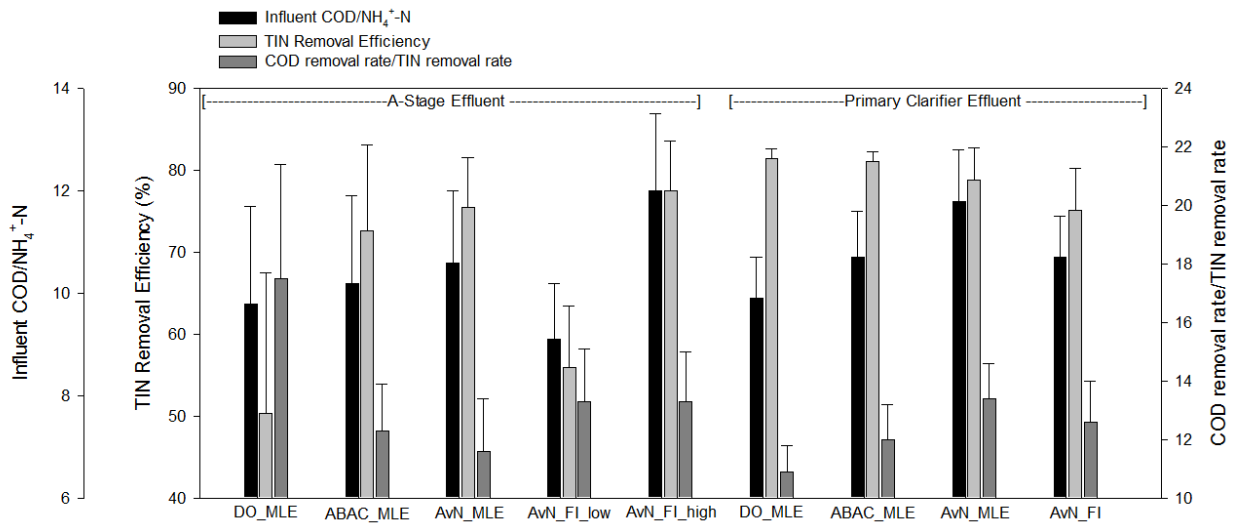


Figure 4 – Relationship between the Influent COD/NH<sub>4</sub><sup>+</sup>-N, TIN Removal Efficiency, and ratio of the COD removal rate/TIN removal rate. Error bars represent standard deviation.

DO\_MLE\_PCE and ABAC\_MLE\_PCE yielded the highest TIN removal efficiencies at 81.4 ± 1.2% and 81.1 ± 1.2% respectively. However, a large difference was observed in the nitrogen removal performance between DO control (50.4 ± 17.1%) and ABAC (72.6 ± 10.5%) when the two strategies were fed ASE. This was attributed to the low average DO concentration of ABAC operation (0.96 ± 0.38 mg/L) during this period. When DO Control and ABAC strategies were fed PCE, the increased ammonia loading rate caused the average DO concentration to increase under ABAC (1.47 ± 0.26 mg/L). This caused the

difference in nitrogen removal performance between DO Control and ABAC to diminish, further proving that the benefit of ABAC is only recognized if DO concentrations are kept low.

Both ABAC\_MLE\_ASE and AvN\_MLE\_ASE displayed similar nitrogen removal performance. Feeding ASE resulted in significantly reduced nitrogen removal performance during AvN\_FI\_ASE Low ( $55.9\% \pm 7.6$ ) with an influent C/N ratio of  $9.1 \pm 1.1$  mg COD/mg  $\text{NH}_4^+\text{-N}$ . When the influent C/N ratio was increased during AvN\_FI\_ASE High to  $12.0 \pm 1.5$ , removal performance was significantly improved ( $77.5 \pm 6.1\%$ ). Additional information on removal performance for each configuration may be found in Table 4.

**Table 4 – Loading Conditions and Removal Efficiencies**

Feed Type	A-Stage Effluent (ASE)					Primary Effluent (PCE)			
	DO Control	ABAC	AvN MLE	AvN Low	AvN High	DO Control	ABAC	AvN MLE	AvN
$\text{NH}_4^+\text{-N}$ loading rate (mg-N/L/d)	151 ± 6	143 ± 16	137 ± 13	137 ± 8	141 ± 10	179 ± 11	190 ± 5	175 ± 10	180 ± 5
Influent COD/ $\text{NH}_4^+\text{-N}$	9.8 ± 1.9	10.2 ± 1.7	10.6 ± 1.4	9.1 ± 1.1	12.0 ± 1.5	9.9 ± 0.8	10.7 ± 0.9	11.8 ± 1.0	10.7 ± 0.8
TIN removal rate (mg-N/L/d)	76 ± 26	104 ± 19	103 ± 11	77 ± 11	110 ± 12	146 ± 9	154 ± 5	138 ± 10	135 ± 9
TIN removal efficiency (%)	50.4 ± 17.1	72.6 ± 10.5	75.5 ± 6.0	55.9 ± 7.6	77.5 ± 6.1	81.4 ± 1.2	81.1 ± 1.2	78.8 ± 3.9	75.1 ± 5.1
COD removal rate/TIN removal rate	17.5 ± 3.9	12.3 ± 1.6	11.6 ± 1.8	13.3 ± 1.8	13.3 ± 1.7	10.9 ± 0.9	12.0 ± 1.2	13.4 ± 1.2	12.6 ± 1.4
OP removal efficiency (%)	11.5 ± 19.0	21.7 ± 13.0	19.3 ± 24.2	17.4 ± 14.6	41.2 ± 23.3	44.3 ± 13.5	70.1 ± 10.5	92.5 ± 17.7	79.0 ± 24.1
MLSS (mg/L)	3660 ± 290	3840 ± 330	2967 ± 377	2400 ± 380	3556 ± 505	3939 ± 268	4508 ± 278	4232 ± 279	4051 ± 339
Total SRT (days)	6.9 ± 0.5	7.7 ± 0.4	7.1 ± 1.9	7.8 ± 2.1	7.9 ± 2.2	7.3 ± 0.7	6.7 ± 0.9	5.7 ± 1.2	5.3 ± 0.7
Aerobic Fraction	0.75	0.75	0.43 ± 0.04	0.48 ± 0.06	0.45 ± 0.05	0.75	0.75	0.52 ± 0.09	0.52 ± 0.07
Aerobic SRT (days)	5.2 ± 0.4	5.7 ± 0.3	3.0 ± 0.8	4.0 ± 1.2	3.6 ± 1.0	5.5 ± 0.6	5.0 ± 0.6	3.0 ± 1.0	2.9 ± 0.7
Temperature in 1 <sup>st</sup> B-Stage CSTR (°C)	20.2 ± 0.2	20.2 ± 0.4	20.1 ± 0.3	20.1 ± 0.2	20.0 ± 0.4	20.8 ± 0.9	19.9 ± 0.3	20.4 ± 0.4	20.4 ± 0.3

### 4.3.3 Phosphorus Removal

AvN was shown to result in greater phosphorus removal than DO Control and ABAC (Table 4). Increased phosphorus removal efficiency was seen when strategies were fed PCE due to the increased influent sCOD concentration. The highest degree of phosphorus (measured as orthophosphate) removal over the course of the study was seen during operation of AvN\_MLE\_PCE ( $92.5 \pm 17.7\%$ ). The ability of AvN to perform phosphorus removal was a result of low NO<sub>x</sub> concentrations in the 1<sup>st</sup> CSTR and volatile fatty acids in PCE. Because AvN is an intermittent strategy, phosphorus release and uptake may have occurred during non-aerated and aerated phases respectively. Strategies operating in an MLE configuration may have seen greater nitrogen and lower phosphorus removal performance if IMLR rates were increased; however the maximum IMLR was limited to 300% of the influent flow due to hydraulic constraints.

### 4.3.4 COD Utilization Efficiency

The ratio of the COD removal rate to the TIN removal rate was used to compare each aeration strategy's ability to use COD as an internal carbon source for denitrification. Average values are shown in Figure 4

and Table 4. DO\_MLE\_PCE showed the most efficient use of carbon with the lowest ratio of  $10.9 \pm 0.9$  while DO\_MLE\_ASE exhibited the least efficiency with the highest ratio. AvN\_MLE\_ASE had the second lowest average ratio. Overall ABAC resulted in lower COD to TIN removal rate ratios than fully-intermittent AvN.

Strategies in MLE configurations have the ability to consume COD under anoxic conditions in the 1<sup>st</sup> CSTR increasing efficiency of COD use for denitrification. However, a strategy like fully-intermittent AvN, without a dedicated anoxic zone, mineralized any readily biodegradable COD (rbCOD) present in the influent wastewater during aerated periods. This explains some of the higher COD removal/TIN removal ratios during these scenarios.

The COD removal/TIN removal ratio and TIN removal efficiency were both dependent on the amount and type of influent COD. The amount of influent COD is important because inefficiency can result from either overfeeding or underfeeding COD. If COD is in excess, a large portion of it will be removed aerobically as it's converted to carbon dioxide. If COD is limiting, not enough substrate will be present to perform sufficient nitrogen removal.

The type of COD also has an important role as aeration processes in MLE configurations use rbCOD present in the influent wastewater to perform denitrification in the anoxic selector. This is where the majority of nitrogen removal occurs under DO Control as oxygen concentrations in downstream reactors are too high to achieve significant SND. Good correlation was observed between the influent sCOD concentration and TIN removal efficiency during DO\_MLE\_ASE ( $r = 0.610$ ).

Particulate or slowly biodegradable COD (sbCOD) is important for processes where nitrogen removal is designed to occur in downstream reactors as is the case with ABAC and AvN Control. During ABAC, operation at low DO concentrations allow for nitrogen removal via SND. As sbCOD is hydrolyzed into more readily absorbed forms in downstream reactors, sufficient COD for denitrification is maintained. In the same manner, during AvN operation, sbCOD may be hydrolyzed during aerated phases and consumed in a more readily degradable form during anoxic phases. Correlation values between the influent pCOD and TIN removal were high during both ABAC\_MLE\_ASE ( $r = 0.681$ ) and for the combined data from AvN\_FI\_ASE Low and High ( $r = 0.843$ ).

When the data for AvN\_FI\_ASE Low and High are combined there was a small correlation between sCOD and TIN removal ( $r = 0.486$ ), but less of a correlation existed when the phases were examined separately ( $r = 0.104$  and  $0.404$  for ASE Low and High respectively). This is because during the aerated period any rbCOD present in the influent wastewater was quickly mineralized in the 1<sup>st</sup> CSTR through heterotrophic activity.

When strategies like ABAC and AvN are operated in an MLE configuration, they have the ability to take advantage of both rbCOD and sbCOD for nitrogen removal. This is indicated by the strong correlation between both sCOD and pCOD and TIN removal for ABAC\_MLE\_ASE ( $r = 0.720$  and  $0.681$  respectively). A strong correlation with either COD fraction was not observed during AvN\_MLE\_ASE. This was most likely



due to excessive feeding of COD suggesting that operation of AvN in an MLE configuration could have been performed at lower influent C/N ratios.

Whether COD directed to the B-Stage is used under aerobic or anoxic conditions, it takes up space in the form of mixed liquor suspended solids (MLSS). Because of this, increased COD loading requires increased aeration tank volume regardless of how efficiently the COD is used. For a fixed secondary clarifier volume and total SRT, the MLSS is determined by the influent COD and suspended solids load. So a tradeoff exists in the B-Stage between nitrogen removal efficiency and capacity of the existing basin.

More efficient utilization of COD for denitrification is not only a benefit in terms of nitrogen removal, but can allow for more COD capture in the A-Stage process which can be rerouted for energy production (from methane generated during anaerobic digestion). The dilemma is whether to decrease COD loading to the B-Stage in order to maximize carbon diversion for energy recovery and minimize volume requirements or increase COD loading to maximize BNR performance. The answer will be unique to every treatment facility and may require compromise depending on the value placed on each criterion (energy, volume, and BNR).

#### 4.3.5 Alkalinity Consumption

A comparison of the alkalinity requirements for each configuration is shown in Table 5. AvN\_FI\_ASE High resulted in the least amount of alkalinity addition at  $3.92 \pm 0.53$  mg CaCO<sub>3</sub> added/mg NH<sub>4</sub><sup>+</sup>-N removed. More supplemental alkalinity was required for continuous aeration strategies as AvN was shown to require less alkalinity addition than DO Control and slightly less than ABAC. It was difficult to distinguish whether the AvN, MLE or fully-intermittent configurations, significantly affected the amount of supplemental alkalinity required. Feeding PCE resulted in less alkalinity addition than when strategies were fed ASE. AvN\_MLE\_PCE resulted in the lowest required alkalinity addition at  $17 \pm 14$  mg CaCO<sub>3</sub>/L.

Low influent C/N ratios resulted in a greater supplemental alkalinity requirement due to less alkalinity production from heterotrophic denitrification. PCE contained a large concentration of sCOD compared to that of ASE; therefore strategies fed with PCE saw greater alkalinity return in the first CSTR. Higher influent alkalinity concentrations in PCE compared to ASE also led to less required alkalinity addition for each strategy. AvN required less supplemental alkalinity than ABAC and DO Control due to the higher concentrations of residual ammonia. Alkalinity production during non-aerated periods may have also aided in this reduced requirement.

Table 5 – Comparison of Alkalinity Requirements

Feed Type	A-Stage Effluent (ASE)					Primary Effluent (PCE)				
	Control Strategy	DO Control	ABAC	AvN MLE	AvN Low	AvN High	DO Control	ABAC	AvN MLE	AvN
Effluent pH		6.81 ± 0.06	6.80 ± 0.04	6.79 ± 0.06	6.77 ± 0.07	6.81 ± 0.06	6.85 ± 0.15	6.75 ± 0.10	6.81 ± 0.07	6.70 ± 0.15
Influent NH <sub>4</sub> <sup>+</sup> -N (mg-N/L)		31.7 ± 1.2	30.0 ± 3.4	28.7 ± 2.6	28.8 ± 1.6	29.6 ± 2.0	37.5 ± 2.3	39.9 ± 1.0	36.7 ± 2.2	37.6 ± 1.1
Effluent NH <sub>4</sub> <sup>+</sup> -N (mg-N/L)		0.06 ± 0.03	1.01 ± 0.33	3.58 ± 0.97	6.31 ± 1.27	3.35 ± 0.93	0.19 ± 0.12	1.19 ± 0.26	4.03 ± 1.24	4.40 ± 1.61
TAN Oxidized (mg-N/L)		31.7 ± 1.2	28.9 ± 3.4	25.1 ± 2.4	22.5 ± 1.7	26.2 ± 2.2	37.3 ± 2.3	38.7 ± 1.0	32.7 ± 2.0	33.2 ± 1.8
Influent Alkalinity (mg CaCO <sub>3</sub> /L)		158 ± 4.8	151 ± 25	179 ± 13	164 ± 7	171 ± 14	203 ± 6	209 ± 5	200 ± 7	203 ± 8
Effluent Alkalinity (mg CaCO <sub>3</sub> /L)		108 ± 5.5	123 ± 22	127 ± 15	118 ± 11	114 ± 10	114 ± 47	107 ± 15	86 ± 10	90 ± 3
Bicarbonate Feed (mg CaCO <sub>3</sub> /L)		122 ± 22	95 ± 24	60 ± 12	51 ± 15	40 ± 12	59 ± 23	77 ± 10	17 ± 14	26 ± 14
Alkalinity Added/TAN Oxidized (mg CaCO <sub>3</sub> added/mg NH <sub>4</sub> <sup>+</sup> -N Removed)		5.37 ± 0.69	4.39 ± 0.57	4.40 ± 0.30	4.43 ± 0.28	3.92 ± 0.53	4.38 ± 0.38	4.48 ± 0.10	4.02 ± 0.23	4.17 ± 0.33

### 4.3.6 Molecular Results

Over the course of the study *Nitrobacter*, AOB, and total bacteria populations remained consistent. *Nitrobacter* populations were greater than *Nitrospira* populations. This is opposite to conditions observed in the study by Regmi et al. 2014. The abundance of *Nitrospira* declined during periods of effective NOB suppression. Figure 5 shows effective suppression was achieved during AvN\_FI\_ASE High from day 141 until day 165. During this period the NAR reached a maximum of 70% making effluent well-suited for post treatment in the Anammox MBBR. By providing non-limiting substrate conditions *Nitrospira*, a K-strategist, was able to be out-selected. Activity measurements for AOB and NOB shown in Figure 6 indicated periods of NOB suppression. Higher mixed liquor concentrations led to reduced specific activity rates for AOB (r = 0.820).

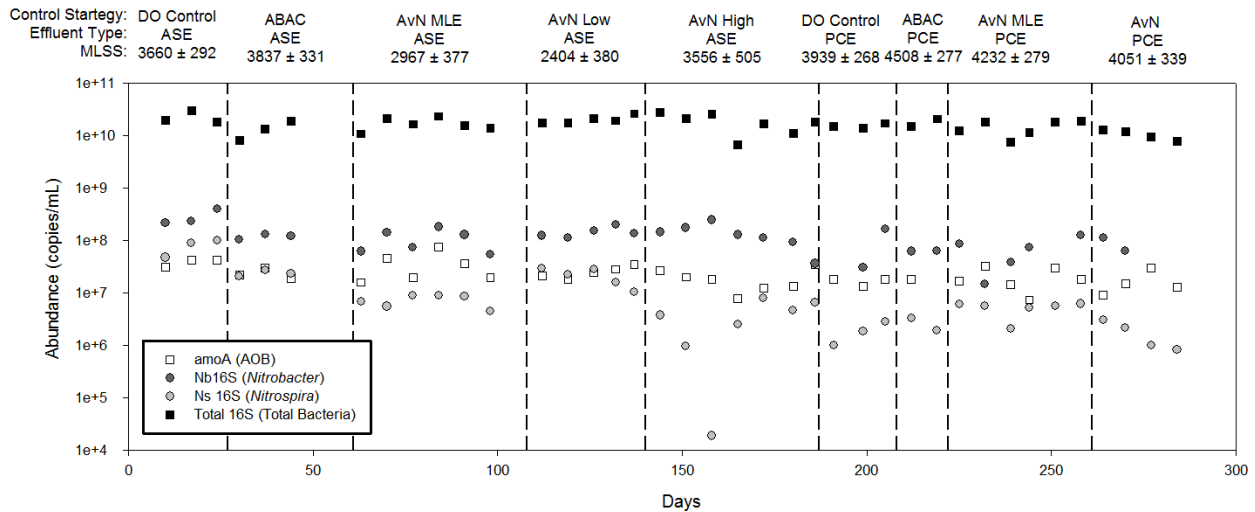


Figure 5 – Molecular analysis for AOB, NOB, and Total Bacteria populations

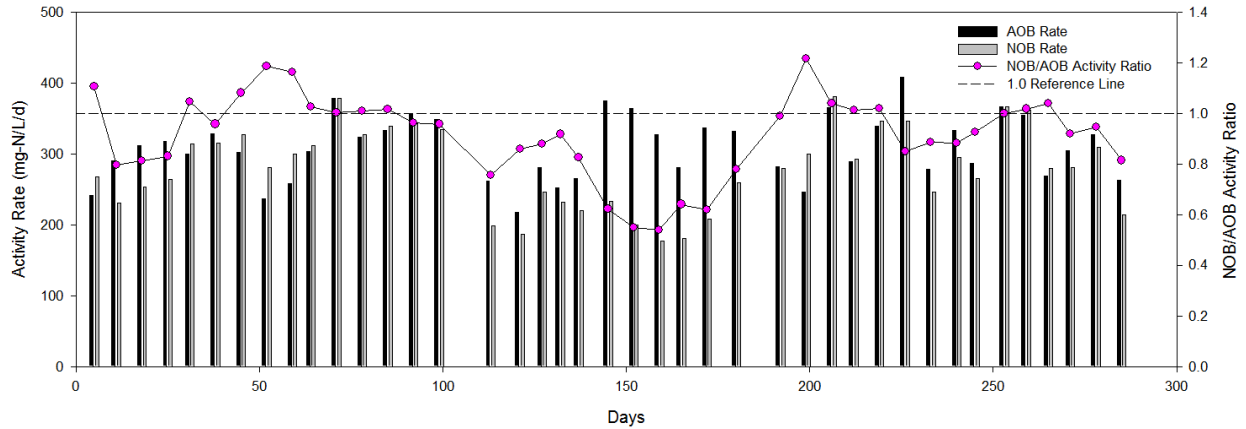


Figure 6 – AOB and NOB Maximum Activity Rates

#### 4.3.7 Nitrite Accumulation and Oxygen Uptake Rate

The influent pCOD fraction also had a strong correlation with NAR during operation of fully-intermittent AvN (Figure 7a). The increased pCOD fraction helped to maintain high oxygen uptake rates (OUR) encouraging heterotrophic competition with NOB for substrate ( $O_2$  and  $NO_2^-$ ) during transition to non-aerated periods. Since pCOD is not consumed as quickly, higher pCOD fractions may also reduce heterotrophic competition with AOB for substrate ( $O_2$ ) and space during aerated periods allowing AOB to operate near maximum activity. As shown in Figures 7c and 7d there was no obvious benefit of feeding pCOD concentrations above 200 mg COD/L with respect to both NAR and TIN Removal. This motivates appropriate COD control to B-Stage processes.

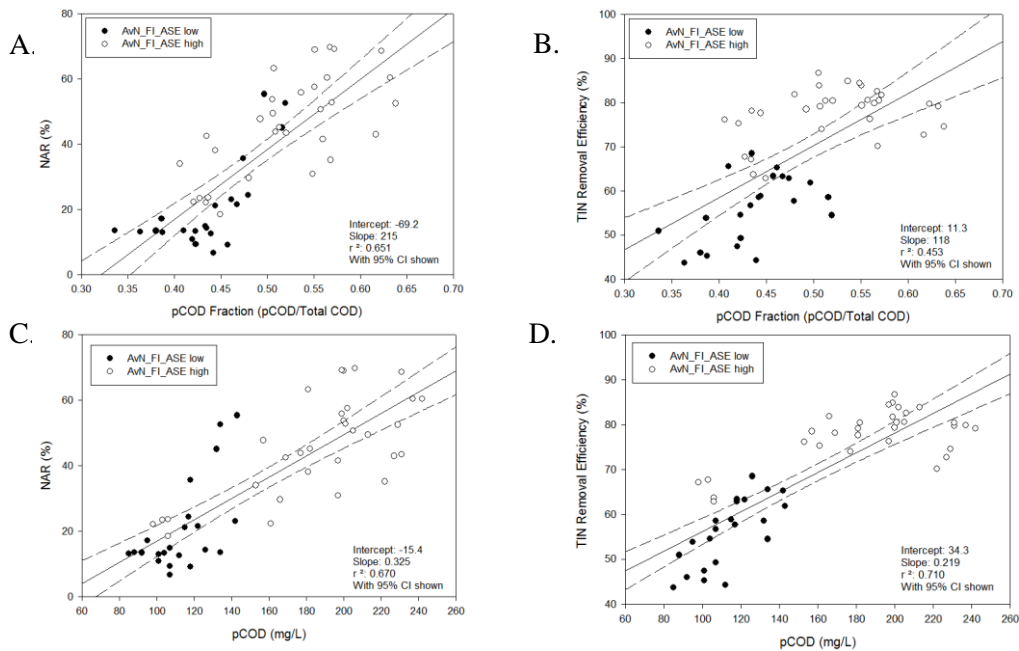


Figure 7 – Combined data from AvN\_FI\_ASE Low and AvN\_FI\_ASE High – a) NAR vs. pCOD fraction b) TIN removal vs. pCOD fraction c) NAR vs. pCOD and d) TIN removal vs. pCOD

The OUR was found to be an important predictor of nitrite accumulation in fully-intermittent AvN operation. The plots in Figure 8 indicated that for fully-intermittent AvN operation there was an optimum OUR range for each B-Stage CSTR providing a maximum effluent NAR. The ability of pCOD to maintain OUR throughout the system maintains heterotrophic pressure on NOB. However, step-feeding of COD to the fully-intermittent AvN process could allow the A-Stage to operate with greater COD removal. This would maintain high OUR and possibly reduce the need to feed a high particulate fraction.

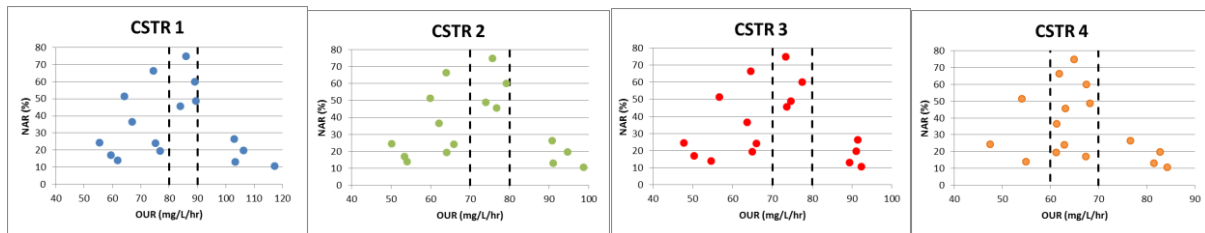


Figure 8 – Effluent NAR vs. OUR in each B-Stage CSTR

Compared to fully-intermittent operation, AvN in a MLE configuration resulted in decreased NAR shown in Figure 9a. This was also previously reported in a study where the NAR for AvN in an MLE configuration was found to decrease as IMLR rates increased (Fredericks, 2014). The lack of nitrite accumulation during operation in MLE configuration may be due to the increased aerobic fraction which the last three reactors had to achieve in order to maintain the ammonia/NO<sub>x</sub> ratio. The higher aerobic fraction may not provide an anoxic period long enough to permit effective heterotrophic competition with NOB or to initiate a lag in NOB response (due to enzymatic activity or substrate limitation) once the aerobic period returns (Gilbert et al, 2014; Malovany et al, 2014).

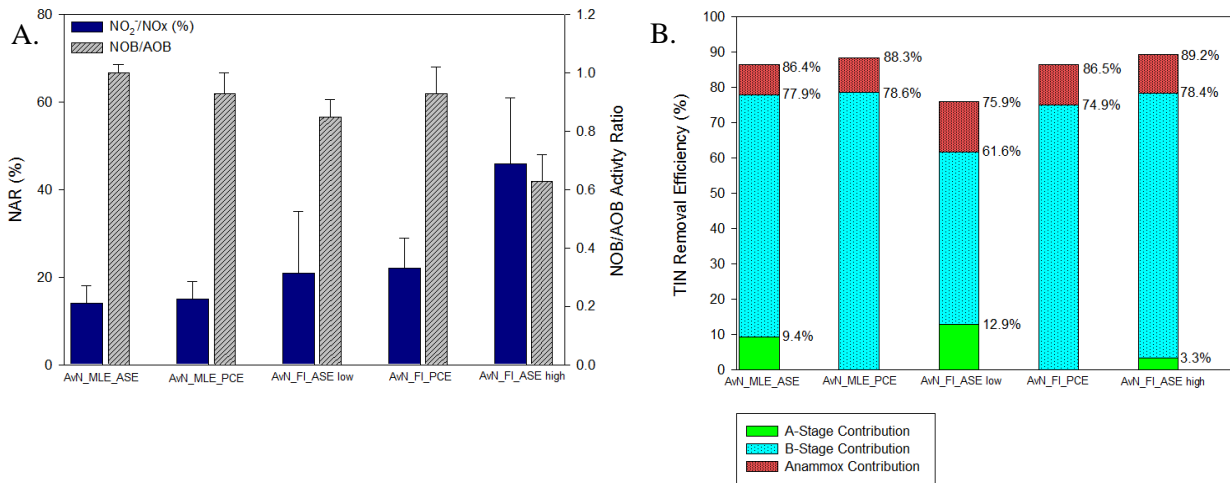


Figure 9 – a) Average NOB/AOB Ratio and NAR for all of AvN operation b) Nitrogen Removal Efficiency with respect to the RWI TAN concentration during all AvN operating modes

Although fully-intermittent AvN produced a greater NAR, it is clear that NOB suppression was significantly greater during AvN\_FI\_ASE High compared with that of AvN\_FI\_ASE Low or AvN\_FI\_PCE. The reason for low NOB suppression during operation of AvN\_FI\_ASE Low may have been that influent pCOD concentrations were insufficient to maintain high OUR in downstream reactors (OUR values are listed in Table 6). This kept AOB rates high but may have resulted in less heterotrophic competition with NOB for substrate as indicated by the low denitrification rate (2.95 mgNO<sub>x</sub>-N/gMLSS/hr) compared to that of AvN\_FI\_ASE High (3.48 mgNO<sub>x</sub>-N/gMLSS/hr).

Table 6 – Comparison of fully-intermittent AvN Modes

Aeration Strategy	AvN_FI_ASE Low	AvN_FI_PCE	AvN_FI_ASE High
Influent COD/NH <sub>4</sub> <sup>+</sup> -N	9.1 ± 1.1	10.7 ± 0.8	12.0 ± 1.5
Influent sCOD Fraction (%)	56 ± 5	52 ± 8	48 ± 7
AOB rate (mgNO <sub>x</sub> -N/gMLSS/hr)	4.62 ± 0.83	3.06 ± 0.53	3.89 ± 0.58
NO <sub>x</sub> removal rate (mg NO <sub>x</sub> -N/gMLSS/hr)	2.95 ± 0.66	3.52 ± 0.38	3.48 ± 0.81
NOB rate/AOB rate	0.85 ± 0.06	0.93 ± 0.09	0.63 ± 0.09
NAR (NO <sub>2</sub> <sup>-</sup> /NO <sub>x</sub> ) (%)	21 ± 14	22 ± 7	46 ± 15
TIN removal efficiency (%)	55.9 ± 7.6	75.1 ± 5.1	77.5 ± 6.1
Average OUR (mg/L/hr)	57.9 ± 5.9	74.6 ± 9.8	71.6 ± 5.8

The reason for low NOB suppression during AvN\_FI\_PCE could stem from the high influent sCOD concentrations that may have led to increased rates of heterotrophic activity indicated by the increased oxygen uptake and denitrification rates (Table 6). Increased heterotrophic activity may have led to competition with AOB as indicated by the reduced AOB rates (3.06 mgNO<sub>x</sub>-N/gMLSS/hr) compared to that of AvN\_FI\_ASE High (3.89 mgNO<sub>x</sub>-N/gMLSS/hr). The increased sCOD load also hindered TIN removal performance shown by a negative correlation value of (r = -0.409).

By maintaining similar AOB and denitrification rates, both high NAR and nitrogen removal was achieved during AvN\_FI\_ASE High. During this phase *Nitrospira* was out selected due to the effects of transient

anoxia and heterotrophic pressure on NOB while maintaining high DO concentrations (1.5 mg/L) and residual ammonia to keep AOB rates high (Figure 6). When effluent from AvN\_FI\_ASE High was fed to the Anammox MBBR, the average TIN removal was  $88.7 \pm 5.7\%$  (B-Stage + Anammox) (Figure 10b).

Effluent from DO Control and ABAC is not suitable for post treatment with Anammox bacteria due to substrate limitation in the MBBR (Godwin, 2015). Therefore the combination of AvN with an Anammox MBBR (AvN+) yields better overall nitrogen removal performance compared to DO Control and ABAC. The ability of the AvN strategy to provide equal parts ammonia and NO<sub>x</sub> prevents substrate limitation resulting in high removal efficiency as seen in Figure 9b.

#### 4.3.8 ASE vs. PCE

The A-Stage removes both rbCOD and sbCOD primarily through bioflocculation and intracellular storage (Miller et al, 2012). Mineralization also accounts for removal of rbCOD in the A-Stage. Primary clarification removes COD through gravitational settling based on particle size and density. Therefore it removes much of the sbCOD and retains the rbCOD. The type of influent feed each process provides determines performance in the BNR process. Primary clarification removes anywhere from 20-30% of the influent COD on average. In this study 33% COD removal was achieved during operation with PCE.

During operation with ASE, the A-Stage removed an average of 43% of the influent COD. The A-Stage has the potential to remove much greater concentrations of COD ( $\leq 80\%$ ) but for the purposes of this study COD removal was controlled. In a similar manner because the effluent C/N ratios from both processes were similar there was little difference in the removal of suspended solids between the A-Stage process (49% TSS removal) and the primary clarifier (48% TSS removal).

Figure 10a illustrates that sCOD and pCOD concentrations in ASE vary based on the desired effluent C/N ratio (DeArmond, 2015). When higher effluent C/N ratios are desired, an increased effluent pCOD fraction exists. The ability of the A-Stage to remove much of the rbCOD is beneficial for processes like fully-intermittent AvN which rely on sbCOD to maintain substrate for denitrification in downstream reactors. Compared with performance of an A-Stage process, primary clarification removes only pCOD while the sCOD concentration remains consistent as seen in Figure 10b. Assimilation in the A-Stage accounts for a reduction in the ammonia load to the B-Stage. Increased COD removal in the A-Stage is correlated with ammonia removal ( $r = 0.487$ ).

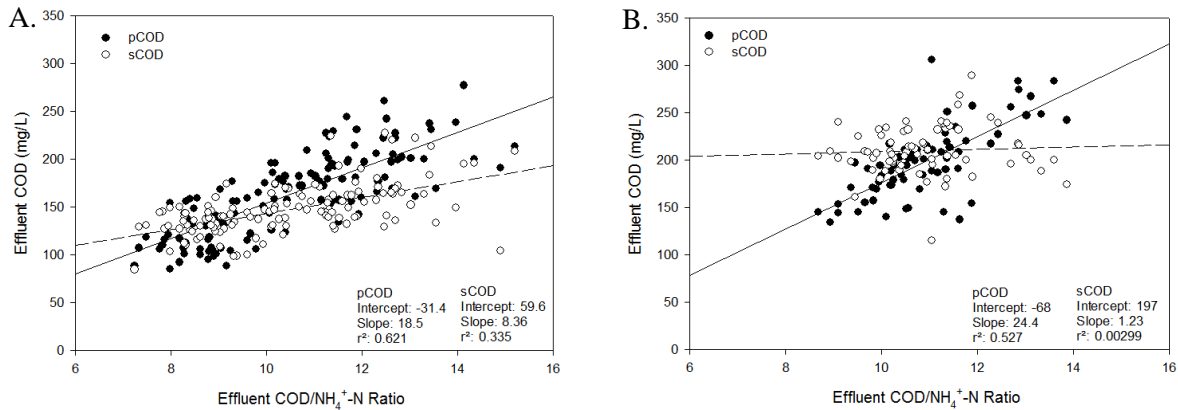


Figure 10 – a) ASE COD Type vs. Effluent C/N Ratio, b) PCE COD Type vs. Effluent C/N Ratio

By containing higher influent rbCOD concentrations, PCE leads to increased heterotrophic competition with nitrifiers for oxygen and space in the B-Stage. This results in lower nitrification activity rates and therefore requires a longer SRT or HRT. For this reason feeding PCE will also result in higher mixed liquor concentrations in B-Stage. In order to reduce the suspended solids concentration the SRT would need to be decreased, but this poses a risk to nitrifier wash-out and reduces the nitrification safety factor. Activity rates can be increased by increasing the dissolved oxygen concentration; however DO concentrations greater than 2.0 mg/L are reported to have very little effect on nitrifier growth rates (Stenstrom et al, 1980).

The ability of the A-Stage to operate in a manner that controls the influent C/N ratio avoids overloading a B-Stage with carbon while increasing the amount of carbon redirected for energy recovery. Feeding PCE can result in improved nutrient removal performance due to increased COD loading; however the COD not used for nutrient removal is lost due to mineralization by heterotrophic activity. The addition of polymer for chemically enhanced primary treatment (CEPT) has the ability to increase COD efficiency in BNR processes fed primary effluent, while control of the dosage may also allow for control of the effluent C/N ratio in primary effluent. This should be explored in future work.

#### 4.4 Conclusions

- Effective out-selection of *Nitrospira* was achieved with fully-intermittent AvN operation at 20°C.
- A high influent pCOD fraction was directly related to the NAR with fully-intermittent AvN operation.
- Effluent from the AvN strategy was amenable to Anammox polishing for additional TIN removal.
- AvN in either configuration required less supplemental alkalinity than DO Control or ABAC.

- Performance of ABAC approaches that of DO Control as ammonia loading rate increases.
- The COD removal/TIN removal ratio and TIN removal efficiency are affected by both the type and amount of influent COD
- More efficient utilization of COD for denitrification is not only a benefit in terms of nitrogen removal and energy recovery, but also tank size required in the BNR process.
- More operator knowledge and specialized sensors are required as you move from operation of DO Control to ABAC to AvN Control.
- PCE provides better nitrogen and phosphorus removal performance than ASE for operation of BNR processes in an MLE configuration.
- The ability of the A-Stage to control the effluent C/N ratio and remove sCOD makes it a good option for nitrite shunt and SND-style processes like fully-intermittent AvN and ABAC.

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## 5. Engineering Significance

Population growth, and the development that follows, is placing increasing strain on the nation's waterways. Increased environmental regulation over the past decade has aimed to restore sensitive watersheds by improving water quality. One of the targeted areas for improvement includes wastewater discharge for its ability to be measured and controlled. Historically wastewater treatment only aimed to achieve the removal of oxygen demand and solids from the water. In time, knowledge of the impacts of discharging limiting nutrients, such as nitrogen and phosphorus, led to increased nutrient removal requirements in specific areas.

Today TMDLs allocate the amount of nutrients and sediment a waterbody can receive without degradation. These TMDLs are becoming increasingly stringent, especially within the Chesapeake Bay watershed. This is pushing wastewater treatment authorities like HRSD and DC Water to innovate. The necessity to improve removal performance drives the development of new technology for greater control and monitoring at treatment facilities. Advanced technology, aiming to make wastewater treatment more sustainable, has been present in Europe for quite some time. Application is slowly transitioning to use in the US as restrictions on discharge limits tighten. The necessity for improved treatment performance is also leading to the development of new design processes and aeration strategies. Operation of these processes hopes to increase efficiency with regards to electricity consumption and external dosage in order to prevent significant cost increase to both the utility and the consumer.

The A/B process studied in this experiment consisted of a HRAS A-Stage for carbon removal, a B-Stage for BNR, and an Anammox MBBR for effluent polishing. This study compared three aeration strategies in the B-Stage: DO Control, ABAC, and AvN. Performance of each strategy was evaluated separately with A-Stage effluent and primary effluent. Results of this study will aid in modeling efforts as well as the design and upgrade of wastewater treatment plants. The comparison will lead to improved nutrient removal performance as wastewater treatment facilities recognize the benefit of switching from conventional DO Control to that of ABAC or AvN. Supplemental alkalinity and external carbon addition are expensive additives for operation of WWTPs and decreasing or eliminating their requirement can dramatically reduce costs. The study discusses how influent feed for each strategy affects efficiency in operation with regard to alkalinity addition and COD usage.

This research also highlights that the A-Stage can successfully be used in conjunction with BNR processes. Its ability to control the C/N ratio makes it an important consideration for full-scale implementation in the US. Currently in the US there is a push towards intensification of treatment processes in order to improve performance without sacrificing efficiency. The ability of the A-Stage to capture large quantities of COD allows significant energy return through methane generation. Reduced COD loading also allows the B-Stage to be operated at smaller volumes than typical BNR processes therefore reducing construction costs and the overall footprint. However, carbon removal upstream necessitates operation of innovative BNR strategies in the B-Stage to perform high degrees of removal

under carbon-limited conditions. Removing COD upstream also allows for a reduction in volume of B-Stage processes, reducing the energy required for BNR, and allowing for operation at reduced HRT and SRT.

Sidestream processes achieving removal via nitrite shunt or deammonification are readily available. This is because NOB out-selection in sidestream conditions is well understood. This research adds to knowledge of mainstream NOB out-selection which is more difficult to achieve. The ability of AvN to be operated in a way which out-selects NOB makes it a viable mainstream partial nitrification process. In combination with an Anammox MBBR, AvN provides a practical two-stage solution to mainstream deammonification. This could result in energy-neutral treatment within the US, as mainstream deammonification is currently the most sustainable nitrogen removal process. In order for mainstream deammonification to achieve near complete nitrogen removal, the partial nitrification step must produce an effluent containing equal parts ammonia and nitrite. The amount removed by Anammox will then depend on the limiting substrate present.

During the study the B-Stage was operated at 20°C. The benefit of ABAC over DO Control was recognized at low ammonia loading rates when low DO concentrations resulted in SND. Many full-scale plants operate at lower ammonia loading rates than those presented in this study. These plants could realize significant advantages by switching from a strategy like DO Control to one of ABAC including savings in alkalinity addition, improved nitrogen and phosphorus removal efficiencies, and improved COD utilization efficiency.

AvN was found to result in comparable nitrogen removal efficiency and better phosphorus removal efficiency than DO Control and ABAC. AvN also required less supplemental alkalinity addition than DO Control or ABAC. No external carbon sources were used during the study. When carbon in wastewater is present in excessive concentrations too much may be oxidized aerobically; resulting in inefficiency and increased biomass production. The efficiency of COD use for denitrification and TIN removal efficiency were both dependent on the type and amount of influent COD. The combination between configuration of the B-Stage and aeration strategy allow BNR processes to benefit from different types of influent COD.

As opposed to high correlations with sCOD for strategies operating in MLE configurations, only high correlation between influent pCOD and TIN removal was seen during fully-intermittent AvN operation. The influent pCOD fraction under fully-intermittent AvN operation also had a strong correlation with NAR. *Nitrospira* populations were significantly reduced during AvN\_FI\_ASE High due to the effects of transient anoxia and heterotrophic pressure on NOB while at the same time maintaining high DO concentrations (1.5 mg/L) and residual ammonia to keep AOB rates high relative to NOB. AvN in a MLE configuration resulted in decreased NAR compared to fully-intermittent AvN but resulted in slightly higher TIN removal for the configuration's ability to utilize sCOD present in the influent wastewater. The ability of the AvN controller to provide equal parts ammonia and NOx prevented substrate limitation within the Anammox MBBR resulted in high TIN removal efficiency. The combination of AvN with an Anammox MBBR (AvN+) yielded superior performance to that of DO Control and ABAC in regards to TIN removal.

Future work in the B-Stage should include the measurement of airflow rates to highlight which strategies conserve the most in regards to aeration. AvN must also be studied at temperatures less than 20°C. Since NOB growth rates are greater than AOB at these temperatures, successful NOB suppression at these temperatures will be difficult. Ongoing efforts to quantify N<sub>2</sub>O and NO production during AvN operation are being made. NO should also be studied for its role or effect in NOB suppression during AvN operation. AvN should be run as a continuous aeration strategy as modeling efforts as well as CE pilot data have shown that this can also provide significant NOB suppression. If the A-Stage could be operated to achieve effluent C/N ratios between 9-10 with a high particulate COD fraction, more sustainable process control using AvN could be achieved in the B-Stage. In addition, a step-feed configuration, in which a portion of influent flow is diverted to downstream reactors, may provide successful NOB suppression at lower C/N ratios during AvN operation.

A method for linking nutrient removal performance in the B-Stage with operation of the A-Stage should be sought. This would allow the B-Stage performance to dictate performance of the A-Stage so that both strategies operate near maximum efficiency. From the research it is clear that control of the C/N ratio is important to maintaining high activity rates in the B-Stage. This makes an A-Stage process advantageous compared to primary effluent which can overload the BNR process with COD. To reduce the effects of excessive COD loading on the B-Stage an additional area of research includes using polymer dosage for CEPT to control the C/N ratio from the primary clarifier to the BNR process.

Full-scale applicability of the AvN process is very possible. The complexity of AvN process control could require more skilled operators at WWTPs in order to maintain sensor calibration and understand the effects of control on process performance. However intermittent aeration may be difficult to achieve full-scale due to physical wear caused by on/off operation of blowers or valves.

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## A.1 Data Collection during DO\_MLE\_ASE

### A.1.1 Performance Data

Removal Performance									
Date	Days	NH <sub>4</sub> <sup>+</sup> -N loading rate (mg-N/L/d)	Influent COD/NH <sub>4</sub> <sup>+</sup> -N	TIN removal rate (mg-N/L/d)	TIN removal Efficiency (%)	COD removal rate (mg/L/d)	COD removal rate/TIN removal rate	OP removal Efficiency (%)	Calculated AOB rate (mg-N/L/d)
<b>Average</b>		151.2	9.8	76.4	50.4	1255	17.5	11.5	163
<b>Sample SD</b>		5.5	1.9	26.1	17.1	278	3.9	19.0	5
28-Sep-14	1	141.7	10.4	93.0	65.6	1262	13.6	22.8	
29-Sep-14	2	147.9	10.7	109.0	73.7	1388	12.7	31.2	156
30-Sep-14	3	156.0	11.3	116.7	74.8	1579	13.5	31.4	158
1-Oct-14	4	151.2	11.3	118.0	78.0	1509	12.8	32.3	159
2-Oct-14	5	148.3	11.3	109.3	73.7	1483	13.6	36.3	154
3-Oct-14	6								
26-Oct-14	7	159.3	14.1	94.9	59.6	1984	20.9	15.4	
27-Oct-14	8	155.0	10.5	97.7	63.0	1391	14.2	25.2	164
28-Oct-14	9	161.2	8.4	89.4	55.4	1138	12.7	4.8	171
29-Oct-14	10	155.5	7.8	66.2	42.6	997	15.1	-4.3	165
30-Oct-14	11	153.6	7.8	67.2	43.8	955	14.2	16.5	164
31-Oct-14	12								
1-Nov-14	13								
2-Nov-14	14	140.7	11.3	68.3	48.5	1235	18.1	15.3	
3-Nov-14	15	147.9	12.5	83.5	56.5	1535	18.4	37.1	161
4-Nov-14	16	156.5	10.9	78.5	50.1	1456	18.6	9.8	172
5-Nov-14	17	153.6	9.0	59.7	38.9	1121	18.8	-25.2	166
6-Nov-14	18	153.1	8.3	53.2	34.7	1051	19.8	-5.5	166
7-Nov-14	19								
8-Nov-14	20								
9-Nov-14	21	145.5	9.0	43.7	30.0	1058	24.2	-20.8	
10-Nov-14	22	146.0	8.7	46.5	31.9	1075	23.1	5.4	159
11-Nov-14	23	153.6	7.3	45.4	29.6	953	21.0	20.4	169
12-Nov-14	24	147.4	7.9	42.8	29.1	944	22.0	-14.6	161
13-Nov-14	25	150.7	7.9	44.2	29.3	979	22.1	-3.9	166
14-Nov-14	26								



### A.1.2 Operational Conditions

Operational Conditions							
Date	Days	Temperature in 1st CSTR (°C)	MLSS (mg/L)	VSS (mg/L)	Total SRT (days)	Aerobic Fraction	Aerobic SRT (days)
<b>Average</b>		20.2	3660	2854	6.9	0.75	5.2
<b>Sample SD</b>		0.2	292	240	0.5	0.00	0.3
28-Sep-14	1					0.75	
29-Sep-14	2	20.3	3810	3005	7.6	0.75	5.70
30-Sep-14	3	20.2	3945	3120	6.9	0.75	5.14
1-Oct-14	4	19.9	4000	3165	7.8	0.75	5.81
2-Oct-14	5	20.6	4025	3170	7.4	0.75	5.56
3-Oct-14	6	20.2	3965	3135	7.3	0.75	5.45
26-Oct-14	7					0.75	
27-Oct-14	8	20.2	3965	3050	6.7	0.75	5.04
28-Oct-14	9	20.1	4095	3180	7.2	0.75	5.42
29-Oct-14	10	20.3	3940	3030	7.2	0.75	5.43
30-Oct-14	11	20.2	3795	2950	7.4	0.75	5.58
31-Oct-14	12	20.0	3615	2780	6.9	0.75	5.15
1-Nov-14	13					0.75	
2-Nov-14	14					0.75	
3-Nov-14	15	19.8	3415	2680	6.1	0.75	4.57
4-Nov-14	16	20.2	3455	2655	6.3	0.75	4.73
5-Nov-14	17	20.2	3620	2825	6.6	0.75	4.93
6-Nov-14	18	20.2	3565	2790	6.7	0.75	5.05
7-Nov-14	19	20.0	3455	2705	6.6	0.75	4.97
8-Nov-14	20					0.75	
9-Nov-14	21					0.75	
10-Nov-14	22	20.1	3370	2630	6.7	0.75	5.03
11-Nov-14	23	20.1	3330	2590	6.9	0.75	5.15
12-Nov-14	24	20.2	3330	2605	7.0	0.75	5.25
13-Nov-14	25	20.2	3310	2550	6.8	0.75	5.10
14-Nov-14	26	20.0	3195	2455	6.1	0.75	4.57

A.1.3 Batch Rate Testing

Batch Rate Testing Results								
Date	Days	AOB rate (mgNOx-N/gMLSS/hr)	NDB rate (mgNO3-N/gMLSS/hr)	NDB rate/AOB rate	Average OUR (mg/L/hr)	Denitrification rate (mgNO3-N/gMLSS/hr)	Denitrification rate (mgNO2-N/gMLSS/hr)	Denitrification rate (mgNOx-N/gMLSS/hr)
<b>Average</b>		3.34	2.90	0.89	57.0	2.38	-0.46	1.92
<b>Sample SD</b>		0.65	0.34	0.15	3.6	0.28	0.46	0.43
28-Sep-14	1							
29-Sep-14	2					2.42	0.07	2.49
30-Sep-14	3				60.5			
1-Oct-14	4							
2-Oct-14	5	2.51	2.77	1.11				
3-Oct-14	6							
26-Oct-14	7							
27-Oct-14	8					2.28	-0.30	1.98
28-Oct-14	9				56.9			
29-Oct-14	10							
30-Oct-14	11	3.19	2.54	0.80				
31-Oct-14	12							
1-Nov-14	13							
2-Nov-14	14							
3-Nov-14	15							
4-Nov-14	16				58.6	2.73	-1.01	1.72
5-Nov-14	17							
6-Nov-14	18	3.65	2.96	0.81				
7-Nov-14	19							
8-Nov-14	20							
9-Nov-14	21							
10-Nov-14	22					2.08	-0.61	1.47
11-Nov-14	23				52.0			
12-Nov-14	24							
13-Nov-14	25	4.01	3.34	0.83				
14-Nov-14	26							

A.1.4 Effluent Characteristics

Average Effluent Characteristics											
Date	Days	Ammonia (mg-N/L)	Nitrite (mg-N/L)	Nitrate (mg-N/L)	OP (mg-P/L)	TSS (mg/L)	SVI 30 (mL/g)	TIN (mg-N/L)	TN (mg-N/L)	TP (mg-P/L)	
Average		0.06	0.11	15.5	1.73	29.2	85	15.7	20.3	2.24	
Sample SD		0.03	0.10	5.4	0.35	6.3	17	5.4	7.2	0.27	
28-Sep-14	1	0.08	0.03	10.1	2.03	20.8		10.2			
29-Sep-14	2	0.06	0.03	8.1	1.94	18.5	113	8.1			
30-Sep-14	3	0.09	0.04	8.1	1.88	19.3	117	8.2	10.6	2.11	
1-Oct-14	4	0.06	0.03	6.9	1.68	24.5	115	7.0			
2-Oct-14	5	0.14	0.07	8.0	1.58	26.8	114	8.2	10.8	1.99	
3-Oct-14	6						106				
26-Oct-14	7	0.10	0.30	13.1	2.42	36.0		13.5			
27-Oct-14	8	0.06	0.17	11.8	2.08	28.3	86	12.0			
28-Oct-14	9	0.06	0.46	14.6	2.00	27.0	85	15.1	17.9	2.41	
29-Oct-14	10	0.05	0.18	18.5	1.93	23.5	86	18.7			
30-Oct-14	11	0.05	0.10	18.0	2.17	30.5	84	18.1	21.6	2.63	
31-Oct-14	12						80				
1-Nov-14	13										
2-Nov-14	14	0.05	0.08	15.1	1.55	42.5		15.2			
3-Nov-14	15	0.02	0.06	13.4	1.41	38.8	70	13.5			
4-Nov-14	16	0.04	0.12	16.2	1.84	35.5	75	16.4	19.9	2.47	
5-Nov-14	17	0.05	0.13	19.5	1.89	32.8	75	19.7			
6-Nov-14	18	0.07	0.08	20.8	1.74	33.5	70	21.0	24.4	2.39	
7-Nov-14	19						77				
8-Nov-14	20										
9-Nov-14	21	0.04	0.05	21.3	1.45	30.8		21.3			
10-Nov-14	22	0.03	0.07	20.8	1.22	28.3	71	20.8			
11-Nov-14	23	0.04	0.09	22.6	1.25	26.0	72	22.7	31.7	1.85	
12-Nov-14	24	0.03	0.09	21.8	1.18	29.3	72	21.9			
13-Nov-14	25	0.03	0.10	22.2	1.34	31.8	69	22.3	25.5	2.09	
14-Nov-14	26						69				

A.1.5 Influent Properties

Influent Properties																							
Date	Days	RWI											A-Stage Effluent										
		COD (mg/L)	sCOD (mg/L)	pCOD (mg/L)	BOD (mg/L)	TSS (mg/L)	VSS (mg/L)	TKN (mg-N/L)	TAN (mg-N/L)	TP (mg-P/L)	OP (mg-P/L)	Alk (mg as CaCO3/L)	COD (mg/L)	sCOD (mg/L)	pCOD (mg/L)	BOD (mg/L)	TSS (mg/L)	VSS (mg/L)	TKN (mg-N/L)	TAN (mg-N/L)	TP (mg-P/L)	OP (mg-P/L)	Alk (mg as CaCO3/L)
Average		562	217	344	295	203	177	45.1	35.4	6.0	2.77	176	311	146	166	124	103	86	39.6	31.7	4.3	2.05	158
Sample SD		80	18	70	94	40	30	2.2	1.8	0.6	0.29	3	61	18	47	30	19	17	2.9	1.2	0.4	0.61	5
28-Sep-14	1	464	208	256		116				32.0		2.93	310	153	157		96	80		29.7			2.63
29-Sep-14	2	502	197	305		195	167			32.6		2.90	333	161	172		103	86		31.0			2.82
30-Sep-14	3	553	196	357	305	214	182	42.2	34.5	5.57	2.78	172	370	147	223	150	126	107	43.7	32.7	4.40	2.74	165
1-Oct-14	4	500	188	312		171	148			34.1		2.33	358	157	201		136	113		31.7			2.48
2-Oct-14	5	450	180	270		187	156	41.3	31.8	5.04	2.49	170	350	144	206		123	106	37.5	31.1	4.37	2.48	161
3-Oct-14	6																						
26-Oct-14	7	715	236	479		236	199			35.7		3.18	472	195	277		119	99		33.4			2.86
27-Oct-14	8	766	238	528		270	234			36.8		3.22	340	169	171		112	99		32.5			2.78
28-Oct-14	9	508	211	297	219	194	164	45.5	37.7	5.87	3.11	178	294	126	158	112	102	88	39.8	33.8	4.45	2.10	158
29-Oct-14	10	543	220	323		175	150			36.7		3.26	255	145	110		89	70		32.6			1.85
30-Oct-14	11	553	202	351		241	208	45.4	36.2	6.5	3.04	173	250	144	106		83	76	36.6	32.2	4.46	2.60	155
31-Oct-14	12																						
1-Nov-14	13																						
2-Nov-14	14	488	232	256		170	144			33.0		2.39	333	154	179		116	101		29.5			1.83
3-Nov-14	15	558	232	326		205	177			34.7		2.81	386	164	222		123	105		31.0			2.24
4-Nov-14	16	596	243	353	424	230	195	47.4	36.1	6.43	2.93	178	356	147	209	146	128	105	44.5	32.8	4.83	2.04	164
5-Nov-14	17	538	211	327		202	175			37.0		2.62	291	123	168		91	75		32.2			1.51
6-Nov-14	18	585	224	361		232	202	47.3	37.1	6.35	2.82	178	268	131	137		96	80	38.9	32.1	4.21	1.65	157
7-Nov-14	19																						
8-Nov-14	20																						
9-Nov-14	21	585	241	344		181	151			35.8		2.52	273	132	141		81	66		30.5			1.20
10-Nov-14	22	550	232	318		190	164			36.0		2.62	267	137	130		87	69		30.6			1.29
11-Nov-14	23	521	221	300	233	196	171	46.1	37.2	5.37	2.60	179	236	129	107	87	82	64	38.0	32.2	3.58	1.57	155
12-Nov-14	24	591	215	376		157	138			36.0		2.34	243	127	116		76	61		30.9			1.03
13-Nov-14	25	670	221	449		291	247	45.4	36.1	6.56	2.56	176	251	130	121		87	72	37.8	31.6	3.72	1.29	151
14-Nov-14	26																						

A.1.6 COD Properties

COD Characteristics														
Date	Days	Influent					Effluent					Removed		
		COD (mg/L)	sCOD (mg/L)	pCOD (mg/L)	% Soluble	% Particulate	COD (mg/L)	sCOD (mg/L)	pCOD (mg/L)	% Soluble	% Particulate	COD (mg/L)	sCOD (mg/L)	pCOD (mg/L)
<b>Average</b>		311	146	166	48%	52%	48.3	23.3	24.9	50%	50%	263	122	141
<b>Sample SD</b>		61	19	47	5%	5%	9.0	1.6	8.5	8%	8%	59	19	45
28-Sep-14	1	310	153	157	49%	51%	45.5	26.0	19.5	57%	43%	265	127	138
29-Sep-14	2	333	161	172	48%	52%	42.0	23.5	18.5	56%	44%	291	138	154
30-Sep-14	3	370	147	223	40%	60%	39.0	22.6	16.4	58%	42%	331	124	207
1-Oct-14	4	358	157	201	44%	56%	41.6	20.6	21.0	50%	50%	316	136	180
2-Oct-14	5	350	144	206	41%	59%	39.2	24.1	15.1	61%	39%	311	120	191
3-Oct-14	6													
26-Oct-14	7	472	195	277	41%	59%	56.1	22.0	34.1	39%	61%	416	173	243
27-Oct-14	8	340	169	171	50%	50%	48.3	23.3	25.0	48%	52%	292	146	146
28-Oct-14	9	284	126	158	44%	56%	45.5	23.4	22.1	51%	49%	239	103	136
29-Oct-14	10	255	145	110	57%	43%	46.0	24.3	21.7	53%	47%	209	121	88
30-Oct-14	11	250	144	106	58%	42%	49.7	22.2	27.5	45%	55%	200	122	79
31-Oct-14	12													
1-Nov-14	13													
2-Nov-14	14	333	154	179	46%	54%	74.0	24.6	49.4	33%	67%	259	129	130
3-Nov-14	15	386	164	222	42%	58%	64.2	27.6	36.6	43%	57%	322	136	185
4-Nov-14	16	356	147	209	41%	59%	50.7	21.6	29.1	43%	57%	305	125	180
5-Nov-14	17	291	123	168	42%	58%	56.0	24.0	32.0	43%	57%	235	99	136
6-Nov-14	18	268	131	137	49%	51%	47.7	22.6	25.1	47%	53%	220	108	112
7-Nov-14	19													
8-Nov-14	20													
9-Nov-14	21	273	132	141	48%	52%	51.2	23.2	28.0	45%	55%	222	109	113
10-Nov-14	22	267	137	130	51%	49%	41.7	22.5	19.2	54%	46%	225	115	111
11-Nov-14	23	236	129	107	55%	45%	36.2	23.4	12.8	65%	35%	200	106	94
12-Nov-14	24	243	127	116	52%	48%	45.1	24.1	21.0	53%	47%	198	103	95
13-Nov-14	25	251	130	121	52%	48%	45.7	21.2	24.5	46%	54%	205	109	97
14-Nov-14	26													

A.1.7a Alkalinity Usage

Alkalinity Consumption									
Date	Days	Influent Ammonia (mg-N/L)	Effluent Ammonia (mg-N/L)	TAN Removal (mg-N/L)	Effluent pH	Influent Alkalinity (mg CaCO <sub>3</sub> /L)	Effluent Alkalinity (mg CaCO <sub>3</sub> /L)	Bicarbonate Feed (mg CaCO <sub>3</sub> /L)	Alk Added/TAN Removed (mg CaCO <sub>3</sub> /mg NH <sub>4</sub> -N)
Average		31.7	0.06	31.6	6.81	158	108	122	5.37
Sample SD		1.2	0.03	1.2	0.06	5	6	22	0.68
28-Sep-14	1	29.7	0.08	29.6				107	
29-Sep-14	2	31.0	0.06	30.9	6.83			91	
30-Sep-14	3	32.7	0.09	32.6	6.86	165	110	86	4.32
1-Oct-14	4	31.7	0.06	31.6	6.74			81	
2-Oct-14	5	31.1	0.14	31.0	6.74	161	106	86	4.56
3-Oct-14	6				6.82			97	
26-Oct-14	7	33.4	0.10	33.3				100	
27-Oct-14	8	32.5	0.06	32.4	6.86			99	
28-Oct-14	9	33.8	0.06	33.7	6.81	158	101	109	4.92
29-Oct-14	10	32.6	0.05	32.6	6.76			131	
30-Oct-14	11	32.2	0.05	32.2	6.82	155	111	135	5.57
31-Oct-14	12				6.78			130	
1-Nov-14	13							125	
2-Nov-14	14	29.5	0.05	29.4				110	
3-Nov-14	15	31.0	0.02	31.0	6.74			116	
4-Nov-14	16	32.8	0.04	32.8	6.86	164	115	133	5.55
5-Nov-14	17	32.2	0.05	32.2	6.87			144	
6-Nov-14	18	32.1	0.07	32.0	6.84	157	112	145	5.92
7-Nov-14	19				6.86			145	
8-Nov-14	20							150	
9-Nov-14	21	30.5	0.04	30.5				145	
10-Nov-14	22	30.6	0.03	30.6	6.87			134	
11-Nov-14	23	32.2	0.04	32.2	6.86	155	106	144	6.01
12-Nov-14	24	30.9	0.03	30.9	6.84			136	
13-Nov-14	25	31.6	0.03	31.6	6.76	151	99	142	6.14
14-Nov-14	26				6.66			144	

A.1.7b Alkalinity Usage

DO_MLE_ASE																	
Date	Total SRT (days)	Net Heterotrophic Yield (g/g)	Influent BOD (mg/L)	Effluent BOD (mg/L)	TKN Used for BOD Oxidation (mg-N/L)	Influent TKN (mg-N/L)	Effluent TKN (mg-N/L)	TKN Nitrified (mg-N/L)	Alk used by Nitrification (mg CaCO3/L)	Effluent Nitrite (mg-N/L)	Effluent Nitrate (mg-N/L)	NOx Denitrified (mg-N/L)	Alk provided by Denitrification (mg CaCO3/L)	Influent Alk (mg CaCO3/L)	Effluent Alk (mg CaCO3/L)	Theoretical Supplemental Alk Req (mg CaCO3/L)	Alk Req for Nit/Den
Average	6.9	0.60	124	20	7.5	39.6	3.9	30	211	0.1	15.5	14.1	65.0	158	108	105	3.58
Sample SD	0.5	0.01	30	1	2.2	2.9	2.1	4	26	0.1	5.4	9.2	17.1	5	6	17	0.78
28-Sep-14										0.03	10.10						
29-Sep-14	7.6	0.59								0.03	8.06						
30-Sep-14	6.9	0.60	150	19	9.4	43.7	2.4	32	228	0.04	8.10	23.8	84.8	165	110	88	2.69
1-Oct-14	7.8	0.59								0.03	6.87						
2-Oct-14	7.4	0.59				37.5	2.8			0.07	7.97			161	106		
3-Oct-14	7.3	0.59															
26-Oct-14										0.30	13.10						
27-Oct-14	6.7	0.60								0.17	11.80						
28-Oct-14	7.2	0.59	112	20	6.5	39.8	2.9	30	217	0.46	14.55	15.4	54.9	158	101	105	3.95
29-Oct-14	7.2	0.59								0.18	18.50						
30-Oct-14	7.4	0.59				36.6	3.5			0.10	17.95			155	111		
31-Oct-14	6.9	0.60															
1-Nov-14										0.08	15.05						
2-Nov-14										0.06	13.40						
3-Nov-14	6.1	0.61								0.12	16.20	15.5	55.3	164	115	123	4.11
4-Nov-14	6.3	0.60	146	20	9.1	44.5	3.6	32	227	0.13	19.50						
5-Nov-14	6.6	0.60								0.08	20.80			157	112		
6-Nov-14	6.7	0.60				38.9	3.5										
7-Nov-14	6.6	0.60															
8-Nov-14																	
9-Nov-14										0.05	21.25						
10-Nov-14	6.7	0.60								0.07	20.75						
11-Nov-14	6.9	0.60	87	21	4.7	38.0	9.0	24	173	0.09	22.55	1.6	5.7	155	106	118	30.40
12-Nov-14	7.0	0.60								0.09	21.80						
13-Nov-14	6.8	0.60				37.8	3.2			0.10	22.20			151	99		
14-Nov-14	6.1	0.61															

## A.2 Data Collection during ABAC\_MLE\_ASE

### A.2.1 Performance Data

Removal Performance										
Date	Days	NH <sub>4</sub> <sup>+</sup> -N loading rate (mg-N/L/d)	Influent COD/NH <sub>4</sub> <sup>+</sup> -N	TIN removal rate (mg-N/L/d)	TIN removal Efficiency (%)	COD removal rate (mg/L/d)	COD removal rate/TIN removal rate	OP removal Efficiency (%)	Calculated AOB rate (mg-N/L/d)	
<b>Average</b>		142.9	10.2	103.7	72.6	1256	12.3	21.7		142
<b>Sample SD</b>		16.2	1.7	19.1	10.5	198	1.6	13.0		24
25-Aug-14	1	153.6	8.5	100.7	65.5	1037	10.3	16.8		163
26-Aug-14	2	153.6	8.0	95.1	61.9	1015	10.7	1.2		162
27-Aug-14	3	152.6	8.3	90.8	59.5	1077	11.9	23.6		160
28-Aug-14	4	159.8	8.5	109.2	68.4	1161	10.6	22.1		172
29-Aug-14	5									
30-Aug-14	6									
31-Aug-14	7									
1-Sep-14	8	156.0	9.3	121.4	77.8	1213	10.0	22.2		
2-Sep-14	9	154.1	10.0	124.1	80.6	1345	10.8	18.6		162
3-Sep-14	10	162.7	10.2	129.3	79.5	1482	11.5	27.8		174
4-Sep-14	11	153.6	10.1	121.4	79.1	1343	11.1	13.7		159
5-Sep-14	12									
6-Sep-14	13									
7-Sep-14	14	162.7	10.2	134.2	82.5	1464	10.9	42.3		
8-Sep-14	15	132.1	14.0	108.1	81.8	1657	15.3	36.1		128
9-Sep-14	16	94.4	14.9	78.9	83.5	1200	15.2	8.5		76
10-Sep-14	17	122.1	11.5	100.6	82.4	1213	12.1	29.7		110
11-Sep-14	18	133.6	11.4	108.0	80.8	1325	12.3	25.8		129
12-Sep-14	19									
13-Sep-14	20									
14-Sep-14	21	135.0	11.2	106.9	79.2	1336	12.5	21.3		
15-Sep-14	22	149.3	11.1	120.6	80.8	1454	12.1	32.7		147
16-Sep-14	23	149.3	10.7	119.8	80.2	1518	12.7	41.8		152
17-Sep-14	24	141.7	11.3	112.1	79.1	1436	12.8	33.5		144
18-Sep-14	25	148.3	10.7	111.6	75.2	1419	12.7	27.2		139
19-Sep-14	26									
20-Sep-14	27									
21-Sep-14	28	135.0	9.1	87.3	64.7	1049	12.0	23.1		
22-Sep-14	29	141.7	9.3	91.4	64.5	1131	12.4	25.6		140
23-Sep-14	30	146.9	8.3	83.1	56.5	1068	12.9	17.9		145
24-Sep-14	31	129.7	9.4	63.2	48.7	1054	16.7	-3.4		127
25-Sep-14	32	118.8	9.3	68.2	57.4	897	13.1	-8.4		112
26-Sep-14	33									



## A.2.2 Operational Conditions

Operational Conditions							
Date	Days	Temperature in 1st CSTR (°C)	MLSS (mg/L)	VSS (mg/L)	Total SRT (days)	Aerobic Fraction	Aerobic SRT (days)
Average		20.2	3837	3070	7.7	0.75	5.7
Sample GD		0.4	331	269	0.4	0.00	0.3
25-Aug-14	1	20.1	3370	2710	6.5	0.75	4.90
26-Aug-14	2	20.5	3335	2685	7.0	0.75	5.26
27-Aug-14	3	20.5	3400	2700	7.5	0.75	5.59
28-Aug-14	4	20.6	3235	2555	7.5	0.75	5.65
29-Aug-14	5	20.7	3365	2705	7.6	0.75	5.67
30-Aug-14	6					0.75	
31-Aug-14	7					0.75	
1-Sep-14	8					0.75	
2-Sep-14	9	20.8	3550	2845	7.1	0.75	5.32
3-Sep-14	10	20.1	3490	2770	7.7	0.75	5.81
4-Sep-14	11	20.1	3745	3010	7.9	0.75	5.91
5-Sep-14	12	20.3	3825	3110	7.9	0.75	5.92
6-Sep-14	13					0.75	
7-Sep-14	14					0.75	
8-Sep-14	15	21.3	3995	3255	7.8	0.75	5.81
9-Sep-14	16	19.8	4195	3350	7.9	0.75	5.95
10-Sep-14	17	20.1	4370	3510	7.8	0.75	5.86
11-Sep-14	18	20.3	4115	3315	8.1	0.75	6.07
12-Sep-14	19	20.5	4150	3300	8.0	0.75	5.96
13-Sep-14	20					0.75	
14-Sep-14	21					0.75	
15-Sep-14	22	20.2	4245	3420	7.7	0.75	5.81
16-Sep-14	23	20.1	3965	3200	7.7	0.75	5.79
17-Sep-14	24	20.2	3770	3015	7.9	0.75	5.89
18-Sep-14	25	20.1	4095	3295	7.8	0.75	5.88
19-Sep-14	26	19.9	4110	3300	7.9	0.75	5.96
20-Sep-14	27					0.75	
21-Sep-14	28					0.75	
22-Sep-14	29	20.0	4045	3215	7.7	0.75	5.79
23-Sep-14	30	20.0	4100	3225	7.8	0.75	5.83
24-Sep-14	31	19.9	3860	3075	7.8	0.75	5.82
25-Sep-14	32	19.9	3900	3085	7.5	0.75	5.63
26-Sep-14	33	19.8	3850	3040		0.75	

A.2.3 Batch Rate Testing

Batch Rate Testing Results								
Date	Days	AOB rate (mgNO <sub>x</sub> -N/gMLSS/hr)	NOB rate (mgNO <sub>3</sub> -N/gMLSS/hr)	NOB rate/AOB rate	Average OUR (mg/L/hr)	Denitrification rate (mgNO <sub>3</sub> -N/gMLSS/hr)	Denitrification rate (mgNO <sub>2</sub> -N/gMLSS/hr)	Denitrification rate (mgNO <sub>x</sub> -N/gMLSS/hr)
<b>Average</b>		3.15	3.39	1.09	67.5	2.49	-0.21	2.28
<b>Sample SD</b>		0.61	0.44	0.09	6.0	1.01	0.39	1.19
25-Aug-14	1							
26-Aug-14	2				72.6			
27-Aug-14	3							
28-Aug-14	4	3.86	4.04	1.05				
29-Aug-14	5							
30-Aug-14	6							
31-Aug-14	7							
1-Sep-14	8							
2-Sep-14	9					3.44	-0.57	2.87
3-Sep-14	10				72.1			
4-Sep-14	11	3.66	3.51	0.96				
5-Sep-14	12							
6-Sep-14	13							
7-Sep-14	14							
8-Sep-14	15							
9-Sep-14	16							
10-Sep-14	17				69.9			
11-Sep-14	18	3.06	3.31	1.08		2.48	-0.22	2.26
12-Sep-14	19							
13-Sep-14	20							
14-Sep-14	21							
15-Sep-14	22					3.46	0.25	3.71
16-Sep-14	23				64.2			
17-Sep-14	24							
18-Sep-14	25	2.41	2.86	1.19				
19-Sep-14	26							
20-Sep-14	27							
21-Sep-14	28							
22-Sep-14	29					2.01	0.08	2.09
23-Sep-14	30				58.5			
24-Sep-14	31							
25-Sep-14	32	2.76	3.21	1.16				
26-Sep-14	33							

### A.2.4 Effluent Characteristics

Average Effluent Characteristics										
Date	Days	Ammonia (mg-N/L)	Nitrite (mg-N/L)	Nitrate (mg-N/L)	OP (mg-P/L)	TSS (mg/L)	SVI 30 (mL/g)	TIN (mg-N/L)	TN (mg-N/L)	TP (mg-P/L)
<b>Average</b>		1.01	0.21	6.98	1.74	19.6	129	8.2	10.2	1.91
<b>Sample SD</b>		0.33	0.12	3.12	0.24	2.7	9	3.1	3.3	0.27
25-Aug-14	1	0.98	0.32	9.80	1.63	25.8	119	11.1		
26-Aug-14	2	1.20	0.37	10.70	1.63	20.3	117	12.3	14.3	1.97
27-Aug-14	3	1.14	0.43	11.40	1.78	18.3	115	13.0		
28-Aug-14	4	1.08	0.40	9.12	1.87	19.0	117	10.6	12.7	2.13
29-Aug-14	5						122			
30-Aug-14	6									
31-Aug-14	7									
1-Sep-14	8	0.94	0.28	6.04	1.86	27.0		7.3		
2-Sep-14	9	0.93	0.28	5.07	1.88	17.5	130	6.3	8.4	2.00
3-Sep-14	10	0.93	0.33	5.73	2.03	16.8	140	7.0		
4-Sep-14	11	0.94	0.35	5.46	2.20	17.0	128	6.7	9.0	2.29
5-Sep-14	12						123			
6-Sep-14	13									
7-Sep-14	14	0.90	0.27	4.79	1.61	19.8		6.0		
8-Sep-14	15	0.90	0.32	3.81	1.77	18.3	130	5.0		
9-Sep-14	16	0.82	0.22	2.22	1.18	20.5	136	3.3	5.8	1.41
10-Sep-14	17	0.97	0.19	3.36	1.35	15.8	124	4.5		
11-Sep-14	18	0.94	0.17	4.26	1.67	17.5	126	5.4	8.0	1.79
12-Sep-14	19						130			
13-Sep-14	20									
14-Sep-14	21	1.24	0.10	4.55	2.00	21.3		5.9		
15-Sep-14	22	1.06	0.10	4.86	1.73	20.0	125	6.0		
16-Sep-14	23	0.84	0.10	5.25	1.46	17.3	141	6.2	8.3	1.62
17-Sep-14	24	0.77	0.09	5.34	1.51	19.0	146	6.2		
18-Sep-14	25	2.37	0.10	5.24	1.79	17.5	144	7.7	9.9	1.89
19-Sep-14	26						131			
20-Sep-14	27									
21-Sep-14	28	0.78	0.08	9.13	1.76	20.5		10.0		
22-Sep-14	29	0.88	0.10	9.57	2.03	20.0	129	10.5		
23-Sep-14	30	1.13	0.11	12.15	1.97	19.0	139	13.4	15.7	2.10
24-Sep-14	31	0.74	0.11	13.10	1.84	23.0	137	13.9		
25-Sep-14	32	0.82	0.11	9.68	1.42	21.0	123	10.6		
26-Sep-14	33						114			

A.2.5 Influent Properties

Influent Properties																							
Date	Days	RWI											A-Stage Effluent										
		COD (mg/L)	sCOD (mg/L)	pCOD (mg/L)	BOD (mg/L)	TSS (mg/L)	VSS (mg/L)	TKN (mg-N/L)	TAN (mg-N/L)	TP (mg-P/L)	OP (mg-P/L)	Alk (mg as CaCO3/L)	COD (mg/L)	sCOD (mg/L)	pCOD (mg/L)	BOD (mg/L)	TSS (mg/L)	VSS (mg/L)	TKN (mg-N/L)	TAN (mg-N/L)	TP (mg-P/L)	OP (mg-P/L)	Alk (mg as CaCO3/L)
Average		464	182	284	181	172	146	38.4	32.1	4.7	2.72	163	303	134	169	109	104	86	36.3	30.0	4.0	2.27	151
Sample SD		75	18	67	22	28	24	5.4	3.8	0.9	0.48	23	40	22	25	27	14	12	4.7	3.4	0.7	0.43	25
25-Aug-14	1	543	188	355		225	187		36.4		2.63		275	116	159		107	94		32.2		1.96	
26-Aug-14	2	437	175	262	203	181	154	42.0	35.4	5.00	2.41	185	257	103	154	95	102	84	39.4	30.0	3.81	1.65	172
27-Aug-14	3	441	181	260		178	148		35.2		2.78		266	110	156		91	75		32.0		2.33	
28-Aug-14	4	455	186	269		186	160	41.8	36.4	5.50	2.75	185	284	136	148		102	89	38.5	33.5	4.41	2.40	178
29-Aug-14	5																						
30-Aug-14	6																						
31-Aug-14	7																						
1-Sep-14	8	505	200	305		172	147		35.5		3.07		304	148	156		93	78		32.7		2.39	
2-Sep-14	9	519	192	327	154	211	178	43.9	35.2	6.30	2.98	172	322	147	175	90	106	88	39.7	32.3	4.37	2.31	156
3-Sep-14	10	707	197	510		232	197		37.1		3.64		347	151	196		124	101		34.1		2.81	
4-Sep-14	11	438	182	256		210	184	44.1	34.2	5.10	3.13	168	325	129	196		118	99	39.7	32.2	5.06	2.55	158
5-Sep-14	12																						
6-Sep-14	13																						
7-Sep-14	14	441	192	249		138	117		32.7		3.86		347	174	173		105	86		34.1		2.79	
8-Sep-14	15	523	160	363		199	165		27.5		2.85		387	149	238		129	106		27.7		2.77	
9-Sep-14	16	347	133	214	166	154	128	26.7	20.8	3.00	1.58	107	295	104	191	110	123	101	27.3	19.8	2.70	1.29	94
10-Sep-14	17	364	167	197		143	125		28.6		2.12		295	138	157		109	93		25.6		1.92	
11-Sep-14	18	383	152			144	120	35.3	28.6	4.10	2.36	152	320	127	193		107	90	35.5	28.0	4.07	2.25	147
12-Sep-14	19																						
13-Sep-14	20																						
14-Sep-14	21	423	186	237		156	124		30.2		2.75		317	145	172		117	94		28.3		2.54	
15-Sep-14	22	491	211	280		152	134		31.7		2.71		348	171	177		104	96		31.3		2.57	
16-Sep-14	23	403	189	214	181	138	117	37.2	32.7	4.30	2.53	167	335	163	172	155	109	89	37.3	31.3	4.09	2.51	156
17-Sep-14	24	427	175	252		134	111		30.8		2.50		337	144	193		114	93		29.7		2.27	
18-Sep-14	25	456	187	269		171	146	40.9	32.8	4.60	2.60	169	332	150	182		97	84	40.1	31.1	4.12	2.46	165
19-Sep-14	26																						
20-Sep-14	27																						
21-Sep-14	28	484	199	285		188	159		32.2		2.84		258	127	131		85	71		28.3		2.29	
22-Sep-14	29	545	210	335		166	136		33.1		3.04		277	134	143		86	66		29.7		2.73	
23-Sep-14	30	442	189	253	202	156	136	38.3	34.2	5.20	2.88	176	255	112	143	93	80	68	37.1	30.8	4.01	2.40	162
24-Sep-14	31	465	176	289		173	151		29.6		2.53		255	99	156		90	78		27.2		1.78	
25-Sep-14	32	424	167	257		159	137	33.4	27.6	3.89	2.05	150	232	98	134		87	66	28.4	24.9	2.97	1.31	123
26-Sep-14	33																						

A.2.6 COD Properties

COD Characteristics														
Date	Days	Influent					Effluent					Removed		
		COD (mg/L)	sCOD (mg/L)	pCOD (mg/L)	% Soluble	% Particulate	COD (mg/L)	sCOD (mg/L)	pCOD (mg/L)	% Soluble	% Particulate	COD (mg/L)	sCOD (mg/L)	pCOD (mg/L)
Average		303	134	189	44%	56%	39.7	23.1	16.6	60%	40%	263	111	153
Sample SD		40	22	25	4%	4%	7.4	2.4	6.4	14%	14%	42	23	26
25-Aug-14	1	275	116	159	42%	58%	57.5	27.9	29.6	49%	51%	218	88	129
26-Aug-14	2	257	103	154	40%	60%	44.3	28.5	15.8	64%	36%	213	75	138
27-Aug-14	3	266	110	156	41%	59%	40.2	24.5	15.7	61%	39%	226	86	140
28-Aug-14	4	284	136	148	48%	52%	40.7	23.5	17.2	58%	42%	243	113	131
29-Aug-14	5													
30-Aug-14	6													
31-Aug-14	7													
1-Sep-14	8	304	148	156	49%	51%	49.8	23.7	26.1	48%	52%	254	124	130
2-Sep-14	9	322	147	175	46%	54%	40.1	26.0	14.1	65%	35%	282	121	161
3-Sep-14	10	347	151	196	44%	56%	36.3	23.8	12.5	66%	34%	311	127	184
4-Sep-14	11	325	129	196	40%	60%	43.5	24.2	19.3	56%	44%	282	105	177
5-Sep-14	12													
6-Sep-14	13													
7-Sep-14	14	347	174	173	50%	50%	40.1	23.1	17.0	58%	42%	307	151	156
8-Sep-14	15	387	149	238	39%	61%	39.7	21.8	17.9	55%	45%	347	127	220
9-Sep-14	16	295	104	191	35%	65%	43.5	19.5	24.0	45%	55%	252	85	167
10-Sep-14	17	295	138	157	47%	53%	40.7	19.5	21.2	48%	52%	254	119	136
11-Sep-14	18	320	127	193	40%	60%	42.2	22.4	19.8	53%	47%	278	105	173
12-Sep-14	19													
13-Sep-14	20													
14-Sep-14	21	317	145	172	46%	54%	37.0	21.5	15.5	58%	42%	280	124	157
15-Sep-14	22	348	171	177	49%	51%	43.1	24.3	18.8	56%	44%	305	147	158
16-Sep-14	23	335	163	172	49%	51%	16.8	19.0	-2.2	113%	-13%	318	144	174
17-Sep-14	24	337	144	193	43%	57%	35.9	21.7	14.2	60%	40%	301	122	179
18-Sep-14	25	332	150	182	45%	55%	34.6	20.6	14.0	60%	40%	297	129	168
19-Sep-14	26													
20-Sep-14	27													
21-Sep-14	28	258	127	131	49%	51%	38.1	23.5	14.6	62%	38%	220	104	116
22-Sep-14	29	277	134	143	48%	52%	39.9	24.5	15.4	61%	39%	237	110	128
23-Sep-14	30	255	112	143	44%	56%	31.0	23.0	8.0	74%	26%	224	89	135
24-Sep-14	31	255	99	156	39%	61%	34.1	22.8	11.3	67%	33%	221	76	145
25-Sep-14	32	232	98	134	42%	58%	44.0	21.7	22.3	49%	51%	188	76	112
26-Sep-14	33													

A.2.7a Alkalinity Usage

Alkalinity Consumption										
Date	Days	Influent Ammonia (mg-N/L)	Effluent Ammonia (mg-N/L)	TAN Removal (mg-N/L)	Effluent pH	Influent Alkalinity (mg CaCO <sub>3</sub> /L)	Effluent Alkalinity (mg CaCO <sub>3</sub> /L)	Bicarbonate Feed (mg CaCO <sub>3</sub> /L)	Alk Added	TAN Removed (mg CaCO <sub>3</sub> /mg NH <sub>4</sub> -N)
<b>Average</b>		30.0	1.01	28.9	6.80	151	123	95		4.39
<b>Sample SD</b>		3.4	0.33	3.3	0.04	25	22	24		0.57
25-Aug-14	1	32.2	0.98	31.2	6.74			174		
26-Aug-14	2	32.2	1.20	31.0	6.82	172	181	161		4.90
27-Aug-14	3	32.0	1.14	30.9	6.89			126		
28-Aug-14	4	33.5	1.08	32.4	6.78	178	125	108		4.95
29-Aug-14	5				6.80			105		
30-Aug-14	6							95		
31-Aug-14	7							95		
1-Sep-14	8	32.7	0.94	31.8				99		
2-Sep-14	9	32.3	0.93	31.4	6.82	156	120	82		3.76
3-Sep-14	10	34.1	0.93	33.2	6.81			88		
4-Sep-14	11	32.2	0.94	31.3	6.83	158	115	78		3.88
5-Sep-14	12				6.82			103		
6-Sep-14	13							75		
7-Sep-14	14	34.1	0.90	33.2				77		
8-Sep-14	15	27.7	0.90	26.8				74		
9-Sep-14	16	19.8	0.82	19.0	6.75	94	112	86		3.58
10-Sep-14	17	25.6	0.97	24.6	6.79			78		
11-Sep-14	18	28.0	0.94	27.1	6.76	147	115	76		4.01
12-Sep-14	19				6.79			85		
13-Sep-14	20							73		
14-Sep-14	21	28.3	1.24	27.1				73		
15-Sep-14	22	31.3	1.06	30.2	6.80			70		
16-Sep-14	23	31.3	0.84	30.5	6.77	156	98	75		4.36
17-Sep-14	24	29.7	0.77	28.9	6.81			83		
18-Sep-14	25	31.1	2.37	28.7	6.82	165	118	78		4.37
19-Sep-14	26				6.83			90		
20-Sep-14	27							78		
21-Sep-14	28	28.3	0.78	27.5				83		
22-Sep-14	29	29.7	0.88	28.8	6.82			97		
23-Sep-14	30	30.8	1.13	29.7	6.84	162	126	120		5.25
24-Sep-14	31	27.2	0.74	26.5	6.85			124		
25-Sep-14	32	24.9	0.82	24.1	6.77	123	117	110		4.82
26-Sep-14	33				6.76			110		

A.2.7b Alkalinity Usage

ABAC_MLE_ASE																	
Date	Total SRT (days)	Net Heterotrophic Yeild (g/g)	Influent BOD (mg/L)	Effluent BOD (mg/L)	TKN Used for BOD Oxidation (mg-N/L)	Influent TKN (mg-N/L)	Effluent TKN (mg-N/L)	TKN Nitrified (mg-N/L)	Alk used by Nitrification (mg CaCO3/L)	Effluent Nitrite (mg-N/L)	Effluent Nitrate (mg-N/L)	NOx Denitrified (mg-N/L)	Alk provided by Denitrification (mg CaCO3/L)	Influent Alk (mg CaCO3/L)	Effluent Alk (mg CaCO3/L)	Theoretical Supplemental Alk Req (mg CaCO3/L)	Alk Req for Nit/Den
Average	7.7	0.59	109	20	6.2	36.3	3.4	27	191	0.2	7.0	20.2	72.1	151	123	99	2.60
Sample SD	0.4	0.00	27	1	1.9	4.7	0.5	6	41	0.1	3.1	4.6	16.4	25	22	45	0.36
25-Aug-14	6.5	0.60								0.32	9.80						
26-Aug-14	7.0	0.60	95	20	5.4	39.4	3.3	31	220	0.37	10.70	19.7	70.3	172	181	158	3.12
27-Aug-14	7.5	0.59								0.43	11.40						
28-Aug-14	7.5	0.59				38.5	3.2			0.40	9.12			178	125		
29-Aug-14	7.6	0.59															
30-Aug-14																	
31-Aug-14																	
1-Sep-14										0.28	6.04						
2-Sep-14	7.1	0.59	90	21	4.9	39.7	3.1	32	226	0.28	5.07	26.4	94.1	156	120	96	2.41
3-Sep-14	7.7	0.59								0.33	5.73						
4-Sep-14	7.9	0.58				39.7	3.2			0.35	5.46			158	115		
5-Sep-14	7.9	0.58															
6-Sep-14																	
7-Sep-14										0.27	4.79						
8-Sep-14	7.8									0.32	3.81						
9-Sep-14	7.9	0.58	110	20	6.3	27.3	3.3	18	126	0.22	2.22	15.2	54.4	94	112	90	2.32
10-Sep-14	7.8	0.59								0.19	3.36						
11-Sep-14	8.1	0.58				35.5	3.6			0.17	4.26			147	115		
12-Sep-14	8.0	0.58															
13-Sep-14																	
14-Sep-14										0.10	4.55						
15-Sep-14	7.7	0.59								0.10	4.86						
16-Sep-14	7.7	0.59	155	19	9.6	37.3	2.9	25	177	0.10	5.25	19.5	69.5	156	98	50	2.55
17-Sep-14	7.9	0.59								0.09	5.34						
18-Sep-14	7.8	0.59				40.1	4.5			0.10	5.24			165	118		
19-Sep-14	7.9	0.58															
20-Sep-14																	
21-Sep-14										0.08	9.13						
22-Sep-14	7.7	0.59								0.10	9.57						
23-Sep-14	7.8	0.59	93	21	5.1	37.1	3.5	29	204	0.11	12.15			162	126		
24-Sep-14	7.8	0.59								0.11	13.10						
25-Sep-14	7.5	0.59				28.4				0.11	9.68			123	117		
26-Sep-14																	

### A.3 Data Collection during AvN\_MLE\_ASE

#### A.3.1 Performance Data

Removal Performance									
Date	Days	NH <sub>4</sub> <sup>+</sup> -N loading rate (mg-N/L/d)	Influent COD/NH <sub>4</sub> <sup>+</sup> -N	TIN removal rate (mg-N/L/d)	TIN removal Efficiency (%)	COD removal rate (mg/L/d)	COD removal rate/TIN removal rate	OP removal Efficiency (%)	Calculated AOB rate (mg-N/L/d)
<b>Average</b>		137.0	10.6	103.3	75.5	1191	11.6	19.3	250
<b>Sample SD</b>		12.5	1.4	10.8	6.0	235	1.8	24.2	34
17-Mar-15	1	128.8	9.6	93.9	72.9	974	10.4	7.1	270
18-Mar-15	2	137.4	10.3	95.5	69.5	1203	12.6	14.8	219
19-Mar-15	3	142.1	11.8	94.8	66.7	1564	16.5	17.7	212
20-Mar-15	4								
21-Mar-15	5								
22-Mar-15	6	136.4	12.7	107.7	79.0	1449	13.5	38.6	
23-Mar-15	7	136.9	12.6	109.8	80.2	1443	13.1	36.7	257
24-Mar-15	8	143.1	10.2	112.4	78.5	1213	10.8	51.2	262
25-Mar-15	9	149.3	10.1	116.2	77.8	1278	11.0	22.5	279
26-Mar-15	10	142.1	11.4	108.0	76.0	1357	12.6	15.5	272
27-Mar-15	11								
28-Mar-15	12								
29-Mar-15	13	137.9	11.6	109.2	79.2	1358	12.4	15.6	
30-Mar-15	14	128.8	11.8	106.0	82.3	1240	11.7	22.9	261
31-Mar-15	15	146.9	10.4	111.5	75.9	1355	12.1	22.4	266
01-Apr-15	16	146.9	10.3	101.6	69.1	1180	11.6	7.2	238
02-Apr-15	17	158.4	9.3	100.9	63.7	1162	11.5	3.7	240
03-Apr-15	18								
04-Apr-15	19								
05-Apr-15	20					830		-25.7	
06-Apr-15	21	134.5	10.4	83.5	62.1	1130	13.5	50.9	284
07-Apr-15	22	141.2	8.8	98.0	69.4	996	10.2	27.5	232
08-Apr-15	23	142.6	9.1	100.3	70.3	1067	10.6	13.1	237
09-Apr-15	24	147.9	8.8	103.0	69.6	1102	10.7	1.9	239
10-Apr-15	25								
11-Apr-15	26								
12-Apr-15	27	138.8	11.3	102.7	74.0	1249	12.2	17.3	
13-Apr-15	28	148.8	10.9	113.3	76.2	1381	12.2	25.5	259
14-Apr-15	29	149.3	12.5	114.0	76.4	1566	13.7	18.0	238
15-Apr-15	30	114.0	7.2	81.5	71.5	564	6.9	-41.0	185
16-Apr-15	31	125.9	9.9	87.8	69.7	983	11.2	-0.5	207
17-Apr-15	32								
18-Apr-15	33								
19-Apr-15	34	139.3	12.0	112.6	80.8	1431	12.7	40.4	
20-Apr-15	35	106.4	13.5	89.6	84.3	1208	13.5	57.1	199
21-Apr-15	36	108.8	9.8	88.2	81.1	843	9.6	49.4	221
22-Apr-15	37	120.7	8.6	95.4	79.1	852	8.9	-38.0	238
23-Apr-15	38	128.3	9.0	99.6	77.6	945	9.5	6.0	252
24-Apr-15	39								
25-Apr-15	40								
26-Apr-15	41								
27-Apr-15	42	129.3	11.1	107.9	83.5	1254	11.6	23.3	277
28-Apr-15	43	136.4	10.4	109.8	80.5	1210	11.0	44.1	258
29-Apr-15	44	146.4	9.8	119.2	81.4	1183	9.9	57.6	292
30-Apr-15	45	153.6	11.7	127.7	83.1	1551	12.1	13.8	354
01-May-15	46								



### A.3.2 Operational Conditions

Operational Conditions							
Date	Days	Temperature in 1st CSTR (°C)	MLSS (mg/L)	VSS (mg/L)	Total SRT (days)	Aerobic Fraction	Aerobic SRT (days)
<b>Average</b>		20.1	2967	2520	7.1	0.43	3.0
<b>Sample SD</b>		0.3	377	249	1.9	0.04	0.8
17-Mar-15	1	20.3	3170	2660	5.6	0.36	2.0
18-Mar-15	2	20.0	2780	2395	5.7	0.46	2.6
19-Mar-15	3	20.2	2965	2495	6.9	0.49	3.4
20-Mar-15	4	19.5	2985	2555	7.6	0.41	3.1
21-Mar-15	5					0.47	
22-Mar-15	6					0.44	
23-Mar-15	7	20.3	3210	2245	6.8	0.43	3.0
24-Mar-15	8	20.0	3375	2885	7.4	0.44	3.2
25-Mar-15	9	20.2	3250	2840	7.3	0.43	3.2
26-Mar-15	10	20.7	2720	2305	6.5	0.42	2.7
27-Mar-15	11	20.3	3360	2875	6.4	0.38	2.5
28-Mar-15	12					0.41	
29-Mar-15	13					0.41	
30-Mar-15	14	20.3	2905	2408	4.8	0.38	1.8
31-Mar-15	15	20.1	2685	2310	5.0	0.43	2.2
01-Apr-15	16	20.1	2525	2200	5.4	0.47	2.5
02-Apr-15	17	20.1	2415	2100	5.1	0.49	2.5
03-Apr-15	18	20.3	2535	2195	6.0	0.47	2.8
04-Apr-15	19					0.60	
05-Apr-15	20						
06-Apr-15	21	19.1	1805		7.0	0.36	2.6
07-Apr-15	22	20.4	2695	2415	10.8	0.48	5.2
08-Apr-15	23	20.4	2870	2435	8.1	0.47	3.8
09-Apr-15	24	20.1	2740	2315	6.3	0.47	3.0
10-Apr-15	25	20.1	2480	2095	5.8	0.43	2.5
11-Apr-15	26					0.45	
12-Apr-15	27					0.44	
13-Apr-15	28	20.1	2805	2365	5.0	0.43	2.2
14-Apr-15	29	20	2980	2540	5.2	0.46	2.4
15-Apr-15	30	20.1	3015	2595	5.3	0.41	2.1
16-Apr-15	31	20.1	3095	2585	5.6	0.43	2.4
17-Apr-15	32	20.1	2815	2360	6.6	0.36	2.4
18-Apr-15	33					0.45	
19-Apr-15	34					0.44	
20-Apr-15	35	20.0	3220	2740	7.1	0.41	2.9
21-Apr-15	36	19.9	3200	2645	7.7	0.39	3.0
22-Apr-15	37	19.9	3125	2630	7.6	0.41	3.1
23-Apr-15	38	20.4	2970	2460	8.8	0.42	3.7
24-Apr-15	39	20.4	2910	2410	10.2	0.36	3.7
25-Apr-15	40					0.43	
26-Apr-15	41					0.41	
27-Apr-15	42	20.2	3175	2600		0.40	
28-Apr-15	43	20.0	3415	2815	11.1	0.44	4.8
29-Apr-15	44	20.1	3430	2800	10.9	0.42	4.6
30-Apr-15	45	19.9	3790	3080	9.7	0.36	3.5
01-May-15	46	20.1	3460	2860	10.3	0.42	4.3

A.3.3 Batch Rate Testing

Batch Rate Testing Results								
Date	Days	AOB rate (mgNOx-N/gMLSS/hr)	NOB rate (mgNO3-N/gMLSS/hr)	NOB rate/AOB rate	Average OUR (mg/L/hr)	Denitrification rate (mgNO3-N/gMLSS/hr)	Denitrification rate (mgNO2-N/gMLSS/hr)	Denitrification rate (mgNOx-N/gMLSS/hr)
<b>Average</b>		5.07	5.05	1.00	71.8	3.25	-0.35	2.90
<b>Sample SD</b>		0.56	0.58	0.03	3.1	0.56	0.37	0.37
17-Mar-15	1				74.2			
18-Mar-15	2					2.94	-0.12	2.82
19-Mar-15	3	4.27	4.38	1.03				
20-Mar-15	4							
21-Mar-15	5							
22-Mar-15	6							
23-Mar-15	7					3.86	-0.28	3.58
24-Mar-15	8				73.9			
25-Mar-15	9							
26-Mar-15	10	5.79	5.81	1.00				
27-Mar-15	11							
28-Mar-15	12							
29-Mar-15	13							
30-Mar-15	14					3.56	-0.55	3.01
31-Mar-15	15				66.2			
01-Apr-15	16							
02-Apr-15	17	5.59	5.65	1.01				
03-Apr-15	18							
04-Apr-15	19							
05-Apr-15	20							
06-Apr-15	21							
07-Apr-15	22							
08-Apr-15	23				70.5	3.09	-0.42	2.67
09-Apr-15	24	5.07	5.16	1.02				
10-Apr-15	25							
11-Apr-15	26							
12-Apr-15	27							
13-Apr-15	28							
14-Apr-15	29					3.69	-0.90	2.79
15-Apr-15	30				73.7			
16-Apr-15	31	4.79	4.61	0.96				
17-Apr-15	32							
18-Apr-15	33							
19-Apr-15	34							
20-Apr-15	35							
21-Apr-15	36							
22-Apr-15	37				72.2			
23-Apr-15	38	4.89	4.69	0.96		2.36	0.18	2.54
24-Apr-15	39							
25-Apr-15	40							
26-Apr-15	41							
27-Apr-15	42							
28-Apr-15	43							
29-Apr-15	44							
30-Apr-15	45							
01-May-15	46							

### A.3.4 Effluent Characteristics

Average Effluent Characteristics												
Date	Days	Ammonia (mg-N/L)	Nitrite (mg-N/L)	Nitrate (mg-N/L)	NAR (NO <sub>2</sub> -N/NO <sub>x</sub> -N) (%)	NO <sub>x</sub> /Ammonia	OP (mg-P/L)	TSS (mg/L)	SVI 30 (mL/g)	TIN (mg-N/L)	TN (mg-N/L)	TP (mg-P/L)
<b>Average</b>		3.58	0.48	3.01	14%	0.98	2.29	29.0	149	7.1	10.9	3.08
<b>Sample SD</b>		0.97	0.13	1.07	4%	0.18	0.75	6.2	23	2.0	2.7	0.58
17-Mar-15	1	3.63	0.35	3.33	12%	1.01	2.88	30.8	126	7.3	9.9	3.29
18-Mar-15	2	4.48	0.41	3.88	10%	0.96	3.05	31.3	133	8.8		
19-Mar-15	3	4.92	0.45	4.56	10%	1.02	3.17	39.3	132	9.9	13.6	3.68
20-Mar-15	4				9%				124			
21-Mar-15	5											
22-Mar-15	6	2.94	0.49	2.59		1.05	2.96	43.3		6.0		
23-Mar-15	7	2.90	0.48	2.30	16%	0.96	2.50	30.8	153	5.7		
24-Mar-15	8	3.19	0.45	2.80	17%	1.02	2.41	30.3	145	6.4	9.2	3.01
25-Mar-15	9	3.36	0.51	3.08	14%	1.07	2.99	31.3	151	6.9		
26-Mar-15	10	3.52	0.52	3.12	14%	1.04	3.22	30.3	165	7.2	10.3	3.87
27-Mar-15	11								170			
28-Mar-15	12											
29-Mar-15	13	2.84	0.46	2.70	15%	1.11	2.98	33.8		6.0		
30-Mar-15	14	2.34	0.44	2.00	18%	1.04	2.12	31.8	138	4.8		
31-Mar-15	15	3.21	0.52	3.69	12%	1.31	2.74	28.8	119	7.4	11.6	3.26
01-Apr-15	16	4.01	0.64	4.86	12%	1.37	3.59	38.8	115	9.5		
02-Apr-15	17	5.20	0.83	6.02	12%	1.32	3.09	37.3	112	12.1	16.2	3.72
03-Apr-15	18								118			
04-Apr-15	19											
05-Apr-15	20						3.42					
06-Apr-15	21	6.21	0.59	3.90	13%	0.72	1.04	24.5	122	10.7		
07-Apr-15	22	4.72	0.44	3.90	10%	0.92	2.06	28.0	134	9.1	12.4	2.52
08-Apr-15	23	4.43	0.51	3.93	11%	1.00	2.58	29.0	139	8.9		
09-Apr-15	24	4.53	0.56	4.32	11%	1.08	2.12	28.3	139	9.4	13.5	2.85
10-Apr-15	25											
11-Apr-15	26											
12-Apr-15	27	3.96	0.59	3.01	16%	0.91	1.96	38.3		7.6		
13-Apr-15	28	4.12	0.65	2.67	20%	0.81	2.34	29.5	157	7.4		
14-Apr-15	29	4.08	0.61	2.70	18%	0.81	2.33	29.0	151	7.4	10.4	3.28
15-Apr-15	30	4.28	0.51	2.02	20%	0.59	1.65	26.5	159	6.8		
16-Apr-15	31	3.92	0.61	3.47	15%	1.04	1.89	27.5	136	8.0	11.4	2.83
17-Apr-15	32								171			
18-Apr-15	33											
19-Apr-15	34	3.32	0.59	1.69	26%	0.69	1.71	24.5		5.6		
20-Apr-15	35	2.03	0.38	1.10	26%	0.73	0.86	20.8	155	3.5		
21-Apr-15	36	2.28	0.37	1.67	18%	0.89	0.62	26.5	172	4.3	6.3	1.65
22-Apr-15	37	2.54	0.39	2.36	14%	1.08	1.78	21.5	160	5.3		
23-Apr-15	38	2.73	0.43	2.86	13%	1.21	1.88	19.8	168	6.0	8.4	2.79
24-Apr-15	39								151			
25-Apr-15	40											
26-Apr-15	41											
27-Apr-15	42	2.37	0.29	1.82	14%	0.89	1.68	17.5	192	4.5		
28-Apr-15	43	2.85	0.29	2.45	10%	0.96	1.23	18.8	193	5.6		
29-Apr-15	44	2.90	0.24	2.57	9%	0.97	1.91	30.0	181	5.7		
30-Apr-15	45	3.20	0.27	1.96	12%	0.70	2.43	22.3	195	5.4	7.8	3.25
01-May-15	46								147			

### A.3.5 Influent Properties

Influent Properties																							
Date	Days	RWI											A-Stage Effluent										
		COD (mg/L)	sCOD (mg/L)	pCOD (mg/L)	BOD (mg/L)	TSS (mg/L)	VSS (mg/L)	TKN (mg-N/L)	TAN (mg-N/L)	TP (mg-P/L)	OP (mg-P/L)	Alk (mg as CaCO3/L)	COD (mg/L)	sCOD (mg/L)	pCOD (mg/L)	BOD (mg/L)	TSS (mg/L)	VSS (mg/L)	TKN (mg-N/L)	TAN (mg-N/L)	TP (mg-P/L)	OP (mg-P/L)	Alk (mg as CaCO3/L)
<b>Average</b>		623	208	420	245	247	224	44.6	31.8	6.2	3.94	185	303	138	165	114	109	95	38.4	28.8	4.7	2.94	179
<b>Sample SD</b>		113	30	115	49	44	36	4.5	2.7	0.8	1.00	14	47	21	37	21	30	29	4.0	2.6	0.7	0.99	13
17-Mar-15	1	565	168	397	211	234	212	39.7	30.2	5.65	4.37	179	259	100	159	124	87	74	32.3	27.0	4.36	3.10	169
18-Mar-15	2	612	175	437		243	232		31.1		4.96		298	121	177		109	94		28.8		4.7	3.58
19-Mar-15	3	622	204	418		295	259	41.6	32.2	6.23	4.78	194	353	139	214		133	119	40.4	29.8	5.34	3.85	187
20-Mar-15	4																						
21-Mar-15	5																						
22-Mar-15	6	541	199	342		240	217		30.5		4.74		363	136	227		240	217		28.6		4.82	
23-Mar-15	7	710	214	496		185			30.9		4.79		362	165	197		103			28.7		3.95	
24-Mar-15	8	560	215	345	197	229	210	41.7	31.8	6.16	4.70	188	305	147	158	108	108	98	38.7	30.0	5.20	4.94	187
25-Mar-15	9	627	206	421		294	261		32.9		5.37		317	131	186		114	97		31.3		3.86	
26-Mar-15	10	637	222	415		264	227	45.9	32.3	6.64	4.81	204	339	144	195		121	103	40.8	29.8	5.44	3.81	191
27-Mar-15	11																						
28-Mar-15	12																						
29-Mar-15	13	586	244	342		209	192		31.6		4.69		335	156	179		105	98		28.9		3.53	
30-Mar-15	14	627	247	380		220	199		31.2		4.13		318	162	156		84	71		27.0		2.75	
31-Mar-15	15	697	235	452	248	245	221	50.3	32.2	7.06	4.89	187	320	138	182	120	110	96	42.4	30.8	5.14	3.53	182
01-Apr-15	16	533	219	314		236	217		34.1		4.89		316	137	179		119	107		30.8		3.87	
02-Apr-15	17	562	204	358		258	231	48.4	35.0	6.47	3.90	189	308	131	177		99	89	42.7	33.2	5.07	3.21	185
03-Apr-15	18																						
04-Apr-15	19																						
05-Apr-15	20	580	273	307		223			34.2		3.87		316	173	143		122			30.4		2.72	
06-Apr-15	21	556	252	304		232	226		33.1		3.37		293	170	123		103	92		28.2		2.12	
07-Apr-15	22	581	226	355	313	261	233	46.9	33.4	6.05	3.74	182	260	144	116	101	99	85	39.7	29.6	4.21	2.84	169
08-Apr-15	23	550	220	330		256	229		34.3		3.99		272	140	132		113	98		29.9		2.97	
09-Apr-15	24	623	229	394		309	275	48.5	35.8	6.01	3.52	197	274	131	143		119	102	41.5	31.0	4.40	2.16	178
10-Apr-15	25																						
11-Apr-15	26																						
12-Apr-15	27	725	262	463		239	221		33.1		3.27		329	139	190		126	113		29.1		2.37	
13-Apr-15	28	774	228	546		305	273		35.2		4.38		341	156	185		95	83		31.2		3.14	
14-Apr-15	29	989	193	796	294	355	309	50.0	32.1	6.79	3.54	176	390	149	241	145	131	115	42.7	31.3	5.42	2.84	185
15-Apr-15	30	762	169	593		215	183		28.6		2.68		173	85	88		50	42		23.9		1.17	
16-Apr-15	31	704	180	524		223	195	41.4	30.4	5.39	2.83	172	262	111	151		87	73	35.4	26.4	4.00	1.88	163
17-Apr-15	32																						
18-Apr-15	33																						
19-Apr-15	34	523	237	286		218	203		29.5		3.06		350	190	160		101	87		29.2		2.87	
20-Apr-15	35	571	158	413		214	192		23.4		2.38		302	133	169		99	81		22.3		2.01	
21-Apr-15	36	439	171	268	208	182	163	35.7	25.9	4.61	2.17	150	223	117	106	83	91	81	30.5	22.8	3.43	1.22	152
22-Apr-15	37	465	176	289		208	179		28.6		2.55		218	118	100		70	51		25.3		1.29	
23-Apr-15	38	519	147	372		236	213	43.0	30.2	6.14	2.63	182	243	108	135		107	89	35.2	26.9	4.24	2.00	173
24-Apr-15	39																						
25-Apr-15	40																						
26-Apr-15	41	591	209	382		212	188						283	130	153		92	76					
27-Apr-15	42	700	206	494		227	201		30.6		3.46		302	145	157		108	88		27.1		2.19	
28-Apr-15	43	676	190	486		219	192		33.7		3.47		298	130	168		105	89		28.6		2.20	
29-Apr-15	44	658	203	455		279	244		34.4		6.60		302	137	165		116	98		30.7		4.51	
30-Apr-15	45	880	195	685		375	340	47.3	34.2	8.01	3.45	201	376	132	244		143	128	37.4	32.2	5.33	2.82	202
01-May-15	46																						

A.3.6 COD Properties

COD Characteristics														
Date	Days	Influent					Effluent					Removed		
		COD (mg/L)	sCOD (mg/L)	pCOD (mg/L)	% Soluble	% Particulate	COD (mg/L)	sCOD (mg/L)	pCOD (mg/L)	% Soluble	% Particulate	COD (mg/L)	sCOD (mg/L)	pCOD (mg/L)
<b>Average</b>		303	137	166	46%	54%	53.9	23.2	31.5	44%	56%	251	115	138
<b>Sample SD</b>		47	21	39	6%	6%	18.4	3.0	16.7	12%	12%	49	20	42
17-Mar-15	1	259	100	159	0.39	0.61	54.9	22.4	32.5	0.41	0.59	204	78	127
18-Mar-15	2	298	121	177	0.41	0.59	45.9	17.9	28.0	0.39	0.61	252	103	149
19-Mar-15	3	353	139	214	0.39	0.61	25.1	17.5	7.6	0.70	0.30	328	122	206
20-Mar-15	4													
21-Mar-15	5													
22-Mar-15	6	363	136	227	0.37	0.63	59.2	20.2	39.0	0.34	0.66	304	116	188
23-Mar-15	7	362	165	197	0.46	0.54	59.4	25.1	34.3	0.42	0.58	303	140	163
24-Mar-15	8	305	147	158	0.48	0.52	50.8	21.9	28.9	0.43	0.57	254	125	129
25-Mar-15	9	317	131	186	0.41	0.59	49.1	22.3	26.8	0.45	0.55	268	109	159
26-Mar-15	10	339	144	195	0.42	0.58	54.6	21.4	33.2	0.39	0.61	284	123	162
27-Mar-15	11													
28-Mar-15	12													
29-Mar-15	13	335	156	179	0.47	0.53	50.4	20.1	30.3	0.40	0.60	285	136	149
30-Mar-15	14	318	162	156	0.51	0.49	58.1	21.2	36.9	0.36	0.64	260	141	119
31-Mar-15	15	320	138	182	0.43	0.57	35.9	21.7	14.2	0.60	0.40	284	116	168
01-Apr-15	16	316	137	179	0.43	0.57	68.6	24.4	44.2	0.36	0.64	247	113	135
02-Apr-15	17	308	131	177	0.43	0.57	64.3	26.7	37.6	0.42	0.58	244	104	139
03-Apr-15	18													
04-Apr-15	19													
05-Apr-15	20	316	173	143	0.55	0.45	142.0	31.3	110.7	0.22	0.78	174	142	32
06-Apr-15	21	293	170	123	0.58	0.42	56.0	27.9	28.1	0.50	0.50	237	142	95
07-Apr-15	22	260	144	116	0.55	0.45	51.1	27.7	23.4	0.54	0.46	209	116	93
08-Apr-15	23	272	140	132	0.51	0.49	48.3	26.8	21.5	0.55	0.45	224	113	111
09-Apr-15	24	274	131	143	0.48	0.52	43.0	23.8	19.2	0.55	0.45	231	107	124
10-Apr-15	25													
11-Apr-15	26													
12-Apr-15	27	329	139	190	0.42	0.58	67.1	26.5	40.6	0.39	0.61	262	113	149
13-Apr-15	28	341	156	185	0.46	0.54	51.4	24.7	26.7	0.48	0.52	290	131	158
14-Apr-15	29	390	129	261	0.33	0.67	61.7	25.9	35.8	0.42	0.58	328	103	225
15-Apr-15	30	173	84.6	88.4	0.49	0.51	54.8	22.5	32.3	0.41	0.59	118	62	56
16-Apr-15	31	262	111	151	0.42	0.58	55.9	23.8	32.1	0.43	0.57	206	87	119
17-Apr-15	32													
18-Apr-15	33													
19-Apr-15	34	350	190	160	0.54	0.46	50.0	22.8	27.2	0.46	0.54	300	167	133
20-Apr-15	35	302	133	169	0.44	0.56	48.8	21.6	27.2	0.44	0.56	253	111	142
21-Apr-15	36	223	117	106	0.52	0.48	46.3	21.9	24.4	0.47	0.53	177	95	82
22-Apr-15	37	218	118	100	0.54	0.46	39.3	21.9	17.4	0.56	0.44	179	96	83
23-Apr-15	38	243	108	135	0.44	0.56	44.9		44.9	0.00	1.00	198	108	90
24-Apr-15	39													
25-Apr-15	40													
26-Apr-15	41	283	130	153	0.46	0.54						283	130	153
27-Apr-15	42	302	145	157	0.48	0.52	39.1	22.5	16.6	0.58	0.42	263	123	140
28-Apr-15	43	298	130	168	0.44	0.56	44.3	21.0	23.3	0.47	0.53	254	109	145
29-Apr-15	44	302	137	165	0.45	0.55	53.9	21.7	32.2	0.40	0.60	248	115	133
30-Apr-15	45	376	132	244	0.35	0.65	50.9	21.4	29.5	0.42	0.58	325	111	215
01-May-15	46													

A.3.7a Alkalinity Usage

Alkalinity Consumption									
Date	Days	Influent Ammonia (mg-N/L)	Effluent Ammonia (mg-N/L)	TAN Removal (mg-N/L)	Effluent pH	Influent Alkalinity (mg CaCO <sub>3</sub> /L)	Effluent Alkalinity (mg CaCO <sub>3</sub> /L)	Bicarbonate Feed (mg CaCO <sub>3</sub> /L)	Alk Added/TAN Removed (mg CaCO <sub>3</sub> /mg NH <sub>4</sub> -N)
<b>Average</b>		28.7	3.58	25.1	6.79	179	127	60	4.40
<b>Sample SD</b>		2.6	0.97	2.4	0.06	13	15	12	0.30
17-Mar-15	1	27.0	3.63	23.4	6.86	169	128	56	4.15
18-Mar-15	2	28.8	4.48	24.3	6.80			63	
19-Mar-15	3	29.8	4.92	24.9	6.84	187	127	61	4.85
20-Mar-15	4				6.81			62	
21-Mar-15	5							61	
22-Mar-15	6	28.6	2.94	25.7				44	
23-Mar-15	7	28.7	2.90	25.8	6.80			41	
24-Mar-15	8	30.0	3.19	26.8	6.81	187	128	51	4.12
25-Mar-15	9	31.3	3.4	27.9	6.79			63	
26-Mar-15	10	29.8	3.5	26.3	6.79	191	133	47	3.98
27-Mar-15	11				6.83			47	
28-Mar-15	12							44	
29-Mar-15	13	28.9	2.8	26.1				43	
30-Mar-15	14	27.0	2.3	24.7	6.83			43	
31-Mar-15	15	30.8	3.2	27.6	6.82	182	124	55	4.11
01-Apr-15	16	30.8	4.0	26.8	6.82			60	
02-Apr-15	17	33.2	5.2	28.0	6.83	185	135	74	4.42
03-Apr-15	18				6.86			84	
04-Apr-15	19							67	
05-Apr-15	20								
06-Apr-15	21	28.2	6.2	22.0	6.72			75	
07-Apr-15	22	29.6	4.7	24.9	6.8	169	135	72	4.26
08-Apr-15	23	29.9	4.4	25.5	6.82			73	
09-Apr-15	24	31.0	4.5	26.5	6.81	178	137	74	4.36
10-Apr-15	25				6.81			70	
11-Apr-15	26							65	
12-Apr-15	27	29.1	4.0	25.1				69	
13-Apr-15	28	31.2	4.1	27.1	6.8			58	
14-Apr-15	29	31.3	4.1	27.2	6.8	185	116	61	4.76
15-Apr-15	30	23.9	4.3	19.6	6.84			63	
16-Apr-15	31	26.4	3.9	22.5	6.78	163	131	78	4.88
17-Apr-15	32				6.8			75	
18-Apr-15	33							51	
19-Apr-15	34	29.2	3.3	25.9				37	
20-Apr-15	35	22.3	2.0	20.3	6.84			59	
21-Apr-15	36	22.8	2.3	20.5	6.83	152	136	76	4.49
22-Apr-15	37	25.3	2.5	22.8	6.81			80	
23-Apr-15	38	26.9	2.7	24.2	6.83	173	136	71	4.46
24-Apr-15	39				6.79			69	
25-Apr-15	40							57	
26-Apr-15	41							53	
27-Apr-15	42	27.1	2.4	24.7	6.79			43	
28-Apr-15	43	28.6	2.9	25.8	6.79			51	
29-Apr-15	44	30.7	2.9	27.8	6.63				
30-Apr-15	45	32.2	3.2	29.0	6.65	202	80		
01-May-15	46				6.58			51	

A.3.7b Alkalinity Usage

AvN_MLE_ASE																	
Date	Total SRT (days)	Net Heterotrophic Yield (g/g)	Influent BOD (mg/L)	Effluent BOD (mg/L)	TKN Used for BOD Oxidation	Influent TKN (mg-N/L)	Effluent TKN (mg-N/L)	TKN Nitrified (mg-N/L)	Alk used by Nitrification	Effluent Nitrite (mg-)	Effluent Nitrate (mg-)	NOx Denitrified (mg-N/L)	Alk provided by Denitrification	Influent Alk (mg CaCO3/L)	Effluent Alk (mg CaCO3/L)	Theoretical Supplemental Alk Req (mg)	Alk Req for Ni/Den
Average	7.1	0.59	114	20	6.8	38.4	6.9	24	175	0.5	3.0	21.0	74.9	179	127	53	2.34
Sample SD	1.9	0.02	21	1	1.8	4.0	1.5	4	25	0.1	1.1	3.3	11.9	13	15	16	0.10
17-Mar-15	5.6	0.61	124	20	7.7	32.3	6.2	18	132	0.35	3.33	14.7	52.6	169	128	38	2.50
18-Mar-15	5.7	0.61								0.41	3.88						
19-Mar-15	6.9	0.60				40.4	8.6			0.45	4.56			187	127		
20-Mar-15	7.6	0.59															
21-Mar-15																	
22-Mar-15										0.49	2.59						
23-Mar-15	6.8	0.60								0.48	2.30						
24-Mar-15	7.4	0.59	108	19	6.3	38.7	5.9	26	189	0.45	2.80	23.2	82.9	187	128	47	2.28
25-Mar-15	7.3	0.59								0.51	3.08						
26-Mar-15	6.5	0.60				40.8	6.7			0.52	3.12			191	133		
27-Mar-15	6.4	0.60															
28-Mar-15																	
29-Mar-15										0.46	2.70						
30-Mar-15	4.8	0.62								0.44	2.00						
31-Mar-15	5.0	0.62	120	21	7.4	42.4	7.4	28	197	0.52	3.69	23.4	83.4	182	124	55	2.36
01-Apr-15	5.4	0.62								0.64	4.86						
02-Apr-15	5.1	0.62				42.7	9.3			0.83	6.02			185	135		
03-Apr-15	6.0	0.61															
04-Apr-15																	
05-Apr-15																	
06-Apr-15	7.0	0.60								0.59	3.90						
07-Apr-15	10.8	0.55	101	20	5.4	39.7	8.1	26	187	0.44	3.90	21.9	78.2	169	135	75	2.40
08-Apr-15	8.1	0.58								0.51	3.93						
09-Apr-15	6.3	0.60				41.5	8.6			0.56	4.32			178	137		
10-Apr-15	5.8	0.61															
11-Apr-15																	
12-Apr-15										0.59	3.01						
13-Apr-15	5.0	0.62								0.65	2.67						
14-Apr-15	5.2	0.62	145	18	9.4	42.7	7.1	26	187	0.61	2.70	22.8	81.5	185	116	36	2.29
15-Apr-15	5.3	0.62								0.51	2.02						
16-Apr-15	5.6	0.61				35.4	7.4			0.61	3.47			163	131		
17-Apr-15	6.6	0.60															
18-Apr-15																	
19-Apr-15										0.59	1.69						
20-Apr-15	7.1	0.59								0.38	1.10						
21-Apr-15	7.7	0.59	83	20	4.4	30.5	4.2	22	156	0.37	1.67	19.8	70.6	152	136	69	2.21
22-Apr-15	7.6	0.59								0.39	2.36						
23-Apr-15	8.8	0.57				35.2	5.1			0.43	2.86			173	136		
24-Apr-15	10.2	0.56															
25-Apr-15																	
26-Apr-15																	
27-Apr-15										0.29	1.82						
28-Apr-15	11.1	0.55								0.29	2.45						
29-Apr-15	10.9	0.55								0.24	2.57						
30-Apr-15	9.7	0.56				37.4	5.6			0.27	1.96			202	80		
01-May-15	10.3	0.56															

## A.4 Data Collection during AvN\_FI\_ASE Low

### A.4.1 Performance Data

Removal Performance										
Date	Days	NH <sub>4</sub> <sup>+</sup> -N loading rate (mg-N/L/d)	Influent COD/NH <sub>4</sub> <sup>+</sup> -N	TIN removal rate (mg-N/L/d)	TIN removal Efficiency (%)	COD removal rate (mg/L/d)	COD removal rate/TIN removal rate	OP removal Efficiency (%)	Calculated AOB rate (mg-N/L/d)	
<b>Average</b>		137.3	9.1	76.7	55.9	1008	13.3	17.4		193
<b>Sample SD</b>		7.5	1.1	10.6	7.6	125	1.8	14.6		22
30-Nov-14	1	137.9	8.9	75.1	54.5	980	13.0	13.8		
01-Dec-14	2	136.4	10.1	84.4	61.9	1178	14.0	64.0		187
02-Dec-14	3	144.5	8.4	84.7	58.6	1033	12.2	47.8		191
03-Dec-14	4	158.8	7.5	99.7	62.8	960	9.6	20.8		232
04-Dec-14	5	142.1	8.2	82.0	57.7	943	11.5	10.9		205
05-Dec-14	6									
06-Dec-14	7									
07-Dec-14	8	128.8	9.6	75.8	58.9	1034	13.6	7.1		
08-Dec-14	9	123.1	11.9	80.3	65.3	1244	15.5	21.1		158
09-Dec-14	10	128.8	9.7	81.4	63.2	1024	12.6	18.8		160
10-Dec-14	11	133.6	8.8	71.9	53.9	921	12.8	20.2		166
11-Dec-14	12	138.8	8.3	65.8	47.4	913	13.9	18.3		188
12-Dec-14	13									
13-Dec-14	14									
14-Dec-14	15	136.4	8.8	67.3	49.3	970	14.4	15.4		
15-Dec-14	16	135.5	11.5	88.8	65.6	1311	14.8	33.7		208
16-Dec-14	17	136.9	10.1	93.8	68.5	1158	12.3	12.5		210
17-Dec-14	18	139.8	8.8	88.6	63.4	995	11.2	9.9		211
18-Dec-14	19	139.8	8.3	81.8	58.5	909	11.1	13.1		198
19-Dec-14	20									
28-Dec-14	21									
29-Dec-14	22	130.2	9.0	73.9	56.7	754	10.2	4.2		224
30-Dec-14	23	126.9	9.2	69.2	54.5	874	12.6	9.8		215
31-Dec-14	24									
03-Jan-15	25									
04-Jan-15	26	139.3	8.9	63.1	45.3	1009	16.0	9.4		
05-Jan-15	27	136.4	9.2	69.5	50.9	1044	15.0	16.8		179
06-Jan-15	28	141.2	8.2	65.0	46.0	949	14.6	2.8		172
07-Jan-15	29	139.8	8.0	61.1	43.7	933	15.3	1.6		182
08-Jan-15	30	146.4	8.3	64.9	44.3	1034	15.9	10.9		184
09-Jan-15	31									



### A.4.2 Operational Conditions

Operational Conditions							
Date	Days	Temperature in 1st CSTR (°C)	MLSS (mg/L)	VSS (mg/L)	Total SRT (days)	Aerobic Fraction	Aerobic SRT (days)
Average		20.1	2404	2042	7.8	0.50	4.0
Sample SD		0.2	380	284	2.1	0.04	1.2
30-Nov-14	1					0.54	
01-Dec-14	2	19.9	2505	1990	8.8	0.55	4.8
02-Dec-14	3	20.0	2815	2250	10.4	0.56	5.8
03-Dec-14	4	20.3	3060	2445	9.6	0.51	4.9
04-Dec-14	5	20.3	2785	2260	9.4	0.50	4.7
05-Dec-14	6	20.3	3025	2450	7.0	0.47	3.3
06-Dec-14	7					0.47	
07-Dec-14	8					0.46	
08-Dec-14	9	20.1	2415	1990	3.7	0.47	1.7
09-Dec-14	10	20.2	2350	1965	4.0	0.50	2.0
10-Dec-14	11	20.1	2155	1825	5.1	0.52	2.6
11-Dec-14	12	20.0	2090	1765	9.2	0.54	4.9
12-Dec-14	13	20.0	2170	1800	8.1	0.50	4.0
13-Dec-14	14					0.51	
14-Dec-14	15					0.52	
15-Dec-14	16	20.2	2400	2075	9.1	0.52	4.8
16-Dec-14	17	20.4	2800	2395	9.3	0.52	4.8
17-Dec-14	18	20.3	2810	2420	8.8	0.49	4.3
18-Dec-14	19	20.1	2605	2245	7.8	0.49	3.8
19-Dec-14	20	20.0	2760	2405	7.8	0.48	3.7
28-Dec-14	21					0.41	
29-Dec-14	22	20.4	2205			0.42	
30-Dec-14	23	20.2	2385	2055	4.8	0.41	2.0
31-Dec-14	24	20.1	2365	2065	5.4	0.41	2.2
03-Jan-15	25					0.49	
04-Jan-15	26					0.50	
05-Jan-15	27	20.3	1705	1545	6.3	0.52	3.3
06-Jan-15	28	20.0	1905	1685	8.4	0.55	4.6
07-Jan-15	29	20.1	1835	1640	9.2	0.53	4.9
08-Jan-15	30	19.9	2025	1800	10.0	0.55	5.5
09-Jan-15	31	19.9	2130	1845	10.0	0.51	5.0

A.4.3 Batch Rate Testing

Batch Rate Testing Results								
Date	Days	AOB rate (mgNOx-N/gMLSS/hr)	NOB rate (mgNO3-N/gMLSS/hr)	NOB rate/AOB rate	Average OUR (mg/L/hr)	Denitrification rate (mgNO3-N/gMLSS/hr)	Denitrification rate (mgNO2-N/gMLSS/hr)	Denitrification rate (mgNOx-N/gMLSS/hr)
<b>Average</b>		4.62	3.92	0.85	57.9	2.63	0.26	2.95
<b>Sample SD</b>		0.83	0.74	0.06	5.9	0.44	0.53	0.66
30-Nov-14	1							
01-Dec-14	2					3.00	-0.23	2.77
02-Dec-14	3				58.7			
03-Dec-14	4							
04-Dec-14	5	3.92	2.97	0.76				
05-Dec-14	6							
06-Dec-14	7							
07-Dec-14	8							
08-Dec-14	9							
09-Dec-14	10				50.2			
10-Dec-14	11					2.36	-0.07	2.29
11-Dec-14	12							
12-Dec-14	13	4.18	3.59	0.86				
13-Dec-14	14							
14-Dec-14	15							
15-Dec-14	16					3.25	0.23	3.48
16-Dec-14	17				66.7			
17-Dec-14	18							
18-Dec-14	19	4.49	3.95	0.88				
19-Dec-14	20							
28-Dec-14	21							
29-Dec-14	22							
30-Dec-14	23				57.6	2.19	0.23	2.42
31-Dec-14	24	4.46	4.09	0.92				
03-Jan-15	25							
04-Jan-15	26							
05-Jan-15	27							
06-Jan-15	28							
07-Jan-15	29	6.04	4.99	0.83	56.3			
08-Jan-15	30					2.67	1.14	3.81
09-Jan-15	31							

#### A.4.4 Effluent Characteristics

Average Effluent Characteristics													
Date	Days	Ammonia (mg-N/L)	Nitrite (mg-N/L)	Nitrate (mg-N/L)	NAR (NO2-N/NOx-N) (%)	NOx/Ammonia	OP (mg-P/L)	TSS (mg/L)	SVI 30 (mL/g)	TIN (mg-N/L)	TN (mg-N/L)	TP (mg-P/L)	
<b>Average</b>		6.31	1.30	5.10	21%	1.02	2.39	26.0	107	12.7	15.0	2.92	
<b>Sample SD</b>		1.27	0.92	1.51	14%	0.16	0.69	8.3	23	2.4	2.4	0.40	
30-Nov-14	1	5.88	3.82	3.45	53%	1.24	0.69	23.8		13.2			
01-Dec-14	2	5.00	3.27	2.64	55%	1.18	0.87	19.3	128	10.9			
02-Dec-14	3	5.96	2.97	3.62	45%	1.11	2.00	20.5	124	12.6	14.8	2.23	
03-Dec-14	4	6.09	2.24	4.06	36%	1.03	2.13	22.0	131	12.4			
04-Dec-14	5	6.45	1.50	4.65	24%	0.95	2.46	29.0	158	12.6	16.0	2.96	
05-Dec-14	6								169				
06-Dec-14	7												
07-Dec-14	8	6.14	1.05	3.92	21%	0.81	2.21	20.5		11.1			
08-Dec-14	9	4.91	0.93	3.12	23%	0.83	1.98	22.3	128	9.0			
09-Dec-14	10	5.09	1.04	3.80	21%	0.95	1.95	26.5	111	9.9	11.3	2.52	
10-Dec-14	11	6.79	1.05	5.08	17%	0.90	2.09	28.5	102	12.9			
11-Dec-14	12	6.99	0.90	7.42	11%	1.19	2.28	32.8	105	15.3	17.6	2.81	
12-Dec-14	13								101				
13-Dec-14	14												
14-Dec-14	15	6.39	0.76	7.35	9%	1.27	2.53	26.8		14.5			
15-Dec-14	16	4.13	0.76	4.89	13%	1.37	2.20	26.3	92	9.8			
16-Dec-14	17	4.08	0.71	4.25	14%	1.22	2.51	23.5	86	9.0	11.3	2.78	
17-Dec-14	18	5.50	0.48	4.76	9%	0.95	2.56	22.0	82	10.7			
18-Dec-14	19	6.60	0.37	5.19	7%	0.84	2.58	21.3	92	12.2	14.6	2.91	
19-Dec-14	20								91				
28-Dec-14	21												
29-Dec-14	22	5.98	0.87	4.97	15%	0.98	2.96	55.0	91	11.8			
30-Dec-14	23	6.31	0.77	5.02	13%	0.92	2.84	42.0	96	12.1	14.8	3.32	
31-Dec-14	24								80				
03-Jan-15	25												
04-Jan-15	26	8.31	0.99	6.68	13%	0.92	3.19	25.5		16.0			
05-Jan-15	27	7.51	0.88	5.65	13%	0.87	3.07	23.3	100	14.0			
06-Jan-15	28	8.61	0.99	6.38	13%	0.86	3.14	21.8	94	16.0	15.9	3.30	
07-Jan-15	29	7.93	1.12	7.44	13%	1.08	3.06	20.3	104	16.5			
08-Jan-15	30	8.22	1.12	7.76	13%	1.08	3.34	18.5	99	17.1	18.5	3.45	
09-Jan-15	31								94				

A.4.5 Influent Properties

Influent Properties																							
Date	Days	RWI										A-Stage Effluent											
		COD (mg/L)	sCOD (mg/L)	pCOD (mg/L)	BOD (mg/L)	TSS (mg/L)	VSS (mg/L)	TKN (mg-N/L)	TAN (mg-N/L)	TP (mg-P/L)	OP (mg-P/L)	Alk (mg as CaCO3/L)	COD (mg/L)	sCOD (mg/L)	pCOD (mg/L)	BOD (mg/L)	TSS (mg/L)	VSS (mg/L)	TKN (mg-N/L)	TAN (mg-N/L)	TP (mg-P/L)	OP (mg-P/L)	Alk (mg as CaCO3/L)
<b>Average</b>		536	237	299	291	178	161	43.1	33.1	5.6	4.27	169	260	147	114	115	68	62	36.1	28.8	4.0	2.90	164
<b>Sample SD</b>		50	16	48	98	27	25	4.3	1.6	0.5	0.66	7	23	17	17	45	13	12	4.0	1.6	0.4	0.64	7
30-Nov-14	1	478	213	265		179	150			33.1	1.95		258	124	134		86	70					0.80
01-Dec-14	2	605	245	360		240	211			32.8	4.00		288	145	143		96	87					2.43
02-Dec-14	3	495	261	234	235	182	164	45.9	34.5	5.40	4.26	172	256	124	132	101	80	72	42.6	30.3	3.68	3.83	166
03-Dec-14	4	518	229	289		171	155			36.6	4.26		249	131	118		65	58					2.69
04-Dec-14	5	526	228	298		180	163	50.9	34.3	5.38	4.39	177	244	127	117		71	66	41.2	29.8	3.81	2.76	163
05-Dec-14	6																						
06-Dec-14	7																						
07-Dec-14	8	468	244	224		163	143			30.8	3.85		259	144	115		69	58		27.0			2.38
08-Dec-14	9	487	245	242		152	137			30.2	3.73		308	166	142		85	77		25.8			2.51
09-Dec-14	10	464	211	253	293	151	140	36.1	31.0	4.70	3.45	155	261	139	122	107	76	73	34.4	27.0	3.48	2.40	153
10-Dec-14	11	489	242	247		136	125			32.0	3.86		246	151	95		58	56		28.0			2.62
11-Dec-14	12	475	220	255		165	141	43.1	33.6	5.51	4.24	171	241	140	101		58	41	35.1	29.1	3.71	2.79	160
12-Dec-14	13																						
13-Dec-14	14																						
14-Dec-14	15	552	253	299		136	122			33.3	4.54		253	146	107		67	60		28.6			2.99
15-Dec-14	16	580	249	331		155	140			33.5	4.46		327	193	134		82	80		28.4			3.32
16-Dec-14	17	630	236	394	444	222	201	42.5	33.0	5.98	4.46	164	290	164	126	192	87	79	37.0	28.7	4.29	2.87	159
17-Dec-14	18	546	230	316		162	144			33.5	4.38		258	140	118		63	60		29.3			2.84
18-Dec-14	19	540	227	313		164	148	46.7	34.8	5.66	5.10	168	242	135	107		57	55	38.1	29.3	3.90	2.97	159
19-Dec-14	20																						
28-Dec-14	21																						
29-Dec-14	22	622	230	392		215	192			31.1	4.64		247	140	107		56	50		27.3			3.09
30-Dec-14	23	558	223	335	182	200	185	40.2	30.5	6.01	4.56	165	246	142	104	71	59	56	31.1	26.6	3.90	3.15	162
31-Dec-14	24																						
03-Jan-15	25																						
04-Jan-15	26	580	265	315		172	166			33.1	4.95		261	160	101		50	51		29.2			3.52
05-Jan-15	27	534	263	271		196	179			32.9	4.98		262	174	88		64	55		28.6			3.69
06-Jan-15	28	515	229	286	300	174	161	40.4	34.8	5.76	4.76	177	242	150	92	104	55	53	32.2	29.6	4.18	3.23	173
07-Jan-15	29	584	246	338		189	174			33.4	4.60		234	149	85		50	48		29.3			3.11
08-Jan-15	30	538	214	324		201	193	42.0	34.5	6.37	4.57	176	255	143	112		63	55	33.0	30.7	4.66	3.75	177
09-Jan-15	31																						

A.4.6 COD Properties

COD Characteristics														
Date	Days	Influent					Effluent					Removed		
		COD (mg/L)	sCOD (mg/L)	pCOD (mg/L)	% Soluble	% Particulate	COD (mg/L)	sCOD (mg/L)	pCOD (mg/L)	% Soluble	% Particulate	COD (mg/L)	sCOD (mg/L)	pCOD (mg/L)
Average		260	147	114	56%	44%	49.1	24.8	24.3	52%	48%	211	122	89
Sample SD		23	17	17	5%	5%	10.6	2.5	11.1	11%	11%	26	16	21
30-Nov-14	1	258	124	134	48%	52%	52.5	25.2	27.3	48%	52%	206	99	107
01-Dec-14	2	288	145	143	50%	50%	41.1	26.7	14.4	65%	35%	247	118	129
02-Dec-14	3	256	124	132	48%	52%	39.5	27.9	11.6	71%	29%	217	96	120
03-Dec-14	4	249	131	118	53%	47%	47.8	24.1	23.7	50%	50%	201	107	94
04-Dec-14	5	244	127	117	52%	48%	46.3	21.8	24.5	47%	53%	198	105	93
05-Dec-14	6													
06-Dec-14	7													
07-Dec-14	8	259	144	115	56%	44%	42.2	24.7	17.5	59%	41%	217	119	98
08-Dec-14	9	308	166	142	54%	46%	47.1	23.3	23.8	49%	51%	261	143	118
09-Dec-14	10	261	139	122	53%	47%	46.4	27.4	19.0	59%	41%	215	112	103
10-Dec-14	11	246	151	95	61%	39%	53.0	23.8	29.2	45%	55%	193	127	66
11-Dec-14	12	241	140	101	58%	42%	49.6	21.1	28.5	43%	57%	191	119	73
12-Dec-14	13													
13-Dec-14	14													
14-Dec-14	15	253	146	107	58%	42%	49.7	22.5	27.2	45%	55%	203	124	80
15-Dec-14	16	327	193	134	59%	41%	52.2	22.8	29.4	44%	56%	275	170	105
16-Dec-14	17	290	164	126	57%	43%	47.3	31.1	16.2	66%	34%	243	133	110
17-Dec-14	18	258	140	118	54%	46%	49.3	22.1	27.2	45%	55%	209	118	91
18-Dec-14	19	242	135	107	56%	44%	51.4	22.3	29.1	43%	57%	191	113	78
19-Dec-14	20													
28-Dec-14	21													
29-Dec-14	22	247	140	107	57%	43%	88.9	25.4	63.5	29%	71%	158	115	44
30-Dec-14	23	246	142	104	58%	42%	62.7	25.6	37.1	41%	59%	183	116	67
31-Dec-14	24													
03-Jan-15	25													
04-Jan-15	26	261	160	101	61%	39%	49.5	24.3	25.2	49%	51%	212	136	76
05-Jan-15	27	262	174	98	66%	34%	43.2	28.4	14.8	66%	34%	219	146	73
06-Jan-15	28	242	150	92	62%	38%	43.1	27.6	15.5	64%	36%	199	122	77
07-Jan-15	29	234	149	85	64%	36%	38.4	23.7	14.7	62%	38%	196	125	70
08-Jan-15	30	255	143	112	56%	44%	38.2	23.8	14.4	62%	38%	217	119	98
09-Jan-15	31													

A.4.7a Alkalinity Usage

Alkalinity Consumption										
Date	Days	Influent Ammonia (mg-N/L)	Effluent Ammonia (mg-N/L)	TAN Removal (mg-N/L)	Effluent pH	Influent Alkalinity (mg CaCO <sub>3</sub> /L)	Effluent Alkalinity (mg CaCO <sub>3</sub> /L)	Bicarbonate Feed (mg CaCO <sub>3</sub> /L)	Alk Added (mg CaCO <sub>3</sub> )	TAN Removed (mg NH <sub>4</sub> -N)
<b>Average</b>		28.8	6.31	22.5	6.77	164	118	51		4.43
<b>Sample SD</b>		1.6	1.27	1.7	0.07	7	11	17		0.28
30-Nov-14	1	28.9	5.88	23.0					78	
01-Dec-14	2	28.6	5.00	23.6	6.79				59	
02-Dec-14	3	30.3	5.96	24.3	6.79	166	108		48	4.34
03-Dec-14	4	33.3	6.09	27.2	6.83				47	
04-Dec-14	5	29.8	6.45	23.4	6.79	163	105		44	4.37
05-Dec-14	6				6.73				55	
06-Dec-14	7								42	
07-Dec-14	8	27	6.14	20.9					26	
08-Dec-14	9	25.8	4.91	20.9	6.63				70	
09-Dec-14	10	27	5.09	21.9	6.70	153	120		63	4.37
10-Dec-14	11	28	6.79	21.2	6.71				69	
11-Dec-14	12	29.1	6.99	22.1	6.78	160	144		92	4.86
12-Dec-14	13				6.81				101	
13-Dec-14	14								34	
14-Dec-14	15	28.6	6.39	22.2					28	
15-Dec-14	16	28.4	4.13	24.3	6.58				40	
16-Dec-14	17	28.7	4.08	24.6	6.83	159	112		55	4.12
17-Dec-14	18	29.3	5.50	23.8	6.78				55	
18-Dec-14	19	29.3	6.60	22.7	6.81	159	122		53	3.96
19-Dec-14	20				6.83				55	
20-Dec-14	21								49	
29-Dec-14	22	27.3	5.98	21.3	6.80					
30-Dec-14	23	26.6	6.31	20.3	6.84	162	117		50	4.66
31-Dec-14	24				6.80				40	
03-Jan-15	25								39	
04-Jan-15	26	29.2	8.31	20.9					33	
05-Jan-15	27	28.6	7.51	21.1	6.80				41	
06-Jan-15	28	29.6	8.61	21.0	6.75	173	116		40	4.60
07-Jan-15	29	29.3	7.93	21.4	6.66				47	
08-Jan-15	30	30.7	8.22	22.5	6.86	177	118		44	4.57
09-Jan-15	31				6.85				39	

A.4.7b Alkalinity Usage

AvN_FI_ASE Low																	
Date	Total SRT (days)	Net Heterotrophic Yield (g/g)	Influent BOD (mg/L)	Effluent BOD (mg/L)	TKN Used for BOD Oxidation	Influent TKN (mg-N/L)	Effluent TKN (mg-N/L)	TKN Nitrified (mg-N/L)	Alk used by Nitrification	Effluent Nitrite (mg-)	Effluent Nitrate (mg-)	NOx Denitrified (mg-N/L)	Alk provided by Denitrification	Influent Alk (mg CaCO3/L)	Effluent Alk (mg CaCO3/L)	Theoretical Supplemental Alk Req (mg)	Alk Req for NiVDen
Average	8.3	0.56	118	18	6.9	33.5	7.2	19	133	1.3	4.3	14.2	50.6	152	107	40	2.39
Sample SD	2.8	0.11	49	7	3.0	9.0	2.4	7	53	0.8	1.9	6.0	21.3	42	31	17	0.98
30-Nov-14										3.82	3.45						
01-Dec-14	8.8	0.57								3.27	2.64						
02-Dec-14	10.4	0.56	101	22	5.3	42.6	8.2	29	208	2.97	3.62	22.5	80.5	166	108	70	2.58
03-Dec-14	9.6	0.56								2.24	4.06						
04-Dec-14	9.4	0.57				41.2	9.8			1.50	4.65			163	105		
05-Dec-14	7.0	0.60															
06-Dec-14																	
07-Dec-14										1.05	3.92						
08-Dec-14	3.7	0.64								0.93	3.12						
09-Dec-14	4.0	0.64	107	19	6.7	34.4	6.5	21	151	1.04	3.80	16.4	58.4	153	120	60	2.59
10-Dec-14	5.1	0.62								1.05	5.08						
11-Dec-14	9.2	0.57				35.1	9.2			0.90	7.42			160	144		
12-Dec-14	8.1	0.58															
13-Dec-14																	
14-Dec-14										0.76	7.35						
15-Dec-14	9.1	0.57								0.76	4.89						
16-Dec-14	9.3	0.57	192	19	11.8	37.0	6.3	19	135	0.71	4.25	13.9	49.6	159	112	38	2.71
17-Dec-14	8.8	0.57								0.48	4.76						
18-Dec-14	7.8	0.59				38.1	9.0			0.37	5.19			159	122		
19-Dec-14	7.8	0.59															
28-Dec-14																	
29-Dec-14										0.87	4.97						
30-Dec-14	4.8	0.62	71	21	3.7	31.1	9.0	18	131	0.77	5.02	12.6	44.9	162	117	41	2.92
31-Dec-14	5.4	0.62															
03-Jan-15																	
04-Jan-15										0.99	6.68						
05-Jan-15	6.3	0.60								0.88	5.65						
06-Jan-15	8.4	0.58	104	20	5.8	32.2	8.5	18	127	0.99	6.38	10.5	37.4	173	116	33	3.41
07-Jan-15	9.2	0.57								1.12	7.44						
08-Jan-15	10.0	0.56				33.0	9.6			1.12	7.76			177	118		
09-Jan-15	10.0	0.56															

## A.5 Data Collection during AvN\_FI\_ASE High

### A.5.1 Performance Data

Removal Performance									
Date	Days	NH <sub>4</sub> <sup>+</sup> -N loading rate (mg-N/L/d)	Influent COD/NH <sub>4</sub> <sup>+</sup> -N	TIN removal rate (mg-N/L/d)	TIN removal Efficiency (%)	COD removal rate (mg/L/d)	COD removal rate/TIN removal rate	OP removal Efficiency (%)	Calculated AOB rate (mg-N/L/d)
<b>Average</b>		141.1	12.0	109.5	77.5	1474	13.3	41.2	239
<b>Sample SD</b>		9.7	1.5	12.1	6.1	284	1.7	23.3	27
11-Jan-15	1	158.4	11.4	120.6	76.2	1564	13.0	23.3	
12-Jan-15	2	146.9	12.6	114.9	78.2	1665	14.5	24.0	239
13-Jan-15	3	134.5	12.3	99.6	74.0	1468	14.7	12.6	291
14-Jan-15	4	133.6	11.4	104.8	78.5	1343	12.8	19.4	278
15-Jan-15	5	138.8	12.6	111.8	80.5	1530	13.7	19.2	306
16-Jan-15	6								
17-Jan-15	7								
18-Jan-15	8	132.1	15.2	110.8	83.8	1635	14.8	28.5	
19-Jan-15	9	131.7	14.3	114.2	86.8	1692	14.8	42.4	259
20-Jan-15	10	138.8	12.7	117.9	84.9	1597	13.5	46.8	253
21-Jan-15	11	130.2	13.3	103.4	79.4	1535	14.8	49.0	213
22-Jan-15	12	148.8	11.9	118.6	79.7	1585	13.4	43.3	237
23-Jan-15	13								
24-Jan-15	14								
25-Jan-15	15	129.3	13.0	104.1	80.5	1447	13.9	59.5	
26-Jan-15	16	136.4	12.8	114.3	83.8	1588	13.9	67.9	225
27-Jan-15	17	140.7	12.3	116.1	82.5	1567	13.5	71.5	227
28-Jan-15	18	141.7	11.7	115.7	81.7	1459	12.6	68.2	217
29-Jan-15	19	143.6	11.9	113.6	79.1	1541	13.6	52.0	212
30-Jan-15	20								
31-Jan-15	21								
01-Feb-15	22	146.9	12.7	103.0	70.1	1527	14.8	32.5	
02-Feb-15	23	149.3	13.4	119.3	79.9	1829	15.3	59.4	233
03-Feb-15	24	146.0	12.5	115.5	79.2	1652	14.3	74.5	221
04-Feb-15	25	150.3	11.4	112.0	74.5	1553	13.9	59.3	218
05-Feb-15	26	156.0	11.3	113.3	72.7	1547	13.7	50.8	224
06-Feb-15	27								
07-Feb-15	28								
08-Feb-15	29	156.0	12.5	121.1	77.6	1751	14.5	55.6	
09-Feb-15	30	157.4	13.5	126.6	80.4	1891	14.9	72.6	246
10-Feb-15	31	153.6	11.0	123.6	80.5	1538	12.4	72.0	256
11-Feb-15	32	146.4	11.7	123.6	84.4	1489	12.0	37.3	272
12-Feb-15	33	139.3	12.1	106.2	76.3	1430	13.5	25.6	233
13-Feb-15	34								
14-Feb-15	35								
15-Feb-15	36								
16-Feb-15	37								
17-Feb-15	38	130.7	8.9	83.3	63.8	740	8.9	6.4	
18-Feb-15	39	130.7	8.8	88.5	67.7	813	9.2	5.5	248
19-Feb-15	40	130.7	8.6	82.2	62.9	784	9.5	5.3	230
20-Feb-15	41								
21-Feb-15	42								
22-Feb-15	43	139.3	13.1	104.9	75.3	1602	15.3	47.4	
23-Feb-15	44	134.0	12.3	109.8	81.9	1429	13.0	55.0	218
24-Feb-15	45	121.2	8.9	81.4	67.2	908	11.2	-8.6	193
25-Feb-15	46								



### A.5.2 Operational Conditions

Operational Conditions							
Date	Days	Temperature in 1st CSTR (°C)	MLSS (mg/L)	VSS (mg/L)	Total SRT (days)	Aerobic Fraction	Aerobic SRT (days)
<b>Average</b>		20.0	3556	3013	7.9	0.45	3.6
<b>Sample SD</b>		0.4	505	406	2.2	0.05	1.0
11-Jan-15	1					0.53	
12-Jan-15	2	20.2	2940	2615	13.8	0.52	7.2
13-Jan-15	3	20.2	3215	2815	14.1	0.38	5.4
14-Jan-15	4	19.8	3345	2930	12.0	0.41	4.9
15-Jan-15	5	20.0	3545	3095	10.2	0.38	3.9
16-Jan-15	6	20.2	3825	3325	9.3	0.41	3.8
17-Jan-15	7					0.46	
18-Jan-15	8					0.46	
19-Jan-15	9		3845	3340	6.9	0.43	2.9
20-Jan-15	10	20.2	3965	3330	8.5	0.44	3.8
21-Jan-15	11	20.2	4030	3410	7.5	0.45	3.4
22-Jan-15	12	20.1	3960	3385	7.0	0.47	3.3
23-Jan-15	13	19.9	4250	3630	7.4	0.43	3.2
24-Jan-15	14					0.45	
25-Jan-15	15					0.42	
26-Jan-15	16	19.7	4080	3415	7.2	0.45	3.2
27-Jan-15	17	20.4	4015	3330	6.5	0.45	2.9
28-Jan-15	18	20.3	4125	3460	6.5	0.47	3.0
29-Jan-15	19	20.2	3930	3295	6.3	0.49	3.1
30-Jan-15	20	19.7	3975	3330	6.6	0.46	3.0
31-Jan-15	21					0.37	
01-Feb-15	22					0.36	
02-Feb-15	23	20.4	3220	2695	7.2	0.51	3.6
03-Feb-15	24	20.0	3510	2915	7.1	0.50	3.5
04-Feb-15	25	20.3	3545	2955	8.0	0.51	4.1
05-Feb-15	26	20.2	3530	2930	8.3	0.52	4.3
06-Feb-15	27	20.0	3550	2945	8.4	0.47	3.9
07-Feb-15	28					0.51	
08-Feb-15	29					0.51	
09-Feb-15	30	20.3	4010	3340	9.6	0.51	4.9
10-Feb-15	31	20.1	4010	3335	9.1	0.48	4.4
11-Feb-15	32	20.2	3940	3250	8.3	0.44	3.6
12-Feb-15	33	20.2	3705	3105	8.1	0.45	3.6
13-Feb-15	34	20.0	3690	3100	7.0	0.41	2.9
14-Feb-15	35					0.42	
15-Feb-15	36					0.40	
16-Feb-15	37					0.44	
17-Feb-15	38					0.43	
18-Feb-15	39	19.0	2800	2405	4.8	0.39	1.9
19-Feb-15	40	19.5	2905	2450	5.5	0.40	2.2
20-Feb-15	41	18.9	2505	2160	5.2	0.40	2.1
21-Feb-15	42					0.48	
22-Feb-15	43					0.51	
23-Feb-15	44	19.3	2760	2385	6.4	0.49	3.1
24-Feb-15	45	20.8	2925	2505	6.3	0.44	2.8
25-Feb-15	46	20.3	2580	2210	7.3	0.40	2.9

### A.5.3 Batch Rate Testing

Batch Rate Testing Results								
Date	Days	AOB rate (mgNO <sub>x</sub> -N/gMLSS/hr)	NOB rate (mgNO <sub>3</sub> -N/gMLSS/hr)	NOB rate/AOB rate	Average OUR (mg/L/hr)	Denitrification rate (mgNO <sub>3</sub> -N/gMLSS/hr)	Denitrification rate (mgNO <sub>2</sub> -N/gMLSS/hr)	Denitrification rate (mgNO <sub>x</sub> -N/gMLSS/hr)
<b>Average</b>		3.89	2.45	0.63	71.6	3.02	0.47	3.48
<b>Sample SD</b>		0.56	0.68	0.09	5.8	0.78	0.69	0.81
11-Jan-15	1							
12-Jan-15	2					3.41	-0.82	2.59
13-Jan-15	3							
14-Jan-15	4				74.3			
15-Jan-15	5	4.41	2.75	0.62				
16-Jan-15	6							
17-Jan-15	7							
18-Jan-15	8							
19-Jan-15	9							
20-Jan-15	10				78.3			
21-Jan-15	11							
22-Jan-15	12	3.83	2.11	0.55				
23-Jan-15	13					2.10	0.85	2.95
24-Jan-15	14							
25-Jan-15	15							
26-Jan-15	16					2.88	0.62	3.51
27-Jan-15	17				75.0			
28-Jan-15	18							
29-Jan-15	19	3.47	1.87	0.54				
30-Jan-15	20							
31-Jan-15	21							
01-Feb-15	22							
02-Feb-15	23					3.34	1.25	4.59
03-Feb-15	24							
04-Feb-15	25	3.31	2.12	0.64	66.2			
05-Feb-15	26							
06-Feb-15	27							
07-Feb-15	28							
08-Feb-15	29							
09-Feb-15	30							
10-Feb-15	31				76.6	2.64	0.98	3.62
11-Feb-15	32	3.56	2.20	0.62				
12-Feb-15	33							
13-Feb-15	34							
14-Feb-15	35							
15-Feb-15	36							
16-Feb-15	37							
17-Feb-15	38							
18-Feb-15	39				67.5	2.34	0.34	2.68
19-Feb-15	40	4.77	3.72	0.78				
20-Feb-15	41							
21-Feb-15	42							
22-Feb-15	43							
23-Feb-15	44					4.40	0.05	4.46
24-Feb-15	45				63.5			
25-Feb-15	46							

### A.5.4 Effluent Characteristics

Average Effluent Characteristics												
Date	Days	Ammonia (mg-N/L)	Nitrite (mg-N/L)	Nitrate (mg-N/L)	NAR (NO <sub>2</sub> -N/NO <sub>x</sub> -N) (%)	NO <sub>x</sub> /Ammonia	OP (mg-P/L)	TSS (mg/L)	SVI 30 (mL/g)	TIN (mg-N/L)	TN (mg-N/L)	TP (mg-P/L)
<b>Average</b>		3.35	1.41	1.86	46%	1.00	2.17	25.0	157	6.6	9.4	2.68
<b>Sample SD</b>		0.93	0.38	0.95	15%	0.24	0.67	10.8	25	1.7	2.3	0.82
11-Jan-15	1	2.94	1.69	3.28	34%	1.69	3.23	9.5		7.9		
12-Jan-15	2	2.83	1.65	2.23	42%	1.37	3.08	18.3	122	6.7		
13-Jan-15	3	3.64	1.61	2.07	44%	1.01	2.91	20.3	134	7.3	8.9	3.03
14-Jan-15	4	2.73	1.57	1.72	48%	1.21	2.57	17.3	152	6.0		
15-Jan-15	5	2.43	1.64	1.60	51%	1.33	2.95	21.5	161	5.7	7.9	3.02
16-Jan-15	6								133			
17-Jan-15	7											
18-Jan-15	8	1.77	1.34	1.37	49%	1.53	2.83	53.5		4.5		
19-Jan-15	9	1.80	1.00	0.86	54%	1.03	2.32	17.0	172	3.7		
20-Jan-15	10	2.13	1.26	1.00	56%	1.06	2.19	20.3	164	4.4	5.9	2.32
21-Jan-15	11	3.02	1.80	0.81	63%	0.86	2.24	20.0	189	5.6		
22-Jan-15	12	3.21	2.14	0.98	63%	0.97	2.51	23.3	184	6.3	8.7	2.83
23-Jan-15	13								169			
24-Jan-15	14											
25-Jan-15	15	2.93	1.24	1.11	53%	0.80	1.59	15.8		5.3		
26-Jan-15	16	2.61	1.16	0.86	57%	0.77	1.28	20.0	184	4.6		
27-Jan-15	17	3.00	1.50	0.65	70%	0.72	1.13	20.3	187	5.2	7.0	1.48
28-Jan-15	18	2.92	1.74	0.78	63%	0.86	1.32	23.3	192	5.4		
29-Jan-15	19	3.25	1.92	1.12	63%	0.94	2.04	23.3	201	6.3	10.0	2.37
30-Jan-15	20								179			
31-Jan-15	21											
01-Feb-15	22	4.09	1.80	3.32	35%	1.25	2.80	31.8		9.2		
02-Feb-15	23	3.52	1.68	1.10	60%	0.79	1.72	26.0	137	6.3		
03-Feb-15	24	3.55	1.71	1.12	60%	0.80	1.12	22.0	162	6.4	8.2	1.67
04-Feb-15	25	4.57	1.81	1.64	52%	0.75	1.53	22.0	181	8.0		
05-Feb-15	26	4.82	1.77	2.35	43%	0.85	1.47	26.5	184	8.9	11.3	2.09
06-Feb-15	27								127			
07-Feb-15	28											
08-Feb-15	29	3.77	1.35	2.19	38%	0.94	2.17	21.0		7.3		
09-Feb-15	30	3.49	1.29	1.68	43%	0.85	1.29	26.3	157	6.5		
10-Feb-15	31	3.21	1.39	1.69	45%	0.96	1.13	20.0	162	6.3	8.2	1.67
11-Feb-15	32	1.99	0.87	1.94	31%	1.41	2.42	14.5	165	4.8		
12-Feb-15	33	3.78	1.31	1.85	42%	0.83	2.82	28.5	162	6.9	9.5	3.45
13-Feb-15	34								157			
14-Feb-15	35											
15-Feb-15	36											
16-Feb-15	37											
17-Feb-15	38	5.09	1.14	3.70	24%	0.95	2.94	60.0		9.9	13.8	4.13
18-Feb-15	39	4.45	1.03	3.37	23%	0.99	2.76	41.5	125	8.9		
19-Feb-15	40	5.22	0.92	4.04	18%	0.95	2.87	40.3	120	10.2	13.4	3.72
20-Feb-15	41								120			
21-Feb-15	42											
22-Feb-15	43	3.84	0.75	2.61	22%	0.87	2.01	26.8		7.2		
23-Feb-15	44	2.63	0.73	1.73	30%	0.93	1.58	27.5	116	5.1		
24-Feb-15	45	4.54	0.84	2.96	22%	0.84	2.40	17.5	137	8.3	9.4	2.80
25-Feb-15	46								140			

A.5.5 Influent Properties

Influent Properties																							
Date	Days	RWI											A-Stage Effluent										
		COD (mg/L)	sCOD (mg/L)	pCOD (mg/L)	BOD (mg/L)	TSS (mg/L)	VSS (mg/L)	TKN (mg-N/L)	TAN (mg-N/L)	TP (mg-P/L)	OP (mg-P/L)	Alk (mg as CaCO3/L)	COD (mg/L)	sCOD (mg/L)	pCOD (mg/L)	BOD (mg/L)	TSS (mg/L)	VSS (mg/L)	TKN (mg-N/L)	TAN (mg-N/L)	TP (mg-P/L)	OP (mg-P/L)	Alk (mg as CaCO3/L)
Average		551	206	345	261	194	178	37.9	30.6	5.9	4.37	168	356	169	186	148	107	96	34.6	29.6	5.8	3.85	171
Sample SD		76	33	73	68	41	36	2.2	1.7	0.5	0.37	9	52	29	40	50	21	16	5.5	2.0	3.2	0.57	14
11-Jan-15	1	555	255	300		192	175				31.6		377	224	153		85	78				33.2	4.21
12-Jan-15	2	540	238	302		167	165				30.6		389	220	169		102	101				30.8	4.05
13-Jan-15	3	557	197	360	281	222	200	38.5	29.0	5.34	3.59	162	348	171	177	171	97	89	34.8	28.2	4.68	3.33	160
14-Jan-15	4	491	175	316		134	122				28.8		319	162	157		91	84				28.0	3.19
15-Jan-15	5	518	186	332		187	175	36.1	29.4	5.21	3.95	156	368	163	205		117	101	35.3	29.1	4.86	3.65	163
16-Jan-15	6																						
17-Jan-15	7																						
18-Jan-15	8	669	314	355		244	218				27.5		421	208	213		128	109			27.7		3.96
19-Jan-15	9	562	219	343		194	164				27.8		396	196	200		95	86			27.6		4.03
20-Jan-15	10	540	193	347	371	213	201	38.6	29.9	6.00	4.29	163	371	172	199	174	119	102	36.7	29.1	5.34	4.12	162
21-Jan-15	11	526	186	340		222	206				28.5		363	163	200		106	97			27.3		4.39
22-Jan-15	12	521	158	363		242	214	40.2	32.4	6.63	4.79	179	371	140	231		137	119	37.4	31.2	5.93	4.43	181
23-Jan-15	13																						
24-Jan-15	14																						
25-Jan-15	15	481	179	302		113	112				27.9		353	152	201		95	87			27.1		3.93
26-Jan-15	16	485	182	303		156	138				29.3		367	165	202		118	105			28.6		3.99
27-Jan-15	17	500	173	327	204	212	192	34.3	28.8	5.39	4.12	163	363	157	206	149	105	92	32.0	29.5	4.86	3.96	162
28-Jan-15	18	479	172	307		106	101				30.2		348	149	199		105	92			29.7		4.15
29-Jan-15	19	519	204	315		232	213	38.3	30.6	6.02	4.55	175	357	176	181		110	99	35.3	30.1	5.51	4.25	181
30-Jan-15	20																						
31-Jan-15	21																						
01-Feb-15	22	846	198	648		161	150				31.6		391	169	222		96	87			30.8		4.15
02-Feb-15	23	589	202	387		209	188				31.5		420	183	237		123	111			31.3		4.24
03-Feb-15	24	622	167	455	292	283	249	41.7	31.6	6.46	4.71	173	383	141	242	180	142	126	42.3	30.6	16.20	4.39	198
04-Feb-15	25	540	171	369		226	202				32.4		359	130	229		140	118			31.5		3.76
05-Feb-15	26	621	171	450		229	216	40.3	32.6	6.33	4.43	183	368	141	227		157	139	40.1	32.7	5.36	2.99	187
06-Feb-15	27																						
07-Feb-15	28																						
08-Feb-15	29	569	250	319		191	174				33.1		408	227	181		111	98			32.7		4.89
09-Feb-15	30	669	255	414		224	205				32.9		444	213	231		123	112			33.0		4.71
10-Feb-15	31	532	215	317	295	197	187	36.7	33.0	6.39	4.60	170	355	173	182	203	113	102	38.5	32.2	5.58	4.03	176
11-Feb-15	32	556	221	335		172	156				33.8		359	162	197		107	99			30.7		3.86
12-Feb-15	33	637	221	416		218	207	38.2	32.0	5.85	4.77	172	352	155	197		110	96	36.2	29.2	5.03	3.79	180
13-Feb-15	34																						
14-Feb-15	35																						
15-Feb-15	36																						
16-Feb-15	37																						
17-Feb-15	38	490	214	276	178	165	157	34.8	32.2	5.51	4.46	163	243	137	106	85	71	68	31.2	27.4	4.23	3.14	168
18-Feb-15	39	496	209	287		162	150				31.0		241	138	103		63	58			27.4		2.92
19-Feb-15	40	528	207	321		207	188	38.5	30.3	5.96	4.48	170	236	130	106		66	58	20.3	27.4	4.07	3.03	162
20-Feb-15	41																						
21-Feb-15	42																						
22-Feb-15	43	492	232	260		116	106				28.5		383	222	161		92	82			29.2		3.82
23-Feb-15	44	501	211	290		193	176				29.7		346	180	166		115	105			28.1		3.51
24-Feb-15	45	479	199	280	203	196	177	36.3	29.6	5.34	3.74	154	226	128	98	73	82	73	30.2	25.4	3.45	2.21	147
25-Feb-15	46	519	204	315		232	213				30.6		357	176	181		110	99			30.1		4.25

A.5.6 COD Properties

COD Characteristics														
Date	Days	Influent					Effluent					Removed		
		COD (mg/L)	sCOD (mg/L)	pCOD (mg/L)	% Soluble	% Particulate	COD (mg/L)	sCOD (mg/L)	pCOD (mg/L)	% Soluble	% Particulate	COD (mg/L)	sCOD (mg/L)	pCOD (mg/L)
Average		356	169	186	48%	52%	46.6	22.2	24.4	51%	49%	309	147	162
Sample SD		53	30	40	7%	7%	14.3	1.7	13.8	11%	11%	59	29	47
11-Jan-15	1	377	224	153	59%	41%	49.2	27.6	21.6	56%	44%	328	196	131
12-Jan-15	2	389	220	169	57%	43%	40.0	22.8	17.2	57%	43%	349	197	152
13-Jan-15	3	348	171	177	49%	51%	40.3	22.0	18.3	55%	45%	308	149	159
14-Jan-15	4	319	162	157	51%	49%	37.5	21.0	16.5	56%	44%	282	141	141
15-Jan-15	5	368	163	205	44%	56%	47.3	22.3	25	47%	53%	321	141	180
16-Jan-15	6													
17-Jan-15	7													
18-Jan-15	8	421	208	213	49%	51%	78.2	21.9	56.3	28%	72%	343	186	157
19-Jan-15	9	396	196	200	49%	51%	41.2	22.4	18.8	54%	46%	355	174	181
20-Jan-15	10	371	172	199	46%	54%	36.2	22.3	13.9	62%	38%	335	150	185
21-Jan-15	11	363	163	200	45%	55%	41.3	24.4	16.9	59%	41%	322	139	183
22-Jan-15	12	371	140	231	38%	62%	38.8	22.5	16.3	58%	42%	332	118	215
23-Jan-15	13													
24-Jan-15	14													
25-Jan-15	15	353	152	201	43%	57%	49.7	22.0	27.7	44%	56%	303	130	173
26-Jan-15	16	367	165	202	45%	55%	34.1	21.1	13	62%	38%	333	144	189
27-Jan-15	17	363	157	206	43%	57%	34.4	23.1	11.3	67%	33%	329	134	195
28-Jan-15	18	348	149	199	43%	57%	42.2	20.5	21.7	49%	51%	306	129	177
29-Jan-15	19	357	176	181	49%	51%	33.9	21.8	12.1	64%	36%	323	154	169
30-Jan-15	20													
31-Jan-15	21													
01-Feb-15	22	391	169	222	43%	57%	70.8	23.4	47.4	33%	67%	320	146	175
02-Feb-15	23	420	183	237	44%	56%	36.5	21.4	15.1	59%	41%	384	162	222
03-Feb-15	24	383	141	242	37%	63%	36.7	21.8	14.9	59%	41%	346	119	227
04-Feb-15	25	359	130	229	36%	64%	33.4	18.8	14.6	56%	44%	326	111	214
05-Feb-15	26	368	141	227	38%	62%	43.6	21.3	22.3	49%	51%	324	120	205
06-Feb-15	27													
07-Feb-15	28													
08-Feb-15	29	408	227	181	56%	44%	41.0	21.0	20	51%	49%	367	206	161
09-Feb-15	30	444	213	231	48%	52%	47.6	24.7	22.9	52%	48%	396	188	208
10-Feb-15	31	355	173	182	49%	51%	32.6	20.8	11.8	64%	36%	322	152	170
11-Feb-15	32	369	162	197	45%	55%	46.9	23.2	23.7	49%	51%	312	139	173
12-Feb-15	33	352	155	197	44%	56%	52.3	23.5	28.8	45%	55%	300	132	168
13-Feb-15	34													
14-Feb-15	35													
15-Feb-15	36													
16-Feb-15	37													
17-Feb-15	38	243	137	106	56%	44%	87.8	24.6	63.2	28%	72%	155	112	43
18-Feb-15	39	241	138	103	57%	43%	70.5	20.8	49.7	30%	70%	171	117	53
19-Feb-15	40	236	130	106	55%	45%	71.7	24.1	47.6	34%	66%	164	106	58
20-Feb-15	41													
21-Feb-15	42													
22-Feb-15	43	383	222	151	58%	42%	47.2	20.6	26.6	44%	56%	336	201	134
23-Feb-15	44	346	180	166	52%	48%	46.5	20.9	25.6	45%	55%	300	159	140
24-Feb-15	45	226	128	98	57%	43%	35.7	19.6	16.1	55%	45%	190	108	82
25-Feb-15	46													

A.5.7a Alkalinity Usage

Alkalinity Consumption										
Date	Days	Influent Ammonia (mg-N/L)	Effluent Ammonia (mg-N/L)	TAN Removal (mg-N/L)	Effluent pH	Influent Alkalinity (mg CaCO <sub>3</sub> /L)	Effluent Alkalinity (mg CaCO <sub>3</sub> /L)	Bicarbonate Feed (mg CaCO <sub>3</sub> /L)	Alk Added (mg CaCO <sub>3</sub> /mg NH <sub>4</sub> -N)	TAN Removed (mg NH <sub>4</sub> -N)
<b>Average</b>		29.6	3.35	26.2	6.81	171	114	40		3.92
<b>Sample SD</b>		2.0	0.93	2.2	0.06	14	10	12		0.53
11-Jan-15	1	33.2	2.94	30.3					35	
12-Jan-15	2	30.8	2.83	28.0	6.84				30	
13-Jan-15	3	28.2	3.64	24.6	6.86	160	100		29	3.61
14-Jan-15	4	28.0	2.73	25.3	6.73				31	
15-Jan-15	5	29.1	2.43	26.7	6.72	163	109		41	3.55
16-Jan-15	6				6.74				51	
17-Jan-15	7								43	
18-Jan-15	8	27.7	1.77	25.9					34	
19-Jan-15	9	27.6	1.80	25.8					35	
20-Jan-15	10	29.1	2.13	27.0	6.68	162	129		57	3.32
21-Jan-15	11	27.3	3.02	24.3	6.90				53	
22-Jan-15	12	31.2	3.21	28.0	6.89	181	113		40	3.84
23-Jan-15	13				6.87				40	
24-Jan-15	14								26	
25-Jan-15	15	27.1	2.93	24.2					21	
26-Jan-15	16	28.6	2.61	26.0	6.86				17	
27-Jan-15	17	29.5	3.00	26.5	6.72	162	101		23	3.17
28-Jan-15	18	29.7	2.92	26.8	6.81				33	
29-Jan-15	19	30.1	3.25	26.9	6.85	181	112		31	3.73
30-Jan-15	20				6.86				28	
31-Jan-15	21								24	
01-Feb-15	22	30.8	4.09	26.7					18	
02-Feb-15	23	31.3	3.52	27.8	6.71				29	
03-Feb-15	24	30.6	3.55	27.1	6.84	198	125		45	4.36
04-Feb-15	25	31.5	4.57	26.9	6.83				51	
05-Feb-15	26	32.7	4.82	27.9	6.79	187	128		58	4.20
06-Feb-15	27				6.76				54	
07-Feb-15	28								41	
08-Feb-15	29	32.7	3.77	28.9					30	
09-Feb-15	30	33.0	3.49	29.5	6.84					
10-Feb-15	31	32.2	3.21	29.0	6.83	176	111		38	3.55
11-Feb-15	32	30.7	1.99	28.7	6.81					
12-Feb-15	33	29.2	3.78	25.4	6.79	180	117		41	4.11
13-Feb-15	34				6.80				46	
14-Feb-15	35								36	
15-Feb-15	36								37	
16-Feb-15	37								39	
17-Feb-15	38	27.4	5.09	22.3		168	98		42	5.03
18-Feb-15	39	27.4	4.45	23.0	6.87				47	
19-Feb-15	40	27.4	5.22	22.2	6.82	162	115		55	4.58
20-Feb-15	41				6.80				56	
21-Feb-15	42								48	
22-Feb-15	43	29.2	3.84	25.4					47	
23-Feb-15	44	28.1	2.63	25.5	6.88				54	
24-Feb-15	45	25.4	4.54	20.9	6.81	147	119		54	3.92
25-Feb-15	46				6.80				63	

A.5.7b Alkalinity Usage

AvN_FI_ASE High																	
Date	Total SRT (days)	Net Heterotrophic Yield (g/g)	Influent BOD (mg/L)	Effluent BOD (mg/L)	TKN Used for BOD Oxidation	Influent TKN (mg-N/L)	Effluent TKN (mg-N/L)	TKN Nitrified (mg-N/L)	Alk used by Nitrification	Effluent Nitrite (mg-)	Effluent Nitrate (mg-)	NOx Denitrified (mg-N/L)	Alk provided by Denitrification	Influent Alk (mg CaCO3/L)	Effluent Alk (mg CaCO3/L)	Theoretical Supplemental Alk Req (mg)	Alk Req for Ni/Dep
Average	7.9	0.59	148	21	9.5	34.6	6.0	21	152	1.4	1.9	18.3	65.5	171	114	33	2.33
Sample SD	2.2	0.03	50	2	3.1	5.5	1.5	2	18	0.4	0.9	2.6	9.1	14	10	20	0.10
11-Jan-15												1.69	3.28				
12-Jan-15	13.8	0.52										1.65	2.23				
13-Jan-15	14.1	0.52	171	22	9.2	34.8	5.2	20	145	1.61	2.07	16.7	59.5	160	100	26	2.44
14-Jan-15	12.0	0.54								1.57	1.72						
15-Jan-15	10.2	0.56				35.3	4.7			1.64	1.60			163	109		
16-Jan-15	9.3	0.57															
17-Jan-15																	
18-Jan-15												1.34	1.37				
19-Jan-15	6.9	0.60								1.00	0.86						
20-Jan-15	8.5	0.58	174	20	10.7	36.7	3.6	22	160	1.26	1.00	20.2	72.0	152	129	55	2.22
21-Jan-15	7.5	0.59								1.80	0.81						
22-Jan-15	7.0	0.60				37.4	5.5			2.14	0.98			181	113		
23-Jan-15	7.4	0.59															
24-Jan-15																	
25-Jan-15										1.24	1.11						
26-Jan-15	7.2	0.59								1.16	0.96						
27-Jan-15	6.5	0.60	149	21	9.3	32.0	4.9	18	128	1.50	0.65	15.7	56.2	162	101	11	2.27
28-Jan-15	6.5	0.60								1.74	0.78						
29-Jan-15	6.3	0.60				35.3	7.0			1.92	1.12			181	112		
30-Jan-15	6.6	0.60															
31-Jan-15																	
01-Feb-15										1.80	3.32						
02-Feb-15	7.2	0.59								1.68	1.10						
03-Feb-15	7.1	0.59	180	18	11.6	42.3	5.4	25	181	1.71	1.12	22.6	80.6	198	125	28	2.25
04-Feb-15	8.0	0.58								1.81	1.64						
05-Feb-15	8.3	0.58				40.1	7.1			1.77	2.35			187	128		
06-Feb-15	8.4	0.58															
07-Feb-15																	
08-Feb-15										1.35	2.19						
09-Feb-15	9.6	0.56								1.29	1.68						
10-Feb-15	9.1	0.57	203	22	12.4	38.5	5.1	21	150	1.39	1.69	17.9	63.9	176	111	21	2.34
11-Feb-15	8.3	0.58								0.87	1.94						
12-Feb-15	8.1	0.58				36.2	6.4			1.31	1.85			180	117		
13-Feb-15	7.0	0.60															
14-Feb-15																	
15-Feb-15																	
16-Feb-15																	
17-Feb-15			85	24		31.2	9.0			1.14	3.70			168	98		
18-Feb-15	4.8	0.63								1.03	3.37						
19-Feb-15	5.5	0.62				20.3	8.4			0.92	4.04			162	115		
20-Feb-15	5.2	0.62															
21-Feb-15																	
22-Feb-15										0.75	2.61						
23-Feb-15	6.4	0.60								0.73	1.73						
24-Feb-15	6.3	0.60	73	21	3.8	30.2	5.6	21	148	0.84	2.96	17.0	60.7	147	119	60	2.45
25-Feb-15	7.3	0.59															

## A.6 Data Collection during DO\_MLE\_PCE

### A.6.1 Performance Data

Removal Performance									
Date	Days	NH <sub>4</sub> <sup>+</sup> -N loading rate (mg-N/L/d)	Influent COD/NH <sub>4</sub> <sup>+</sup> -N	TIN removal rate (mg-N/L/d)	TIN removal Efficiency (%)	COD removal rate (mg/L/d)	COD removal rate/TIN removal rate	OP removal Efficiency (%)	Calculated AOB rate (mg-N/L/d)
<b>Average</b>		178.7	9.9	145.5	81.4	1587	10.9	44.3	193
<b>Sample SD</b>		10.9	0.8	9.2	1.2	96	0.9	13.5	13
12-Jul-15	1	156	10.8	127.4	81.4	1458	11.4	25.4	
13-Jul-15	2	173	10.4	145.4	84.0	1646	11.3	55.0	188
14-Jul-15	3	181	9.9	147.3	81.3	1539	10.4	53.2	191
15-Jul-15	4	181	9.4	146.5	81.0	1546	10.6	47.9	189
16-Jul-15	5	186	9.1	150.5	80.9	1498	9.9	40.0	202
17-Jul-15	6								
18-Jul-15	7								
19-Jul-15	8								
20-Jul-15	9	172	10.6	141.4	82.1	1665	11.8	41.8	186
21-Jul-15	10	177	10.2	145.1	82.0	1619	11.2	38.7	188
22-Jul-15	11	180	9.7	147.5	82.0	1578	10.7	32.1	185
23-Jul-15	12	162	11.3	127.8	79.0	1650	12.9	26.7	165
24-Jul-15	13								
25-Jul-15	14								
26-Jul-15	15								
27-Jul-15	16	195	10.2	158.7	81.5	1812	11.4	72.4	217
28-Jul-15	17	192	8.7	157.4	82.1	1500	9.5	61.2	206
29-Jul-15	18	183	8.9	146.6	80.1	1495	10.2	40.3	198
30-Jul-15	19	186	9.5	149.5	80.6	1623	10.9	40.9	203
31-Jul-15	20								



### A.6.2 Operational Conditions

Operational Conditions							
Date	Days	Temperature in 1st CSTR (°C)	MLSS (mg/L)	VSS (mg/L)	Total SRT (days)	Aerobic Fraction	Aerobic SRT (days)
<b>Average</b>		20.8	3939	3271	7.3	0.8	5.5
<b>Sample SD</b>		0.9	266	213	0.7	0.0	0.6
12-Jul-15	1					0.75	
13-Jul-15	2	20.6	3675	3060	6.5	0.75	4.89
14-Jul-15	3	20.5	3720	3090		0.75	
15-Jul-15	4	20.6	3805	3155	5.6	0.75	4.23
16-Jul-15	5	20.7	3700	3070	6.9	0.75	5.20
17-Jul-15	6	20.6	3685	3055	7.5	0.75	5.63
18-Jul-15	7					0.75	
19-Jul-15	8					0.75	
20-Jul-15	9	22.7	4045	3370	7.9	0.75	5.93
21-Jul-15	10	23.1	4140	3470	7.7	0.75	5.76
22-Jul-15	11	21.4	4115	3385	6.7	0.75	4.99
23-Jul-15	12	20.3	3945	3285	7.2	0.75	5.41
24-Jul-15	13	20.3	4015	3320	7.3	0.75	5.44
25-Jul-15	14					0.75	
26-Jul-15	15					0.75	
27-Jul-15	16	19.8	3380	2845	6.9	0.75	5.20
28-Jul-15	17	20.8	4325	3565	7.7	0.75	5.80
29-Jul-15	18	20.4	4305	3555	8.4	0.75	6.30
30-Jul-15	19	20.4	4155	3450	8.4	0.75	6.29
31-Jul-15	20	20.5	4070	3390	7.5	0.75	5.61

A.6.3 Batch Rate Testing

Batch Rate Testing Results									
Date	Days	AOB rate (mgNOx-N/gMLSS/hr)	NOB rate (mgNO3-N/gMLSS/hr)	NOB rate/AOB rate	Average OUR (mg/L/hr)	Denitrification rate (mgNO3-N/gMLSS/hr)	Denitrification rate (mgNO2-N/gMLSS/hr)	Denitrification rate (mgNOx-N/gMLSS/hr)	Denitrification rate (mgNOx-N/gMLSS/hr)
<b>Average</b>		3.15	3.38	1.08	67.1	2.77	0.36		3.12
<b>Sample SD</b>		0.53	0.38	0.12	2.5	0.46	0.29		0.50
12-Jul-15	1								
13-Jul-15	2								
14-Jul-15	3								
15-Jul-15	4								
16-Jul-15	5	3.18	3.15	0.99		3.28	0.25		3.54
17-Jul-15	6				70				
18-Jul-15	7								
19-Jul-15	8								
20-Jul-15	9								
21-Jul-15	10								
22-Jul-15	11				65				
23-Jul-15	12	2.60	3.17	1.22		2.43	0.13		2.56
24-Jul-15	13								
25-Jul-15	14								
26-Jul-15	15								
27-Jul-15	16								
28-Jul-15	17				67				
29-Jul-15	18								
30-Jul-15	19	3.67	3.82	1.04					
31-Jul-15	20					2.58	0.69		3.27

### A.6.4 Effluent Characteristics

Average Effluent Characteristics										
Date	Days	Ammonia (mg-N/L)	Nitrite (mg-N/L)	Nitrate (mg-N/L)	OP (mg-P/L)	TSS (mg/L)	SVI 30 (mL/g)	TIN (mg-N/L)	TN (mg-N/L)	TP (mg-P/L)
<b>Average</b>		0.19	0.21	6.57	2.11	18.0	182	7.0	9.5	2.71
<b>Sample SD</b>		0.12	0.12	0.62	0.45	7.9	23	0.6	0.7	0.50
12-Jul-15	1	0.37	0.43	5.30	2.65	30.8		6.1		
13-Jul-15	2	0.06	0.21	5.55	1.56		155	5.8		
14-Jul-15	3	0.16	0.38	6.57	2.31	37.5	161	7.1	10.7	3.15
15-Jul-15	4	0.25	0.33	6.60	2.12	20.8	176	7.2		
16-Jul-15	5	0.42	0.37	6.66	2.54	22.0	154	7.4	10.1	3.08
17-Jul-15	6						176			
18-Jul-15	7									
19-Jul-15	8					17.3				
20-Jul-15	9	0.12	0.11	6.23	2.34	13.3	195	6.5		
21-Jul-15	10	0.10	0.13	6.46	2.39	16.3	193	6.7	8.8	2.99
22-Jul-15	11	0.10	0.14	6.54	2.47	11.8	182	6.8		
23-Jul-15	12	0.14	0.14	6.83	2.09	16.3	183	7.1	8.9	2.63
24-Jul-15	13						204			
25-Jul-15	14									
26-Jul-15	15					18.3				
27-Jul-15	16	0.38	0.22	6.93	1.21	15.8	148	7.5		
28-Jul-15	17	0.13	0.10	6.97	1.35	11.5	187	7.2	9.2	1.81
29-Jul-15	18	0.09	0.09	7.48	2.22	11.5	188	7.7		
30-Jul-15	19	0.10	0.11	7.36	2.15	9.0	189	7.6	9.6	2.58
31-Jul-15	20						238			

A.6.5 Influent Properties

Influent Properties																								
Date	Days	RWI											Primary Clarifier Effluent											
		COD (mg/L)	sCOD (mg/L)	pCOD (mg/L)	BOD (mg/L)	TSS (mg/L)	VSS (mg/L)	TKN (mg-N/L)	TAN (mg-N/L)	TP (mg-P/L)	OP (mg-P/L)	Alk (mg as CaCO <sub>3</sub> /L)	COD (mg/L)	sCOD (mg/L)	pCOD (mg/L)	BOD (mg/L)	TSS (mg/L)	VSS (mg/L)	TKN (mg-N/L)	TAN (mg-N/L)	TP (mg-P/L)	OP (mg-P/L)	Alk (mg as CaCO <sub>3</sub> /L)	
<b>Average</b>		548	203	345	206	204	178	43.3	37.1	5.9	3.85	200	370	207	163	159	99	84	43.0	37.7	5.5	3.82	202	
<b>Sample SD</b>		81	20	87	46	40	95	1.7	2.3	0.3	0.95	5	18	21	23	21	9	9	3.1	2.5	0.2	0.49	6	
12-Jul-15	1	607	187	420		256	218				32.6		354	185	169		111	89				32.8		3.55
13-Jul-15	2	625	199	426		194	168				35.7		378	194	184		99	82				36.3		3.47
14-Jul-15	3	666	181	485	175	322	280	40.2	35.8	5.54	4.01	190	376	207	169	175	108	95	42.9	38.0	5.68	4.94		195
15-Jul-15	4	566	154	412		205	178				37.8		358	161	197		95	81				37.9		4.07
16-Jul-15	5	509	198	311		181	160	44.4	37.8	6.22	3.86	202	355	202	153		88	73	40.6	39.0	5.46	4.23		205
17-Jul-15	6																							
18-Jul-15	7																							
19-Jul-15	8	530	186	344		199	171				35.6		360	189	171		98	76				36.7		3.95
20-Jul-15	9	530	211	319		192	165				35.4		381	232	149		90	81				36.1		4.02
21-Jul-15	10	566	209	357	259	216	190	42.4	37.0	6.22	3.57	200	379	206	173	166	99	89	41.1	37.1	5.31	3.90		201
22-Jul-15	11	548	216	332		220	195				37.0		364	209	155		89	74				37.7		3.64
23-Jul-15	12	534	209	325		178	151	43.9	38.5	6.11	3.01	205	383	238	145		90	75	41.7	33.9	5.71	2.85		212
24-Jul-15	13																							
25-Jul-15	14																							
26-Jul-15	15	536	237	299		192	165				34.7		384	240	144		107	91				42.2		3.48
27-Jul-15	16	668	219	449		201	173				41.9		415	198	217		109	91				40.8		4.39
28-Jul-15	17	337	206	131	183	154	134	44.9	39.9	5.58	3.53	202	349	204	145	135	105	95	49.1	40.2	5.15	3.48		203
29-Jul-15	18	489	204	285		175	160				38.2		343	209	134		101	88				38.4		3.72
30-Jul-15	19	502	228	274		173	156	43.8	38.7	5.63	3.44	199	370	225	145		90	78	42.7	38.9	5.44	3.64		197
31-Jul-15	20																							

A.6.6 COD Properties

COD Characteristics														
Date	Days	Influent					Effluent					Removed		
		COD (mg/L)	sCOD (mg/L)	pCOD (mg/L)	% Soluble	% Particulate	COD (mg/L)	sCOD (mg/L)	pCOD (mg/L)	% Soluble	% Particulate	COD (mg/L)	sCOD (mg/L)	pCOD (mg/L)
<b>Average</b>		370	207	163	56%	44%	36.7	21.6	15.2	60%	40%	333	185	148
<b>Sample SD</b>		19	21	23	5%	5%	6.7	16	7.0	11%	11%	20	21	22
12-Jul-15	1	354	185	169	52%	48%	48.4	22.7	25.7	47%	53%	306	162	143
13-Jul-15	2	378	194	184	51%	49%	32.9	20.2	12.7	61%	39%	345	174	171
14-Jul-15	3	376	207	169	55%	45%	53.4	21.3	32.1	40%	60%	323	186	137
15-Jul-15	4	358	161	197	45%	55%	33.9	18.9	15.0	56%	44%	324	142	182
16-Jul-15	5	355	202	153	57%	43%	41.0	20.9	20.1	51%	49%	314	181	133
17-Jul-15	6													
18-Jul-15	7													
19-Jul-15	8	360	189	171	53%	48%	38.7	19.6	19.1	51%	49%	321	169	152
20-Jul-15	9	381	232	149	61%	39%	32.0	19.9	12.1	62%	38%	349	212	137
21-Jul-15	10	379	206	173	54%	46%	39.6	20.8	18.8	53%	47%	339	185	154
22-Jul-15	11	364	209	155	57%	43%	33.2	23.4	9.8	70%	30%	331	186	145
23-Jul-15	12	383	238	145	62%	38%	37.0	21.7	15.3	59%	41%	346	216	130
24-Jul-15	13													
25-Jul-15	14													
26-Jul-15	15	384	240	144	63%	38%	31.9	21.2	10.7	66%	34%	352	219	133
27-Jul-15	16	415	198	217	48%	52%	35.1	24.8	10.3	71%	29%	380	173	207
28-Jul-15	17	349	204	145	58%	42%	34.6	23.6	11.0	68%	32%	314	180	134
29-Jul-15	18	343	209	134	61%	39%	29.6	22.6	7.0	76%	24%	313	186	127
30-Jul-15	19	370	225	145	61%	39%	29.7	21.9	7.8	74%	26%	340	203	137
31-Jul-15	20													

A.6.7a Alkalinity Usage

Alkalinity Consumption										
Date	Days	Influent Ammonia (mg-N/L)	Effluent Ammonia (mg-N/L)	TAN Removal (mg-N/L)	Effluent pH	Influent Alkalinity (mg CaCO <sub>3</sub> /L)	Effluent Alkalinity (mg CaCO <sub>3</sub> /L)	Bicarbonate Feed (mg CaCO <sub>3</sub> /L)	Alk Added	TAN Removed (mg CaCO <sub>3</sub> /mg NH <sub>4</sub> -N)
<b>Average</b>		37.5	0.19	37.3	6.85	202	114	59		4.38
<b>Sample SD</b>		2.3	0.12	2.3	0.13	6	47	23		0.38
12-Jul-15	1	32.8	0.37	32.4						
13-Jul-15	2	36.3	0.06	36.2	6.84					
14-Jul-15	3	38.0	0.16	37.8	7.10	195	205			
15-Jul-15	4	37.9	0.25	37.6	7.14					
16-Jul-15	5	39.0	0.42	38.6	6.93	205	80	37		4.20
17-Jul-15	6				6.80				34	
18-Jul-15	7								45	
19-Jul-15	8									
20-Jul-15	9	36.1	0.12	36.0	6.74				34	
21-Jul-15	10	37.1	0.10	37.0	6.75	201	84	35		4.12
22-Jul-15	11	37.7	0.10	37.6	6.73				44	
23-Jul-15	12	33.9	0.14	33.8	6.78	212	90	48		5.03
24-Jul-15	13				6.73				52	
25-Jul-15	14								84	
26-Jul-15	15									
27-Jul-15	16	40.8	0.38	40.4	6.87				68	
28-Jul-15	17	40.2	0.13	40.1	6.86	203	121	85		4.17
29-Jul-15	18	38.4	0.09	38.3	6.82				82	
30-Jul-15	19	38.9	0.10	38.8	6.82	197	103	75		4.36
31-Jul-15	20								99	

A.6.7b Alkalinity Usage

DO_MLE_PCE																	
Date	Total SRT (days)	Net Heterotrophic Yield (g/g)	Influent BOD (mg/L)	Effluent BOD (mg/L)	TKN Used for BOD Oxidation	Influent TKN (mg-N/L)	Effluent TKN (mg-N/L)	TKN Nitrified (mg-N/L)	Alk used by Nitrification	Effluent Nitrite (mg-)	Effluent Nitrate (mg-)	NOx Denitrified (mg-N/L)	Alk provided by Denitrification	Influent Alk (mg CaCO3/L)	Effluent Alk (mg CaCO3/L)	Theoretical Supplemental Alk Req (mg)	Alk Req for Ni&Den
Average	7.3	0.59	159	20	9.2	43.0	2.5	34	241	0.2	6.6	27.0	96.3	202	114	46	2.52
Sample SD	0.7	0.01	21	1	1.6	3.1	0.7	7	52	0.1	0.6	7.0	25.0	6	47	52	0.11
12-Jul-15										0.43	5.30						
13-Jul-15	6.5	0.60								0.21	5.55						
14-Jul-15			175	19		42.9	3.7			0.38	6.57			195	205		
15-Jul-15	5.6	0.61								0.33	6.60						
16-Jul-15	6.9	0.60				40.6	3.1			0.37	6.66			205	80		
17-Jul-15	7.5	0.59															
18-Jul-15																	
19-Jul-15																	
20-Jul-15	7.9	0.58								0.11	6.23						
21-Jul-15	7.7	0.59	166	20	10.3	41.1	2.2	29	204	0.13	6.46	22.0	78.7	201	84	9	2.60
22-Jul-15	6.7	0.60								0.14	6.54						
23-Jul-15	7.2	0.59				41.7	2.0			0.14	6.83			212	90		
24-Jul-15	7.3	0.59															
25-Jul-15																	
26-Jul-15																	
27-Jul-15	6.9	0.60								0.22	6.93						
28-Jul-15	7.7	0.59	135	21	8.0	49.1	2.1	39	278	0.10	6.97	31.9	114.0	203	121	82	2.44
29-Jul-15	8.4	0.58								0.09	7.48						
30-Jul-15	8.4	0.58				42.7	2.2			0.11	7.36			197	103		
31-Jul-15	7.5	0.59															

## A.7 Data Collection during ABAC\_MLE\_PCE

### A.7.1 Performance Data

Removal Performance									
Date	Days	NH <sub>4</sub> <sup>+</sup> -N loading rate (mg-N/L/d)	Influent COD/NH <sub>4</sub> <sup>+</sup> -N	TIN removal rate (mg-N/L/d)	TIN removal Efficiency (%)	COD removal rate (mg/L/d)	COD removal rate/TIN removal rate	OP removal Efficiency (%)	Calculated AOB rate (mg-N/L/d)
<b>Average</b>		190.2	10.7	154.3	81.1	1852	12.0	70.1	191
<b>Sample SD</b>		4.7	0.9	4.8	1.2	146	1.2	10.5	9
02-Aug-15	1	190	10.2	151.2	79.6	1743	11.5	62.7	
03-Aug-15	2	189	10.5	155.0	82.1	1799	11.6	81.1	196
04-Aug-15	3	190	10.1	155.9	81.9	1755	11.3	73.8	195
05-Aug-15	4	190	11.3	153.4	80.6	1914	12.5	56.0	195
06-Aug-15	5	185	11.4	150.6	81.4	1975	13.1	70.8	188
07-Aug-15	6								
08-Aug-15	7								
09-Aug-15	8	188	10.6	148.2	78.6	1745	11.8	60.9	
10-Aug-15	9	182	12.9	148.1	81.5	2208	14.9	81.6	171
11-Aug-15	10	196	9.7	162.1	82.7	1798	11.1	86.3	196
12-Aug-15	11	196	10.0	160.1	81.6	1782	11.1	69.1	195
13-Aug-15	12	195	10.0	158.0	81.0	1799	11.4	59.3	189
14-Aug-15	13								



### A.7.2 Operational Conditions

Operational Conditions							
Date	Days	Temperature in 1st CSTR (°C)	MLSS (mg/L)	VSS (mg/L)	Total SRT (days)	Aerobic Fraction	Aerobic SRT (days)
<b>Average</b>		19.9	4508	3731	6.7	0.75	5.0
<b>Sample SD</b>		0.3	277	242	0.9	0.00	0.6
02-Aug-15	1					0.75	
03-Aug-15	2	20.7	3925	3265	6.8	0.75	5.09
04-Aug-15	3	20.1	4415	3640	7.4	0.75	5.57
05-Aug-15	4	20.1	4445	3640	7.5	0.75	5.61
06-Aug-15	5	20.0	4315	3560	6.9	0.75	5.15
07-Aug-15	6	20.0	4565	3755	6.3	0.75	4.69
08-Aug-15	7					0.75	
09-Aug-15	8					0.75	
10-Aug-15	9	19.6	4405	3650	5.7	0.75	4.27
11-Aug-15	10	19.6	4620	3765	4.9	0.75	3.70
12-Aug-15	11	19.7	4920	4115	7.5	0.75	5.59
13-Aug-15	12	19.6	4780	4000	7.1	0.75	5.36
14-Aug-15	13	19.8	4690	3920	7.3	0.75	5.45

A.7.3 Batch Rate Testing

Batch Rate Testing Results								
Date	Days	AOB rate (mgNO <sub>x</sub> -N/gMLSS/hr)	NOB rate (mgNO <sub>3</sub> -N/gMLSS/hr)	NOB rate/AOB rate	Average OUR (mg/L/hr)	Denitrification rate (mgNO <sub>3</sub> -N/gMLSS/hr)	Denitrification rate (mgNO <sub>2</sub> -N/gMLSS/hr)	Denitrification rate (mgNO <sub>x</sub> -N/gMLSS/hr)
<b>Average</b>		2.80	2.84	1.02	81.2	2.34	0.51	2.85
<b>Sample SD</b>		0.12	0.13	0.00	2.0	0.31	0.20	0.11
02-Aug-15	1							
03-Aug-15	2							
04-Aug-15	3							
05-Aug-15	4	2.71	2.75	1.01	80			
06-Aug-15	5							
07-Aug-15	6					2.56	0.37	2.93
08-Aug-15	7							
09-Aug-15	8							
10-Aug-15	9							
11-Aug-15	10							
12-Aug-15	11	2.88	2.93	1.02	83			
13-Aug-15	12					2.12	0.65	2.77
14-Aug-15	13							

A.7.4 Effluent Characteristics

Average Effluent Characteristics										
Date	Days	Ammonia (mg-N/L)	Nitrite (mg-N/L)	Nitrate (mg-N/L)	OP (mg-P/L)	TSS (mg/L)	SVI 30 (mL/g)	TIN (mg-N/L)	TN (mg-N/L)	TP (mg-P/L)
<b>Average</b>		1.19	0.30	6.04	1.21	17.1	186	7.5	9.2	1.72
<b>Sample SD</b>		0.26	0.09	0.27	0.41	6.5	17	0.5	0.3	0.52
02-Aug-15	1	1.56	0.377	6.17	1.44	18.8		8.1		
03-Aug-15	2	1.01	0.323	5.77	0.81	15.5	209	7.1		
04-Aug-15	3	0.98	0.325	5.93	1.21	16.5	208	7.2	9.0	1.84
05-Aug-15	4	1.01	0.384	6.34	1.58	21.0	180	7.7		
06-Aug-15	5	0.95	0.334	5.95	0.93	21.3	190	7.2	9.3	1.70
07-Aug-15	6						186			
08-Aug-15	7									
09-Aug-15	8	1.74	0.415	6.29	1.81	28.8		8.4		
10-Aug-15	9	1.17	0.288	5.59	0.73	18.8	198	7.0		
11-Aug-15	10	1.09	0.214	5.81	0.66	15.50	173	7.1	8.8	1.04
12-Aug-15	11	1.12	0.193	6.23	1.25	8.50	185	7.5		
13-Aug-15	12	1.26	0.153	6.36	1.65	6.00	186	7.8	9.5	2.30
14-Aug-15	13						149			

### A.7.5 Influent Properties

Influent Properties																							
Date	Days	RWI											Primary Clarifier Effluent										
		COD (mg/L)	sCOD (mg/L)	pCOD (mg/L)	BOD (mg/L)	TSS (mg/L)	VSS (mg/L)	TKN (mg-N/L)	TAN (mg-N/L)	TP (mg-P/L)	OP (mg-P/L)	Alk (mg as CaCO3/L)	COD (mg/L)	sCOD (mg/L)	pCOD (mg/L)	BOD (mg/L)	TSS (mg/L)	VSS (mg/L)	TKN (mg-N/L)	TAN (mg-N/L)	TP (mg-P/L)	OP (mg-P/L)	Alk (mg as CaCO3/L)
<b>Average</b>		556	222	342	242	178	160	45.4	39.9	6.1	3.77	207	424	223	198	182	104	92	43.8	39.9	5.9	4.10	209
<b>Sample SD</b>		50	9	46	4	30	30	1.8	1.4	0.6	0.32	5	28	13	34	4	12	13	1.4	1.0	0.6	0.50	5
02-Aug-15	1	518	220	298		160	136		38.9		3.98		406	218	188		91	83		39.8			3.86
03-Aug-15	2	605	205	400		190	164		39.2		3.76		415	204	211		99	83		39.6			4.28
04-Aug-15	3	529	222	307	239	206	192	44.9	38.6	6.7	3.91	213	403	234	140	185	109	84	45.4	39.9	6.56	4.61	211
05-Aug-15	4	501	227	274		154	135		39.8		3.36		449	241	208		88	84		39.9			3.59
06-Aug-15	5	487				148	135	43.8	38.6	5.3	3.16	208	441	239	202		101	89	43.2	38.8	5.13	3.18	214
07-Aug-15	6																						
08-Aug-15	7																						
09-Aug-15	8	606	232	374		217	200		40.0		3.97		420	214	206		119	91		39.5			4.63
10-Aug-15	9	572	216	356		185	159		38.8		3.72		490	216	274		115	93		38.1			3.97
11-Aug-15	10	575	220	355	245	221	208	48.0	41.5	6.6	4.26	201	399	208	191	179	102	110	42.2	41.1	5.82	4.80	203
12-Aug-15	11	635	233	402		161	145		41.0		3.67		409	232	177		89	81		41.1			4.04
13-Aug-15	12	529	220	309		140	126	44.7	42.6	6.0	3.88	206	409	226	183		122	118	44.4	40.9	5.89	4.05	209
14-Aug-15	13																						

A.7.6 COD Properties

COD Characteristics														
Date	Days	Influent					Effluent					Removed		
		COD (mg/L)	sCOD (mg/L)	pCOD (mg/L)	% Soluble	% Particulate	COD (mg/L)	sCOD (mg/L)	pCOD (mg/L)	% Soluble	% Particulate	COD (mg/L)	sCOD (mg/L)	pCOD (mg/L)
<b>Average</b>		424	223	201	53%	47%	36	24	12	70%	30%	388	199	189
<b>Sample SD</b>		28	13	29	4%	4%	10	3	10	18%	18%	31	14	31
02-Aug-15	1	406	218	188	54%	46%	40.6	23.7	16.9	58%	42%	365	194	171
03-Aug-15	2	415	204	211	49%	51%	37.9	24.4	13.5	64%	36%	377	180	198
04-Aug-15	3	403	234	169	58%	42%	35.1	27.2	7.9	77%	23%	368	207	161
05-Aug-15	4	449	241	208	54%	46%	47.8	19.6	28.2	41%	59%	401	221	180
06-Aug-15	5	441	239	202	54%	46%	26.9	17.1	9.8	64%	36%	414	222	192
07-Aug-15	6													
08-Aug-15	7													
09-Aug-15	8	420	214	206	51%	49%	54.1	26.2	27.9	48%	52%	366	188	178
10-Aug-15	9	490	216	274	44%	56%	27.1	25.1	2.0	93%	7%	463	191	272
11-Aug-15	10	399	208	191	52%	48%	22.0	20.9	1.1	95%	5%	377	187	190
12-Aug-15	11	409	232	177	57%	43%	35.4	26.0	9.4	73%	27%	374	206	168
13-Aug-15	12	409	226	183	55%	45%	31.9	27.5	4.4	86%	14%	377	199	179
14-Aug-15	13													

A.7.7a Alkalinity Usage

Alkalinity Consumption										
Date	Days	Influent Ammonia (mg-N/L)	Effluent Ammonia (mg-N/L)	TAN Removal (mg-N/L)	Effluent pH	Influent Alkalinity (mg CaCO <sub>3</sub> /L)	Effluent Alkalinity (mg CaCO <sub>3</sub> /L)	Bicarbonate Feed (mg CaCO <sub>3</sub> /L)	Alk Added (mg CaCO <sub>3</sub> )	TAN Removed (mg NH <sub>4</sub> -N)
<b>Average</b>		39.9	1.19	38.7	6.75	209	107	77		4.48
<b>Sample SD</b>		1.0	0.26	1.0	0.10	5	15	10		0.10
02-Aug-15	1	39.8	1.56	38.2					79	
03-Aug-15	2	39.6	1.01	38.6	6.78					
04-Aug-15	3	39.9	0.98	38.9	6.46	211	101	69		4.59
05-Aug-15	4	39.9	1.01	38.9	6.77				79	
06-Aug-15	5	38.8	0.95	37.8	6.80	214	128	85		4.52
07-Aug-15	6				6.79				99	
08-Aug-15	7								77	
09-Aug-15	8	39.5	1.74	37.8					65	
10-Aug-15	9	38.1	1.17	36.9	6.74				74	
11-Aug-15	10	41.1	1.09	40.0	6.80	203	104	76		4.37
12-Aug-15	11	41.1	1.12	40.0	6.77				70	
13-Aug-15	12	40.9	1.26	39.6	6.79	209	94	62		4.45
14-Aug-15	13				6.78				87	

A.7.7b Alkalinity Usage

ABAC_MLE_PCE																	
Date	Total SRT (days)	Net Heterotrophic Yield (g/g)	Influent BOD (mg/L)	Effluent BOD (mg/L)	TKN Used for BOD Oxidation	Influent TKN (mg-N/L)	Effluent TKN (mg-N/L)	TKN Nitrified (mg-N/L)	Alk used by Nitrification	Effluent Nitrite (mg-)	Effluent Nitrate (mg-)	NOx Denitrified (mg-N/L)	Alk provided by Denitrification	Influent Alk (mg CaCO3/L)	Effluent Alk (mg CaCO3/L)	Theoretical Supplemental Alk Req (mg)	Alk Req for NivDen
Average	6.7	0.60	182	20	11.9	43.8	2.9	27	196	0.3	6.0	21.5	76.7	209	107	21	2.56
Sample SD	0.9	0.01	4	#DIV/0!	#DIV/0!	14	0.1	#DIV/0!	#DIV/0!	0.1	0.3	#DIV/0!	#DIV/0!	5	15	#DIV/0!	#DIV/0!
02-Aug-15										0.38	6.17						
03-Aug-15	6.8	0.60								0.32	5.77						
04-Aug-15	7.4	0.59	185			45.4	2.8			0.33	5.93			211	101		
05-Aug-15	7.5	0.59								0.38	6.34						
06-Aug-15	6.9	0.60				43.2	3.1			0.33	5.95			214	128		
07-Aug-15	6.3	0.61															
08-Aug-15																	
09-Aug-15										0.42	6.29						
10-Aug-15	5.7	0.61								0.29	5.59						
11-Aug-15	4.9	0.62	179	20	11.9	42.2	2.8	27	196	0.21	5.81	21.5	76.7	203	104	21	2.56
12-Aug-15	7.5	0.59								0.19	6.23						
13-Aug-15	7.1	0.59				44.4	3.0			0.15	6.36			209	94		
14-Aug-15	7.3	0.59															

## A.8 Data Collection during AvN\_MLE\_PCE

### A.8.1 Performance Data

Removal Performance									
Date	Days	NH <sub>4</sub> <sup>+</sup> -N loading rate (mg-N/L/d)	Influent COD/NH <sub>4</sub> <sup>+</sup> -N	TIN removal rate (mg-N/L/d)	TIN removal Efficiency (%)	COD removal rate (mg/L/d)	COD removal rate/TIN removal rate	OP removal Efficiency (%)	Calculated AOB rate (mg-N/L/d)
<b>Average</b>		175.1	11.8	137.9	78.8	1834	13.4	92.5	233
<b>Sample SD</b>		10.4	1.0	10.0	3.9	121	1.2	17.7	57
4-May-15	1	156.0	13.3	128.3	82.3	1875	14.6	40.4	395
5-May-15	2	167.4	11.4	139.8	83.5	1702	12.2	89.5	285
6-May-15	3	170.3	11.8	142.9	83.9	1809	12.7	100.0	265
7-May-15	4	170.8	10.9	139.2	81.5	1678	12.1	100.0	233
8-May-15	5								
9-May-15	6								
10-May-15	7	190.8	11.4	143.9	75.4	1858	12.9	70.5	
11-May-15	8	165.5	13.0	140.0	84.6	1950	13.9	91.3	209
12-May-15	9	169.8	13.1	140.7	82.8	1941	13.8	100.0	195
13-May-15	10	169.3	13.6	126.0	74.4	2047	16.2	100.0	163
14-May-15	11	185.6	12.9	146.4	78.9	2110	14.4	100.0	155
15-May-15	12								
16-May-15	13								
17-May-15	14	166.0	11.6	127.6	76.9	1683	13.2	100.0	
18-May-15	15	169.8	12.7	139.4	82.1	1929	13.8	100.0	218
19-May-15	16	168.4	11.3	134.8	80.1	1679	12.5	100.0	211
20-May-15	17	143.1	13.9	104.0	72.7	1708	16.4	100.0	140
21-May-15	18	176.0	11.9	125.8	71.5	1866	14.8	100.0	184
22-May-15	19								
1-Jun-15	20	180.8	11.6	137.2	75.9	1832	13.4	78.1	245
2-Jun-15	21	175.1	11.1	132.3	75.6	1751	13.2	100.0	192
3-Jun-15	22	182.2	10.5	126.7	69.6	1664	13.1	32.1	170
4-Jun-15	23								
5-Jun-15	24								
6-Jun-15	25								
7-Jun-15	26	179.4	12.3	140.3	78.2	2006	14.3	100.0	
8-Jun-15	27	178.9	11.2	144.4	80.7			100.0	252
9-Jun-15	28	181.7	11.5	148.8	81.9	1918	12.9	100.0	288
10-Jun-15	29	185.1	10.7	150.7	81.4	1811	12.0	100.0	297
11-Jun-15	30	183.2	10.7	147.0	80.3	1773	12.1	100.0	298
12-Jun-15	31								
13-Jun-15	32								
14-Jun-15	33	186.5	10.5	148.4	79.6	1813	12.2	100.0	
15-Jun-15	34	177.9	11.3	140.6	79.0	1902	13.5	99.2	244
16-Jun-15	35	181.7		140.9	77.5			98.2	242
17-Jun-15	36	183.2	11.0	146.8	80.1	1795	12.2	99.4	244
18-Jun-15	37	183.2	10.9	141.1	77.0	1760	12.5	98.5	224
19-Jun-15	38								



## A.8.2 Operational Conditions

Operational Conditions							
Date	Days	Temperature in 1st CSTR (°C)	MLSS (mg/L)	VSS (mg/L)	Total SRT (days)	Aerobic Fraction	Aerobic SRT (days)
<b>Average</b>		20.4	4232	3433	5.7	0.52	3.0
<b>Sample SD</b>		0.4	279	226	1.2	0.09	1.0
4-May-15	1	19.9	4105	3315	6.2	0.31	1.9
5-May-15	2	20.2	3795	3105	6.0	0.44	2.7
6-May-15	3	20.2	4160	3415	6.1	0.47	2.9
7-May-15	4	20.4	4055	3330	5.2	0.50	2.6
8-May-15	5	20.1	4155	3330	5	0.42	2.2
9-May-15	6					0.42	
10-May-15	7					0.39	
11-May-15	8	21.3	4270	3480	4.6	0.54	2.5
12-May-15	9	21.0	4025	3260	4.3	0.56	2.4
13-May-15	10	20.5	3775	3085	4.1	0.58	2.4
14-May-15	11	20.9	3900	3130	4.5	0.75	3.3
15-May-15	12	20.7	3950	3215	5.3	0.40	2.1
16-May-15	13					0.59	
17-May-15	14					0.59	
18-May-15	15	20.4	4205	3445	6.0	0.58	3.5
19-May-15	16	20.4	4360	3505	4.9	0.54	2.7
20-May-15	17	20.3	4285	3420	4.5	0.57	2.5
21-May-15	18	20.0	4035	3345	5.4	0.59	3.2
22-May-15	19	19.7	4125	3305	6.3	0.58	3.7
1-Jun-15	20					0.55	
2-Jun-15	21	20.7	3915	3160	5.9	0.64	3.8
3-Jun-15	22	20.1	3740	3035	8.1	0.75	6.0
4-Jun-15	23	20.2	4290	3440	9.4	0.65	6.2
5-Jun-15	24	19.9	4195	3380		0.56	
6-Jun-15	25					0.55	
7-Jun-15	26					0.53	
8-Jun-15	27	19.9	4520	3655	6.8	0.52	3.6
9-Jun-15	28	20.3	4445	3610	6.5	0.47	3.1
10-Jun-15	29	20.6	4600	3715	6.5	0.46	3.0
11-Jun-15	30	20.8	4575	3705	6.8	0.46	3.1
12-Jun-15	31	20.3	4620	3710	6.2	0.43	2.7
13-Jun-15	32					0.47	
14-Jun-15	33					0.49	
15-Jun-15	34	20.5	4575	3755	5.6	0.50	2.8
16-Jun-15	35	20.6	4640	3780	5.6	0.50	2.8
17-Jun-15	36	20.7	4705	3840	5.1	0.50	2.5
18-Jun-15	37	20.6	4325	3485	4.7	0.53	2.5
19-Jun-15	38	20.7	4380	3600	5.1	0.52	2.7

A.8.3 Batch Rate Testing

Batch Rate Testing Results								
Date	Days	AOB rate (mgNO <sub>x</sub> -N/gMLSS/hr)	NOB rate (mgNO <sub>3</sub> -N/gMLSS/hr)	NOB rate/AOB rate	Average OUR (mg/L/hr)	Denitrification rate (mgNO <sub>3</sub> -N/gMLSS/hr)	Denitrification rate (mgNO <sub>2</sub> -N/gMLSS/hr)	Denitrification rate (mgNO <sub>x</sub> -N/gMLSS/hr)
<b>Average</b>		3.36	3.10	0.93	88.4	2.94	0.37	3.31
<b>Sample SD</b>		0.49	0.42	0.07	11.6	0.19	0.22	0.27
4-May-15	1							
5-May-15	2				93.7			
6-May-15	3							
7-May-15	4	4.19	3.57	0.85		3.15	0.36	3.50
8-May-15	5							
9-May-15	6							
10-May-15	7							
11-May-15	8							
12-May-15	9							
13-May-15	10					3.15	0.56	3.71
14-May-15	11	2.97	2.64	0.89				
15-May-15	12							
16-May-15	13							
17-May-15	14							
18-May-15	15							
19-May-15	16				90.4			
20-May-15	17					2.75	0.48	3.23
21-May-15	18	3.44	3.04	0.88				
22-May-15	19							
1-Jun-15	20							
2-Jun-15	21							
3-Jun-15	22				68.3			
4-Jun-15	23	2.79	2.58	0.93		2.74	0.60	3.34
5-Jun-15	24							
6-Jun-15	25							
7-Jun-15	26							
8-Jun-15	27							
9-Jun-15	28				91.3			
10-Jun-15	29							
11-Jun-15	30					2.82	0.15	2.98
12-Jun-15	31	3.31	3.31	1.00				
13-Jun-15	32							
14-Jun-15	33							
15-Jun-15	34							
16-Jun-15	35				98.1			
17-Jun-15	36							
18-Jun-15	37	3.42	3.48	1.02		3.03	0.06	3.09
19-Jun-15	38							

### A.8.4 Effluent Characteristics

Average Effluent Characteristics												
Date	Days	Ammonia (mg-N/L)	Nitrite (mg-N/L)	Nitrate (mg-N/L)	NAR (NO2-N/NOx-N) (%)	NOx/Ammonia	OP (mg-P/L)	TSS (mg/L)	SVI 30 (mL/g)	TIN (mg-N/L)	TN (mg-N/L)	TP (mg-P/L)
<b>Average</b>		4.03	0.56	3.20	15%	1.03	0.31	22.2	156	7.8	10.1	0.85
<b>Sample SD</b>		1.24	0.24	0.81	4%	0.45	0.72	7.1	20	1.5	1.8	0.31
4-May-15	1	3.92	0.27	1.61	14%	0.48	2.04	17.5	207	5.8		
5-May-15	2	3.60	0.35	1.84	16%	0.61	0.37	18.0	198	5.8	7.7	1.27
6-May-15	3	3.37	0.42	1.96	18%	0.71	0.0	17.3	190	5.7		
7-May-15	4	3.84	0.51	2.27	18%	0.72	0.0	17.3	187	6.6	8.8	0.56
8-May-15	5								183			
9-May-15	6											
10-May-15	7	7.53	0.35	1.95	15%	0.31	2.48	31.0		9.8		
11-May-15	8	2.27	0.53	2.55	17%	1.36	0.36	19.8	162	5.4		
12-May-15	9	2.80	0.48	2.83	15%	1.18	0.0	30.3	154	6.1	9.0	1.01
13-May-15	10	5.95	0.51	2.62	16%	0.53	0.0	44.8	140	9.1		
14-May-15	11	3.94	0.70	3.56	16%	1.08	0.0	24.8	156	8.2		
15-May-15	12								132			
16-May-15	13											
17-May-15	14	3.42	0.83	3.79	18%	1.35	0.0	23.8		8.0		
18-May-15	15	1.88	0.78	3.71	17%	2.39	0.0	23.0	147	6.4		
19-May-15	16	2.28	0.82	3.94	17%	2.09	0.0	23.8	147	7.0	9.7	0.76
20-May-15	17	3.26	1.00	3.93	20%	1.51	0.0	23.3	135	8.2		
21-May-15	18	6.16	0.82	3.54	19%	0.71	0.0	24.8	134	10.5	13.6	0.82
22-May-15	19								133			
1-Jun-15	20	3.83	0.51	4.81	10%	1.39	0.74			9.1		
2-Jun-15	21	4.21	0.65	4.11	14%	1.13	0.0	32.0	130	9.0	12.4	1.12
3-Jun-15	22	6.25	1.35	4.03	25%	0.86	2.22	28.5	158	11.6		
4-Jun-15	23							26.3	149			1.40
5-Jun-15	24								153			
6-Jun-15	25											
7-Jun-15	26	4.02	0.32	3.85	8%	1.04	0.0			8.2		
8-Jun-15	27	3.86	0.35	3.03	10%	0.87	0.0	25.0	159	7.2		
9-Jun-15	28	3.74	0.37	2.80	12%	0.85	0.0	20.0	164	6.9	9.0	0.68
10-Jun-15	29	3.98	0.41	2.83	13%	0.81	0.0	20.8	161	7.2		
11-Jun-15	30	4.06	0.42	3.10	12%	0.87	0.0	16.3	153	7.6	9.6	0.53
12-Jun-15	31							16.8	160			
13-Jun-15	32											
14-Jun-15	33	4.03	0.48	3.48	12%	0.98	0.0			8.0		
15-Jun-15	34	3.95	0.47	3.40	12%	0.98	0.03	18.8	160	7.8		
16-Jun-15	35	4.45	0.49	3.62	12%	0.92	0.06	11.8	157	8.6	10.3	0.50
17-Jun-15	36	3.73	0.50	3.40	13%	1.05	0.02	9.5	145	7.6		
18-Jun-15	37	4.35	0.56	3.91	13%	1.03	0.05	15.5	141	8.8	10.8	0.67
19-Jun-15	38							20.3	142			

### A.8.5 Influent Properties

Influent Properties																								
Date	Days	RWI											Primary Clarifier Effluent											
		COD (mg/L)	sCOD (mg/L)	pCOD (mg/L)	BOD (mg/L)	TSS (mg/L)	VSS (mg/L)	TKN (mg-N/L)	TAN (mg-N/L)	TP (mg-P/L)	OP (mg-P/L)	Alk (mg as CaCO <sub>3</sub> /L)	COD (mg/L)	sCOD (mg/L)	pCOD (mg/L)	BOD (mg/L)	TSS (mg/L)	VSS (mg/L)	TKN (mg-N/L)	TAN (mg-N/L)	TP (mg-P/L)	OP (mg-P/L)	Alk (mg as CaCO <sub>3</sub> /L)	
Average		702	199	503	285	268	236	46.2	36.4	6.4	3.88	195	429	204	225	202	120	103	42.8	36.7	5.7	3.73	200	
Sample SD		112	22	115	60	207	179	2.9	2.1	0.9	0.83	8	28	20	29	13	18	15	1.5	2.2	0.6	1.01	7	
4-May-15	1	751	181	570		216	196		31.5		3.16		436	188	248							32.7	3.42	
5-May-15	2	659	179	480	314	240	206	43.4	34.7	6.06	3.51	189	399	180	219	211			40.5		5.73	3.49	193	
6-May-15	3	631	184	447		230	216		34.7		3.76		420	200	220		124	106				35.7	3.88	
7-May-15	4	596	176	420		255	215	45.0	34.9	7.15	3.66	207	392	177	215		127	98	42.5		6.73	3.75	203	
8-May-15	5																							
9-May-15	6																							
10-May-15	7	682	264	418		241	206		38.4		7.24		455	204	251		127	108				40.0	8.40	
11-May-15	8	713	204	509		256	227		34.0		3.57		452	205	247		138	119				34.7	4.10	
12-May-15	9	906	182	724	382	323	281	53.2	34.7	8.38	4.13	196	467	200	267	212	147	128	45.8		6.51	4.25	195	
13-May-15	10	838	191	647		266	237		35.3		3.89		483	200	283		155	130				35.5	4.49	
14-May-15	11	660	187	473		245	215		38.9		3.67		500	217	283		151	128				38.9	4.33	
15-May-15	12																							
16-May-15	13																							
17-May-15	14	615	196	419		235	204		35.4		3.63		405	173	232		126	115				34.8	3.39	
18-May-15	15	681	186	495		264	230		35.5		3.54		452	196	256		132	117				35.6	3.68	
19-May-15	16	792	167	625	285	270	240	47.5	34.9	6.75	3.36	185	400	172	228	212	131	110	44.2		5.55	3.38	188	
20-May-15	17	640	183	457		244	214		31.4		3.25		416	174	242		124	104				30.0	3.29	
21-May-15	18	576	181	395		1305	1135	46.4	36.4	5.96	3.30	200	439	182	257		125	109	44.6		5.57	3.45	206	
22-May-15	19																							
1-Jun-15	20	647	222	425		207	186		36.6		3.58		440	232	208		107	92				37.9	3.35	
2-Jun-15	21	597	196	401	270	216	192	44.7	36.1	5.86	3.29	188	406	195	211	200	114	98	42.6		5.20	3.15	197	
3-Jun-15	22	684	210	474		189	169		37.5		3.60		402	208	194		105	91				38.2	3.27	
4-Jun-15	23	628	183	445		202	181	44.0		5.32		186	398	205	193		113	96	41.5		4.88		198	
5-Jun-15	24																							
6-Jun-15	25																							
7-Jun-15	26	618	233	385		167	151		37.1		3.49		462	245	217		99	84				37.6	3.01	
8-Jun-15	27	612	215	397		160	147		36.9		3.31		419	232	187		98	86				37.5	3.32	
9-Jun-15	28	1041	200	841	257	260	234	47.8	38.3	6.89	4.19	200	440	205	235	197	116	105	41.9		5.88	3.45	198	
10-Jun-15	29	652	197	455		226	193		38.4		4.21		417	206	211		111	96				38.8	3.38	
11-Jun-15	30	811	206	605		247	208	47.6	38.9	6.72	3.95	203	411	212	199		103	78	42.3		5.73	3.14	210	
12-Jun-15	31																							
13-Jun-15	32																							
14-Jun-15	33	669	230	439		288	258		39.2		5.37		409	230	179		139	119				39.1	3.95	
15-Jun-15	34	655	222	433		166	145		38.1		4.88		423	233	190		116	105				37.3	3.55	
16-Jun-15	35				202	187	163	44.2	38.5	5.71	3.96	203				180	94	81	42.5		5.17	3.28	202	
17-Jun-15	36	895	213	682		196	176		37.2		3.89		421	211	210		98	85				38.4	3.22	
18-Jun-15	37	700	189	511		209	189	44.2	39.0	5.82	3.36	201	418	217	201		90	86	42.2		5.31	3.40	209	
19-Jun-15	38																							

A.8.6 COD Properties

COD Characteristics														
Date	Days	Influent					Effluent					Removed		
		COD (mg/L)	sCOD (mg/L)	pCOD (mg/L)	% Soluble	% Particulate	COD (mg/L)	sCOD (mg/L)	pCOD (mg/L)	% Soluble	% Particulate	COD (mg/L)	sCOD (mg/L)	pCOD (mg/L)
Average		429	207	222	48%	52%	46.0	25.5	22.1	54%	46%	386	183	202
Sample SD		28	23	34	6%	6%	9.7	9.2	8.8	11%	11%	25	24	28
4-May-15	1	436	188	248	43%	57%	43.0	22.3	20.7	52%	48%	393	166	227
5-May-15	2	399	180	219	45%	55%	42.2	21.9	20.3	52%	48%	357	158	199
6-May-15	3	420	200	220	48%	52%	40.8	21.8	19.0	53%	47%	379	178	201
7-May-15	4	392	177	215	45%	55%	40.2	23.5	16.7	58%	42%	352	154	198
8-May-15	5													
9-May-15	6													
10-May-15	7	455	204	251	45%	55%	65.5	26.0	39.5	40%	60%	390	178	212
11-May-15	8	452	205	247	45%	55%	43.2	23.4	19.8	54%	46%	409	182	227
12-May-15	9	467	200	267	43%	57%	60.1	23.1	37.0	38%	62%	407	177	230
13-May-15	10	483	200	283	41%	59%	53.9	24.6	29.3	46%	54%	429	175	254
14-May-15	11	500	217	283	43%	57%	57.6	24.2	33.4	42%	58%	442	193	250
15-May-15	12													
16-May-15	13													
17-May-15	14	405	268	137	66%	34%	52.1	24.6	27.5	47%	53%	353	243	110
18-May-15	15	452	196	256	43%	57%	47.7	23.6	24.1	49%	51%	404	172	232
19-May-15	16	400	172	228	43%	57%	48.0	23.9	24.1	50%	50%	352	148	204
20-May-15	17	416	174	242	42%	58%	58.0	22.9	35.1	39%	61%	358	151	207
21-May-15	18	439	182	257	41%	59%	47.9	24.2	23.7	51%	49%	391	158	233
22-May-15	19													
1-Jun-15	20	440	232	208	53%	47%	56.0	26.6	29.4	48%	53%	384	205	179
2-Jun-15	21	406	195	211	48%	52%	38.9	22.4	16.5	58%	42%	367	173	195
3-Jun-15	22	402	208	194	52%	48%	53.2	69.6				349	138	194
4-Jun-15	23	398	205	193	52%	48%						398	205	193
5-Jun-15	24													
6-Jun-15	25													
7-Jun-15	26	462	245	217	53%	47%	41.4	21.9	19.5	53%	47%	421	223	198
8-Jun-15	27	419	232	187	55%	45%		24.7				419	207	187
9-Jun-15	28	440	205	235	47%	53%	37.8	22.9	14.9	61%	39%	402	182	220
10-Jun-15	29	417	206	211	49%	51%	37.3	23.5	13.8	63%	37%	380	183	197
11-Jun-15	30	411	212	199	52%	48%	39.2	23.7	15.5	60%	40%	372	188	184
12-Jun-15	31													
13-Jun-15	32													
14-Jun-15	33	409	230	179	56%	44%	29.0	21.2	7.8	73%	27%	380	209	171
15-Jun-15	34	423	233	190	55%	45%	24.3	20.8	3.5	86%	14%	399	212	187
16-Jun-15	35													
17-Jun-15	36	421	211	210	50%	50%	44.6	25.8	18.8	58%	42%	376	185	191
18-Jun-15	37	418	217	201	52%	48%	49.0	29.5	19.5	60%	40%	369	188	182
19-Jun-15	38													

A.8.7a Alkalinity Usage

Alkalinity Consumption										
Date	Days	Influent Ammonia (mg-N/L)	Effluent Ammonia (mg-N/L)	TAN Removal (mg-N/L)	Effluent pH	Influent Alkalinity (mg CaCO <sub>3</sub> /L)	Effluent Alkalinity (mg CaCO <sub>3</sub> /L)	Bicarbonate Feed (mg CaCO <sub>3</sub> /L)	Alk Added (mg CaCO <sub>3</sub> /mg NH <sub>4</sub> -N)	TAN Removed (mg NH <sub>4</sub> -N)
<b>Average</b>		36.7	4.03	32.7	6.81	200	86	18		4.02
<b>Sample SD</b>		2.2	1.24	2.0	0.07	7	10	14		0.23
4-May-15	1	32.7	3.92	28.8	6.88			6		
5-May-15	2	35.1	3.60	31.5	6.80	193	95	21		3.76
6-May-15	3	35.7	3.37	32.3	6.82			18		
7-May-15	4	35.8	3.84	32.0	6.79	203	94	23		4.12
8-May-15	5				6.72			26		
9-May-15	6							2		
10-May-15	7	40.0	7.53	32.5				5		
11-May-15	8	34.7	2.27	32.4	6.69			32		
12-May-15	9	35.6	2.8	32.8	6.75	195	96	34		4.06
13-May-15	10	35.5	5.95	29.6	6.81			11		
14-May-15	11	38.9	3.94	35.0	6.77			35		
15-May-15	12				6.79			40		
16-May-15	13							18		
17-May-15	14	34.8	3.42	31.4				18		
18-May-15	15	35.6	1.88	33.7	6.82			22		
19-May-15	16	35.3	2.28	33.0	6.80	188	73	17		4.00
20-May-15	17	30.0	3.26	26.7	6.80			29		
21-May-15	18	36.9	6.16	30.7	6.82	206	88	18		4.43
22-May-15	19				6.83			25		
1-Jun-15	20	37.9	3.83	34.1	6.74			27		
2-Jun-15	21	36.7	4.21	32.5	6.81	197	94	34		4.20
3-Jun-15	22	38.2	6.25	32.0	6.90			28		
4-Jun-15	23				7.00	198	102	46		
5-Jun-15	24				6.97			53		
6-Jun-15	25							6		
7-Jun-15	26	37.6	4.02	33.6				3		
8-Jun-15	27	37.5	3.86	33.6	6.92			9		
9-Jun-15	28	38.1	3.74	34.4	6.86	198	76	4		3.67
10-Jun-15	29	38.8	3.98	34.8	6.83			4		
11-Jun-15	30	38.4	4.06	34.3	6.85	210	80	8		4.01
12-Jun-15	31				6.80			13		
13-Jun-15	32							0		
14-Jun-15	33	39.1	4.03	35.1				3		
15-Jun-15	34	37.3	3.95	33.4	6.79			0		
16-Jun-15	35	38.1	4.45	33.7	6.78	202	77	2		3.78
17-Jun-15	36	38.4	3.73	34.7	6.77			5		
18-Jun-15	37	38.4	4.35	34.1	6.76	209	74	7		4.18
19-Jun-15	38				6.75			12		

A.8.7b Alkalinity Usage

AvN_MLE_PCE																	
Date	Total SRT (days)	Net Heterotrophic Yield (g/g)	Influent BOD (mg/L)	Effluent BOD (mg/L)	TKN Used for BOD Oxidation	Influent TKN (mg-N/L)	Effluent TKN (mg-N/L)	TKN Nitrified (mg-N/L)	Alk used by Nitrification	Effluent Nitrite (mg-)	Effluent Nitrate (mg-)	NOx Denitrified (mg-N/L)	Alk provided by Denitrification	Influent Alk (mg CaCO3/L)	Effluent Alk (mg CaCO3/L)	Theoretical Supplemental Alk Req (mg)	Alk Req for NH4Den
Average	5.7	0.62	202	19	13.5	42.8	6.4	23	167	0.6	3.2	19.7	70.3	200	86	-13	2.38
Sample SD	1.2	0.02	13	1	1.0	1.5	1.2	2	13	0.2	0.8	1.8	6.4	7	10	11	0.12
4-May-15	6.2	0.61								0.27	1.61						
5-May-15	6.0	0.61	211	18	14.1	40.5	5.5	21	149	0.35	1.84	18.7	66.8	193	95	-16	2.23
6-May-15	6.1	0.61								0.42	1.96						
7-May-15	5.2	0.62				42.5	6.0			0.51	2.27			203	94		
8-May-15	5.3	0.62															
9-May-15																	
10-May-15										0.35	1.95						
11-May-15	4.6	0.63								0.53	2.55						
12-May-15	4.3	0.63	212	19	14.6	45.8	5.7	25	182	0.48	2.83	22.2	79.1	195	96	4	2.30
13-May-15	4.1	0.63								0.51	2.62						
14-May-15	4.5	0.63								0.70	3.56						
15-May-15	5.3	0.62															
16-May-15																	
17-May-15										0.83	3.79						
18-May-15	6.0	0.61								0.78	3.71						
19-May-15	4.9	0.62	212	21	14.3	44.2	5.0	25	178	0.82	3.94	20.2	72.0	188	73	-9	2.47
20-May-15	4.5	0.63								1.00	3.93						
21-May-15	5.4	0.62				44.6	9.2			0.82	3.54			206	88		
22-May-15	6.3	0.61															
1-Jun-15		0.70								0.51	4.81						
2-Jun-15	5.9	0.61	200	17	13.4	42.6	7.6	22	154	0.65	4.11	16.8	60.1	197	94	-9	2.57
3-Jun-15	8.1	0.58								1.35	4.03						
4-Jun-15	9.4	0.57				41.5	7.0							198	102		
5-Jun-15																	
6-Jun-15																	
7-Jun-15										0.32	3.85						
8-Jun-15	6.8	0.60								0.35	3.03						
9-Jun-15	6.5	0.60	197	19	12.9	41.9	5.9	23	166	0.37	2.80	20.0	71.5	198	76	-28	2.32
10-Jun-15	6.5	0.60								0.41	2.83						
11-Jun-15	6.8	0.60				42.3	6.0			0.42	3.10			210	80		
12-Jun-15	6.2	0.61															
13-Jun-15																	
14-Jun-15										0.48	3.48						
15-Jun-15	5.6	0.61								0.47	3.40						
16-Jun-15	5.6	0.61	180	18	11.9	42.5	6.2	24	174	0.49	3.62	20.3	72.4	202	77	-23	2.40
17-Jun-15	5.1	0.62								0.50	3.40						
18-Jun-15	4.7	0.63				42.2	6.3			0.56	3.91			209	74		
19-Jun-15	5.1	0.62															

## A.9 Data Collection during AvN\_FI\_PCE

### A.9.1 Performance Data

Removal Performance									
Date	Days	NH <sub>4</sub> <sup>+</sup> -N loading rate (mg-N/L/d)	Influent COD/NH <sub>4</sub> <sup>+</sup> -N	TIN removal rate (mg-N/L/d)	TIN removal Efficiency (%)	COD removal rate (mg/L/d)	COD removal rate/TIN removal rate	OP removal Efficiency (%)	Calculated AOB rate (mg-N/L/d)
<b>Average</b>		179.5	10.7	134.7	75.1	1690	12.6	79.0	223
<b>Sample SD</b>		5.3	0.8	8.6	5.1	152	1.4	24.1	28
25-May-15	1	184.6	11.6	147.2	79.8	1832	12.8	100.0	
26-May-15	2	178.9	12.4	134.8	75.4	1932	14.3	100.0	210
27-May-15	3	187.5	11.4	130.1	69.4	1872	14.4	100.0	191
28-May-15	4	187.9	10.6	120.4	64.1	1671	13.9	100.0	167
29-May-15	5								
21-Jun-15	6	176.5	10.9	142.9	81.0	1690	11.8	98.6	
22-Jun-15	7	181.7	11.0	149.9	82.5	1790	11.9	98.9	281
23-Jun-15	8	178.9	10.2	142.3	79.5	1628	11.4	98.7	256
24-Jun-15	9	167.9	11.1	135.2	80.5	1649	12.2	98.2	238
25-Jun-15	10	174.6	10.2	132.0	75.6	1569	11.9	97.8	228
26-Jun-15	11								
27-Jun-15	12								
28-Jun-15	13	175.5	10.2	138.5	78.9	1560	11.3	70.7	
29-Jun-15	14	178.9	10.0	140.2	78.4	1582	11.3	71.3	241
30-Jun-15	15	177.9	10.1	130.9	73.6	1592	12.2	72.7	225
01-Jul-15	16	184.1	10.3	131.7	71.6			58.1	232
02-Jul-15	17								
03-Jul-15	18								
04-Jul-15	19								
05-Jul-15	20	176.5	10.5	117.9	66.8	1724	14.6	79.0	
06-Jul-15	21	177.9	11.9	126.5	71.1	1951	15.4	67.3	230
07-Jul-15	22	180.3	10.4	132.1	73.3	1696	12.8	46.8	229
08-Jul-15	23	174.1	9.8	128.8	74.0	1444	11.2	32.0	221
09-Jul-15	24	187.9	9.4	142.8	76.0	1491	10.4	31.4	251
10-Jul-15	25								



## A.9.2 Operational Conditions

Operational Conditions							
Date	Days	Temperature in 1st CSTR (°C)	MLSS (mg/L)	VSS (mg/L)	Total SRT (days)	Aerobic Fraction	Aerobic SRT (days)
<b>Average</b>		20.4	4051	3288	5.3	0.52	2.9
<b>Sample SD</b>		0.3	339	270	0.7	0.07	0.7
25-May-15	1					0.57	
26-May-15	2	21.3	4295	3445	5.7	0.56	3.2
27-May-15	3	20.4	4275	3440	5.6	0.66	3.7
28-May-15	4	20.4	4405	3520	6.1	0.69	4.2
29-May-15	5	20.4	4405	3575	5.9	0.62	3.7
21-Jun-15	6					0.46	
22-Jun-15	7	20.5	4580	3745	5.1	0.47	2.4
23-Jun-15	8	20.6	4505	3650	4.5	0.47	2.1
24-Jun-15	9	20.5	4315	3520	4.3	0.47	2.1
25-Jun-15	10	20.4	4195	3400	4.6	0.50	2.3
26-Jun-15	11	20.3	4075	3305	5.3	0.41	2.2
27-Jun-15	12					0.41	
28-Jun-15	13					0.52	
29-Jun-15	14	20.0	3765	3085	4.8	0.52	2.5
30-Jun-15	15	20.2	3700	2995	4.5	0.52	2.3
01-Jul-15	16	20.2	3545	2850	5.5	0.56	3.1
02-Jul-15	17	20.3	3595	2930	4.1	0.46	1.9
03-Jul-15	18					0.49	
04-Jul-15	19					0.50	
05-Jul-15	20					0.48	
06-Jul-15	21	20.3	4035	3255	6.4	0.53	3.4
07-Jul-15	22	20.1	3975	3240	5.9	0.55	3.3
08-Jul-15	23	20.4	3890	3215	5.9	0.56	3.3
09-Jul-15	24	20.5	3825	3140	5.6	0.56	3.1
10-Jul-15	25	20.6	3535	2870	6.1		

A.9.3 Batch Rate Testing

Batch Rate Testing Results									
Date	Days	AOB rate (mgNOx-N/gMLSS/hr)	NOB rate (mgNO3-N/gMLSS/hr)	NOB rate/AOB rate	Average OUR (mg/L/hr)	Denitrification rate (mgNO3-N/gMLSS/hr)	Denitrification rate (mgNO2-N/gMLSS/hr)	Denitrification rate (mgNOx-N/gMLSS/hr)	Denitrification rate (mgNOx-N/gMLSS/hr)
<b>Average</b>		3.06	2.84	0.93	74.6	3.04	0.48		3.52
<b>Sample SD</b>		0.53	0.53	0.09	9.8	0.28	0.46		0.38
25-May-15	1								
26-May-15	2								
27-May-15	3								
28-May-15	4	2.55	2.65	1.04		3.35	0.46		3.81
29-May-15	5				67.3				
21-Jun-15	6								
22-Jun-15	7								
23-Jun-15	8				88.1				
24-Jun-15	9								
25-Jun-15	10	3.03	2.79	0.92		3.12	-0.15		2.97
26-Jun-15	11								
27-Jun-15	12								
28-Jun-15	13								
29-Jun-15	14								
30-Jun-15	15								
01-Jul-15	16				67.5				
02-Jul-15	17	3.79	3.59	0.95		3.00	0.71		3.71
03-Jul-15	18								
04-Jul-15	19								
05-Jul-15	20								
06-Jul-15	21								
07-Jul-15	22				75.6				
08-Jul-15	23								
09-Jul-15	24	2.87	2.34	0.82		2.68	0.90		3.58
10-Jul-15	25								

### A.9.4 Effluent Characteristics

Average Effluent Characteristics													
Date	Days	Ammonia (mg-N/L)	Nitrite (mg-N/L)	Nitrate (mg-N/L)	NAR (NO2-N/NOx-N) (%)	NOx/Ammonia	DP (mg-P/L)	TSS (mg/L)	SVI 30 (mL/g)	TIN (mg-N/L)	TN (mg-N/L)	TP (mg-P/L)	
<b>Average</b>		4.40	1.06	3.94	22%	1.23	0.85	27.8	164	9.4	12.0	1.36	
<b>Sample SD</b>		1.61	0.35	1.16	7%	0.34	0.95	16.1	15	2.1	1.1	0.81	
25-May-15	1	3.31	1.03	3.49	23%	1.37	0.0	27.3		7.8			
26-May-15	2	5.47	0.82	2.95	22%	0.69	0.0	34.0	133	9.2	13.1	1.16	
27-May-15	3	4.48	0.80	6.74	11%	1.68	0.0	31.0	131	12.0			
28-May-15	4	6.67	0.60	6.88	8%	1.12	0.0	37.0	177	14.1			
29-May-15	5								143				
21-Jun-15	6	2.87	0.75	3.42	18%	1.45	0.05	19.3		7.0			
22-Jun-15	7	2.63	0.88	3.16	22%	1.53	0.04	17.8	164	6.7			
23-Jun-15	8	3.04	0.99	3.64	21%	1.52	0.05	17.8	151	7.7	10.2	0.64	
24-Jun-15	9	2.68	1.11	3.06	27%	1.56	0.07	19.5	165	6.9			
25-Jun-15	10	3.88	1.07	3.97	21%	1.30	0.09	16.3	167	8.9	11.9	0.68	
26-Jun-15	11								174				
27-Jun-15	12												
28-Jun-15	13	3.22	0.79	3.76	17%	1.41	1.13	23.0		7.8			
29-Jun-15	14	3.68	0.85	3.59	19%	1.21	1.15	20.8	175	8.1			
30-Jun-15	15	4.65	1.01	4.20	19%	1.12	1.12	21.3	165	9.9	12.6	1.74	
01-Jul-15	16	5.16	1.02	4.80	18%	1.13	1.84	86.5	166	11.0			
02-Jul-15	17								167				
03-Jul-15	18												
04-Jul-15	19												
05-Jul-15	20	8.96	0.95	2.38	28%	0.37	0.91	22.0		12.3			
06-Jul-15	21	5.81	1.39	3.59	28%	0.86	1.55	19.3	181	10.8			
07-Jul-15	22	4.82	1.47	3.81	28%	1.10	2.07	20.3	184	10.1	12.3	2.56	
08-Jul-15	23	4.20	1.55	3.75	29%	1.26	2.59	33.5	177	9.5			
09-Jul-15	24	3.74	2.02	3.71	35%	1.53	2.60	34.0	173	9.5			
10-Jul-15	25								167				

A.9.5 Influent Properties

Influent Properties																							
Date	Days	RWI											Primary Clarifier Effluent										
		COD (mg/L)	sCOD (mg/L)	pCOD (mg/L)	BOD (mg/L)	TSS (mg/L)	VSS (mg/L)	TKN (mg-N/L)	TAN (mg-N/L)	TP (mg-P/L)	OP (mg-P/L)	Alk (mg as CaCO3/L)	COD (mg/L)	sCOD (mg/L)	pCOD (mg/L)	BOD (mg/L)	TSS (mg/L)	VSS (mg/L)	TKN (mg-N/L)	TAN (mg-N/L)	TP (mg-P/L)	OP (mg-P/L)	Alk (mg as CaCO3/L)
<b>Average</b>		586	198	388	273	217	187	47.0	37.4	6.3	3.78	199	401	210	192	210	107	91	44.4	37.6	5.6	3.92	203
<b>Sample SD</b>		69	19	70	23	36	29	2.4	1.0	0.7	0.26	8	32	36	35	29	11	12	1.9	1.1	0.3	0.34	8
25-May-15	1	645	234	411		208	185		37.9		3.53		449	258	191		122	109		38.7		3.66	
26-May-15	2	760	215	545	307	237	211	48.4	36.4	6.53	3.81	199	466	239	227	241	129	116	46.7	37.5	5.89	3.92	206
27-May-15	3	591	221	370		214	186		39.4		3.89		449	236	213		120	94		39.3		3.79	
28-May-15	4	657	203	454		193	165		38.0		3.33		416	214	202		106	86		39.4		3.23	
29-May-15	5																						
21-Jun-15	6	565	216	349		189	168		37.4		3.45		402	218	184		102	90		37.0		3.48	
22-Jun-15	7	532	218	314		191	165		37.8		3.53		421	115	306		96	81		38.1		3.64	
23-Jun-15	8	462	204	258	261	177	160	44.5	37.5	5.65	4.05	187	382	209	173	196	95	85	42.1	37.5	5.46	3.97	195
24-Jun-15	9	555	195	360		204	164		35.1		3.57		389	201	188		103	83		35.2		3.81	
25-Jun-15	10	580	200	380		197	172	44.6	36.4	5.69	3.74	193	375	197	178		92	81	43.7	36.6	5.40	4.07	190
26-Jun-15	11																						
27-Jun-15	12																						
28-Jun-15	13	538	180	358		237	195		36.6		3.58		377	198	179		104	78		36.8		3.86	
29-Jun-15	14	586	182	404		285	247		37.7		3.79		374	180	194		112	93		37.5		4.00	
30-Jun-15	15	688	167	521	258	282	242	48.8	37.0	7.27	3.89	209	376	188	188	226	108	87	43.9	37.3	5.81	4.11	211
01-Jul-15	16	550	184	366		244	207		37.8		3.95		396	202	194		114	99		38.6		4.39	
02-Jul-15	17																						
03-Jul-15	18																						
04-Jul-15	19																						
05-Jul-15	20	554	204	350		240	202		37.8		4.07		389	241	148		88	72		37.0		4.31	
06-Jul-15	21	578	210	368		237	204		37.9		4.43		443	289	154		116	111		37.3		4.74	
07-Jul-15	22	640	173	467	266	235	196	50.1	37.4	6.95	3.72	205	392	189	203	178	113	97	46.5	37.8	5.95	3.89	207
08-Jul-15	23	522	173	349		167	148		36.4		3.72		359	202	157		96	82		36.5		3.81	
09-Jul-15	24	549	188	361		162	145	45.3	39.0	5.81	3.93	201	369	198	171		101	88	43.2	39.4	5.17	3.79	208
10-Jul-15	25																						

A.9.6 COD Properties

COD Characteristics														
Date	Days	Influent					Effluent					Removed		
		COD (mg/L)	sCOD (mg/L)	pCOD (mg/L)	% Soluble	% Particulate	COD (mg/L)	sCOD (mg/L)	pCOD (mg/L)	% Soluble	% Particulate	COD (mg/L)	sCOD (mg/L)	pCOD (mg/L)
Average		401	210	192	52%	48%	47.3	25.9	21.2	57%	43%	357	184	172
Sample SD		32	36	35	8%	8%	10.0	5.0	10.0	14%	14%	32	37	34
25-May-15	1	449	258	191	57%	43%	52.4	24.2	28.2	46%	54%	397	234	163
26-May-15	2	466	239	227	51%	49%	61.0	27.9	33.1	46%	54%	405	211	194
27-May-15	3	449	236	213	53%	47%	56.6	23.8	32.8	42%	58%	392	212	180
28-May-15	4	416	214	202	51%	49%	65.6	27.9	37.7	43%	57%	350	186	164
29-May-15	5													
21-Jun-15	6	402	218	184	54%	46%	47.6	23.6	24.0	50%	50%	354	194	160
22-Jun-15	7	421	115	306	27%	73%	45.8	23.4	22.4	51%	49%	375	92	284
23-Jun-15	8	382	209	173	55%	45%	40.8	24.3	16.5	60%	40%	341	185	157
24-Jun-15	9	389	201	188	52%	48%	43.3	25.3	18.0	58%	42%	346	176	170
25-Jun-15	10	375	197	178	53%	47%	46.1	26.2	19.9	57%	43%	329	171	158
26-Jun-15	11													
27-Jun-15	12													
28-Jun-15	13	377	198	179	53%	47%	50.0	45.0	5.0	90%	10%	327	153	174
29-Jun-15	14	374	180	194	48%	52%	42.4	23.6	18.8	56%	44%	332	156	175
30-Jun-15	15	376	188	188	50%	50%	42.2	24.3	17.9	58%	42%	334	164	170
01-Jul-15	16	396	202	194	51%	49%		22.4			396	180	194	
02-Jul-15	17													
03-Jul-15	18													
04-Jul-15	19													
05-Jul-15	20	389	241	148	62%	38%	27.5	23.6	3.9	86%	14%	362	217	144
06-Jul-15	21	443	289	154	65%	35%	33.9	23.0	10.9	68%	32%	409	266	143
07-Jul-15	22	392	189	203	48%	52%	36.4	25.4	11.0	70%	30%	356	164	192
08-Jul-15	23	359	202	157	56%	44%	56.2	25.7	30.5	46%	54%	303	176	127
09-Jul-15	24	369	198	171	54%	46%	56.5	26.4	30.1	47%	53%	313	172	141
10-Jul-15	25													

A.9.7a Alkalinity Usage

Alkalinity Consumption										
Date	Days	Influent Ammonia (mg-N/L)	Effluent Ammonia (mg-N/L)	TAN Removal (mg-N/L)	Effluent pH	Influent Alkalinity (mg CaCO <sub>3</sub> /L)	Effluent Alkalinity (mg CaCO <sub>3</sub> /L)	Bicarbonate Feed (mg CaCO <sub>3</sub> /L)	Alk Added (mg CaCO <sub>3</sub> )	TAN Removed (mg NH <sub>4</sub> -N)
<b>Average</b>		37.6	4.40	33.2	6.70	203	90	26		4.17
<b>Sample SD</b>		1.1	1.6	1.8	0.15	8	3	14		0.33
25-May-15	1	38.7	3.31	35.4				39		
26-May-15	2	37.5	5.47	32.0	6.77	206	95	19		4.06
27-May-15	3	39.3	4.48	34.8	6.79			42		
28-May-15	4	39.4	6.67	32.7	6.79			47		
29-May-15	5				6.8			55		
21-Jun-15	6	37.0	2.87	34.1				19		
22-Jun-15	7	38.1	2.63	35.5	6.73			12		
23-Jun-15	8	37.5	3.04	34.5	6.72	195	86	24		3.86
24-Jun-15	9	35.2	2.68	32.5	6.81			32		
25-Jun-15	10	36.6	3.08	32.7	6.75	190	90	33		4.08
26-Jun-15	11				6.81			29		
27-Jun-15	12							38		
28-Jun-15	13	36.8	3.22	33.6				34		
29-Jun-15	14	37.5	3.68	33.8	6.76			24		
30-Jun-15	15	37.3	4.65	32.7	6.77	211	88	32		4.74
01-Jul-15	16	38.6	5.16	33.4	6.77			25		
02-Jul-15	17				6.73			15		
03-Jul-15	18							0		
04-Jul-15	19							1		
05-Jul-15	20	37.0	8.96	28.0				0		
06-Jul-15	21	37.3	5.81	31.5	6.61			12		
07-Jul-15	22	37.8	4.82	33.0	6.72	207	92	20		4.10
08-Jul-15	23	36.5	4.2	32.3	6.53			25		
09-Jul-15	24	39.4	3.74	35.7	6.42	208		33		
10-Jul-15	25				6.26			37		

A.9.7b Alkalinity Usage

AvN_FI_PCE																	
Date	Total SRT (days)	Net Heterotrophic Yield (g/g)	Influent BOD (mg/L)	Effluent BOD (mg/L)	TKN Used for BOD Oxidation	Influent TKN (mg-N/L)	Effluent TKN (mg-N/L)	TKN Nitrified (mg-N/L)	Alk used by Nitrification	Effluent Nitrite (mg-)	Effluent Nitrate (mg-)	NOx Denitrified (mg-N/L)	Alk provided by Denitrification	Influent Alk (mg CaCO3/L)	Effluent Alk (mg CaCO3/L)	Theoretical Supplemental Alk Req (mg)	Alk Req for NitrDen
Average	5.3	0.62	210	19	14.3	44.4	7.3	23	166	1.1	3.9	18.5	66.0	203	90	-15	2.52
Sample SD	0.7	0.01	29	1	2.1	1.9	1.3	3	23	0.3	1.2	3.0	10.5	8	3	15	0.10
25-May-15											1.03	3.49					
26-May-15	5.7	0.61	241	20	16.2	46.7	9.3	21	151	0.82	2.95	17.4	62.0	206	95	-22	2.43
27-May-15	5.6	0.61								0.80	6.74						
28-May-15	6.1	0.61								0.60	6.88						
29-May-15	5.9	0.61															
21-Jun-15										0.75	3.42						
22-Jun-15	5.1	0.62								0.88	3.16						
23-Jun-15	4.5	0.63	196	18	13.4	42.1	5.6	23	165	0.99	3.64	18.4	65.8	195	86	-10	2.50
24-Jun-15	4.3	0.63								1.11	3.06						
25-Jun-15	4.6	0.63				43.7	6.9			1.07	3.97			190	90		
26-Jun-15	5.3	0.62															
27-Jun-15																	
28-Jun-15										0.79	3.76						
29-Jun-15	4.8	0.63								0.85	3.59						
30-Jun-15	4.5	0.63	226	18	15.7	43.9	7.4	21	148	1.01	4.20	15.6	55.6	211	88	-30	2.67
01-Jul-15	5.5	0.62								1.02	4.80						
02-Jul-15	4.1	0.64															
03-Jul-15																	
04-Jul-15																	
05-Jul-15										0.95	2.38						
06-Jul-15	6.4	0.60								1.39	3.59						
07-Jul-15	5.9	0.61	178	19	11.6	46.5	7.1	28	199	1.47	3.81	22.5	80.4	207	92	3	2.47
08-Jul-15	5.9	0.61								1.55	3.75						
09-Jul-15	5.6	0.61				43.2				2.02	3.71			208			
10-Jul-15	6.1	0.61															

## A.10 Comparisons between Operational Configurations

### A.10.1 Influent Properties

Feed Type	A-Stage Effluent (ASE)					Primary Clarifier Effluent (PCE)			
	DO Control	ABAC	AvN MLE	AvN Low	AvN High	DO Control	ABAC	AvN MLE	AvN
COD (mg/L)	311 ± 61	303 ± 40	303 ± 47	260 ± 23	356 ± 52	370 ± 18	424 ± 28	429 ± 28	401 ± 32
sCOD (mg/L)	146 ± 18	134 ± 22	138 ± 21	147 ± 17	169 ± 29	207 ± 21	223 ± 13	204 ± 20	210 ± 36
pCOD (mg/L)	166 ± 47	169 ± 25	165 ± 37	114 ± 17	186 ± 40	163 ± 23	198 ± 34	225 ± 29	192 ± 35
BOD (mg/L)	124 ± 30	109 ± 27	114 ± 21	115 ± 45	148 ± 50	159 ± 21	182 ± 4	202 ± 13	210 ± 29
TSS (mg/L)	103 ± 19	104 ± 14	109 ± 30	68 ± 13	107 ± 21	99 ± 8	104 ± 12	120 ± 18	107 ± 11
VSS (mg/L)	86 ± 17	86 ± 12	95 ± 29	62 ± 12	96 ± 18	84 ± 8	92 ± 13	103 ± 15	91 ± 12
TKN (mg-N/L)	39.6 ± 2.9	36.3 ± 4.7	38.4 ± 4.0	36.1 ± 4.0	34.6 ± 5.5	43.0 ± 3.1	43.8 ± 1.4	42.8 ± 1.5	44.4 ± 1.9
TAN (mg-N/L)	31.7 ± 1.2	30.0 ± 3.4	28.8 ± 2.6	28.8 ± 1.6	29.6 ± 2.0	37.7 ± 2.5	39.9 ± 1.0	36.7 ± 2.2	37.6 ± 1.1
TP (mg-P/L)	4.3 ± 0.4	4.0 ± 0.7	4.7 ± 0.7	4.0 ± 0.4	5.8 ± 3.2	5.5 ± 0.2	5.9 ± 0.6	5.7 ± 0.6	5.6 ± 0.3
OP (mg-P/L)	2.0 ± 0.6	2.3 ± 0.4	2.9 ± 1.0	2.9 ± 0.6	3.9 ± 0.6	3.8 ± 0.5	4.1 ± 0.5	3.7 ± 1.0	3.9 ± 0.3
Alkalinity (mg/L as CaCO <sub>3</sub> )	158 ± 5	151 ± 25	179 ± 13	164 ± 7	171 ± 14	202 ± 6	209 ± 5	200 ± 7	203 ± 8



### A.10.2 Loading Conditions and Removal Efficiencies

Feed Type	A-Stage Effluent (ASE)					Primary Clarifier Effluent (PCE)			
	DO Control	ABAC	AvN MLE	AvN Low	AvN High	DO Control	ABAC	AvN MLE	AvN
Control Strategy									
NH <sub>4</sub> <sup>+</sup> -N loading rate (mg-N/L/d)	151 ± 6	143 ± 16	137 ± 13	137 ± 8	141 ± 10	179 ± 11	190 ± 5	175 ± 10	180 ± 5
Influent COD/NH <sub>4</sub> <sup>+</sup> -N	9.8 ± 1.9	10.2 ± 1.7	10.6 ± 1.4	9.1 ± 1.1	12.0 ± 1.5	9.9 ± 0.8	10.7 ± 0.9	11.8 ± 1.0	10.7 ± 0.8
COD removal rate (mg/L/d)	1255 ± 278	1256 ± 198	1191 ± 235	1008 ± 125	1474 ± 284	1587 ± 96	1852 ± 146	1834 ± 121	1690 ± 152
TIN removal rate (mg-N/L/d)	76 ± 26	104 ± 19	103 ± 11	77 ± 11	110 ± 12	146 ± 9	154 ± 5	138 ± 10	135 ± 9
TIN removal efficiency (%)	50.4 ± 17.1	72.6 ± 10.5	75.5 ± 6.0	55.9 ± 7.6	77.5 ± 6.1	81.4 ± 1.2	81.1 ± 1.2	78.8 ± 3.9	75.1 ± 5.1
COD removal rate/TIN removal rate	17.5 ± 3.9	12.3 ± 1.6	11.6 ± 1.8	13.3 ± 1.8	13.3 ± 1.7	10.9 ± 0.9	12.0 ± 1.2	13.4 ± 1.2	12.6 ± 1.4
OP removal efficiency (%)	11.5 ± 19.0	21.7 ± 13.0	19.3 ± 24.2	17.4 ± 14.6	41.2 ± 23.3	44.3 ± 13.5	70.1 ± 10.5	92.5 ± 17.7	79.0 ± 24.1
MLSS (mg/L)	3660 ± 290	3840 ± 330	2967 ± 377	2400 ± 380	3556 ± 505	3939 ± 268	4508 ± 278	4232 ± 279	4051 ± 339
Total SRT (days)	6.9 ± 0.5	7.7 ± 0.4	7.1 ± 1.9	7.8 ± 2.1	7.9 ± 2.2	7.3 ± 0.7	6.7 ± 0.9	5.7 ± 1.2	5.3 ± 0.7
Aerobic Fraction	0.75	0.75	0.43 ± 0.04	0.48 ± 0.06	0.45 ± 0.05	0.75	0.75	0.52 ± 0.09	0.52 ± 0.07
Aerobic SRT (days)	5.2 ± 0.4	5.7 ± 0.3	3.0 ± 0.8	4.0 ± 1.2	3.6 ± 1.0	5.5 ± 0.6	5.0 ± 0.6	3.0 ± 1.0	2.9 ± 0.7
Temperature in 1 <sup>st</sup> B-Stage CSTR (°C)	20.2 ± 0.2	20.2 ± 0.4	20.1 ± 0.3	20.1 ± 0.2	20.0 ± 0.4	20.8 ± 0.9	19.9 ± 0.3	20.4 ± 0.4	20.4 ± 0.3

### A.10.3 Effluent Characteristics

Feed Type	A-Stage Effluent (ASE)					Primary Clarifier Effluent (PCE)			
	DO Control	ABAC	AvN MLE	AvN Low	AvN High	DO Control	ABAC	AvN MLE	AvN
Effluent NH <sub>4</sub> <sup>+</sup> (mg-N/L)	0.06 ± 0.03	1.01 ± 0.33	3.58 ± 0.97	6.31 ± 1.27	3.35 ± 0.93	0.19 ± 0.12	1.19 ± 0.26	4.03 ± 1.24	4.40 ± 1.61
Effluent NO <sub>2</sub> <sup>-</sup> (mg-N/L)	0.11 ± 0.10	0.21 ± 0.12	0.48 ± 0.13	1.30 ± 0.92	1.41 ± 0.38	0.21 ± 0.12	0.30 ± 0.09	0.56 ± 0.24	1.06 ± 0.35
Effluent NO <sub>3</sub> <sup>-</sup> (mg-N/L)	15.5 ± 5.38	6.98 ± 3.12	3.01 ± 1.07	5.10 ± 1.51	1.86 ± 0.95	6.57 ± 0.62	6.04 ± 0.27	3.20 ± 0.81	3.94 ± 1.16
NAR (NO <sub>2</sub> <sup>-</sup> /NOx*100%)	N/A	N/A	14 ± 4	21 ± 14	46 ± 15	N/A	N/A	15 ± 4	22 ± 7
NOx/Ammonia Ratio	N/A	N/A	0.98 ± 0.18	1.02 ± 0.16	1.00 ± 0.24	N/A	N/A	1.03 ± 0.45	1.23 ± 0.34
Effluent OP (mg-P/L)	1.73 ± 0.35	1.74 ± 0.24	2.29 ± 0.75	2.39 ± 0.68	2.17 ± 0.67	2.11 ± 0.45	1.21 ± 0.41	0.31 ± 0.72	0.85 ± 0.95
Effluent TIN (mg-N/L)	15.7 ± 5.37	8.21 ± 3.13	7.07 ± 1.99	12.7 ± 2.41	6.62 ± 1.68	6.97 ± 0.58	7.53 ± 0.48	7.79 ± 1.52	9.40 ± 2.06
Effluent TN (mg-N/L)	20.3 ± 7.23	10.2 ± 3.30	10.9 ± 2.69	15.0 ± 2.45	9.40 ± 2.30	9.55 ± 0.74	9.17 ± 0.30	10.1 ± 1.77	12.0 ± 1.10
SVI 30 (mL/g)	85 ± 17	129 ± 9	149 ± 23	107 ± 23	157 ± 25	182 ± 23	186 ± 17	157 ± 20	164 ± 15
Effluent TSS (mg/L)	29 ± 6	20 ± 3	29 ± 6	26 ± 8	25 ± 11	18 ± 8	17 ± 7	22 ± 7	28 ± 16

### A.10.4 Alkalinity Usage

Feed Type	A-Stage Effluent (ASE)					Primary Clarifier Effluent (PCE)			
	DO Control	ABAC	AvN MLE	AvN Low	AvN High	DO Control	ABAC	AvN MLE	AvN
Control Strategy									
Effluent pH	6.81 ± 0.06	6.80 ± 0.04	6.79 ± 0.06	6.77 ± 0.07	6.81 ± 0.06	6.85 ± 0.15	6.75 ± 0.10	6.81 ± 0.07	6.70 ± 0.15
Influent Ammonia (mg-N/L)	31.7 ± 1.2	30.0 ± 3.4	28.7 ± 2.6	28.8 ± 1.6	29.6 ± 2.0	37.5 ± 2.3	39.9 ± 1.0	36.7 ± 2.2	37.6 ± 1.1
Effluent Ammonia (mg-N/L)	0.06 ± 0.03	1.01 ± 0.33	3.58 ± 0.97	6.31 ± 1.27	3.35 ± 0.93	0.19 ± 0.12	1.19 ± 0.26	4.03 ± 1.24	4.40 ± 1.61
TAN Oxidized (mg-N/L)	31.7 ± 1.2	28.9 ± 3.4	25.1 ± 2.4	22.5 ± 1.7	26.2 ± 2.2	37.3 ± 2.3	38.7 ± 1.0	32.7 ± 2.0	33.2 ± 1.8
Influent Alkalinity (mg CaCO <sub>3</sub> /L)	158 ± 4.8	151 ± 25	179 ± 13	164 ± 7	171 ± 14	203 ± 6	209 ± 5	200 ± 7	203 ± 8
Effluent Alkalinity (mg CaCO <sub>3</sub> /L)	108 ± 5.5	123 ± 22	127 ± 15	118 ± 11	114 ± 10	114 ± 47	107 ± 15	86 ± 10	90 ± 3
Bicarbonate Feed (mg CaCO <sub>3</sub> /L)	122 ± 22	95 ± 24	60 ± 12	51 ± 15	40 ± 12	59 ± 23	77 ± 10	17 ± 14	26 ± 14
Alkalinity Added/TAN Oxidized (mg CaCO <sub>3</sub> added/ mg NH <sub>4</sub> <sup>+</sup> -N Removed)	5.37 ± 0.69	4.39 ± 0.57	4.40 ± 0.30	4.43 ± 0.28	3.92 ± 0.53	4.38 ± 0.38	4.48 ± 0.10	4.02 ± 0.23	4.17 ± 0.33

A.10.5 COD Properties

Feed Type	A-Stage Effluent (ASE)					Primary Clarifier Effluent (PCE)			
	DO Control	ABAC	AvN MLE	AvN Low	AvN High	DO Control	ABAC	AvN MLE	AvN
Total Influent COD (mg/L)	311 ± 61	303 ± 40	303 ± 47	260 ± 23	356 ± 53	370 ± 18	424 ± 28	429 ± 28	401 ± 32
Influent pCOD (mg/L)	166 ± 47	169 ± 25	166 ± 38	114 ± 17	186 ± 40	163 ± 23	201 ± 29	222 ± 34	192 ± 35
Influent sCOD (mg/L)	146 ± 18	134 ± 22	137 ± 21	147 ± 17	169 ± 30	207 ± 21	223 ± 13	207 ± 23	210 ± 36
Influent sCOD Fraction (%)	48 ± 5	44 ± 4	46 ± 6	56 ± 5	48 ± 7	56 ± 5	53 ± 4	48 ± 6	52 ± 8
Effluent COD (mg/L)	48 ± 9	40 ± 7	54 ± 18	49 ± 11	47 ± 14	37 ± 7	36 ± 10	46 ± 10	47 ± 10
Total COD Removed (mg/L/day)	263 ± 58	263 ± 42	251 ± 49	211 ± 26	309 ± 59	333 ± 20	388 ± 31	386 ± 25	357 ± 32
pCOD Removed (mg/L)	141 ± 45	153 ± 26	135 ± 42	89 ± 21	162 ± 47	148 ± 22	189 ± 31	202 ± 28	172 ± 34
sCOD Removed (mg/L)	122 ± 18	111 ± 23	115 ± 20	122 ± 16	147 ± 29	185 ± 21	199 ± 14	183 ± 24	184 ± 37

### A.10.6 Batch Test Results

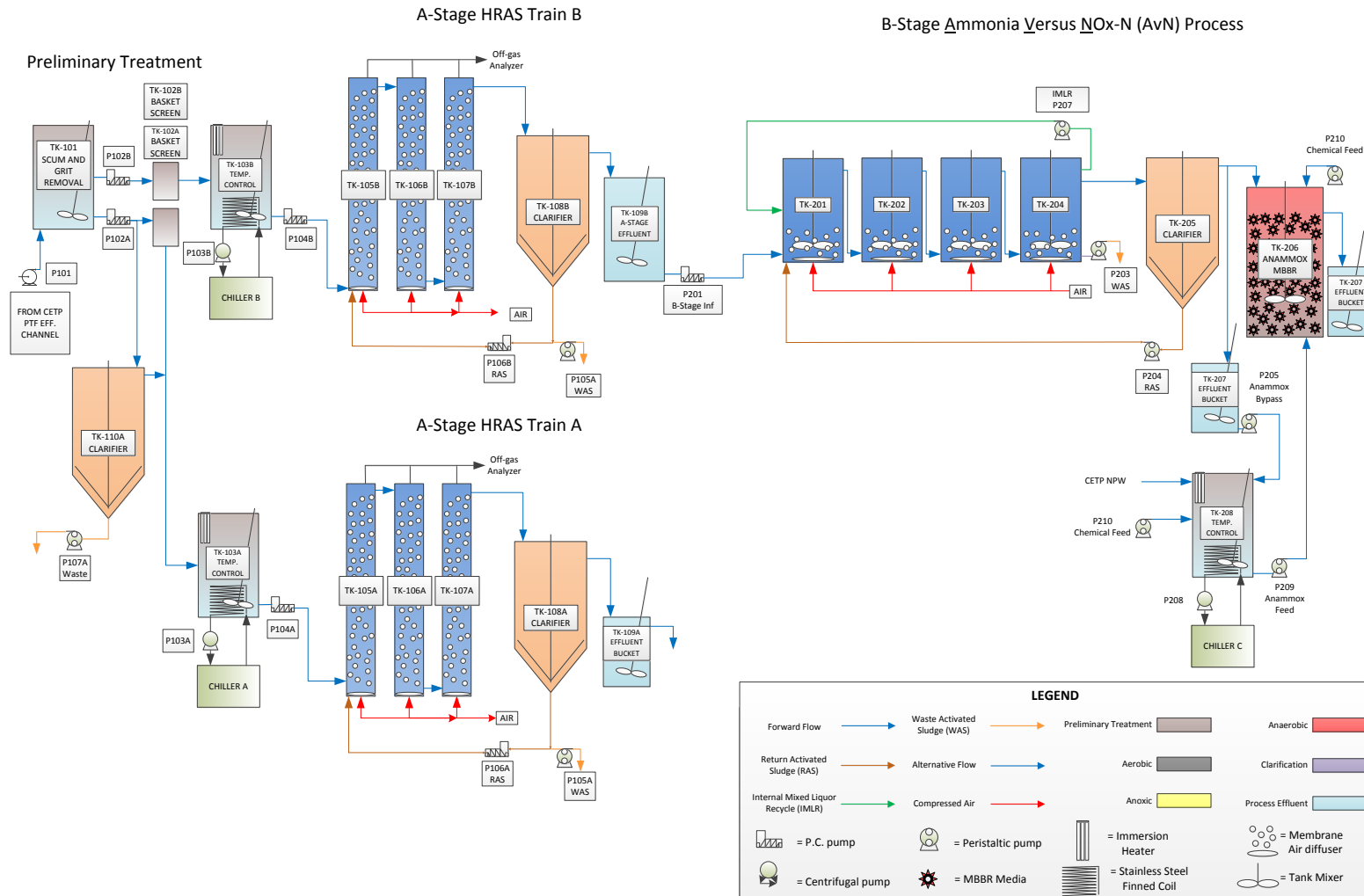
Feed Type	A-Stage Effluent (ASE)					Primary Clarifier Effluent (PCE)			
	DO Control	ABAC	AvN MLE	AvN Low	AvN High	DO Control	ABAC	AvN MLE	AvN
AOB rate (mgNO <sub>x</sub> -N/gMLSS/hr)	3.34 ± 0.65	3.15 ± 0.61	5.07 ± 0.56	4.62 ± 0.83	3.89 ± 0.58	3.15 ± 0.53	2.80 ± 0.12	3.36 ± 0.49	3.06 ± 0.53
NOB rate (mg NO <sub>3</sub> <sup>-</sup> -N/gMLSS/hr)	2.9 ± 0.34	3.39 ± 0.44	5.05 ± 0.58	3.92 ± 0.74	2.46 ± 0.68	3.38 ± 0.38	2.84 ± 0.13	3.10 ± 0.42	2.84 ± 0.53
NOB rate/AOB rate	0.89 ± 0.15	1.09 ± 0.09	1.00 ± 0.03	0.85 ± 0.06	0.63 ± 0.09	1.08 ± 0.12	1.02 ± 0.00	0.93 ± 0.07	0.93 ± 0.09
NO <sub>3</sub> <sup>-</sup> removal rate (mg NO <sub>3</sub> <sup>-</sup> -N/gMLSS/hr)	2.38 ± 0.28	2.49 ± 1.01	3.25 ± 0.56	2.69 ± 0.44	3.02 ± 0.78	2.77 ± 0.46	2.34 ± 0.31	2.94 ± 0.19	3.04 ± 0.28
NO <sub>2</sub> <sup>-</sup> removal rate (mg NO <sub>2</sub> <sup>-</sup> -N/gMLSS/hr)	-0.46 ± 0.46	-0.21 ± 0.38	-0.35 ± 0.37	0.26 ± 0.53	0.47 ± 0.69	0.36 ± 0.29	0.51 ± 0.20	0.37 ± 0.22	0.48 ± 0.46
NO <sub>x</sub> removal rate (mg NO <sub>x</sub> -N/gMLSS/hr)	1.92 ± 0.43	2.28 ± 1.19	2.90 ± 0.37	2.95 ± 0.66	3.48 ± 0.81	3.12 ± 0.50	2.85 ± 0.11	3.31 ± 0.27	3.52 ± 0.38
Oxygen Uptake Rate	57.0 ± 3.6	67.5 ± 6.0	71.8 ± 3.1	57.9 ± 5.9	71.6 ± 5.8	67.1 ± 2.5	81.2 ± 2.0	88.4 ± 11.6	74.6 ± 9.8

## **B: Appendix – Schematics and Photographs**

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## B.1 Complete Schematic of the CE Pilot

### Hampton Roads Sanitation District Chesapeake-Elizabeth Nutrient Removal Pilot Study Process Flow Schematic



**B.2 A-Stage Photograph**

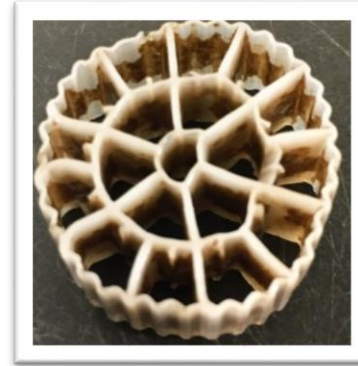




**B.3 B-Stage Photograph**



**B.4 Secondary Clarifier and Anammox MBBR Photographs**



**B.5 Primary Clarifier Photograph**

